U.S. Department of the Interior
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# SIMULATION OF THE GROUND-WATER FLOW SYSTEM IN 1992, AND SIMULATED EFFECTS OF PROJECTED GROUND-WATER WITHDRAWALS IN 2020 IN THE NEW JERSEY COASTAL PLAIN

**Water-Resources Investigations Report 03-4000**

**Prepared in cooperation with the**

**NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION**

science for a changing world

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***by Alison D. Gordon***

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**NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION**

**West Trenton, New Jersey**

**2003**

USGS
science for a changing world

**U.S. DEPARTMENT OF THE INTERIOR**

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**U.S. GEOLOGICAL SURVEY**

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# CONVERSION FACTORS AND VERTICAL DATUM

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter |
| inch (in.) | 25.4 | millimeter |
| foot (ft) | 0.3048 | meter |
| mile (mi) | 1.609 | kilometer |
| | Volume | |
| gallon (gal) | 3.785 | liter |
| gallon (gal) | 0.003785 | cubic meter |
| million gallons (Mgal) | 3,785 | cubic meters |
| | Flow | |
| million gallons per day (Mgal/d) | 0.04381 | cubic meters per second |
| gallons per minute (gal/min) | 0.06308 | liters per second |
| inch per year (in/yr) | 25.4 | millimeter per year |
| | Hydraulic conductivity | |
| foot per day (ft/d) | 0.3048 | meter per day |
| | Transmissivity | |
| foot squared per day ($ft^2/d$)[1] | 0.09290 | meter squared per day |
| | Density | |
| grams per cubic centimeter ($g/cm^3$) | 62.43 | pounds per cubic foot |

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 29).

[1] This unit is used to express transmissivity, the capacity of an aquifer to transmit water. Conceptually, transmissivity is cubic feet (of water) per day per square foot (of aquifer area) times feet (of aquifer thickness), or $(ft^3/d)/ft^2 \times ft$. In this report, this expression is reduced to its simplest form, $ft^2/d$.

# SIMULATION OF THE GROUND-WATER FLOW SYSTEM IN 1992, AND SIMULATED EFFECTS OF PROJECTED GROUND-WATER WITHDRAWALS IN 2020 IN THE NEW JERSEY COASTAL PLAIN

***by Alison D. Gordon***


## ABSTRACT

In 1992, ground-water withdrawals from the unconfined and confined aquifers in the New Jersey Coastal Plain totaled about 300 million gallons per day, and about 70 percent (200 million gallons per day) of this water was pumped from confined aquifers. The withdrawals have created large cones of depression in several Coastal Plain aquifers near populated areas, particularly in Camden and Ocean Counties. The continued decline of water levels in confined aquifers could cause saltwater intrusion, reduction of stream discharge near the outcrop areas of these aquifers, and depletion of the ground-water supply. Because of this, withdrawals from wells located within these critical areas have been reduced in the Potomac-Raritan-Magothy aquifer system, the Englishtown aquifer system, and the Wenonah-Mount Laurel aquifer.

A computer-based model that simulates freshwater and saltwater flow was used to simulate transient ground-water flow conditions and the location of the freshwater-saltwater interface during 1989-92 in the New Jersey Coastal Plain. This simulation was used as the baseline for comparison of water levels and flow budgets. Four hypothetical withdrawal scenarios were simulated in which ground-water withdrawals were either increased or decreased. In scenario 1, withdrawals from wells located within critical area 2 in the Potomac-Raritan-Magothy aquifer system were reduced by amounts ranging from 0 to 35 percent of withdrawals prior to 1992. Critical area 2 is mainly located in Camden County, and most of Burlington and Gloucester Counties. With the reductions, water levels recovered about 30 feet in the regional cone of depression centered in Camden County in the Upper Potomac-Raritan-Magothy aquifer and by 20 ft in the Lower and Middle Potomac-Raritan-Magothy aquifers.

In scenarios 2 to 4, withdrawals projected for 2020 were input to the model. In scenario 2, withdrawal restrictions within the critical areas were imposed in the Potomac-Raritan-Magothy aquifer system, the Englishtown aquifer system, and the Wenonah-Mount Laurel aquifer, but withdrawals were increased outside the critical areas to the projected 2020 demand. With withdrawals restrictions in the critical areas, water levels recovered about 20 feet at the center of a regional cone of depression in the Upper Potomac-Raritan-Magothy aquifer. Water levels recovered by about 20 feet at the center of a regional cone of depression in the Englishtown aquifer system in Ocean County, and by about 20 feet in the Wenonah-Mount Laurel aquifer in the same area. In scenario 3, withdrawals were increased to the projected 2020 demand inside and outside the critical areas. As a result, water levels declined as much as 20 feet at the center of a regional cone of depression in the Englishtown aquifer system in Ocean County, and as much as 10 feet in the Wenonah-Mount Laurel aquifer near this area. The Englishtown aquifer system and the Wenonah-Mount Laurel aquifer are particularly sensitive to increases and decreases in withdrawals because in certain areas the transmissivities of these aquifers are lower than the transmissivities of other confined aquifers of the New Jersey Coastal Plain, and because these aquifers are hydraulically connected. Simulated water levels declined by as much as 10 ft at the center of the regional cone of depression in Atlantic County. In scenario 4, withdrawal amounts were equal to that in scenario 2, except an additional 13.2 million gallons per day was

withdrawn from hypothetical wells located outside the critical areas in the Upper Potomac-Raritan-Magothy aquifer, Englishtown aquifer system, and the Wenonah-Mount Laurel aquifer. The additional withdrawals resulted in increased leakage from overlying aquifers to the Wenonah-Mount Laurel aquifer and subsequently to the Englishtown aquifer system.

## INTRODUCTION

In 1992, ground-water withdrawals from the unconfined and confined aquifers in the New Jersey Coastal Plain totaled about 300 Mgal/d. Almost 70 percent (200 Mgal/d) of this water was pumped from the confined aquifers. The development of ground water has occurred primarily near large population centers, creating large regional cones of depression in several of the New Jersey Coastal Plain aquifers. Continued decline of water levels in confined aquifers poses the threat of serious adverse effects to the water supply in some areas, including the depletion of ground-water supplies in some aquifers, saltwater intrusion, and reduction of ground water to streams near outcrop areas. Management of the ground-water resources requires identifying specific areas where ground-water supplies may be threatened. Therefore, certain areas of New Jersey where excessive water use or water diversions present undue stress or long-term adverse effects on a water supply have been designated as areas of critical water supply (critical areas) (New Jersey Department of Environmental Protection, 1995).

The designation of critical areas is based on several concerns, including the shortage of ground water due to the progressive lowering of water levels so that the operation of existing wells is threatened or well water is contaminated by saltwater intrusion (New Jersey Administrative Code, 1995). A chloride concentration of 250 mg/L is the secondary maximum contamination level, the level above which the taste of water may become objectionable to the consumer. Concentrations below this level provide a reasonable level of protection for the public welfare (Shelton, 1996). The water-level criterion used to identify areas of concern was defined as areas where water levels are deeper than the -30 ft contour on the 1983 potentiometric surface maps of Eckel and Walker (1986) (New Jersey Administrative Code, 1995).

Water supply critical area 1 encompasses most of Monmouth County and parts of Ocean and Middlesex Counties; it includes the Farrington and Old Bridge aquifers (Middle and Upper Potomac-Raritan-Magothy aquifers), the Englishtown aquifer system, and the Wenonah-Mount Laurel aquifer; water supply critical area 2 encompasses all of Camden County, most of Burlington and Gloucester Counties, and parts of Atlantic, Cumberland, Monmouth, Ocean, and Salem Counties and includes the Potomac-Raritan-Magothy aquifer system (New Jersey Department of Environmental Protection, 1996). In an effort to improve the management of ground-water resources in the confined aquifers of the New Jersey Coastal Plain, reductions in withdrawals of 40 to 50 percent went into effect in critical area 1 (fig. 1) by 1991 for the Middle and Upper Potomac-Raritan-Magothy aquifers, the Englishtown aquifer system, and the Wenonah-Mount Laurel aquifer in Monmouth County and parts of Middlesex and Ocean Counties (New Jersey Administrative Code, 1995). A reduction in ground-water withdrawals for critical area 2 had not been fully implemented for the Potomac-Raritan-Magothy aquifer system as of 1996. In these areas, withdrawals have been reduced on average about 22 percent (Jan Gheen, N.J. Department of Environmental Protection, oral commun., 1998).

A study was conducted by the U.S. Geological Survey, in cooperation with the NJDEP, that used a previously developed calibrated ground-water flow model of the New Jersey Coastal Plain (Pope and Gordon, 1999) to evaluate the effects of increased and decreased ground-water withdrawals on the ground-water flow system, particularly in the critical areas. The study investigated four water-resources management strategies by incorporating projected growth in total average water demand in the watershed planning areas in the New Jersey Coastal Plain. As part of the New Jersey statewide water-supply plan, the State of New Jersey was divided into 23 regional water-resource planning areas (RWRPA's) on the basis of surface water-sheds (New Jersey Department of Environmental Protection, 1996). RWRPA's 10 through 23 are

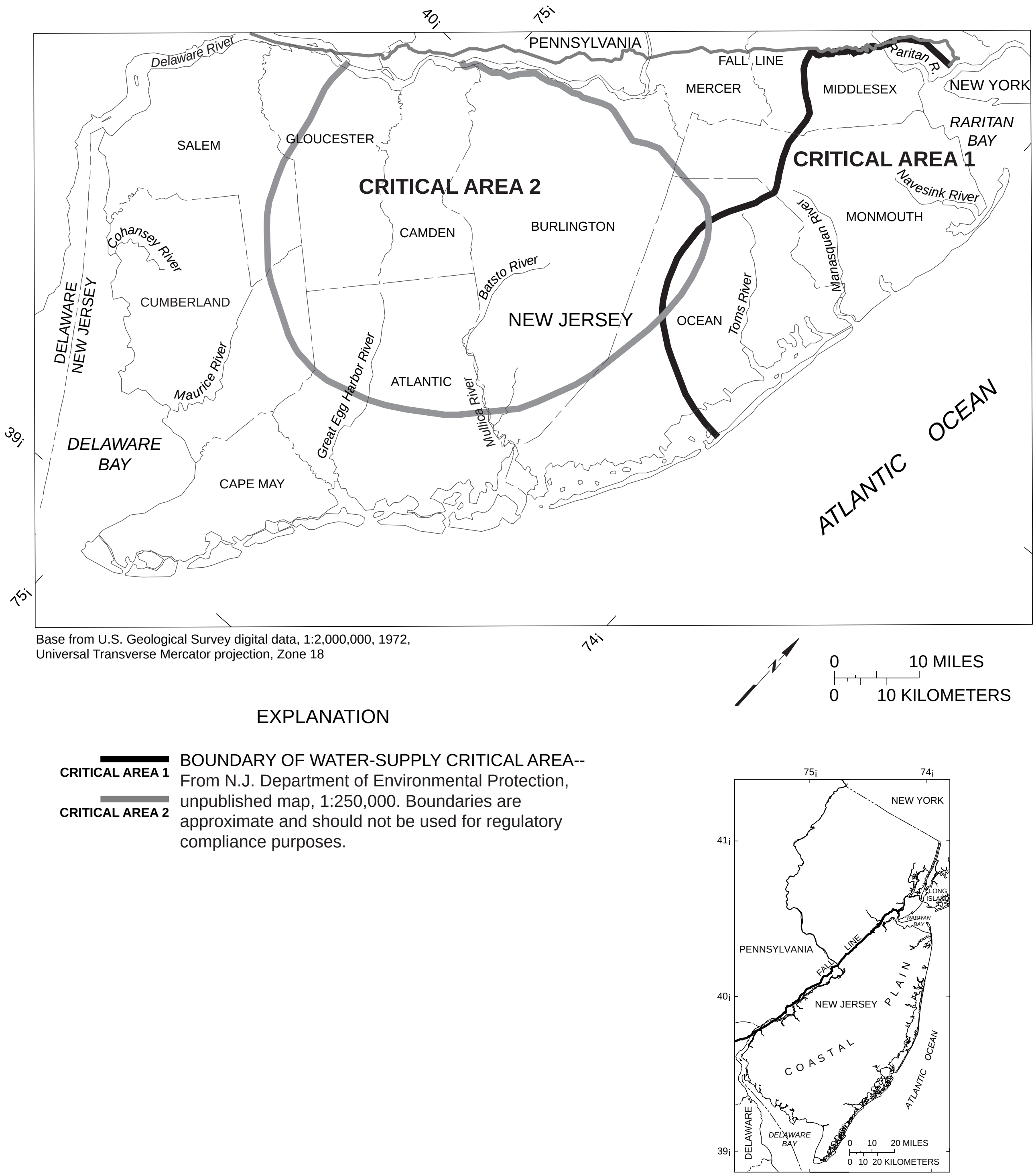



**Figure 1.** Location of study area and water-supply critical areas 1 and 2 in New Jersey.

within the New Jersey Coastal Plain (fig. 2). Anticipated growth in water demand for the study area was based on the increase in average water demand projected for 2020 for these RWRPA's. A baseline and four hypothetical scenarios were simulated for the study. The scenarios are (1) maintaining 1992 pumpage in most of the study area but reducing withdrawals from the Potomac-Raritan-Magothy aquifer system in critical area 2; (2) increasing withdrawals from all Coastal Plain aquifers outside the critical water supply areas but incorporating the withdrawal reductions in the Potomac-Raritan-Magothy aquifer system in critical area 2, as in scenario 1, and withdrawal restrictions in critical area 1 in the Middle and Upper Potomac-Raritan-Magothy aquifers, Englishtown aquifer system and the Wenonah-Mount Laurel aquifer; (3) increasing withdrawals in existing withdrawal wells in all aquifers in the study area inside and outside the critical areas; and (4) incorporating the same withdrawals as scenario 2 and adding withdrawals from hypothetical wells completed in the Upper Potomac-Raritan-Magothy aquifer, the Englishtown aquifer system, and the Wenonah-Mount Laurel aquifer outside the critical areas.

## PURPOSE AND SCOPE

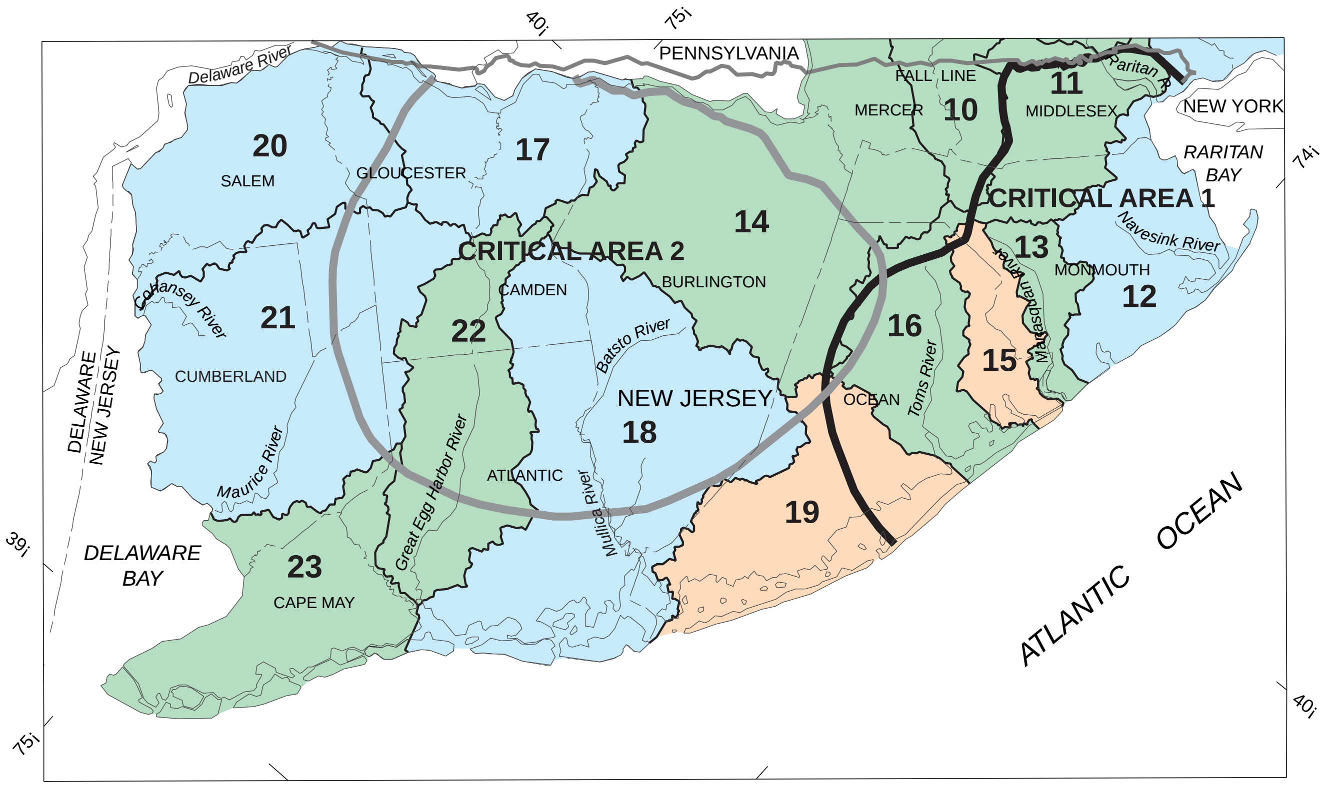
This report describes the results of simulations done by use of a previously developed ground-water flow model of the New Jersey Coastal Plain. Average 1992 ground-water withdrawals from more than 1,100 wells were used to provide a baseline for comparison with water levels and flow budgets for eight confined aquifers in the New Jersey Coastal Plain that resulted from simulations for four hypothetical withdrawal scenarios. The location of the freshwater-saltwater interface also was simulated. Results of the four subsequent simulations were used to determine the effects on the flow system, particularly in the critical water supply management areas, of decreased and increased ground-water withdrawals. The first scenario was designed to observe the effect of reduced withdrawals on water levels in critical area 2. The other three scenarios represent a range of potential water-supply strategies during 1993-2020, including decreased, increased, or relocated ground-water withdrawals. Simulated water levels and the freshwater-saltwater interface tip and toe for the confined aquifers for the baseline simulation and each scenario are illustrated. The flow budgets are discussed and are presented in a table.

## LOCATION AND EXTENT OF STUDY AREA

The New Jersey Coastal Plain extends from the Fall Line to the Atlantic Ocean in the east and to the Delaware Bay in the south (fig. 1). The study area includes all of Atlantic, Burlington, Camden, Cape May, Cumberland, Gloucester, Monmouth, Ocean, and Salem Counties, as well as parts of Middlesex and Mercer Counties. The model area includes all of the study area and parts of Delaware and Pennsylvania. The model area extends from the Fall Line in the northwest to the edge of the Continental Shelf in the southeast, and from the Delaware Bay in the southwest to Raritan Bay in the northeast.

## PREVIOUS INVESTIGATIONS

Zapecza (1989) describes the hydrogeologic framework of the New Jersey Coastal Plain aquifers in onshore areas. This framework was used in the ground-water flow model of Pope and Gordon (1999). Eckel and Walker (1986), Rosman and others (1995), and Lacombe and Rosman (1997) describe the collection and interpretation of synoptic water-level data for fall 1983, 1988, and 1993, respectively, and present contour maps of the potentiometric surfaces of the Coastal Plain aquifers. Water-level data from Eckel and Walker (1986) and Rosman and others (1995) were used to describe the ground-water flow system and calibrate the flow model discussed in Pope and Gordon (1999). The freshwater flow system in the New Jersey Coastal Plain was simulated by Martin (1998) with a numerical ground-water flow model as part of the Regional Aquifer System Analysis (RASA) program. Martin's (1998) model was modified by Pope and Gordon (1999) to include the saltwater flow system in downdip areas of the New Jersey Coastal Plain sediments.




Base from U.S. Geological Survey digital data, 1:2,000,000, 1972,
Universal Transverse Mercator projection, Zone 18

EXPLANATION

PERCENT INCREASE IN PREDICTED GROUND-WATER WITHDRAWLS FOR 2020

- 0 to 15
- Greater than 15 to 30
- Greater than 30 to 52.7

CRITICAL AREA 1
CRITICAL AREA 2
BOUNDARY OF WATER-SUPPLY CRITICAL AREA--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

**20** Regional water resource planning area boundary and number (From N.J. Department of Environmental Protection, 1992)

| | |
|---|---|
| **10** | Raritan River |
| **11** | South River |
| **12** | Navesink/Swimming Rivers |
| **13** | Manasquan River |
| **14** | Rancocas Creek |
| **15** | Metedeconk River |
| **16** | Toms River |
| **17** | Camden Delaware Tributaries |
| **18** | Mullica River |
| **19** | Atlantic Coastal |
| **20** | Salem River |
| **21** | Maurice River |
| **22** | Great Egg Harbor River |
| **23** | Cape May Coastal |

**Figure 2.** Location of regional water resource planning areas in the New Jersey Coastal Plain.

Several studies used available ground-water flow models to predict future changes in the ground-water flow system in the Coastal Plain of New Jersey under a variety of withdrawal scenarios. Battaglin and Hill (1989) used the RASA model developed by Martin (1998) to test the effects of increased withdrawals on water levels in the Coastal Plain aquifers. Navoy (1994) investigated the possible development of the Wenonah-Mount Laurel aquifer for future water supply for the Camden County area, and Spitz (1998) tested the feasibility of water-supply development alternatives in Cape May County by use of ground-water flow simulations.

## HYDROGEOLOGIC SETTING AND CONCEPTUAL MODEL

The Coastal Plain aquifer system in New Jersey is composed of seaward dipping layers of sand, silt, and clay overlying crystalline basement. The sediments generally strike northeast-southwest and dip 10 to 60 ft/mi to the southeast (Martin, 1998). The confined aquifers of the New Jersey Coastal Plain are composed predominantly of sand but may also include interbedded silts and clays that range from about 50 to more than 600 ft in thickness and are separated by confining units. The confining units are composed of silts and clays with minor amounts of sand and range in thickness from 50 to 1,000 ft (Martin, 1998). The aquifers are recharged by precipitation on outcrop areas. The recharge flows laterally downdip and downward to underlying units. The confined aquifers discharge to withdrawal wells or eventually to Raritan or Delaware Bays and to the Atlantic Ocean. Detailed descriptions of the hydrogeology of the New Jersey Coastal Plain aquifers and confining units are given in Zapecza (1989), Martin (1998), and Pope and Gordon (1999).

The conceptual model used to represent the aquifer system is based on the New Jersey RASA model (Martin,1998), which simulated the freshwater flow system in the Coastal Plain. The Coastal Plain sediments were modeled as 10 layers, representing 10 aquifers and 9 intervening confining units. The aquifers and corresponding geologic units are shown in table 1. Some modifications were made to the RASA model (Martin, 1998) and subsequently to the model of Pope and Gordon (1999) to adapt the hydrogeologic units to a model framework. The lower Kirkwood-Cohansey aquifer and the confined Kirkwood aquifer are designated as model unit A8. In downdip areas, the model unit A8 represents the Atlantic City 800-foot-sand aquifer and the overlying, relatively minor, Rio Grande water-bearing zone. In this report, the Atlantic City 800-foot sand and the Rio Grande water-bearing zone are together referred to as the confined Kirkwood aquifer. The updip limit of the confined Kirkwood aquifer is also the updip limit of the overlying confining unit. In updip areas, model unit A8 represents the lower part (approximately the lower third) of the unconfined Kirkwood-Cohansey aquifer system and is referred to as the lower Kirkwood-Cohansey aquifer. The Kirkwood-Cohansey aquifer system was subdivided into an upper and lower aquifer in updip areas to better represent vertical head distribution in the unconfined aquifer system and to provide a lateral connection between the confined Kirkwood and lower Kirkwood-Cohansey aquifers (Martin, 1998). The modeled unconfined aquifers include the updip parts of the lower Kirkwood-Cohansey aquifer (model unit A8) and the upper Kirkwood-Cohansey aquifer (model unit A9). The upper Kirkwood-Cohansey aquifer is modeled as unconfined because it is overlain by the estuarine clay confining unit (model unit C9) only in offshore areas and in peninsular Cape May County where it is overlain by the Holly Beach water-bearing zone (model unit A10). A generalized hydrogeologic section of the Coastal Plain (fig. 3) shows the conceptual model of the aquifers and confining units in onshore areas.

## SIMULATION OF THE GROUND-WATER FLOW SYSTEM

The ground-water flow model of the New Jersey Coastal Plain developed by Pope and Gordon (1999) was used in this study to simulate the ground-water flow system in eight confined aquifers for the period 1989-92 and for various ground-water withdrawal scenarios for the period

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

[Modified from Martin (1989, table 2), Zapecza (1984, table 2) and Seaber (1965, table 3); shading indicates adjacent geologic or hydrogeologic unit is not present]

| SYSTEM | SERIES | GEOLOGIC UNIT | HYDROGEOLOGIC UNIT | MODEL UNITS | |
|---|---|---|---|---|---|
| | | | | Updip | Downdip |
| Quaternary | Holocene | Alluvial deposits | Undifferentiated | Upper Kirkwood-Cohansey aquifer (A9) | |
| | | Beach sand and gravel | | | Holly Beach water-bearing zone (A10) |
| | Pleistocene | Cape May Formation | Kirkwood-Cohansey[1] | | Estuarine Clay confining unit (C9) |
| | | | | | Upper Kirkwood-Cohansey aquifer (A9) |
| Tertiary | Miocene | Pennsauken Formation | | Upper Kirkwood-Cohansey aquifer (A9) | |
| | | Bridgeton Formation | Kirkwood-Cohansey aquifer system | | Upper Kirkwood-Cohansey aquifer (A9) |
| | | Beacon Hill Gravel | | | |
| | | Cohansey Sand | | | |
| | | Kirkwood Formation | | Lower Kirkwood-Cohansey aquifer (A8) | |
| | | | Confining unit | | Confining unit overlying the Rio Grande water-bearing zone (C8) |
| | | | Rio Grande[2] | | Confined Kirkwood aquifer (A8) |
| | | | Confining unit | | |
| | | | Atlantic City 800-foot sand | | |
| | | | Composite confining unit | Basal Kirkwood confining unit (C7) | |
| | Oligocene | Piney Point Formation | Piney Point aquifer | Piney Point aquifer (A7) | |
| | Eocene | Shark River Formation | | Vincentown-Manasquan confining unit (C6) | |
| | | Manasquan Formation | | | |
| | Paleocene | Vincentown Formation | Vincentown aquifer | Vincentown aquifer (A6) | |
| | | Hornerstown Sand | | Navesink-Hornerstown confining unit (C5) | |
| Cretaceous | Upper Cretaceous | Tinton Sand | | | |
| | | Red Bank Sand | Red Bank sand | | |
| | | Navesink Formation | | | |
| | | Mount Laurel Sand | Wenonah-Mount Laurel aquifer | Wenonah-Mount Laurel aquifer (A5) | |
| | | Wenonah Formation | | | |
| | | Marshalltown Formation | Marshalltown-Wenonah confining unit | Marshalltown-Wenonah confining unit (C4) | |
| | | Englishtown Formation | Englishtown aquifer system | Englishtown aquifer (A4) | |
| | | Woodbury Clay | Merchantville-Woodbury confining unit | Merchantville-Woodbury confining unit (C3) | |
| | | Merchantville Formation | | | |
| | | Magothy Formation | Potomac-Raritan-Magothy aquifer system: Upper aquifer | Upper Potomac-Raritan-Magothy aquifer (A3) | |
| | | Raritan Formation | Confining unit | Confining unit between the Middle and Upper Potomac-Raritan-Magothy aquifers (C2) | |
| | | | Middle aquifer | Middle Potomac-Raritan-Magothy aquifer (A2) | |
| | | Potomac Group | Confining unit | Confining unit between the Lower and Middle Potomac-Raritan-Magothy aquifers (C1) | |
| | Lower Cretaceous | | Lower aquifer | Lower Potomac-Raritan-Magothy aquifer (A1) | |
| Pre-Cretaceous | | Bedrock | Bedrock confining unit | | |

[1] Kirkwood-Cohansey aquifer system
[2] Rio Grande water-bearing zone

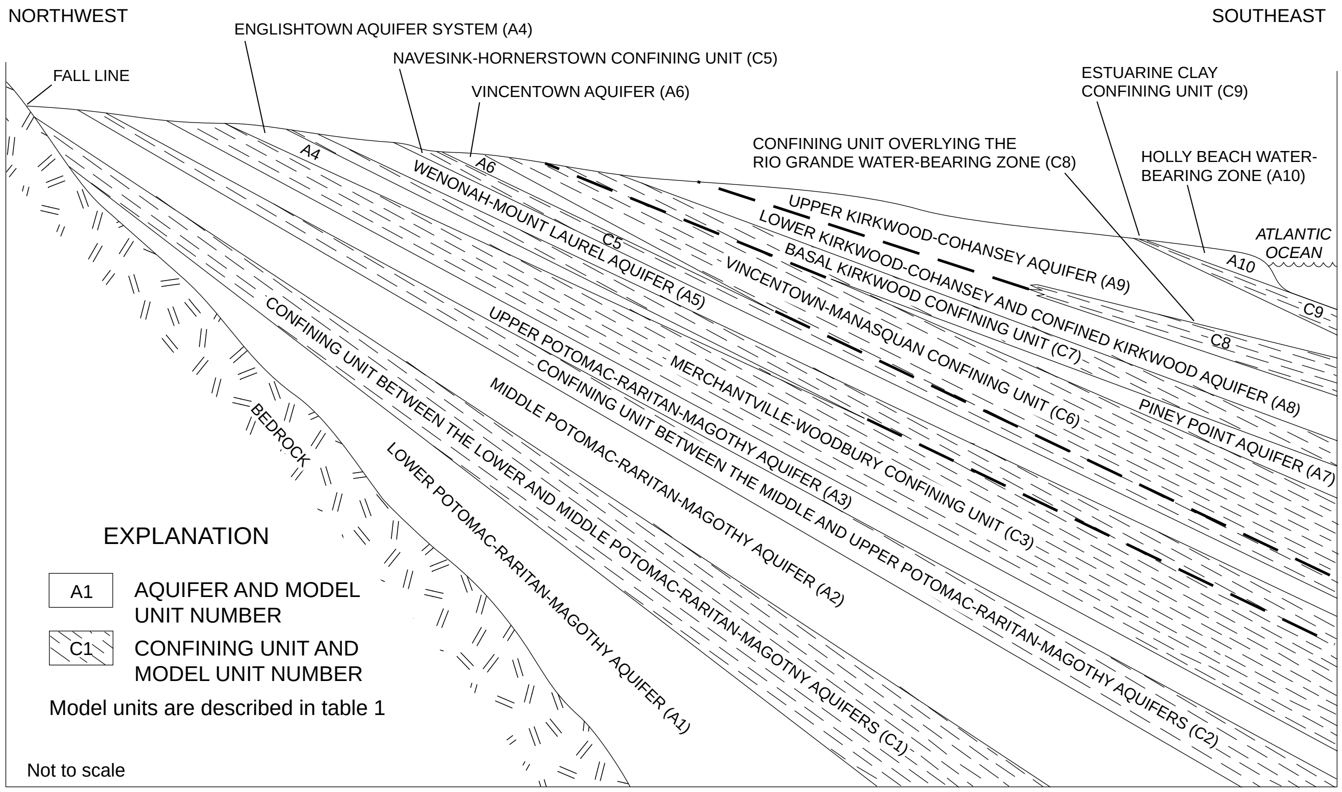



**Figure 3**. Generalized hydrogeologic section through the onshore part of New Jersey Coastal Plain. (Modified from Martin, 1998, fig. 2.)

1993-2020. That model uses the SHARP model code (Essaid, 1990). The SHARP model (Essaid, 1990) is a quasi-three-dimensional finite-difference ground-water flow model that simulates both freshwater and saltwater flow separated by a sharp interface. The freshwater-saltwater interface is defined as the hypothetical line seaward of which the chloride concentration is equal to or greater than 10,000 mg/L (Pope and Gordon, 1999). For this report, freshwater is defined as water with chloride concentrations less than 10,000 mg/L. The concentration of chloride in seawater is given as 19,000 mg/L (Hem, 1985). The interface that separates freshwater and saltwater is commonly considered to be a transition zone created by the mixing of freshwater and saltwater (Essaid, 1990). In the SHARP-model approach, however, the freshwater-saltwater interface is assumed to be abrupt, so the interface that separates freshwater from saline ground water lacks a transition zone. Because of the density difference between freshwater and saltwater, freshwater rises above the denser, saltier water and a wedge-shaped body of saltwater forms that is defined by a toe at the intersection with the bottom of the aquifer and by a tip at the intersection with the top of the aquifer.

Although the simulated freshwater-saltwater interface is described and shown on illustrations in this report, the emphasis of the simulations is to observe the change in water levels and flow budgets as withdrawals are increased or decreased. Information about the location of the freshwater-saltwater interface is relevant to the freshwater flow system and to water supply concerns inside and outside of the critical areas because declining water levels resulting from withdrawals have affected the ground-water supply in certain areas of the New Jersey Coastal Plain by permitting saltwater intrusion (McAuley and others, 2001; Spitz, 1998; Schaefer and Walker, 1981). The observed location of the 250-mg/L chloride concentration interface, however, is not easily compared to model results. Chloride concentrations between the freshwater-saltwater interface and the 250 mg/L isochlor are variable. Because the model used in this study does not simulate the location of the 250-mg/L chloride concentration interface, the 250-mg/L isochlor determined by Lacombe and Rosman (1997) from chloride-concentration data was included in the figures of aquifers of concern for the 1989-92 simulation. This was done to provide information to the reader about current areas of concern. The chloride-concentration data used to determine the location of the isochlor for several aquifers is described in more detail in Lacombe and Rosman (1997).

## MODEL LIMITATIONS

Discretization of the regional-scale model of the study area requires that the hydraulic properties, recharge, and streamflow within model cells are averaged, so local-scale heterogeneities are not simulated. The grid-cell size is at least 2.5 mi on a side, so flow gradients from local cones of depressions may not be accurately simulated in some areas. The regional gradients are accurately simulated, however.

In general, flow in confining units cannot be simulated by using the SHARP model because it is a quasi-three dimensional model in which the confining units are not explicitly represented. Because of this, the simulated movement of the freshwater-saltwater interface in low-permeability sediments is less reliable than that in more permeable units. The vertical movement of saltwater into either underlying or overlying freshwater aquifers is not simulated; therefore, the location of the freshwater-saltwater interface tip and toe simulated by the model represents only the horizontal movement of saltwater. Areas in which saltwater could be moving vertically into freshwater areas are identified by analyzing vertical flow rates from the model output and are considered as possible sources of saltwater. The limitations of the SHARP model are discussed in more detail in Pope and Gordon (1999).

## MODEL DESIGN AND INPUT DATA

The ground-water flow model of Pope and Gordon (1999) consists of 10 layers that represent 10 aquifers and 9 intervening confining units. The model dimensions are 50 rows by 49 columns. The grid is shown in figure 4. The cells in the outside row and column on each side are not active but are

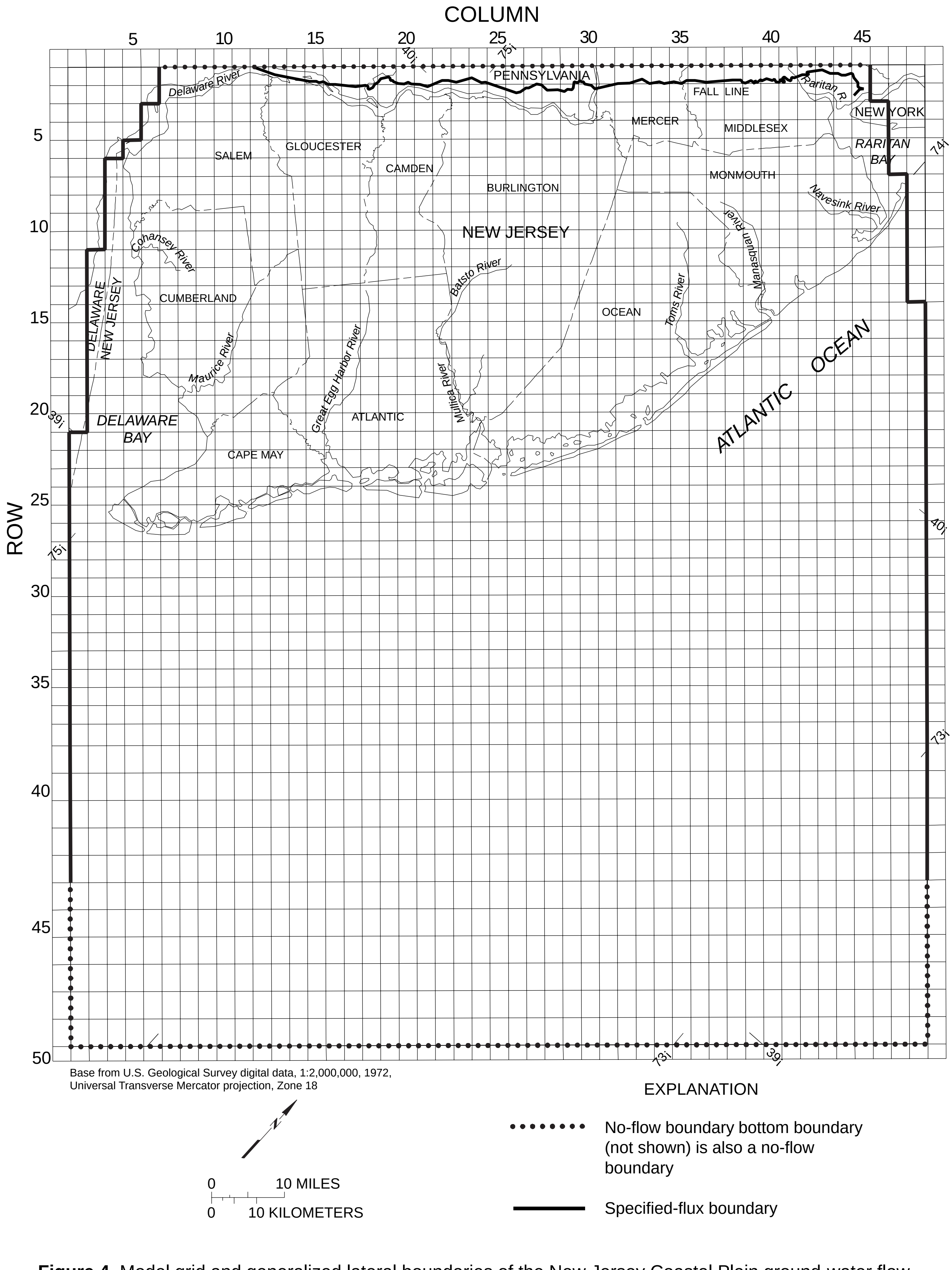



**Figure 4.** Model grid and generalized lateral boundaries of the New Jersey Coastal Plain ground-water flow model. (From Pope and Gordon, 1999, fig. 5.)

used to establish the lateral boundaries. Onshore and in updip areas, the model grid spacing is 13,200 ft (2.5 mi) on each side. Further offshore, the row spacing increases to a maximum of 19,800 ft (3.75 mi), whereas the column spacing remains at 13,200 ft. The grid is aligned approximately parallel to the Fall Line and the strike of the Coastal Plain hydrogeologic units.

The recharge and boundary fluxes from the calibrated transient model of Pope and Gordon (1999) were used as boundary conditions. Generalized lateral model boundaries are shown in figure 4. The northwestern boundary of model unit A1 is the Fall Line; the northwestern boundary of all other model units (layers) is the updip limit of the aquifer. The updip limits and the Fall Line are represented as no-flow boundaries in the model. The northeastern boundary of the model approximates a flow line in a ground-water discharge area in Raritan Bay. The southwestern model boundary approximates a flow line along a ground-water divide near Delaware Bay. These boundaries are simulated as specified flux. Fluxes are generally small along these boundaries. The southeastern model boundary approximates the downdip boundaries of the model units. These boundaries are represented by a no-flow boundary for model units A1-A7. The downdip boundary for model units A8 and A9 are simulated as constant saltwater heads where these units subcrop offshore. The lower boundary of the model represents the top of the underlying crystalline basement in the updip areas of the aquifer and the Jurassic Period sequence of sediments in offshore areas of the aquifer. The lower boundary is modeled as a no-flow boundary. The upper boundary in onshore areas represents the water table and streams in the outcrop areas of aquifers. Streams in these cells are represented by a constant head in the overlying layer as an average long-term stream stage for the outcrop cell. Model cells in the outcrop (unconfined) areas of aquifers receive recharge. Recharge is applied at a uniform rate of 20 in/yr (Martin, 1998) but is not applied to cells in offshore areas. The outcrop areas in offshore areas are represented by constant-head cells.

Because the model by Pope and Gordon (1999) was designed primarily to study the confined aquifers in the New Jersey Coastal Plain, unconfined aquifers, where they were modeled (updip parts of the confined aquifers and the upper Kirkwood-Cohansey aquifer), were included to serve as boundary conditions so that flow to and from these areas to the underlying or adjacent confined aquifers could be simulated. Results of simulations for these areas are discussed only in terms of their effect on the confined part of other aquifers.

The 1988 simulated freshwater heads and the location of the freshwater-saltwater interface tip and toe from the calibrated model of Pope and Gordon (1999) were used as the initial conditions for the 1989-92 simulation and for scenario 1. The 1992 simulated freshwater heads and the location of the freshwater-saltwater interface tip and toe were used as the initial conditions for scenarios 2 to 4.

Ground-water withdrawals are averaged over the length of the simulated pumping periods. The 1989-92 simulation incorporated one pumping period. This simulation is similar to the 1983-88 simulation described in Pope and Gordon (1999), except withdrawals were averaged 1992 amounts. Scenario 1 incorporates two pumping periods of 4 and 5 years in length. For the first pumping period, 1989-92 conditions were simulated. For the second pumping period, the simulation was designed to show water levels when all reductions in withdrawals in critical area 2 were imposed. The simulations for the period 1993 to 2020 (scenarios 2 to 4) incorporated three pumping periods of 8, 10, and 10 in length.

All aquifers are assumed to be isotropic. The storage terms and streambed leakances are those used in the calibrated model of Pope and Gordon (1999). The vertical leakances of confining units (vertical hydraulic conductivity divided by thickness) are those used in the calibrated model of Pope and Gordon (1999) for all layers; transmissivities are from Pope and Gordon (1999), except for the transmissivity in model unit A5. Maps showing the transmissivity of each aquifer and the vertical leakance of each confining unit are presented in Pope and Gordon (1999, app. 1a-8a and 1b-8b, respectively). The maps showing confining-unit leakance are limited to areas where leakance in the model represents the presence of a confining unit, and the maps do not include areas where leakance in the model is used to represent conductances to overlying streams. Transmissivity values range from 500 to 16,000 $ft^2$/d, and vertical leakance values range from $5x10^{-9}$ to $5x10^{-3}$ (ft/d)/ft. Values of vertical leakance typically are greater in updip areas near outcrops of aquifers than in downdip areas. The transmissivities in the Wenonah-Mount Laurel aquifer (model unit A5) were decreased by 20 percent of the value used in Pope and Gordon (1999) to improve the simulation of local cones of depression in that aquifer. The decrease in transmissivity resulted in water levels near pumped wells in Camden, Burlington, and Monmouth Counties about 5 ft lower than those simulated in Pope and Gordon (1999), but water levels declined much less outside areas of pumping.

The model by Pope and Gordon (1999) was calibrated primarily to the water levels measured during fall 1988 that are shown on the potentiometric-surface maps by Rosman and others (1995). Model calibration was considered acceptable when the difference between the average measured water level and the simulated water level for the last stress period at most observation wells was within 15 ft, the calibration criterion used by Pope and Gordon (1999). This value was considered to be reasonable in comparison to the change in water levels over the study area during the last stress period. Hydrographs of simulated water levels were matched to within 15 ft of measured water levels in 141 observations wells to calibrate long-term trends in water levels. The calibration of the location of the freshwater-saltwater interface was accomplished by use of available chloride-concentration data, interface locations based on the depth to the 10,000-mg/L chloride concentrations in Meisler (1989), and other chloride-concentration data collected by the USGS. More information on the calibration of the model is given in Pope and Gordon (1999).

## GROUND-WATER-WITHDRAWAL DATA

Ground-water-withdrawal data for 1992 for more than 1,100 wells were obtained from the USGS, New Jersey District, water-use database, referred to as SWUDS, and were included in the model input. Data on withdrawals from the Englishtown aquifer system and the Wenonah-Mount Laurel aquifer during 1993 were input for these two aquifers. Total withdrawals during 1993 from these two aquifers were similar to those during 1992. In general, withdrawal data for wells with ground-water withdrawals greater than 10,000 gal/d were input into the model, but data from some lower capacity wells were included. Data from many domestic and some irrigation wells were not included because they constitute a small percentage of the total withdrawals from confined aquifers.

Scenarios 2 to 4 include projected increases in ground-water withdrawals from 1993 to 2020. The Water Supply Master Plan (WSMP) (CH2M Hill and others, 1994) projected water-supply demand to 2020 for each designated RWRPA (fig. 2). The percentage increase for each RWRPA was determined by calculating the percentage increase from the average water demand for 1995 to the amount projected for 2020. To obtain the 2020 withdrawal amount for scenarios 2 to 4, the annual amount withdrawn in 1992, by well, was adjusted by the percentage increase specified for the RWRPA where the well is located. The projected increases range from 0 to 52.7 percent (table 2).

**Table 2.** Percentage increase in average water demand by regional water resource planning area from 1995 to 2020

| Water resource planning area and number | Projected percentage increase in average demand from 1995 to 2020[1] |
|---|---|
| 10 Raritan River | 21.9 |
| 11 South River | 21.6 |
| 12 Navesink/Swimming Rivers | 0 |
| 13 Manasquan River | 21.4 |
| 14 Rancocas Creek | 18.9 |
| 15 Metedeconk River | 32.1 |
| 16 Toms River | 29.7 |
| 17 Camden Delaware Tributaries | 10.6 |
| 18 Mullica River | 15 |
| 19 Atlantic Coastal | 52.7 |
| 20 Salem River | 8.7 |
| 21 Maurice River | 13.4 |
| 22 Great Egg Harbor River | 18.9 |
| 23 Cape May Coastal | 20.8 |

[1] Percentage from Water Supply Database hardcopy, New Jersey Statewide Water Supply Master Plan, Final (CH2M Hill, Metcalf and Eddy, Inc., and New Jersey First, Inc., 1994).

## DESCRIPTION OF THE GROUND-WATER-WITHDRAWAL SIMULATIONS

A calibrated ground-water flow model (Pope and Gordon, 1999) was first run to simulate ground-water flow conditions during 1989-92 by incorporating averaged 1992 withdrawals. This simulation was used as a baseline for comparison with four ground-water-withdrawal scenarios, which were designed to evaluate the effects of increased or decreased withdrawals inside and outside critical areas 1 and 2 under transient conditions.

Scenario 1 incorporates 1992 withdrawals but imposes reductions in withdrawals from existing wells completed in the Potomac-Raritan-Magothy aquifer system and located within critical area 2 (fig. 1). Reductions in withdrawals ranged from 0 to 35 percent for each well; the percentage of reduction varied by water-supply purveyor. Withdrawals at each well within critical area 2 were reduced by a percentage of the 1988 withdrawals because by 1991 withdrawals at some wells within critical area 2 had already been reduced. The 1988 withdrawal data were obtained from the SWUDS database. The total amount withdrawn in 1988 at each individual well was multiplied by the percentage reduction specified for each purveyor by the New Jersey Department of Environmental Protection Water Supply Element (Steven Nieswand, New Jersey Department of Environmental Protection, written commun., 1993); the results were used as input.

Scenarios 2 through 4 represent a range of potential water-supply strategies to determine the effects on the flow system of increased, decreased, and relocated ground-water withdrawals, particularly in the critical areas. Scenario 2 incorporates the withdrawal reductions from scenario 1 in critical area 2; withdrawals during 1992 were maintained in wells within critical area 1 that are completed in the Middle and Upper Potomac-Raritan-Magothy aquifers, the Englishtown aquifer system, and the Wenonah-Mount Laurel aquifer. Withdrawals from wells outside the critical areas were increased to the projected 2020 demand by a percentage determined from the WSMP. Scenario 3 incorporates the projected increase in average water demand to 2020 for each RWRPA by increasing the withdrawals in all wells outside and inside the critical areas. Scenario 4 incorporates the same withdrawals as scenario 2 but adds withdrawals from 17 hypothetical wells located outside the critical areas in the Upper Potomac-Raritan-Magothy aquifer, the Englishtown aquifer system, and the Wenonah-Mount Laurel aquifer. The ground-water-withdrawal scenarios are summarized below.

| Pumping scenario | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|
| Withdrawal restrictions in critical area 1 | No | Yes | No | Yes |
| Withdrawal reductions in critical area 2 | Yes | Yes | No | Yes |
| Withdrawals increased outside the critical areas | No | Yes | Yes | Yes |
| Hypothetical withdrawal wells outside the critical areas | No | No | No | Yes |

A graph of total withdrawals input for the baseline simulation and each scenario for each confined aquifer is shown in figure 5. Withdrawals from the confined aquifers in 1998 also are shown in figure 5 for comparison with those input into the model (1992 withdrawals). Some water is withdrawn from wells screened in the outcrop (unconfined) areas of the Middle and Upper Potomac-Raritan-Magothy aquifers and Wenonah-Mount Laurel aquifer. These wells are not considered to be in the confined part of the aquifer, so the withdrawals are not included in figure 5 or in the withdrawals listed in the flow budget discussed in the section "Baseline Simulation, 1989-92." The locations of these wells are shown in the figures (see section "Baseline Simulation, 1989-92") because the withdrawals were input to the model as sites of ground-water withdrawal in the aquifer.

## SIMULATION RESULTS

The simulated water levels, simulated location of the freshwater-saltwater interface, and flow budgets for the baseline simulation are discussed for each aquifer. The water levels and flow budgets for scenarios 1 to 3 are compared to those of the baseline simulation (1992). The water levels and flow budgets for scenario 4 are compared to those of scenario 2. The location of freshwater-saltwater interface for scenario 3 is compared to the location for the baseline simulation.

A schematic representation of an aquifer showing each term used in the flow budgets, except for the withdrawal term, is shown in figure 6. The saltwater flow term includes flow from the aquifer outcrop or overlying confining unit outcrop in the Delaware or Raritan Bay. This flow term represents freshwater flow from areas that are known to contain saltwater. The model does not simulate inflow of saltwater, but these areas represent potential or real sources of saltwater to the system (Pope and Gordon, 1999). The overlying-unconfined-aquifer term includes flow from the outcrop of the overlying unconfined aquifer as well as from the outcrop of an overlying confining unit.

## Baseline Simulation, 1989-92

### Lower Potomac-Raritan-Magothy Aquifer (Model Unit A1)

The location of ground-water withdrawals, the simulated potentiometric surface, areas where the simulated water levels are lower than 30 ft below NGVD of 29, and the simulated freshwater-saltwater interface tip and toe in the Lower Potomac-Raritan-Magothy aquifer in 1992 are shown in figure 7. Ground-water withdrawals totaled about 57.8 Mgal/d in 1992, and were primarily from updip areas near the Delaware River in Camden, northwestern Burlington, and northeastern Gloucester Counties. The percentage of withdrawals in each county from this aquifer in 1992 is given in table 3.

Water in this aquifer flows toward the large cone of depression centered in northern Camden County and the low water levels in southern Salem County. The low water levels in Salem County are the result of withdrawals from this aquifer across the Delaware River in Delaware. Water levels in large areas of Camden County range from 40 ft to more than 80 feet below NGVD of 29. Gradients in areas downdip from the cone of depression in Camden County are not as steep as those updip, near the river.

The toe of the simulated freshwater-saltwater interface is about 10 mi downdip from the cone of depression centered in Camden County and extends through southern Salem County. Areas of saltwater encroachment near the Delaware River and the Delaware Bay are present in Salem and Gloucester Counties. Simulated freshwater heads in the area between the tip and toe of the freshwater-saltwater interface are lower than 30 ft below NGVD of 29 in Salem County because of pumping in Delaware. The movement of water toward areas of withdrawals has resulted in saltwater intrusion into this aquifer from the Delaware River, which is tidal, and from the gradual movement of saltwater from the southwest in downdip areas where the aquifer contains salty water (Barksdale and others, 1958). The 250-mg/L isochlor determined from chloride-concentration data by Lacombe and Rosman (1997)

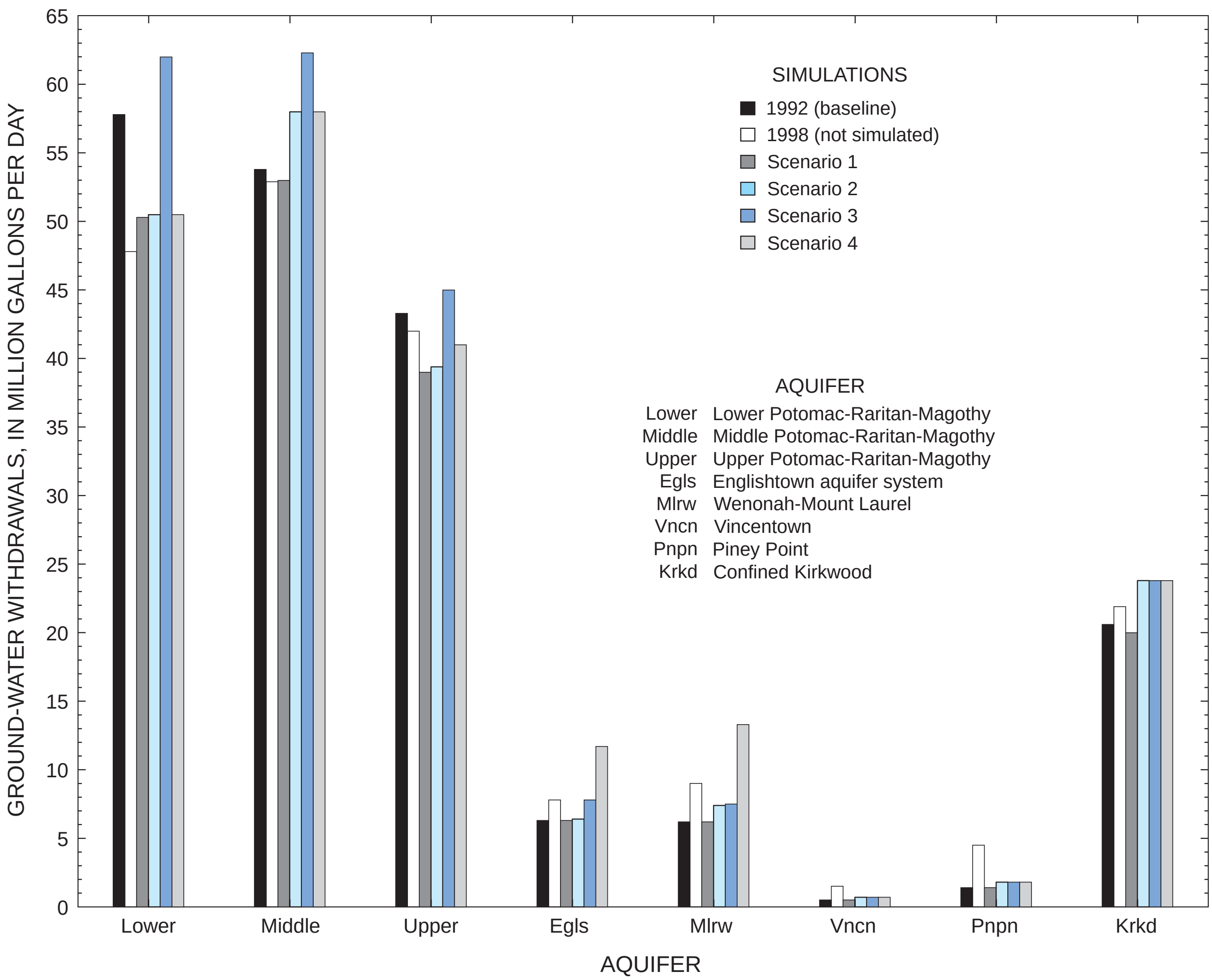



**Figure 5.** Annual withdrawals from confined aquifers in the New Jersey Coastal Plain for 1992 and 1998, and withdrawals input for model scenarios.

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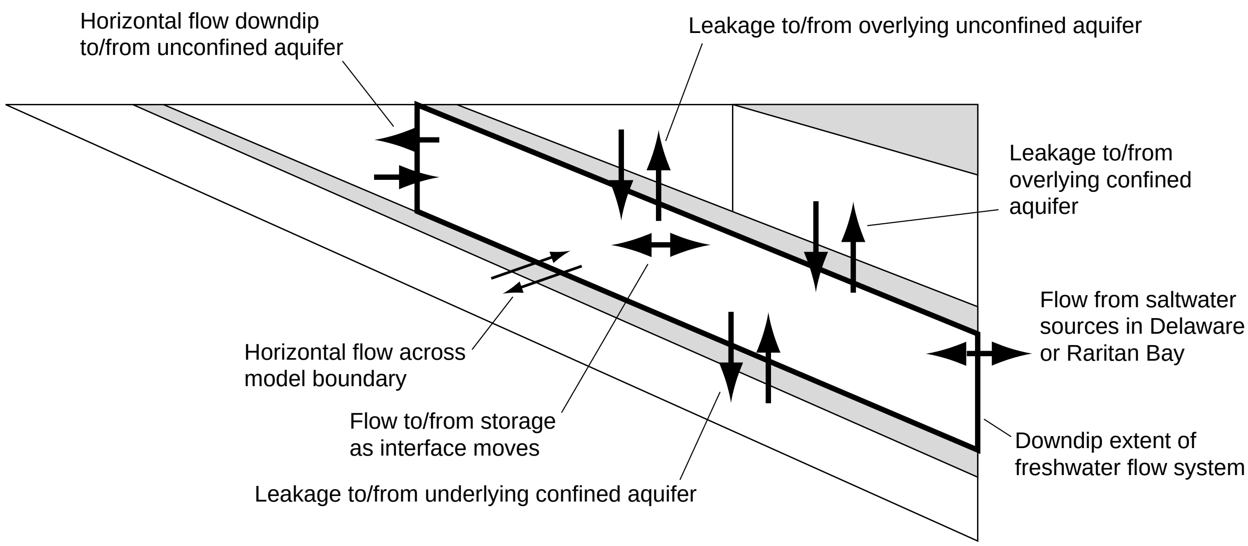



**Figure 6**. Generalized schematic representation of budget terms used to describe flow budgets in each aquifer in the New Jersey Coastal Plain flow model. (Modified from Pope and Gordon, 1999, p. 40)

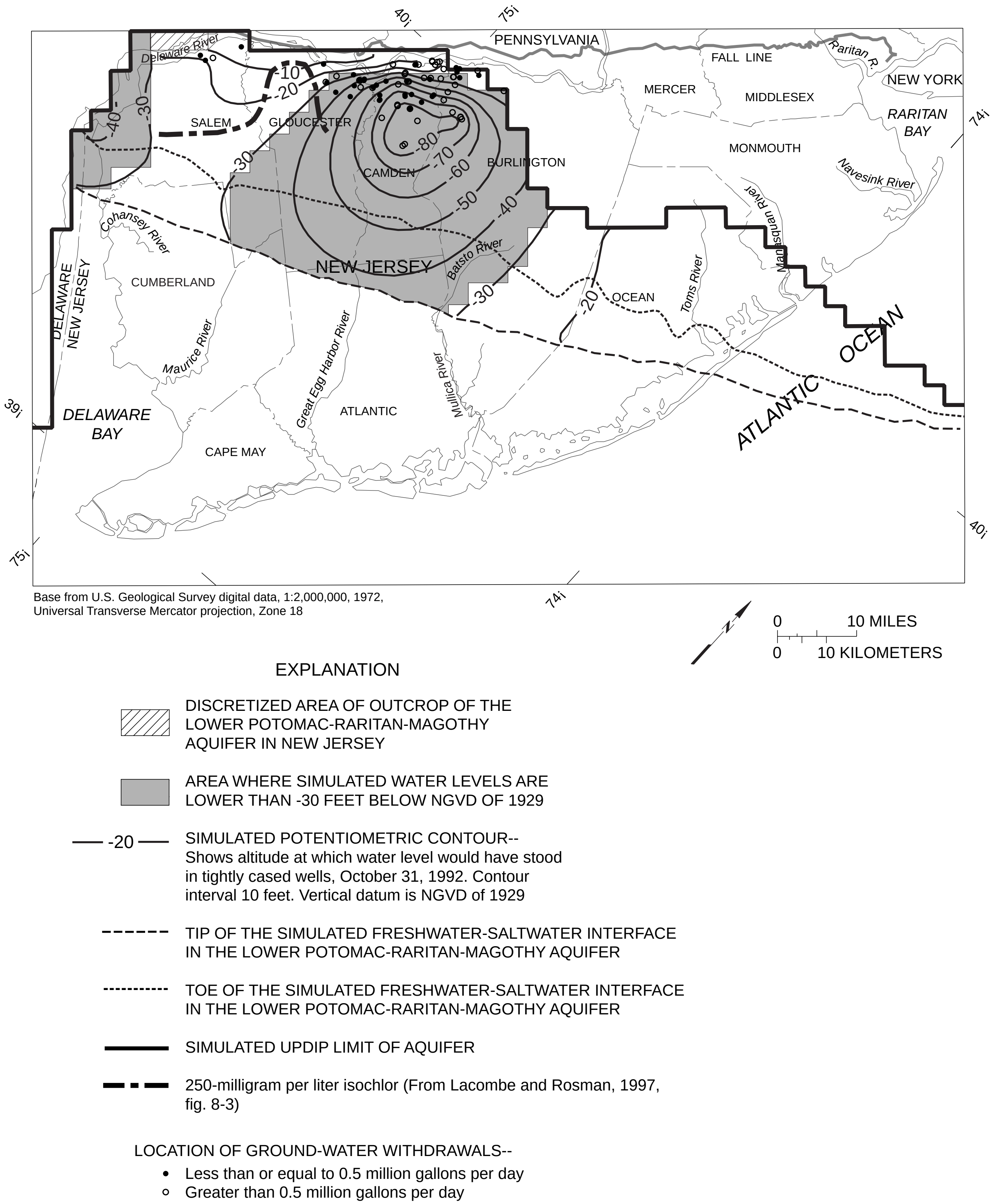



**Figure 7.** Simulated potentiometric surface, location of the freshwater-saltwater interface tip and toe, and location of withdrawal wells in the Lower Potomac-Raritan-Magothy aquifer (baseline), New Jersey Coastal Plain, 1992.

**Table 3.** Percentage of ground-water withdrawals from confined aquifers in the New Jersey Coastal Plain, by county, 1992

[--, no withdrawals reported; PRM, Potomac-Raritan-Magothy aquifer; all values are in percent of total yearly withdrawals for each aquifer]

| County | Model unit and aquifer | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 Lower PRM | 2 Middle PRM | 3 Upper PRM | 4 English-town aquifer system[1] | 5 Wenonah-Mount Laurel[1] | 6 Vincen-town | 7 Piney Point | 8 Confined Kirkwood |
| Atlantic | -- | -- | -- | -- | -- | -- | 22 | 50 |
| Burlington | 22 | 30 | 8 | 2 | 37 | -- | 1 | -- |
| Camden | 66 | 13 | 20 | 6 | 32 | -- | 1 | -- |
| Cape May | -- | -- | -- | -- | -- | -- | -- | 32 |
| Cumberland | -- | -- | -- | -- | -- | -- | -- | -- |
| Gloucester | 10 | 10 | 19 | -- | 14 | -- | -- | -- |
| Mercer | -- | 11 | 2 | -- | -- | -- | -- | -- |
| Middlesex | -- | 17 | 30 | -- | -- | -- | -- | -- |
| Monmouth | -- | 7 | 11 | 46 | 8 | 66 | -- | -- |
| Ocean | -- | 7 | 6 | 46 | 1 | 34 | 76 | 18 |
| Salem | 2 | 5 | 4 | -- | 8 | -- | -- | -- |

[1] Percentage is based on 1993 ground-water withdrawals.

is shown in figure 7. The isochlor crosses Salem County, then loops toward the Delaware River in Gloucester County. The concentrations of chloride in the ground water downdip from the 250-mg/L isochlor range from greater than 250 mg/L to less than the chloride concentration at the simulated interface (10,000 mg/L).

The flow budget for this aquifer is shown in table 4. Water is released from storage near the interface as a result of the landward movement of saltwater and the displacement of freshwater (4 percent of inflow). This aquifer does not crop out in New Jersey but is continuous into Delaware (Martin, 1998). The aquifer is recharged in updip areas by flow from the overlying confined and unconfined (outcrop regions) Middle Potomac-Raritan-Magothy aquifer in Camden County and also in Burlington and Gloucester Counties. This vertical flow represents 92 percent of the inflow to the Lower Potomac-Raritan-Magothy aquifer. Discharge from the aquifer consists primarily of withdrawals from wells and represents 87 percent of outflow, and flow across the model boundary near Delaware (8 percent).

## Middle Potomac-Raritan-Magothy Aquifer (Model Unit A2)

The location of ground-water withdrawals, the simulated potentiometric surface, areas where the simulated water levels are lower than 30 feet below NGVD of 29, and the simulated freshwater-saltwater interface tip and toe in the Middle Potomac-Raritan-Magothy aquifer in 1992 are shown in figure 8. Ground-water withdrawals from the confined part of the aquifer totaled about 53.8 Mgal/d in 1992. More than 50 percent of the withdrawals are concentrated in Burlington, Camden, and Gloucester Counties. The percentage of withdrawals in each county from the confined aquifer in 1992 is given in table 3.

A large cone of depression centered in Camden County, similar to that in the Lower Potomac-Raritan-Magothy aquifer, is present in the Middle Potomac-Raritan-Magothy aquifer. Gradients are much steeper updip from the cone of depression in outcrop areas near the Delaware River than downdip. Simulated 1992 water levels recovered 20 ft near the Toms River in Ocean County and 30 ft in southeastern Middlesex County, when compared to simulated 1988 water levels (Pope and Gordon, 1999, fig. 19) because of the incorporation into the model of withdrawal restrictions put into effect after 1988 in critical area 1.

The simulated freshwater-saltwater interface is located less than 30 mi downdip from the major withdrawal centers in this aquifer. Saltwater contamination in downdip parts of the aquifer may be the result of vertical flow from the underlying Lower Potomac-Raritan-Magothy aquifer in areas where it contains salty water downdip from its interface (Pope and Gordon, 1999). The 250-mg/L isochlor determined by Lacombe and Rosman (1997) for this aquifer is more than 15 mi updip from the toe of the interface in Camden County, but about 5 mi updip from the toe near the coast in Ocean County (fig. 8); it is also shown in the Raritan Bay area in Middlesex County.

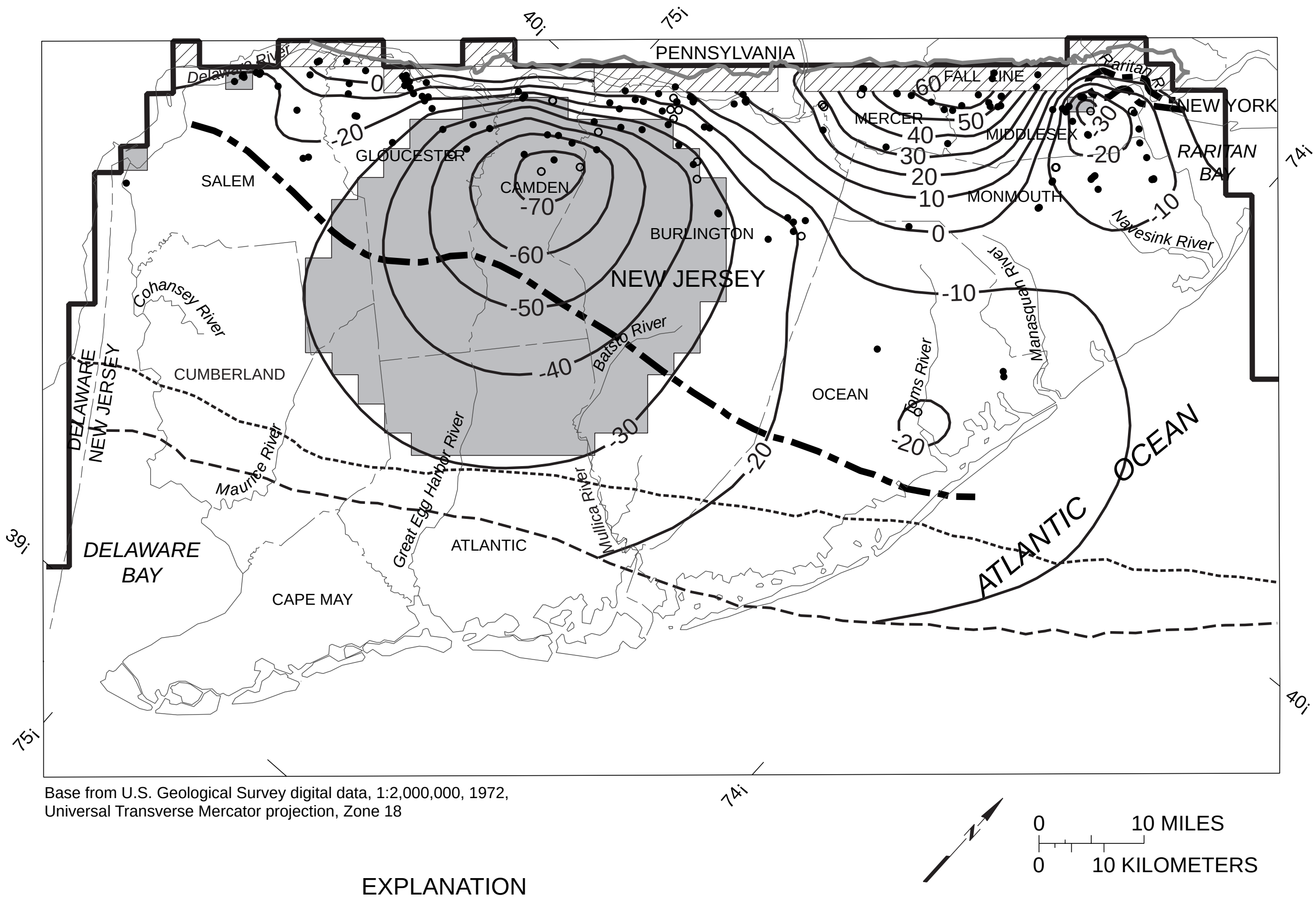
The flow budget for the confined Middle Potomac-Raritan-Magothy aquifer is included in table 4. The major recharge areas in the Middle Potomac-Raritan-Magothy aquifer are the areas of high ground-water levels near the border of Mercer and Middlesex Counties. Recharge (inflow) to the confined aquifer is primarily vertical flow (70 percent) from the unconfined region (outcrop) of the Upper Potomac-Raritan-Magothy aquifer and the confining unit overlying the Middle Potomac-Raritan-Magothy aquifer, which has higher vertical leakance in updip areas (Pope and Gordon, 1999, fig. 2b). Ground water from the recharge area flows toward the regional cone of depression centered in Camden County and a smaller cone in Middlesex County. Horizontal flow from the unconfined (outcrop) Middle Potomac-Raritan-Magothy aquifer occurs in updip areas and represents about 11 percent of inflow to the confined aquifer. Flow from the confined Upper Potomac-Raritan-Magothy aquifer represents 13 percent of inflow. Ground-water withdrawals account for 45 percent of the outflow from the confined Middle Potomac-Raritan-Magothy aquifer, whereas vertical flow to the underlying Lower Potomac-Raritan-Magothy aquifer accounts for about 49 percent of the outflow.

**Table 4.--**Simulated flow budgets for the confined aquifers in the New Jersey Coastal Plain for 1992 and scenarios 1 to 4.

[Values are in million gallons per day; (A1), indicates model unit]

| | | Inflow | | | | | | | | Outflow | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Model unit | Model simulation | Storage | Flow downdip from unconfined aquifer | Salt-water | Leakage from over-lying unconfined aquifer | Leakage from over-lying confined aquifer | Leakage from under-lying confined aquifer | Flow across model boundary | Total | Storage | Flow downdip to unconfined aquifer | Salt-water | Leakage to over-lying unconfined aquifer | Leakage to over-lying confined aquifer | Leakage to under-lying confined aquifer | Flow across model boundary | With-drawals[1] | Total |
| Lower | 1992-baseline | 2.8 | 2 | 0 | 2.8 | 58.2 | 0 | .4 | 66.2 | 0.2 | 0 | 0 | 0 | 3.1 | 0 | 5.1 | 57.8 | 66.2 |
| Potomac- | scenario 1 | 2.2 | 2 | 0 | 2.6 | 51.3 | 0 | .4 | 58.5 | .2 | 0 | 0 | 0 | 2.9 | 0 | 5.1 | 50.3 | 58.5 |
| Raritan | scenario 2 | 2.4 | 2 | 0 | 2.7 | 51.3 | 0 | .4 | 58.8 | .2 | 0 | 0 | 0 | 3. | 0 | 5.1 | 50.5 | 58.8 |
| Magothy | scenario 3 | 3.1 | 2.1 | 0 | 2.9 | 62.3 | 0 | .4 | 70.8 | .3 | 0 | 0 | 0 | 3.4 | 0 | 5.1 | 62 | 70.8 |
| aquifer (A1) | scenario 4 | 2.4 | 2 | 0 | 2.7 | 51.3 | 0 | .4 | 58.8 | .2 | 0 | 0 | 0 | 3. | 0 | 5.1 | 50.5 | 58.8 |
| Middle | 1992-baseline | .9 | 13.4 | .1 | 83.7 | 15.5 | 3.1 | 2.7 | 119.4 | .3 | .1 | 0 | .3 | 3.2 | 58.2 | 3.5 | 53.8 | 119.4 |
| Potomac- | scenario 1 | .7 | 12.8 | .1 | 77.1 | 14.8 | 2.9 | 2.7 | 111.1 | .2 | .1 | 0 | .4 | 2.6 | 51.3 | 3.5 | 53 | 111.1 |
| Raritan- | scenario 2 | .7 | 13.6 | .1 | 80.4 | 15.3 | 3 | 2.7 | 115.8 | .1 | .1 | 0 | .3 | 2.5 | 51.3 | 3.5 | 58 | 115.8 |
| Magothy | scenario 3 | 1 | 15.2 | .2 | 91.6 | 17.2 | 3.5 | 2.7 | 131.4 | .1 | .1 | 0 | .3 | 2.8 | 62.3 | 3.5 | 62.3 | 131.4 |
| aquifer (A2) | scenario 4 | .8 | 13.6 | .1 | 81 | 14.5 | 3.1 | 2.7 | 115.8 | .1 | .1 | 0 | .3 | 2.6 | 51.2 | 3.5 | 58 | 115.8 |
| Upper | 1992-baseline | .7 | 20.6 | .1 | 16.7 | 16.6 | 3.2 | 2.7 | 60.6 | .3 | .9 | 0 | 0 | .1 | 15.6 | .4 | 43.3 | 60.6 |
| Potomac- | scenario 1 | .5 | 18.1 | .1 | 15.8 | 15.6 | 2.6 | 2.7 | 55.4 | .1 | .1 | 0 | 0 | .2 | 14.7 | .4 | 39 | 55.4 |
| Raritan- | scenario 2 | .4 | 18.7 | .1 | 16.2 | 15.8 | 2.4 | 2.7 | 56.3 | 0 | 1 | 0 | 0 | .1 | 15.4 | .4 | 39.4 | 56.3 |
| Magothy | scenario 3 | .7 | 22.1 | .1 | 17.8 | 17.2 | 2.8 | 2.7 | 63.4 | 0 | .6 | 0 | 0 | .1 | 17.3 | .4 | 45 | 63.4 |
| aquifer (A3) | scenario 4 | .5 | 19.3 | .1 | 16.6 | 15.2 | 2.6 | 2.7 | 57 | 0 | .8 | 0 | 0 | .2 | 14.6 | .4 | 41 | 57 |
| English- | 1992-baseline | 0 | .2 | 0 | 8.7 | 16.2 | .1 | .4 | 25.6 | .1 | 2 | .3 | 0 | .6 | 16.3 | 0 | 6.3 | 25.6 |
| town | scenario 1 | 0 | .2 | 0 | 8.4 | 15.5 | .1 | .4 | 24.6 | .1 | 2 | .3 | 0 | .6 | 15.3 | 0 | 6.3 | 24.6 |
| aquifer | scenario 2 | 0 | .1 | 0 | 8.5 | 15.7 | .1 | .4 | 24.8 | 0 | 2 | .3 | 0 | .6 | 15.5 | 0 | 6.4 | 24.8 |
| system | scenario 3 | 0 | .2 | .1 | 8.9 | 17.6 | .1 | .4 | 27.3 | 0 | 1.9 | .3 | 0 | .5 | 16.8 | 0 | 7.8 | 27.3 |
| (A4) | scenario 4 | 0 | 1.6 | 0 | 10.5 | 17 | .2 | .4 | 29.7 | 0 | 1.7 | .3 | 0 | .6 | 15 | 0 | 12.1 | 29.7 |
| Wenonah- | 1992-baseline | .1 | .5 | .1 | 6.8 | 17.7 | .7 | .1 | 26 | .2 | 1.1 | 0 | 1. | .9 | 16.5 | .1 | 6.2 | 26 |
| Mount | scenario 1 | 0 | .6 | 0 | 6.8 | 17.3 | .7 | .1 | 25.6 | .1 | 1.3 | 0 | 1.1 | .9 | 15.9 | .1 | 6.2 | 25.6 |
| Laurel | scenario 2 | 0 | .6 | 0 | 7 | 18.5 | .6 | .1 | 26.8 | 0 | 1.3 | .1 | 1.1 | .8 | 16 | .1 | 7.4 | 26.8 |
| aquifer | scenario 3 | 0 | .6 | 0 | 7.5 | 19.5 | .6 | .1 | 28.4 | 0 | 1.2 | 0 | .9 | .7 | 18 | .1 | 7.5 | 28.4 |
| (A5) | scenario 4 | 0 | 1 | 0 | 8.7 | 23 | .6 | .1 | 33.4 | 0 | 1 | 0 | 1.1 | .7 | 17.2 | .1 | 13.3 | 33.4 |
| Vincen- | 1992-baseline | 0 | 2.7 | .1 | 0 | 16.6 | .1 | 0 | 19.5 | 0 | 1.5 | .1 | 0 | 1.5 | 15.9 | 0 | .5 | 19.5 |
| town | scenario 1 | 0 | 2.7 | 0 | 0 | 16.5 | .1 | 0 | 19.3 | 0 | 1.6 | .1 | 0 | 1.5 | 15.6 | 0 | .5 | 19.3 |
| aquifer | scenario 2 | 0 | 2.7 | 0 | 0 | 17.5 | .1 | 0 | 20.3 | 0 | 1.5 | .1 | 0 | 1.5 | 16.5 | 0 | .7 | 20.3 |
| (A6) | scenario 3 | 0 | 2.8 | 0 | 0 | 18.2 | .1 | 0 | 21.1 | 0 | 1.4 | .1 | 0 | 1.4 | 17.5 | 0 | .7 | 21.1 |
| | scenario 4 | 0 | 2.7 | 0 | 0 | 21.4 | .1 | 0 | 24.2 | 0 | 1.4 | .1 | 0 | 1.3 | 20.7 | 0 | .7 | 24.2 |
| Piney | 1992-baseline | .3 | 0 | 1.1 | 7.9 | 0 | .7 | 0 | 10. | .1 | 0 | 0 | 1.5 | 2.6 | .8 | 3.6 | 1.4 | 10. |
| Point | scenario 1 | .2 | 0 | 1.1 | 7.9 | 0 | .7 | 0 | 9.9 | .1 | 0 | 0 | 1.5 | 2.6 | .7 | 3.6 | 1.4 | 9.9 |
| aquifer | scenario 2 | .1 | 0 | 1.1 | 8.5 | .1 | .7 | 0 | 10.5 | .2 | 0 | 0 | 1.2 | 3 | .7 | 3.6 | 1.8 | 10.5 |
| (A7) | scenario 3 | .2 | 0 | 1.1 | 8.5 | .1 | .6 | 0 | 10.5 | .1 | 0 | 0 | 1.1 | 3.1 | .8 | 3.6 | 1.8 | 10.5 |
| | scenario 4 | .2 | 0 | 1.1 | 8.6 | .1 | .6 | 0 | 10.6 | .1 | 0 | 0 | 1.1 | 3 | 1 | 3.6 | 1.8 | 10.6 |
| Confined | 1992-baseline | 2 | 12.7 | 2.1 | 1.4 | .1 | 2.6 | .8 | 21.7 | .1 | .2 | .3 | 0 | 0 | 0 | .5 | 20.6 | 21.7 |
| Kirkwood | scenario 1 | 1.9 | 12.7 | 2.2 | 1.4 | .1 | 2.6 | .8 | 21.7 | .1 | .2 | .3 | 0 | 0 | 0 | .5 | 20.6 | 21.7 |
| aquifer | scenario 2 | 2 | 14.5 | 2.8 | 1.5 | .1 | 3 | .8 | 24.7 | 0 | .1 | .2 | 0. | 0 | .1 | .5 | 23.8 | 24.7 |
| (A8) | scenario 3 | 2 | 14.5 | 2.8 | 1.5 | .1 | 3 | .8 | 24.7 | 0 | .1 | .2 | 0 | 0 | .1 | .5 | 23.8 | 24.7 |
| | scenario 4 | 2 | 14.5 | 2.8 | 1.5 | .1 | 3 | .8 | 24.7 | 0 | .1 | .2 | 0 | 0 | .1 | .5 | 23.8 | 24.7 |

[1]Does not include withdrawals from outcrop (unconfined) region of aquifer.




EXPLANATION

- DISCRETIZED AREA OF OUTCROP OF THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER IN NEW JERSEY
- AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929
- -20 — SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude at which water level would have stood in tightly cased wells, October 31, 1992. Contour interval 10 feet. Vertical datum is NGVD of 1929
- TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER
- TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER
- SIMULATED UPDIP LIMIT OF AQUIFER
- 250-milligram per liter isochlor (From Lacombe and Rosman, 1997, fig. 7-3)

LOCATION OF GROUND-WATER WITHDRAWALS--

- • Less than or equal to 0.5 million gallons per day
- ○ Greater than 0.5 million gallons per day

**Figure 8.** Simulated potentiometric surface, location of the freshwater-saltwater interface tip and toe, and location of withdrawal wells in the Middle Potomac-Raritan-Magothy aquifer (baseline), New Jersey Coastal Plain, 1992.

## Upper Potomac-Raritan-Magothy Aquifer (Model Unit A3)

The location of ground-water withdrawals, the simulated potentiometric surface, areas where the simulated water levels are lower than 30 feet below NGVD of 29, and the simulated freshwater-saltwater interface tip and toe in the Upper Potomac-Raritan-Magothy aquifer in 1992 are shown in figure 9. Ground-water withdrawals from the confined part of the aquifer in 1992 totaled about 43.3 Mgal/d. The percentage of withdrawals in each county from the confined aquifer in 1992 is given in table 3.

Ground water in this aquifer flows from the recharge areas in Mercer and Middlesex Counties and updip areas along the Delaware River to the large cone of depression centered in Camden County and to the Atlantic Coast. Simulated water levels are lower than 90 ft below NGVD of 29 at the center of the cone of depression in Camden County. Simulated water levels in this aquifer are generally lower than water levels in the overlying Englishtown aquifer system and Wenonah-Mount Laurel aquifer, except downdip in Monmouth and Ocean Counties where a regional cone of depression is present in the Englishtown aquifer system and Wenonah-Mount Laurel aquifer.

The toe of the simulated freshwater-saltwater interface is more than 30 mi downdip from the major pumping center in Camden County. Areas of saltwater intrusion are present in this aquifer. The 250-mg/L isochlor determined by Lacombe and Rosman (1997) traverses central Salem County (fig. 9). In the 1970's, ground-water withdrawals from near Raritan Bay in Monmouth County resulted in the landward movement of saltwater (Schaefer and Walker, 1981). High chloride concentrations were reported in samples from wells near the coast, as high as 660 mg/L reported in one well (Schaefer, 1983), but concentrations declined when withdrawals from the Upper Potomac-Raritan-Magothy aquifer near the coast were discontinued (Pope and Gordon, 1999).

The flow budget for the confined Upper Potomac-Raritan-Magothy aquifer for 1992 is included in table 4. About 34 percent of the recharge (inflow) to the aquifer is horizontal flow from the unconfined region (outcrop) of the aquifer. Vertical flow from the overlying unconfined (outcrop) Englishtown aquifer system and the outcrop of the Merchantville-Woodbury confining unit, and flow from the confined Englishtown aquifer system in updip areas provide 55 percent of the inflow to the Upper Potomac-Raritan-Magothy aquifer. Vertical flow from the underlying Middle Potomac-Raritan-Magothy aquifer (5 percent) is greatest near the center of the cone of depression in Camden County because of the increased vertical flow gradient there. The simulated water levels in the Upper Potomac-Raritan-Magothy aquifer are 20 ft lower than those in the Middle Potomac-Raritan-Magothy aquifer at the center of the cone.

Ground-water withdrawals account for 71 percent of the discharge (outflow) from this aquifer. About 26 percent of the outflow is downward flow to the Middle Potomac-Raritan-Magothy aquifer, which is greatest in updip areas in northern Burlington County and southern Middlesex and Mercer Counties.

## Englishtown Aquifer System (Model Unit A4)

The location of ground-water withdrawals, the simulated potentiometric surface, and areas where the simulated water levels are less than 30 feet below NGVD of 29 in the Englishtown aquifer system in 1992 are shown in figure 10. Ground-water withdrawals totaled about 6.3 Mgal/d. Withdrawals are made primarily in Ocean and Monmouth Counties. The percentage of withdrawals in each county from this aquifer is given in table 3.

A large, deep cone of depression is present in northeastern Ocean County where measured water levels in 1993 (Lacombe and Rosman, 1997, fig. 5-3) and simulated water levels are lower than 100 ft below NGVD of 29. The area of high water levels in Monmouth County represents the major recharge area for the aquifer. The simulated 1992 water levels indicate that the water withdrawn at the cone of depression is supplied from this recharge area.

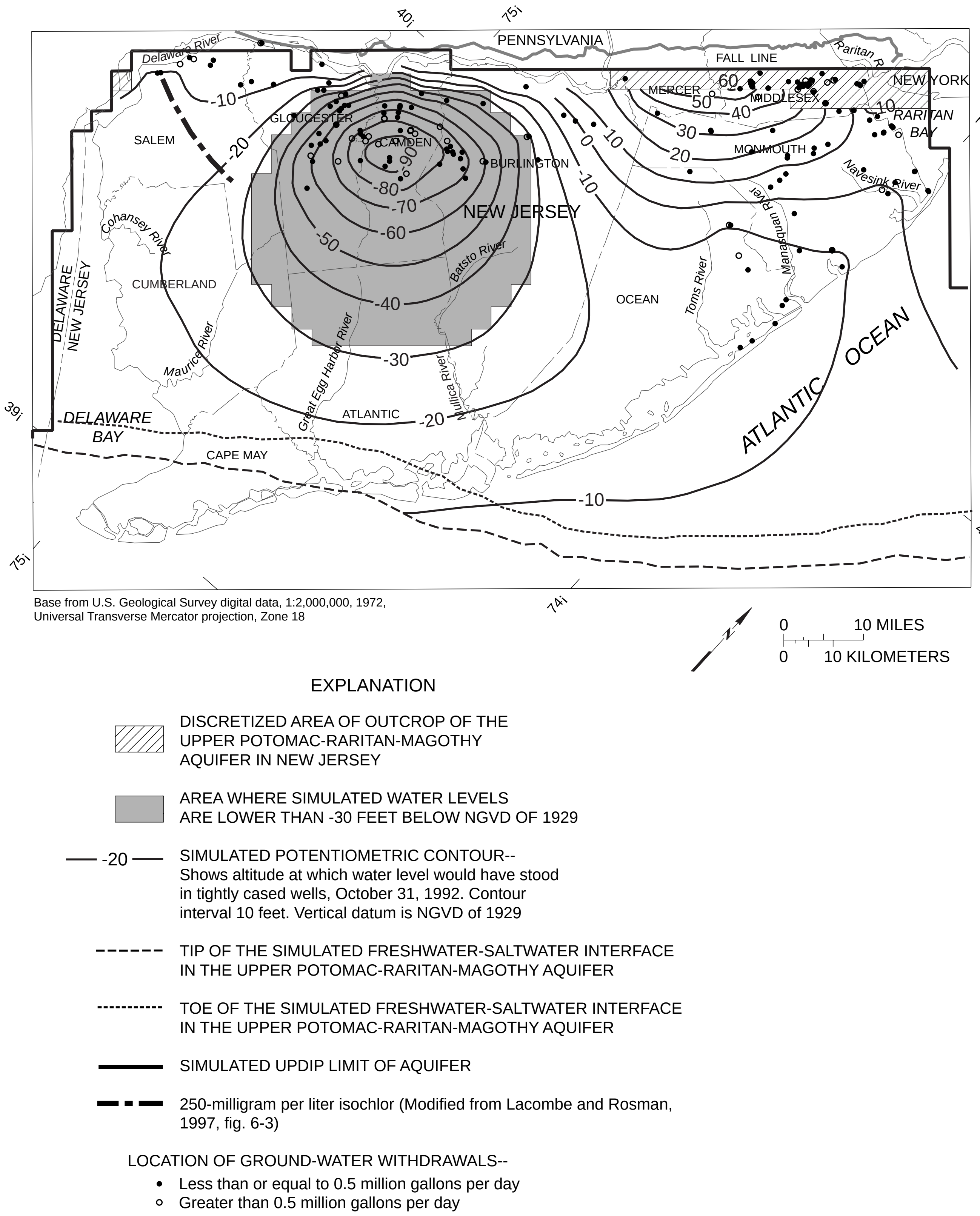



**Figure 9.** Simulated potentiometric surface, location of the freshwater-saltwater interface tip and toe, and location of withdrawal wells in the Upper Potomac-Raritan-Magothy aquifer (baseline), New Jersey Coastal Plain, 1992.

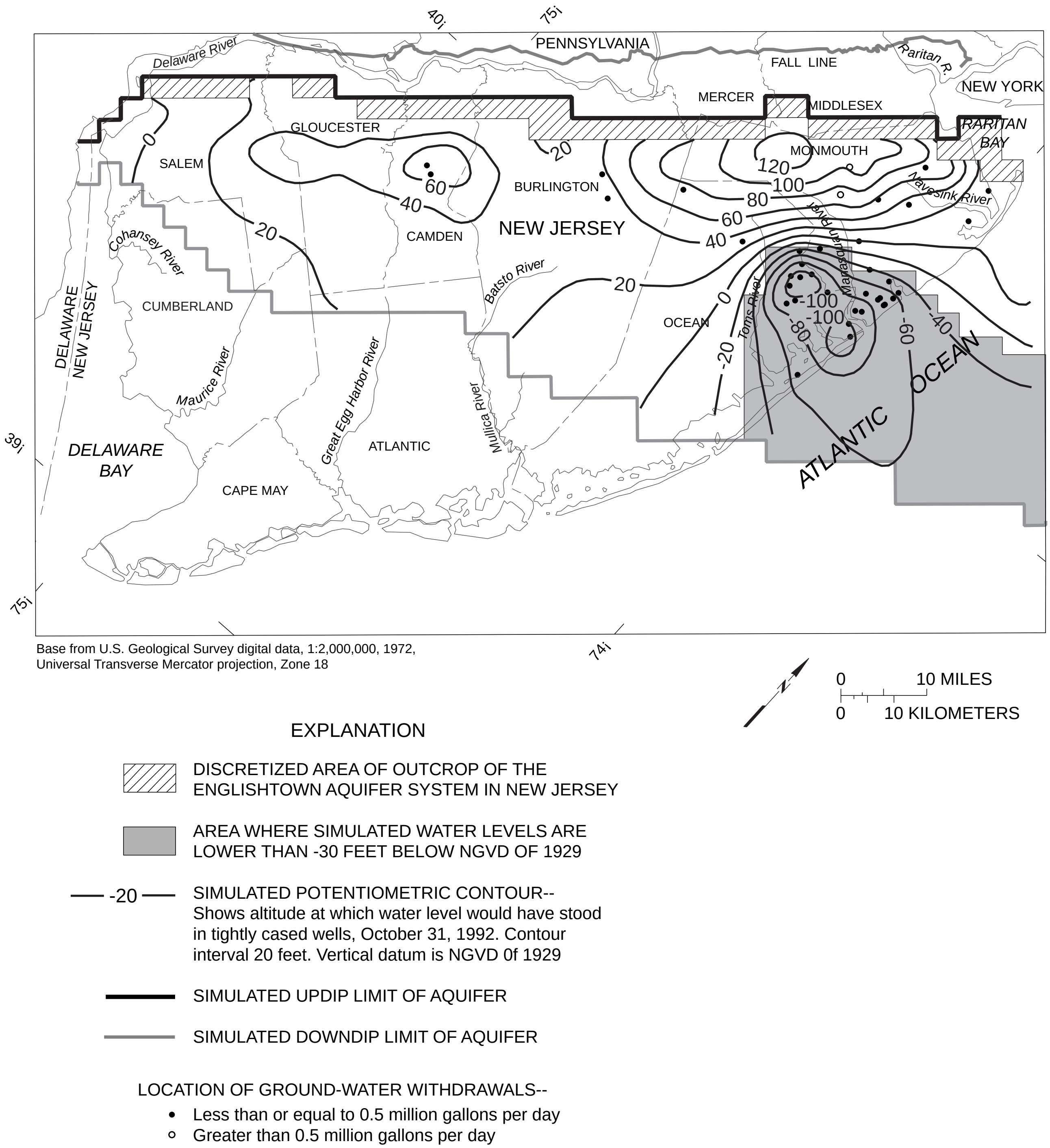



**Figure 10.** Simulated potentiometric surface and the location of withdrawal wells in the Englishtown aquifer system (baseline), New Jersey Coastal Plain, 1992.

Water levels in the Englishtown aquifer system are generally about 20 ft lower than the overlying Wenonah-Mount Laurel aquifer throughout the model area, except near the cone of depression in northern Ocean County and southeastern Monmouth County where water level differences between these aquifers at the center of the cone exceed 40 ft. Ground-water flow is from the Wenonah-Mount Laurel aquifer to the Englishtown aquifer system, except in some areas of pumping in the Wenonah-Mount Laurel aquifer in central Burlington County where localized cones of depression are present. In the model used by Pope and Gordon (1999), the freshwater-saltwater interface of the Englishtown aquifer system was initialized downdip in a less permeable part of the aquifer system where the low-permeable sediments limit movement of the interface; therefore, the location is not shown within the aquifer boundary.

The flow budget for the confined Englishtown aquifer system is included in table 4. Most of the recharge (inflow) to the Englishtown aquifer system is from the overlying unconfined (outcrop) and confined Wenonah-Mount Laurel aquifer (97 percent) near areas of high water levels in Camden and Gloucester Counties and in Monmouth County. The outcrop of the Englishtown aquifer system generally is a recharge area, but most of the water flows vertically to recharge the underlying Upper Potomac-Raritan-Magothy aquifer. Discharge (outflow) from the confined Englishtown aquifer system consists primarily of flow to the underlying Upper Potomac-Raritan-Magothy aquifer (64 percent), and ground-water withdrawals (25 percent). A small amount of flow discharges horizontally to the aquifer outcrop in Raritan Bay (8 percent).

## Wenonah Mount-Laurel Aquifer (Model Unit A5)

The location of ground-water withdrawals, the simulated potentiometric surface, areas where simulated the water levels are lower than 30 feet below NGVD of 29, and the simulated freshwater-saltwater interface tip and toe in the Wenonah Mount-Laurel aquifer in 1992 are shown in figure 11. Withdrawals in updip areas are made in Salem, Gloucester, Camden, and Burlington Counties. Wells in deeper parts of the aquifer are located downdip in Monmouth and Ocean Counties. Average ground-water withdrawals totaled about 6.2 Mgal/d in 1992. The percentage of withdrawals in each county from the confined aquifer is given in table 3.

The flow system in the Wenonah-Mount Laurel aquifer is similar to that in the underlying Englishtown aquifer system. Simulated water levels are more than 140 ft above NGVD of 29 near the outcrop area in Monmouth County, where recharge occurs. The lowest water levels are in southern Monmouth County and northeastern Ocean County near the coast, where water levels are from 20 ft below NGVD of 29 to lower than 60 ft below NGVD of 29. The cone of depression in this area is primarily the result of withdrawals from the underlying Englishtown aquifer system. The Wenonah-Mount Laurel aquifer is hydraulically connected to adjacent aquifers (Navoy, 1994), so a cone of depression in the underlying Englishtown aquifer system could cause a sympathetic cone of depression to form in this aquifer and could lower water levels in the overlying Vincentown aquifer. Ground water in the Wenonah-Mount Laurel aquifer flows from a recharge area in Monmouth County and the adjacent Ocean County toward the cone of depression near the coast of northeastern Ocean and southeastern Monmouth Counties, and from a recharge area at the ground-water highs in Camden and Gloucester Counties downdip toward the cone of depression in Ocean and Monmouth Counties and toward Delaware Bay. The freshwater-saltwater interface tip and toe are located near the southernmost part of Cape May County, more than 40 mi downdip from withdrawal wells.

The flow budget for the confined Wenonah-Mount Laurel aquifer is included in table 4. Horizontal flow from the outcrop of the Wenonah-Mount Laurel aquifer supplies only 2 percent of inflow. The aquifer is recharged primarily from overlying confined (68 percent) and unconfined (26 percent) aquifers. The recharge flows downward to the underlying Englishtown aquifer system and eventually to the Upper Potomac-Raritan-Magothy aquifer. Flow from the Wenonah-Mount Laurel aquifer to the underlying aquifers represents 63

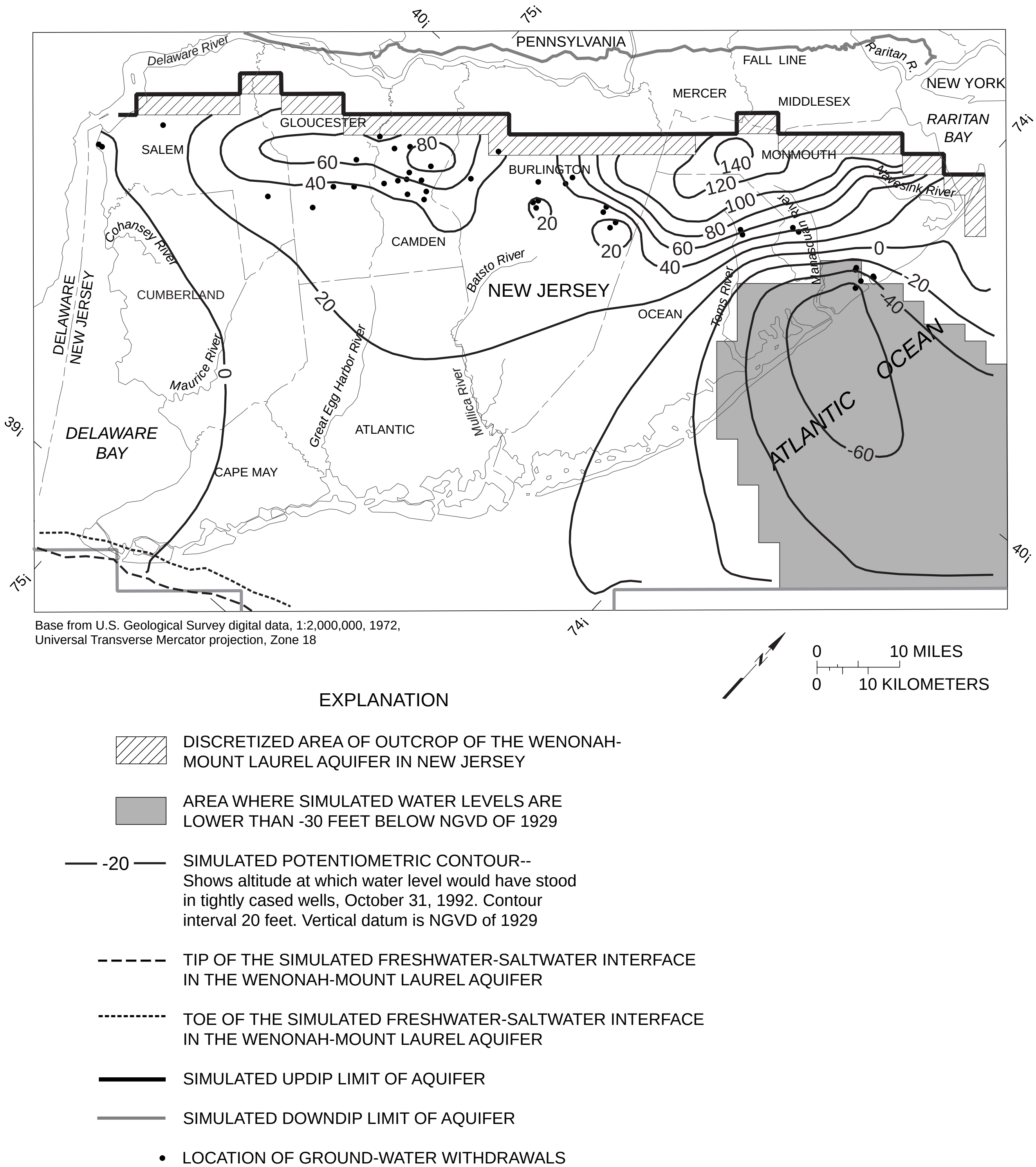



**Figure 11.** Simulated potentiometric surface, location of the freshwater-saltwater interface tip and toe, and the location of withdrawal wells in the Wenonah-Mount Laurel aquifer (baseline), New Jersey Coastal Plain, 1992.

percent of aquifer discharge (outflow). Most of the vertical flow occurs near the ground-water highs updip in Monmouth County, in Camden and Gloucester Counties, and at the cone of depression in the Englishtown aquifer system in Ocean County (fig. 10). Ground-water withdrawals from the confined Wenonah-Mount Laurel aquifer account for 24 percent of outflow. Ground water also discharges horizontally to the outcrop of the aquifer in Salem and Gloucester Counties (4 percent).

## Vincentown Aquifer (Model Unit A6)

Ground-water withdrawals from the Vincentown aquifer were relatively small and totaled about 0.5 Mgal/d in 1992. The location of ground-water withdrawals and the simulated water levels in the Vincentown aquifer in 1992 are shown in figure 12. Ground-water withdrawal wells are located in Monmouth and Ocean Counties (table 3).

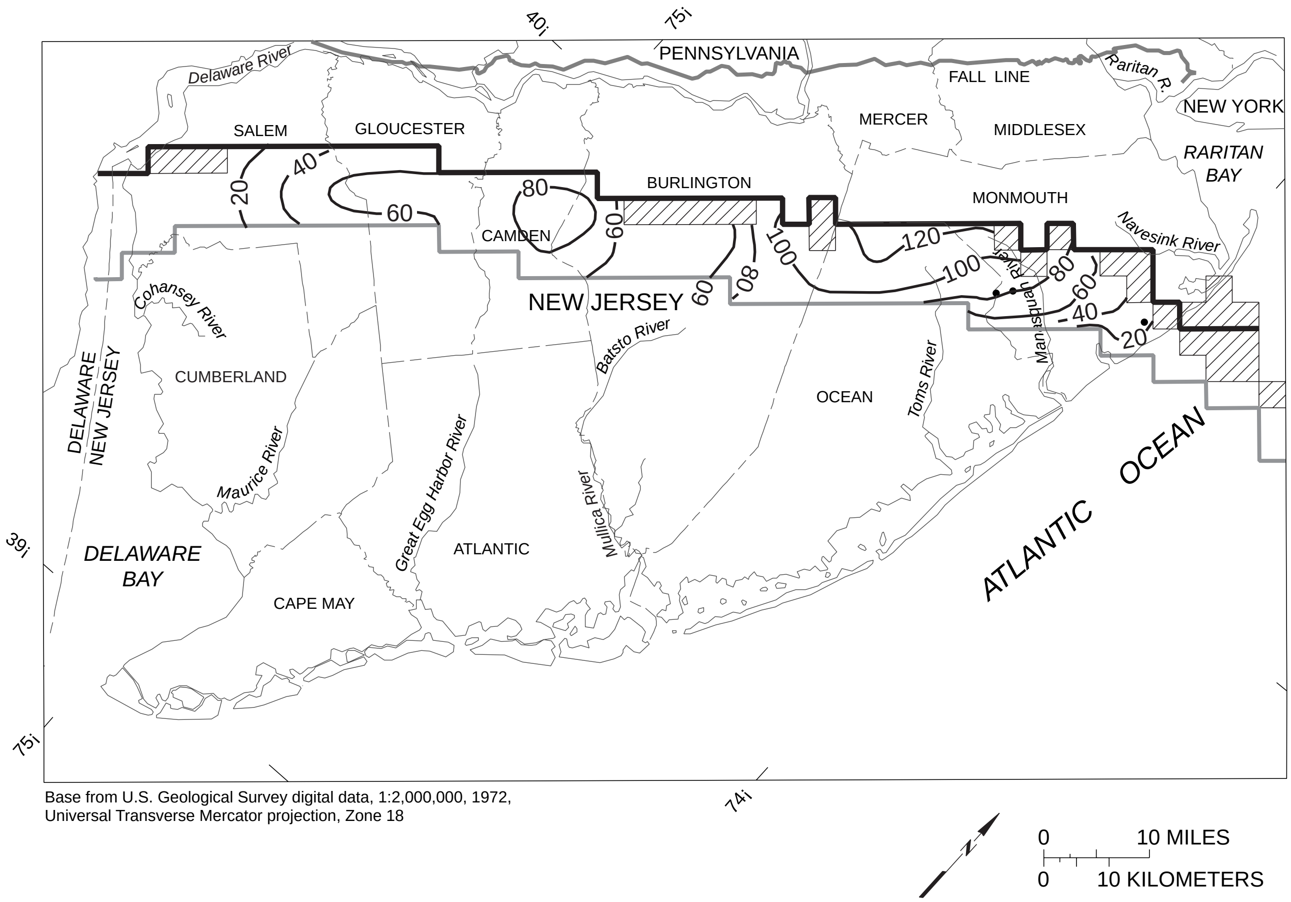
Flow is from the ground-water high in central Camden County toward Delaware Bay and from the ground-water high at the border of Ocean and Monmouth Counties toward the Atlantic Ocean. In the area between the two ground-water highs, water flows vertically down to the Wenonah-Mount Laurel aquifer and, subsequently, the Englishtown aquifer system. The water levels in the Vincentown aquifer and underlying Wenonah-Mount Laurel aquifer are similar in some parts of Salem, Gloucester, and Camden Counties. In the model used by Pope and Gordon (1999), the freshwater-saltwater interface in the Vincentown aquifer was initialized downdip from the permeable part of the aquifer within an area of low permeability (Pope and Gordon, 1999); therefore, its location is not shown within the aquifer boundary.

The flow budget for the confined Vincentown aquifer is included in table 4. In general, the Vincentown aquifer is recharged by vertical flow from the overlying lower Kirkwood-Cohansey aquifer (model unit A8) (85 percent), except near southern Monmouth County, and by horizontal flow from the outcrop areas (14 percent) in Burlington, Ocean, and Monmouth Counties. In southern Monmouth County, water discharges to the underlying Wenonah-Mount Laurel aquifer (82 percent) and to the overlying lower Kirkwood-Cohansey and confined Kirkwood aquifers (8 percent). Water also discharges horizontally to the outcrop of the Vincentown aquifer near the Atlantic Coast (8 percent).

## Piney Point Aquifer (Model Unit A7)

The location of ground-water withdrawals, the simulated potentiometric surface, and freshwater-saltwater interface tip and toe in 1992 are shown in figure 13. Ground-water withdrawals from the Piney Point aquifer totaled about 1.4 Mgal/d in 1992. The percentage of withdrawals in each county from this aquifer is given in table 3. The freshwater-saltwater interface of the Piney Point aquifer is more than 5 mi off the barrier islands in Ocean and Atlantic Counties.

The flow budget for the Piney Point aquifer is included in table 4. This aquifer does not crop out, so recharge (inflow) to the aquifer is primarily from the overlying lower Kirkwood-Cohansey aquifer (model unit A8) (79 percent). Most of this recharge occurs updip along the border of Burlington and Ocean Counties, where the overlying confining unit is thin and water levels in the overlying aquifer are greater than 120 ft above NGVD of 29. The low heads in the Delaware Bay are the result of withdrawals from this aquifer in Delaware. Inflow to the Piney Point aquifer is also from upward flow from the confined Wenonah-Mount Laurel aquifer (7 percent), and from downward flow from the overlying lower Kirkwood-Cohansey and confined Kirkwood aquifers in the Delaware Bay (11 percent). The downward flow is included in the saltwater flow term in table 4. Recharge to the Piney Point aquifer updip does not flow down to deeper underlying aquifers but discharges primarily across the model boundary near Delaware Bay (36 percent), to the overlying lower Kirkwood-Cohansey aquifer (15 percent), to the overlying confined Kirkwood aquifer (26 percent), and to withdrawals wells (14 percent).




EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE VINCENTOWN AQUIFER IN NEW JERSEY

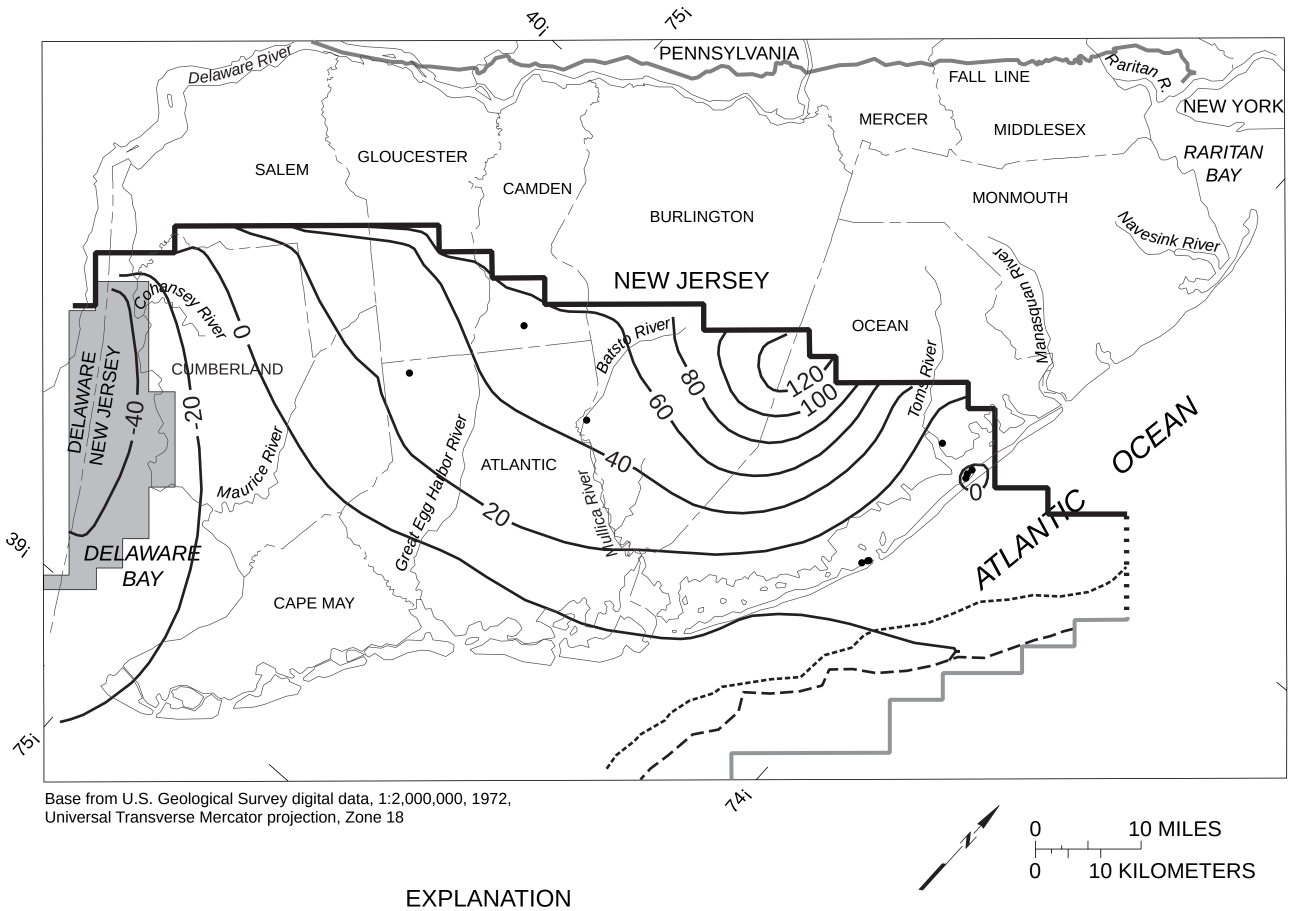
—20— SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude at which water level would have stood in tightly cased wells, October 31, 1992. Contour interval 20 feet. Vertical datum is NGVD of 1929

SIMULATED UPDIP LIMIT OF AQUIFER

SIMULATED DOWNDIP LIMIT OF AQUIFER

• LOCATION OF GROUND-WATER WITHDRAWALS

**Figure 12.** Simulated potentiometric surface and the location of withdrawal wells in the Vincentown aquifer (baseline), New Jersey Coastal Plain, 1992.




EXPLANATION

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude at which water level would have stood in tightly cased wells, October 31, 1992. Contour interval 20 feet. Vertical datum is NGVD of 1929

TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE PINEY POINT AQUIFER

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE PINEY POINT AQUIFER

SIMULATED UPDIP LIMIT OF AQUIFER

SIMULATED DOWNDIP LIMIT OF AQUIFER

SIMULATED LATERAL LIMIT OF AQUIFER

• LOCATION OF GROUND-WATER WITHDRAWALS

**Figure 13.** Simulated potentiometric surface, location of the freshwater-saltwater interface tip and toe, and location of withdrawal wells in the Piney Point aquifer (baseline), New Jersey Coastal Plain,1992.

## Confined Kirkwood Aquifer (Model Unit A8)

The location of ground-water withdrawals, the simulated potentiometric surface, the areas where simulated water levels are lower than 30 feet below NGVD of 29, and the simulated freshwater-saltwater interface toe in the confined Kirkwood aquifer in 1992 are shown in figure 14. Ground-water withdrawals from the confined Kirkwood aquifer totaled about 20.6 Mgal/d in 1992; these wells are located primarily along the Atlantic Coast. The total percentage of withdrawals from this aquifer in each county in 1992 is given in table 3.

Water levels lower than 50 ft below NGVD of 29 at the center of a cone of depression are the result of withdrawals from the confined Kirkwood aquifer along the coast of Atlantic County. The decline in water levels at the cone of depression centered in Atlantic County permits the lateral movement of saltwater toward withdrawal wells in Atlantic County and has allowed salty water to move inland in Cape May County (McAuley and others, 2001). West of Cape May County in the Delaware Bay, near the estimated updip limit of the overlying confining unit, simulated water levels range from 10 to 20 ft below NGVD of 29. The toe of the freshwater-saltwater interface traverses the southernmost part of Cape May County from Delaware Bay to the Atlantic Ocean; the tip is farther offshore beyond the boundary of the figure. The 250-mg/L isochlor determined from chloride-concentration data by Lacombe and Rosman (1997) traverses a path similar to that of the simulated interface and follows the Atlantic Coast toward Ocean County but is about 5 mi inland at the southernmost part of Cape May County (fig. 14).

The flow budget for the confined Kirkwood aquifer is included in table 4. Recharge to the aquifer is primarily horizontal flow from the unconfined lower Kirkwood-Cohansey aquifer (model unit A8), which accounts for 59 percent of the inflow. Flow from the underlying Piney Point aquifer contributes 12 percent of inflow to the aquifer. The overlying unconfined part of the upper Kirkwood-Cohansey aquifer (model unit A9) contributes 6 percent of the inflow to the aquifer, and flow from saltwater areas in the Delaware Bay and other offshore areas supplies about 10 percent. Storage, which is from water displaced by the movement of the freshwater-saltwater interface, accounts for 9 percent of the inflow. Ground water discharges primarily to withdrawal wells; this accounts for 95 percent of the outflow.

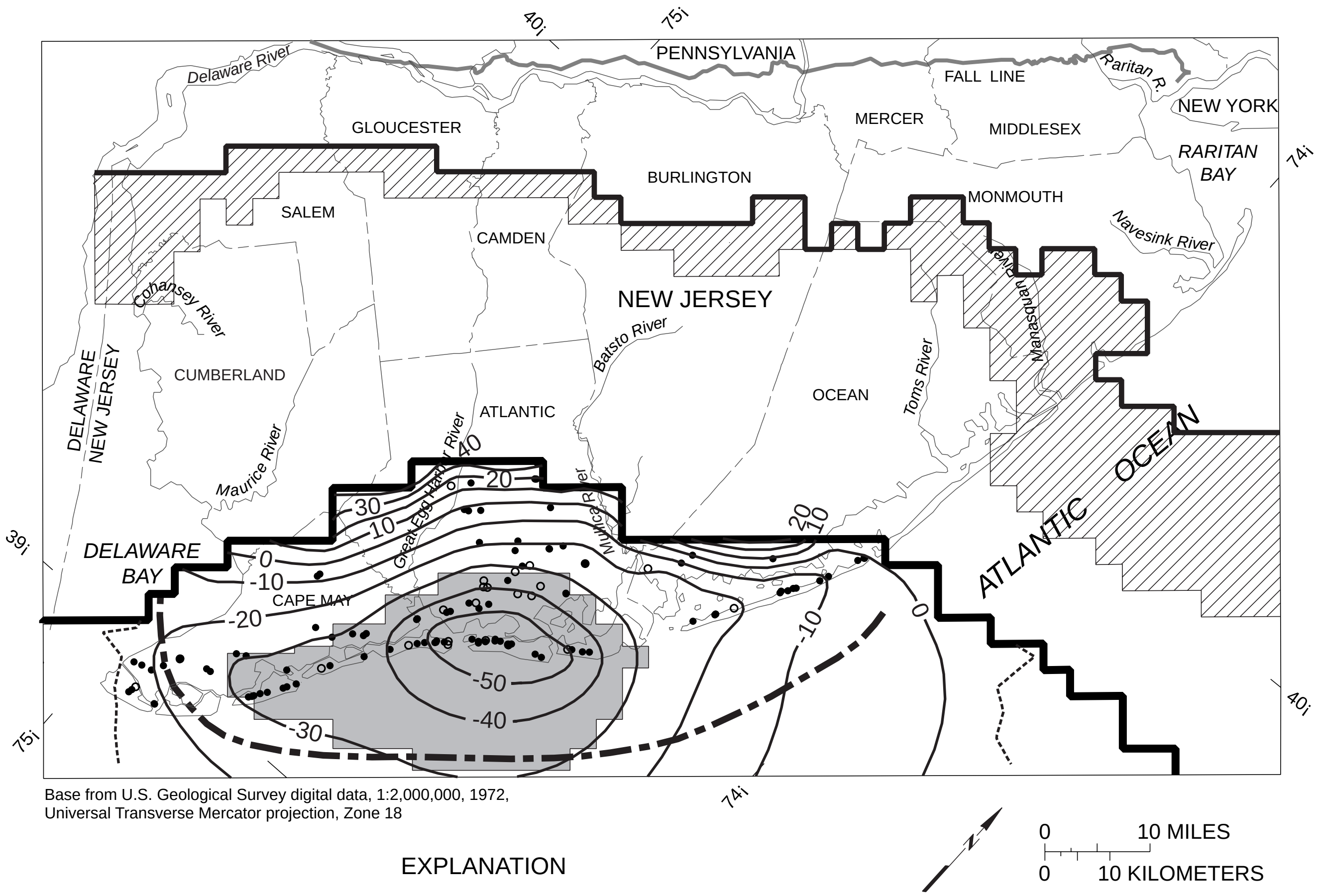
# Simulation of Withdrawal Scenarios

## Scenario 1--Ground-Water System With Withdrawal Reductions In Critical Area 2 After 1992

In scenario 1, withdrawals from wells within critical area 2 completed in the Potomac-Raritan-Magothy aquifer system were reduced by 12.6 Mgal/d from withdrawals in 1992. The location of ground-water withdrawals, the simulated potentiometric surface, the areas where the simulated water levels are lower than 30 feet below NGVD of 29, and the simulated location of the freshwater-saltwater interface tip and toe for the Lower, Middle, and Upper Potomac-Raritan-Magothy aquifers are shown in figures 15 to 17.

When compared to simulated water levels for 1992 (figs. 7 and 8), the simulated water levels in the Lower and Middle Potomac-Raritan-Magothy aquifers for scenario 1 recovered by about 20 ft in Camden County, and in general, recovered more than 10 ft in parts of Gloucester and Burlington Counties. Water levels in the Upper Potomac-Raritan-Magothy aquifer recovered by about 30 ft in Camden County at the center of the regional cone of depression and more than 10 ft in parts of Gloucester, Burlington, and northern Atlantic Counties. The simulated water levels for the Englishtown aquifer system and Wenonah-Mount Laurel, Vincentown, Piney Point, and confined Kirkwood aquifers are not shown because there was little change in water levels between the 1992 simulation (baseline) and this simulation.

With withdrawal reductions in effect in critical area 2, leakage from the overlying unconfined (outcrop) and confined Middle Potomac-Raritan-Magothy aquifer to the Lower Potomac-




EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE KIRKWOOD FORMATION IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, October 31, 1992. Contour interval 10 feet. Vertical datum is NGVD of 1929

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE CONFINED KIRKWOOD AQUIFER

SIMULATED UPDIP LIMIT OF AQUIFER (model unit A8)

SIMULATED UPDIP LIMIT OF THE OVERLYING CONFINING UNIT

250-milligram per liter isochlor (From Lacombe and Rosman, 1997, fig. 2-3)

LOCATION OF GROUND-WATER WITHDRAWALS--

- Less than or equal to 0.5 million gallons per day
- Greater than 0.5 million gallons per day

**Figure 14.** Simulated potentiometric surface, location of the toe of the freshwater-saltwater interface, and location of withdrawal wells in the confined Kirkwood aquifer (baseline), New Jersey Coastal Plain, 1992.

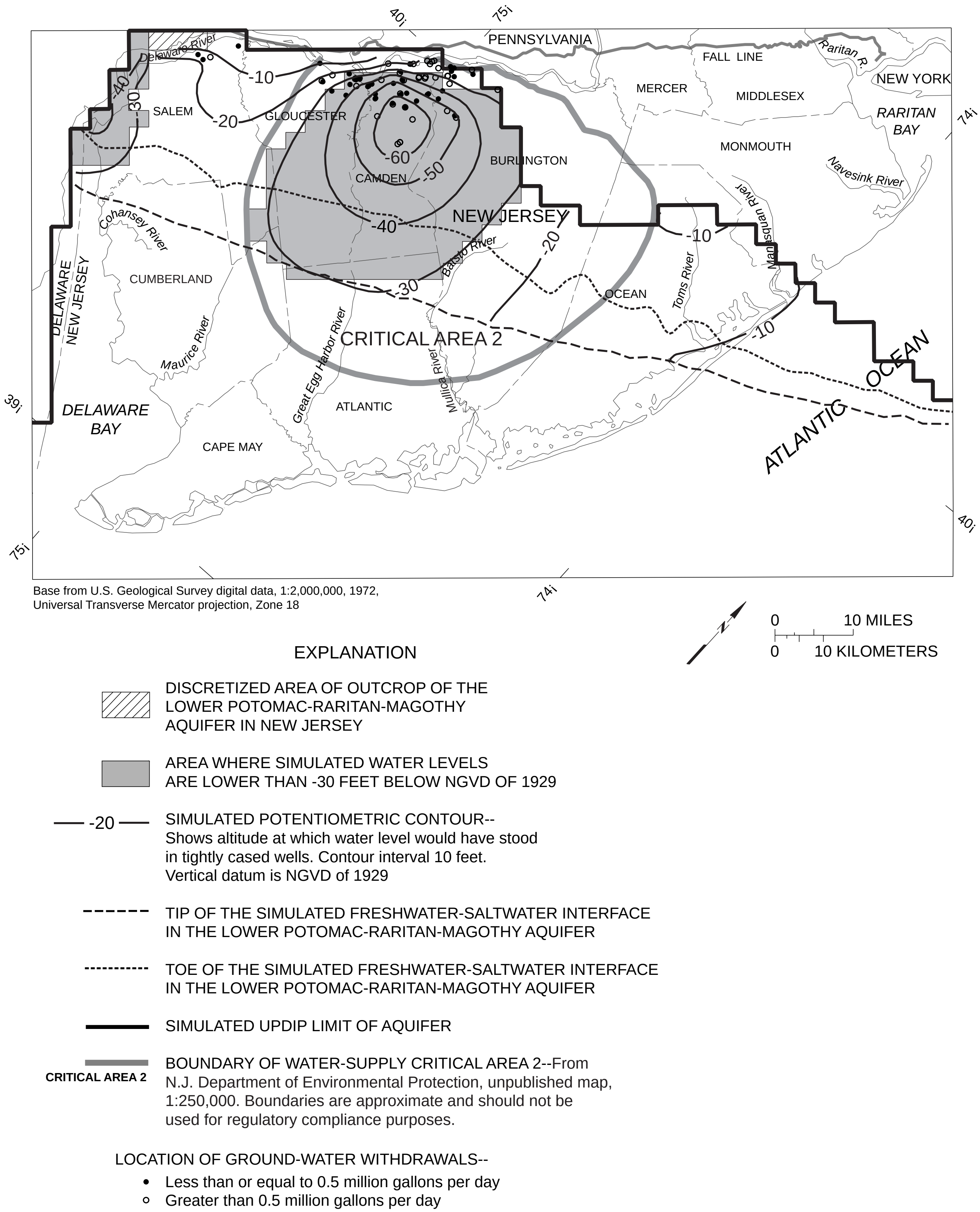
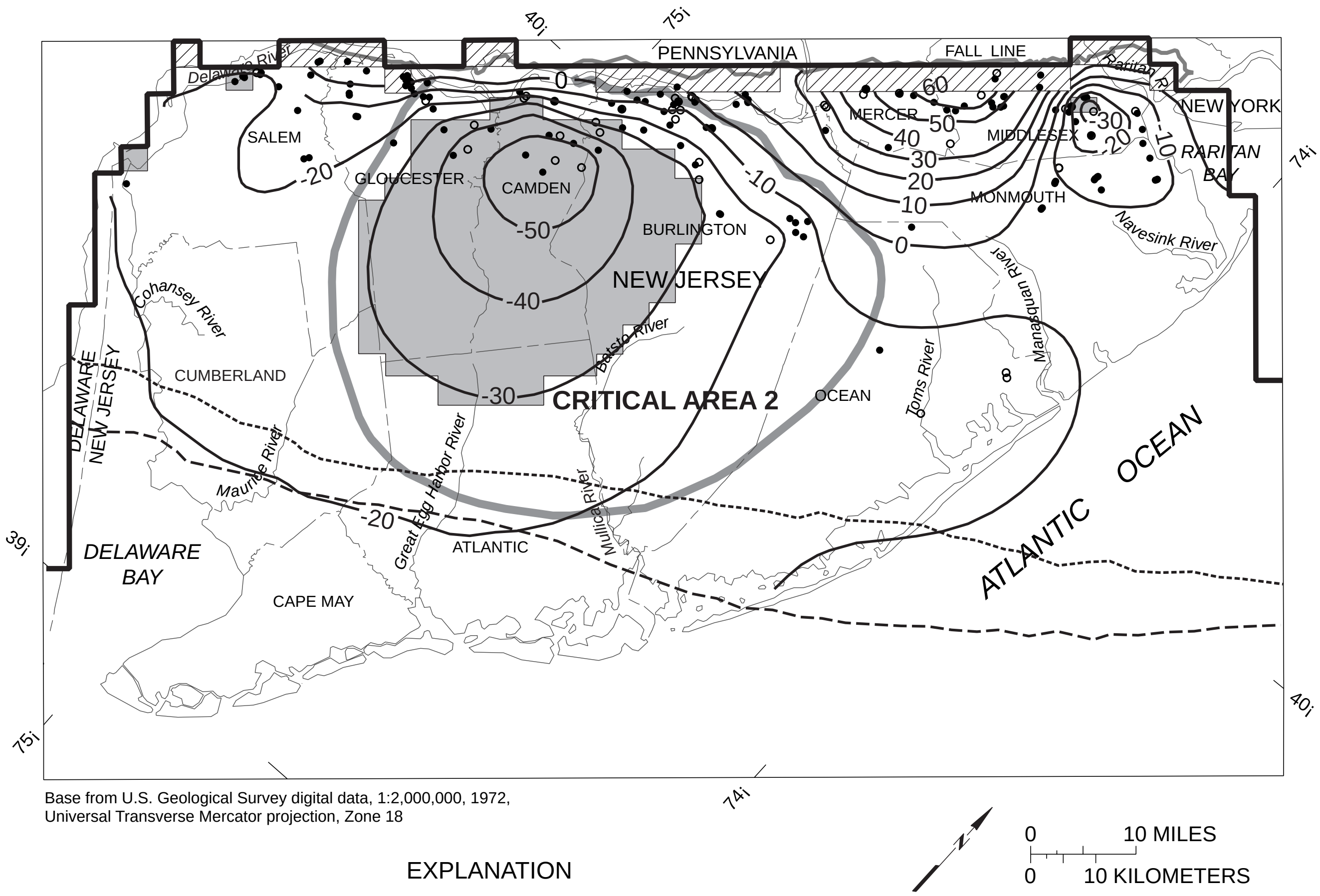



**Figure 15.** Simulated potentiometric surface in the Lower Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal reductions in critical area 2 (scenario 1). (Baseline conditions for Lower Potomac-Raritan-Magothy aquifer shown in fig. 7)




EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 10 feet. Vertical datum is NGVD of 1929

TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER

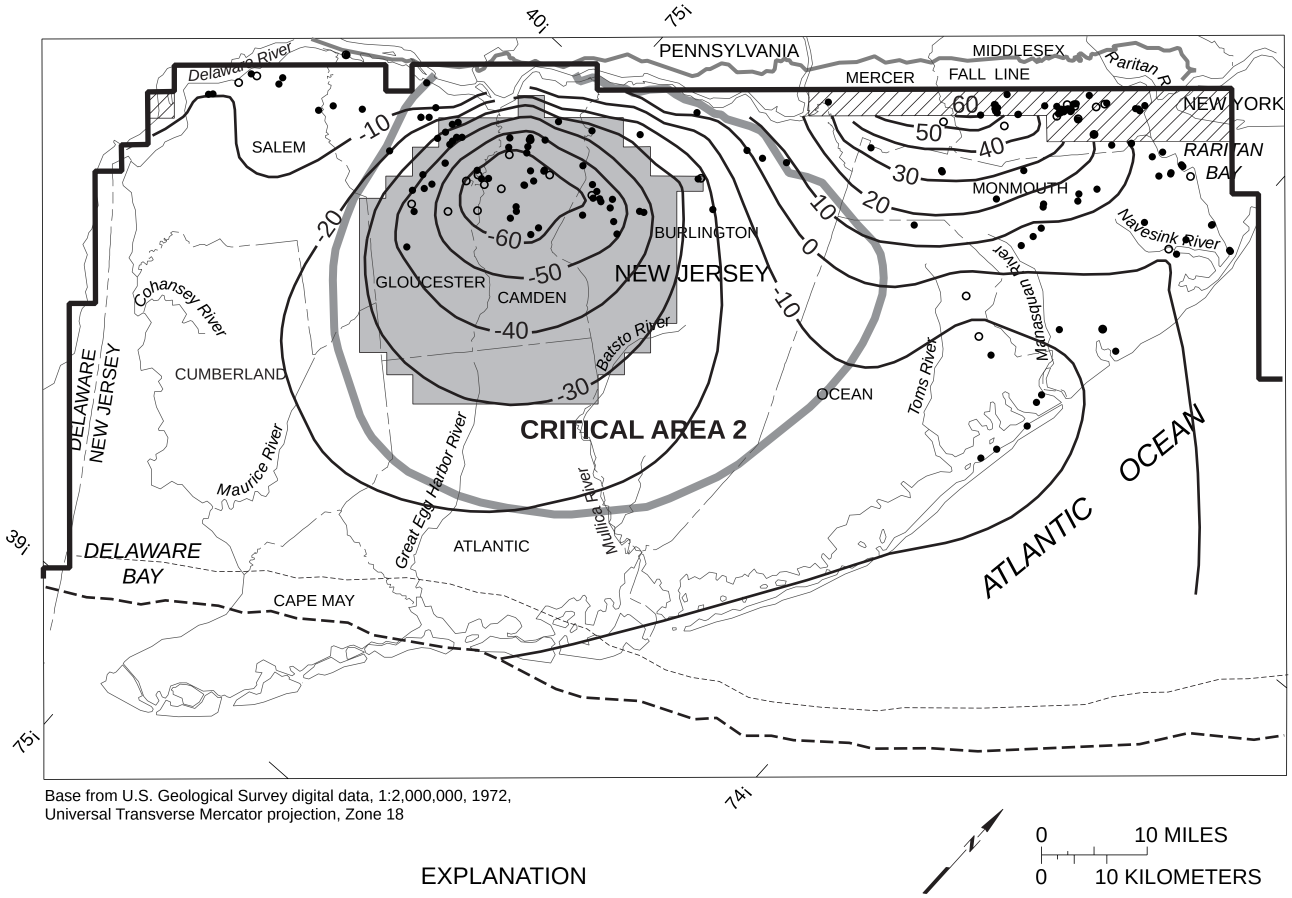
SIMULATED UPDIP LIMIT OF AQUIFER

CRITICAL AREA 2 BOUNDARY OF WATER-SUPPLY CRITICAL AREA 2--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

LOCATION OF GROUND-WATER WITHDRAWALS--

- Less than or equal to 0.5 million gallons per day
- Greater than 0.5 million gallons per day

**Figure 16.** Simulated potentiometric surface in the Middle Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal reductions in critical area 2 (scenario 1). (Baseline conditions for Middle Potomac-Raritan-Magothy shown in fig. 8)




Base from U.S. Geological Survey digital data, 1:2,000,000, 1972,
Universal Transverse Mercator projection, Zone 18

EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE UPPER POTOMAC-RARITAN-MAGOTHY AQUIFER IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 10 feet. Vertical datum is NGVD of 1929

TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE UPPER POTOMAC-RARITAN-MAGOTHY AQUIFER

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE UPPER POTOMAC-RARITAN-MAGOTHY AQUIFER

SIMULATED UPDIP LIMIT OF AQUIFER

CRITICAL AREA 2 BOUNDARY OF WATER-SUPPLY CRITICAL AREA 2--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

LOCATION OF GROUND-WATER WITHDRAWALS--
- Less than or equal to 0.5 million gallons per day
- Greater than 0.5 million gallons per day

**Figure 17.** Simulated potentiometirc surface in the Upper Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal reductions in critical area 2 (scenario 1). (Baseline conditions for Upper Potomac-Raritan-Magothy shown in fig. 9)

Raritan-Magothy aquifer decreased about 6 percent, and leakage from the confined Englishtown aquifer system to the underlying Upper Potomac-Raritan-Magothy aquifer decreased 4 percent when compared with the budget of the 1992 simulation (table 4). Flow downdip from the unconfined region (outcrop) of the Upper Potomac-Raritan-Magothy aquifer to the confined Upper Potomac-Raritan-Magothy aquifer also decreased by 4 percent.

## Scenario 2--Ground-Water System With Withdrawal Restrictions In Critical Area 1 And Withdrawal Reductions In Critical Area 2, 1993-2020

In scenario 2, increased withdrawals projected for 2020 were simulated for wells outside critical areas 1 and 2 in operation in 1992. The same withdrawals reductions were imposed in critical area 2 in the Potomac-Raritan-Magothy aquifer system as in scenario 1, and withdrawals at the 1992 amount were maintained in critical area 1 in the Middle and Upper Potomac-Raritan-Magothy aquifers, the Englishtown aquifer system, and the Wenonah-Mount Laurel aquifer. For this scenario, it was assumed that the ground-water supply would be supplemented from surface-water sources, such as reservoirs and the Delaware River. Surface water from reservoirs and the Delaware River has become an additional water-supply source in areas where ground-water withdrawals have been reduced or restricted (New Jersey Water Supply Authority, 1998).

The location of ground-water withdrawals, simulated potentiometric surfaces, areas where the simulated water levels are lower then 30 feet below NGVD of 29, and the simulated freshwater-saltwater interface tip and toe for the Potomac-Raritan-Magothy aquifer system, the Englishtown aquifer system, and the Wenonah-Mount Laurel aquifer are shown in figures 18 to 22. The interface is not shown in figure 21 because it is located farther downdip in a less permeable part of the aquifer system. The increase in withdrawals at wells outside critical areas 1 and 2 in the Potomac-Raritan-Magothy aquifer system totaled 5.6 Mgal/d. Although ground-water withdrawals were increased outside the critical areas, simulated water levels within the critical areas recovered from 1992 simulated levels. When compared with simulated water levels for 1992, the simulated water levels in the Lower and Middle Potomac-Raritan-Magothy aquifers for scenario 2 recovered by more than 10 ft at the cone of depression centered in Camden County and more than 5 ft downdip from the center of the cone of depression (figs. 18 and 19). In the Upper Potomac-Raritan-Magothy aquifer, water levels recovered 20 ft at the center of the cone of depression in Camden County and more than 5 ft in Burlington, Gloucester, and northern Atlantic Counties downdip from the center of the cone of depression (fig. 20). Water levels recovered as much as 20 ft in the Englishtown aquifer system and the Wenonah-Mount Laurel aquifer in critical area 1 near the northeastern border of Ocean and Monmouth Counties (figs. 21 and 22).

The flow budget that resulted from this scenario along with the budget for the baseline simulation is listed in table 4. When compared with the flow budget for the baseline simulation, withdrawal restrictions in critical areas 1 and 2 resulted in a 6 percent decrease in leakage from the confined Middle Potomac-Raritan-Magothy aquifer to the Lower Potomac-Raritan-Magothy aquifer, a 3 percent decrease in leakage from the confined Englishtown aquifer system to the underlying Upper Potomac-Raritan-Magothy aquifer, and a 3 percent decrease in flow downdip from the unconfined region (outcrop) of the Upper Potomac-Raritan-Magothy aquifer to the confined region of the aquifer. The water levels simulated in scenario 2 for the Vincentown, Piney Point, and confined Kirkwood aquifers are not shown in a figure because they are very similar to the water levels simulated in scenario 3.

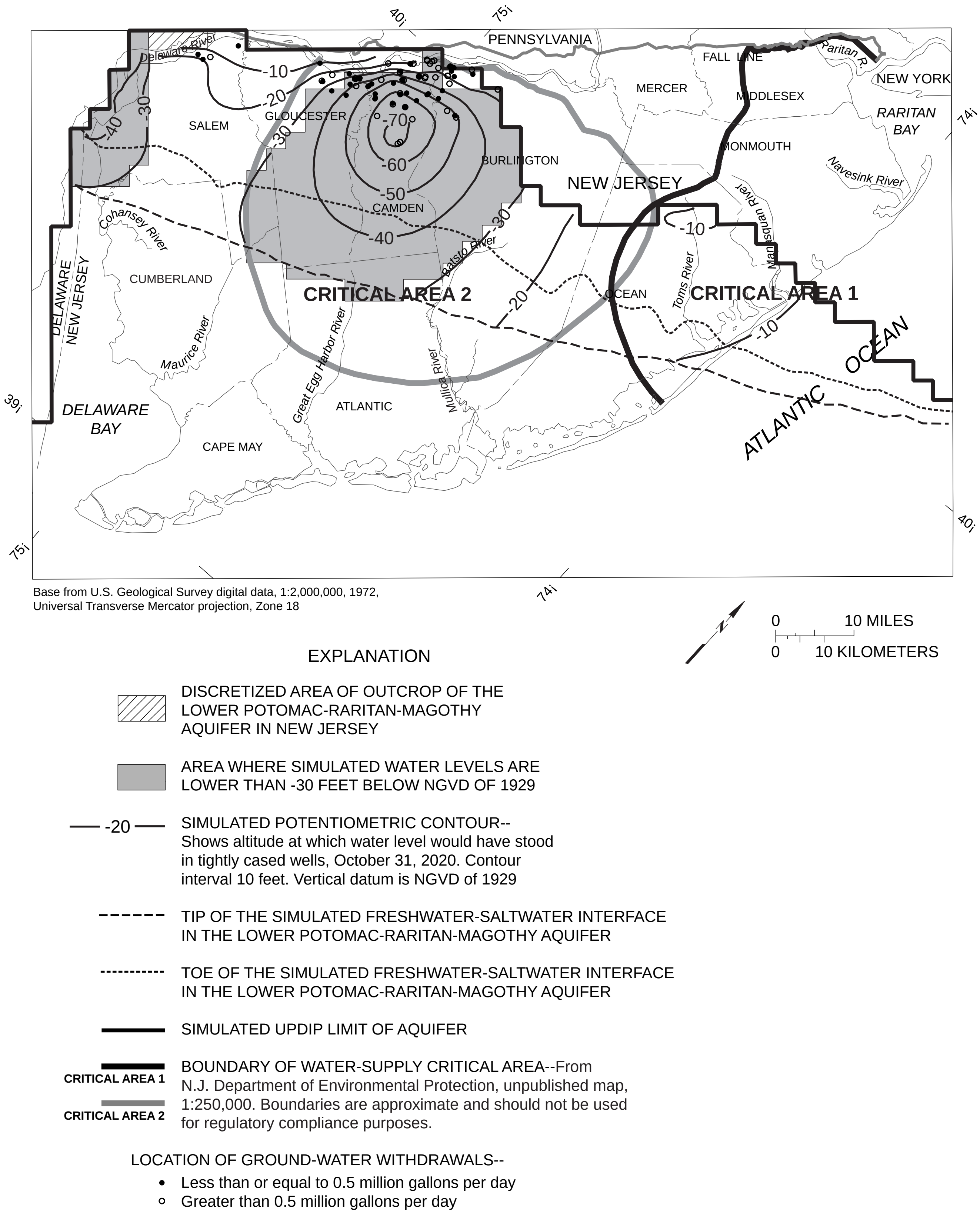
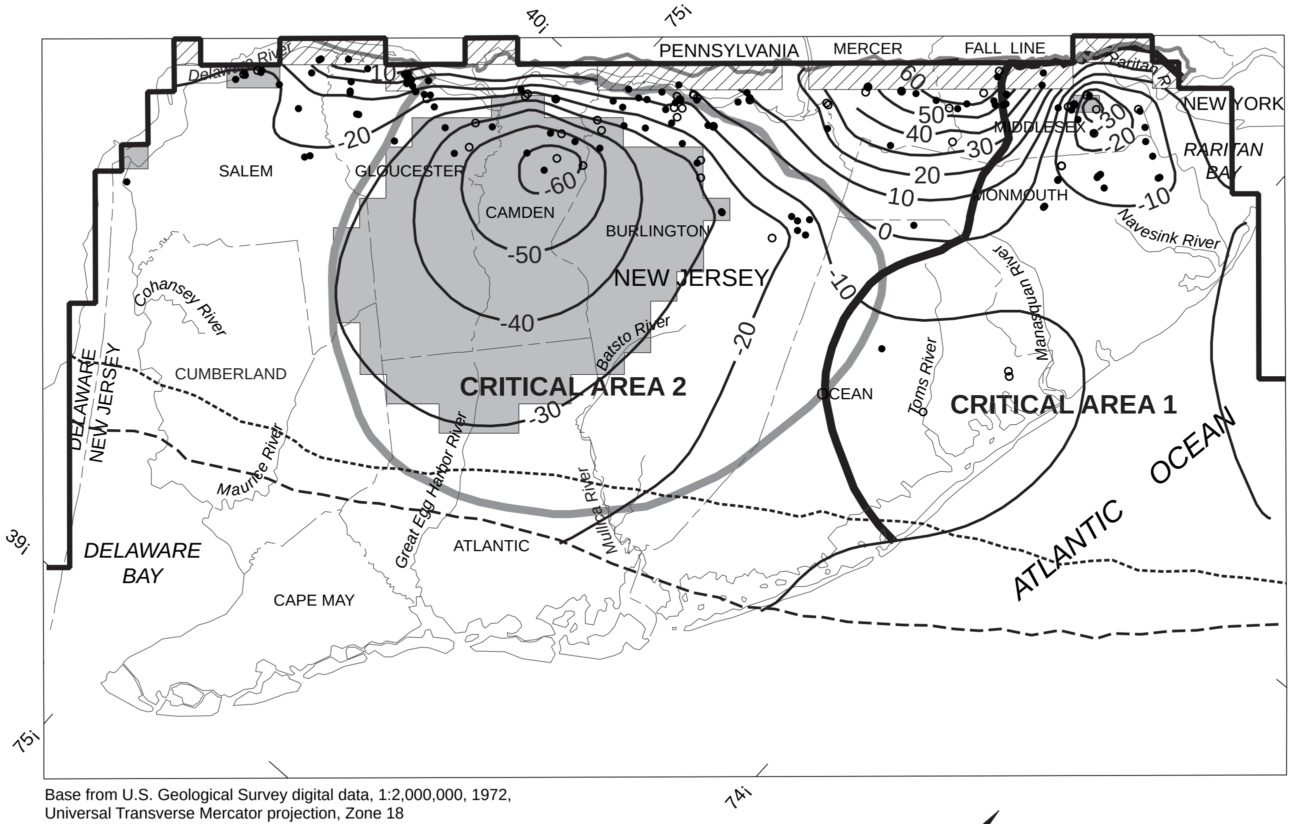
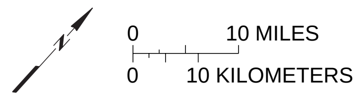



**Figure 18.** Simulated potentiometric surface in the Lower Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1 in overlying aquifers and withdrawal reductions in critical area 2 (scenario 2), 2020. (Baseline conditions for the Lower Potomac-Raritan-Magothy aquifer shown in fig. 7)




EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, October 31, 2020. Contour interval 10 feet. Vertical datum is NGVD of 1929

TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER

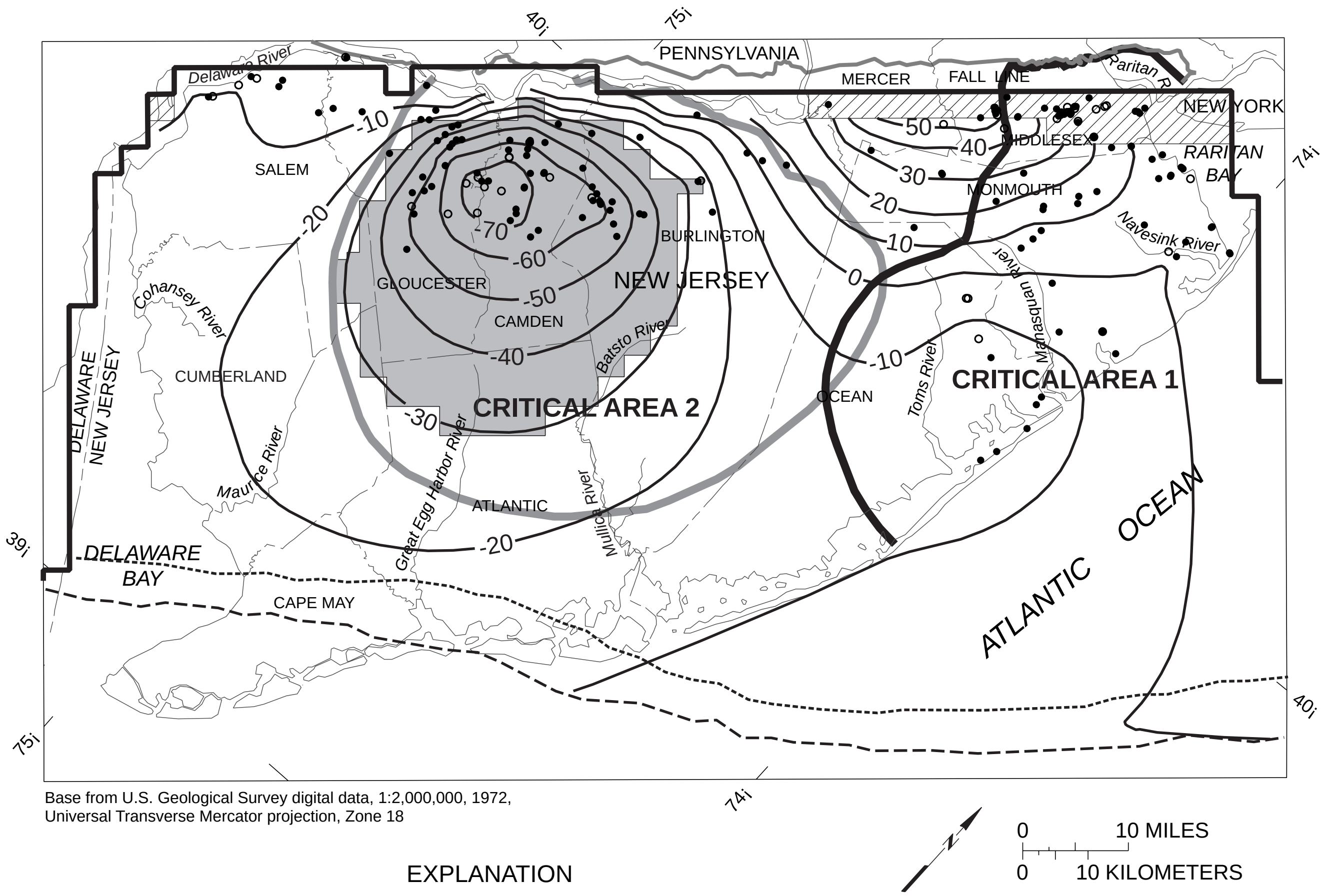
SIMULATED UPDIP LIMIT OF AQUIFER

CRITICAL AREA 1
CRITICAL AREA 2
BOUNDARY OF WATER-SUPPLY CRITICAL AREA--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

LOCATION OF GROUND-WATER WITHDRAWAL--

- Less than or equal to 0.5 million gallons per day
- Greater than 0.5 million gallons per day

**Figure 19.** Simulated potentiometric surface in the Middle Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1 and withdrawal reductions in critical area 2 (scenario 2), 2020. (Baseline conditions for Middle Potomac-Raritan-Magothy aquifer shown in fig. 8)




Base from U.S. Geological Survey digital data, 1:2,000,000, 1972,
Universal Transverse Mercator projection, Zone 18

EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE UPPER POTOMAC-RARITAN-MAGOTHY AQUIFER IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, October 31, 2020. Contour interval 10 feet. Vertical datum is NGVD of 1929

TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE UPPER POTOMAC-RARITAN-MAGOTHY AQUIFER

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE UPPER POTOMAC-RARITAN-MAGOTHY AQUIFER

SIMULATED UPDIP LIMIT OF AQUIFER

CRITICAL AREA 1
CRITICAL AREA 2
BOUNDARY OF WATER-SUPPLY CRITICAL AREA--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

LOCATION OF GROUND-WATER WITHDRAWALS--

- Less than or equal to 0.5 million gallons per day
- Greater than 0.5 million gallons per day

**Figure 20.** Simulated potentiometric surface in the Upper Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1 and withdrawal reductions in critical area 2 (scenario 2), 2020. (Baseline conditions for Upper Potomac-Raritan-Magothy aquifer shown in fig. 9)

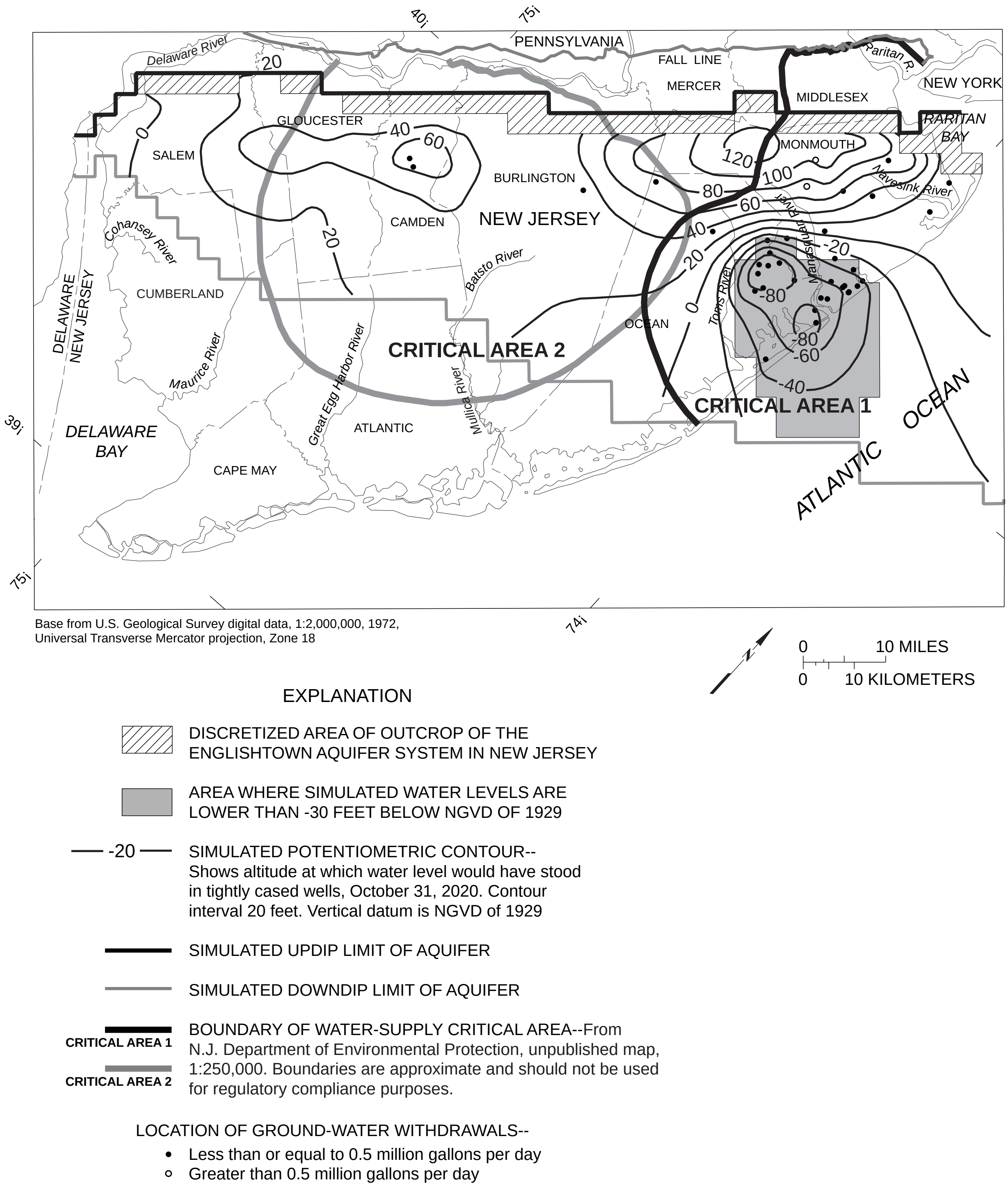



**Figure 21.** Simulated potentiometric surface in the Englishtown aquifer system, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1 and withdrawal reductions in critical area 2 in underlying aquifers (scenario 2), 2020. (Baseline conditions for the Englishtown aquifer system shown in fig. 10)

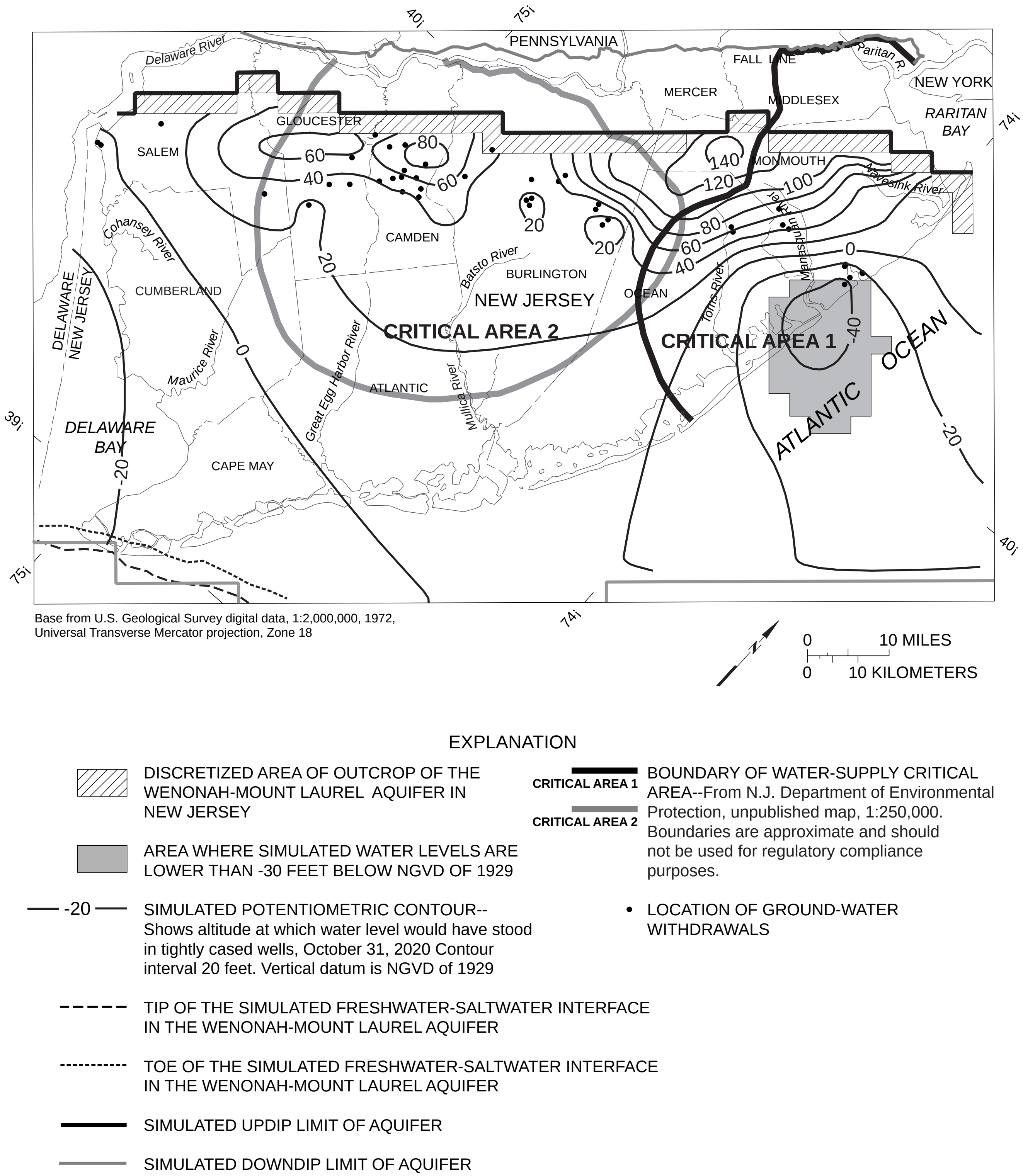



**Figure 22.** Simulated potentiometric surface in the Wenonah-Mount Laurel aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1 and withdrawal reductions in critical area 2 in underlying aquifers (scenario 2), 2020. (Baseline conditions for the Wenonah-Mount Laurel aquifer shown in fig. 11)

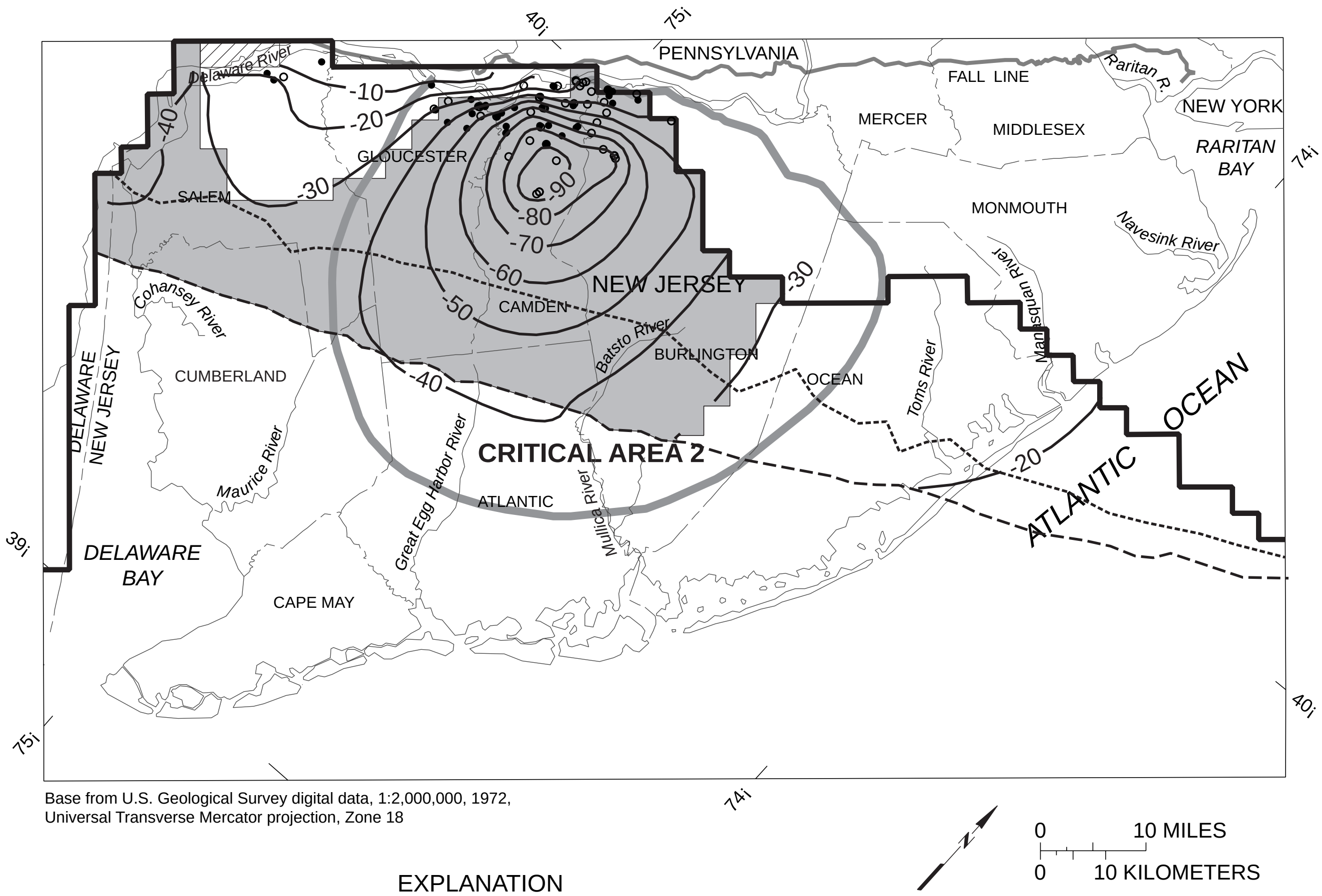
## Scenario 3--Ground-Water System With Increased Withdrawals Inside And Outside The Critical Areas, 1993-2020

In this scenario, the response of water levels to projected increases in ground-water withdrawals from all wells is simulated for 1993-2020. The location of ground-water withdrawals, simulated potentiometrics surfaces, and areas where the simulated water levels are lower than 30 ft below NGVD of 29 in the confined aquifers in the New Jersey Coastal Plain are shown in figures 23 to 30. The simulated location of the freshwater-saltwater interface tip and toe are shown in figures 23 to 25, 27, and 29. The freshwater-saltwater interface toe only is shown in figure 30, the tip is located farther offshore and is not shown in this figure. The projected increase in total withdrawals during 1993-2020 from wells completed in the confined aquifers is 21 Mgal/d. The percentage increase designated for each water-supply region within the New Jersey Coastal Plain is given in table 2. Total ground-water withdrawals input to the model for each confined aquifer are shown in table 4.

The potentiometric surfaces of the confined aquifers simulated for this scenario are similar to the potentiometric surfaces simulated for 1992 (fig. 7-14), but the cones of depression centered in Camden County in the Potomac-Raritan-Magothy aquifer system and in southern Monmouth and northern Ocean Counties in the Englishtown aquifer system and the Wenonah-Mount Laurel aquifer are broader and deeper. A 10-ft decline in water levels at the center of the cone of depression in Camden County in the Lower Potomac-Raritan-Magothy aquifer resulted from the simulation, and the area where the simulated water levels are lower than -30 ft extended throughout southern Salem County and into adjacent Cumberland County (fig. 23). A 10-ft decline in water levels was simulated for the Middle Potomac-Raritan-Magothy aquifer at the center of the cone of depression in Middlesex County near Raritan Bay (fig. 24). Also, a localized cone of depression developed in Ocean County south of the Manasquan River, and a 10-ft decline in water levels occurred at a pre-existing localized cone of depression in the area near the Toms River in Ocean County (fig. 8). The WSMP (CH2M Hill and others, 1994) projected about a 30-percent increase in average water demand from 1995 to 2020 for the Toms River RWRPA (table 2). Simulated water levels declined more than 20 ft in the Englishtown aquifer system within the regional cone of depression located between Ocean and Monmouth Counties (fig. 26). The Wenonah-Mount Laurel aquifer showed declines of more than 10 ft downdip from the outcrop region for this aquifer in Gloucester County (fig. 27). The Piney Point aquifer showed declines of as much as 10 ft in central and southern Cape May County and at the coast of Ocean County (fig. 29). Simulated water levels declined by 10 ft in the cone of depression in the confined Kirkwood aquifer centered in Atlantic County (fig. 30).

In the flow budget for this simulation (table 4), an increase in ground-water withdrawals resulted in an increase in downward leakage, particularly to the Lower, Middle, and Upper Potomac-Raritan-Magothy aquifers from overlying aquifers. The increase in withdrawals projected from 1993 to 2020 totaled 14.4 Mgal/d for the confined Potomac-Raritan-Magothy aquifer system. When compared to the 1992 flow budgets, there was more than a 3 percent increase in flow downward to the underlying Lower Potomac-Raritan-Magothy aquifer from the Middle Potomac-Raritan Magothy aquifer, whereas in the Upper Potomac-Raritan-Magothy aquifer, flow from the outcrop region downdip to the confined part of the aquifer increased by almost 3 percent. Downward flow to the confined Englishtown aquifer system from the confined Wenonah-Mount Laurel aquifer increased by 6 percent, and downward flow from the Vincentown aquifer to the confined Wenonah-Mount Laurel aquifer increased by 8 percent. In the confined Kirkwood aquifer, inflow from the saltwater areas in the Delaware Bay and other offshore areas increased by 3 percent.

When compared with the simulated location of the interface for each aquifer in the baseline simulation, the increase in withdrawals to 2020 resulted in a small movement (about 0.01 mi or less) of the freshwater-saltwater interface in the confined aquifers (figs. 23-25, 27, and 29-30). The largest movement of the interface occurred in the Lower and Middle Potomac-Raritan-Magothy and




EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE LOWER POTOMAC-RARITAN MAGOTHY AQUIFER IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, October 31, 2020. Contour interval 10 feet. Vertical datum is NGVD of 1929

TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE LOWER POTOMAC-RARITAN MAGOTHY AQUIFER

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE LOWER POTOMAC-RARITAN MAGOTHY AQUIFER

SIMULATED UPDIP LIMIT OF AQUIFER

CRITICAL AREA 2 BOUNDARY OF WATER-SUPPLY CRITICAL AREA 2--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

LOCATION OF GROUND-WATER WITHDRAWAL--

- • Less than or equal to 0.5 million gallons per day
- ○ Greater than 0.5 million gallons per day

**Figure 23.** Simulated potentiometric surface in the Lower Potomac-Raritan Magothy aquifer, New Jersey Coastal Plain (scenario 3), 2020. (Baseline conditions for the Lower Potomac-Raritan Magothy aquifer shown in fig. 7)

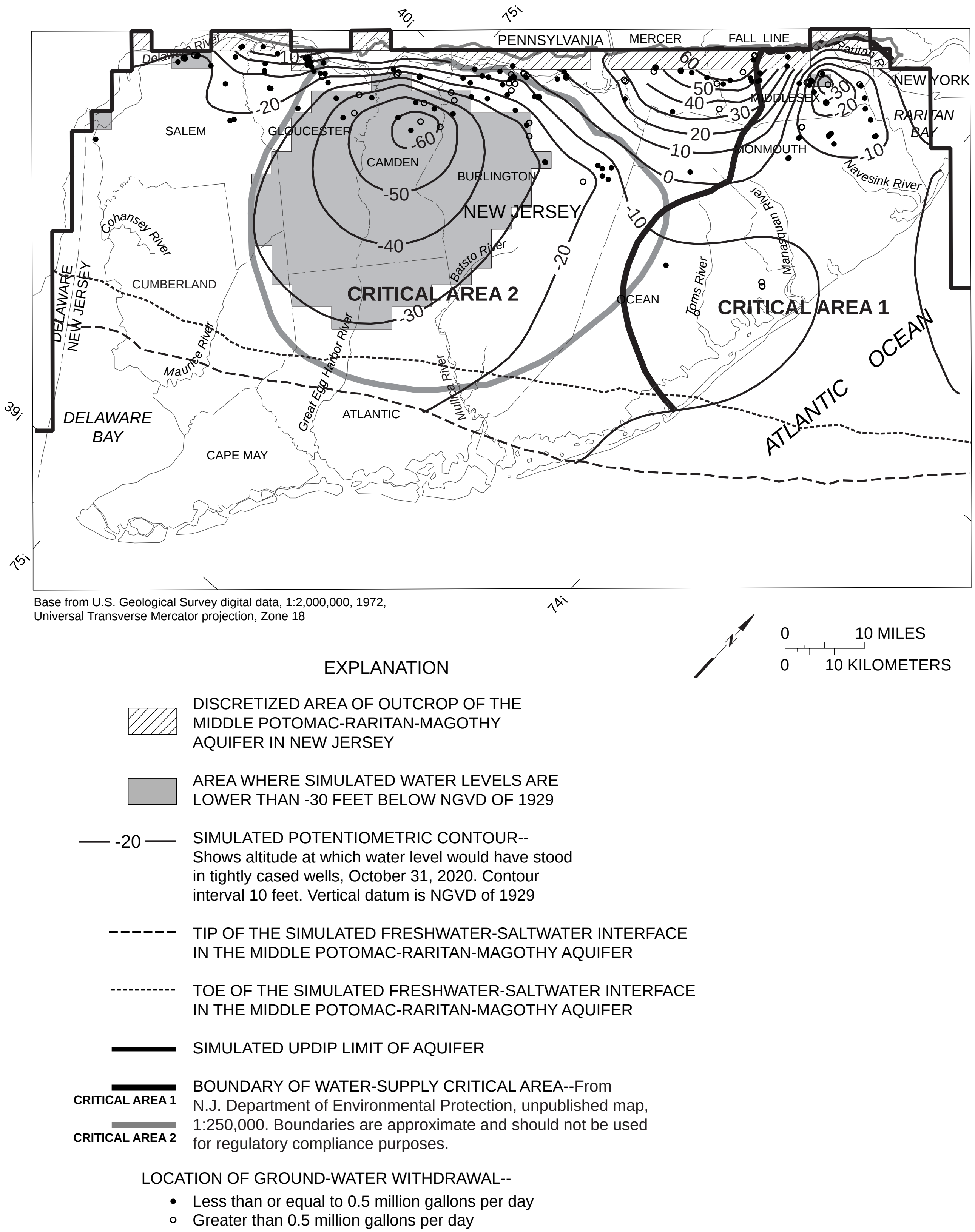



**Figure 19.** Simulated potentiometric surface in the Middle Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1 and withdrawal reductions in critical area 2 (scenario 2), 2020. (Baseline conditions for Middle Potomac-Raritan-Magothy aquifer shown in fig. 8)

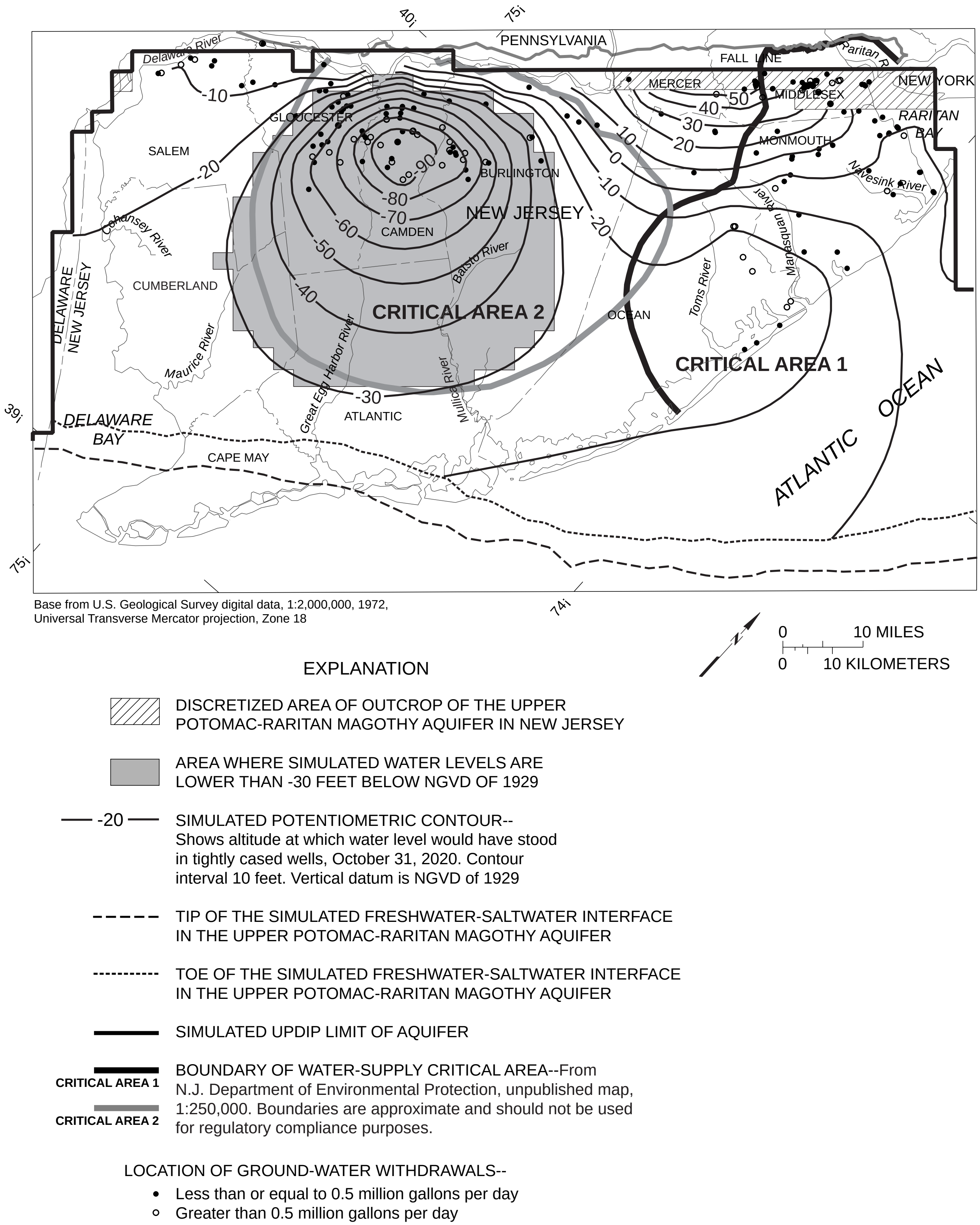
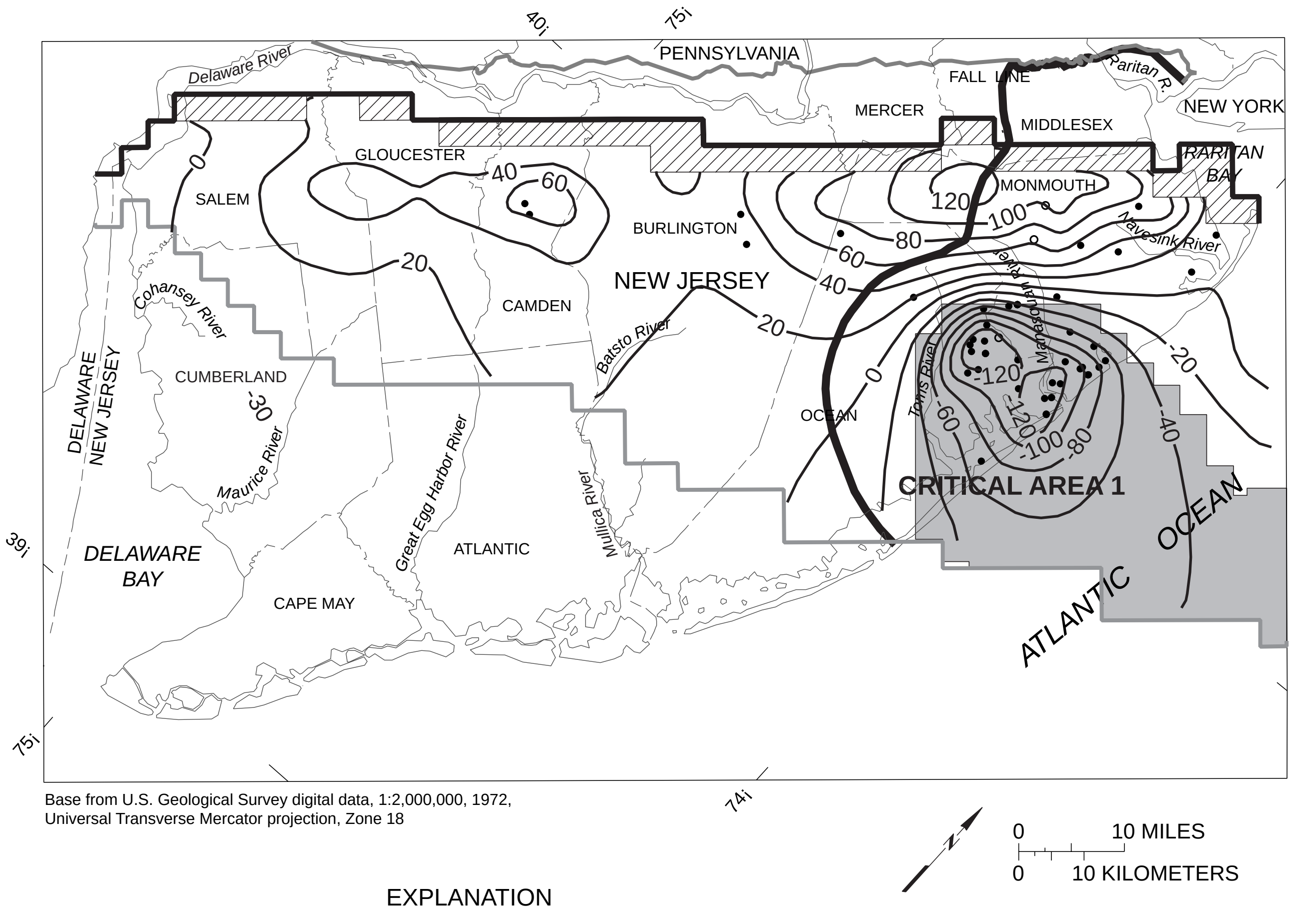



**Figure 25.** Simulated potentiometric surface in the Upper Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain (scenario 3), 2020. (Baseline conditions for the Upper Potomac-Raritan Magothy aquifer shown in fig. 9)




EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE ENGLISHTOWN AQUIFER SYSTEM IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude at which water level would have stood in tightly cased wells, October 31, 2020. Contour interval 20 feet. Vertical datum is NGVD of 1929

SIMULATED UPDIP LIMIT OF AQUIFER

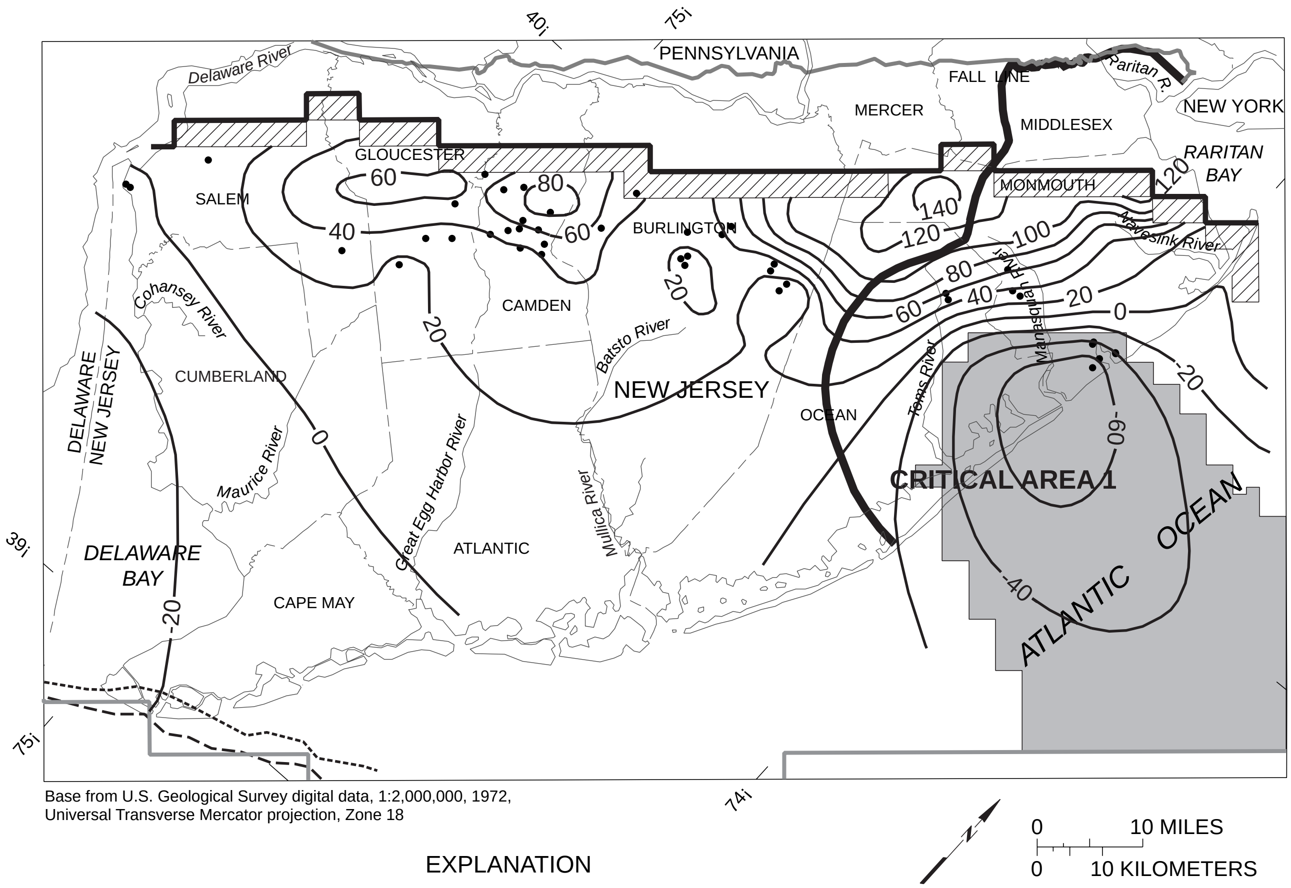
SIMULATED DOWNDIP LIMIT OF AQUIFER

CRITICAL AREA 1 BOUNDARY OF WATER-SUPPLY CRITICAL AREA 1--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

LOCATION OF GROUND-WATER WITHDRAWALS--

- Less than or equal to 0.5 million gallons per day
- Greater than 0.5 million gallons per day

**Figure 26.** Simulated potentiometric surface in the Englishtown aquifer system, New Jersey Coastal Plain (scenario 3), 2020. (Baseline conditions for the Englishtown aquifer system shown in fig. 10)




EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE WENONAH-MOUNT LAUREL AQUIFER IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, October 31, 2020. Contour interval 20 feet. Vertical datum is NGVD of 1929

TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE WENONAH-MOUNT LAUREL AQUIFER

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE WENONAH-MOUNT LAUREL AQUIFER

SIMULATED UPDIP LIMIT OF AQUIFER

SIMULATED DOWNDIP LIMIT OF AQUIFER

CRITICAL AREA 1 BOUNDARY OF WATER-SUPPLY CRITICAL AREA 1--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

• LOCATION OF GROUND-WATER WITHDRAWALS

**Figure 27.** Simulated potentiometric surface in the Wenonah-Mount Laurel aquifer, New Jersey Coastal Plain (scenario 3), 2020. (Baseline conditions for the Wenonah-Mount Laurel aquifer shown in fig. 11)

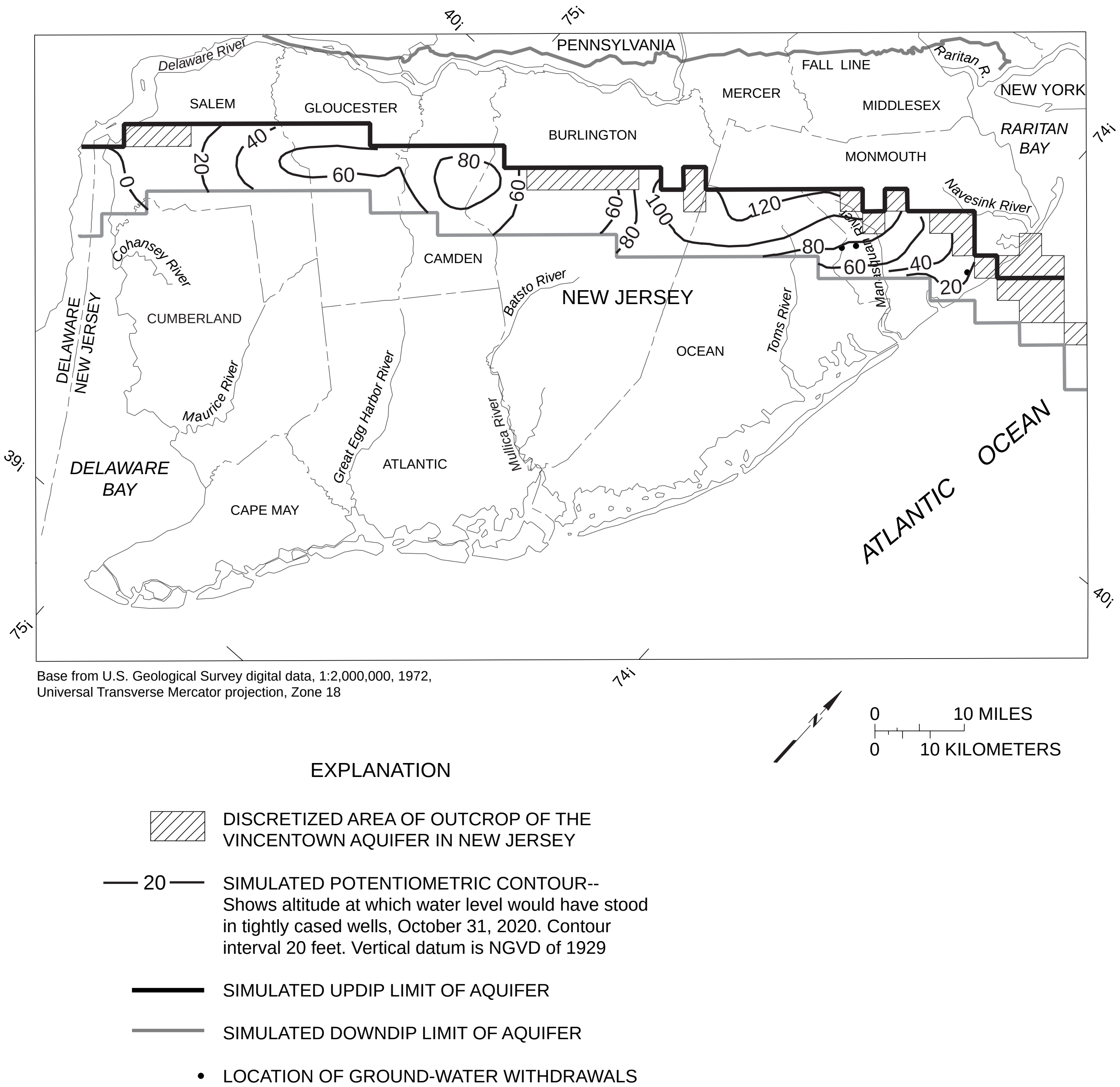
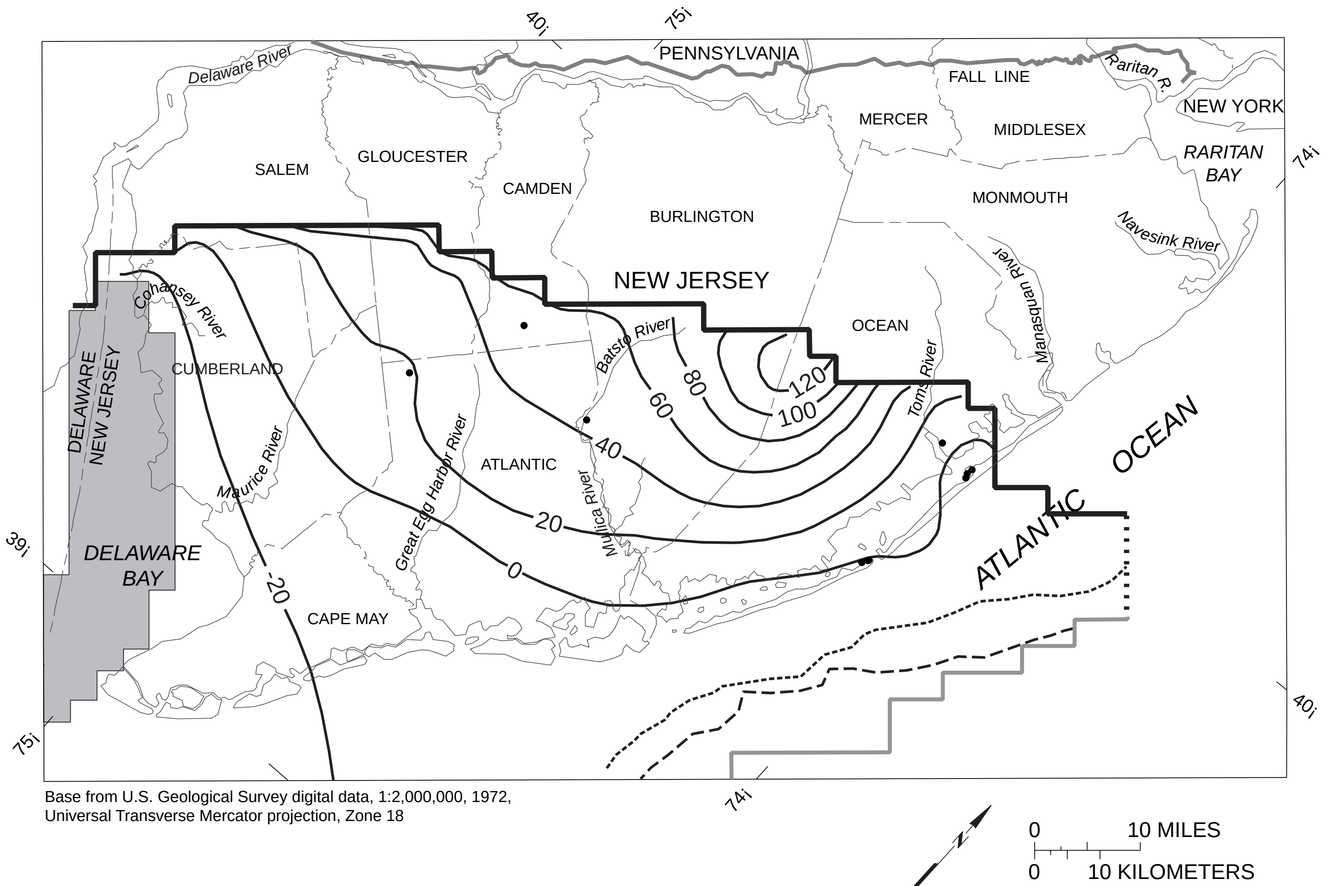



**Figure 28.** Simulated potentiometric surface in the Vincentown aquifer, New Jersey Coastal Plain (scenario 3), 2020. (Baseline conditions for the Vincentown aquifer shown in fig. 12)




EXPLANATION

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude at which water level would have stood in tightly cased wells, October 31, 2020. Contour interval 20 feet. Vertical datum is NGVD of 1929

TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE PINEY POINT AQUIFER

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE PINEY POINT AQUIFER

SIMULATED UPDIP LIMIT OF AQUIFER

SIMULATED DOWNDIP LIMIT OF AQUIFER

SIMULATED LATERAL LIMIT OF AQUIFER

• LOCATION OF GROUND-WATER WITHDRAWALS

**Figure 29.** Simulated potentiometric surface in the Piney Point aquifer, New Jersey Coastal Plain (scenario 3), 2020. (Baseline conditions for Piney Point aquifer shown in fig. 13)

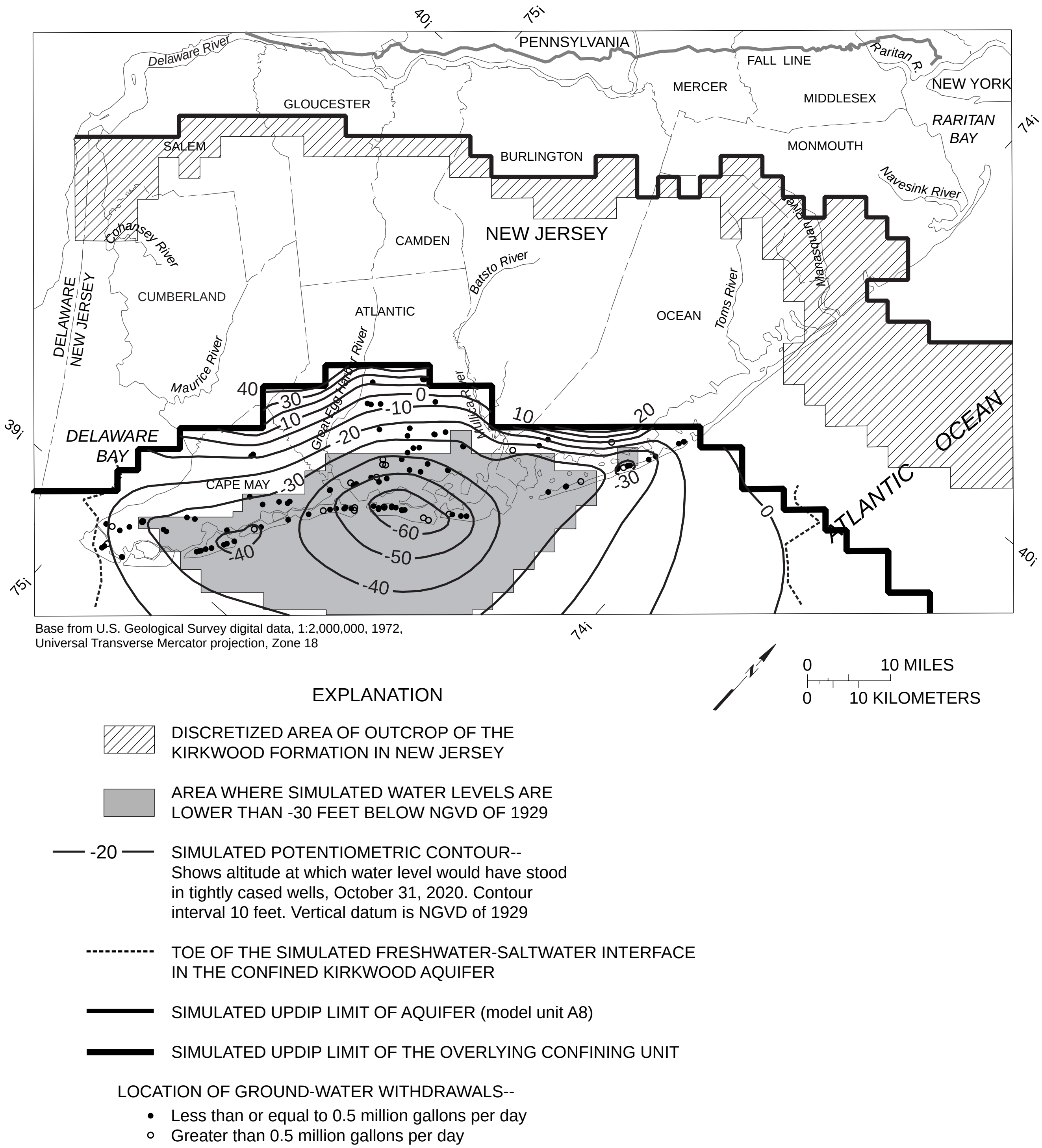



**Figure 30.** Simulated potentiometric surface in the confined Kirkwood aquifer, New Jersey Coastal Plain (scenario 3), 2020. (Baseline conditions for the confined Kirkwood aquifer shown in fig. 14)

confined Kirkwood aquifers. In the Lower and Middle Potomac-Raritan-Magothy aquifers, the toe of the interface moved about 0.1 mi within critical area 2 in Camden County. The interface in the Lower Potomac-Raritan-Magothy aquifer is about 10 mi south of the center of regional cone of depression located in Camden County (fig. 23); the interface in the Middle Potomac-Raritan-Magothy aquifer is located about 25 mi south of this cone (fig. 24). Water levels declined by as much as 5 ft near of the interface of these aquifers. Outside the critical area, the simulated movement of the interface toe was much smaller; the average rate of movement was about 0.004 ft/d updip. In the confined Kirkwood aquifer, maximum movement of the toe of the interface was almost 0.1 mi inland in southern Cape May County (fig. 30), and the average rate of movement was less than 0.004 ft/d inland in this area. The water levels near the toe of the interface in Cape May County declined by about 5 ft.

Water-level declines near the interface in response to pumping result in changes in the hydraulic gradient, which can threaten water-supply wells with saltwater intrusion. The decline in water levels permits the lateral movement of saltwater. Salty water replaces freshwater as water levels decline, and chloride concentrations increase. The rate of movement accelerates as the decline in water levels increases. Although ground-water withdrawals can affect the movement of saltwater into freshwater areas (McAuley and others, 2001; Spitz, 1998; Schaefer and Walker, 1981), in general, movement of the interface in scenarios 2 to 4 is small (less than 0.1 mi). Other factors affect the movement of the interface; for example, recharge to the ground-water flow system could impede the inland movement of the interface.

The model of Pope and Gordon (1999) was used to simulate the location and movement of the freshwater-saltwater interface, which is represented as the location at which the dissolved chloride concentration of the ground water is approximately 10,000 mg/L; however, the location of the observed interface for potable water (the approximate location of the 250-mg/L chloride concentration) and the estimated movement are not easily compared to model results. The increase in chloride concentrations affects the salinity of the potable water supply, so monitoring of chloride concentrations in wells downdip from pumping centers and updip of the interface would be needed, particularly in the Potomac-Raritan-Magothy aquifer system, and in the Wenonah-Mount Laurel, Piney Point, and confined Kirkwood aquifers.

## Scenario 4--Ground-Water System With Withdrawal Restrictions In Critical Area 1, Withdrawal Reductions In Critical Area 2, And Withdrawals From Hypothetical Wells, 1993-2020

Scenario 4 incorporated the same simulated withdrawals as scenario 2, but additional withdrawal sites were included to supplement withdrawals that are not allowed within the critical areas. The additional withdrawals input at these sites totaled 13.2 Mgal/d. The location of ground-water withdrawals, the simulated potentiometric surfaces, and areas where the simulated water levels are lower than 30 ft below NGVD of 29 are shown in figures 31 to 36. The simulated location of freshwater-saltwater interface tip and toe are shown in figures 31 to 33 and 35.

In scenario 4, withdrawals from 17 hypothetical wells placed outside the critical areas were input into the model. Three wells were placed in the Upper Potomac-Raritan-Magothy aquifer, six wells were placed in the Englishtown aquifer system, and eight wells were placed in the Wenonah-Mount Laurel aquifer. An additional 1.6 Mgal/d was withdrawn from the three hypothetical wells placed outside the critical areas in the Upper Potomac-Raritan-Magothy aquifer in Monmouth and Ocean Counties in an area downdip from the aquifer recharge area (fig. 33). The simulated water levels were similar to those simulated for this aquifer in scenario 2 (fig. 20), except for those near the hypothetical wells. A decrease in water levels of about 8 ft resulted near the hypothetical wells outside the critical areas; inside critical area 1, the decrease was about 6 ft. An additional 4.8 Mgal/d was withdrawn from four hypothetical wells placed in the Englishtown aquifer system in Burlington County (fig. 34).

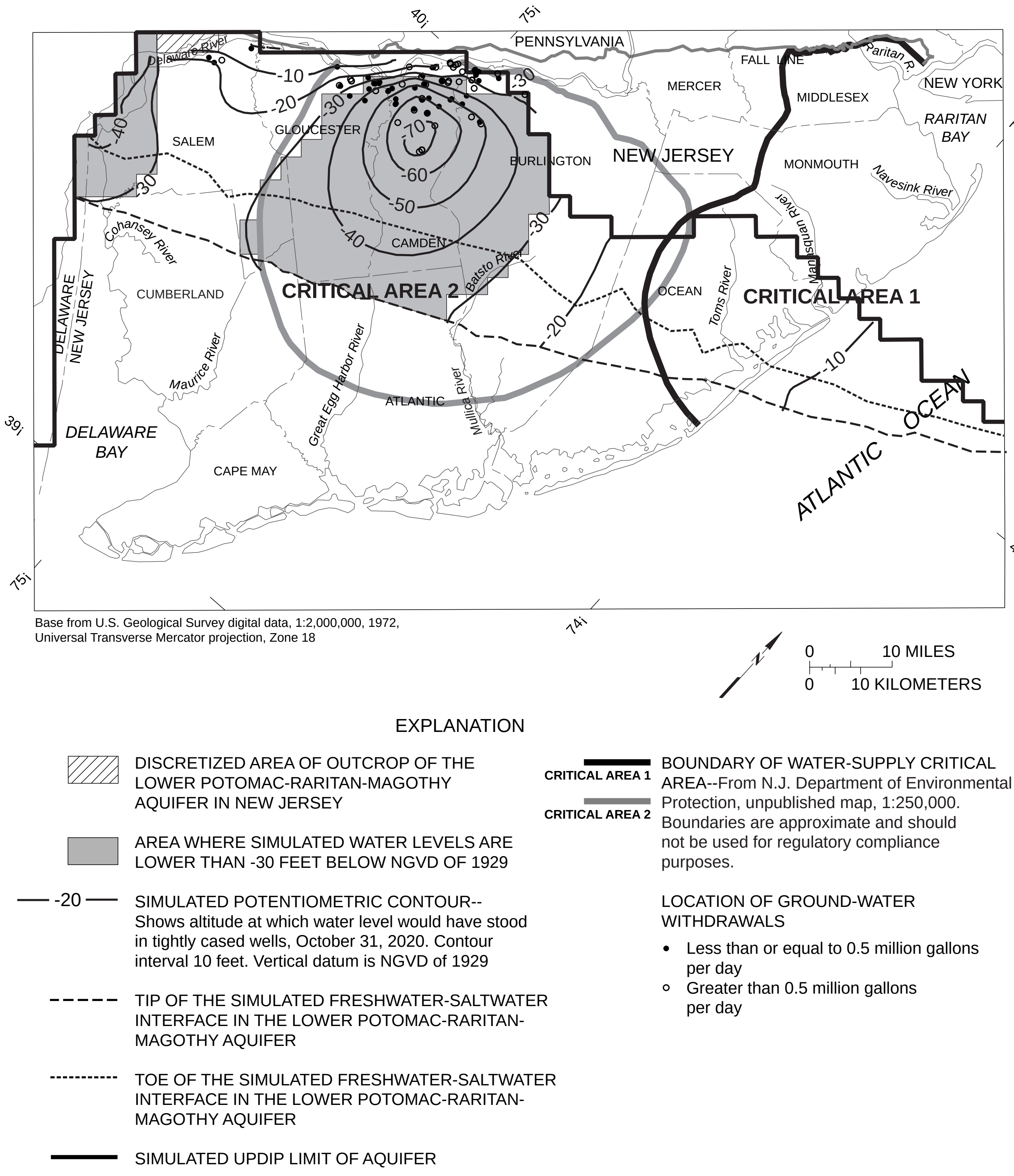
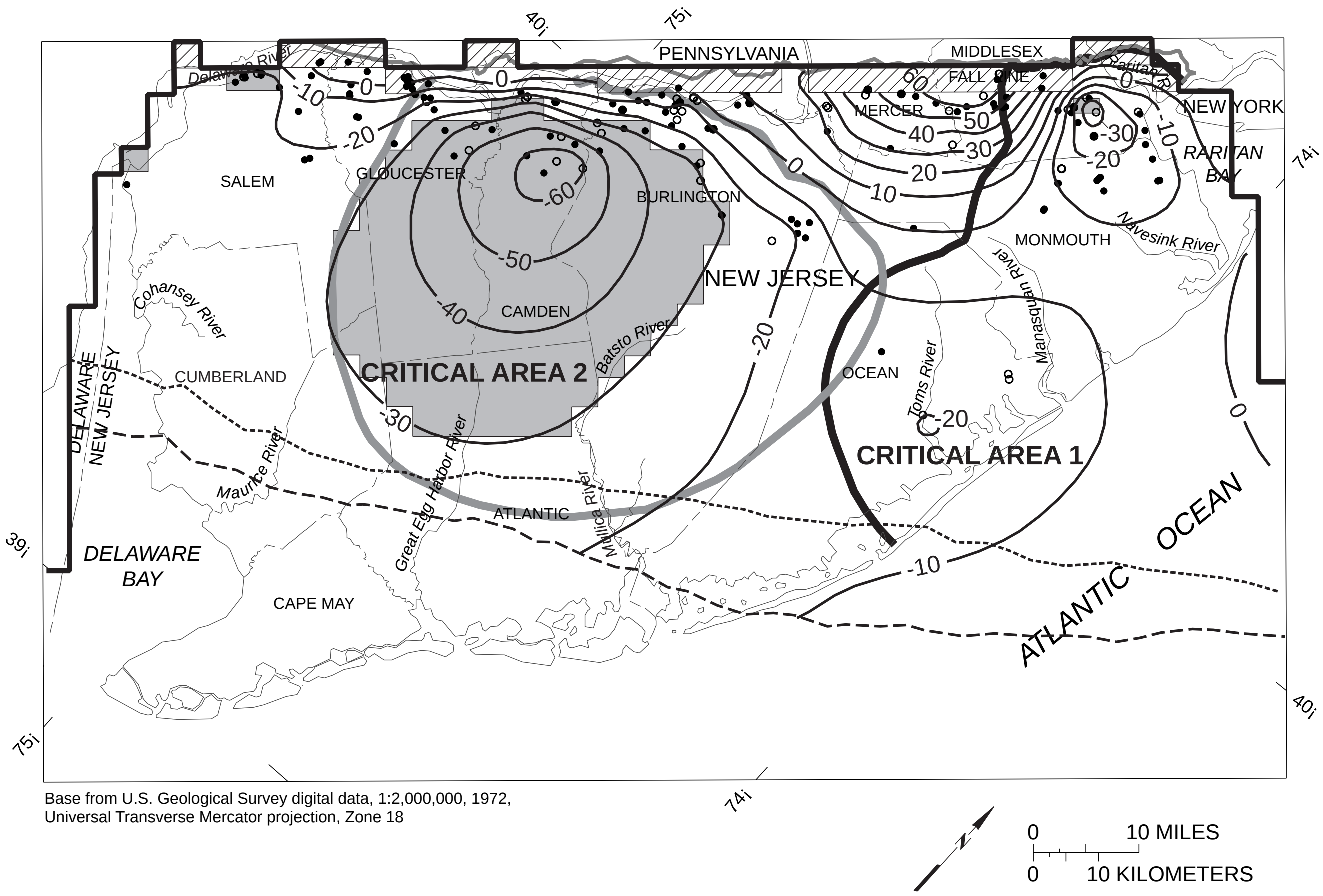



**Figure 31.** Simulated potentiometric surface in the Lower Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1 in overlying aquifers, withdrawal reductions in critical area 2, and hypothetical withdrawals in overlying aquifers (scenario 4), 2020. (Baseline conditions for the Lower Potomac-Raritan-Magothy aquifer shown in fig. 7)




Base from U.S. Geological Survey digital data, 1:2,000,000, 1972,
Universal Transverse Mercator projection, Zone 18

EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, October 31, 2020. Contour interval 10 feet. Vertical datum is NGVD of 1929

TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE MIDDLE POTOMAC-RARITAN-MAGOTHY AQUIFER

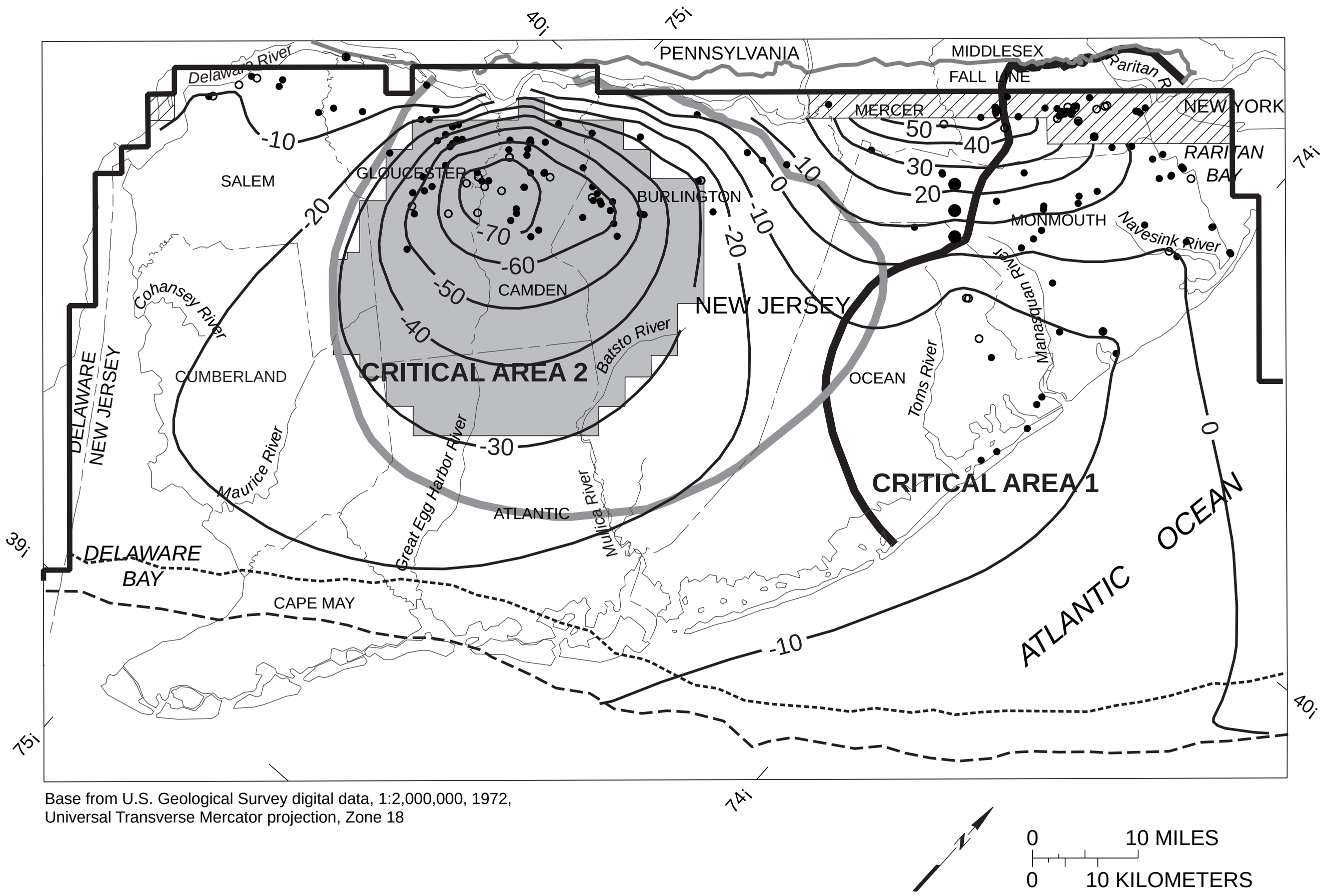
SIMULATED UPDIP LIMIT OF AQUIFER

CRITICAL AREA 1
CRITICAL AREA 2
BOUNDARY OF WATER-SUPPLY CRITICAL AREA--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

LOCATION OF GROUND-WATER WITHDRAWALS

- Less than or equal to 0.5 million gallons per day
- Greater than 0.5 million gallons per day

**Figure 32.** Simulated potentiometric surface in the Middle Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1, withdrawal reductions in critical area 2, and hypothetical withdrawals in overlying aquifers (scenario 4), 2020. (Baseline conditions for the Middle Potomac-Raritan-Magothy aquifer shown in fig. 8)




EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE UPPER POTOMAC-RARITAN-MAGOTHY AQUIFER IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, October 31, 2020. Contour interval 10 feet. Vertical datum is NGVD of 1929

TIP OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE UPPER POTOMAC-RARITAN-MAGOTHY AQUIFER

TOE OF THE SIMULATED FRESHWATER-SALTWATER INTERFACE IN THE UPPER POTOMAC-RARITAN-MAGOTHY AQUIFER

SIMULATED UPDIP LIMIT OF AQUIFER

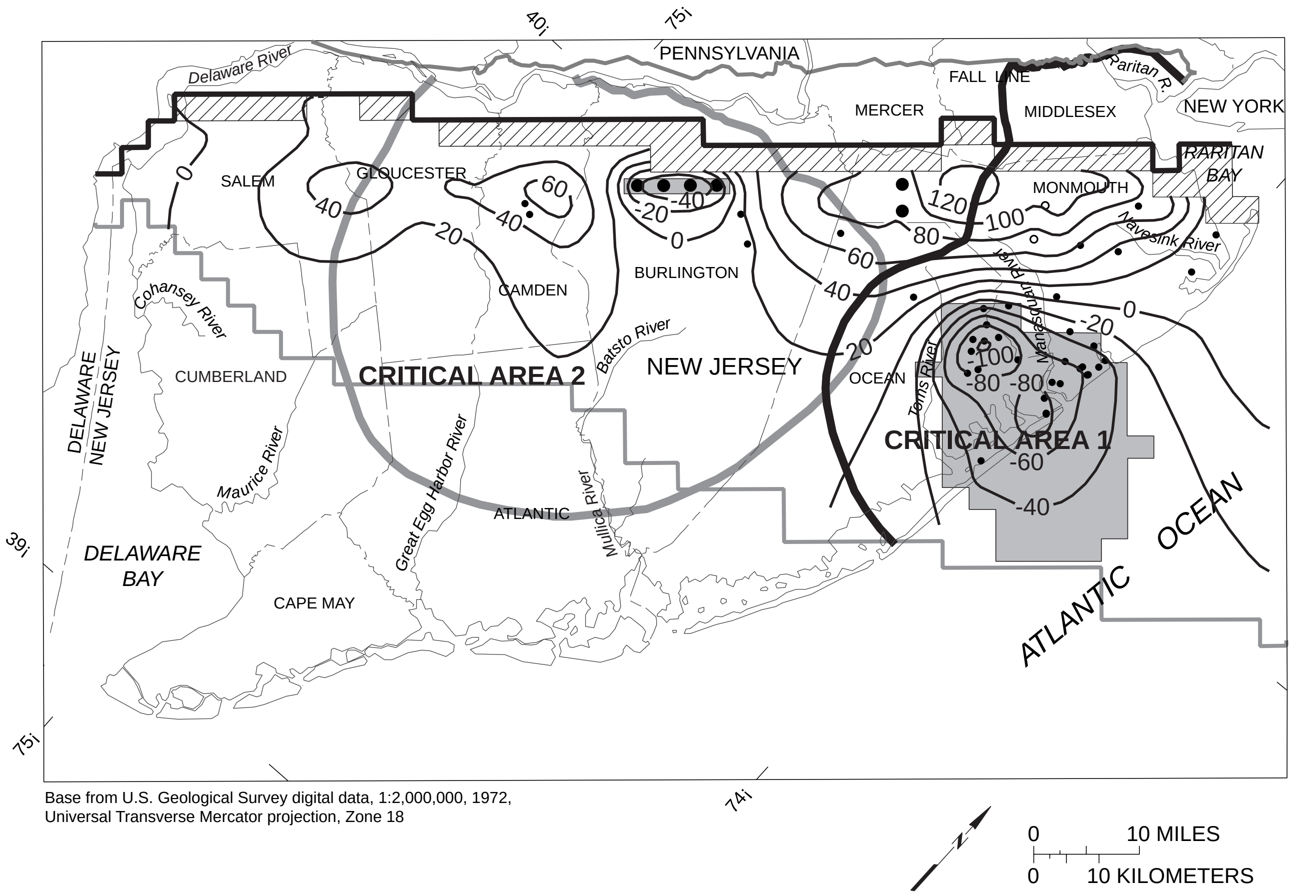
CRITICAL AREA 1
CRITICAL AREA 2
BOUNDARY OF WATER-SUPPLY CRITICAL AREA--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

LOCATION OF GROUND-WATER WITHDRAWALS

- • Less than or equal to 0.5 million gallons per day
- ○ Greater than 0.5 million gallons per day

● LOCATION OF HYPOTHETICAL GROUND-WATER WITHDRAWALS

**Figure 33.** Simulated potentiometric surface in the Upper Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1, withdrawal reductions in critical area 2, and hypothetical withdrawals (scenario 4), 2020. (Baseline conditions for the Upper Potomac-Raritan-Magothy aquifer shown in fig. 9)




EXPLANATION

DISCRETIZED AREA OF OUTCROP OF THE ENGLISHTOWN AQUIFER SYSTEM IN NEW JERSEY

AREA WHERE SIMULATED WATER LEVELS ARE LOWER THAN -30 FEET BELOW NGVD OF 1929

-20 SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, October 31, 2020. Contour interval 20 feet. Vertical datum is NGVD of 1929

SIMULATED UPDIP LIMIT OF AQUIFER

SIMULATED DOWNDIP LIMIT OF AQUIFER

CRITICAL AREA 1
CRITICAL AREA 2
BOUNDARY OF WATER-SUPPLY CRITICAL AREA--From N.J. Department of Environmental Protection, unpublished map, 1:250,000. Boundaries are approximate and should not be used for regulatory compliance purposes.

LOCATION OF GROUND-WATER WITHDRAWALS

- Less than or equal to 0.5 million gallons per day
- Greater than 0.5 million gallons per day

LOCATION OF HYPOTHETICAL GROUND-WATER WITHDRAWALS

**Figure 34.** Simulated potentiometric surface in the Englishtown aquifer system, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1, withdrawal reductions in critical area 2 in underlying aquifers, and hypothetical withdrawals (scenario 4), 2020. (Baseline conditions for the Englishtown aquifer system shown in fig. 10)

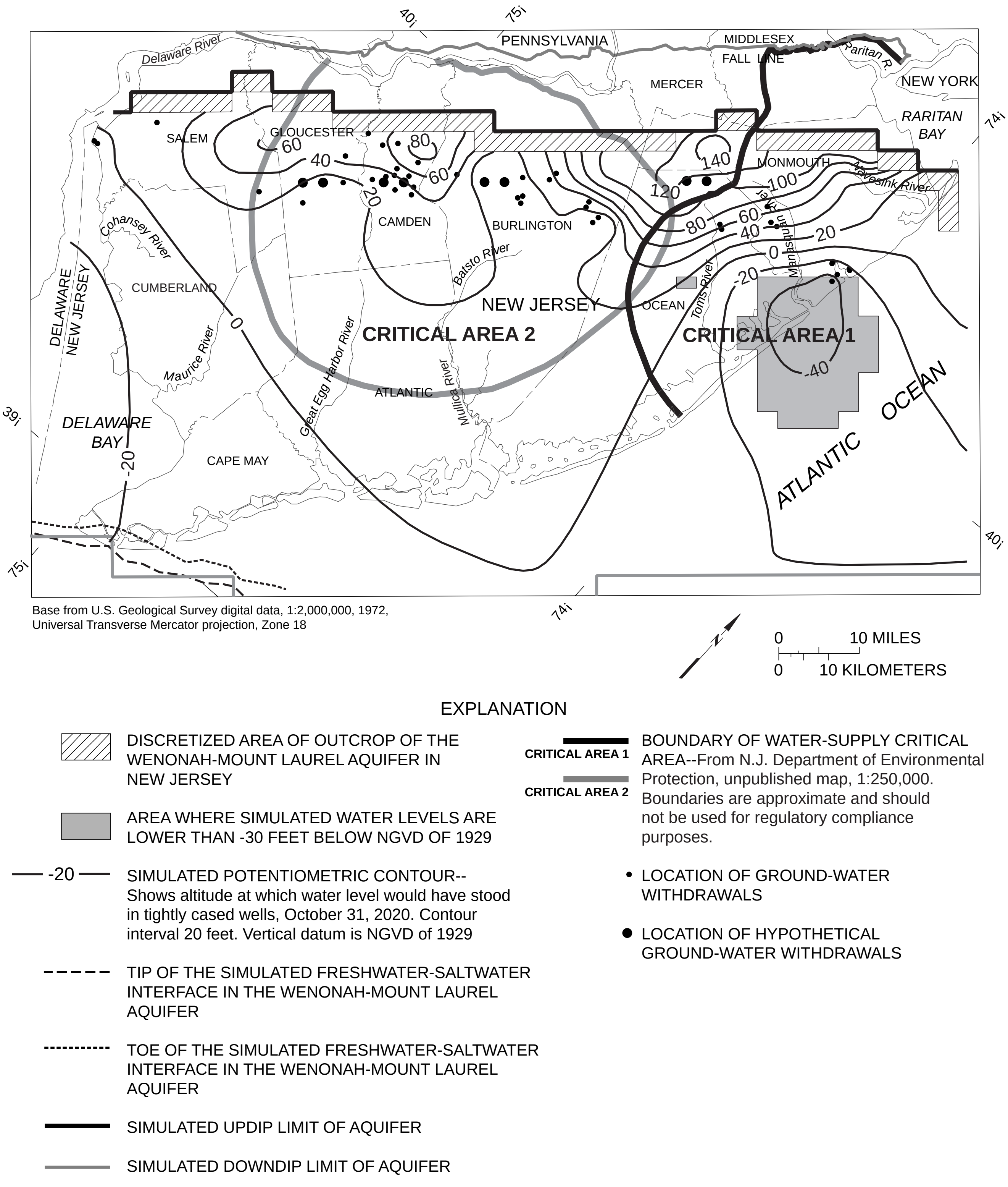



**Figure 35.** Simulated potentiometric surface in the Wenonah-Mount Laurel aquifer, New Jersey Coastal Plain, with baseline conditions modified by withdrawal restrictions in critical area 1, withdrawal reductions in critical area 2 in underlying aquifers, and hypothetical withdrawals (scenario 4), 2020. (Baseline conditions for the Wenonah-Mount Laurel aquifer shown in fig. 11)

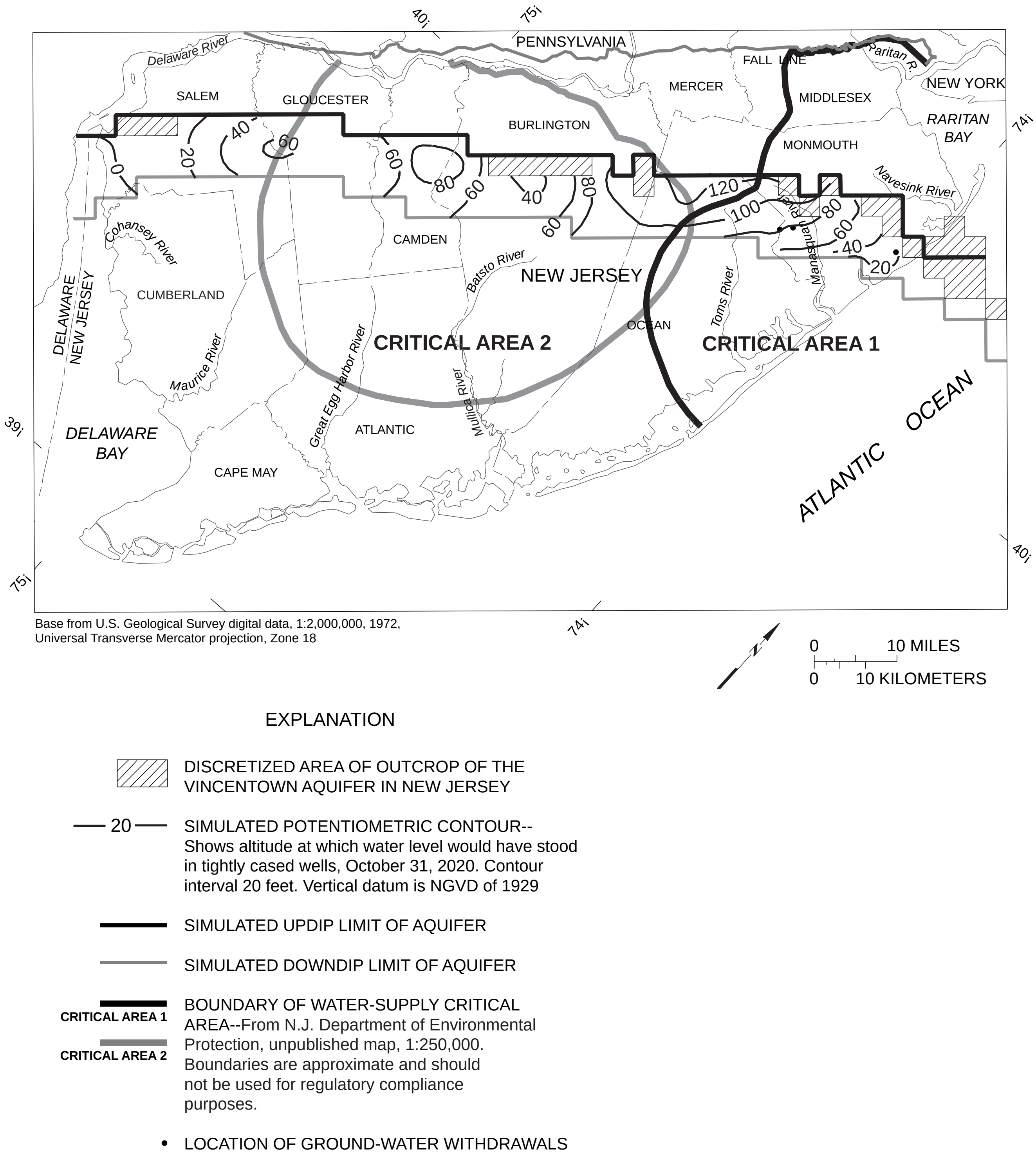



**Figure 36.** Simulated potentiometric surface in the Vincentown aquifer, New Jersey Coastal Plain, with baseline conditions in underlying aquifers modified by withdrawal restrictions in critical area 1, withdrawal reductions in critical area 2, and hypothetical withdrawals (scenario 4), 2020. (Baseline conditions for the Vincentown aquifer shown in fig. 12)

This resulted in a cone of depression with water-level declines of more than 60 ft in the center of the cone when compared with the water levels from scenario 2 (fig. 21). The transmissivity of the Englishtown aquifer system in this area is about 500 $ft^2$/d, which is lower than the transmissivities of other Coastal Plain aquifers (Pope and Gordon, 1999, figs. 1a-8a); however, the Englishtown aquifer system and the overlying Wenonah-Mount Laurel aquifer, which has similar transmissivities, are the primary source of drinking water in some areas of the Coastal Plain. About 0.9 Mgal/d was withdrawn from two hypothetical wells placed in the Englishtown aquifer system in the area outside critical area 1 downdip from the aquifer recharge area in Monmouth County (fig. 34). This resulted in water-level declines of about 20 ft downdip from the wells in Monmouth and northern Ocean Counties and about a 5-ft decline in the vicinity of these wells within the boundary of critical area 1 in northern Ocean County. Farther downdip from the hypothetical wells and within the critical area, the water-level declines were much smaller (1 ft or less). An additional 1.1 Mgal/d was withdrawn from two hypothetical wells in the area outside critical area 1 downdip from the outcrop of the Wenonah-Mount Laurel aquifer in northwestern Ocean County (fig. 35). This resulted in water-level declines of as much as 8 ft outside the critical areas near the wells when compared with the water levels from scenario 2 (fig. 22). An additional 4.8 Mgal/d was withdrawn from the Wenonah-Mount Laurel aquifer. The withdrawals were evenly distributed among six hypothetical wells, two each in Gloucester, Camden, and Burlington Counties (fig. 35). The additional withdrawals decreased water levels by more than 15 ft in Gloucester County, less than 15 ft in areas of Burlington County, and as much as 10 ft in Camden County. More than a 10-ft decline in water levels occurred in the Vincentown aquifer in Burlington and Gloucester Counties (fig. 36) when compared with water levels from scenario 3 (fig. 28), and with water levels in 1992 (fig. 12).

When the flow budget for scenario 4 was compared with the flow budget for scenario 2 (table 4), an additional 11.6 Mgal/d of ground-water withdrawals from the Englishtown aquifer system and Wenonah-Mount Laurel aquifer resulted in an almost 5-percent increase in leakage downward from the overlying Wenonah-Mount Laurel aquifer to the Englishtown aquifer system. Flow from the unconfined part (outcrop) of the Englishtown aquifer system to the confined part of the Englishtown aquifer system increased 6 percent. The additional withdrawals resulted in a 21-percent increase in leakage from the Vincentown aquifer to the underlying aquifers. Simulated water levels for the Piney Point and the confined Kirkwood aquifers are not shown, but water levels in these aquifers are similar to those of scenario 3 shown in figures 29 and 30.

## SUMMARY

Ground-water withdrawals from the confined aquifers in the New Jersey Coastal Plain, which totaled about 200 Mgal/d in 1992, have caused large regional cones of depression to form in several Coastal Plain aquifers near populated areas, particularly in Camden and Monmouth Counties. Because of declining water levels within designated areas of critical water supply (critical areas), withdrawal restrictions were imposed within these areas by the New Jersey Department of Environmental Protection, and alternative surface-water supply sources are being used or considered. The continued decline of water levels in the confined aquifers can cause saltwater intrusion and can threaten the ground-water supply in some areas. As part of the New Jersey statewide water-supply plan, the State of New Jersey was divided into 23 regional water-resource planning areas (RWRPA's) on the basis of surface watersheds. Anticipated growth in water demand for the study area was based on the increase in average water demand projected for 2020 for these RWRPA's. Generally, the increase ranged from 0 to 52.7 percent among the RWRPAs.

A ground-water flow model of the New Jersey Coastal Plain, which simulates freshwater and saltwater flow in eight confined aquifers, was used to simulate transient ground-water flow conditions from 1989 through 1992 using average 1992 withdrawals. The simulated water levels and flow budgets were used as the baseline for comparison with three of four ground-water withdrawal scenarios (scenarios 1 to 3). All withdrawal

scenarios were simulated to predict the effects of increased or decreased withdrawals inside and outside of the critical areas, particularly on water levels and flow budgets.

In scenario 1, flow conditions were simulated with 1992 average withdrawals except for withdrawals from wells in the Potomac-Raritan-Magothy aquifer system within critical area 2, which were reduced by 0 to 35 percent. The total decrease in ground-water withdrawals from 1992 amounts for critical area 2 was 12.6 Mgal/d. Simulated water levels in scenario 1 indicated that water levels rose 20 ft within the cone of depression centered in Camden County in the Lower and Middle Potomac-Raritan-Magothy aquifers and about 30 ft in the Upper Potomac-Raritan-Magothy aquifer within critical area 2.

In scenario 2, projected ground-water withdrawals for 2020 were input to the model. The same withdrawals reductions were imposed in critical area 2 in the Potomac-Raritan-Magothy aquifer system as in scenario 1, and 1992 withdrawals were maintained in critical area 1 in the Middle and Upper Potomac-Raritan-Magothy aquifers, the Englishtown aquifer system and the Wenonah-Mount Laurel aquifer. Withdrawals were increased outside the critical areas to amounts projected for each RWRPA for 2020. The percentage increase differed for each RWRPA located within the New Jersey Coastal Plain. Simulated water levels recovered by 20 ft in critical area 1 near the border of Ocean and Monmouth Counties in the Englishtown aquifer system and Wenonah-Mount Laurel aquifer when withdrawals restrictions were imposed.

In scenario 3, 1992 withdrawals were increased in all RWRPAs at actual withdrawal sites to the amount projected for 2020. This is a total increase of 21 Mgal/d over the 1992 withdrawals from the confined aquifers. The largest percentage increase in projected withdrawals occurred in the RWRPA encompassing Ocean County. Results of the simulation indicate that projected increases in ground-water withdrawals in the Lower, Middle, and Upper Potomac-Raritan-Magothy aquifers, the Englishtown aquifer system, and the Wenonah-Mount Laurel and confined Kirkwood aquifers will cause cones of depression in areas of 1992 withdrawals to deepen and broaden. The projected increase in ground-water withdrawals for 2020 resulted in simulated water-level declines of more than 20 ft at the center of a regional cone of depression in the Englishtown aquifer system in Ocean County because of increases in withdrawals in Ocean and Monmouth Counties. Water levels declined more than 10 ft in the Wenonah-Mount Laurel aquifer downdip from the outcrop area for this aquifer in Gloucester County, and water levels declined 10 ft at the cone of depression in the confined Kirkwood aquifer centered in Atlantic County.

In scenario 4, the same withdrawal considerations were applied as in scenario 2, but withdrawals from 17 hypothetical wells located outside the critical areas in the Upper Potomac-Raritan-Magothy aquifer, Englishtown aquifer system, and Wenonah-Mount Laurel aquifer were added. Simulated water levels declined in the vicinity of the additional withdrawals when compared with the simulated water levels in scenario 2. The maximum declines in water levels occurred when an additional 4.8 Mgal/d was withdrawn from the Englishtown aquifer system in Burlington County; water levels declined by more than 60 ft in the center of a cone of depression. Transmissivities are lower in the Englishtown aquifer system and Wenonah-Mount Laurel aquifer than in the Potomac-Raritan-Magothy aquifer system; however, the Englishtown aquifer system and the Wenonah-Mount Laurel aquifer are the primary source of drinking water in some areas of the Coastal Plain. The additional withdrawals resulted in increased leakage from the overlying Vincentown aquifer to the Wenonah-Mount Laurel aquifer and subsequently to the Englishtown aquifer system.

The simulated freshwater-saltwater interface represents a hypothetical line where the dissolved chloride concentration of the ground water is approximately 10,000 milligrams per liter. In general, the greatest movement of the simulated interface occurred in areas of increased withdrawals, even though the movement was small. When compared with the simulated location of the interface in 1992, maximum movement (about 0.1 mile) of the simulated freshwater-saltwater interface in 2020 (scenario 3) occurred in the downdip area of the

Lower and Middle Potomac-Raritan-Magothy aquifers in Camden County and in the confined Kirkwood aquifer in the Delaware Bay offshore of Cape May County. When withdrawals were increased to the projected 2020 amounts, water levels declined as much as 5 ft in Camden County near the freshwater-saltwater interface in the Lower and Middle Potomac-Raritan-Magothy aquifers when compared with simulated water levels for 1992. Water levels declined by 5 ft near the interface in the confined Kirkwood aquifer in Atlantic County. This decline in water levels signifies changes in the gradient near the interface that could affect the salinity of water in wells updip from the interface. The location of the observed potable-water interface (250-mg/L isochlor), however, is not easily compared to model results. The chloride concentrations in samples from monitoring wells that are (1) downdip from large pumping centers that tap the Lower and Middle Potomac-Raritan-Magothy and confined Kirkwood aquifers and located between the 250-mg/L isochlor and freshwater-saltwater interface, and (2) downdip from pumping centers that tap the Wenonah-Mount Laurel and Piney Point aquifers and located updip of the freshwater-saltwater interface, could be used to quantify the increase in salinity.

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