SIMULATED EFFECTS OF FUTURE WITHDRAWALS ON WATER LEVELS IN THE NORTHEASTERN COASTAL PLAIN AQUIFERS OF NEW JERSEY

by William A. Battaglin and Mary C. Hill

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply Inch-Pound Unit	By	To Obtain Metric Unit
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.00405	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity and Transmissivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

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ABSTRACT

In the northeastern Coastal Plain of New Jersey, ground-water withdrawals have produced large cones of depression in all four major regional aquifers and caused the migration of saltwater into the two most-productive aquifers. In 1983, when total withdrawals exceeded 90 million gallons per day, water levels were as low as 185 feet below sea level in the Wenonah-Mount Laurel aquifer; 225 feet below sea level in the Englishtown aquifer system; 56 feet below sea level in the upper aquifer of the Potomac-Raritan-Magothy aquifer system; and, 82 feet below sea level in the middle aquifer of the Potomac-Raritan-Magothy aquifer system. Prior to development, water levels in the four aquifers were 20 to 120 feet above sea level.

An 11-layer finite-difference model of the entire New Jersey Coastal Plain was used to simulate the effects of six scenarios of future ground-water withdrawals on water levels in the northeastern New Jersey Coastal Plain through the year 2020. The model was developed as part of a U.S. Geological Survey Regional Aquifer-System Analysis (RASA) project. In the simulation with the most severe reductions, most of the ground-water withdrawals in the northeastern and west-central areas of the Coastal Plain were limited to 50 percent of 1983 withdrawals after 1990. Even with such restrictions, the lowest simulated water levels in the northeastern part of the Coastal Plain for 2010 are still well below sea level. If withdrawals are unrestricted and continue to increase at historic rates, simulated potentiometric levels for 2010 are substantially lower than 1983 water levels. These results are summarized below:

Aquifer	1983 water levels[1] (feet) near center of cone of depression	2010 water levels[1] (feet) simulated with: reduced withdrawals	2010 water levels[1] (feet) simulated with: unrestricted withdrawals
Wenonah-Mount Laurel aquifer	-185	-91	-350
Englishtown aquifer system	-225	-113	-420
Upper aquifer of the Potomac-Raritan-Magothy aquifer system	-56	-29	-126
Middle aquifer of the Potomac-Raritan-Magothy aquifer system	-82	-52	-126

[1] Datum is sea level.

INTRODUCTION

In the northeastern Coastal Plain of New Jersey, which includes all of Monmouth and parts of Middlesex, Mercer, Burlington, and Ocean Counties, ground-water withdrawals near Raritan Bay and along the Atlantic Coast have produced large cones of depression in the Wenonah-Mount Laurel aquifer, the Englishtown aquifer system, and the upper and middle aquifers of the Potomac-Raritan-Magothy aquifer system (locally called the Old Bridge and Farrington aquifers). Under prepumping conditions, ground-water levels in these four aquifers were 20 to 120 ft (feet) above sea level, and the direction of ground-water flow was towards Raritan Bay or the Atlantic Ocean (Zapecza and others, 1987, figs. 4-6). As the area became more developed, ground-water withdrawals increased and in some locations the direction of ground-water flow reversed. This has resulted in the movement of saltwater into parts of the upper and middle aquifers of the Potomac-Raritan-Magothy aquifer system along the south shore of Raritan Bay. Chloride concentrations at the Perth Amboy Water Department well number 2 (near Sayreville) increased from about 10 mg/L (milligrams per liter) in 1970 to over 50 mg/L in 1981; chloride concentrations at the Union Beach well field increased from about 10 mg/L in 1970 to over 650 mg/L in 1977 (Schaefer and Walker, 1981, fig. 8, and Schaefer, 1983, fig. 4). There is potential for saltwater intrusion to occur in other parts of the Potomac-Raritan-Magothy aquifer system and in the Wenonah-Mount Laurel aquifer and the Englishtown aquifer system near Raritan Bay and along the Atlantic coast. In an effort to minimize the potential for degradation of these aquifers, New Jersey State officials are considering severe reductions of ground-water withdrawals.

Purpose and Scope

This report presents the results of a study in which a calibrated numerical model was used to simulate the effects of six scenarios of future withdrawals on water levels in the major aquifers of the northeastern New Jersey Coastal Plain, and on flow rates into and out of selected areas and aquifers.

The simulations are from January 1, 1984, through December 31, 2020, and can be categorized as follows: (1) no withdrawal restrictions are implemented, (2) withdrawal reductions are implemented in the northeastern Coastal Plain, and (3) withdrawal reductions are implemented in the northeastern and west-central Coastal Plain. Estimates of unrestricted future withdrawals were provided by the New Jersey Department of Environmental Protection, Division of Water Resources (NJDEP/DWR) or were estimated using a linear regression of historical withdrawal data. The estimates of reduced future withdrawals were based on the prospective management alternatives being considered by the NJDEP/DWR.

Location

The study area encompasses about 2,200 square miles (mi^2) within the Atlantic Coastal Plain physiographic province and includes all of Monmouth County and parts of Burlington, Mercer, Middlesex, and Ocean Counties. The numerical model used in this study encompasses a much larger area, about 12,500 mi^2, and includes the entire New Jersey Coastal Plain, extending from Delaware Bay in the southwest to Raritan Bay in the northeast, and from the Fall Line in the northwest to the Atlantic Ocean in the southeast (Martin, 1987, 249 p.). The model boundary and the study area are shown in figure 1.

Hydrogeologic Setting

The study area is characterized by broad lowlands that range in altitude from sea level to 150 ft above sea level. A ridge that ranges in altitude from 0 to 391 ft stretches southwest from Raritan Bay through Freehold and into Ocean County. This ridge forms the divide between streams draining into the Atlantic Ocean on the east and streams draining into the Raritan and Delaware Rivers on the north and west (Jablonski, 1968, p 9-10).

Major rivers in the study area include the Raritan, South, Navesink, Manasquan, and Delaware Rivers. Major population centers include Freehold, Asbury Park, Bricktown, Manasquan, Toms River, and Pemberton.

The northeastern Coastal Plain of New Jersey is a wedge-shaped mass of unconsolidated and partly consolidated marine, marginal marine, and non-marine deposits of clay, silt, sand, and gravel. The sediments range in age from Early Cretaceous to Holocene and lie uncomformably on pre-Cretaceous bedrock consisting chiefly of Precambrian and lower Paleozoic crystalline rocks (Zapecza, 1984, p. 6). The thickness of the Coastal Plain sediments in the onshore parts of the study area ranges from a featheredge along the Fall Line (fig. 1) to about 5,000 ft in southern Ocean County (Jablonski, 1968, fig. 12). The Tertiary and Cretaceous sediments generally strike southwest to northeast and dip gently to the southeast from 10 to 60 ft per mile. The overlying Quarternary deposits, where present, are essentially flatlying (Zapecza, 1984, p. 6). The lithology, thickness, elevation, and areal extent of all of the aquifers and confining units in the New Jersey Coastal Plain are described in detail by Zapecza (1984).

A geologic section through the study area is shown in figure 2. The principal aquifers in the study area from youngest to oldest are: the Wenonah-Mount Laurel aquifer; the Englishtown aquifer system; the upper aquifer of the Potomac-Raritan-Magothy aquifer system; and the middle aquifer of the Potomac-Raritan-Magothy aquifer system. In the study area, the upper aquifer of the Potomac-Raritan-Magothy aquifer system is equivalent to the Old Bridge aquifer; the middle aquifer of the Potomac-Raritan-Magothy aquifer system is equivalent to the Farrington aquifer (Zapecza, 1984, p. 17-18). The lower aquifer of the Potomac-Raritan-Magothy aquifer system exists only in the extreme southern part of the study area. The principal aquifers underlie several other aquifers, including (from youngest to oldest): the Kirkwood-Cohansey aquifer system; the Piney Point aquifer; and the Vincentown aquifer. The geologic and hydrogeologic units of the New Jersey Coastal Plain are shown in table 1. Outcrop areas shown on plates 1 through 5 were modified from those compiled by J. P. Owens in Miscellaneous Geologic Investigations Map I-514-B (U.S. Geological Survey, 1967).

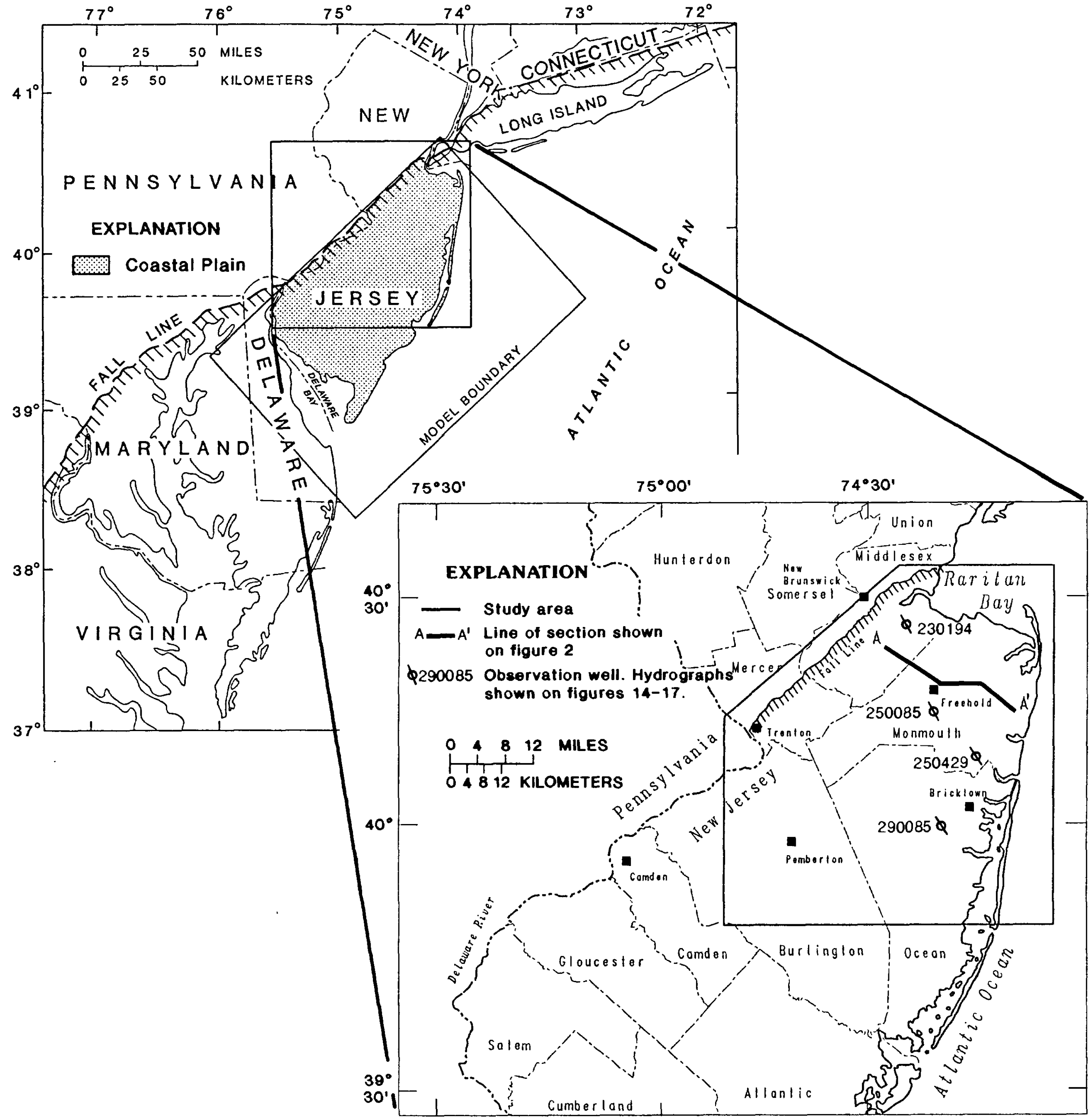


Figure 1.--Location of study area, the Fall Line, and the New Jersey Regional Aquifer-System Analysis model boundary.

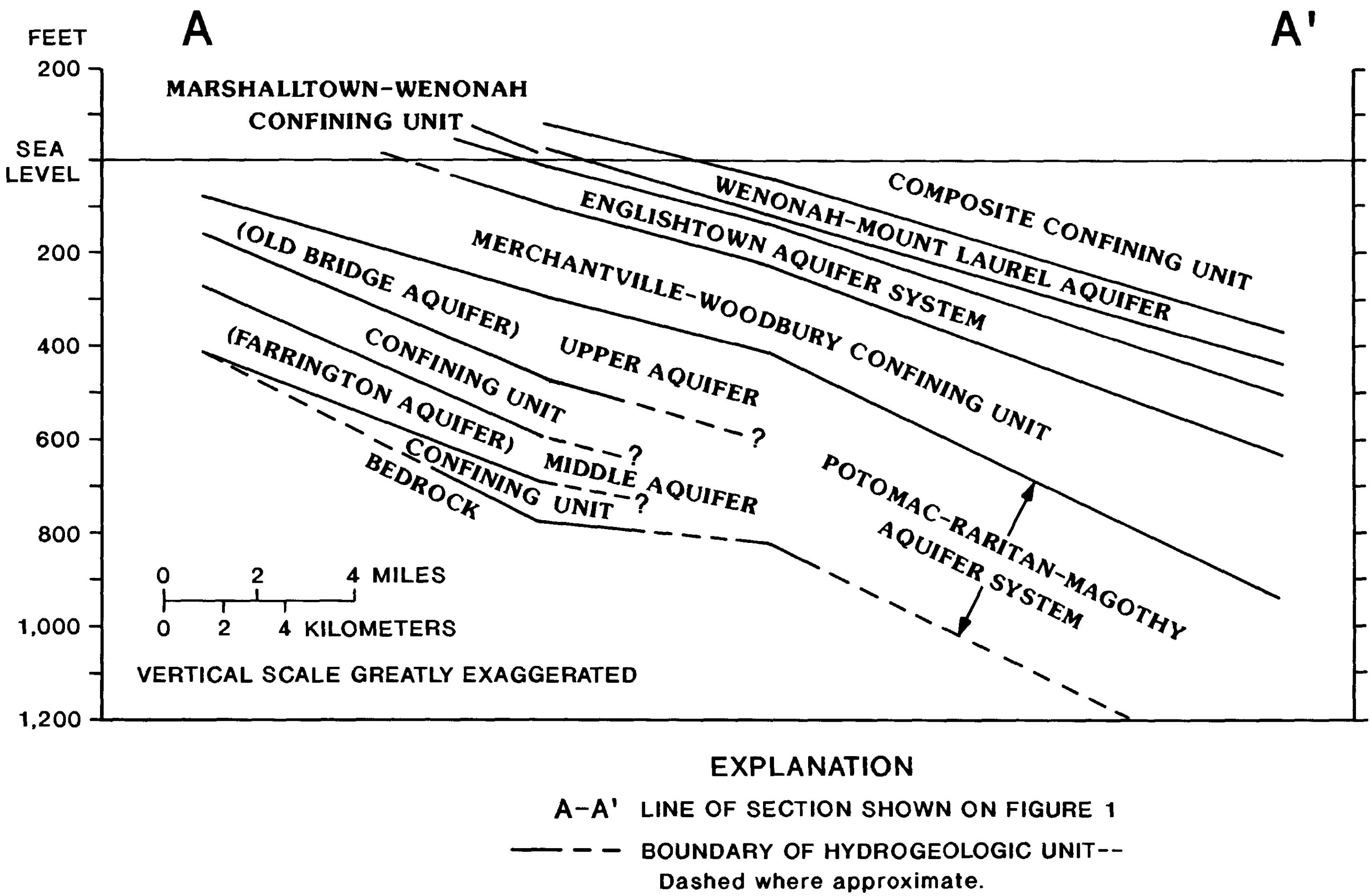


Figure 2.--Hydrogeologic section of New Jersey Coastal Plain sediments in Middlesex and Monmouth Counties. (Modified from Zapecza, 1984, plate 3.)

Table 1.--Geologic and hydrogeologic units of the New Jersey Coastal Plain and model units used in this study

[Modified from Zapecza, 1984, table 1]

SYSTEM	SERIES	GEOLOGIC UNIT	LITHOLOGY	HYDROGEOLOGIC UNIT	MODEL UNIT[1] UPDIP	MODEL UNIT[1] DOWNDIP
Quaternary	Holocene	Alluvial deposits	Sand, silt, and black mud.	Undifferentiated	—	—
Quaternary	Holocene	Beach sand and gravel	Sand, quartz, light-colored, medium-to coarse-grained, pebbly.	Undifferentiated	—	A10
Quaternary	Pleistocene	Cape May Formation	Sand, quartz, light-colored, heterogeneous clayey, pebbly.	Undifferentiated	—	C9
Quaternary	Pleistocene	Cape May Formation	Sand, quartz, light-colored, heterogeneous clayey, pebbly.	Undifferentiated	—	A9
Tertiary	Miocene	Pensauken Formation	Sand, quartz, light-colored, heterogeneous clayey, pebbly.	Undifferentiated	—	—
Tertiary	Miocene	Bridgeton Formation	Sand, quartz, light-colored, heterogeneous clayey, pebbly.	Kirkwood-Cohansey aquifer system	A9	A9
Tertiary	Miocene	Beacon Hill Gravel	Gravel, quartz, light colored, sandy.	Kirkwood-Cohansey aquifer system	A9	A9
Tertiary	Miocene	Cohansey Sand	Sand, quartz, light-colored, medium to coarse-grained, pebbly; local clay beds.	Kirkwood-Cohansey aquifer system	A9	A9
Tertiary	Miocene	Kirkwood Formation	Sand, quartz, gray and tan, very fine-to, medium-grained, micaceous, and dark-colored diatomaceous clay.	Confining unit	A8	C8
Tertiary	Miocene	Kirkwood Formation	Sand, quartz, gray and tan, very fine-to, medium-grained, micaceous, and dark-colored diatomaceous clay.	Rio Grande water bearing zone	A8	A8
Tertiary	Miocene	Kirkwood Formation	Sand, quartz, gray and tan, very fine-to, medium-grained, micaceous, and dark-colored diatomaceous clay.	Confining unit	A8	A8
Tertiary	Miocene	Kirkwood Formation	Sand, quartz, gray and tan, very fine-to, medium-grained, micaceous, and dark-colored diatomaceous clay.	Atlantic City 800-foot sand	A8	A8
Tertiary	Miocene	Kirkwood Formation	Sand, quartz, gray and tan, very fine-to, medium-grained, micaceous, and dark-colored diatomaceous clay.	Composite confining unit	C7	C7
Tertiary	Oligocene	Piney Point Formation	Sand, quartz and glauconite, fine-to coarse-grained.	Composite confining unit: Piney Point aquifer	A7	A7
Tertiary	Eocene	Shark River Formation	Sand, quartz and glauconite, fine-to coarse-grained.	Composite confining unit: Piney Point aquifer	A7	A7
Tertiary	Eocene	Manasquan Formation	Clay, silty and sandy, glauconitic, green, gray and brown, fine-grained quartz sand.	Composite confining unit	C6	C6
Tertiary	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	A6	A6
Tertiary	Paleocene	Hornerstown Sand	Sand, clayey, glauconitic, dark green, fine to coarse-grained.	Composite confining unit	C5	C5
Cretaceous	Upper Cretaceous	Tinton Sand	Sand, quartz, and glauconite, brown and gray, fine-to coarse-grained, clayey, micaceous.	Composite confining unit	C5	C5
Cretaceous	Upper Cretaceous	Red Bank Sand	Sand, quartz, and glauconite, brown and gray, fine-to coarse-grained, clayey, micaceous.	Composite confining unit: Red Bank sand	C5	C5
Cretaceous	Upper Cretaceous	Navesink Formation	Sand, clayey, silty, glauconitic, green and black, medium-to coarse-grained.	Composite confining unit	C5	C5
Cretaceous	Upper Cretaceous	Mount Laurel Sand	Sand, quartz, brown and gray, fine-to coarse-grained, slightly glauconitic.	Wenonah-Mount Laurel aquifer	A5	A5
Cretaceous	Upper Cretaceous	Wenonah Formation	Sand, very fine-to fine-grained, gray and brown, silty, slightly glauconitic.	Marshalltown-Wenonah confining unit	C4	C4
Cretaceous	Upper Cretaceous	Marshalltown Formation	Clay, silty, dark greenish gray, glauconitic quartz sand.	Marshalltown-Wenonah confining unit	C4	C4
Cretaceous	Upper Cretaceous	Englishtown Formation	Sand, quartz, tan and gray, fine-to medium-grained; local clay beds.	Englishtown aquifer system	A4	A4
Cretaceous	Upper Cretaceous	Woodbury Clay	Clay, gray and black, micaceous silt.	Merchantville-Woodbury confining unit	C3	C3
Cretaceous	Upper Cretaceous	Merchantville Formation	Clay, glauconitic, micaceous, gray and black; locally very fine-grained quartz and glauconitic sand.	Merchantville-Woodbury confining unit	C3	C3
Cretaceous	Upper Cretaceous	Magothy Formation	Sand, quartz, light-gray, fine-to coarse-grained. Local beds of dark-gray lignitic clay.	Potomac-Raritan-Magothy aquifer system: Upper aquifer	A3	A3
Cretaceous	Upper Cretaceous	Raritan Formation	Sand, quartz, light-gray, fine-to coarse-grained, pebbly, arkosic, red, white, and variegated clay.	Potomac-Raritan-Magothy aquifer system: Confining unit	C2	C2
Cretaceous	Upper Cretaceous	Raritan Formation	Sand, quartz, light-gray, fine-to coarse-grained, pebbly, arkosic, red, white, and variegated clay.	Potomac-Raritan-Magothy aquifer system: Middle aquifer	A2	A2
Cretaceous	Lower Cretaceous	Potomac Group	Alternating clay, silt, sand, and gravel.	Potomac-Raritan-Magothy aquifer system: Confining unit	C1	C1
Cretaceous	Lower Cretaceous	Potomac Group	Alternating clay, silt, sand, and gravel.	Potomac-Raritan-Magothy aquifer system: Lower aquifer	A1	A1
Pre-Cretaceous		Bedrock	Precambrian and lower Paleozic crystalline rocks, metamorphic schist and gneiss; locally Triassic sandstone, shale and Jurassic basalt.	Bedrock confining unit		

— Units not present

[1] 'A' refers to modeled aquifer, 'C' refers to modeled confining unit, number refers to model layer

Only freshwater flow has been simulated. For this report, freshwater is defined as water with chloride concentrations less than 10,000 mg/L. The estimated locations of 10,000-mg/L chloride concentrations within the aquifers are based on data presented by Meisler (1980) and are referred to in this report as the idealized freshwater-saltwater interface.

Each of the aquifers, except for the Kirkwood-Cohansey aquifer system, is overlain entirely or nearly entirely by a confining unit. The Kirkwood-Cohansey aquifer system and the outcrop areas of the underlying (older) aquifers are unconfined, and are the major source of recharge to the confined aquifers.

The Merchantville-Woodbury confining unit, which is the most extensive confining unit in the northeastern Coastal Plain of New Jersey, lies between the Englishtown aquifer system and the upper aquifer of the Potomac-Raritan-Magothy aquifer system (Zapecza, 1984, p. 19). This confining unit consists of the Merchantville Formation and the Woodbury Clay. In southern Ocean County, this confining unit lies interjacent to the upper aquifer of the Potomac-Raritan-Magothy aquifer system and the Wenonah-Mount Laurel aquifer. In this area, the confining unit also includes fine-grained sediments of the Englishtown, Marshalltown, and Wenonah Formations (Zapecza, 1984, p. 20). The Merchantville-Woodbury confining unit ranges in thickness from a featheredge at its outcrop to more than 450 ft in southern Ocean County (Zapecza, 1984, pl. 12). Other confining units in the study area are less widespread and generally are less restrictive to vertical flow than the Merchantville-Woodbury confining unit.

Previous Investigations

Previous studies have provided a general definition of Coastal Plain geology, aquifer and confining bed properties, and the ground-water flow system for the Coastal Plain of New Jersey. Hydrogeologic framework reports include those of Barksdale and others (1943), Barksdale and others (1958), Jablonski (1968), Gill and Farlekas (1976), Zapecza (1984), Zapecza and others (1987).

Reports concerning modeling of ground-water systems in the New Jersey Coastal Plain include those of Nichols (1977), Nemickas (1976), Farlekas (1979), Luzier (1980), Leahy (1982), Leahy and Martin (1986), and Martin (in press). Water-level data for 1978 and 1983 can be found in Walker (1983), and Eckel and Walker (1986).

Acknowledgments

The writers acknowledge the assistance of the New Jersey Department of Environmental Protection, Division of Water Resources (NJDEP/DWR), for providing ground-water-withdrawal data. Special thanks are extended to Arthur Hunnewell and Jeffrey Hoffman for their help in coordinating the State input into this joint project. This work was funded in part by the New Jersey Department of Environmental Protection.

METHODS AND APPROACH

Ground-water flow in the New Jersey Coastal Plain aquifers is simulated using a finite-difference model that was developed as part of the U.S. Geological Survey New Jersey Coastal Plain Regional Aquifer-System Analysis (RASA) project (Martin, in press). The New Jersey RASA study used a modified version (Leahy, 1982) of the Trescott (1975) computer program to simulate water levels in 10 Atlantic Coastal Plain aquifers.

Six scenarios of ground-water withdrawals for 1984 through 2020 were simulated using the 11-layer New Jersey RASA model (Martin, in press). In scenario A, withdrawal restrictions were not imposed. Estimates of unrestricted future withdrawals for parts of Monmouth, Middlesex, and Camden Counties were provided by the NJDEP/DWR; elsewhere, unrestricted withdrawals were estimated based on historic pumping trends determined using a linear regression of total annual withdrawals in each model cell. In the other five scenarios (B, C, D, E, and F), withdrawals in specified areas and aquifers were reduced according to different management alternatives being considered by the NJDEP/DWR. Preliminary investigations by the authors indicate that future withdrawals from the Potomac-Raritan-Magothy aquifer system near Camden had a significant effect on simulated-water levels in the Potomac-Raritan-Magothy aquifer system in the northeastern Coastal Plain of New Jersey. New Jersey State officials are also considering reductions of ground-water withdrawals near Camden for this aquifer system. The area near Camden was included as an area of reduced withdrawals in three of the five reduced-withdrawal scenarios.

Water levels in this report were derived from interpreted potentiometric surface maps of measured water-level data. The water levels were produced in the following way: (1) measured water levels were contoured to produce maps of the potentiometric surfaces for each aquifer (Walker, 1983; Eckel and Walker, 1986), (2) the interpreted contour maps were discretized using the grid shown in figure 7, and (3) the point values at each grid node are used as the water levels. Therefore, the water levels in this report are average values for areas of six or more square miles. These average values appropriately represent the potentiometric surface of the aquifer system for the purposes of this report.

Simulated water levels for the six scenarios were calculated by adding simulated changes in water levels for 1984 through 2020 to 1983 water levels. The New Jersey RASA model was used to simulate water-level changes for the years 1984 through 2020. Changes in water levels for 1984 through 2020 are caused by changes in withdrawals after 1983 and by the transient effects of prior withdrawals. Ground-water flows were calculated for rectangular budget areas from simulated water levels.

Definition and Location of Central Areas

The State intends to regulate ground-water withdrawals from the central areas of major cones of depression within the Wenonah-Mount Laurel aquifer, the Englishtown aquifer system, and the Potomac-Raritan-Magothy aquifer system. The central areas were defined by State personnel in accordance with criteria defined in the New Jersey Water Supply Management Act Rules (A. Hunnewell and J. Hoffman, New Jersey Department of Environmental

Protection, Division of Water Resources, written commun., 1985) as the area within the -30 foot contour on 1983 potentiometric surface maps by Eckel and Walker (1986). The central areas are called depleted areas by Hoffman and Hunnewell (1986). Less stringent restrictions would be applied to 3-mile-wide margins, called threatened margins by Hoffman and Hunnewell (1986), around each central area. Figures 3, 4, 5, and 6 show the -30 foot contours and the model representation of the central areas and associated margins of the aquifers. Central areas 4, 3, 2, and 1 apply to the Wenonah-Mount Laurel aquifer, the Englishtown aquifer system, the upper aquifer of the Potomac-Raritan-Magothy aquifer system, and the middle aquifer of the Potomac-Raritan-Magothy aquifer system, respectively (figs. 3-6). Central areas 5 and 6 (fig. 6) apply to both the middle and lower aquifers of the Potomac-Raritan-Magothy aquifer system. Area 7 (fig. 5) applies to the upper aquifer of the Potomac-Raritan-Magothy aquifer system.

Description of Modeled Ground-Water-Withdrawal Scenarios

The modeled scenarios are described briefly in table 2. Scenario A results show the effect of simulated growth with no restrictions on estimated future withdrawals. Scenarios B, C, and D simulate withdrawals reduced to 50 percent of 1983 rates after 1990 in central areas 1-4, 1-5, and 1-7, respectively. Results of these three scenarios show the effect of reducing withdrawals in central areas within and outside of the study area, and the regional nature of ground-water flow in the New Jersey Coastal Plain. Scenarios E and F are similar to scenario D, except withdrawals are reduced to 60 and 70 percent of 1983 rates, respectively. Results of Scenarios D, E, and F show the effects of allowing different percentages of 1983 withdrawals to be pumped after 1990.

For scenarios B, C, D, E, and F, withdrawals from central and margin areas increase at one-half the projected rate of growth from 1984 through 1990. After 1990, withdrawals in the margin areas for these scenarios are kept at 1983 levels. Outside of the central and margins areas, unrestricted future withdrawal estimates are used.

Model Design

The model consists of a finite-difference grid with 29 rows and 51 columns. Most grid cells in inland areas of the Coastal Plain are 6.3 mi^2 in area; those in offshore areas are as large as 47.5 mi^2. Model nodes are located in the center of each grid cell and are designated by layer, row, and column number. The 10 model layers representing Coastal Plain aquifers and their relationship to geologic and hydrologic units of the Coastal Plain are shown in table 1. The model grid is shown in figure 7.

The top, lateral, and bottom boundaries of the model are represented as constant head or specified flux. The top boundary of the model (layer 11) is a constant-head boundary at stream altitudes. Stream constant-head nodes are above the unconfined outcrop areas of the aquifers and represent the average altitude of all streams within a cell. Recharge to the water table is assumed to be 20 inches per year; it is represented as specified flux to the aquifer nodes representing the unconfined outcrop areas of the aquifers.

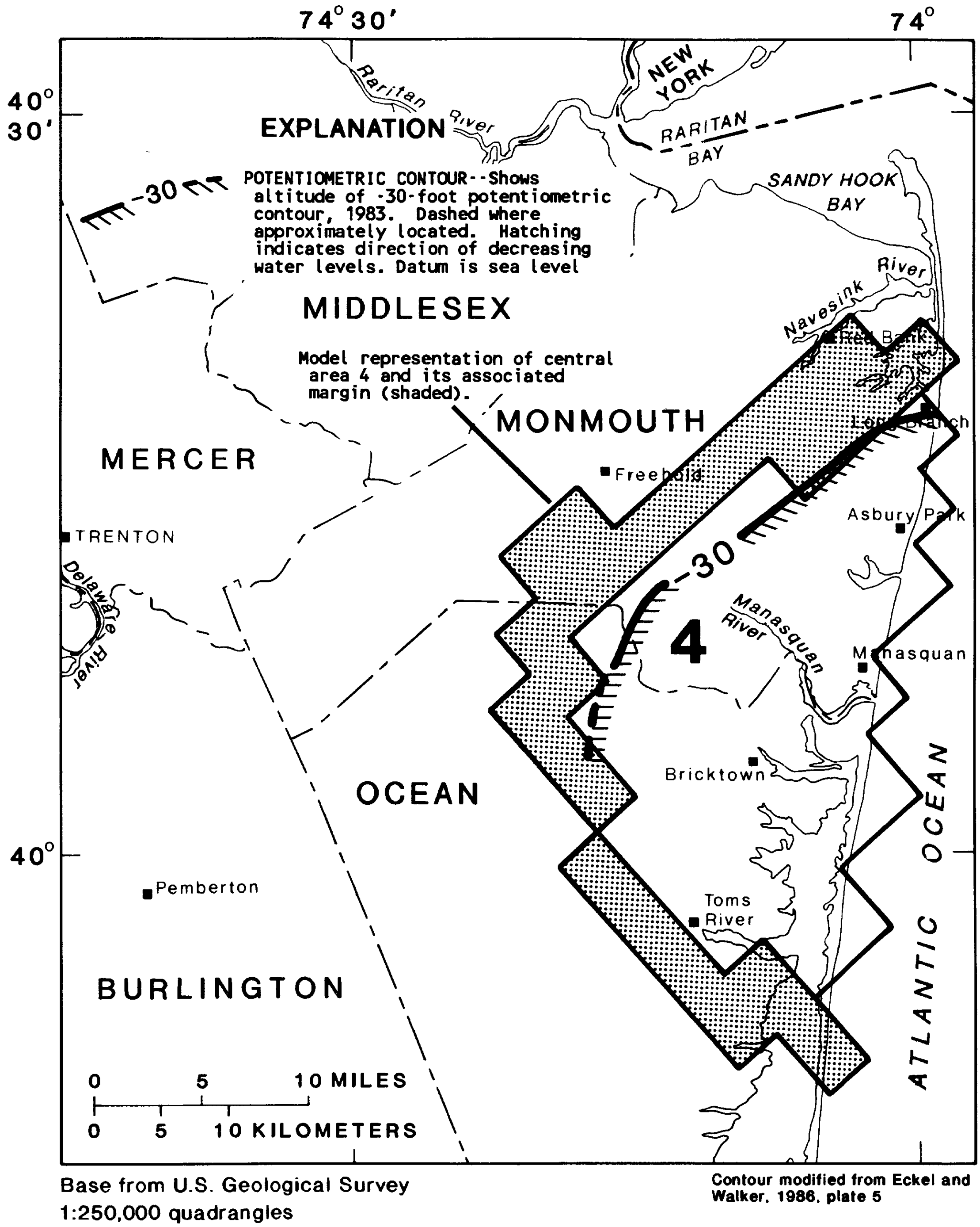


Figure 3.--Model representation of central and margin areas in the Wenonah-Mount Laurel aquifer.

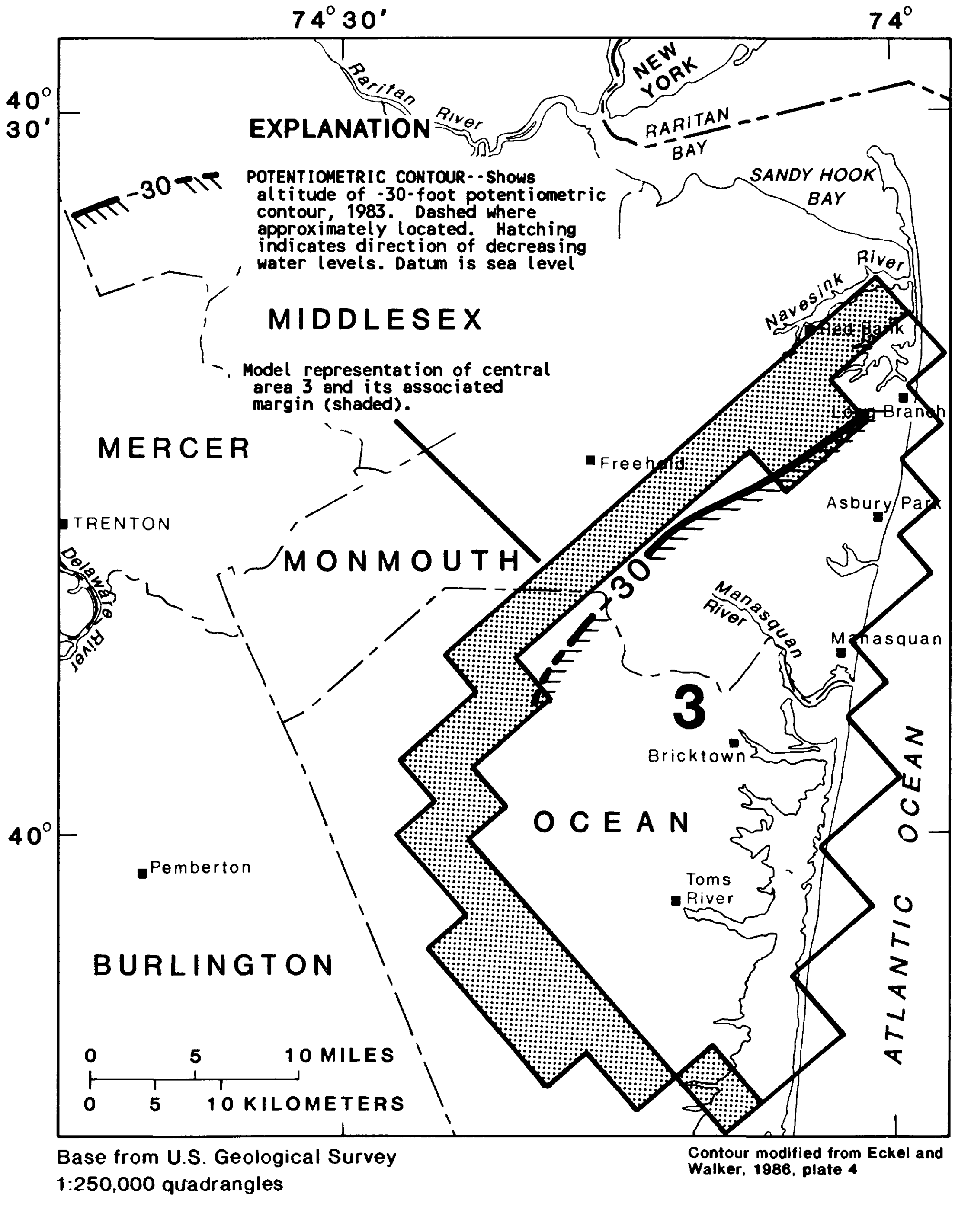
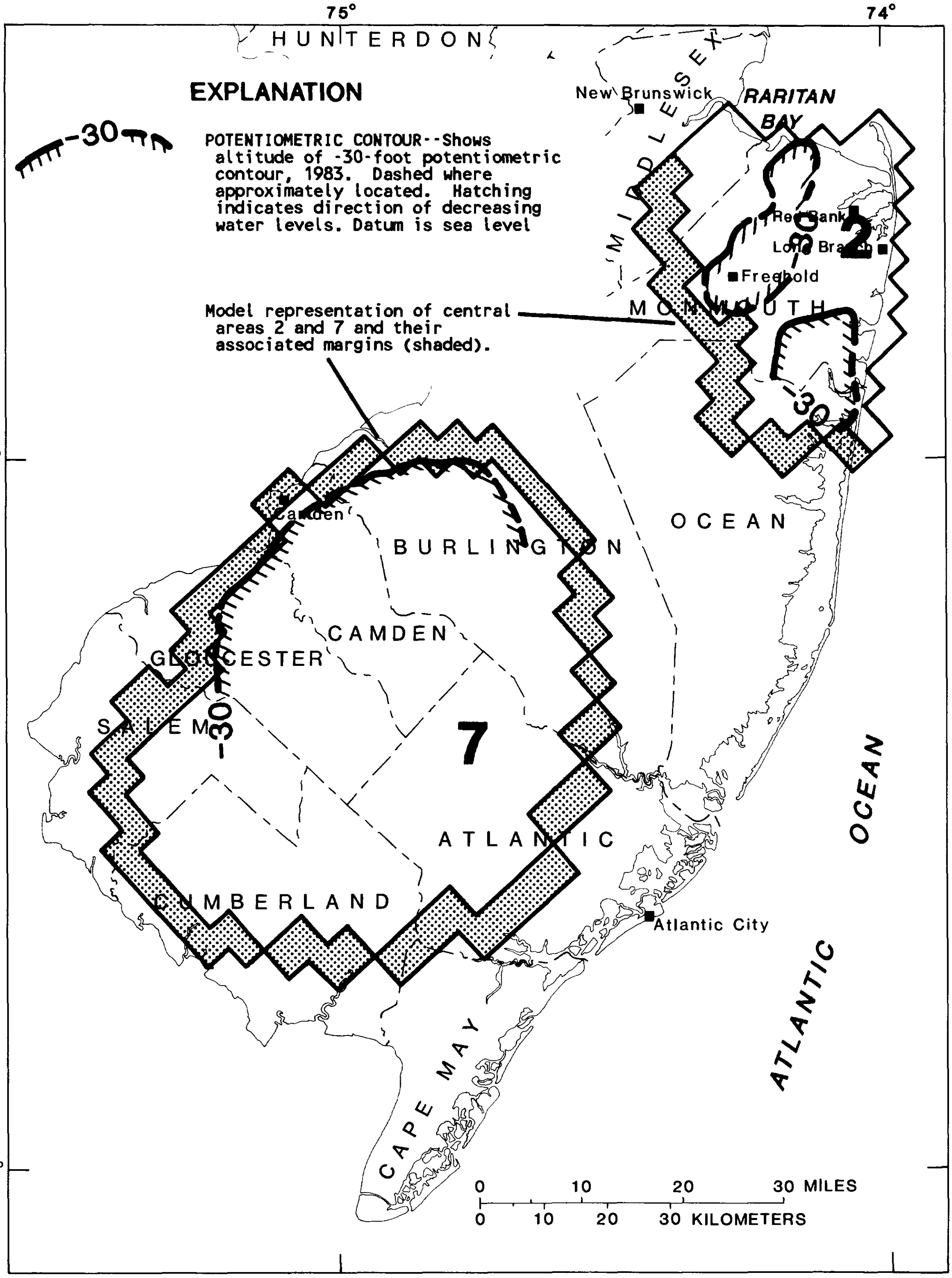


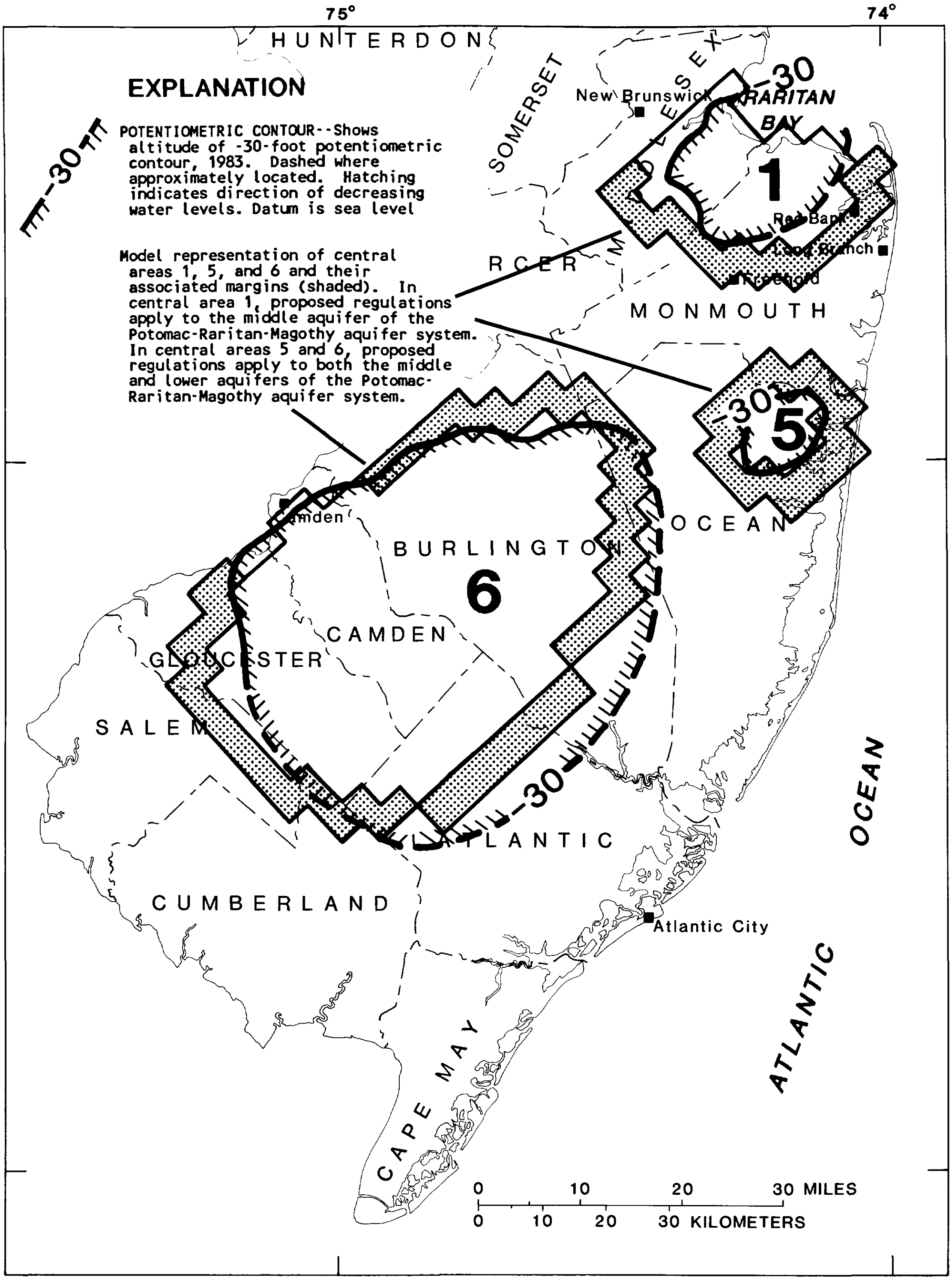
Figure 4.--Model representation of central and margin areas in the Englishtown aquifer system.



Base from U.S. Geological Survey
1:250,000 quadrangles

Contour modified from Eckel and Walker, 1986, plate 3.

Figure 5.--Model representation of central and margin areas in the upper aquifer of the Potomac-Raritan-Magothy aquifer system.



Base from U.S. Geological Survey 1:250,000 quadrangles

Contour modified from Eckel and Walker, 1986, plate 3.

Figure 6.--Model representation of central and margin areas in the middle and lower aquifers of the Potomac-Raritan-Magothy aquifer system.

Table 2.--Description of modeled ground-water-withdrawal scenarios

Scenario	Percent of 1983 rates[3]	Central areas affected[4]	Aquifers affected
A[1]	Unrestricted	All	All
B[2]	50	1	Middle[5]
		2	Upper[5]
		3	Englishtown aquifer system
		4	Wenonah-Mount Laurel
C[2]	50	1	Middle[5]
		2	Upper[5]
		3	Englishtown aquifer system
		4	Wenonah-Mount Laurel
		5	Lower and middle[5]
D[2]	50	1	Middle[5]
		2	Upper[5]
		3	Englishtown aquifer system
		4	Wenonah-Mount Laurel
		5	Lower and middle[5]
		6	Lower and middle[5]
		7	Upper[5]
E[2]	60	1	Middle[5]
		2	Upper[5]
		3	Englishtown aquifer system
		4	Wenonah-Mount Laurel
		5	Lower and middle[5]
		6	Lower and middle[5]
		7	Upper[5]
F[2]	70	1	Middle[5]
		2	Upper[5]
		3	Englishtown aquifer system
		4	Wenonah-Mount Laurel
		5	Lower and middle[5]
		6	Lower and middle[5]
		7	Upper[5]

[1] Scenario A--Unrestricted ground-water-withdrawal data are used for all active model cells for 1984 through 2020.

[2] Scenarios B-F--between 1983 and 1990, ground-water withdrawals in central and margin areas (fig. 3-6) that experience reductions for a given scenario are allowed to increase at one-half the unrestricted rate between 1983 and 1990. After 1990, withdrawals in the margin areas that experience reductions for a given scenario are restricted to 1983 rates. Withdrawals outside central and margin areas are unrestricted.

[3] Ground-water withdrawals after 1990 are reduced to a percentage of the 1983 rates.

[4] Central areas shown on figures 3-6.

[5] Aquifers of the Potomac-Raritan-Magothy aquifer system.

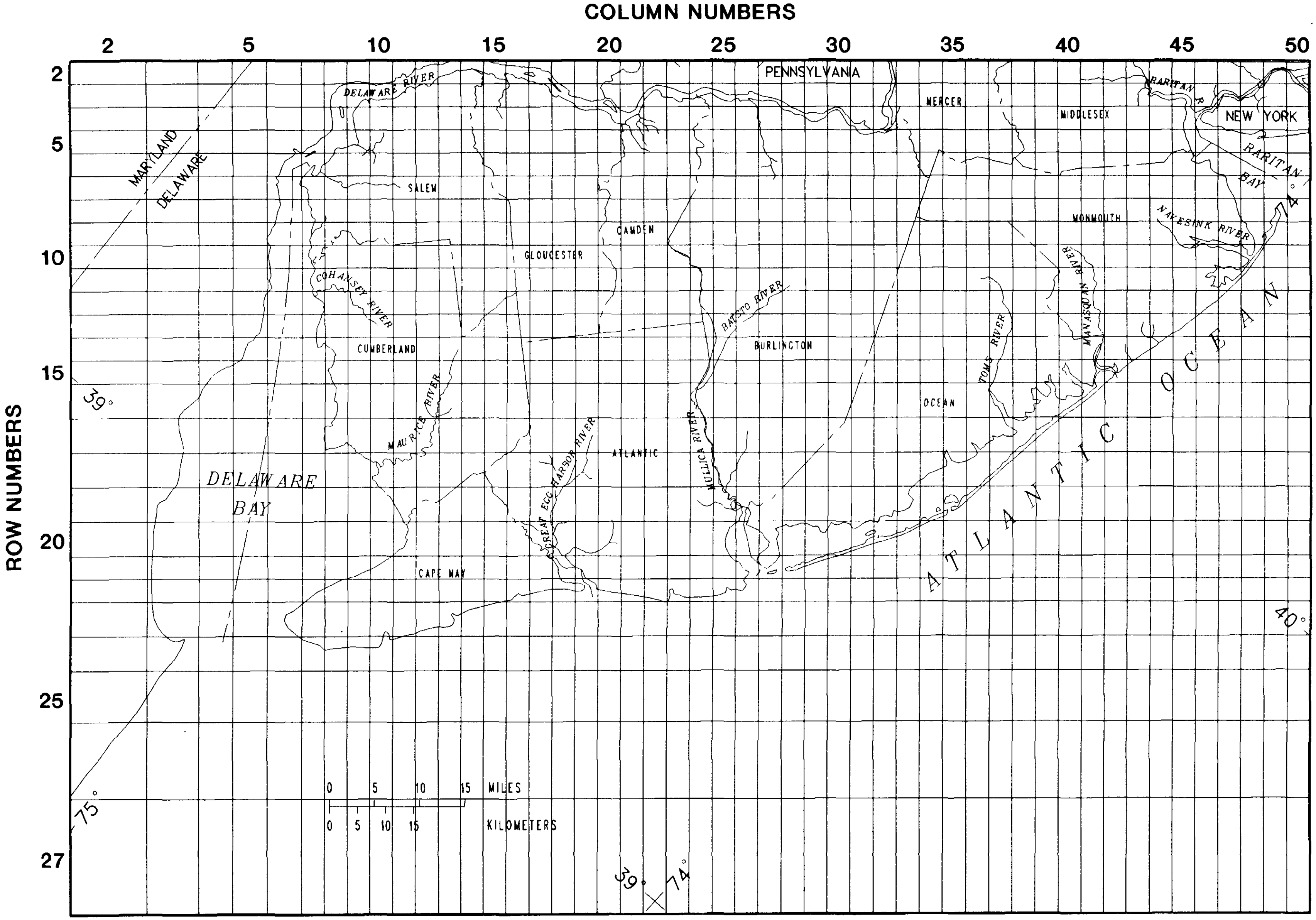


Figure 7.--Regional Aquifer-System Analysis (RASA) grid.

The northeastern, southeastern, and southwestern lateral boundaries of the aquifer system are no-flow or flux boundaries, depending on whether an aquifer extends beyond the modeled area. Downdip no-flow boundaries represent either the limits of aquifers or an idealized freshwater-saltwater interface at the estimated location of 10,000-mg/L chloride concentrations within the aquifers (Martin, in press, figs. 30-34). Flows for the lateral flux boundaries, up to 1981, were calculated using the regional RASA model of the northern Atlantic Coastal Plain (New York to North Carolina) described by Leahy and Martin (1986, p. 169-172). Boundary fluxes used in the six simulations, for 1981 through 2020 were assumed to be equal to fluxes used in the New Jersey RASA model for the 1978 through 1980 pumping period. The bottom boundary, which is a no-flow boundary, represents the sloping contact of the Coastal Plain sediments with the crystalline basement rock. This contact intersects land surface at the Fall Line (fig. 1) which is represented as a lateral no-flow boundary to the northwest. See Martin (in press) for a more complete discussion of model boundaries.

Annual withdrawal data for the New Jersey RASA model is represented in simulations as average pumping over the length of each pumping period. All pumping periods began and ended on January 1. Average pumping for all historical pumping periods was based on annual pumpage data collected by the U.S. Geological Survey. Pumping periods for the calibration period (1896-1980) were between 3 and 25 years long; those for the predictive period (1984-2020) were 5 years long, except for the first pumping period, 1984 through 1985, which was 2-years long. A three-year pumping period, 1981 through 1983, was used as a verification period for the model. This pumping period did not indicate any serious problems with the calibration or predictive capability of the model.

GROUND-WATER WITHDRAWALS

Ground-Water Withdrawals in 1983

In Monmouth and Ocean Counties ground-water withdrawals in 1983 were about 1 Mgal/d (million gallons per day) from the Wenonah-Mount Laurel aquifer, and about 9 Mgal/d from the Englishtown aquifer system (Eckel and Walker, 1986, p. 8). Pumping from the Englishtown aquifer system has created large regional cones of depression in both the Wenonah-Mount Laurel aquifer and the Englishtown aquifer system (Walker, 1983, p. 37 and 52, plates 3-4). The cones are centered in southeastern Monmouth and northeastern Ocean Counties near the Atlantic Coast. In the Wenonah-Mount Laurel cone, water levels were as low as 185 ft below sea level, and in the Englishtown cone, water levels were as low as 225 ft below sea level.

Within the study area, the Potomac-Raritan-Magothy aquifer system is the most heavily used, with ground-water withdrawals in Mercer, Middlesex, Monmouth, and Ocean Counties totaling about 83 Mgal/d in 1983 (Eckel and Walker, 1983, p. 8). Most of these withdrawals were from wells located within 10 miles of the aquifer's outcrop area. In 1983, in a major cone of depression near Freehold in Monmouth County, water levels in the upper aquifer of the Potomac-Raritan-Magothy aquifer system were as low as 56 ft below sea level. In a major cone of depression south of Raritan Bay, and in a cone of depression near Bricktown in Ocean County, water levels in the middle aquifer of the Potomac-Raritan-Magothy aquifer system were as low as

82 and 35 ft below sea level, respectively. Pumping from the Potomac-Raritan-Magothy aquifer system has caused water levels in the upper aquifer to decline well below sea level beneath Raritan Bay (Schaefer and Walker, 1981, p. 8-13).

Outside of the study area, significant pumping has caused large cones of depression in the Potomac-Raritan-Magothy aquifer system in the west-central Coastal Plain of New Jersey, which includes parts of Camden, Burlington, Ocean, Atlantic, Gloucester, Salem, and Cumberland Counties. Near Camden, water levels in 1983 were more than 90 ft below sea level in the Potomac-Raritan-Magothy aquifer system (Eckel and Walker, 1986, pl. 1-3).

Estimation of Future Ground-Water Withdrawals

Unrestricted Withdrawals

Unrestricted withdrawals were estimated for all aquifers of the New Jersey Coastal Plain for the years 1984 through 2020. Unrestricted withdrawals in parts of Monmouth, Middlesex, and Camden Counties were estimated from reports provided by the NJDEP/DWR. Elsewhere, unrestricted withdrawals were estimated by projecting historical (1960 through 1983) trends using linear regression. The withdrawal data for the period 1960 through 1983 is from the U.S. Geological Survey Ground-Water Withdrawal Inventory, which consists of monthly withdrawal-rate data on individual wells or well fields with pump capacities of 100,000 gallons per day or greater (Vowinkel, 1984, p. 5).

Withdrawal estimates for the major municipalities and purveyors in Monmouth, Middlesex, and Camden Counties were given in three reports provided by the NJDEP/DWR. Metcalf and Eddy, Inc. (1984) listed total withdrawals for public purveyors in Monmouth County for 1982 and estimated withdrawals for 2000 and 2020; the Middlesex County Planning Board (written commun., 1985) listed total withdrawals for public purveyors in Middlesex County for 1983 and estimated withdrawals for 2000 and 2020; and Camp, Dresser and McKee (1984) listed total withdrawals for public purveyors in the Camden area for 1980 and estimated withdrawals for 2000 and 2020. These data are shown in table 3. The 1980, 1982, or 1983 data were compared with U.S. Geological Survey monthly withdrawal records to insure consistency between the data from the various sources. In general, the data were consistent with the withdrawal records maintained by the U.S. Geological Survey. Most municipalities and purveyors pump from several wells which may have differing locations or be screened in different aquifers. Estimated withdrawals for 2000 and 2020 were proportioned into withdrawals for individual wells on the basis of 1980 withdrawal records. Total annual withdrawals (2000 and 2020) for each grid cell were calculated by totaling the proportioned withdrawals from wells within the same aquifer and grid cell.

Annual withdrawal estimates for 1984 through 2020 were calculated for all model grid cells by using a standard linear regression method on historical data (Draper and Smith, 1981, p. 8-16). The data used in the regression were total annual withdrawals at each cell for 1960 through 1983.

If zero withdrawals occurred for more than 4 years, all previous data were ignored in the regression analysis. Regressions were done for 469 cells of the model, other cells had no simulated withdrawals for 1984 through 2020.

Simulated unrestricted withdrawals in Middlesex, Monmouth, and Camden Counties were calculated using both the estimates from the reports provided by the State (table 3) and those developed using linear regression methods. The relative magnitude of the two estimates at each cell were used to determine simulated withdrawals in the following ways:

1. If report estimates of withdrawals from municipalities and purveyors listed in table 3 accounted for 75 to 100 percent of the total withdrawals at a model cell in 1980, these withdrawal values were divided by the percent of the modeled 1980 withdrawals at that cell to calculate an estimate of withdrawals for 2000 and 2020. Unlisted users (not listed in table 3) were assumed to have increased their withdrawals at the same rate as the listed users.

2. If report estimates of withdrawals from the listed municipalities and purveyors accounted for 25 to 75 percent of the total withdrawals at a model cell in 1980, these estimates were subtracted from the modeled withdrawals for 1980, and the difference was added to the estimated withdrawals for 2000 and 2020 for the municipalities and purveyors at the cell. This sum was compared with the withdrawals for 2000 and 2020 as estimated from the linear regression technique. The larger of the two estimates was used as the modeled withdrawal in that cell node. With this method, unlisted users were assumed to have no increase in their withdrawals between 1980 and 2020, unless the historical pumpage of the unlisted users indicated an increasing withdrawal trend.

3. If report estimates of withdrawals from the listed municipalities and purveyors accounted for less than 25 percent of the total withdrawals in a model cell in 1980, the regression value was used as the modeled withdrawal for that cell for 2000 and 2020.

In all cases, linear interpolation was used to calculate estimated withdrawals between 1980 and 2000, and between 2000 and 2020. The 1980 value used in the interpolation was taken from the linear regression curve. Actual withdrawals were not used in order to avoid biasing the interpolation with yearly variations in withdrawals. This explains the break between historical and estimated withdrawals shown in figures 8-12.

Reduced Withdrawals

Simulated withdrawals were increased at one-half the projected rate of growth from 1984 through 1990 within the central areas and their associated margins for all reduced withdrawal scenarios. This increase was calculated by subtracting the unrestricted annual withdrawals from the 1983 withdrawal value, dividing the difference by two, and adding this number to the 1983 value. The lowered growth rate reflects the NJDEP/DWR's belief that increased water conservation efforts, in expectation of future withdrawal reductions, will slow withdrawal increases.

Table 3.-- Ground-water withdrawals by municipalities and purveyors in Monmouth, Middlesex, and parts of Camden Counties, for 1980, 1982, or 1983, and projected withdrawals for 2000 and 2020

Municipality or purveyor	Average daily withdrawals (million gallons per day) Year		
	1982	2000	2020
Monmouth County[1]			
Allenhurst	0.14	0.16	0.18
Atlantic Highlands	.60	.75	.86
Avon	.26	.30	.31
Allentown	.22	.31	.37
Belmar Water Department	.92	1.12	1.18
Brielle	.52	.59	.66
Brick	4.47	6.23	7.40
Englishtown	.08	.11	.12
Farmingdale	.22	.27	.32
Freehold Borough	1.40	1.88	2.14
Freehold Township	1.85	2.90	4.02
Highlands	.57	.67	.70
Howell	1.11	2.31	3.52
Jackson	1.32	4.42	8.26
Keyport	.87	1.02	1.08
Keansburg	1.26	1.46	1.56
Lakewood	3.59	5.99	7.98
Matawan & Aberdeen	2.51	3.48	4.36
Monmouth Consolidated Water Company	29.11	36.34	42.35
Manasquan	.70	.72	.76
Manalapan & Marlboro	4.35	6.38	8.07
New Jersey Water Company - Ocean	1.34	1.71	2.07
Point Pleasant	2.02	2.77	3.32
Point Pleasant Beach	.84	1.06	1.27
Red Bank	1.68	2.06	2.20
Roosevelt	.10	.10	.11
Sea Girt	.28	.36	.38
Spring Lake	.53	.60	.66
Spring Lake Heights	.59	.86	1.02
Union Beach	.73	.87	.93
West Keansburg Water Company	3.27	4.32	4.87
Wall	1.54	2.83	3.76

Table 3.-- Ground-water withdrawals by municipalities and purveyors in Monmouth, Middlesex, and parts of Camden Counties--Continued

Municipality or purveyor	Average daily withdrawals (million gallons per day)		
	Year		
	1982	2000	2020
Middlesex County[2]			
Cranbury	0.15	0.66	0.89
East Brunswick	4.48	6.01	8.34
Helmetta	.09	.09	.09
Jamesburg	.39	.59	.85
Monroe	1.53	3.59	4.29
New Brunswick	10.37	9.80	9.62
Old Bridge	5.35	8.41	11.82
Perth Amboy	5.57	4.84	4.60
Sayreville	4.80	5.86	6.21
South Amboy	.83	.85	.90
South Brunswick	2.68	6.87	9.19
South River	1.40	1.38	1.52
Spotswood	.69	.64	.84
North Brunswick	3.20	6.00	6.73
Camden area[3]			
Bellmawr Water Department	1.32	1.35	1.35
Berlin Water Department	1.06	1.80	2.00
Brooklawn Water Department	.23	.19	.18
Camden City Water Department	20.90	20.00	19.50
Clementon Water Department	.63	.60	.71
Collingswood Water Department	2.25	2.24	2.23
Deptford Municipal Utilities Authority	2.56	5.18	5.95
Evesham Municipal Utilities Authority	1.89	3.16	3.89
Garden State Water Company	2.15	2.92	3.90
Gloucester City Water Department	1.84	1.76	1.69
Haddon Twp Water Department	1.48	1.35	1.24
Haddonfield Water Department	1.70	1.70	1.70
King's Grant Water Company	.04	.79	1.18
Maple Shade Water Department	2.11	2.22	2.31
Merchantville-Pennsauken Water Company	6.80	7.07	7.13

Table 3.--Ground-water withdrawals by municipalities and purveyors in Monmouth, Middlesex, and parts of Camden Counties--Continued

Municipality or purveyor	Average daily withdrawals (million gallons per day)		
	Year		
	1982	2000	2020
Camden area[3]			
Moorestown Water Department	2.13	2.40	2.72
Mount Holly Water Company	2.40	3.02	3.79
Mount Laurel Municipal Utility Authority	1.77	2.89	4.68
National Park Water Department	.31	.29	.28
New Jersey Water Company - Delaware	7.09	7.50	7.97
New Jersey Water Company - Haddon	24.70	27.50	31.60
Pine Hill Municipal Utility Authority	.79	1.24	1.24
Washington Municipal Utility Authority	2.29	3.74	5.55
Wenonah Water Department	.27	.26	.26
West Deptford Water Department	2.12	2.88	3.88
Westville Water Department	.85	.79	.74
Woodbury City Water Department	1.08	.80	.76
Woodbury Heights Water Department	.33	.31	.30

[1] Data from Metcalf and Eddy, Inc., 1984

[2] Data from S. Noble, New Jersey Department of Environmental Protection, written commun., 1984

[3] Data from Camp, Dresser and McKee, Inc., 1984

After 1990, withdrawals within the central areas were restricted to 50, 60, or 70 percent of 1983 rates, and withdrawals in the margins were restricted to 1983 rates. Graphs of historical and projected withdrawals within the modeled representations of the central areas are shown in figures 8-12. In all areas outside the central areas and their associated margins and in all other model layers, unrestricted withdrawals were applied.

SIMULATED EFFECTS OF ESTIMATED FUTURE WITHDRAWALS

Assumptions and Limitations of Analysis

Several assumptions and limitations of this analysis affect the interpretation of the model results (M. Martin, U.S. Geological Survey, oral commun., 1985). Four factors are--

(1) The RASA model of New Jersey Coastal Plain aquifers was developed to study regional ground-water flow. Local features, such as the deepest parts of cones of depression, are not simulated by this model.

(2) In this study, the New Jersey RASA model is used to simulate changes in water levels for 1984 through 2020. The accuracy with which the model represents changes in water levels is influenced by the accuracy of the initial calibration and the accuracy of the simulated withdrawal data. The New Jersey RASA model was calibrated against interpreted water-level maps for each pumping period and against hydrographs for 89 observation wells for the calibration period (1896-1980). The accuracy of RASA model results may vary regionally and between aquifers.

(3) Simulations that used future withdrawal rates that are similar to the withdrawal rates of the calibration period are more accurate than simulations that used future withdrawal rates that are much larger than those of the calibration period.

(4) Values for the boundary flows into or out of the southeast, southwest, and northeast lateral boundaries of the model are assumed to be the same as the values used in the 1978 through 1980 pumping period.

The RASA model of the New Jersey Coastal Plain aquifers is a tool developed for analysis of regional ground-water flow. Simulated hydrologic properties such as water levels, recharge, pumpage, transmissivity, and aquifer storativity are averaged over cells which represent six or more square miles. Because of this averaging, local features, such as the deepest parts of cones of depression, are not reproduced in the model results. Therefore, interpretation of results on a local basis is not justified. To insure that local features of the ground-water-flow system are not compared to the regional results of the model, this report used the following guidelines: only maps of hydraulic head that cover areas of at least 1,000 mi^2 were used; ground-water budgets are evaluated for areas of at least 100 mi^2; ground-water budget areas did not include aquifer

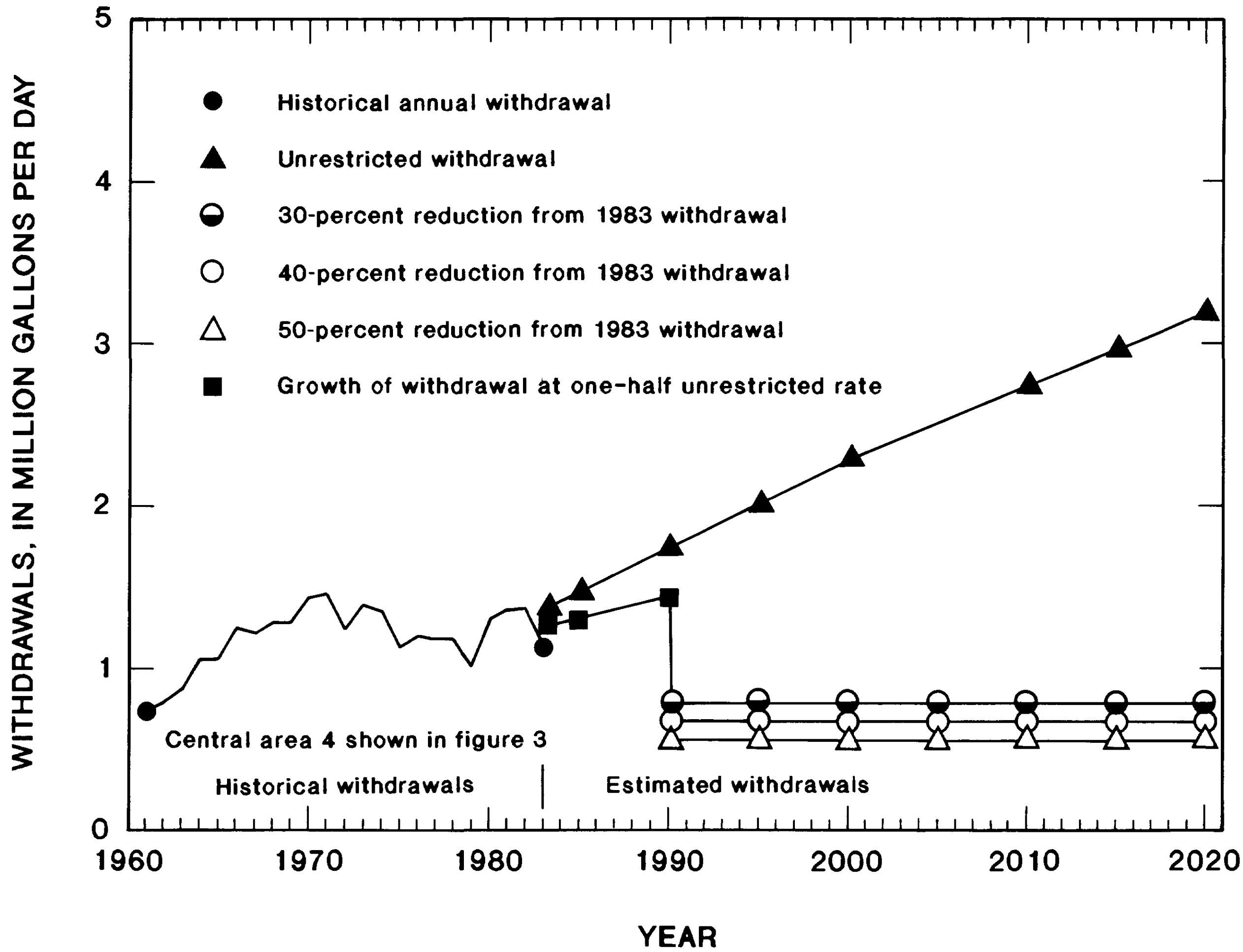


Figure 8.--Historical (1961-83) and estimated (1984-2020) withdrawals for central area 4 in the Wenonah-Mount Laurel aquifer.

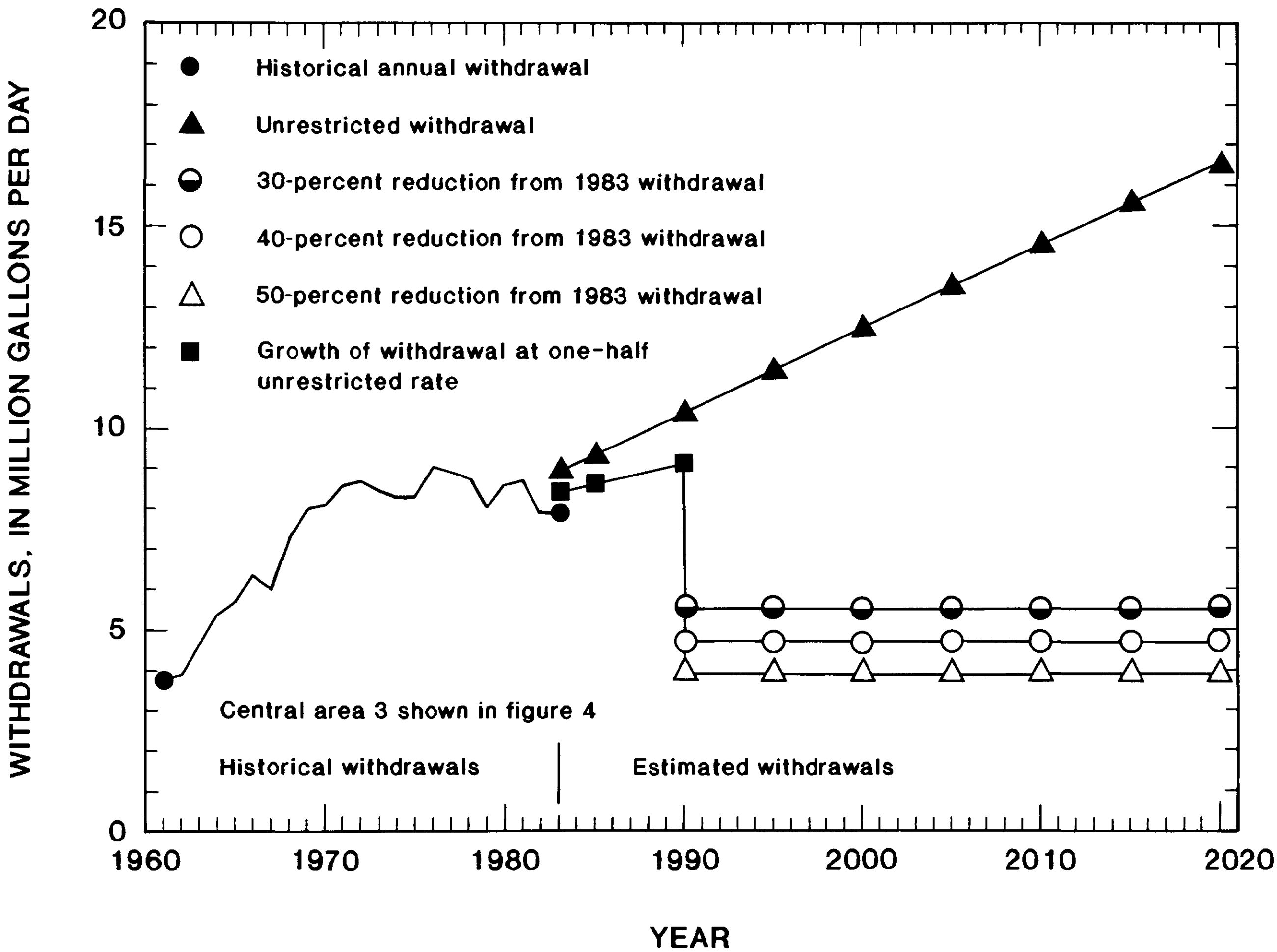


Figure 9.--Historical (1961-83) and estimated (1984-2020) withdrawals for central area 3 in the Englishtown aquifer system.

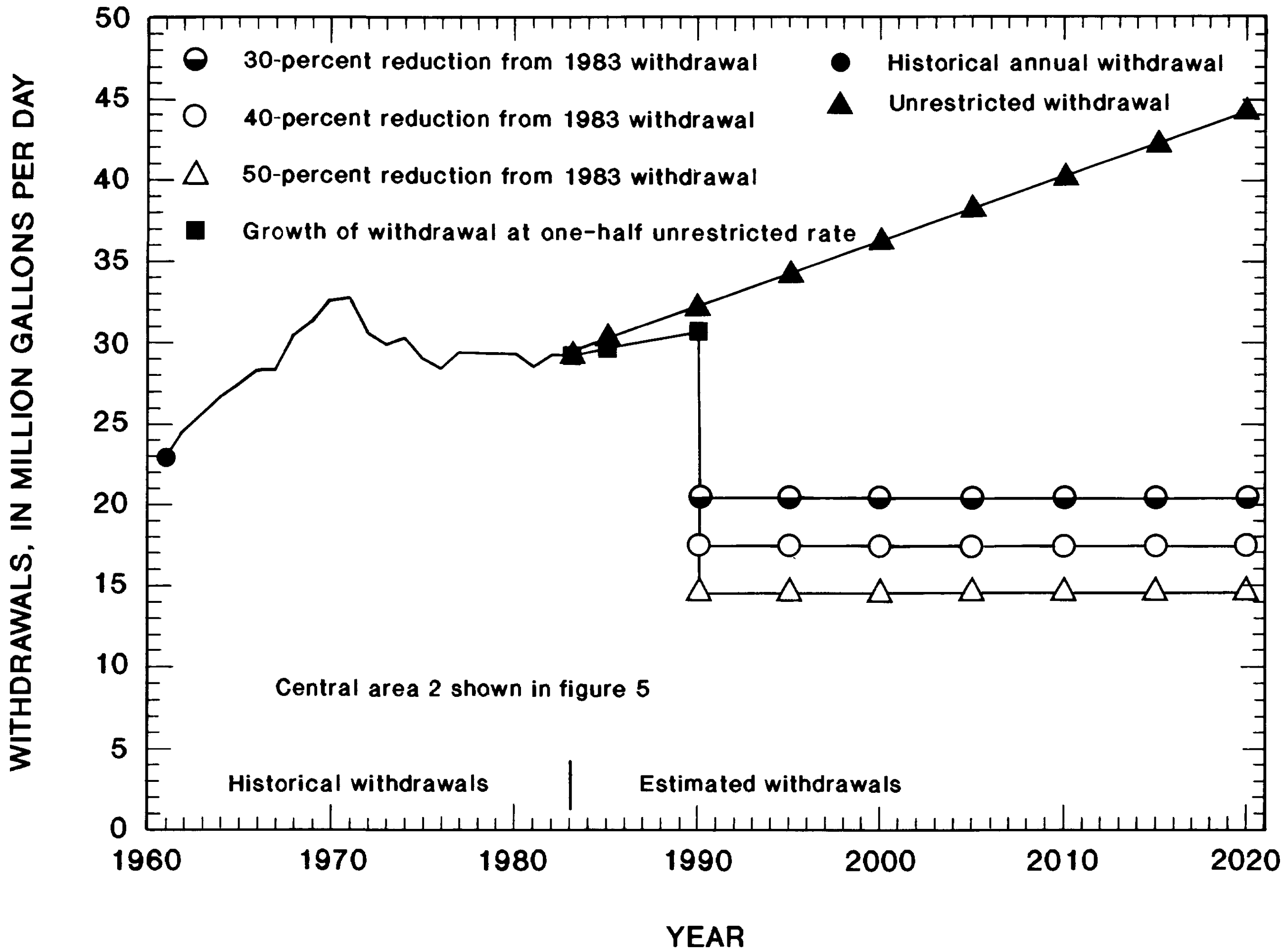


Figure 10.--Historical (1961-83) and estimated (1984-2020) withdrawals for central area 2 in the upper aquifer of the Potomac-Raritan-Magothy aquifer system.

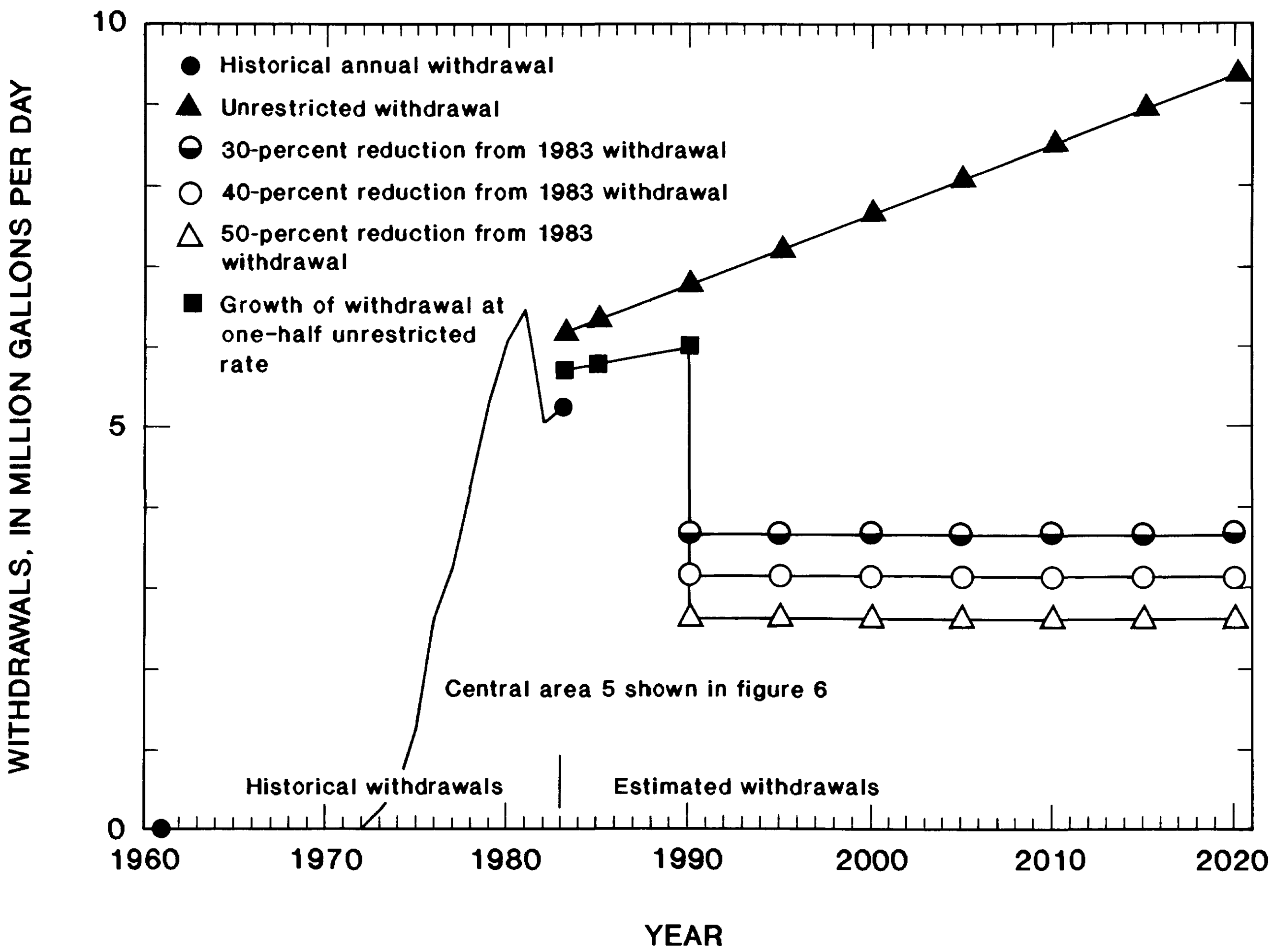


Figure 11.--Historical (1961-83) and estimated (1984-2020) withdrawals for central area 5 in the middle and lower aquifers of the Potomac-Raritan-Magothy aquifer system.

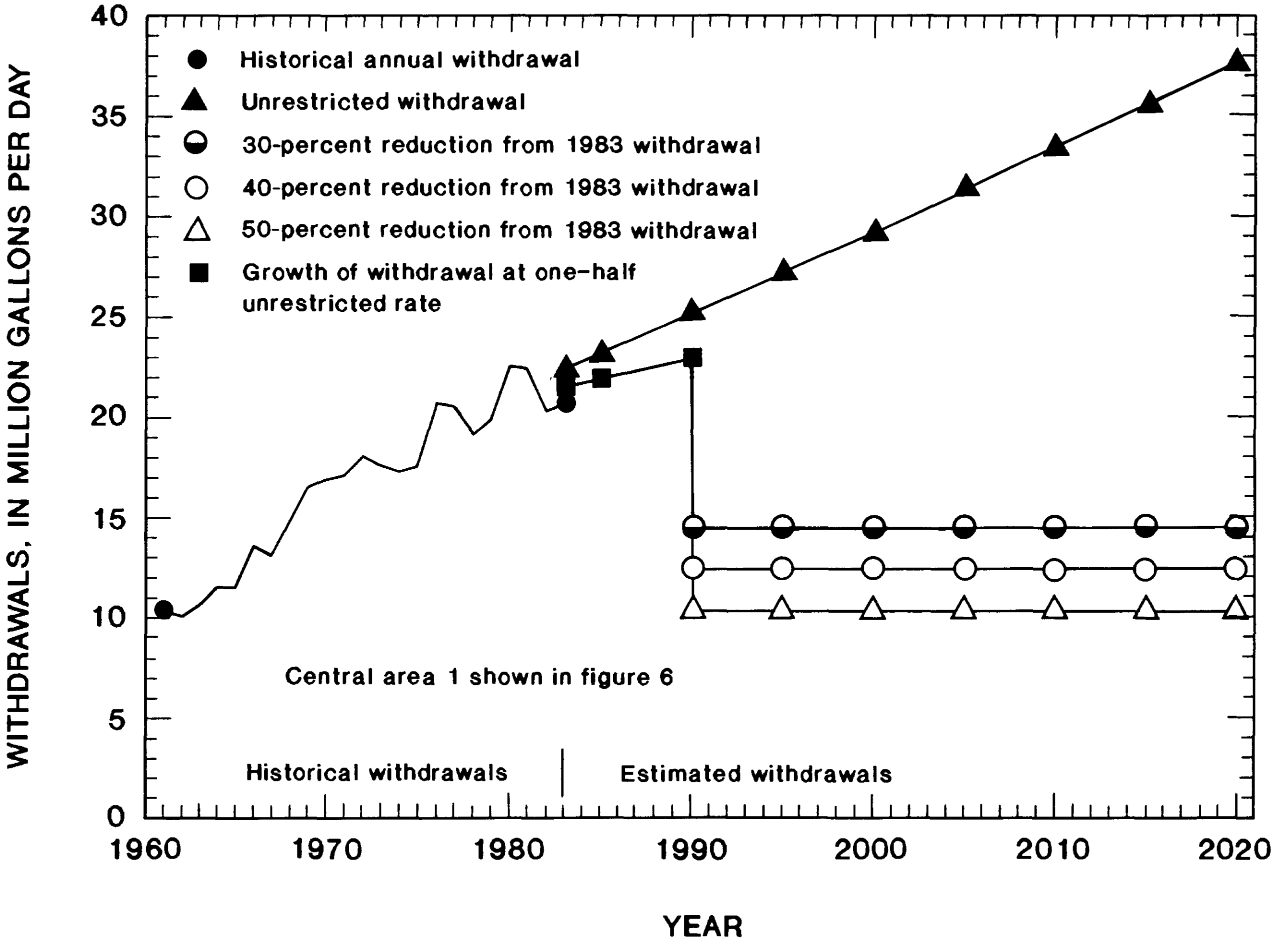


Figure 12.--Historical (1961-83) and estimated (1984-2020) withdrawals for central area 1 in the middle aquifer of the Potomac-Raritan-Magothy aquifer system.

outcrops, because the width of the outcrops is small compared to the grid size and ground-water flow near the outcrops is generally shallow and local. Within these limitations, results of the New Jersey RASA model define regional ground-water flow.

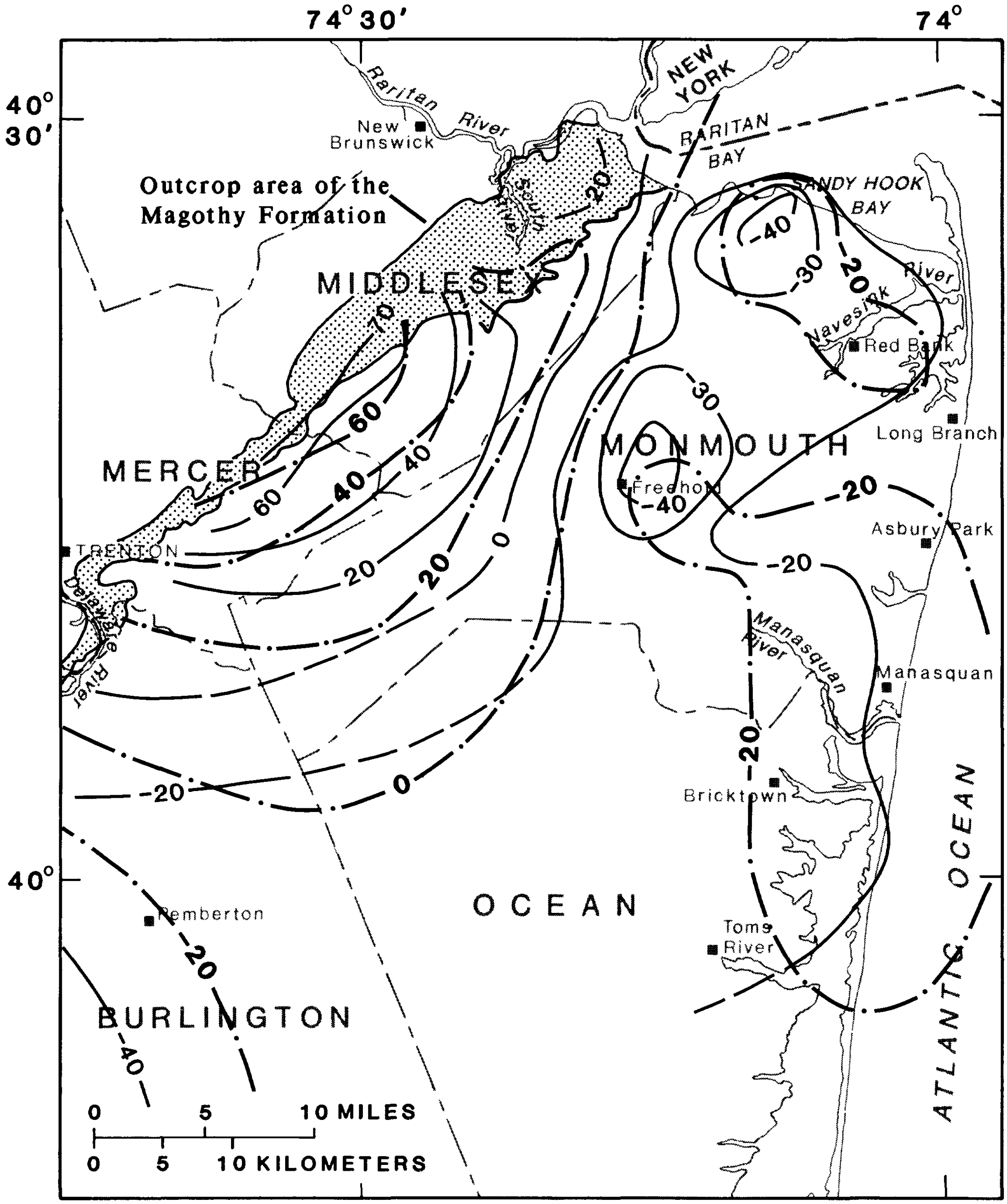
Factor 2 is concerned with the accuracy with which the model represents changes in water levels. The accuracy can be evaluated by comparing simulated and measured water levels and drawdowns during the calibration and verification periods.

Martin (in press) compared simulated and interpreted potentiometric surfaces for prepumping conditions and for the pumping period ending in 1978, and simulated and measured water levels from hydrographs for 89 observation wells. Simulated and interpreted potentiometric surfaces for 1978 for the upper and middle aquifers of the Potomac-Raritan-Magothy aquifer system in the northeastern Coastal Plain are shown in figures 13 and 14, respectively. The 1978 simulated and interpreted potentiometric surfaces for the Wenonah-Mount Laurel aquifer and the Englishtown aquifer system are similar to the 1983 surfaces shown on plate 1. For the calibration period, differences between simulated and measured water levels at most observation wells were less than 10 ft. An exception to this is that simulated water levels were about 25 ft lower than measured water levels for 1973 through 1980 in the middle aquifer of the Potomac-Raritan-Magothy aquifer system in southeastern Ocean County. Simulated water levels are probably 15 to 25 ft below actual water levels in eastern Ocean and southeastern Burlington Counties in all three aquifers of the Potomac-Raritan-Magothy aquifer system.

Figures 15-18 show hydrographs of simulated and measured drawdowns through 1983 for four observation wells that are closest to the major cones of depression in the study area. The match between simulated and measured drawdowns is very good within the period of historical record, except at well 250085 (fig. 16) in the Freehold area of the upper aquifer of the Potomac-Raritan-Magothy aquifer system, where simulated drawdowns are about 20 feet greater than measured drawdowns between 1973 and 1978. This difference could be the result of the averaging of hydrologic properties or of inaccuracies in the withdrawal data set; however, an examination of the model did not clearly suggest such problems.

The years 1981 through 1983 were used as a short period of model verification. Maps of simulated and interpreted 1983 potentiometric surfaces are shown on plate 1, and hydrographs of measured and simulated 1981 through 1983 drawdowns are shown in figures 15-18.

Simulated and interpreted potentiometric surfaces for the Wenonah-Mount Laurel aquifer change less than 10 ft within the study area for 1978 through 1983, except near Pemberton. There, both simulated and measured water levels decline 20 feet over the 5-year period. Simulated and interpreted potentiometric surfaces for the Englishtown aquifer system change less than 10 ft for 1978 through 1983 within the study area. The simulated and interpreted 1983 potentiometric surfaces are shown on plate 1. The close agreement between simulated and measured water levels in the Wenonah-Mount Laurel aquifer and in the Englishtown aquifer system suggests that simulated results are relatively reliable for these aquifers.



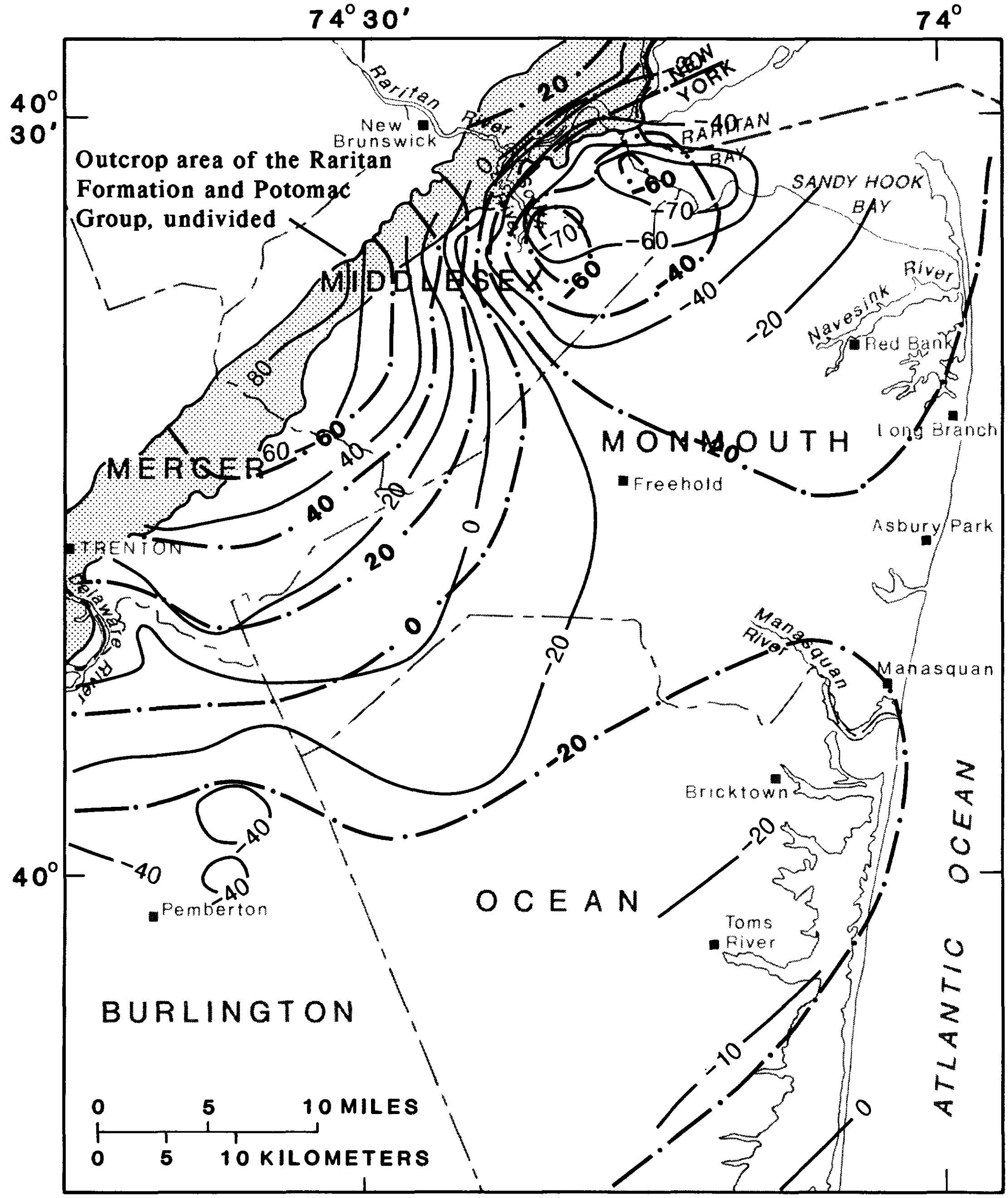
Base from U.S. Geological Survey
1:250,000 quadrangles

EXPLANATION

— -20— — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour intervals 10 and 20 feet. Datum is sea level. (Modified from Walker, 1983, plate 1.)

—·-20·— POTENTIOMETRIC CONTOUR--Shows altitude of simulated January 1, 1978, potentiometric surface. Contour interval is 20 feet. (Modified from Martin, in press.)

Figure 13.--Simulated and interpreted 1978 potentiometric surfaces for the upper aquifer of the Potomac-Raritan-Magothy aquifer system in the northeastern Coastal Plain of New Jersey.



Base from U.S. Geological Survey
1:250,000 quadrangles

EXPLANATION

—— -20 —— POTENTIOMETRIC CONTOUR -- Shows altitude at which water level would have stood in tightly cased well. Contour intervals 10 and 20 feet. Datum is sea level. (Modified from Walker, 1983, plate 1.)

——• 20 •—— POTENTIOMETRIC CONTOUR -- Shows altitude of simulated January 1, 1978 potentiometric surface. Contour Interval is 20 feet. (Modified from Martin, in press)

Figure 14.--Simulated and interpreted 1978 potentiometric surfaces for the middle aquifer of the Potomac-Raritan-Magothy aquifer system in the northeastern Coastal Plain of New Jersey.

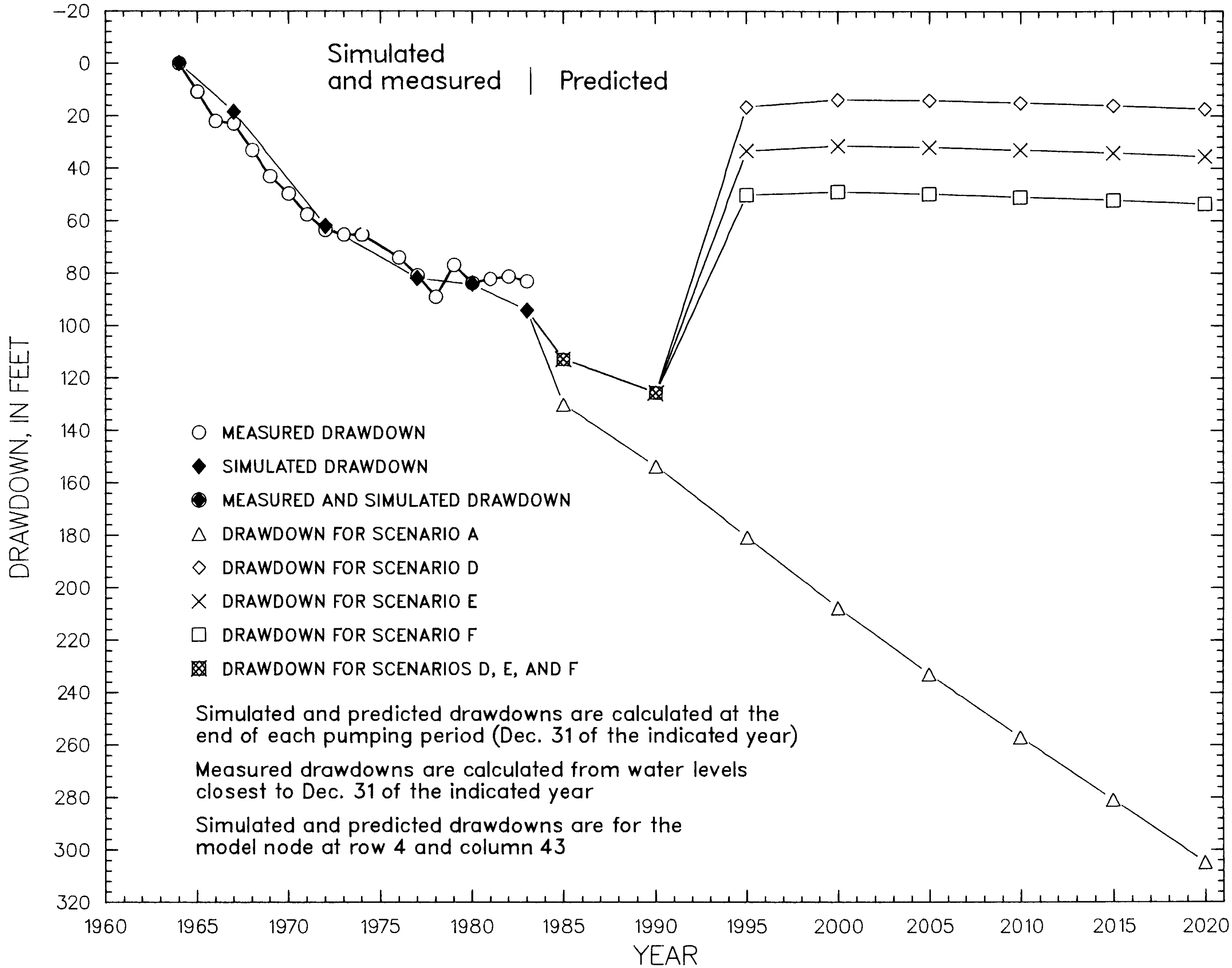


Figure 15.--Simulated and measured drawdowns, 1965 through 1983, and predicted drawdowns, 1984 through 2020, at well 250429 in the Englishtown aquifer system.

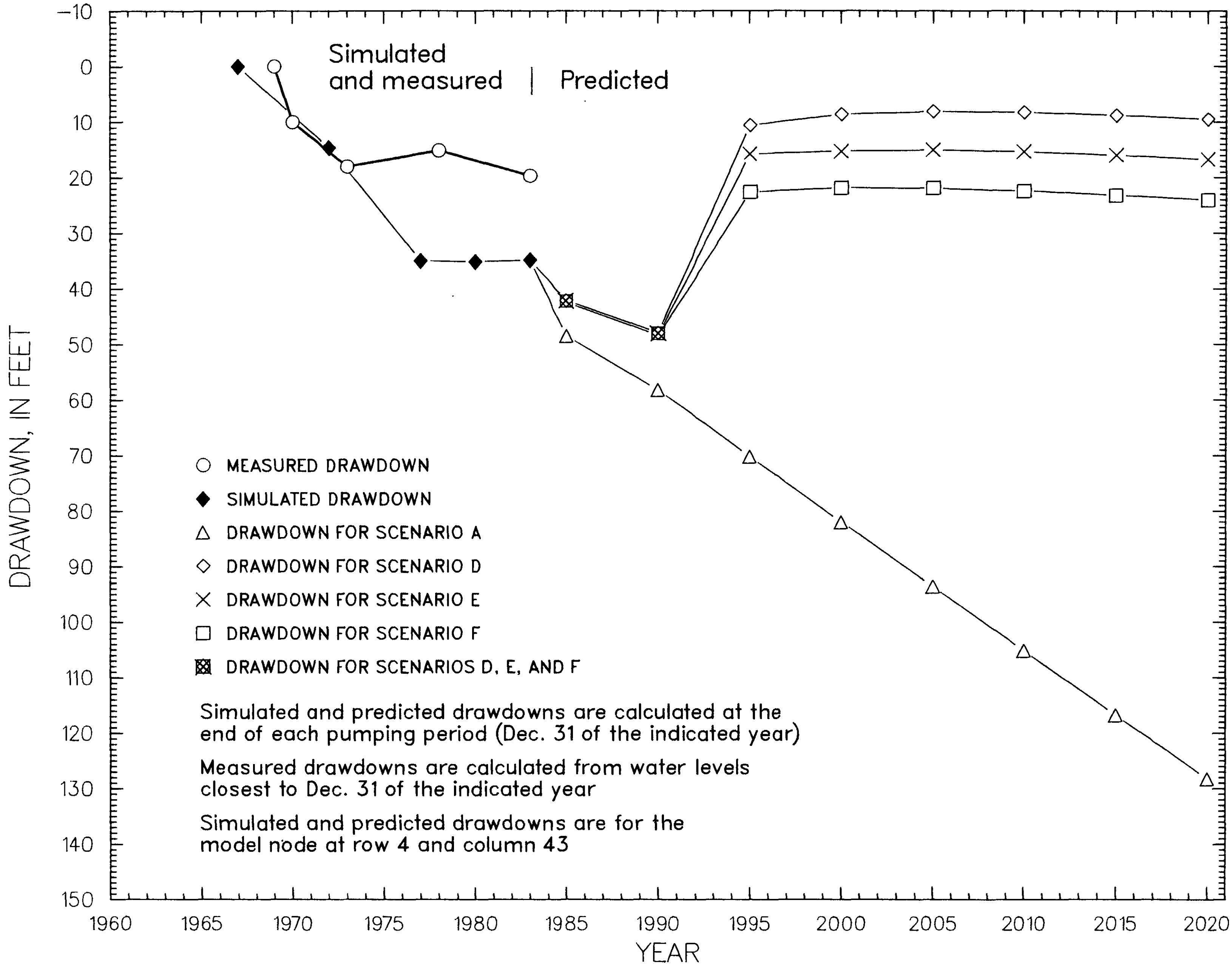


Figure 16.--Simulated and measured drawdowns, 1968 through 1983, and predicted drawdowns, 1984 through 2020, at well 250085 in the upper aquifer of the Potomac-Raritan-Magothy aquifer system.

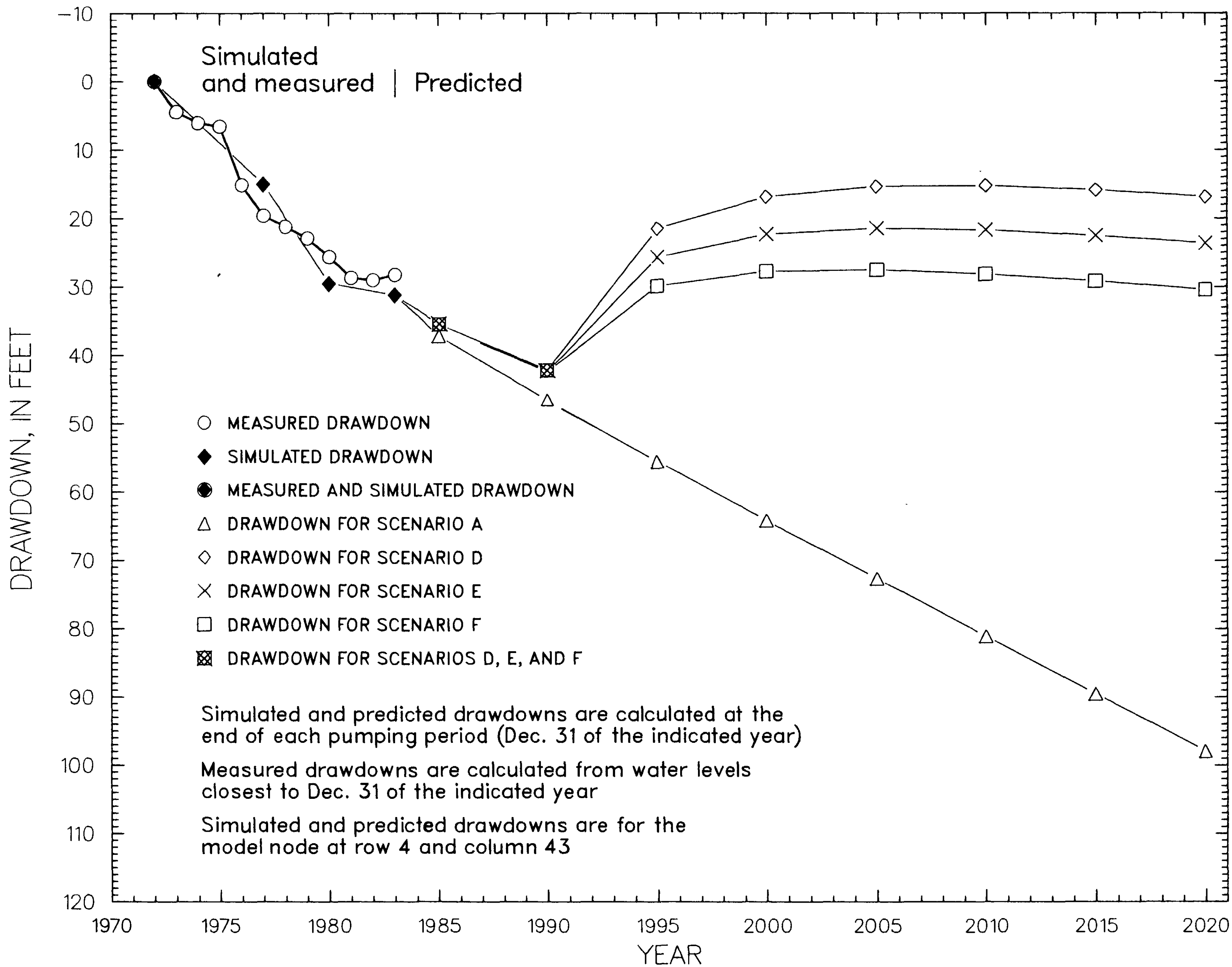


Figure 17.--Simulated and measured drawdowns, 1970 through 1983, and predicted drawdowns, 1984 through 2020, at well 290085 in the middle aquifer of the Potomac-Raritan-Magothy aquifer system.

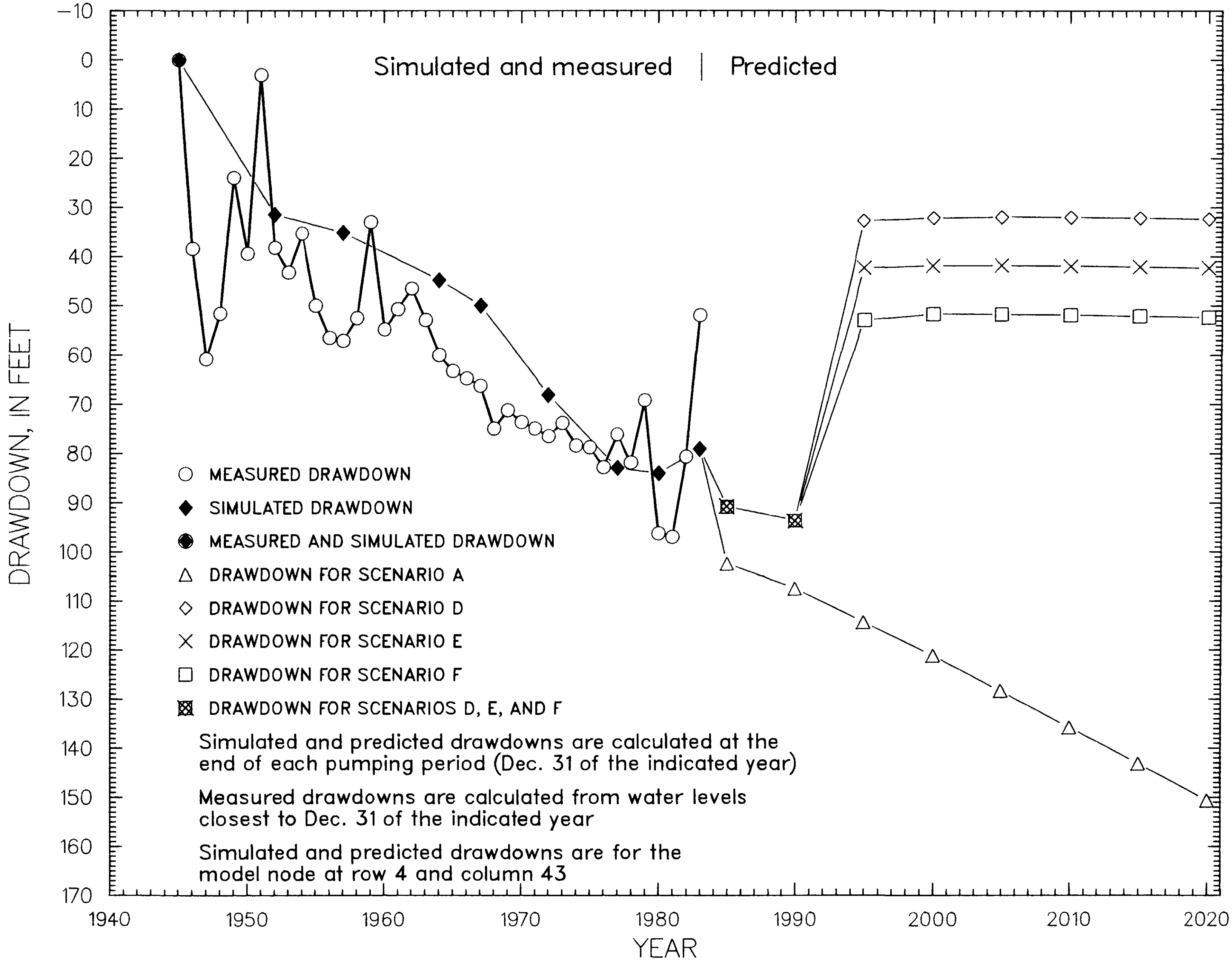


Figure 18.--Simulated and measured drawdowns, 1946 through 1983, and predicted drawdowns, 1984 through 2020, at well 230194 in the middle aquifer of the Potomac-Raritan-Magothy aquifer system.

The match between simulated and interpreted potentiometric surfaces in the upper aquifer of the Potomac-Raritan-Magothy aquifer system in 1978 and in 1983 was not as good as the match between simulated and interpreted potentiometric surfaces for the middle aquifer of the Potomac-Raritan-Magothy aquifer system. Simulated water levels were as much as 20 ft higher than measured water levels in 1978 (fig. 13), and as much as 30 ft higher than measured water levels in 1983 (pl. 1). Although a general decline in water levels is simulated, drawdown at the cone near Freehold (fig. 16), as well as drawdowns at cones northwest of Manasquan and east of Bricktown, were not closely simulated (pl. 1). These differences in simulated and measured drawdowns do not appear to be caused by inaccurate withdrawal data, but may be the result of limitations of the model framework in representing the physical system in these areas. Simulated 1983 water levels in downdip areas of this aquifer are less accurate than those of other aquifers, and may only be within 30 ft of actual water levels.

In the middle aquifer of the Potomac-Raritan-Magothy aquifer system, the match between simulated and interpreted potentiometric surfaces for 1983 (pl. 1) generally is similar to the match for 1978 (fig. 14). The 20-foot declines in measured water levels for 1978 through 1983 at cones near Pemberton and Bricktown are associated with simulated 15- to 20-foot declines in water levels at those locations. The overall declines observed in the major cones of depression are accurately simulated with three significant exceptions: south of Raritan Bay, measured water levels decline 10 to 20 ft at the center of the cone, but simulated water levels decline less than 10 ft; near South River, measured water levels recovered about 10 ft, whereas simulated levels stayed about the same; and, in central Ocean County, a cone with water levels 40 ft below sea level was simulated where none was observed. These differences between measured and simulated 1983 water levels or drawdowns appear to be caused by differences between actual and simulated withdrawals. South of Raritan Bay and near South River, withdrawals are from both the middle and upper aquifers of the Potomac-Raritan-Magothy aquifer system; however, withdrawals are reported only as totals by well fields, not by aquifer. Withdrawals from each of the aquifers in these areas was estimated based on all available historical information, but these estimates may be inaccurate. Near South River and in central Ocean County, average withdrawals for the January 1, 1981, through December 31, 1983, pumping period were much larger than actual withdrawals during the fall of 1983, when potentiometric levels were measured.

In areas apart from those mentioned above, the model accurately simulates the response of the middle aquifer of the Potomac-Raritan-Magothy aquifer system to the 1981 through 1983 changes in withdrawals. Some inaccuracies in the simulated response in the middle aquifer of the Potomac-Raritan-Magothy aquifer system to changes in withdrawals for the years 1981 to 1983 occur because changes in water levels are simulated as an average over the area of a model grid cell (6 or more square miles). Other sources of error include inaccuracies in the withdrawal data and limitations of the model framework in representing the physical framework.

Although the verification period is very short and the results cannot be considered conclusive, it does provide some information on the models performance.

The analysis of calibration and verification results indicates that the New Jersey RASA model accurately represents drawdowns and water levels in most of the aquifers of the northeastern New Jersey Coastal Plain. Drawdowns and water levels in most areas of the Wenonah-Mount Laurel aquifer, the Englishtown aquifer system, and the middle aquifer of the Potomac-Raritan-Magothy aquifer system were well represented by the model, and are probably accurate to within 5 or 10 ft. Drawdowns and water levels in the upper and parts of the middle aquifers of the Potomac-Raritan-Magothy aquifer system were represented with less precision. In eastern Ocean and southeastern Burlington Counties, simulated drawdowns and water levels in these aquifers may be in error by as much as 20 to 30 ft. In other areas of the upper aquifer of the Potomac-Raritan-Magothy aquifer system, errors are smaller.

In factor 3, it is noted that simulations where the future ground-water withdrawals are similar to the withdrawals of the calibration period (1896 through 1980), are more accurate than simulations where the withdrawals are much greater than those of the calibration period. In scenario A, estimated withdrawals in 2020 are nearly twice the withdrawals in 1983. The other scenarios (B-F) have withdrawals that are 50 to 70 percent of 1983 withdrawals. These withdrawals are similar to those reported for the 1960's or earlier. Errors in the simulation of unrestricted withdrawals in scenario A may be several times those encountered during calibration, and the errors in the simulations of reduced withdrawals, scenarios B to F, are probably similar to or smaller than those encountered during calibration.

Boundary Flows

For the calibration period (1896-1980), flows into and out of the southeastern, southwestern, and northeastern boundaries of the New Jersey RASA model were estimated using the regional RASA model of the North Atlantic Coastal Plain (Martin, in press). The regional RASA model simulated water levels from 1900 through 1980. As stated previously, boundary flows for the period 1981 through 2020 were the same as the values used in the 1978 through 1980 pumping period. Errors in simulated water levels and ground-water flows of the northeastern Coastal Plain caused by using the 1978 through 1980 boundary flows in simulations representing the years 1981 through 2020 are expected because boundary flows would not be constant after 1980. Lateral gradients near the model boundaries would be affected by changes in ground-water withdrawals within New Jersey and adjacent States after 1980.

The error that might be caused by maintaining boundary flows at 1978 through 1980 levels was quantified by considering: the amount that boundary flows would be expected to change in the various scenarios and the sensitivity of simulated water levels to changes in boundary flows.

The amount that boundary flows would be expected to change because of changes in withdrawals after 1980 can be estimated by considering past changes in withdrawals and the associated changes in boundary flows. Table 4 shows the boundary flows for the northeast, southwest, and southeast boundaries of the New Jersey RASA model in two pumping periods representing the years 1953 through 1957 and 1978 through 1980. Withdrawals and total boundary flows from the New Jersey Coastal Plain more than doubled between

Table 4.--Simulated and projected lateral flow through the boundaries of the New Jersey RASA Model, 1953 through 1957 and 1978 through 1980

[Rates in million gallons per day; --, no flow]

Boundary	Flow was IN or OUT of the modeled area	Simulated: 1953 through 1957	Simulated: 1978 through 1980	Projected: Scenario A 2020
Northeast	IN	--	5.1	13.0
	OUT	3.6	0.4	--
Southwest	IN	2.5	4.7	6.9
	OUT	0.8	4.5	8.3
Southeast	IN	0.1	0.9	1.9
	OUT	0.4	0.1	--
Net boundary flow[1]	IN	2.6	10.7	21.8
	OUT	4.8	5.0	8.3
Total simulated withdrawals		174.8	358.2	546.8

[1] Differences between these values and values reported in Martin (in press) are due to rounding.

these pumping periods, and large increases in withdrawals also occurred to the southwest of the New Jersey Coastal Plain. In both cases, boundary flows are small compared to withdrawals, generally less than 3 percent. Changes in boundary flows between the two pumping periods generally were less than 5 Mgal/d.

In the present work, the most extreme changes in boundary flows after 1980 would be expected under the conditions of scenario A. Total simulated withdrawals in scenario A for the year 2020 were 546.8 Mgal/d, or 188.6 Mgal/d greater than the simulated 1978 through 1980 withdrawals (table 4). This increase is similar to the 183.4-Mgal/d increase in withdrawals that occurred between the two pumping periods, 1953 through 1957 and 1978 through 1980, shown in table 4. Because the system is linear, the two similar increases in pumpage should produce similar changes in boundary flows. The last column of table 4 shows projected boundary flows in 2020 for scenario A. These flows are calculated by changing the boundary flows the same amount that they had changed between the two pumping periods. Note that, if these calculations produced a negative outflow, as occurred for the northeastern boundary, the negative outflow was included as a positive inflow. These calculations are accurate if the increase in pumpage between the two pumping periods occurred at the same location as the simulated increase for scenario A, and if the pumpage external to the New Jersey RASA model changed in the same way for 1980 through 2020 as it had between the two pumping periods.

Simulations to test the sensitivity of the calculated water levels to changes in boundary flows were made by Martin (in press). The sensitivity simulations show the change in water levels within New Jersey aquifers caused by changing boundary flows using the transmissivity and confining unit hydraulic conductivity of the calibrated model. Three simulations were made (1) with no boundary flows, (2) with 2 times the boundary flows of the calibrated model, and (3) with 10 times the boundary flows used in the calibrated model. The results of the sensitivity simulations with no boundary flows and twice the calibrated boundary flows showed that simulated water levels generally changed less than 15 ft near the boundaries and less than 10 ft near the major cones of depression. However, in the middle and lower aquifers of the Potomac-Raritan-Magothy aquifer system a large, though very localized, water-level change of about 200 ft occurs along the southwest model boundary. The simulation using 10 times the boundary flows had water-level changes of 50 ft near the boundaries in most aquifers, and water-level changes greater than 100 ft near the southwestern model boundaries of the middle and lower Potomac-Raritan-Magothy aquifer system. Several cells away from the boundary and near the major cones of depression, simulated changes in water levels were less than 10 ft. The sensitivity analysis indicates that very large errors in boundary flows affect water levels in most of the system by less than 10 ft, and that the largest changes in water levels occurred in the southwestern part of the model.

The difference between simulated 1978 through 1980 and projected scenario A, 2020 boundary flows is approximated most closely by the sensitivity simulations in which boundary flows were doubled or multiplied by 10. Therefore, simulated water levels for 1981 through 2020 are likely to be 5 to 15 ft lower than water levels would be if simulated using updated boundary fluxes. The error is smaller for scenarios B through F, because withdrawals are closer to historic values.

Water Levels

Water levels for 1984 through 2020 were calculated by adding simulated post-1983 changes in water levels (calculated using the New Jersey RASA model) to the potentiometric-surface map of 1983 water levels. To generate the potentiometric-surface maps, maps of 1983 potentiometric surfaces from Eckel and Walker (1986, pl. 1-5) were discretized using the grid from the New Jersey RASA model (fig. 7). Simulated post-1983 changes in water levels are the result of estimated changes in ground-water withdrawals after 1983, and the transient effects of pre-1984 withdrawals. The transient effects would occur even if withdrawals were maintained at the 1983 values through 2020. All simulated water levels or drawdowns are calculated for December 31 of the year indicated.

Simulated drawdowns for the six scenarios are shown for four observation wells near the deepest parts of four cones of depression in three aquifers (fig. 15-18). Well locations are shown on figure 1. Table 5 shows interpreted water levels for 1983 and simulated water levels for 1990, 1995, 2000, 2010, and 2020 near the deepest parts of the major cones of depression. Plates 2 through 5 show simulated potentiometric surfaces for the four major aquifers in the northeastern Coastal Plain for selected years and scenarios. For scenario A, with unrestricted withdrawals, and scenario D, with the most severe reductions considered, simulated water levels for all four aquifers for 1990, 1995, 2000, and 2010 are shown (pl. 2 and 3). For other scenarios, many maps were omitted because they were similar to maps of scenario D or to each other. The 1990 maps for scenarios B, C, D, E, and F are all very similar, so only those for scenario D are shown; maps for 1995, 2000, and 2010 for scenarios C, D, E, and F are very similar within each layer, as shown on plate 3 for scenario D, so only maps from the year 2000 are shown for scenarios C, E, and F (pl. 5); and, maps from the Wenonah-Mount Laurel aquifer and Englishtown aquifer system are very similar in scenarios B and D, so these aquifers are not included for scenario B (pl. 4). Maps for 2020 are not shown because of their similarity to maps of simulated water levels in 2010 for scenarios B, D, E and F and the predictable rate of potentiometric decline for scenario A.

The estimated unrestricted withdrawals of scenario A produce deep cones of depression in the simulated potentiometric surfaces (pl. 2, table 5 and fig. 15-18). As expected, the deepest cones, with simulated water levels of 420 and 350 ft below sea level in 2010 are located in the less permeable Wenonah-Mount Laurel aquifer and Englishtown aquifer system, respectively (table 5). Simulated water levels for 2020 in the Pemberton area of the Wenonah-Mount Laurel aquifer are about 25 ft below the top of the aquifer. The RASA model does not simulate unconfined conditions in the aquifers; therefore, simulated water levels are not accurate in this area after 2010. In cones of depression, in both the upper and middle aquifers of the Potomac-Raritan-Magothy aquifer system, simulated water levels in 2010 are 126 ft below sea level.

In the scenarios representing reduced withdrawals, simulated water levels in all aquifers quickly (within 5 years) approach steady-state after 1990, when withdrawals in central areas are restricted to constant levels (table 5, fig. 8-12). For scenario D, 80 to 97 percent of the recovery occurs by 1995. Within central areas and aquifers where withdrawals are

Table 5.--Interpreted 1983 and simulated 1990 through 2020 water levels, near the center of the major cones of depression in the northeastern New Jersey Coastal Plain

[Datum is sea level]

Aquifer or aquifer system	Location of model cell[4]	Year	Scenario[3] (feet)					
			A	B	C	D	E	F
Wenonah-Mount Laurel	Deepest part of cone in Central area 4	1983	-185	-185	-185	-185	-185	-185
		1990	-248	-218	-218	-218	-218	-218
		1995	-276	-96	-95	-95	-114	-133
		2000	-302	-93	-92	-91	-111	-131
		2010	-350	-95	-93	-91	-112	-132
		2020	-395	-98	-95	-93	-114	-134
	[1]Deepest part of cone near Pemberton	1983	-30	-30	-30	-30	-30	-30
		1990	-89	-88	-88	-88	-88	-88
		1995	-120	-112	-112	-104	-110	-111
		2000	-150	-139	-138	-135	-136	-138
		2010	-213	-199	-198	-192	-194	-196
		2020	--[5]	--[5]	--[5]	--[5]	--[5]	--[5]
Englishtown aquifer system	[2]Deepest part of cone in Central area 3	1983	-225	-225	-225	-225	-225	-225
		1990	-298	-263	-263	-263	-263	-263
		1995	-331	-118	-117	-117	-140	-163
		2000	-362	-115	-114	-112	-136	-160
		2010	-420	-118	-116	-113	-138	-162
		2020	-472	-121	-118	-115	-140	-164
Upper aquifer of the Potomac-Raritan-Magothy aquifer system	[2]Deepest part of cone in Central area 2	1983	-56	-56	-56	-56	-56	-56
		1990	-79	-70	-69	-69	-70	-70
		1995	-90	-38	-34	-32	-38	-44
		2000	-103	-38	-33	-30	-36	-43
		2010	-126	-41	-34	-29	-36	-44
		2020	-149	-44	-37	-31	-38	-45
Middle aquifer of the Potomac-Raritan-Magothy aquifer system	[2]Deepest part of cone in Central area 1	1983	-82	-82	-82	-82	-82	-82
		1990	-96	-91	-90	-90	-90	-90
		1995	-104	-59	-56	-54	-61	-67
		2000	-111	-59	-55	-53	-59	-66
		2010	-126	-60	-55	-52	-59	-66
		2020	-140	-62	-56	-52	-59	-67
	[2]Deepest part of cone in Central area 5	1983	-35	-35	-35	-35	-35	-35
		1990	-54	-52	-48	-48	-48	-48
		1995	-64	-46	-27	-21	-26	-31
		2000	-73	-48	-24	-16	-23	-29
		2010	-92	-55	-26	-14	-22	-29
		2020	-110	-64	-30	-16	-23	-31

[1] Not included in any regulated area.
[2] Drawdowns at observation wells near the cones of depression are shown in figures 14-17 for scenarios A, D, E, and F.
[3] Table 2 gives a description of each scenario.
[4] Central areas 1-5 are shown in figures 3-6.
[5] Simulated water level is below the top of the aquifer.

reduced, simulated water levels change 7 ft or less for 1995 through 2010 (table 5, fig. 15-18, pl. 3). The declines in simulated water levels that occur after 1995 are caused by increased pumping in other areas of the aquifers.

Scenarios B, C, and D show the regional nature of the ground-water-flow system of the New Jersey Coastal Plain. As withdrawals in central areas 5, 6, and 7 of the aquifers are reduced, simulated 1995 water levels in the study area increase in the central area of all aquifers (table 5, and pl. 3-5).

In central area 4 of the Wenonah-Mount Laurel aquifer (fig. 3), 1995 minimum simulated water levels for scenario B are 89 ft above interpreted 1983 water levels; in central area 3 of the Englishtown aquifer system (fig. 4), they are 107 ft above interpreted 1983 levels. These large recoveries are only slightly increased as withdrawals in central areas 5, 6, and 7 (figs. 5 and 6) are reduced in scenarios C and D. In scenario C, the 1995 simulated water levels in central areas 4 and 3 were 1 foot higher than in scenario B because pumping is reduced in central area 5. In the scenario D, the 1995 simulated water levels in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system in central areas 4 and 3 are the same as in scenario C.

In central areas 2 and 1 of the upper and middle aquifers of the Potomac-Raritan-Magothy aquifer system (figs. 5 and 6), 1995 minimum simulated water levels for scenario B were 18 and 23 ft, respectively, above 1983 minimum water levels (table 5). In scenario C, decreased pumping in central area 5 of the middle and lower aquifers of the Potomac-Raritan-Magothy aquifer system (fig. 5) causes simulated water levels to recover an additional 4 and 3 ft in central areas 2 and 1, respectively. In scenario D, decreased pumping in central areas 6 and 7 of the Potomac-Raritan-Magothy aquifers (figs. 5 and 6) causes simulated water levels to recover another 2 ft in central areas 2 and 1. Thus, simulated water levels in central areas 2 and 1 recovered an additional 33 and 22 percent, respectively, as a result of reduced withdrawals in areas 5, 6, and 7 in the middle and lower aquifers of the Potomac-Raritan-Magothy aquifer system.

In central area 5 of the middle and lower Potomac-Raritan-Magothy aquifer system (fig. 5), 1995 minimum simulated water levels for scenario C are 8 ft above 1983 water levels; for scenario D, they recover an additional 6 ft (table 5).

In scenarios D, E, and F, post-1990 withdrawals in all seven central areas (fig. 3-6) are reduced to 50, 60, and 70 percent of 1983 withdrawals, respectively. By increasing withdrawals 10 percent, from 50 to 60 and 70 percent of the 1983 withdrawals the 1995 through 2010 simulated water levels in scenarios E and F are affected in similar ways (pls. 3 and 5, figs. 15-18, and table 5). For each 10-percent increase, minimum simulated water levels in central area 4 of the Wenonah-Mount Laurel aquifer decline 20 ft (table 5); minimum simulated water levels in central area 3 of the Englishtown aquifer system decline 24 ft; minimum simulated water levels in central area 2 of the upper aquifer of the Potomac-Raritan-Magothy aquifer system decline 6 to 8 ft; and, minimum simulated water levels in central areas 1 and 5 of the middle aquifer of the Potomac-Raritan-Magothy aquifer system decline 5 to 8 ft. The cone near Pemberton in the Wenonah-Mount Laurel aquifer is outside the area of restricted withdrawals, but the minimum simulated water levels in that cone decline 1 to 6 ft for each 10-percent increase in withdrawals.

In all scenarios in areas where pumping was reduced, 80 to 100 percent of the total simulated recovery occurs by 1995, and the total simulated recovery occurs by or before 2010 (table 5). The time it takes the system to reach steady state is similar to that calculated by Martin (in press) for budget areas in the Wenonah-Mount Laurel aquifer, the Englishtown aquifer system, and the upper, middle, and lower aquifers of the Potomac-Raritan-Magothy aquifer system. Water levels in central areas 1 through 5 remain constant or decline slightly for 2000 through 2020 for scenarios B, C, D, E, and F, with the exception of simulated water levels in central area 5 for scenario B (pumping is not reduced in central area 5 in scenario B). The slight (1-6 ft) decline in simulated water levels is caused by increased pumping in areas outside of the central areas and their associated margins.

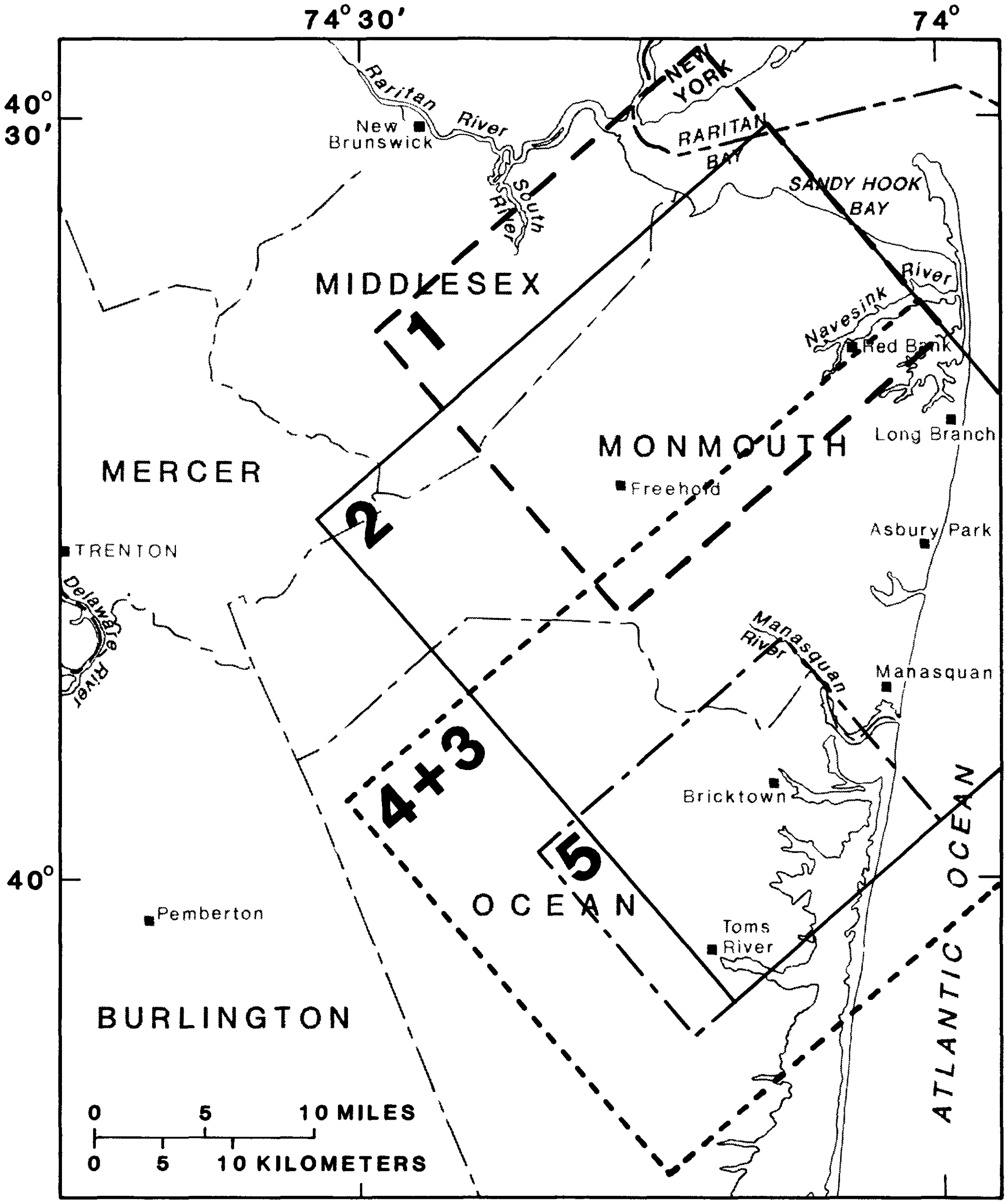
Ground-Water Flow

Simulated ground-water flows into and out of the central areas of the five major cones of depression in the northeastern Coastal Plain aquifers (central areas 1-5, figs. 3-6) are strongly influenced by the reduced withdrawals simulated in scenarios B though F. Ground-water budgets are presented for five areas, each of which covers one of the five major cones of depression in the northeastern Coastal Plain. The ground-water budgets include flows through the sides, top, and bottom of, and the change in storage within, the rectangular areas of the aquifers. The budget areas, shown on figure 19, are located at least 4 miles from the outcrop area of each aquifer. This was done to avoid inaccuracies caused by the modeling of flows in the narrow, unconfined outcrop area with the New Jersey RASA model.

Tables 6-10 show the simulated components of the ground-water budgets for 1983, 1990, 1995, 2000, 2010, and 2020. Figures 20-24 show schematic diagrams of the simulated ground-water flows and withdrawals for 1983 and 2010 of scenarios A through E; the minimum interpreted and simulated water levels for each scenario also are included. All budget values are the total of negative and positive values. Actual flows through a budget-area side may be a combination of inflows and outflows, but only the total value is reported.

The ground-water flows and the rate of change of storage shown in tables 6-10 are calculated from water levels simulated at the ends of selected pumping periods. The pumping periods, which end on December 31 of the years indicated, are 5 years long, except the pumping period ending in 1983, which is 3 years long. Withdrawals are constant throughout each pumping period, and are the average of the yearly withdrawals. The percent error in tables 6-10 is the difference between flows into and out of a budget area (including withdrawals and storage) divided by one-half the magnitude of the positive and negative components of the budget, multiplied by 100. This can be expressed by the following formula:

$$\text{Percent error} = \frac{|\Sigma \text{ Positive values }| - |\Sigma \text{ Negative values }|}{(\Sigma| \text{ all values }|)/2} \cdot 100.$$



Base from U.S. Geological Survey
1:250,000 quadrangles

EXPLANATION

1 — Budget area for the middle aquifer of the Potomac-Raritan-Magothy aquifer system, south of Raritan Bay. (Covers central area 1 on figure 6)

2 — Budget area for the upper aquifer of the Potomac-Raritan-Magothy aquifer system. (Covers central area 2 on figure 5)

4+3 — Budget areas for the Wenonah-Mount Laurel aquifer and Englishtown aquifer system. (Covers central areas 4 and 3 on figures 3 and 4)

5 — Budget area for the combined middle and upper aquifers of the Potomac-Raritan-Magothy aquifer system, near Bricktown. (Covers central area 5 on figure 6)

Figure 19.--Ground-water-budget areas.

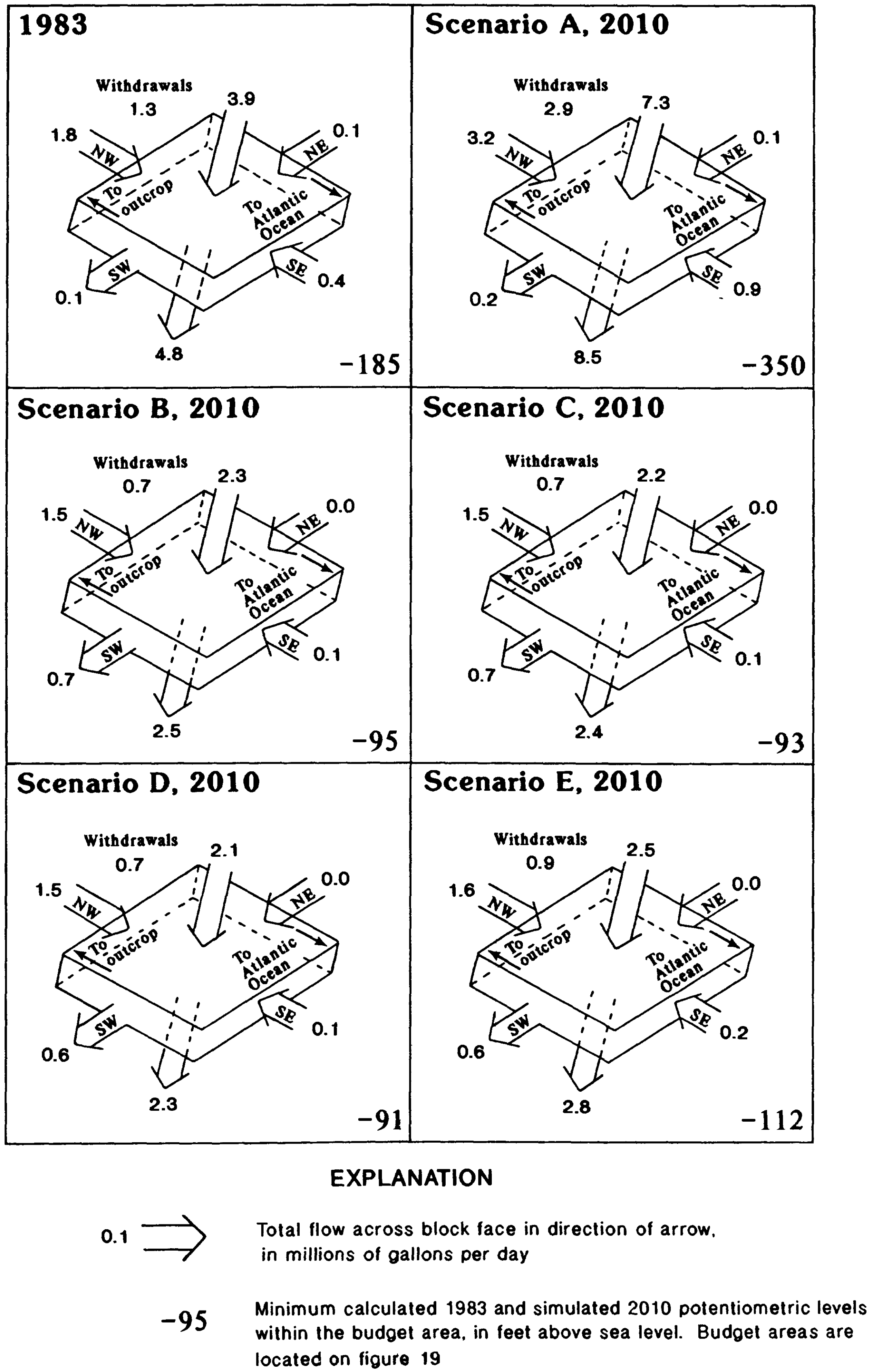
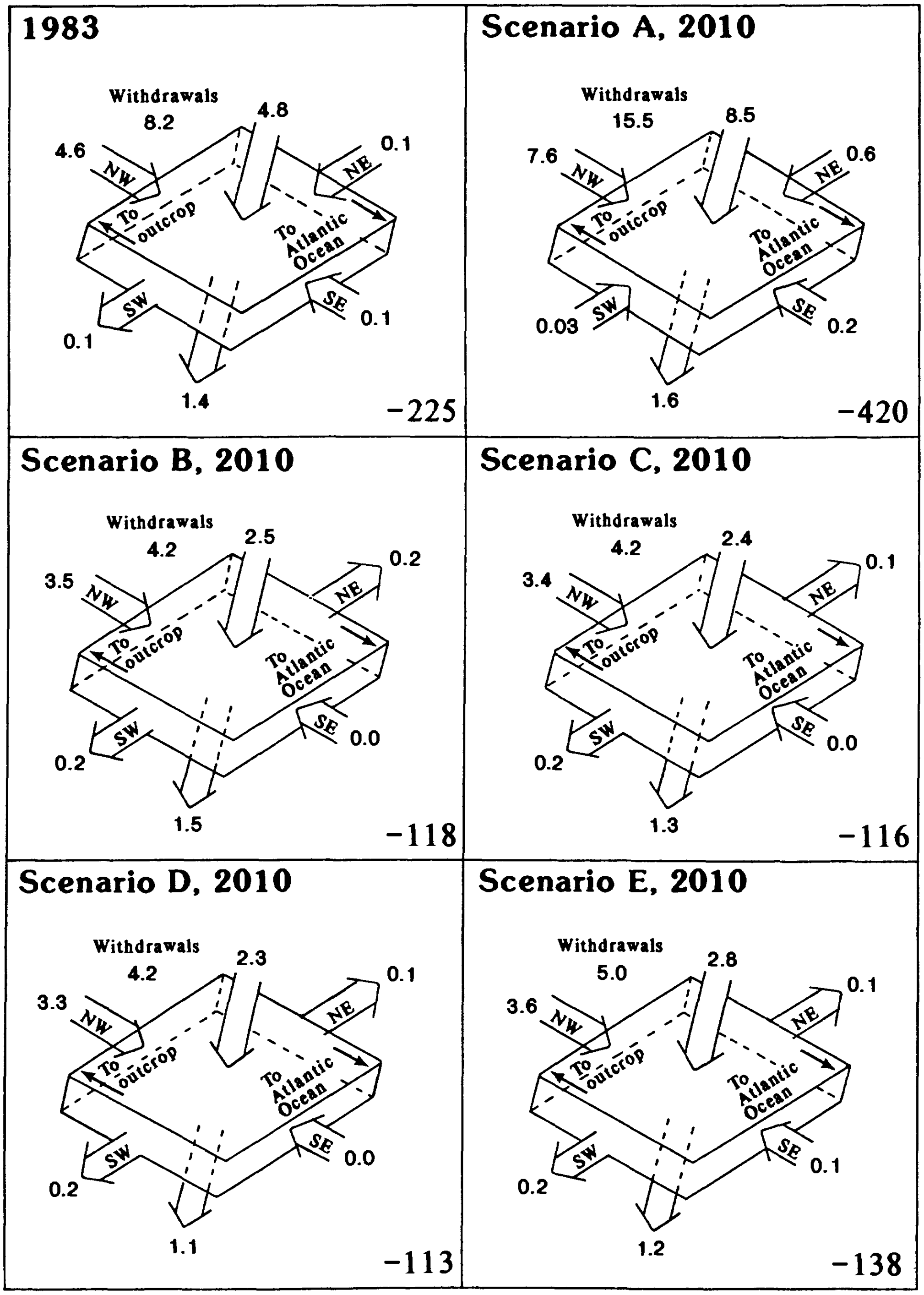


Figure 20.--Simulated ground-water flows for budget area 4 in the Wenonah-Mount Laurel aquifer for scenarios A through E, 1983 and 2010.

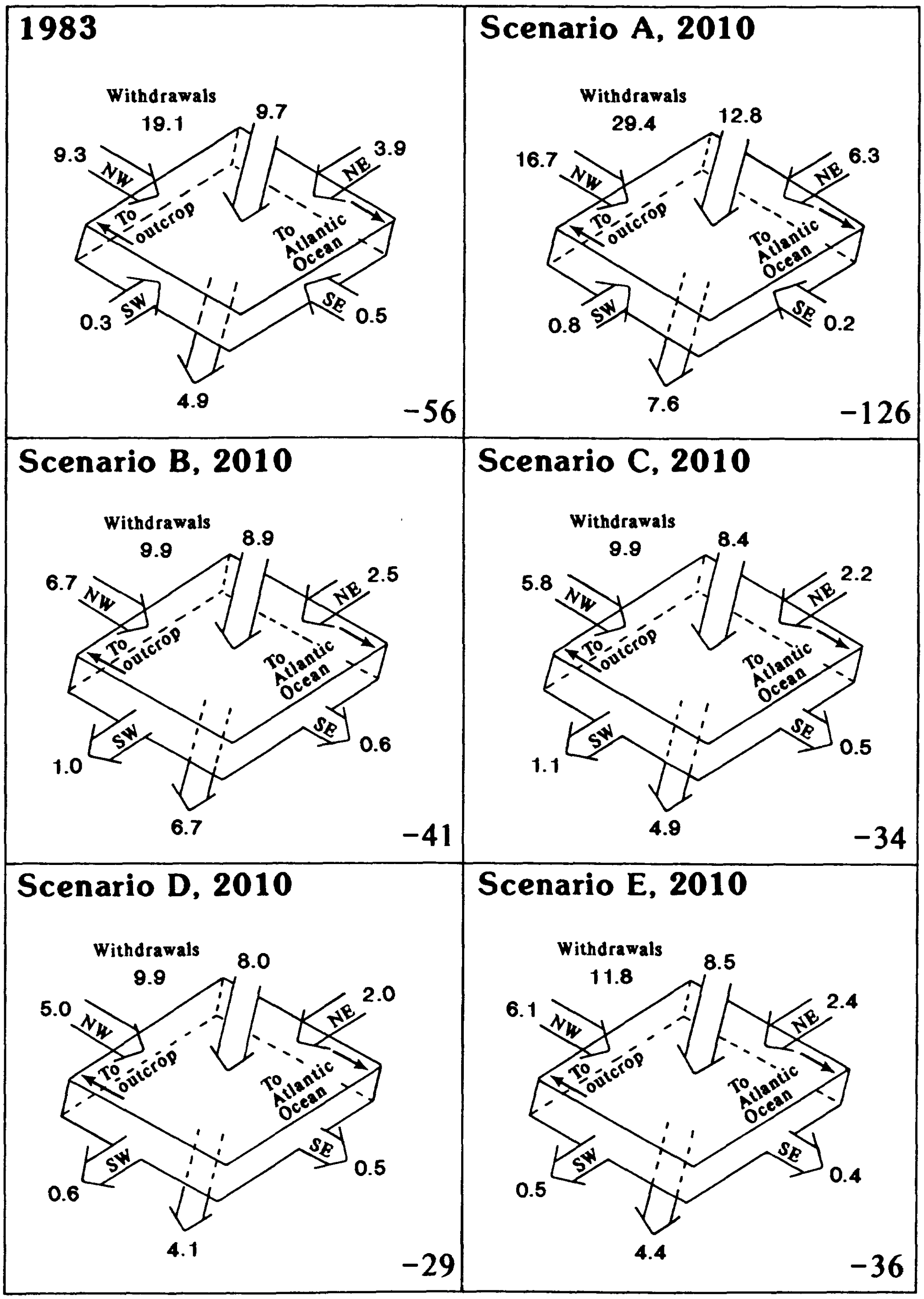


EXPLANATION

0.1 ⟹ Total flow across block face in direction of arrow, in millions of gallons per day

−225 Minimum calculated 1983 and simulated 2010 potentiometric levels within the budget area, in feet above sea level. Budget areas are located on figure 19

Figure 21.--Simulated ground-water flows for budget area 3 in the Englishtown aquifer system for scenarios A through E, 1983 and 2010.

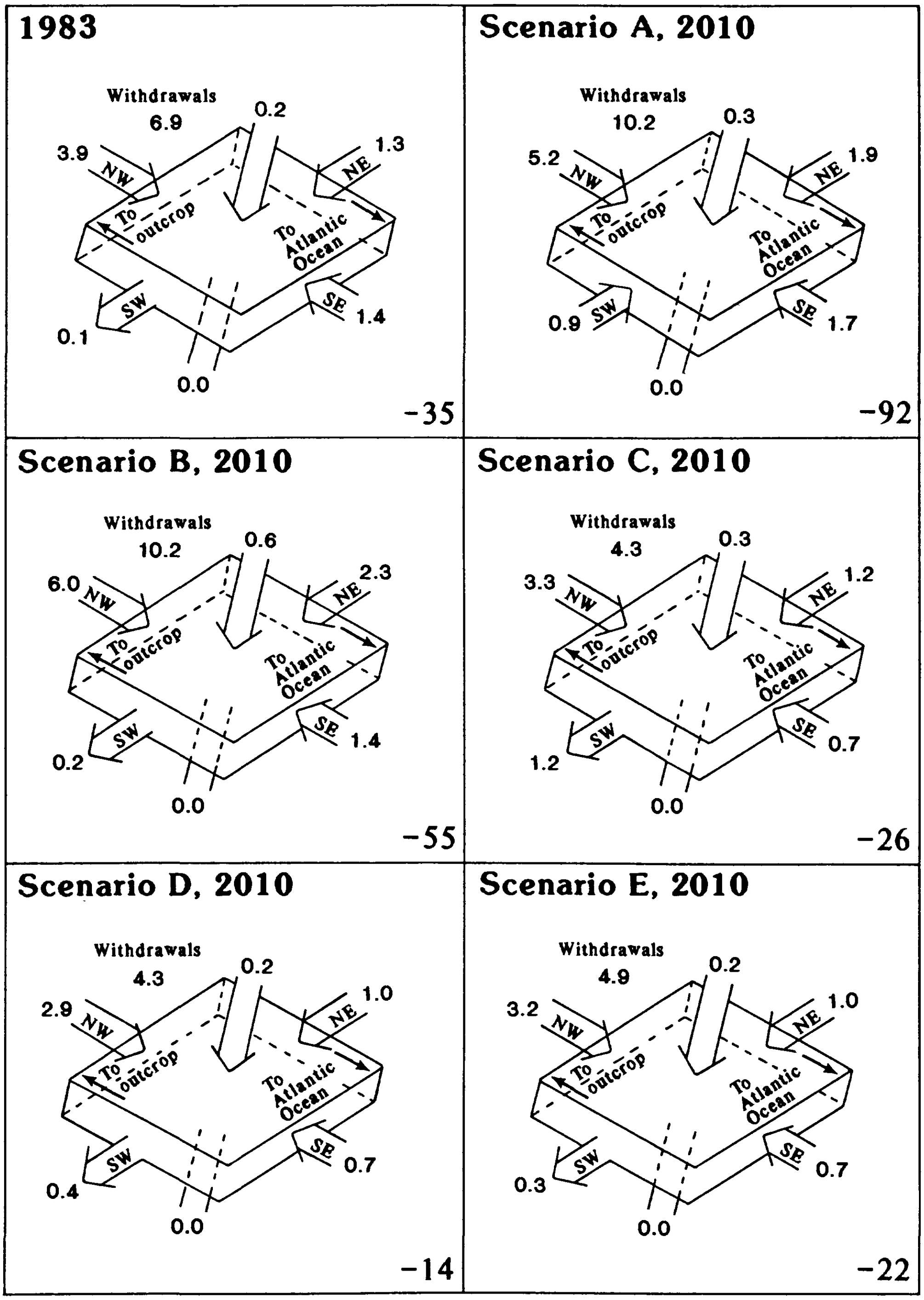


EXPLANATION

4.9 ⟹ Total flow across block face in direction of arrow, in millions of gallons per day

−34 Minimum calculated 1983 and simulated 2010 potentiometric levels within the budget area, in feet above sea level. Budget areas are located on figure 19

Figure 22.--Simulated ground-water flows for budget area 2 in the upper aquifer of the Potomac-Raritan-Magothy aquifer system for scenarios A through E, 1983 and 2010.

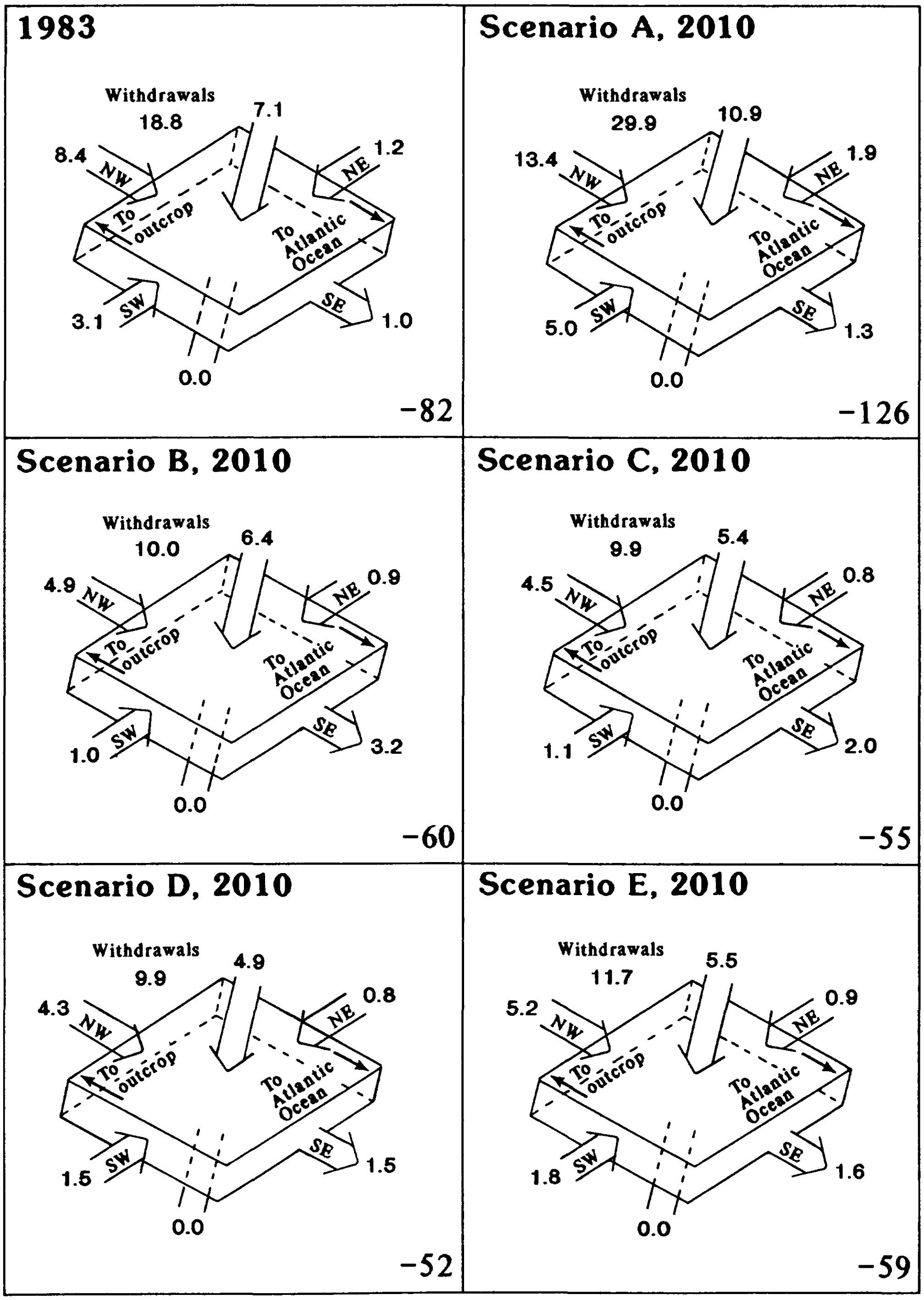


EXPLANATION

3.2 ⟹ Total flow across block face in direction of arrow, in millions of gallons per day

−22 Minimum calculated 1983 and simulated 2010 potentiometric levels within the budget area, in feet above sea level. Budget areas are located on figure 19

Figure 23.--Simulated ground-water flows for budget area 5 in the combined lower and middle aquifers of the Potomac-Raritan-Magothy aquifer system for scenarios A through E, 1983 and 2010.



EXPLANATION

1.5 ⇒ Total flow across block face in direction of arrow, in millions of gallons per day

-60 Minimum calculated 1983 and simulated 2010 potentiometric levels within the budget area, in feet above sea level. Budget areas are located on figure 19

Figure 24.--Simulated ground-water flows for budget area 1 in the middle aquifer of the Potomac-Raritan-Magothy aquifer system for scenarios A through E, 1983 and 2010.

Table 6.--Simulated ground-water flows for budget area 4 in the Wenonah-Mount Laurel aquifer, 1983 through 2020

[NW, northwest; NE, northeast; SW, southwest; SE, southeast]

Scenario	Date[1]	Change in storage[2]	Lateral flow through budget-area sides[3] NW	NE	SW	SE	Total	Vertical Flow[3] From above	From below	Total	With-drawals	Percent error
ALL	1983	-0.03	1.83	0.07	-0.09	0.40	2.21	3.93	-4.84	-0.91	-1.30	-0.48
A	1990	.13	2.30	.09	-.10	.63	2.92	5.11	-6.19	-1.08	-1.91	.73
	1995	.12	2.53	.10	-.11	.70	3.22	5.68	-6.79	-1.11	-2.19	.44
	2000	.12	2.77	.12	-.14	.77	3.52	6.26	-7.38	-1.12	-2.47	.50
	2010	.12	3.23	.14	-.19	.91	4.09	7.32	-8.53	-1.21	-2.93	.60
	2020	.12	3.69	.16	-.25	1.04	4.64	8.34	-9.66	-1.32	-3.38	.45
B	1990	.08	2.11	.07	-.16	.50	2.52	4.55	-5.52	-.97	-1.60	.41
	1995	-.46	1.44	.02	-.44	.02	1.04	2.42	-2.63	-.21	-.74	-9.06
	2000	-.02	1.46	.01	-.53	.04	.98	2.35	-2.58	-.23	-.74	-.26
	2010	.01	1.54	.01	-.68	.05	.92	2.33	-2.54	-.21	-.74	-.51
	2020	.01	1.65	.01	-.83	.06	.89	2.34	-2.50	-.16	-.74	.00
C	1990	.08	2.11	.07	-.16	.50	2.52	4.54	-5.51	-.97	-1.60	.41
	1995	-.47	1.42	.02	-.44	.03	1.03	2.39	-2.58	-.19	-.74	-9.15
	2000	-.02	1.44	.02	-.53	.05	.98	2.28	-2.51	-.23	-.74	-.26
	2010	.00	1.51	.02	-.67	.08	.94	2.24	-2.44	-.20	-.74	.00
	2020	.01	1.61	.02	-.82	.09	.90	2.22	-2.38	-.16	-.74	.25
D	1990	.07	2.11	.07	-.15	.50	2.53	4.53	-5.50	-.97	-1.60	.41
	1995	-.47	1.41	.02	-.41	.03	1.05	2.33	-2.53	-.20	-.74	-9.07
	2000	-.03	1.41	.02	-.49	.06	1.00	2.20	-2.44	-.24	-.74	-.27
	2010	.00	1.48	.02	-.62	.10	.98	2.10	-2.34	-.24	-.74	.00
	2020	.01	1.57	.02	-.76	.12	.95	2.05	-2.27	-.22	-.74	.00
E	1990	.08	2.11	.07	-.15	.50	2.53	4.53	-5.51	-.98	-1.60	.41
	1995	-.40	1.52	.03	-.38	.10	1.27	2.67	-2.99	-.32	-.85	-6.71
	2000	-.02	1.54	.03	-.46	.12	1.23	2.56	-2.92	-.36	-.85	.00
	2010	.00	1.60	.03	-.59	.15	1.19	2.49	-2.83	-.34	-.85	.00
	2020	.01	1.70	.03	-.73	.17	1.17	2.44	-2.75	-.31	-.85	.46
F	1990	.08	2.11	.07	-.15	.50	2.53	4.54	-5.51	-.97	-1.60	.55
	1995	-.33	1.64	.04	-.36	.16	1.48	3.00	-3.45	-.45	-.97	-5.43
	2000	-.02	1.66	.04	-.43	.18	1.45	2.92	-3.39	-.47	-.97	-.21
	2010	.00	1.73	.04	-.57	.20	1.40	2.86	-3.30	-.44	-.97	-.21
	2020	.01	1.82	.04	-.71	.22	1.37	2.82	-3.23	-.41	-.97	.00

[1] Evaluated December 31 of the year indicated.
[2] In million gallons per day. Average rate of change in storage over the preceding 5-year period, except for the 1983 value, which is evaluated for the preceding 3-year period. Negative values indicate increased volume of water in storage; positive values indicate water is released from storage.
[3] In million gallons per day. Negative values are outflows; positive values are inflows.

Table 7.--Simulated ground-water flows for budget area 3 in the Englishtown aquifer system, 1983 through 2020

[NW, northwest; NE, northeast; SW, southwest; SE, southeast]

			Lateral flow through budget-area sides[3]					Vertical flow[3]				
Scenario	Date[1]	Change in storage[2]	NW	NE	SW	SE	Total	From above	From below	Total	With-drawals	Percent error
ALL	1983	-0.04	4.56	0.13	-0.08	0.09	4.70	4.84	-1.38	3.46	-8.16	-0.42
A	1990	.15	5.58	.35	-.04	.14	6.03	6.19	-1.37	4.82	-10.94	.48
	1995	.14	6.10	.43	-.02	.15	6.66	6.79	-1.43	5.36	-12.09	.52
	2000	.14	6.62	.50	.00	.16	7.28	7.38	-1.50	5.88	-13.25	.34
	2010	.13	7.62	.64	.03	.19	8.48	8.53	-1.61	6.92	-15.46	.41
	2020	.13	8.60	.77	.06	.21	9.64	9.66	-1.73	7.93	-17.65	.26
B	1990	.08	5.13	.23	-.08	.11	5.39	5.52	-1.44	4.08	-9.55	.00
	1995	-.53	3.43	-.15	-.20	.03	3.11	2.63	-1.40	1.23	-4.24	-6.82
	2000	-.02	3.42	-.17	-.21	.03	3.07	2.58	-1.41	1.17	-4.24	-.33
	2010	.01	3.51	-.16	-.23	.03	3.15	2.54	-1.45	1.09	-4.24	.16
	2020	.01	3.64	-.16	-.26	.03	3.25	2.50	-1.51	.99	-4.24	.16
C	1990	.08	5.12	.23	-.08	.11	5.38	5.51	-1.42	4.09	-9.55	.00
	1995	-.54	3.38	-.14	-.19	.03	3.08	2.58	-1.30	1.28	-4.24	-6.77
	2000	-.03	3.34	-.15	-.21	.03	3.01	2.51	-1.28	1.23	-4.24	-.51
	2010	.00	3.40	-.14	-.23	.04	3.07	2.44	-1.26	1.18	-4.24	.17
	2020	.01	3.50	-.13	-.25	.04	3.16	2.38	-1.30	1.08	-4.24	.17
D	1990	.08	5.12	.23	-.07	.11	5.39	5.50	-1.41	4.09	-9.55	.09
	1995	-.55	3.34	-.14	-.17	.03	3.06	2.53	-1.24	1.29	-4.24	-7.19
	2000	-.04	3.28	-.14	-.17	.03	3.00	2.44	-1.18	1.26	-4.24	-.35
	2010	.00	3.29	-.12	-.19	.04	3.02	2.34	-1.13	1.21	-4.24	-.18
	2020	.00	3.37	-.11	-.20	.04	3.10	2.27	-1.12	1.15	-4.24	.18
E	1990	.08	5.12	.23	-.07	.11	5.39	5.51	-1.42	4.09	-9.55	.09
	1995	-.46	3.63	-.09	-.15	.04	3.43	2.99	-1.29	1.70	-5.03	-5.26
	2000	-.03	3.58	-.09	-.16	.04	3.37	2.92	-1.25	1.67	-5.03	-.31
	2010	.00	3.62	-.07	-.17	.05	3.43	2.83	-1.21	1.62	-5.03	.31
	2020	.01	3.70	-.06	-.19	.05	3.50	2.75	-1.22	1.53	-5.03	.15
F	1990	.08	5.12	.23	-.07	.11	5.39	5.51	-1.42	4.09	-9.55	.09
	1995	-.38	3.91	-.03	-.14	.05	3.79	3.45	-1.35	2.10	-5.81	-3.97
	2000	-.02	3.89	-.04	-.15	.05	3.75	3.39	-1.32	2.07	-5.81	-.14
	2010	.00	3.94	-.03	-.16	.06	3.81	3.30	-1.30	2.00	-5.81	.00
	2020	.01	4.02	-.02	-.18	.06	3.88	3.23	-1.31	1.92	-5.81	.00

[1] Evaluated December 31 of the year indicated.
[2] In million gallons per day. Average rate of change in storage over the preceding 5-year period, except for the 1983 value, which is evaluated for the preceding 3-year period. Negative values indicate increased volume of water in storage; positive values indicate water is released from storage.
[3] In million gallons per day. Negative values are outflows; positive values are inflows.

Table 8.--Simulated ground-water flows for budget area 2 in the upper aquifer of the Potomac-Raritan-Magothy aquifer system, 1983 through 2020

[NW, northwest; NE, northeast; SW, southwest; SE, southeast]

Scenario	Date[1]	Change in storage[2]	Lateral flow through budget-area sides[3] NW	NE	SW	SE	Total	Vertical Flow[3] From above	From below	Total	With-drawals	Percent error
ALL	1983	0.36	9.29	3.89	0.32	0.49	13.99	9.73	-4.93	4.80	-19.11	0.17
	1990	.29	11.73	4.65	.43	.26	17.07	10.60	-5.85	4.75	-22.13	-.07
	1995	.30	12.99	5.08	.53	.22	18.82	11.16	-6.29	4.87	-24.00	-.03
A	2000	.29	14.23	5.51	.63	.21	20.58	11.70	-6.71	4.99	-25.87	-.03
	2010	.28	16.74	6.29	.75	.17	23.95	12.73	-7.60	5.13	-29.38	-.05
	2020	.27	19.23	7.07	.85	.16	27.31	13.75	-8.51	5.24	-32.82	.00
	1990	.22	10.96	4.37	.29	.23	15.85	10.31	-5.83	4.48	-20.61	-.23
	1995	-.53	6.33	2.31	-.63	-.76	7.25	8.69	-6.05	2.64	-9.88	-2.96
B	2000	-.02	6.36	2.35	-.74	-.64	7.33	8.73	-6.24	2.49	-9.88	-.46
	2010	.05	6.71	2.47	-1.02	-.58	7.58	8.90	-6.74	2.16	-9.89	-.55
	2020	.07	7.19	2.63	-1.30	-.61	7.91	9.16	-7.32	1.84	-9.89	-.37
	1990	.20	10.85	4.33	.28	.22	15.68	10.26	-5.62	4.64	-20.58	-.23
	1995	-.64	5.79	2.14	-.69	-.84	6.40	8.43	-4.84	3.59	-9.90	-3.31
C	2000	-.09	5.65	2.13	-.81	-.67	6.30	8.36	-4.77	3.59	-9.91	-.68
	2010	.01	5.77	2.19	-1.11	-.53	6.32	8.41	-4.92	3.49	-9.91	-.55
	2020	.04	6.06	2.30	-1.41	-.51	6.44	8.57	-5.20	3.37	-9.92	-.41
	1990	.20	10.82	4.32	.32	.21	15.67	10.24	-5.59	4.65	-20.58	-.23
	1995	-.73	5.38	2.03	-.31	-.92	6.18	8.24	-4.35	3.89	-9.90	-3.52
D	2000	-.15	5.07	1.98	-.38	-.71	5.96	8.10	-4.11	3.99	-9.91	-.72
	2010	-.01	4.96	1.98	-.58	-.50	5.86	8.03	-4.06	3.97	-9.91	-.60
	2020	.01	5.07	2.03	-.79	-.43	5.88	8.10	-4.16	3.94	-9.92	-.59
	1990	.20	10.69	4.34	.34	.22	15.59	10.29	-5.57	4.72	-20.58	-.27
	1995	-.58	6.32	2.45	-.22	-.74	7.81	8.63	-4.59	4.04	-11.74	-2.67
E	2000	-.11	6.09	2.41	-.28	-.59	7.63	8.52	-4.41	4.11	-11.75	-.70
	2010	.00	6.05	2.43	-.48	-.43	7.57	8.49	-4.40	4.09	-11.75	-.53
	2020	.02	6.18	2.49	-.68	-.38	7.61	8.57	-4.52	4.05	-11.76	-.46
	1990	.20	10.70	4.34	.34	.22	15.60	10.30	-5.56	4.74	-20.61	-.27
	1995	-.43	7.25	2.86	-.12	-.56	9.43	9.00	-4.82	4.18	-13.57	-2.02
F	2000	-.07	7.10	2.85	-.19	-.46	9.30	8.95	-4.71	4.24	-13.57	-.53
	2010	.01	7.14	2.87	-.38	-.36	9.27	8.96	-4.74	4.22	-13.58	-.42
	2020	.02	7.29	2.94	-.58	-.34	9.31	9.05	-4.88	4.17	-13.58	-.41

[1] Evaluated December 31 of the year indicated.
[2] In million gallons per day. Average rate of change in storage over the preceding 5-year period, except for the 1983 value, which is evaluated for the preceding 3-year period. Negative values indicate increased volume of water in storage; positive values indicate water is released from storage.
[3] In million gallons per day. Negative values are outflows; positive values are inflows.

Table 9.--Simulated ground-water flows for budget area 5 in the middle and lower aquifers of the Potomac-Raritan-Magothy aquifer system, 1983 through 2020

[NW, northwest; NE, northeast; SW, southwest; SE, southeast]

Scenario	Date[1]	Change in storage[2]	Lateral flow through budget-area sides[3] NW	NE	SW	SE	Total	Vertical Flow[3] From above	From below	Total	With-drawals	Percent error
ALL	1983	0.24	3.88	1.31	-0.11	1.41	6.49	0.20	0.00	0.20	-6.93	0.00
	1990	.29	4.47	1.60	.27	1.57	7.91	.28	.00	.28	-8.47	.12
	1995	.27	4.69	1.66	.44	1.58	8.37	.29	.00	.29	-8.91	.22
A	2000	.26	4.89	1.72	.60	1.61	8.82	.29	.00	.29	-9.34	.32
	2010	.25	5.23	1.85	.89	1.71	9.68	.30	.00	.30	-10.19	.39
	2020	.26	5.54	1.99	1.16	1.82	10.51	.31	.00	.31	-11.05	.27
	1990	.25	4.62	1.62	.20	1.50	7.94	.28	.00	.28	-8.47	.00
	1995	-.12	5.69	1.90	-.18	1.07	8.48	.45	.00	.45	-8.91	-1.09
B	2000	.02	5.72	2.07	-.19	1.21	8.81	.49	.00	.49	-9.34	-.21
	2010	.09	5.95	2.33	-.17	1.43	9.54	.55	.00	.55	-10.19	-.10
	2020	.12	6.30	2.59	-.14	1.59	10.34	.61	.00	.61	-11.05	.18
	1990	.22	4.32	1.45	.08	1.38	7.23	.24	.00	.24	-7.70	-.13
	1995	-.49	3.88	1.01	-.93	.31	4.27	.25	.00	.25	-4.33	-5.36
C	2000	-.08	3.57	1.10	-1.04	.49	4.12	.25	.00	.25	-4.33	-.74
	2010	.02	3.28	1.24	-1.20	.70	4.02	.27	.00	.27	-4.33	-.36
	2020	.06	3.18	1.36	-1.32	.76	3.98	.29	.00	.29	-4.33	.00
	1990	.20	4.32	1.44	.12	1.36	7.24	.24	.00	.24	-7.70	-.26
	1995	-.67	3.81	.79	-.30	.13	4.43	.21	.00	.21	-4.33	-7.03
D	2000	-.17	3.35	.87	-.33	.38	4.27	.19	.00	.19	-4.33	-.83
	2010	-.02	2.88	.98	-.36	.65	4.15	.20	.00	.20	-4.33	.00
	2020	.02	2.66	1.05	-.34	.75	4.12	.20	.00	.20	-4.33	.21
	1990	.20	4.30	1.44	.13	1.38	7.25	.24	.00	.24	-7.70	-.13
	1995	-.54	3.93	.89	-.23	.31	4.90	.21	.00	.21	-4.85	-5.11
E	2000	-.13	3.54	.95	-.25	.52	4.76	.20	.00	.20	-4.85	-.38
	2010	.00	3.15	1.04	-.26	.73	4.66	.20	.00	.20	-4.85	.20
	2020	.02	2.95	1.11	-.24	.81	4.63	.21	.00	.21	-4.85	.20
	1990	.20	4.30	1.44	.13	1.38	7.25	.24	.00	.24	-7.70	-.13
	1995	-.40	4.02	.99	-.16	.49	5.34	.21	.00	.21	-5.38	-3.95
F	2000	-.08	3.73	1.04	-.17	.64	5.24	.21	.00	.21	-5.38	-.18
	2010	.00	3.42	1.11	-.17	.81	5.17	.21	.00	.21	-5.38	.00
	2020	.02	3.25	1.17	-.14	.86	5.14	.22	.00	.22	-5.38	.00

[1] Evaluated December 31 of the year indicated.
[2] In million gallons per day. Average rate of change in storage over the preceding 5-year period, except for the 1983 value, which is evaluated for the preceding 3-year period. Negative values indicate increased volume of water in storage; positive values indicate water is released from storage.
[3] In million gallons per day. Negative values are outflows; positive values are inflows.

Table 10.--Simulated ground-water flows for budget area 1 in the middle aquifer of the Potomac-Raritan-Magothy aquifer system, 1983 through 2020

[NW, northwest; NE, northeast; SW, southwest; SE, southeast]

Scenario	Date[1]	Change in storage[2]	Lateral flow through budget-area sides[3] NW	NE	SW	SE	Total	Vertical Flow[3] From above	From below	Total	With-drawals	Percent error
ALL	1983	0.02	8.44	1.18	3.13	-1.03	11.72	7.10	0.00	7.10	-18.83	0.05
A	1990	.02	10.41	1.42	3.86	-1.19	14.50	8.21	.00	8.21	-22.73	.00
	1995	.02	11.17	1.54	4.15	-1.24	15.62	8.87	.00	8.87	-24.52	-.04
	2000	.03	11.92	1.67	4.45	-1.25	16.79	9.52	.00	9.52	-26.33	.04
	2010	.03	13.39	1.94	5.01	-1.31	19.03	10.85	.00	10.85	-29.91	.00
	2020	.03	14.89	2.19	5.57	-1.35	21.30	12.21	.00	12.21	-33.52	.06
B	1990	.01	9.47	1.32	3.44	-1.44	12.79	8.02	.00	8.02	-20.82	.00
	1995	-.10	4.70	.80	1.43	-2.95	3.98	6.00	.00	6.00	-9.94	-.46
	2000	.00	4.73	.83	1.28	-2.97	3.87	6.12	.00	6.12	-9.94	.39
	2010	.00	4.86	.89	1.00	-3.22	3.53	6.43	.00	6.43	-9.95	.08
	2020	.00	5.03	.95	.73	-3.56	3.15	6.82	.00	6.82	-9.95	.15
C	1990	.01	9.43	1.31	3.44	-1.30	12.88	7.91	.00	7.91	-20.82	-.09
	1995	-.12	4.51	.75	1.50	-2.16	4.60	5.35	.00	5.35	-9.93	-.82
	2000	.00	4.49	.77	1.37	-1.98	4.65	5.32	.00	5.32	-9.93	.34
	2010	.00	4.54	.82	1.12	-1.96	4.52	5.43	.00	5.43	-9.94	.08
	2020	.00	4.66	.87	.87	-2.08	4.32	5.65	.00	5.65	-9.94	.25
D	1990	.01	9.43	1.31	3.46	-1.29	12.91	7.89	.00	7.89	-20.82	-.05
	1995	-.13	4.41	.72	1.79	-2.00	4.92	5.05	.00	5.05	-9.93	-.75
	2000	.00	4.34	.73	1.70	-1.69	5.08	4.90	.00	4.90	-9.93	.43
	2010	.00	4.33	.77	1.52	-1.53	5.09	4.86	.00	4.86	-9.94	.09
	2020	.00	4.40	.81	1.33	-1.54	5.00	4.96	.00	4.96	-9.94	.17
E	1990	.01	9.48	1.32	3.54	-1.28	13.06	7.73	.00	7.73	-20.82	-.09
	1995	-.10	5.26	.83	2.04	-1.92	6.21	5.55	.00	5.55	-11.72	-.44
	2000	.00	5.21	.84	1.95	-1.68	6.32	5.45	.00	5.45	-11.73	.30
	2010	.00	5.22	.88	1.77	-1.57	6.30	5.45	.00	5.45	-11.73	.15
	2020	.00	5.30	.92	1.58	-1.60	6.20	5.56	.00	5.56	-11.74	.15
F	1990	.01	9.48	1.32	3.54	-1.27	13.07	7.73	.00	7.73	-20.82	-.05
	1995	-.08	6.10	.93	2.30	-1.83	7.50	6.06	.00	6.06	-13.53	-.32
	2000	.00	6.08	.94	2.20	-1.67	7.55	6.01	.00	6.01	-13.53	.20
	2010	.00	6.11	.99	2.02	-1.61	7.51	6.05	.00	6.05	-13.54	.13
	2020	.00	6.20	1.03	1.84	-1.66	7.41	6.17	.00	6.17	-13.54	.26

[1] Evaluated December 31 of the year indicated.
[2] In million gallons per day. Average rate of change in storage over the preceding 5-year period, except for the 1983 value, which is evaluated for the preceding 3-year period. Negative values indicate increased volume of water in storage; positive values indicate water is released from storage.
[3] In million gallons per day. Negative values are outflows; positive values are inflows.

For example, in 2010, budget area 3, scenario E (table 7):

$$\text{Percent error} = \frac{6.50 - 6.48}{(12.98)/2} \cdot 100 = 0.31 .$$

The percent error is calculated for each pumping period to verify the numerical results of the model.

The ground-water-budget error is from 1 to 10 percent in 1995 for scenarios B through F, because the simulated ground-water flows are calculated for December 31 of the year indicated, whereas the rate of change in storage is calculated as the average for the pumping period ending in the year indicated. The average value is an accurate estimate of the simulated rate of change in storage at the end of the pumping period as long as the change in storage is small. If simulated water levels change significantly over a pumping period, most of the change is simulated in the beginning time steps of the pumping period. The average change in storage for the pumping period, therefore, is larger than the simulated rate of change in storage at the end of the pumping period. Note that for central areas 1 through 5, scenarios B through F, smaller head changes between 1990 and 1995 in table 5, are associated with smaller percent errors in tables 6 to 10. Areas with the smallest head changes in other pumping periods do not necessarily have the smallest percent error. As an example of how the error could be accounted for by inaccurate storage values, consider in 1995, budget area 4, scenario D; the error of -9.07 percent is equivalent to -0.36 Mgal/d. This error could be accounted for by the inaccuracy of the calculated -0.47 Mgal/d storage.

The change in storage in budget areas 1-5, for all scenarios and pumping periods after 1995, is less than 5 percent of withdrawals from those areas. This amount is comparable to that simulated by Martin (in press) for major cones of depression in near steady-state conditions.

The calculated ground-water budgets listed in tables 6-10 and displayed in figures 20-24 indicate the following: (1) flow from the northwest, which is from the aquifer outcrops, is a major source of inflow for all the budget areas; (2) flow from above is a major source of inflow for all the budget areas except area 5; (3) most of the increased storage caused by reduction of pumping in 1990 occurs by 1995; and, (4) the changes in flows in the budgets between scenarios D and E are the same as the changes in flows in the budgets between scenarios E and F.

Most of the differences in ground-water flows for 1990 through 2010 in the scenarios followed expected patterns. The expected responses to reduced withdrawals within a budget area are an increase of water in storage, a decrease of inflows, and an increase of outflows. Increased withdrawals are expected to produce the opposite response. The expected responses in one budget area to the reduction of withdrawals in another budget area are a decrease of outflow or an increase of inflow in the direction of the changed withdrawals.

Although the Merchantville-Woodbury confining unit is recognized as one of the most effective confining units in the New Jersey Coastal Plain (Barksdale and others, 1958, p. 136), a large downward flow through this confining unit into the upper aquifer of the Potomac-Raritan-Magothy aquifer system is shown in figure 22 and table 8 for budget area 2. The simulated leakance (hydraulic conductivity divided by thickness) of the confining unit is 100 times higher updip near the outcrop than in downdip areas (Martin, in press). In the northwestern half of budget area 2 of the middle aquifer of the Potomac-Raritan-Magothy aquifer system, where hydraulic gradients are downward, the confining unit is thinner and has a higher hydraulic conductivity (Luzier, 1980, p. 22 and 29) than in the southeastern half of the budget area, where the hydraulic gradients are upward. The net flow is down into the upper aquifer of the Potomac-Raritan-Magothy aquifer system. The net calculated downward flow from the Englishtown aquifer system (table 7, fig. 21) is also the result of a higher leakance in the updip part of Merchantville-Woodbury confining unit than in downdip areas. Over most of budget area 2 the flow is upward into the Englishtown aquifer system, however, in the area along the northwestern boundary where the permeability of the confining unit is high, a downward hydraulic gradient produces flow from the Englishtown aquifer system through the confining unit and into the upper aquifer of the Potomac-Raritan-Magothy aquifer system. The net flow is downward.

The effects of the six scenarios of future withdrawals on the magnitude and direction of ground-water flows into and out of the budget areas in 2010 are shown in figures 20-24 and tables 6-10. Inflows are largest in scenario A, and show an increase of between 47 and 77 percent from 1983 inflows by 2010. In scenarios B through F, flows into budget areas 1 to 5, except budget area 5, scenario B (fig. 23), decreased from 19 to 42 percent from 1983 inflows by 2010. The simulation of increased withdrawals in scenarios E and F, 2010, produced increased simulated inflows of from 9 to 16 percent, and from 18 to 32 percent, respectively, from inflows for scenario D.

SUMMARY AND CONCLUSIONS

Water levels and ground-water flow in the northeastern New Jersey Coastal Plain for the years 1984 through 2020 were simulated using the New Jersey RASA model (Martin, in press). Six scenarios of ground-water withdrawals were considered. In one scenario, simulated withdrawals were allowed to increase in an unrestricted manner and were estimated using data provided by the NJDEP/DWR on projected future withdrawals or a linear regression of actual 1960 through 1983 withdrawal data. For the other five scenarios, simulated withdrawals after 1990 were equal to 50, 60, or 70 percent of actual 1983 withdrawals within four to seven "depleted" areas, as defined by the New Jersey Department of Environmental Protection. Each area applies to either one or two aquifers and generally encompasses one major cone of depression in the northeastern and west-central parts of the Coastal Plain.

The simulations showed that the reduction of ground-water withdrawals in the northeastern and west-central parts of the Coastal Plain caused significant recoveries of simulated water levels in the northeastern Coastal Plain. Specifically, the simulations indicate the following: (1) if withdrawals increase at the projected unrestricted rates, water levels in the major cones of depression will continue to decline; (2) the ground-water system of the New Jersey Coastal Plain responds quickly to changes in ground-water withdrawals; (3) withdrawals in one part of the system affect water levels and ground-water flow elsewhere in the system; and (4) significant additional recovery is produced when the more stringent of the simulated withdrawal reductions are considered.

The simulation of unrestricted withdrawals for the years 1984 through 2020 produced large simulated drawdowns in all cones of depression of the northeastern Coastal Plain. In the Wenonah-Mount Laurel aquifer, simulated water levels declined 210 ft, over the 36-year period; in the Englishtown aquifer system, simulated water levels declined 47 ft; in the upper and middle aquifers of the Potomac-Raritan-Magothy aquifer system, simulated water levels declined 93 and 58 ft, respectively.

For scenarios in which large reductions in withdrawals were simulated, 80 to 100 percent of the simulated recovery occurred within 5 years. In these scenarios, simulated withdrawals in the northeastern and west-central Coastal Plain were reduced to 50, 60, or 70 percent of the 1983 withdrawals, beginning in 1991. These reductions produced 6 to 113 ft of recovery in the major cones of depression of the northeastern Coastal Plain, most of which occurred within the first 5 years.

The regional nature of the aquifer system was displayed in simulations in which withdrawals were restricted first in the northeastern Coastal Plain, and then in areas of the south-central Coastal Plain. In response to local reductions in simulated withdrawals, simulated water levels in the upper and middle aquifers of the Potomac-Raritan-Magothy aquifer system of the northeastern Coastal Plain recovered 18 and 23 ft, respectively, above 1983 water levels. When simulated withdrawals in parts of the west-central Coastal Plain were reduced, simulated water levels in the northeastern Coastal Plain recovered an additional 7 to 9 ft.

These simulations indicate that each 10-percent reduction in withdrawals from 1983 levels produces an additional 20 to 24 ft of simulated recovery in the major cones in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system, and an additional 6 to 8 ft of simulated recovery in the major cones in the upper and middle aquifers of the Potomac-Raritan-Magothy aquifer system.

Under the most stringent reductions considered, most of the simulated ground-water withdrawals in the four major aquifers of the northeastern and west-central Coastal Plain were restricted to 50 percent of actual 1983 withdrawals after 1990. Even with these severe restrictions, simulated water levels in the major cones of depression in the northeastern Coastal Plain remained well below sea level in 2020. In the Wenonah-Mount Laurel aquifer, simulated 2020 water levels were as low as 93 ft below sea level, in the Englishtown aquifer system, they were 115 ft below sea level, and in the Potomac-Raritan-Magothy aquifers, they were 52 ft below sea level.

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