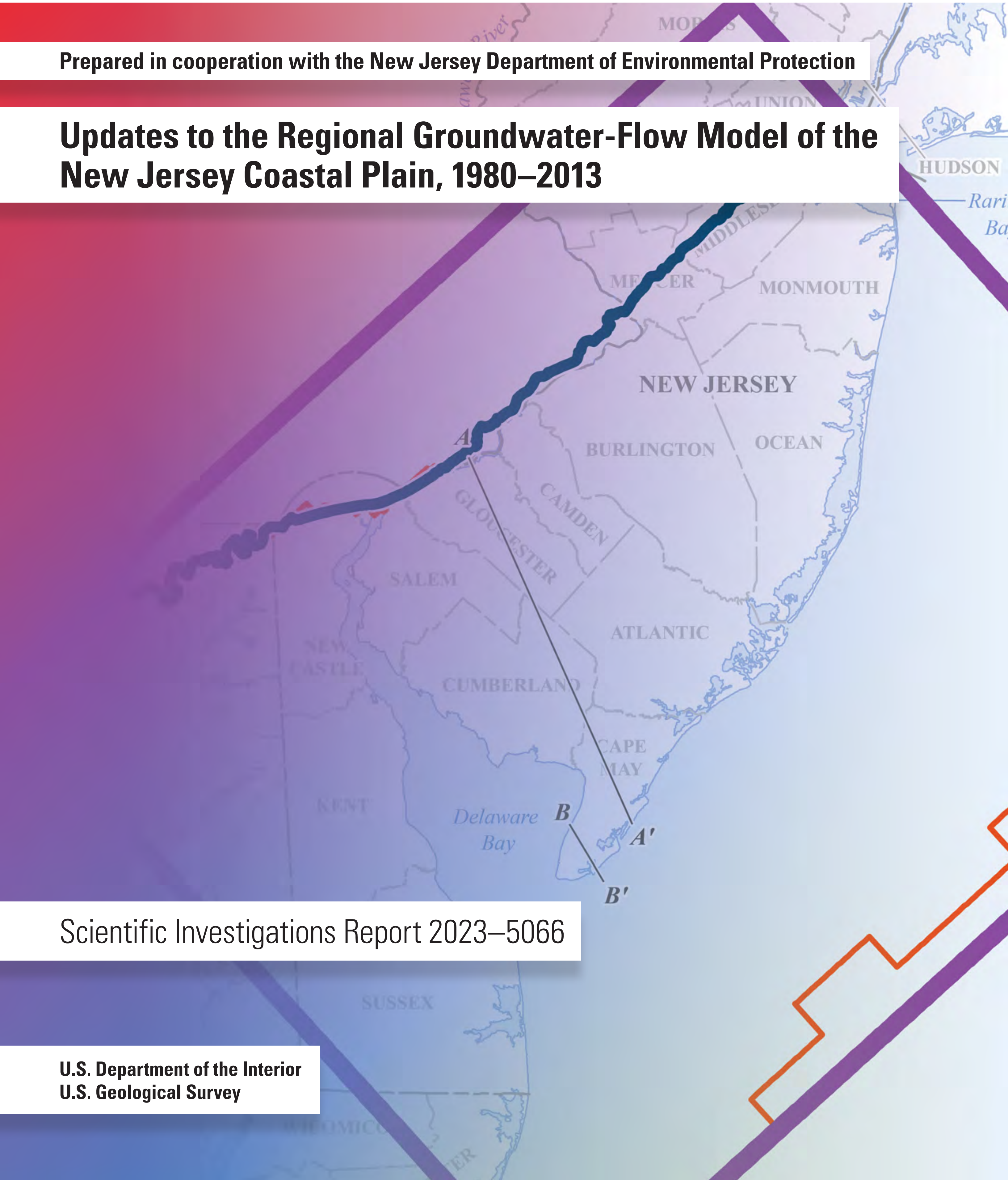
Prepared in cooperation with the New Jersey Department of Environmental Protection

Updates to the Regional Groundwater-Flow Model of the New Jersey Coastal Plain, 1980–2013



Scientific Investigations Report 2023–5066

U.S. Department of the Interior
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Cover. Groundwater is an important resource for water-supply, agricultural, industrial and commercial needs in the New Jersey Coastal Plain. The groundwater-flow model is a representation of the water levels and groundwater flow in the New Jersey Coastal Plain aquifer system and must be updated periodically to maintain its usefulness as a tool for managing water resources and evaluating water-resources-development alternatives because of changing hydrologic stresses, changing water-management needs, and updated knowledge of hydrologic conditions.

Updates to the Regional Groundwater-Flow Model of the New Jersey Coastal Plain, 1980–2013

By Alison D. Gordon and Glen B. Carleton

Prepared in cooperation with the New Jersey Department of Environmental Protection

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U.S. Geological Survey, Reston, Virginia: 2023

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Suggested citation:
Gordon, A.D., and Carleton, G.B., 2023, Updates to the regional groundwater-flow model of the New Jersey Coastal Plain, 1980–2013: U.S. Geological Survey Scientific Investigations Report 2023–5066, 117 p., https://doi.org/10.3133/sir20235066.

Associated data
Carleton, G.B., Gordon, A.D., Kenefic, L.F., Watt, M.K., and Buxton, D.E., 2023, MODFLOW–2005 used to simulate the regional groundwater flow system in the updated New Jersey Coastal Plain model, 1980–2013: U.S. Geological Survey data release, https://doi.org/10.566/P9W6RXFC.

ISSN 2328-0328 (online)

Acknowledgments

This update of a previously published regional groundwater-flow model of the New Jersey Coastal Plain is derived directly from the published work of Mary Martin Chepiga (Martin, 1998) and Lois Voronin (Voronin, 2004) of the U.S. Geological Survey (USGS); the authors are grateful for their insights and their assistance in developing the updated model. Debra Buxton (USGS, retired) completed most of the work to build the three-dimensional hydrogeologic framework for the groundwater-flow model. Liam Kenefic (USGS) assisted with revisions of the framework. Technical reviews of the report and model by Eric Roman (New Jersey Geological and Water Survey) and Leon Kauffman and Paul Misut (USGS) improved the accuracy of the report. The verification by Wesley Zell (USGS) of the model data release accompanying this report is appreciated. The authors also appreciate the additional technical input from members of the New Jersey Geological and Water Survey, particularly Jeffrey Hoffman (New Jersey State Geologist) and Steven Domber.

Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Specific capacity	
gallon per minute per foot ([gal/min]/ft)	0.2070	liter per second per meter ([L/s]/m)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Leakance	
foot per day per foot ([ft/d]/ft)	1	meter per day per meter ([m/d]/m)
inch per year per foot ([in/yr]/ft)	83.33	millimeter per year per meter ([mm/yr]/m)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

AWC	available water capacity
CHD	MODFLOW Time Variant Specified-Head package
DRN	MODFLOW Drain package
mg/L	milligram per liter (parts per million)
GIS	geographic information system
GWSI	Groundwater Site Inventory
NACP	Northern Atlantic Coastal Plain
NAD 83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
NJDEP	New Jersey Department of Environmental Protection
PRM	Potomac-Raritan-Magothy
RASA	Regional Aquifer System Analysis
RIV	MODFLOW River package
SWB	soil-water balance
UCODE	universal inverse modeling computer code
USGS	U.S. Geological Survey
%SEE	percent standard error of estimate

Updates to the Regional Groundwater-Flow Model of the New Jersey Coastal Plain, 1980–2013

By Alison D. Gordon and Glen B. Carleton

Abstract

A 21-layer three-dimensional transient groundwater-flow model of the New Jersey Coastal Plain was developed and calibrated by the U.S. Geological Survey (USGS) in cooperation with the New Jersey Department of Environmental Protection to simulate groundwater-flow conditions during 1980–2013, incorporating average annual groundwater withdrawals and average annual groundwater recharge. This model is the third version of the New Jersey Coastal Plain regional groundwater-flow model that was initially developed as part of the USGS Regional Aquifer System Analysis (RASA) program. The model simulates groundwater flow in 11 aquifers and 10 intervening confining units of the New Jersey Coastal Plain to provide a regional overview of groundwater conditions. Averaged groundwater withdrawal data for 1980 to 2013 were used in the model. The 11 aquifers in New Jersey are, from shallowest to deepest, the Holly Beach water-bearing zone and the confined Cohansey aquifer in Cape May County; the Rio Grande water-bearing zone; the Atlantic City 800-foot sand; the Piney Point, Vincentown, and Wenonah-Mount Laurel aquifers; the Englishtown aquifer system; and the upper, middle, and lower aquifers of the Potomac-Raritan-Magothy (PRM) aquifer system.

The model was developed with the MODFLOW–2005 numerical code and the UCODE parameter estimation technique and calibrated using water-level and base-flow observations. A total of 3,453 water-level observations from 392 wells in New Jersey and 48 wells in Delaware from 1983 to 2013 were used in model calibration, which includes historical water-level trends for 29 wells in New Jersey during 1980–2013 presented in time-series hydrographs. In addition, derived observations also were included by calculating the vertical gradient at 33 pairs of nested observation wells in New Jersey, for a total of 210 observations. Changes in water levels over time were calculated for 134 wells in New Jersey and four wells in Delaware where water levels had varied substantially (approximately 10 ft) over the 30-year span of synoptic water-level measurements, for a total of 767 observations. A total of 1,485 base-flow observations in 47 surface-water basins in New Jersey from 1980 to 2013 were used in model calibration.

Updates to the groundwater-flow model include the conversion to a fully three-dimensional model from the previous quasi-three-dimensional model. The new model will allow for potential future uses such as particle tracking or simulation of variable-density groundwater flow that could not be accomplished with earlier versions of the model. Spatially and temporally variable recharge estimated by using a soil-water balance model resulted in a spatially and temporally finer discretization. The Rio Grande water-bearing zone was added to the model as an aquifer layer to refine estimates of simulated flow in Atlantic and Cape May Counties, New Jersey. Hydrogeologic parameters were updated to include the confining units in New Jersey and corresponding hydrogeologic units in Delaware and eastern Maryland.

The simulated water levels for the New Jersey Coastal Plain aquifers were compared to water-level measurements made during 1980–2013. The average residual for 4,243 water-level observations for New Jersey (simulated water levels minus measured water levels) is 1.5 feet. The simulated water-level contours for the confined aquifers for 2013 were compared to potentiometric surfaces produced from water levels measured during 2013. Simulated water levels generally matched the 2013 potentiometric surfaces of the confined aquifers in the areas of large withdrawals. Hydrographs of wells in the confined Coastal Plain aquifers of New Jersey show that simulated water levels generally match the magnitude and seasonal variation of the observed water levels. Hydrographs of base flow for the 47 streamgaging stations in New Jersey indicate that most of the simulated and estimated data match reasonably well.

Groundwater withdrawals are an important resource for water supply, agricultural, industrial, and commercial needs in the New Jersey Coastal Plain. Groundwater withdrawals from the New Jersey Coastal Plain aquifers have resulted in persistent, regionally extensive cones of depression in the Englishtown aquifer system and Wenonah-Mount Laurel aquifer in Ocean and Monmouth Counties; Wenonah-Mount Laurel and upper, middle, and lower PRM aquifers in Camden County; and Atlantic City 800-foot sand in Atlantic County. Because hydrologic stresses and water-management needs change with time, periodic updates to the groundwater-flow model are required to provide current information about hydrologic conditions in the New Jersey Coastal Plain and to maintain its usefulness as a tool to manage water

resources and develop water-resource strategies. The current updates will support the continued application of this model as a tool for evaluating the regional effects of changes in groundwater withdrawals and of current and potential future water-management strategies on groundwater levels in the New Jersey Coastal Plain.

Introduction

The U.S Geological Survey (USGS) Regional Aquifer System Analysis (RASA) program was begun in 1978 in response to a Congressional mandate to develop quantitative appraisals of the major groundwater systems of the United States (Martin, 1998). The initial New Jersey Coastal Plain groundwater-flow model, constructed by Martin (1998) as part of the New Jersey RASA program, was based on the hydrogeologic framework of the New Jersey Coastal Plain developed by Zapecza (1989). Martin (1998) adapted the hydrogeologic framework presented in Zapecza (1989) for the New Jersey RASA model and represented the Coastal Plain sediments as 10 aquifers and 9 intervening confining units. The RASA model of Martin (1998) was updated by Voronin (2004), who (1) rediscretized the model parameters with a finer cell size, (2) rediscretized stream cells to more accurately represent the streams, (3) used a spatially variable recharge rate based on results of USGS studies conducted in New Jersey since Martin (1998), and (4) updated groundwater-withdrawal data to 1998.

Since its original development, the New Jersey Coastal Plain groundwater-flow model has been used to evaluate the regional effects of groundwater withdrawals on water levels in the confined aquifers in the New Jersey Coastal Plain and as a tool to assess water-management strategies for the region. Studies conducted in New Jersey that have used the model to address water-supply management issues, depletion of streamflow from increased groundwater withdrawals, and continued declining water levels include Navoy (1994), Pope (2006), Watt and Voronin (2006), and Gordon (2007). In some studies (for example, Spitz and others, 2008; Spitz and DePaul, 2008), the regional effect of reducing or increasing groundwater withdrawals on water levels in Water Supply Critical Areas 1 and 2—two areas designated by the New Jersey Department of Environmental Protection (NJDEP) where excessive water use threatens the long-term sustainability of the water supply (fig. 1)—were evaluated. Critical Area 1, designated in 1985, encompasses parts of Middlesex, Monmouth, and Ocean Counties. Regulated aquifers in Critical Area 1 are, in order of increasing depth, the Wenonah-Mount Laurel aquifer, the Englishtown aquifer system, and the upper and middle Potomac-Raritan-Magothy (PRM) aquifers. To improve the management of groundwater resources of the PRM aquifer system in southwestern New Jersey, Critical Area 2 was designated in 1993. This management area encompasses Camden, most of Burlington and Gloucester, and parts of Atlantic, Cumberland, and Salem Counties. Regulated aquifers in Critical Area 2 are, in order of increasing depth, the upper, middle, and lower PRM aquifers.

To maintain the usefulness of the New Jersey Coastal Plain groundwater-flow model as a tool for managing water resources and developing water-resource strategies in light of changing hydrologic conditions, the USGS, in cooperation with the NJDEP, revised the model by updating the hydrogeologic framework, hydraulic parameters, and groundwater withdrawals. The updated hydrogeologic framework includes a three-dimensional framework of the New Jersey Coastal Plain that extends into Delaware and parts of eastern Maryland. These updates may result in (1) refined boundary flows for local models, (2) improved estimates of the simulated interaction between water levels in southwestern New Jersey and withdrawals in Delaware, (3) simulation of the unconfined Kirkwood-Cohansey aquifer system and confined Rio Grande water-bearing zone as model layers, and (4) the ability to conduct particle tracking to determine regional sources of flow and times of travel.

Purpose and Scope

This report describes the development and calibration of a numerical groundwater-flow model of the New Jersey Coastal Plain that extends into Delaware and parts of eastern Maryland. The model simulates transient regional groundwater conditions incorporating annual groundwater withdrawals and recharge from 1980 to 2013 and will be used to assess changes in water levels over the simulated period. The fully three-dimensional flow model described in this report is a 21-layer model that represents 11 aquifers and 10 intervening confining units in the New Jersey Coastal Plain. The groundwater-flow model is based on the USGS New Jersey RASA model (Martin, 1998), which was rediscretized in the late 1990s by Voronin (2004). These two previous quasi-three-dimensional models represented 10 aquifers in the New Jersey Coastal Plain but did not explicitly include the intervening confining units or the Rio Grande water-bearing zone. The confining units were previously represented as leakage by using a vertical leakance parameter. The model simulates the groundwater-flow system in the New Jersey Coastal Plain and offshore sediments that contain water with a chloride concentration less than 10,000 milligrams per liter (mg/L). Model design and input data, boundary conditions, and groundwater withdrawals used in the model calibration are described. The hydrogeologic parameters for each aquifer and confining unit, including the correlated units in Delaware and Maryland, also are discussed. A total of 3,453 annual water-level observations from 392 wells in New Jersey and 48 wells in Delaware from 1983 to 2013 were used in model calibration. Hydrographs of simulated and observed water levels in 29 observation wells and simulated and interpreted potentiometric surfaces for 2013 conditions are shown. Hydrographs of simulated and estimated annual base flows in 47 surface-water basins are presented.

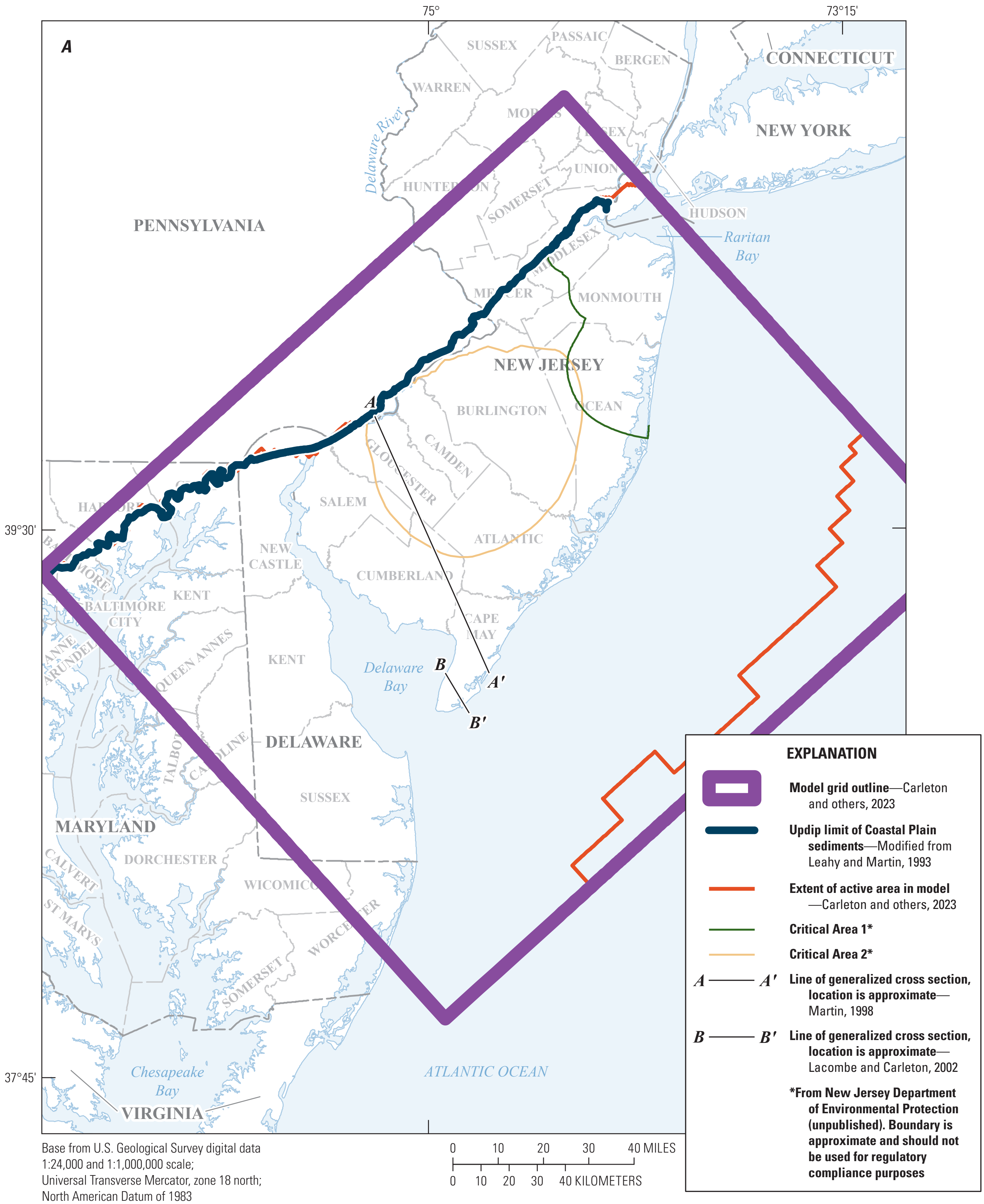
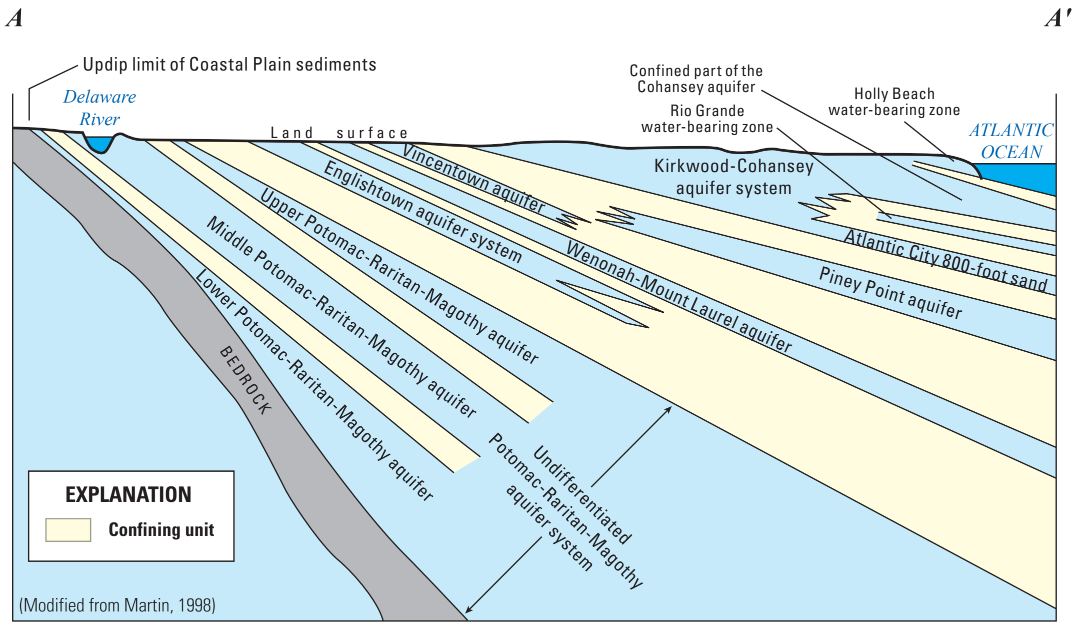


Figure 1. Map showing *A*, location of the study area, *B*, generalized hydrogeologic section *A–A′* through the Coastal Plain of southern New Jersey, and *C*, generalized hydrogeologic section *B–B′* through southern Cape May County, New Jersey.

B



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C

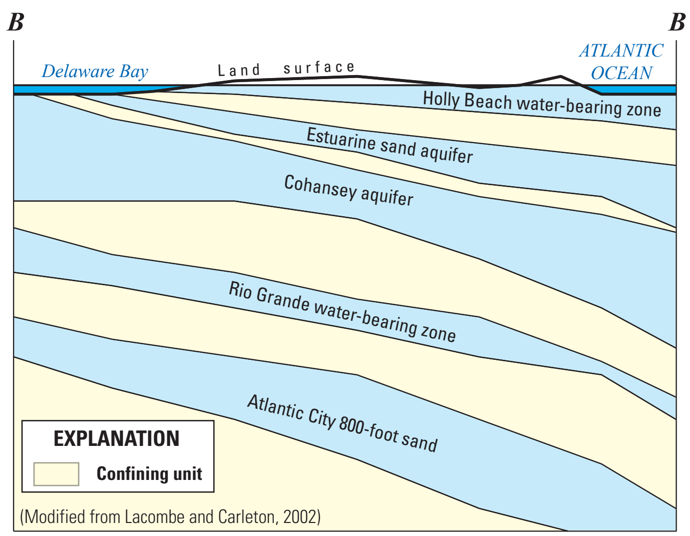

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Figure 1.—Continued

The calibration of the model, conducted by trail-and-error adjustment and by using UCODE (Poeter and others, 2014), is presented. Model parameter sensitivities and limitations are discussed. Estimates of recharge in New Jersey, applied to the groundwater-flow model by using a soil-water balance (SWB) code by Westenbroek and others (2010), is discussed in the appendix. The model archive for the groundwater-flow model described in this report contains the input and output files and the executable file needed to run the model (Carleton and others, 2023). Digital data describing the extents and thicknesses of the units of the updated hydrogeologic framework can be found in Carleton and others (2023).

Location and Extent of the Model Area

The model area encompasses the Coastal Plain Physiographic Province of New Jersey and a small part of southeastern Pennsylvania, and parts of the Coastal Plain in Delaware and eastern Maryland (fig. 1). The model area covers approximately 16,537 square miles (mi^2) and is bounded on the north and northwest by the updip limit of the Coastal Plain sediments (Fall Line), which separates the Coastal Plain sediments from the Piedmont Physiographic Province sediments; on the east and southeast by the Atlantic Ocean; and on the southwest by Delaware Bay, most of Delaware, and part of eastern Maryland. This investigation focused on the Counties of Atlantic, Burlington, Camden, Cape May, Cumberland, Gloucester, Monmouth, Ocean, Salem, and parts of Mercer and Middlesex in New Jersey, and includes New Castle, Kent, and most of Sussex Counties in Delaware and parts of Cecil, Kent, Queen Anne's, Caroline, Wicomico, and Worcester Counties in Maryland. Topography in New Jersey is relatively flat; altitudes range from sea level along estuaries, bays, and the Atlantic Ocean to nearly 400 feet (ft) in northeastern Monmouth County, New Jersey.

Previous Investigations

Martin (1998), Pope and Gordon (1999), and Voronin (2004) describe simulated groundwater flow in the New Jersey Coastal Plain from a regional perspective. These three studies, along with other studies describing regional simulated flow in the New Jersey Coastal Plain or the North Atlantic Coastal Plain, are listed in table 1. Table 1 also includes regional studies completed in Critical Areas 1 and 2 and in the Atlantic City area of the New Jersey Coastal Plain.

In addition to the previous regional simulation studies listed in table 1, the rediscretized RASA model of the New Jersey Coastal Plain (Voronin, 2004) was used by Pope (2006) to simulate the effects of increased withdrawals from the Atlantic City 800-foot sand on water levels, by Watt and Voronin (2006) to simulate sources of water to wells in the Wenonah-Mount Laurel aquifer, and by Gordon (2007) to produce water budgets for confined aquifers in the New Jersey Coastal Plain under various withdrawal scenarios.

Eight synoptic water-level studies of the confined aquifers of the New Jersey Coastal Plain document water-level data and potentiometric-surface maps for those aquifers. Potentiometric-surface maps in these reports show water levels in the Coastal Plain at 5-year intervals from 1978 through 2013: 1978, Walker (1983); 1983, Eckel and Walker (1986); 1988, Rosman and others (1995); 1993 and 1998, Lacombe and Rosman (1997 and 2001, respectively); 2003, DePaul and others (2009); 2008, DePaul and Rosman (2015); and 2013, Gordon and others (2021).

Conceptual Hydrogeologic Model

The hydrogeologic framework of the New Jersey Coastal Plain is based on the hydrogeologic framework presented in Zapecza (1989). The framework consists of a southeastward-dipping and -thickening wedge of unconsolidated deposits of sand, silt, and clay of Cretaceous to Neogene age underlain by basement rocks and overlain by locally occurring Quaternary sediments (fig. 1). Coastal Plain sediments were deposited in various shelf, marginal marine, nearshore or coastal beach, and deltaic environments, the extent of which fluctuated in response to changes in sea level. Units composed of substantially less permeable sediments (predominantly clays and fine-grained silts) form the confining units, and coarser, more permeable sand and gravel units, which readily produce water, form the aquifers. These deposits are less than 50 ft thick along the updip limit of the Coastal Plain sediments (Fall Line) in New Jersey and thicken to more than 6,500 ft in southern Cape May County. Coastal Plain sediments generally strike northeast-southwest and dip gently from 10 to 60 feet per mile to the southeast (Zapecza, 1989); overlying Quaternary deposits are flat. The sediments composing the New Jersey Coastal Plain aquifers and confining units generally crop out near the Fall Line parallel to strike; the aquifer units generally transition into confined aquifers, except the Piney Point aquifer, which is confined throughout the study area. The aquifers and confining units in the New Jersey Coastal Plain range in age from Cretaceous to Quaternary (fig. 2).

Figure 1 is a generalized hydrogeologic cross section through the New Jersey Coastal Plain; aquifers and confining units are shown in figure 2, which also shows the correlation of the corresponding units in Maryland and Delaware with those in New Jersey. Detailed discussions in Zapecza (1989) and Sugarman and others (2005) describe the hydrogeology of New Jersey; Vroblesky and Fleck (1991) describe the hydrogeology of Delaware; and Andreasen and others (2013) describe the hydrogeology of Maryland. In addition, the hydrogeology of Delaware, Maryland, and New Jersey is described in Trapp and Meisler (1992) and Masterson and others (2015).

Martin (1998) and Voronin (2004) adapted the hydrogeologic framework in Zapecza (1989) for use in the New Jersey RASA model and represented the Coastal Plain

Table 1. Previous regional simulation studies conducted for the New Jersey Coastal Plain and Northern Atlantic Coastal Plain.

[Northern Atlantic Coastal Plain includes Delaware and parts of Maryland, New Jersey, New York, North Carolina, and Virginia; Water Supply Critical Area 1 includes parts of Middlesex, Monmouth, and Ocean Counties in New Jersey; Water Supply Critical Area 2 includes Camden and parts of Atlantic, Burlington, Cumberland, Gloucester, Ocean and Salem Counties in New Jersey]

Area of study	Simulated aquifers	Report name	Reference
Northern Atlantic Coastal Plain	Ten regional North Atlantic Coastal Plain aquifers	Geohydrology and simulation of ground-water flow in the Northern Atlantic Coastal Plain aquifer system	Leahy and Martin, 1993.
Water Supply Critical Area 1 in New Jersey	Upper and middle Potomac-Raritan-Magothy aquifers, Englishtown aquifer system, and Wenonah-Mount Laurel aquifer	Hydrogeology, simulation of regional ground-water flow, and saltwater intrusion, Potomac-Raritan-Magothy aquifer system, northern Coastal Plain of New Jersey	Pucci and others, 1994.
Water Supply Critical Area 2 in New Jersey	Upper, middle, and lower Potomac-Raritan-Magothy aquifers	Ground-water flow and future conditions in the Potomac-Raritan-Magothy Aquifer system, Camden area, New Jersey	Navoy and Carleton, 1995.
New Jersey Coastal Plain	Ten regional New Jersey Coastal Plain aquifers	Ground-water flow in the New Jersey Coastal Plain	Martin, 1998.
New Jersey Coastal Plain	Ten regional New Jersey Coastal Plain aquifers	Simulation of groundwater flow and movement of the freshwater-saltwater interface in the New Jersey Coastal Plain	Pope and Gordon, 1999.
Cape May and parts of Atlantic and Ocean Counties in New Jersey	Atlantic City 800-foot sand	Ground-water flow and quality in the Atlantic City 800-foot sand, New Jersey	McAuley and others, 2001.
New Jersey Coastal Plain	Ten regional New Jersey Coastal Plain aquifers	Documentation of revisions to the Regional Aquifer System Analysis model of the New Jersey Coastal Plain	Voronin, 2004.
Water Supply Critical Area 2 in New Jersey	Upper, middle, and lower Potomac-Raritan-Magothy aquifers	Recovery of ground-water levels from 1988 to 2003 and analysis of 2003 and full-allocation withdrawals in Critical Area 2, Southern New Jersey	Spitz and DePaul, 2008.
Water Supply Critical Area 1 in New Jersey	Upper and middle Potomac-Raritan-Magothy aquifers, Englishtown aquifer system, and Wenonah-Mount Laurel aquifer	Recovery of ground-water levels from 1988 to 2003 and analysis of potential water-supply management options in Critical Area 1, east-central New Jersey	Spitz and others, 2008.
Salem and Gloucester Counties in New Jersey	Upper, middle and lower Potomac-Raritan-Magothy aquifers, and Englishtown aquifer system	Simulated effects of allocated and projected 2025 withdrawals from the Potomac-Raritan-Magothy aquifer system, Gloucester and northeastern Salem Counties, New Jersey	Charles and others, 2011.
Atlantic, Burlington, Gloucester, Camden, Ocean, and Cape May Counties in New Jersey	Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, and Atlantic City 800-foot sand	Simulated effects of alternative withdrawal strategies on groundwater flow in the Kirkwood-Cohansey aquifer system, the Rio Grande water-bearing zone, and the Atlantic City 800-foot sand in the Great Egg Harbor and Mullica River Basins, New Jersey	Pope and others, 2012.
Ocean and southern Monmouth Counties in New Jersey	Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, Atlantic City 800-foot sand, Piney Point and Vincentown aquifers	Simulated effects of groundwater withdrawals from aquifers in Ocean County and vicinity, New Jersey	Cauller and others, 2016.
Northern Atlantic Coastal Plain	19 regional North Atlantic Coastal Plain aquifers	Documentation of a groundwater flow model developed to assess groundwater availability in the Northern Atlantic Coastal Plain aquifer system from Long Island, New York, to North Carolina	Masterson and others, 2016a.

System	New Jersey	Delaware	Maryland	North Atlantic Coastal Plain model
Quaternary	Holly Beach water-bearing zone (L1)	Surficial aquifer	Surficial aquifer	Surficial aquifer
	Holly Beach confining unit (L2)	Upper Chesapeake confining unit	Upper Chesapeake confining unit	Upper Chesapeake confining unit
Tertiary	Estuarine sand aquifer/ Unconfined Kirkwood-Cohansey aquifer system (updip) (L3) Confined Cohansey aquifer (downdip) (L3)	Upper Chesapeake aquifer	Pocomoke and Manokin aquifers	Upper Chesapeake aquifer
	confining unit (L4)	St. Mary's confining unit	St Mary's confining unit	Lower Chesapeake confining unit
	Unit absent updip Rio Grande water-bearing zone (downdip) (L5)	Lower Chesapeake aquifer	Choptank aquifer	Lower Chesapeake aquifer
	confining unit (L6)	Lower Chesapeake confining unit	Lower Chesapeake confining unit	
	Unit absent updip Atlantic City 800-foot sand (downdip) (L7)	Calvert aquifer system	Calvert aquifer system	
	Basal Kirkwood confining unit (L8)	Calvert confining unit	Calvert confining unit	Calvert confining unit
	Piney Point aquifer (L9)	Piney Point aquifer	Piney Point aquifer	Piney Point aquifer
	Manasquan-Shark River confining unit (L10)	Nanjemoy-Marlboro confining unit	Nanjemoy confining unit	Nanjemoy-Marlboro confining unit
	Vincentown aquifer (updip) (L11) Unit absent downdip	Rancocas aquifer	Aquia aquifer	Aquia aquifer
Cretaceous	Navesink-Hornerstown confining unit (L12)	Severn confining unit	Severn confining unit	Monmouth-Mount Laurel confining unit
	Wenonah-Mount Laurel aquifer (L13)	Mount Laurel aquifer	Monmouth aquifer	Monmouth-Mount Laurel
	Marshalltown–Wenonah confining unit (L14)	Matawan confining unit	Matawan confining unit	Matawan confining unit
	Englishtown aquifer system (L15)	Matawan aquifer	Matawan aquifer	Matawan aquifer
	Merchantville Woodbury confining unit (L16)	Matawan confining unit	Matawan-Magothy confining unit	Magothy confining unit
	upper Potomac-Raritan-Magothy aquifer (L17)	Magothy aquifer	Magothy aquifer	Magothy aquifer
	confining unit (L18)	Magothy-Patapsco confining unit	Magothy-Patapsco confining unit	Potomac confining unit
	middle Potomac-Raritan-Magothy aquifer (L19)	Potomac-Patapsco aquifer	Patapsco aquifer system	Potomac-Patapsco aquifer
	confining unit (L20)	Potomac confining unit	Potomac-Patapsco confining unit	Potomac-Patapsco confining unit
	lower Potomac-Raritan-Magothy aquifer (L21)	Potomac-Patuxent aquifer	Patuxent aquifer system	Potomac-Patuxent aquifer

Figure 2. Hydrogeologic units for the New Jersey Coastal Plain, and the correlated hydrogeologic units in the New Jersey Coastal Plain groundwater-flow model of the Delaware and Maryland Coastal Plain and the regional hydrogeologic units in the North Atlantic Coastal Plain aquifer system. Unit names for New Jersey are from modified from Zapecza (1989). Unit names for Delaware are modified from Vroblesky and Fleck, (1991) and Masterson and others (2016b). Unit names for Maryland are modified from Andreasen and others (2013) and from Masterson and others (2016b). Units in Maryland are not the primary focus of this report. Unit names in the North Atlantic Coastal Plain groundwater-flow model are from Masterson and others (2016b). Letter and number in parentheses (for example, L1) in the New Jersey column is the model-layer designation in New Jersey, Delaware, and Maryland.

sediments as 10 major aquifers and 9 intervening confining units. In the RASA groundwater-flow models of Martin (1998) and Voronin (2004), the Atlantic City 800-foot sand and the Rio Grande water-bearing zone were simulated by using one aquifer layer. The downdip area of this model layer was referred to by Martin (1998) as the confined Kirkwood aquifer; the updip area of the model layer represents the lower part of the unconfined Kirkwood-Cohansey aquifer system. The model layer above the lower part of the unconfined Kirkwood-Cohansey aquifer system and the confined Kirkwood aquifer represents the unconfined upper Kirkwood-Cohansey aquifer system. Martin (1998) states that the Kirkwood-Cohansey aquifer system was subdivided into an upper and lower aquifer in updip areas to more accurately represent the vertical head distribution in the unconfined aquifer system and to provide a lateral connection between the confined Kirkwood aquifer and the lower Kirkwood-Cohansey aquifer. This framework also was used in the rediscretized RASA model of Voronin (2004).

The updated model described in this report represents aquifers and intervening confining units with a hydrogeologic framework of 21 layers—11 aquifers and 10 confining units. This representation includes the 10 aquifers simulated by Martin (1998) and Voronin (2004) as well as the Rio Grande water-bearing zone, which is represented as a separate aquifer layer to more accurately estimate flow in Atlantic and Cape May Counties, where this aquifer is used as a source of water. Each aquifer layer is represented in the fully three-dimensional groundwater-flow model by specifying its hydraulic parameters; confining units are simulated as layers by specifying their hydraulic parameters.

Only the freshwater parts of the aquifer (where the chloride concentration is less than 10,000 milligrams per liter (mg/L) are represented in this study. The locations of the 10,000-mg/L isochlors for selected aquifers in the New Jersey were obtained from simulation results from the New Jersey Coastal Plain SHARP (Essaid, 1990) model (Pope and Gordon, 1999). SHARP, a quasi-three-dimensional finite-difference model that can simulate freshwater and saltwater flow, was used by Pope and Gordon (1999) to simulate the groundwater-flow system in the New Jersey Coastal Plain, including the location and movement of the freshwater-saltwater interface. The simulated freshwater-saltwater interface was used to define the downdip limit of those aquifers and adjacent confining units where a downdip limit is not defined and is discussed further in the section on boundary conditions. The locations of the 10,000-mg/L isochlors for aquifers in Maryland and Delaware were determined from data published in Meisler (1989), Vroblesky and Fleck (1991), and Trapp and Meisler (1992).

Aquifer and Confining-Unit Characteristics

Below is a brief description of the hydrogeologic properties of the 21 model layers, including the corresponding units in Delaware and Maryland. Additional data on the hydraulic properties of the aquifers and confining units in the New Jersey Coastal Plain are summarized in Martin (1998). The hydrologic properties of the units in Maryland and Delaware were obtained primarily from the Maryland Geologic Survey (Andreasen and others, 2013) and also Masterson and others (2016a).

Estimates of hydraulic conductivity were also made for 3,621 wells in the New Jersey Coastal Plain from results of specific-capacity tests conducted with pumping rates of 250 gallons per minute (gal/min) for a minimum of 8 hours. These data are stored in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2017). The transmissivity of the aquifer in the vicinity of these wells was estimated from specific-capacity data by using the Theis equation as presented in Heath (1983). The hydraulic conductivity for an aquifer at a well location was estimated from the calculated transmissivity value determined by using the length of the screened interval. The range of horizontal hydraulic conductivity estimated for the aquifers is summarized in table 2 and the well locations are shown in figure 3.

Table 2. Horizontal hydraulic conductivities estimated from specific-capacity data for wells in selected aquifers in the New Jersey Coastal Plain.

[ft/d, feet per day; PRM, Potomac-Raritan-Magothy]

Aquifer	Specific-capacity tests[1]			
	Model layer	Number of wells	Range of estimated horizontal hydraulic conductivity[2] (ft/d)	Average estimated hydraulic conductivity (ft/d)
Holly Beach water-bearing zone	1	14	21–104	57
Kirkwood-Cohansey aquifer system	3	1,791	1–1,817	110
Rio Grande water-bearing zone	5	3	17–47	32
Atlantic City 800-foot sand	7	94	5–178	50
Piney Point	9	52	1–1,135	43
Vincentown	11	42	3–220	33
Wenonah-Mount Laurel	13	211	1–733	36
Englishtown aquifer system	15	181	2–249	26
upper PRM	17	517	1–776	102
middle PRM	19	514	4–1,926	119
lower PRM	21	202	6–1,114	137

[1]U.S. Geological Survey (2017)

[2]Hydraulic conductivity for a well was estimated from specific-capacity data by using the equation in Heath (1983) which was used to calculate the transmissivity of the aquifer in the vicinity of the well. The transmissivity was then divided by the length of the screened interval of the well to yield the hydraulic conductivity. These data are stored in the U.S. Geological Survey National Water Information System (NWIS) database (U.S. Geological Survey, 2017).

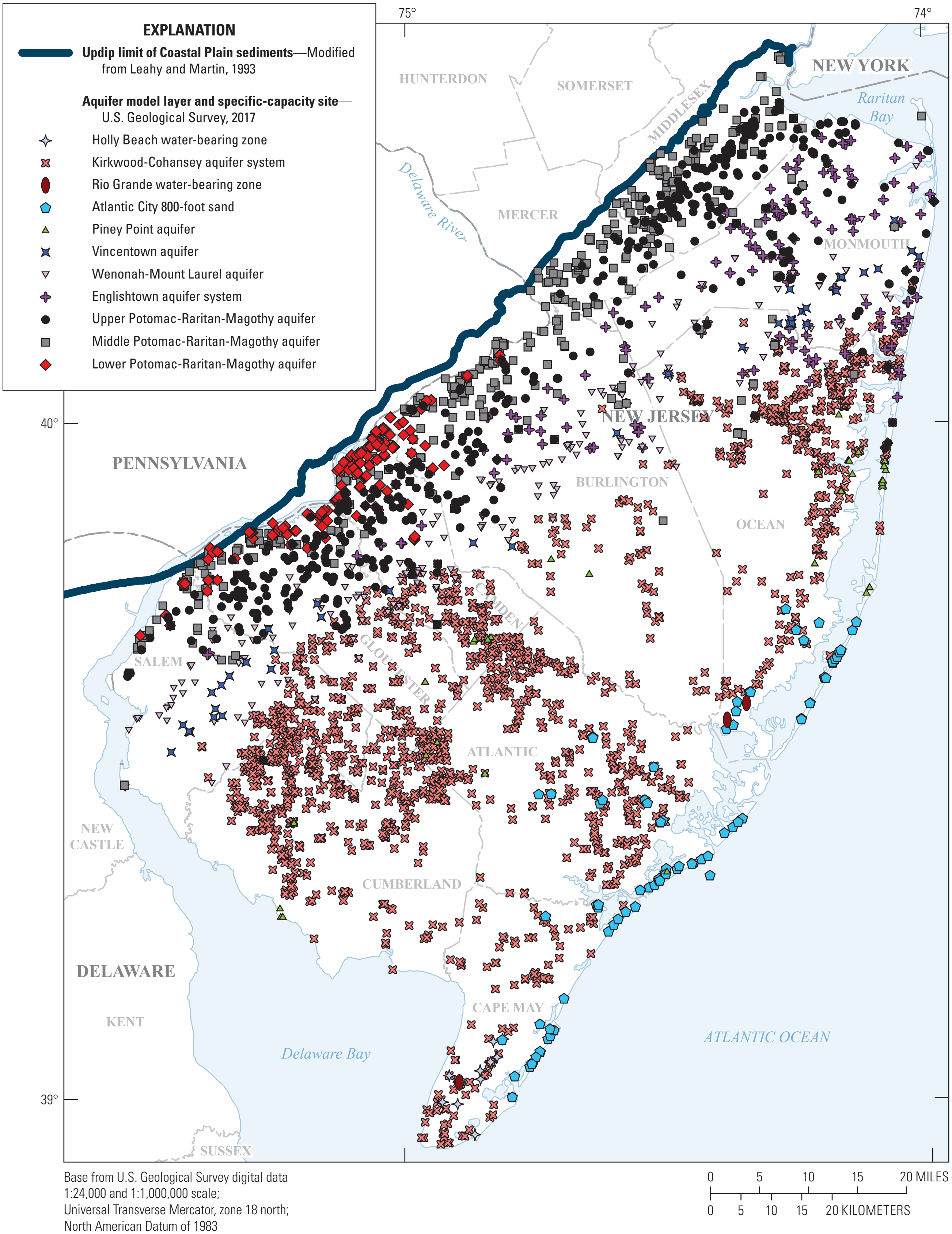


Figure 3. Map showing location of sites of specific-capacity tests, New Jersey Coastal Plain.

Horizontal hydraulic conductivity can vary spatially for each aquifer (fig. 3). Table 2 indicates the order-of-magnitude variability observed in the range of horizontal hydraulic conductivity for some aquifers. Ranges of horizontal hydraulic conductivity values for 11 aquifers in the New Jersey Coastal Plain (table 2) indicate that hydraulic conductivities are greatest at wells screened in the Kirkwood-Cohansey aquifer system and the upper, middle and lower Potomac-Raritan-Magothy aquifers. In addition to the specific-capacity data, the horizontal hydraulic conductivities of the aquifers, vertical hydraulic conductivities of the confining units, and aquifer storage coefficients from selected previously published groundwater-flow models of the New Jersey Coastal Plain are summarized in table 3.

Data on the hydraulic properties of confining units within the modeled area in New Jersey are limited, and most estimates of these hydraulic properties are primarily from the groundwater-flow-model studies listed in table 3. Data on the hydraulic properties of hydrogeologic units within the model area in Delaware and counties in eastern Maryland also are limited and are summarized in table 4. Data presented in table 4 are compiled from the literature of previous estimates of the hydraulic properties of aquifers and confining units within the Delaware and Maryland Coastal Plain and from Andreasen and others, 2013.

Simulation of Groundwater Flow

Groundwater flow in the New Jersey Coastal Plain was simulated under transient conditions for the period 1980–2013. In this section, the previous versions of the New Jersey Coastal Plain models are described briefly, and the development of the three-dimensional groundwater-flow model, model calibration, simulation of groundwater flow, the sensitivity of model parameters to water levels and base flows, and model limitations are discussed.

Groundwater-Flow System

Groundwater flow in the New Jersey Coastal Plain is controlled by topography, the hydraulic properties of the sediments, and hydrologic stresses. Flow within the aquifers is predominantly horizontal, although some vertical flow exists. Hydraulic gradients in the confining units generally are vertical because the horizontal hydraulic conductivity is orders of magnitude less than that in the aquifers. The major source of recharge to the aquifers of the New Jersey Coastal Plain is infiltration of precipitation, although leakage from surface-water bodies, lateral flow from adjacent areas, and in confined aquifers, flow from downdip areas also occurs. Most of the groundwater recharge is discharged to nearby surface-water bodies; a smaller amount infiltrates through confining units to recharge the underlying confined aquifers. In addition to the water that discharges from the aquifers to surface-water bodies (streams that flow to the ocean and bays), some groundwater discharges directly to saltwater bodies as submarine groundwater discharge, or is removed by groundwater evapotranspiration, withdrawals from wells, and lateral flow to adjacent areas. Discharge areas in the New Jersey Coastal Plain include the Atlantic Ocean, Raritan Bay, Delaware River, Delaware Bay, and streams. Because groundwater withdrawals in some areas of the New Jersey Coastal Plain are substantial, large cones of depression developed in several aquifers, and recharge and discharge locations shifted. These changes in regional groundwater-flow patterns were investigated in the eight water-level synoptic studies completed for the New Jersey Coastal Plain in cooperation with the NJDEP and are listed in the “Previous Investigations” section of this report.

Design of Previous Models of the New Jersey Coastal Plain

The New Jersey RASA model (Martin, 1998) was developed in the 1980s from a modified version of the Trescott model code (Trescott, 1975). The grid spacing ranges from 6.25 to 9.375 mi^2 in onshore areas to 47.5 mi^2 in offshore areas. The model used a constant recharge rate of 20 inches per year (in/yr) and withdrawals averaged over time at pumping intervals from 1896–1980. The model was rediscretized in the 1990s (Voronin, 2004) with a smaller grid spacing, recharge based on water-budget equations that used base flow estimated from hydrograph separation of streamflow data for several surface-water basins in of the New Jersey Coastal Plain, and updated withdrawals to 1998, and was run in MODFLOW–96 (Harbaugh and McDonald, 1996). The grid spacing ranged from 0.25 to 0.31 mi^2 in onshore areas to 3.16 mi^2 in offshore areas. Martin (1998) and Voronin (2004) modeled the aquifers of the New Jersey Coastal Plain using a quasi-three-dimensional representation of the aquifers that represented the confining units by using a vertical leakance parameter (vertical hydraulic conductivity divided by thickness). Voronin (2004) simulated the aquifer system using a 10-layer model and simulated streams using the drain (DRN) and river (RIV) packages of MODFLOW–96 (Harbaugh and McDonald, 1996). Martin (1998) simulated the aquifer system and streams by using an 11-layer model in which the top layer was a constant-head layer that represented the streams. The major differences between the two previous versions of the New Jersey RASA model and the version described in this report are summarized in table 5. The development, design, and calibration of the model described in this report are discussed in the following sections.

Model Development

The three-dimensional groundwater-flow model developed to simulate the groundwater-flow system in the New Jersey Coastal Plain is based on the USGS computer

Table 3. Hydraulic properties of aquifers and confining units from selected groundwater-flow models in the New Jersey Coastal Plain.

[PRM, Potomac-Raritan-Magothy; ft/d, feet per day; ft, feet; >, greater than; <, less than; —, no data]

Aquifer	Model layer	Horizontal hydraulic conductivity (ft/d)	Thickness[1] (ft)	Storage coefficient	Reference
Holly Beach water-bearing zone	1	126–219	15–225	6.0×10^{-2}	Spitz, 1998.
Unconfined Kirkwood-Cohansey aquifer system	3	50–60	50–>400	—	Pope and others, 2012.
Rio Grande water-bearing zone	5	50	>0–140	—	Pope and others, 2012.
Atlantic City 800-foot sand	7	50	40–200	1.1×10^{-5}–1.0×10^{-4}	Pope and others, 2012; McAuley and others, 2001.
Piney Point	9	23	>0–>200	3.0×10^{-4}	Rush, 1968.
Vincentown	11	20	20–>140	—	Nicholson and Watt, 1997.
Wenonah-Mount Laurel	13	13–19	<25–>120	1.5×10^{-5}–3.5×10^{-4}	Nemickas, 1976.
Englishtown aquifer system	15	6–70	40–140	—	Charles and others, 2011.
upper PRM	17	18–90	50–>200	1.0×10^{-4}	Navoy and Carleton, 1995; Martin, 1998.
middle PRM	19	7–90	<50–>150	1.0×10^{-4}	Navoy and Carleton, 1995; Martin, 1998.
lower PRM	21	15–150	>0–250	1.0×10^{-4}	Charles and others, 2011; Martin, 1998.
Confining unit	Model layer	Vertical hydraulic conductivity (ft/d)	Thickness (ft)	Storage coefficient	Reference
Confining unit overlying the estuarine sand and confining unit overlying the confined Cohansey aquifer	2	4.0×10^{-3}	20–150	—	Spitz, 1998.
Confining unit overlying the Rio Grande water-bearing zone	4	1.00×10^{-5}	—	—	Pope and others, 2012.
Confining unit overlying the Atlantic City 800-foot sand	6	1.0×10^{-5}	<100–>300	—	Pope and others, 2012.
Composite confining unit[2]	8	1.0×10^{-5}–1.4×10^{-5}	[3]100	—	McAuley and others, 2001.
Composite confining unit[4]	10	5.7×10^{-3}	<50–1,190	—	Rosenau and others, 1969.
Composite confining unit[5]	12	5.6×10^{-2}	60–90	—	Nichols, 1977.
Marshalltown-Wenonah	14	1.5×10^{-5}	20–>180	—	Nichols, 1977.
Merchantville-Woodbury	16	4.3×10^{-6}–3.5×10^{-3}	100–350	—	Nichols, 1977; Pucci and others, 1994.
Confining unit between upper and middle PRM	18	1.8×10^{-5}–8.0×10^{-1}	50–>200	—	Pucci and others, 1994; Charles and others, 2011.
Confining unit between middle and lower PRM	20	2.1×10^{-5}–1.7×10^{-1}	>0–<50	—	Charles and others, 2011.

[1]Thickness from Zapecza (1989), except for model layers 1 and 2 (Spitz, 1998), model layers 3 and 5 (Pope and others, 2012), and model layer 6 (McAuley and others, 2001).

[2]Corresponds to the basal Kirkwood confining unit.

[3]Thickness in vicinity of Atlantic City, New Jersey, from McAuley and others (2001).

[4]Corresponds to the Manasquan-Shark River confining unit.

[5]Martin (1998) referred to this part of the composite confining unit as the Navesink-Hornerstown confining unit.

Table 4. Summary of hydraulic properties of aquifers and confining units in Delaware and counties in eastern Maryland.

[ft, feet; ft^2/d, feet squared per day; ft/d, feet per day; —, no data]

Aquifer or confining unit	Model layer	Average or maximum thickness[1] (ft)	Delaware or county in Maryland[2]	Mean or range of transmissivity[3] (ft^2/d)	Horizontal hydraulic conductivity[3] (ft/d)	Vertical hydraulic conductivity[3] (ft/d)	Storage coefficient[3]
Upper Chesapeake confining unit 2	2	50	Worcester	—	—	—	—
		50	Wicomico	—	—	—	—
Manokin aquifer	3	10–20	Wicomico	480–7,440	54	—	—
		Up to 195	Worcester	4,820–14,800	—	—	—
		[4]30–150	Delaware	—	—	—	—
St. Mary's confining unit	4	Up to 230	Worcester	—	—	—	—
		—	Delaware	—	—	[4]1.0×10^{-4}	—
Choptank aquifer	5	—	Wicomico	440–510	—	—	—
		Up to 170	Worcester	—	—	—	—
Lower Chesapeake confining unit	6	Up to 155	Worcester	—	—	—	—
Calvert aquifer system	7	90	Queen Anne's	30-50	—	—	—
Calvert confining unit	8	—	Queen Anne's	—	0.015	0.02	—
Piney Point aquifer	9	50	Caroline	100–4,670	—	—	—
		—	Queen Anne's	1,203	—	—	1.6×10^{-4}
		Up to 240	Delaware	[5]800–5,350	—	—	[5]2.8×10^{-4}– 3.0×10^{-4}
Nanjemoy confining unit	10	—	Queen Anne's	—	0.011–10.3	2.3×10^{-4} – 8.33	—
Aquia (Rancocas) aquifer[6]	11	—	Kent	350–8,090	—	—	2.0×10^{-4}–4.0×10^{-4}
		Up to 289	Queen Anne's	180–5,600	—	—	3.0×10^{-4}
		—	Delaware[7]	530–2,767	0.15–110	—	1.9×10^{-4}–4.4×10^{-4}
Severn confining unit	12	Up to 78	Kent	—	—	—	—
Monmouth (Mount Laurel) aquifer[6]	13	—	Kent	220–340	—	—	1.2×10^{-3}
		—	Delaware[7]	330–5,600	4.2	—	1.0×10^{-4}–7.7×10^{-3}
Matawan confining unit	14	54	Delaware[8]	—	—	—	—
Matawan aquifer	15	—	Queen Anne's	931	—	—	—
Magothy confining unit	16	152	Delaware[8]	—	—	—	—
Magothy aquifer	17	45	Cecil	3,100–3,440	—	—	1.0×10^{-4}
		—	Kent	500	—	—	3.0×10^{-4}
		—	Queen Anne's	5,800–10,000	—	—	2.2×10^{-4}
		—	Delaware[7]	410–1,760	—	—	3.7×10^{-5}–3.0×10^{-3}
Potomac confining unit	18	119	Delaware[8]	—	—	—	—
Potomac-Patapsco aquifer	19	134	Cecil	100–4,150	—	150	9.6×10^{-3}
		318	Kent	50–2,440	—	40	7.3×10^{-3}
		—	Queen Anne's	1,000–8,800	—	50	1.0×10^{-4}–2.2×10^{-4}
		—	Delaware[7]	455–5,350	—	—	1.0×10^{-4}–2.2×10^{-4}
Potomac confining unit	20	199	Delaware[8]	—	—	—	—
Patuxent aquifer system	21	—	Cecil	380–11,250	—	—	1.0×10^{-4}–1.1×10^{-4}
		Up to 500	Queen Anne's	800	—	—	—

[1]Andreasen and others (2013).

[2]County in Maryland within modeled area.

[3]Data from aquifer tests summarized in Andreasen and others (2013).

[4]Hodges (1984).

[5]Leahy (1979).

[6]Aquifers in parentheses are the correlative aquifer in Delaware.

[7]Values of transmissivity, horizontal hydraulic conductivity, and storage coefficient in Dugan and others (2008).

[8]Average thickness of regional hydrogeologic units in the Northern Atlantic Coastal Plain aquifer system in Masterson and others (2016a).

Table 5. Characteristics of three groundwater-flow models developed for the New Jersey Coastal Plain.

[RASA, Regional Aquifer System Analysis; in/yr, inches per year; SWB, soil-water balance]

Reference	Model computer code[1]	Total model layers[2]	Withdrawal conditions	Most recent water-level data used	Minimum cell size (square miles)	Boundary flows derived from:	Recharge to cells in New Jersey
Martin (1998)	Trescott (1975)	11	1896–1980	1978	6.25	Leahy and Martin (1993)	Constant of 20 in/yr.
Voronin (2004)	MODFLOW–96	10	1968–1998	1998	0.25	Leahy and Martin (1993)[3]	0.01–20 in/yr; varies by cell but not by year.
Gordon and Carleton (2023)	MODFLOW–2005	21	[4]1978–2013	2013	0.25	Masterson and others (2016a)	Used SWB[5] model to vary by cell and by year.

[1]Reference for MODFLOW–96 is Harbaugh and McDonald (1996); for MODFLOW–2005 is Harbaugh (2005).

[2]The groundwater-flow models of Martin (1998) and Voronin (2004) are quasi-three-dimensional models. Confining units are not explicitly modeled but are simulated by a vertical leakance. The vertical leakance is calculated as the hydraulic conductivity divided by thickness.

[3]Boundary flows in Delaware were modified to account for the increase in withdrawals.

[4]Stress periods 1 through 3 are transitional stress periods in this model that generally correspond to the time periods 1970–76 and 1977–79, and 1980, respectively, to set antecedent conditions in the model. The withdrawal rates for these three time periods are based on a percentage of the average annual 1978–81 withdrawals in Voronin (2004).

[5]The SWB model uses a soil-water-balance code (Westenbroek and others, 2010) for estimating an annual recharge for each year simulated in inches per year. The recharge rates for the time periods 1970–76 and 1977–79 (model stress periods 1 and 2), used to set antecedent conditions in the model, are based on a percentage of the 1980 average recharge.

program MODFLOW–2005 (Harbaugh and others, 2005). Updates to the two previous versions of the RASA model include (1) a 21-layer hydrogeologic framework that extends into Delaware and part of Maryland; (2) spatially variable recharge estimated by using the SWB model (Westenbroek and others, 2010); (3) updated hydraulic parameters to include the confining units in New Jersey and the hydrogeologic units in Delaware and eastern Maryland; (4) updated boundary flows from the groundwater-flow model of the North Atlantic Coastal Plain (NACP) (Masterson and others, 2016a); (5) groundwater-withdrawal data for 1980–2013 for the New Jersey Coastal Plain and for 1980–2010 for the modeled areas in Delaware and eastern Maryland; and (6) the Rio Grande water-bearing zone and the confining units above and below it, added as a model layer to refine the estimate of simulated flow in Atlantic and Cape May Counties, New Jersey. The updip part of model layer 5, where the Rio Grande water-bearing zone is absent (fig. 1), is represented in this model by a thin layer that allows for a hydraulic connection between the overlying and underlying model layers. The groundwater-flow model is used to (1) simulate current (2013) conditions of groundwater flow in the New Jersey Coastal Plain and the confined aquifers of Delaware, (2) improve the representation of the groundwater system of the New Jersey Coastal Plain, and (3) provide the NJDEP and other water managers with the information (Carleton and others, 2023) that can be used to calculate groundwater-budget components and evaluate water-resource management decisions.

Spatial and Temporal Discretization

The finite-difference grid for the numerical model consists of 145 rows, 245 columns, and 21 layers. The model grid size is variable, with a grid spacing of 0.25 mi^2 (the smallest) in the northern and southwestern parts of the New Jersey Coastal Plain, 0.31 mi^2 in the southeastern part of the Coastal Plain, and as much as 3.16 mi^2 in the offshore areas. The model area is approximately 16,597 mi^2 and extends from the Fall Line (fig. 1), which is the transition from the consolidated rocks of the upland Piedmont Physiographic Province to the unconsolidated sediments of the Coastal Plain Physiographic Province, to the approximate downdip and (or) freshwater-saltwater interface in each model layer. (The location and extent of the Fall Line in southeastern New York is not shown in figures.) The grid is oriented approximately parallel to the Fall Line and to the strike of the New Jersey Coastal Plain hydrogeologic units (Zapecza, 1989).

A schematic diagram of the model layers used to represent the hydrogeologic units in the New Jersey Coastal Plain and the corresponding hydrogeologic units in Delaware and eastern Maryland is shown in figure 4. Confining units are modeled as individual layers by assigning them appropriate hydrologic properties.

The model area extends vertically from the water table to consolidated bedrock and includes 11 distinct major aquifers and 10 confining units of the New Jersey Coastal Plain. The hydrogeologic framework described by Zapecza (1989)

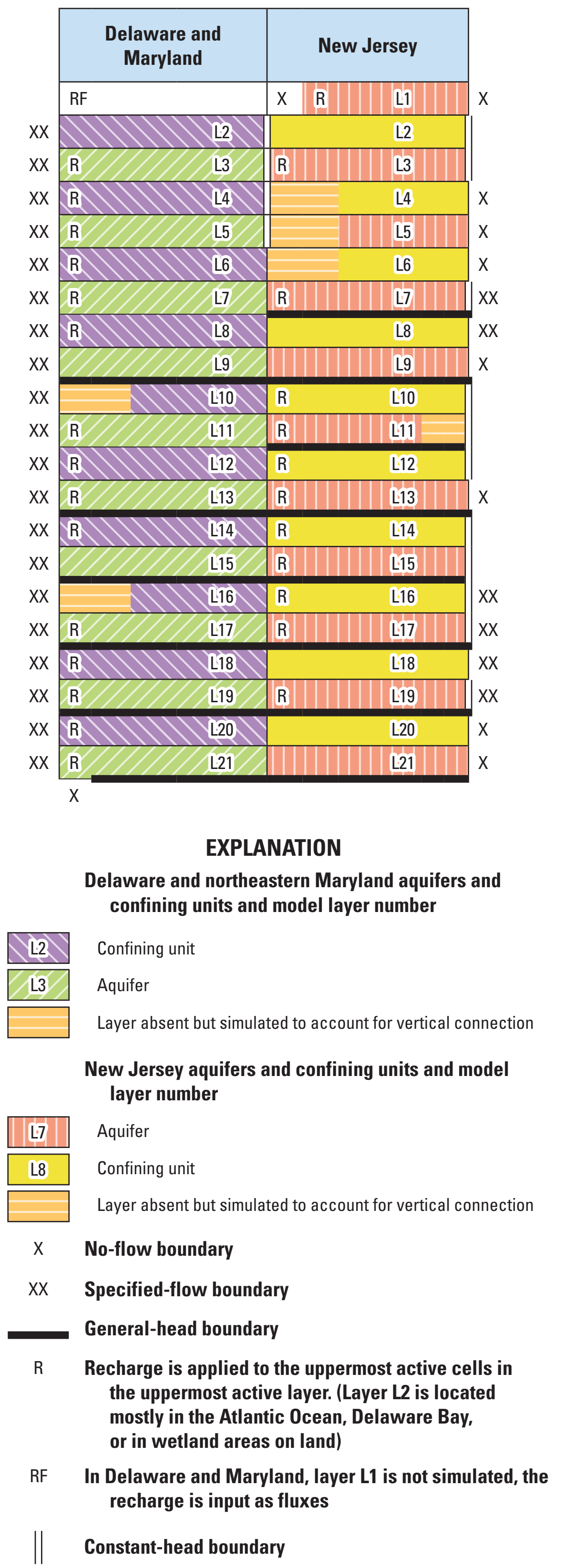


Figure 4. Schematic representation of aquifers, confining units and boundary conditions in the New Jersey Coastal Plain groundwater-flow model.

was revised for this study to improve the simulation of the groundwater-flow system. Extents of each model layer in Delaware and eastern Maryland are based on hydrogeologic data from Meisler (1989), Vroblesky and Fleck (1991) and Andreasen and others (2013). The hydrogeologic framework is described in more detail in the data release for this report (Carleton and others, 2023). This data release contains an ArcGIS shapefile containing the top, bottom, thickness, and extent of each layer in the model used to define the aquifers and confining units incorporated into the New Jersey Coastal Plain model (Carleton and others, 2023).

If a hydrogeologic layer does not extend across a given model layer in the MODFLOW-2005 finite-difference solution method but instead the hydrogeologic layer pinches out, but the model layer above and (or) below is an active area in the model, an area was created in the model layer with the limited extent to make that layer continuous with the above and (or) below layer, if needed, and was given a small thickness (1 foot or more). The hydraulic properties of the overlying model layer were assigned so that the layer would be continuous, thereby achieving a hydraulic connection between the layers above and below. For example, model layer 11 which represents the Vincentown aquifer, an aquifer with a small area, but the areas of the overlying and underlying layers extend beyond the area of the Vincentown aquifer, therefore an area is needed to simulate the flow from overlying aquifers to underlying aquifers to more accurately represent the vertical head distribution in the model layers (fig. 1). Additionally, in the updip area of the Piney Point aquifer (model layer 9) where the aquifer pinches out and does not outcrop, an area is needed to simulate the flow from overlying units to underlying units to more accurately represent the vertical head distribution in the model layers (fig. 1). The same is true for the updip area in model layer 5, which in the downdip area (fig. 1) represents the confined Rio Grande water-bearing zone, and the overlying and underlying confining units (model layers 4 and 6, respectively). In the updip parts of those three model layers, an area is needed to simulate the flow from the overlying model layer 3 to the underlying model layer 7 to more accurately represent the vertical connection in the model layers.

A total of 36 stress periods were simulated—1 steady-state period and 35 transient periods. Stress period 1 is steady-state and stress period 2 is transient and 3 years long. Stress periods 1 and 2 are transitional stress periods that generally correspond to 1970–76 and 1977–79, respectively. Stress periods 3 to 36 are 1 year long and generally represent the period 1980–2013.

Lateral and Lower Boundary Conditions

The model is bounded to the north and northwest and below by the contact between the unconsolidated Coastal Plain deposits and consolidated bedrock that underlies the Coastal Plain sediments. This boundary was represented numerically as a no-flow boundary condition. Lateral boundaries for each layer in the groundwater-flow model are shown in a generalized schematic diagram in figure 4. Although water may flow into the model area along the Fall Line between the subsurface fractured rock and the Coastal Plain sediments, this amount is assumed to be negligible and, therefore, is not considered in this report.

In the two previous New Jersey RASA groundwater-flow models (Martin, 1998; Voronin, 2004), the lateral boundaries in the northeast and southwest are specified-flux boundaries that originally were derived from a model of the NACP (Leahy and Martin, 1993). Some modifications were made to the boundary fluxes near Delaware Bay in the rediscretized RASA model (Voronin, 2004). The Leahy and Martin (1993) model area extended from Long Island, New York, to North Carolina and includes the New Jersey Coastal Plain. In the model described in this report, the lateral model boundaries in the northeast and southwest are specified-flux boundaries derived from the NACP aquifer system model (Masterson and others, 2016a), which also extends from Long Island, New York, to North Carolina, by using the MODFLOW Flow and Head Boundary (FHB) package (Leake and Lilly, 1997). Specified fluxes are applied in areas where the aquifers and confining units intersect the flow boundary. Flows from the NACP model (Masterson and others, 2016a) are incorporated into the FHB package for stress periods 1 through 32. Because the end of the NACP model simulation coincides with stress period 32 of the current New Jersey Coastal Plain model, fluxes for stress period 32 are repeated for stress periods 33 through 36. The FHB package is used to specify lateral boundary fluxes in each active cell along column 1 of the model grid, which traverses eastern Maryland and a small part of southwestern Delaware (fig. 1). Some active cells along column 1 where the flux was zero were not included in the FBH model file. Specified fluxes are also input in New Jersey using the FHB package along the northeastern edge of the active model area for some layers in column 245 for the offshore extent of layers 7 and 8 and in layers 16 to 19 for the offshore part of the upper and middle Potomac-Raritan-Magothy aquifers (layers 17 and 19), the Merchantville-Woodbury confining unit (layer 16*),* and the confining unit between the upper and middle Potomac-Raritan-Magothy aquifers (layer 18). The remaining layers have a no-flow or a constant-head boundary along northeastern limit of the model area (fig. 4).

The southeastern (downdip) boundary of the aquifers and confining-unit model layers in New Jersey, Delaware, and Maryland are simulated as no-flow boundaries except as described in the “General Head Boundary” section of this report. The downdip extents of the aquifers and confining-unit model layers in Delaware and Maryland are from Meisler (1989), Vroblesky and Fleck (1991), and Andreasen and others (2013). The southeastern downdip boundary of the aquifers and confining-unit layers in New Jersey are generally located at the downdip limit of freshwater in the aquifer (10,000 mg/L isochlor) determined by Pope and Gordon (1999). Pope and Gordon (1999) used the SHARP computer model (Essaid, 1990) to simulate the groundwater-flow system, including the location and movement of the freshwater-saltwater interface in nine aquifers and eight intervening confining units in the Coastal Plain. Although the interface position is not static in the model, the actual amount of movement cannot be quantified because of the model’s coarse cell size. Because the SHARP model is quasi-three-dimensional, the downdip limit of the 10,000-mg/L isochlor in those aquifers was assumed to be the same for the overlying confining unit. However, the Englishtown aquifer system and Vincentown aquifer are not continuous throughout the New Jersey Coastal Plain and contain freshwater throughout their confined extent in New Jersey. However, chloride concentrations exceeded 15,000 mg/L at an observation well in the Englishtown aquifer system in Sandy Hook in northeastern Monmouth County (DePaul and Rosman, 2015).

General Head Boundary

The General Head Boundary (GHB) package (McDonald and Harbaugh, 1988) was used to represent flow in the updip direction from limited parts of the downdip lateral boundaries of layers 7, 9, 11, 13, 15, 17, 19, and 21 (fig. 4). However, in model layer 11, the GHB boundary was used in New Jersey only. The GHB head is constant for all stress periods and is set to 0.0 ft (NAVD 88); no attempt was made to estimate the equivalent freshwater head where groundwater density is greater than that of freshwater. A single value of bed conductance of 1 square foot per second (ft^2/s) was applied to all GHB cells.

The GHB boundaries were included to prevent the occurrence of unrealistically low heads downdip from withdrawals; because the boundaries are generally far from the withdrawals, they have only a minor effect on the overall flow system. In 2013, flow into the model from GHB cells is about 0.6 percent of the total flow budget.

Upper Boundary Conditions

The upper boundaries in the model represent the streams and recharge in onshore areas and the Delaware and Raritan Bays and Atlantic Ocean (fig. 1) in offshore areas. In offshore areas, the upper boundary is a constant freshwater equivalent water level specified by using the Time-Variant Specified-Head (CHD) package (Harbaugh, 2005) and is applied across the top active layer of model cells used to represent the Atlantic Ocean and the Delaware and Raritan Bays. CHD cells represent the outcrop of layers 2 through 5 in Delaware Bay, the outcrop in layers 14 through 19 (excluding layer 18) in Raritan Bay, and the outcrop of layers 2, 3, 7, and 10 through 12 in the Atlantic Ocean (fig. 4).

Recharge

The Recharge (RCH) package of the USGS finite-difference groundwater model MODFLOW–2005 was used to apply recharge to the topmost active layer of each onshore model cell. This upper boundary is spatially variable recharge from precipitation estimated by using the Soil-Water Balance (SWB) model (Westenbroek and others, 2010). The SWB model is based on a modified Thornthwaite-Mather method (Thornthwaite and Mather, 1957) that incorporates spatially distributed land cover, soil properties, and daily climate data to produce a detailed spatial and temporal variability of recharge. SWB model-calculated recharge rates from 1980 to 2013 were used as the initial recharge values for New Jersey in the groundwater-flow model. The SWB model is described in appendix 1. Recharge was adjusted as part of the model parameter-estimation process to allow for more variability than that calculated by the SWB model and adjusted for comparison with base-flow estimates at various surface-water drainage basins in the New Jersey Coastal Plain. Average annual precipitation in southern New Jersey (Office of the New Jersey State Climatologist, 2021) during 1970–76 and 1977–79 were 1.23 and 1.31 times the 1980 annual average, respectively. Therefore, the recharge rates applied in model stress periods 1 (associated with 1970–76) and 2 (1977–79) are 1.23 and 1.31 times those applied in stress period 3 (1980). Stress periods 1 and 2 are used in the model to set antecedent conditions for the other years.

Because the surficial aquifer in Delaware and Maryland is not simulated, cell-by-cell vertical flows into or out of active cells in model layer 1 in Delaware and Maryland were calculated from the NACP model (Masterson and others, 2016a) and applied with the recharge.

Drain Package

The MODFLOW Drain package (DRN) is used to represent the rivers and streams in the model where groundwater flows (drains) out of the model area (fig. 5). The DRN package was used for continually gaining stream reaches in the New Jersey Coastal Plain which are not a source of groundwater recharge except on a localized scale (for example, upstream from a dam). Use of the DRN package allows for the representation of headwater reaches, where the streambed elevation may be above the water table in places, preventing simulated small streams from being a source of potentially unlimited volumes of water, as would be the case with the MODFLOW River package (RIV) (discussed below). The drain elevation is the average elevation of a stream or stream tributary in the topmost active layer in each onshore model cell. Streams in New Jersey are those used in the previous model version from Voronin (2004). Model cells containing streams in New Jersey were identified by intersecting the model-grid polygons with streams digitized from USGS 1:24,000-scale topographic maps. Streams in Maryland and Delaware were identified by intersecting the grid with NHDPlus (U.S. Geological Survey, 2005), a comprehensive geospatial dataset developed by the U.S. Environmental Protection Agency and the USGS.

The elevations of drain boundaries are kept constant for all stress periods in the transient model. The drain elevations are long-term averages and do not include annual or seasonal variations. Seasonal variations cannot be considered when annual stress periods are used; neglecting the variation of average elevation from year to year is minor in the context of surface-water elevations averaged over model cells of 0.25 mi^2 or larger.

The DRN package also requires specification of streambed conductance, an aggregate parameter that represents the product of the streambed hydraulic conductivity, the length of the stream reach, and the stream width divided by the streambed thickness. The same streambed conductance is applied to all drains and was adjusted during calibration.

River Package

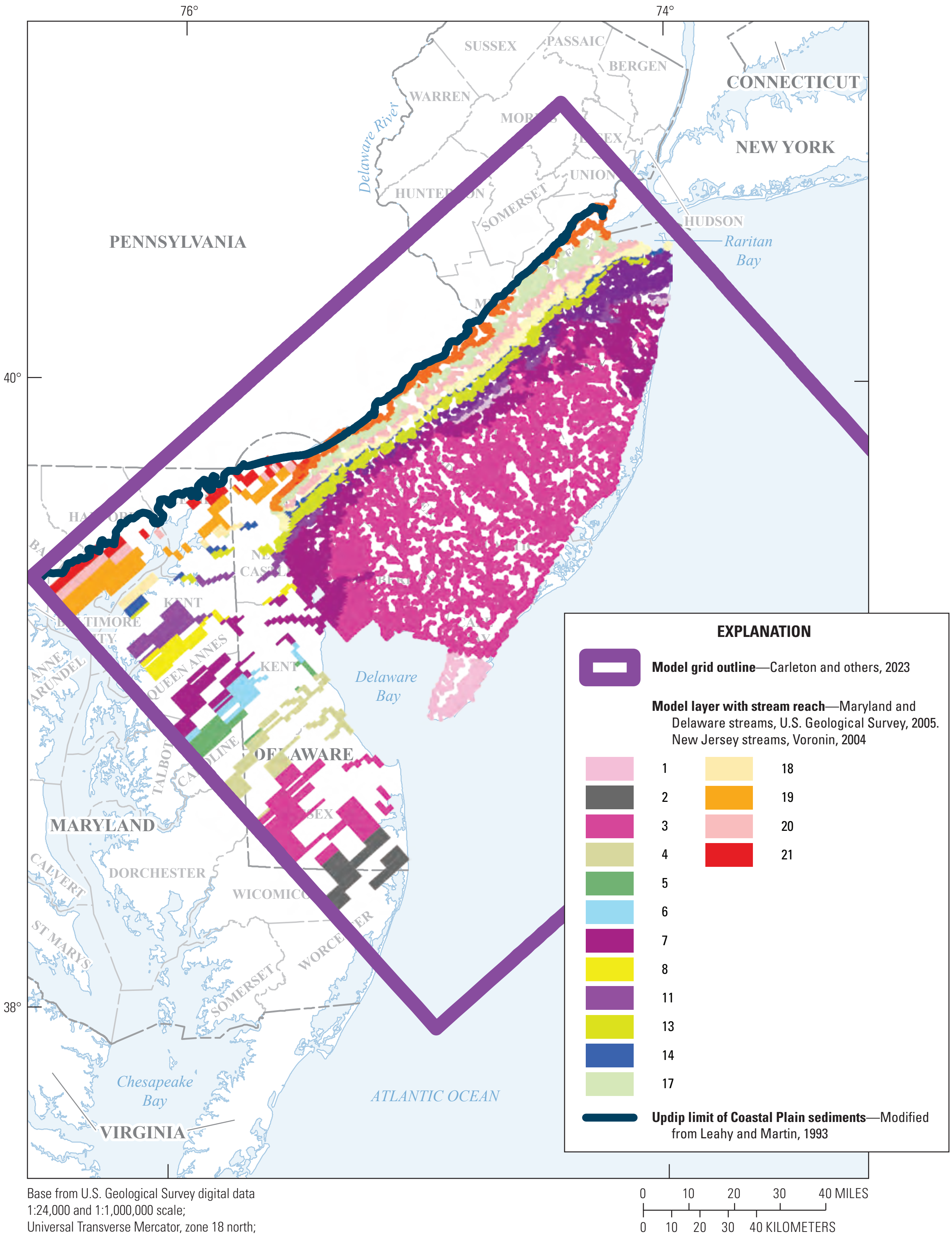
The MODFLOW River package (RIV) package was used to represent the Delaware River (fig. 5). The RIV package (unlike the DRN package) allows the Delaware River to be a source of recharge to the aquifer near pumping centers. This is appropriate because the Delaware River carries substantial flow, is tidal in the simulated area, and can provide unlimited flow to the aquifer. The river stage is constant for all stress periods and increases from 0.0 ft (NAVD 88) at the southwestern extent of model river cells in Delaware Bay to 1.0 ft near Trenton by 0.1 ft in segments of approximately the same length. A single value of riverbed conductance was applied to all river cells, representing the product of the riverbed hydraulic conductivity, length, and width of the river reach in each model cell divided by riverbed thickness. Riverbed conductance was modified during model calibration.

Hydraulic Properties

The hydraulic properties hydraulic conductivity and storage coefficient are described in the “Hydraulic Properties of Aquifers and Confining Units” section near the beginning of this report. As previously mentioned, data for the hydraulic properties of confining units are limited. The hydraulic properties are specified by parameter zones within each layer that are assumed to have similar properties. The initial values are comparable with those from Martin (1998), Voronin (2004) and Masterson and others (2016a). During model calibration, the range of hydraulic properties shown in tables 2 and 3 were used to provide supplemental information for values in areas of New Jersey. The hydraulic conductivities and storage coefficients in table 4 were used to provide supplemental information for values in Delaware and Maryland. Hydraulic-conductivity and storage-coefficient parameters were adjusted manually and by using the parameter-estimation software UCODE-2014 (Poeter and others, 2014) during model calibration as needed to improve the model fit between observed data and simulated results.

Groundwater Withdrawals

Groundwater-withdrawal data for the New Jersey Coastal Plain were tabulated and mapped to assess the volume of water pumped from wells in each of the aquifers. These wells



Base from U.S. Geological Survey digital data
1:24,000 and 1:1,000,000 scale;
Universal Transverse Mercator, zone 18 north;
North American Datum of 1983

Figure 5. Map showing location of stream cells in the model area, New Jersey Coastal Plain groundwater-flow model.

include those used for public supply, large-scale agricultural (irrigation), and commercial or industrial purposes. Withdrawals from small-capacity wells, such as those used for domestic supply, are not incorporated into the model. This is a limitation of the model in the outcrop areas of confined aquifers or the Kirkwood-Cohansey aquifer system in areas where a substantial number of domestic-supply wells are located, but domestic self-supply withdrawals do not make up a substantial part of the groundwater withdrawals. Statewide production from domestic wells accounts for about 3 percent of total withdrawals in New Jersey (New Jersey Department of Environmental Protection, 2017b).

Withdrawal data for 1980–1998 were obtained from Voronin (2004) and were reviewed for updates that may have been made since 2003, such as an update to an aquifer code or surveyed well location. Withdrawal data for 1999–2003 were obtained from data reported to the NJDEP. These data were quality reviewed and incorporated into a water-use database available in the data release accompanying this report (Carleton and others, 2023). This withdrawal information includes permitted data only—that is, only data from wells in which daily withdrawals meet or exceed 100,000 gallons for a period of more than 30 days in a consecutive 365-day period. Withdrawal data for 2004–13 were obtained from the NJWATr database developed by the USGS and maintained by the NJDEP to track water withdrawals, use, treatment, and discharge in New Jersey (New Jersey Department of Environmental Protection, 2017a). Total withdrawals from New Jersey Coastal Plain aquifers input to the model for 2004 to 2013 are shown in figure 6. The largest withdrawals occurred in the unconfined Kirkwood-Cohansey aquifer system, the Atlantic City 800-foot sand, and the upper, middle, and lower Potomac-Raritan-Magothy aquifers (model layers 3, 7, 17, 19, and 21).

Annual withdrawal data for 1980—2013 for Delaware and Maryland were obtained from a dataset of pumping rates for 1980—2010 from the groundwater-flow model developed for a groundwater-availability study of the NACP

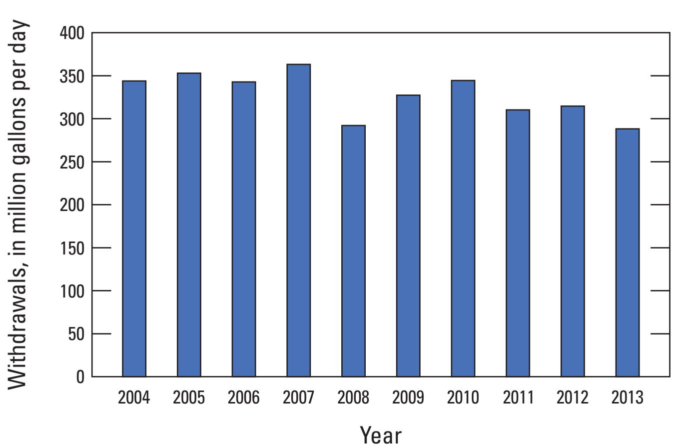


Figure 6. Graph showing estimated groundwater withdrawals from New Jersey Coastal Plain aquifers, 2004–13.

by Masterson and others (2016a) (Jack Monti, Jr., U.S. Geological Survey, written commun., 2014). Agricultural withdrawal data for Delaware and Maryland may be less complete and less well documented (Masterson and others, 2016a) than New Jersey agricultural withdrawals. Masterson and others (2016a) provide a detailed description of the methods used to tabulate and estimate groundwater withdrawals in their study. Withdrawals from the unconfined surficial aquifer in Delaware and Maryland were not included in the New Jersey Coastal Plain groundwater-flow model. The unconfined surficial aquifer in Delaware and eastern Maryland was not included in the model hydrogeologic framework because model layer 1 represents the Holly Beach water-bearing zone in Cape May County, New Jersey, which is not continuous into Delaware.

Stress periods 1 (steady-state) and 2 (transient) are transitional stress periods that generally correspond with 1970–76 and 1977–79, respectively. Stress periods 3 and 4 generally represent 1980 and 1981, respectively. Withdrawals for stress periods 1, 2, and 3 are 73, 86, and 93 percent, respectively, of those in stress period 4, and account for the estimated increase in withdrawals from 1970 to 1980. Withdrawals for stress period 4 generally are an average of 1978–81 withdrawals in Voronin (2004) and represent 1981 withdrawal rates in the groundwater-flow model. Average annual withdrawals were used in the model for stress periods 5 to 36, which are 1 year long, and the average annual withdrawals are equivalent to total annual withdrawals during each of these stress periods. Stress periods 5 through 36 represent each year from 1982 to 2013, respectively.

Model Sensitivity Analysis and Calibration

Model calibration was conducted using manual adjustments of parameters through trial and error and parameter estimation techniques. The UCODE-2014 (Poeter and others, 2014) was used to evaluate the sensitivity of parameters to improve the fit of simulation results to observation data and identify correlated parameters that may not be estimated separately. Parameter estimation is the process of determining which parameters can be statistically estimated and then varying those parameters to minimize the weighted least squares objective function (Hill and Tiedeman, 2007). The objective function measures this fit by quantitatively comparing simulated and observed values. This section of the report describes the observations, residuals, final parameter values, correlations between parameters, and parameter sensitivity achieved by the model calibration and the sensitivity of water levels and base flow to the model parameters.

Effective use of hydrogeologic data and observations to constrain a model is likely to produce a model that improves the accuracy of the representation of groundwater flow and, consequently, simulation results. The match of observed to simulated values is used to evaluate how well a model represents an actual system. The simulated and observed values compared for the New Jersey Coastal Plain groundwater-flow model are water-level altitudes (heads) and groundwater discharge (base flow) to gaged streams which involved the adjustment of model parameters so that residuals (the differences between simulated and observed water levels or base flows) are minimized. During calibration, initial model parameters, such as hydraulic conductivity and storage coefficient, are changed to minimize residuals. All observed and simulated water-level observations and simulated and estimated base-flow observations are available in the data release accompanying this report (Carleton and others, 2023).

Water-Level Observations

The model was calibrated by using water-level observations that include observations derived from selected water-level measurements described below. The water-level observations in New Jersey are a subset of measurements collected during the seven quinquennial New Jersey Coastal Plain water-level synoptic studies (1983, 1988, 1993, 1998, 2003, 2008, and 2013) and were selected to provide a spatial distribution in 10 of the simulated aquifers. The water-level synoptic studies did not include the unconfined Holly Beach water-bearing zone and the unconfined part of the Kirkwood-Cohansey aquifer system. Water levels in correlated aquifers in Delaware were obtained from the Delaware Geological Survey (Delaware Geological Survey, 2017). Most of the water levels were measured during October–December after large summer withdrawals had decreased but before water levels had recovered to those measured during spring, thereby representing an approximation of the annual average water level. Water levels were measured at least once during 1983–2013 in 392 wells in New Jersey and 48 wells in Delaware (fig. 7), yielding a total of 2,533 water-level observations in 440 wells. Hydraulic water levels at each well were calculated by subtracting the water level, in feet below land surface, from the land-surface altitude, in feet above the North American Vertical Datum of 1988 (NAVD 88); the result of this calculation is shown in this report as the water-level altitude.

Average annual water levels were calculated for 29 wells in New Jersey (fig. 7) where continuous water levels were measured: 19 wells with observations for every year during 1980–2013 and 10 wells with data for most of that period (average of 27 years). A total of 920 observations from the 29 wells were included in the model calibration; these data are shown in time-series hydrographs shown in this report in the “Calibration of Water Levels” section.

In addition to the water-level observations used in the model calibration, derived observations also were included by calculating the vertical gradient at nested observation wells in New Jersey. Vertical gradients were calculated for 33 pairs of nested wells, for a total of 210 observations. (Nested well pairs are wells that are near each other but are open to different aquifers.) For each sequential synoptic water-level measurement period, vertical gradients calculated by subtracting water levels in colocated wells screened in different aquifers provided information for calibrating the hydraulic conductivity of the confining units. By attempting to match the gradient across the confining unit, the parameter-estimation function improved the accuracy of the vertical-conductance value, for example, in a situation where simulated water levels in both aquifers were somewhat high but the gradient was exact. Also, the change in water level over time was calculated by subtracting water levels in selected wells in which measurements had been made in sequential water-level synoptic studies; the difference was used in calibrating storage in aquifers and confining units. Changes in water levels over time were calculated for 138 wells, 134 wells in New Jersey and four wells in Delaware, where water levels had varied substantially (approximately 10 ft) over the 30-year span of synoptic water-level measurements, for a total of 767 observations.

Water-level observations and vertical-gradient and change-over-time observations calculated from water-level measurements were all assigned the same weight, except for annual observations from the 29 wells with a continuous water-level recorder. Most water-level hydrographs for selected wells had 34 observations, whereas many synoptically measured wells had at most 7 observations; therefore, synoptic water-level observations and calculated observations were assigned a weight of 5, and hydrograph observations were assigned a weight of 1.1. Hill and Tiedeman (2007) describe methods for assigning weights on the basis of estimated error ranges so that observations with substantial potential errors exert a smaller effect on the parameter estimation function than the more accurate measurements do. This approach was not practical for the model in this study because water-level observations were collected under a wide range of conditions, often unknown. For example, some water-level measurements were made in wells with varying degrees of recent and nearby pumping, whereas others were made in unused wells known to be thousands of feet from current or recent withdrawals; still other water-level measurements were made at production wells that had been pumped as recently as 1 hour earlier. Attempting to quantify potential errors based on proximity in time or space to known and unknown withdrawals for synoptic water-level measurements conducted over a 30-year period was infeasible. Most land-surface-elevation estimates were determined from light detection and ranging (lidar) data considered to be accurate to within 2 ft, a modest error compared to the uncertainties related to proximal withdrawals at the time of measurement.

Base-Flow Observations

The New Jersey Coastal Plain model was calibrated by using a total of 1,485 estimates of base flow from 47 stream basins in New Jersey. The locations of the 47 basins are shown in figure 8. The surface-water basins were selected because of location and availability of data during the period 1980—2013. Annual base flow was calculated by using the hydrograph-separation technique PART in Barlow and others

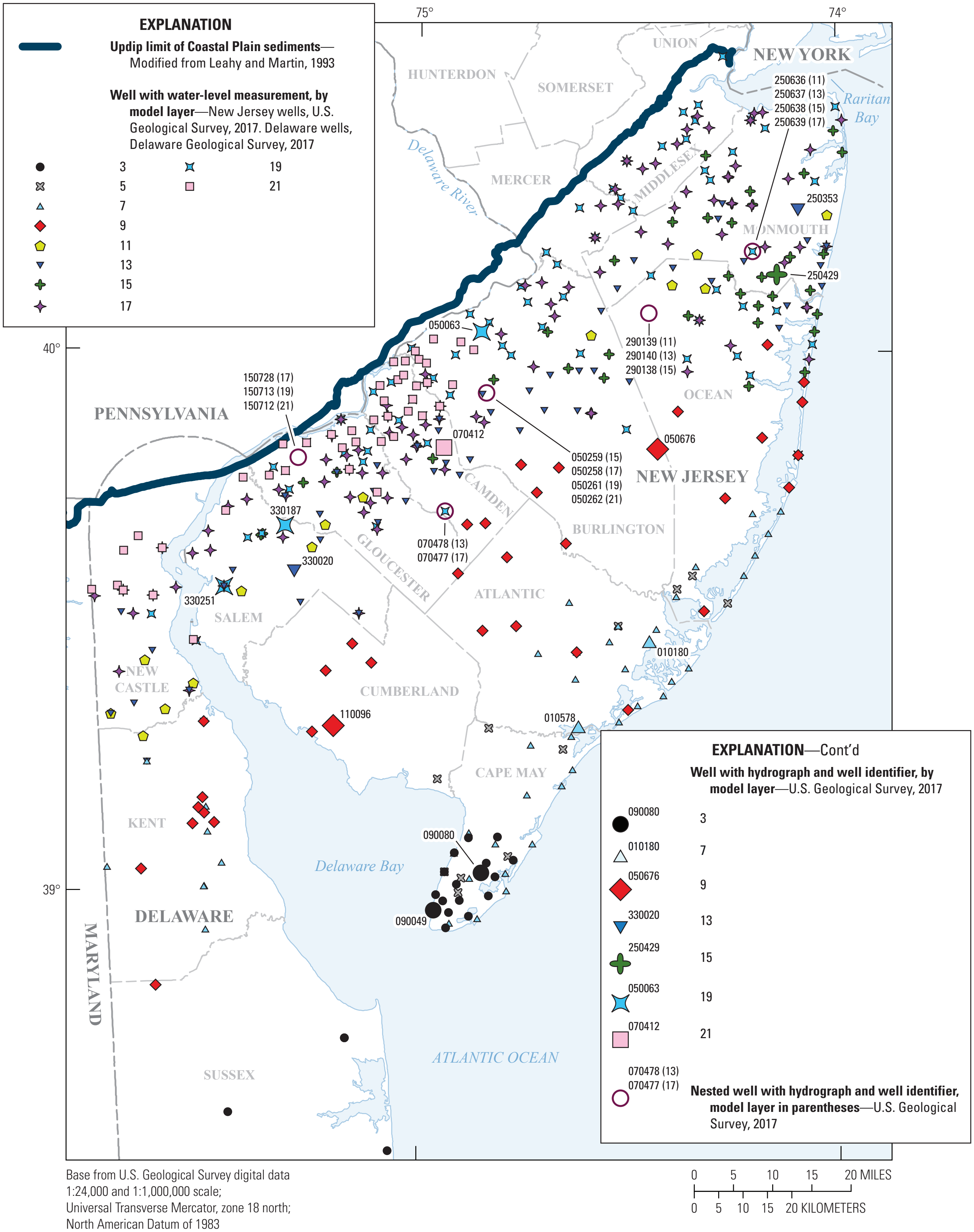


Figure 7. Map showing location of wells with measured water levels, New Jersey Coastal Plain.

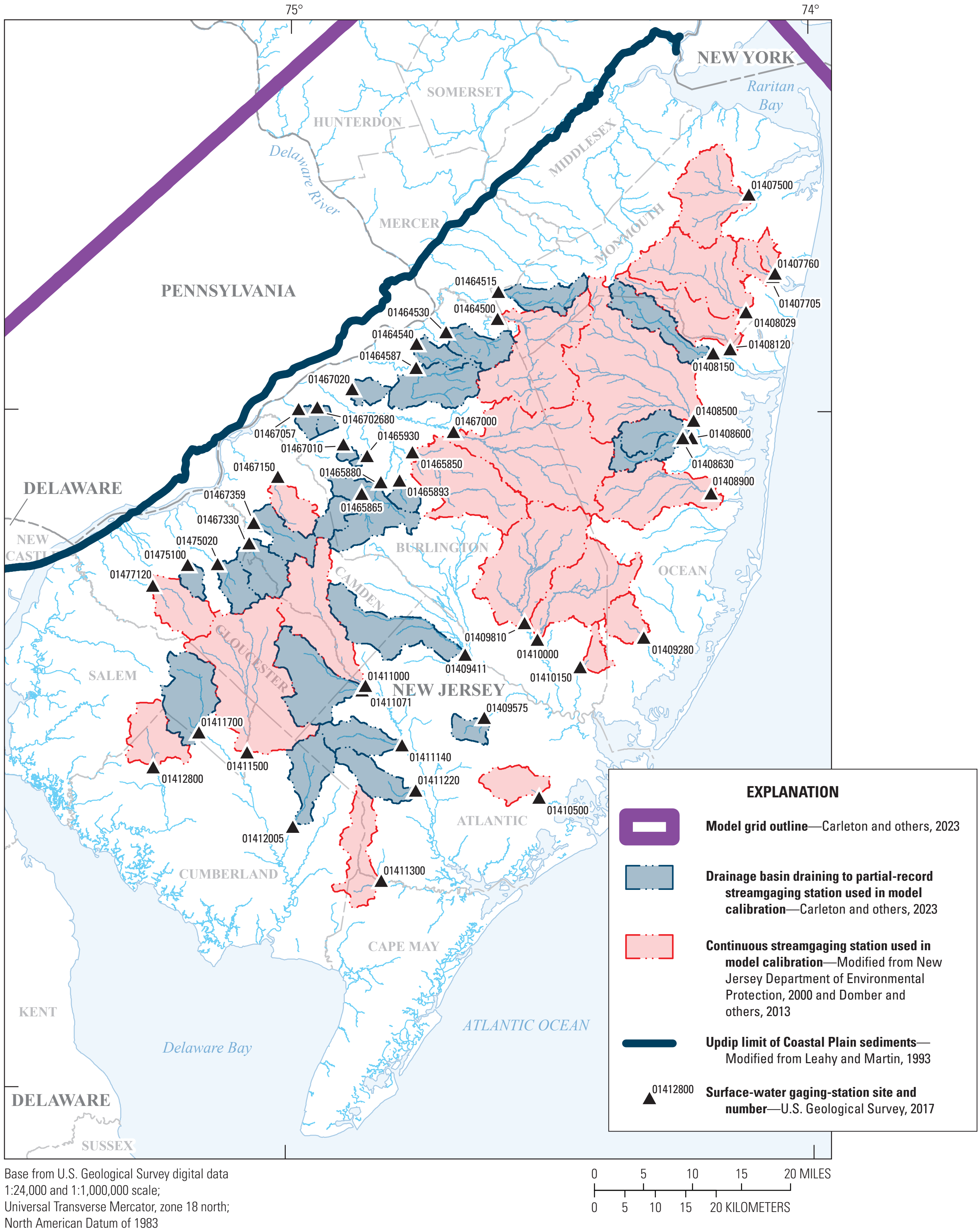


Figure 8. Map showing location of surface-water drainage basins with base-flow observations, New Jersey Coastal Plain.

(2015) for each of the 21 continuous-record gaging stations for each year of record. For 26 partial-record gaging stations in the New Jersey Coastal Plain, an annual base flow was calculated by correlating manual low-flow measurements made at the partial-record stations with same-day flows at index stations by using the MOVE.1 program (Colarullo and others, 2018). Annual base-flow estimates for each of the 47 basins were averaged to obtain a period-of-record average base flow for each basin.

Base-flow observations determined by using the PART hydrograph-separation technique in Barlow and others (2015) of continuous-record-station data were assigned a weight of 1.0. Observations determined from partial-record-station data correlated with measurements from continuous-record index stations were assigned a weight less than 1.0 based on the percent standard error of estimate (%SEE), which is the percent of unexplained variance relative to the value of the estimate. The %SEE is a better measure of uncertainty than the standard error of estimate (SEE) because it accounts for the proportional effect encountered in natural streamflow processes, where variance increases with flow (Amy McHugh, U.S. Geological Survey, written commun., 2020). Colarullo and others (2018) defined weights as the reciprocal of %SEE to lessen the weight of predictions made using MOVE.1 regressions that show a high degree of unexplained variability in flows and increase the weight of predictions made using regressions with a small amount of unexplained flow variability. The weights of measurements made at partial-record stations were set to a number less than 1.0 by dividing 4.5 by the squared average %SEE for each partial record station; resulting weights ranged from 0.95 to 0.22.

Model Parameters

A parameter is defined in this report as a single value assigned to a variable used in the finite-difference groundwater-flow equation at one or more model cells. The 422 parameters used in the model fall into seven categories: horizontal hydraulic conductivity (184 parameters), vertical hydraulic conductivity (184 parameters), storage coefficient (42 parameters), riverbed conductance (1 parameter), streambed conductance (1 parameter), general-head-boundary conductance (8 parameters), and recharge (2 parameter). The initial parameter values for several aquifers and confining units in New Jersey, Delaware, and eastern Maryland were changed during calibration to improve the match with observations and improve model results.

The final calibrated values for horizontal and vertical hydraulic conductivity and storage coefficients for aquifers and confining units are listed in tables 6 through 9. Table 6 lists the horizontal hydraulic conductivity (K_h) for the aquifer layers, table 7 lists the horizontal hydraulic conductivity for the confining-unit layers, and table 8 lists the vertical hydraulic conductivity (K_v) for the model layers. Table 9 lists the storage coefficients for each model layer. Parameter zones in each model layer were created using these values to allow for spatial variability of K_h and K_v. Several parameter zones were added or modified during model calibration. The conversion to a fully three-dimensional model framework and varied recharge resulted in the need for additional K_h parameter zones in the outcrop areas of all layers with updip outcrops following the strike of the hydrogeologic layers, corresponding to model layers 3 through 8 and 10 through 21. During the model calibration, some zones acquired a parameter value equal to or similar to that of an adjacent zone but remained a separate zone and was not incorporated into the adjacent zone. The ratio of horizontal to vertical hydraulic conductivity (K_h:K_v) was initially set to 10:1 for aquifers and 1:1 for confining units. K_h and K_v were adjusted independently during calibration; the sensitivity of K_v is low in most aquifer parameter zones and the sensitivity of K_h is low in most confining-unit parameter zones. The zones are designated by the parameters listed in tables 6 through 9. The location and extent of the K_h zones for the aquifers and K_v zones for the confining units are shown in figures 9 through 19. The parameter names for horizontal hydraulic conductivity for the confining units are zones with prefix “CU”. The location and extent of the horizontal hydraulic conductivity parameter zones for the confining units (table 7) are not shown in figures. The location and extent of the horizontal hydraulic conductivity parameter zones for the confining units coincide with the location and extent of the vertical hydraulic conductivity parameter zones (zones with prefix “VK”) for the confining units shown in figures 9*B* through 18*B* for those model layers.

The final parameters for horizontal and vertical hydraulic conductivity were compared to the values shown in tables 2 and 3 of this report. Many of the parameter values of horizontal hydraulic conductivity, such as those for the confined aquifers and the Holly Beach water-bearing zone in New Jersey, fall within the ranges of the value for horizontal hydraulic conductivity shown in the tables 2 and 3 and also table 1 of Masterson and others (2016a). Some horizontal hydraulic conductivity assigned to the outcrop areas of certain model layers for aquifers were higher (greater than 500 ft/d, table 6) because those areas are thin and the higher value increased model stability in these areas but did not affect the flow farther downdip. Higher values of horizontal hydraulic conductivity were also assigned to the outcrop areas of some confining-unit model layers (table 7) for the same reason. Lower values of horizontal hydraulic conductivity (less than 1 ft/d) were assigned in downdip areas of some aquifers—for example model layer 11 which represents the Vincentown aquifer—because the model layer is not present downdip and the small horizontal hydraulic conductivity value allowed for the lateral connection between the updip and downdip parts of the model layer and (or) a vertical connection between the model layer with the overlying and underlying model layers.

The parameters for riverbed conductance for the Delaware River cells and for streambed conductance for drains cells each have a single value. Although hydrogeologic and stream-width data could be used to justify multiple parameters

Table 6. Final horizontal hydraulic conductivity parameters for the aquifers in the calibrated New Jersey Coastal Plain groundwater-flow model.

[The number of significant figures used is based on the magnitude of the parameter value. Parameter names and zones for horizontal hydraulic conductivity for aquifers are shown in figures 9*A*–19.]

Parameter name	Parameter value (feet per day)	Model layer	Parameter name	Parameter value (feet per day)	Model layer
L1HLBC	173	1	L13DWNDIP	4	13
L3DWNDIP	63	3	L13OCMLRW3	100	13
L3OCMANOK	71	3	L13OCMLRW1	500	13
L3CKKD	26	3	L13OCMLRW2	239	13
L3MANOK	500	3	L13OCMONM1	2	13
L5UPDIP	5	5	L13OCMONM2	2	13
L5OCCHOP	1,000	5	L13DWNDPSW	8.64 E−03	13
L5RIO	23	5	L13MON	6	13
L5CHOPUPDP	22	5	L13BURLMID	16	13
L5UPDIPWES	5	5	L13MIDNE	500	13
L5OUTLIER	247	5	L13MIDSW	14	13
L5CHOPTANK	5.18 E−02	5	L15DWNDIP	1.72 E−01	15
L7UPDIP	5.18 E−01	7	L15DEFTHRU	261	15
L7UPNE	47	7	L15DEEGLS	8.04 E−01	15
L7MIDUP	4.32 E−02	7	L15EGLSCA1	6	15
L7MIDDWN	6	7	L15OCEGLS1	1,000	15
L7800FT	78	7	L15OCEGLS3	432	15
L7CALVERT	24	7	L15OCEGLS2	1,000	15
L7OCCALVR	333	7	L15EGLS	86	15
L7OCKRKD1	136	7	L15MIDNE	1	15
L7OCKRKD3	1,002	7	L15MIDSW	3	15
L7OCKRKD2	1,002	7	L17DWNDIP	21	17
L9UPDIP	2	9	L17CA1	66	17
L9ATLCAPE	8	9	L17BURL	69	17
L9DEPNPN	4	9	L17DEMAGOT	2	17
L9PNPN	3	9	L17GLOU	69	17
L9DEUPDIP	3	9	L17OUTCCA1	500	17
L9DWNDIP	9	9	L17SALEM	21	17
L9CUMB	2	9	L17OCMAG1	107	17
L9SALCUMB	4	9	L17MAGMID	6	17
L9OCEAN	2	9	L17OCSAL	1,002	17
L11DWNDIP	1.73 E−02	11	L17OUTCCA2	1,000	17
L11RANCOC	500	11	L19SALEM	4	19
L11VNCNNE	6.72 E−01	11	L19DNDIP	78	19
L11OCVNCN4	579	11	L19OCUPTPS	461	19
L11OCRANCO	500	11	L19UPTPSCO	7.78 E−01	19
L11OCVNCN2	500	11	L19CA2	104	19
L11OCVNCN1	500	11	L19CA1	78	19
L11OCVNCN3	579	11	L19OCCA2	500	19
L11RANDDIP	72	11	L19OUTCCA1	100	19
L11MIDDPSW	2	11	L21DWNDIP	3.06 E−02	21
L11MIDDPNE	2.59 E−01	11	L21CA2	47	21
L11RANCMD	407	11	L21PATUX	3	21
L11VNCNSW	6.72 E−01	11	L21UPDIP	52	21
L13SALGLO	13	13	L21OCPATX2	43	21
L13BURL	4	13	L21SALEM	2.64 E−01	21
L13DEMLRW	8.02 E−01	13			

Table 7. Final horizontal hydraulic conductivity parameters for confining units in the calibrated New Jersey Coastal Plain groundwater-flow model.

[The number of significant figures used is based on the magnitude of the parameter value.]

Parameter name	Parameter value (feet per day)	Model layer	Parameter name	Parameter value (feet per day)	Model layer
CU2	7.43 E−04	2	CU12SEVERN	1.14 E−06	12
CU2UPCHES	1,000	2	CU12OCSEV1	7.10 E−03	12
CU2DNDIP	1.00 E−06	2	CU12OCNVS3	228	12
CU4DWNDIP	1.65 E−04	4	CU12OCNVS2	308	12
CU4OCSTMAR	448	4	CU12SEVMD	1.12 E−06	12
CU4CAPEMAY	3.29 E−02	4	CU12SAGLMD	1.99 E−06	12
CU4CM	8.64 E−07	4	CU12CABUMD	1.00 E−06	12
CU4OUTLIER	247	4	CU12BURLUD	1.00 E−06	12
CU4STMARY	5.87 E−02	4	CU14DWNDIP	8.64 E−05	14
CU4ACMID	3.58 E−05	4	CU14UPDIP	4.75 E−05	14
CU4UPDIP	5	4	CU14OCR3	20	14
CU6DWNDIP	1.00 E−06	6	CU14OCR2	20	14
CU6LCHES	2.25 E−06	6	CU14OCMAT1	2.48 E−03	14
CU6CAPEALT	1.62 E−04	6	CU14MATAWN	1.00 E−02	14
CU6CM	1.12 E−05	6	CU14OCR1	105	14
CU6UPDIP	5	6	CU14UPDPSW	3.46 E−03	14
CU6COAST	1.17 E−04	6	CU14MIDNE	8.64 E−06	14
CU6OUTLIER	247	6	CU14DEUPDP	9	14
CU6OCLCHE3	72	6	CU14OCMAT2	4.26 E−03	14
CU6OCLCHE1	72	6	CU16DWNDP	1.00 E−06	16
CU6ACMID	2.97 E−04	6	CU16MDDPSW	1.00 E−06	16
CU6OCMID	3.79 E−01	6	CU16MDDPNE	1.00 E−06	16
CU6OCLCHE2	72	6	CU16NWCP	1.00 E−06	16
CU8BASEKRK	2.71 E−04	8	CU16DE	1.00 E−06	16
CU8OCCALV2	106	8	CU16SECP	1.00 E−06	16
CU8UPDIP	8.32 E−04	8	CU16OUTC2	8	16
CU8DWNDIP	2.82 E−02	8	CU16SOC	1.00 E−06	16
CU8CALVERT	1.11 E−05	8	CU16OUTC3	20	16
CU8ALTCUMB	1.00 E−06	8	CU16MATAWN	1.77 E−05	16
CU8OCCALV3	106	8	CU16OUTC1	19	16
CU8OCCALV1	106	8	CU18CP	3.67 E−04	18
CU10ATLCMB	1.05 E−06	10	CU18DNDIP	1.03 E−06	18
CU10DWNDIP	2.09 E−06	10	CU18DEOC1	2	18
CU10DEUPD1	1	10	CU18UPDIP	1.83 E−03	18
CU10OCMAN2	1,000	10	CU18UPDPSW	1.83 E−04	18
CU10NAEMOY	2.30 E−06	10	CU18DEOC2	1,000	18
CU10UPDIP	3.65 E−03	10	CU18DE	1.00 E−06	18
CU10OCMAN1	64	10	CU18DEOC3	207	18
CU10DEUPD2	1	10	CU20DWNDIP	4.84 E−02	20
CU10UPDPSW	3.65 E−03	10	CU20DWNSW	4.84 E−02	20
CU10NOCBRL	6.15 E−05	10	CU20DEOC1	8	20
CU12DWNDIP	1.76 E−03	10	CU20SAL	1.00E−06	20
CU12MON	4.80 E−02	12	CU20DEOC2	8	20
CU12OCSEV2	7.10 E−03	12	CU20DE	1.95 E−04	20
CU12SALGLO	2.25 E−03	12	CU20GLOCAM	2.76 E−01	20
CU12OCNVS1	20	12			

Table 8. Final vertical hydraulic conductivity parameters in the calibrated New Jersey Coastal Plain groundwater-flow model.

[The number of significant figures used is based on the magnitude of the parameter value. Parameter names and zones for vertical hydraulic conductivity for confining units are shown in figures 9*B*–18*B*.]

Parameter name	Parameter value (feet per day)	Model layer	Parameter name	Parameter value (feet per day)	Model layer	Parameter name	Parameter value (feet per day)	Model layer
VK1HLBC	9	1	VK10ATLCMB	1.05 E–07	10	VK15DWNDIP	1.72 E–02	15
VK2	3.54 E–04	2	VK10DWNDIP	2.09 E–07	10	VK15DEFTHR	15	15
VK2UPCHES	100	2	VK10DEUPD1	1.19 E–01	10	VK15DEEGLS	1.67 E–03	15
VK2DNDIP	1.00 E–06	2	VK10OCMAN2	3	10	VK15EGLCA1	6.48 E–01	15
VK3DWNDIP	6	3	VK10NAEMOY	8.36 E–04	10	VK15OCEGL1	500	15
VK3OCMANOK	4	3	VK10UPDIP	1.56 E–02	10	VK15OCEGL3	43	15
VK3CKKD	4	3	VK10OCMAN1	2.90 E–01	10	VK15OCEGL2	6	15
VK3MANOK	50	3	VK10DEUPD2	1.19 E–01	10	VK15EGLS	9	15
VK4DWNDIP	4.34 E–06	4	VK10NOCBRL	4.73 E–07	10	VK15MIDNE	4	15
VK4OCSTMAR	4.69 E–01	4	VK10UPDPSW	2.07 E–05	10	VK15MIDSW	5	15
VK4CAPEMAY	7.39 E–07	4	VK11DWNDIP	5.18 E–02	11	VK16NWCP	1.13 E–07	16
VK4CM	1.39 E–06	4	VK11RANCOC	2.59 E–02	11	VK16DE	1.78 E–05	16
VK4OUTLIER	100	4	VK11VNCNNE	5.50 E–01	11	VK16SECP	1.00 E–06	16
VK4STMARY	5	4	VK11OCVNC4	58	11	VK16OUTC2	1	16
VK4UPDIP	5	4	VK11OCRANC	100	11	VK16OC	1.00 E–06	16
VK4ACMID	1.27 E–06	4	VK11OCVNC2	58	11	VK16OUTC3	2	16
VK5UPDIP	5	5	VK11OCVNC1	58	11	VK16MATAWN	3.37 E–06	16
VK5OCCHOP	100	5	VK11OCVNC3	58	11	VK16OUTC1	2	16
VK5RIO	8.64 E–01	5	VK11RANDDP	4	11	VK16DWNDP	1.12 E–06	16
VK5CHOPTNK	5.18 E–03	5	VK11VNCNSW	5.95 E–02	11	VK16MDDPSW	1.00 E–06	16
VK5CHOPUPD	2	5	VK11MDDPSW	6.05 E–02	11	VK16MDDPNE	1.00 E–06	16
VK5UPDIPWE	5.37 E–01	5	VK11MDDPNE	2.59 E–02	11	VK17DWNDIP	2	17
VK5OUTLIER	34	5	VK11RANCMD	41	11	VK17CA1	8	17
VK6DWNDIP	1.00 E–06	6	VK12DWNDIP	1.73 E–03	12	VK17BURL	7	17
VK6LCHES	7.12 E–07	6	VK12MON	8.73 E–05	12	VK17DEMAGO	6.05 E–01	17
VK6CAPEALT	1.62 E–05	6	VK12OCSEV2	7.10 E–03	12	VK17GLOU	7	17
VK6CM	3.99 E–05	6	VK12SALGLO	2.25 E–03	12	VK17OCCA1	17	17
VK6UPDIP	5	6	VK12OCNVS1	9.42 E–05	12	VK17SALEM	2	17
VK6COAST	1.29 E–05	6	VK12SEVERN	1.14 E–06	12	VK17OCMAG1	26	17
VK6OUTLIER	1,000	6	VK12OCSEV1	7.10 E–03	12	VK17MAGMID	5	17
VK6OCLCHE3	7	6	VK12OCNVS3	4	12	VK17OCSAL	100	17
VK6OCLCHE1	7	6	VK12OCNVS2	4	12	VK17OCCA2	100	17
VK6OCLCHE2	7	6	VK12SEVMD	1.12 E–06	12	VK18CP	1.57 E–04	18
VK6ACMID	1.81 E–04	6	VK12SAGLMD	7.25 E–06	12	VK18DNDIP	1.03 E–06	18
VK6OCMID	6.32 E–01	6	VK12CABUMD	1.00 E–06	12	VK18DEOC1	1.87 E–01	18
VK7UPDIP	5.37 E–01	7	VK12BURLUD	1.00 E–03	12	VK18UPDIP	3.04 E–03	18
VK7UPNE	24	7	VK13SALGLO	1	13	VK18UPDPSW	1.83 E–04	18
VK7MIDUP	4.32 E–01	7	VK13MON	6.05 E–01	13	VK18DEOC2	100	18
VK7MIDDWN	8	7	VK13DEMLRW	8.04 E–02	13	VK18DE	1.00 E–06	18
VK7800FT	2	7	VK13DWNDIP	3.64 E–03	13	VK18DEOC3	21	18
VK7CALVERT	9	7	VK13OCMLR3	3	13	VK19SALEM	4.32 E–01	19
VK7OCCALVR	100	7	VK13OCMLR1	4	13	VK19DNDIP	2	19
VK7OCKRKD1	4.83 E–01	7	VK13OCMLR2	14	13	VK19OCUPTP	23	19
VK7OCKRKD3	100	7	VK13OCMON1	3.88 E–01	13	VK19UPTPSC	7.78 E–02	19
VK7OCKRKD2	100	7	VK13OCMON2	1.61 E–01	13	VK19CA2	10	19
VK8BASEKRK	2.59 E–04	8	VK13MIDNE	38	13	VK19CA1	8	19
VK8OCCALV2	11	8	VK13MIDSW	1	13	VK19OCCA1	11	19

Table 8. Final vertical hydraulic conductivity parameters in the calibrated New Jersey Coastal Plain groundwater-flow model.—Continued

[The number of significant figures used is based on the magnitude of the parameter value. Parameter names and zones for vertical hydraulic conductivity for confining units are shown in figures 9*B*–18*B*.]

Parameter name	Parameter value (feet per day)	Model layer	Parameter name	Parameter value (feet per day)	Model layer	Parameter name	Parameter value (feet per day)	Model layer
VK8UPDIP	4.50 E–03	8	VK13DWNDSW	8.64 E–04	13	VK19OCCA2	49	19
VK8DWNDIP	1.09 E–04	8	VK13BURL	4.32 E–01	13	VK20DWNDIP	4.84 E–02	20
VK8CALVERT	1.00 E–07	8	VK13BURLMD	2	13	VK20DWNSW	4.84 E–02	20
VK8ALTCUMB	1.00 E–07	8	VK14DWNDIP	8.64 E–05	14	VK20DEOC1	8.23 E–01	20
VK8OCCALV3	11	8	VK14UPDIP	4.75 E–05	14	VK20SAL	1.00 E–06	20
VK8OCCALV1	11	8	VK14OCR3	2	14	VK20DEOC2	8.23 E–01	20
VK9UPDIP	772	9	VK14OCR2	2	14	VK20DE	1.49 E–04	20
VK9ATLCAPE	4.82 E–01	9	VK14OCMAT1	2.48 E–03	14	VK20GLOCAM	2.76 E–01	20
VK9DEPNPN	4.22 E–01	9	VK14MATAWN	1.00 E–02	14	VK21DWNDIP	3.86 E–05	21
VK9PNPN	3.46 E–01	9	VK14OCR1	20	14	VK21CA2	5	21
VK9DEUPDIP	100	9	VK14OCMAT2	4.26 E–03	14	VK21PATUX	2.59 E–01	21
VK9DWNDIP	8.64 E–01	9	VK14UPDPSW	1.90 E–06	14	VK21UPDIP	5	21
VK9CUMB	1.73 E–01	9	VK14MIDNE	1.02 E–05	14	VK21OCPAT2	6	21
VK9SALCUMB	4.32 E–01	9	VK14DEUPDP	9	14	VK21SALEM	3.67 E–01	21
VK9OCEAN	86	9						

Table 9. Final storage-coefficient parameters in the calibrated New Jersey Coastal Plain groundwater-flow model.

Confined part of model layer			Unconfined part of model layer		
Parameter name	Parameter value (dimensionless)	Model layer	Parameter name	Parameter value (dimensionless)	Model layer
SS_Par1	4.53 E–05	1	SS_Par2OC	1.50 E–01	2
SS_Par2	1.22 E–06	2	SS_Par3OC	4.00 E–01	3
SS_Par3	1.78 E–06	3	SS_Par4OC	8.86 E–04	4
SS_Par4	2.47 E–04	4	SS_Par5OC	1.50 E–01	5
SS_Par5	1.82 E–05	5	SS_Par6OC	1.96 E–01	6
SS_Par6	3.04 E–06	6	SS_Par7OC	4.00 E–01	7
SS_Par7	1.27 E–05	7	SS_Par8OC	4.00 E–01	8
SS_Par8	5.46 E–07	8	SS_Par10OC	2.23 E–04	10
SS_Par9	2.75 E–06	9	SS_Par11OC	5.80 E–06	11
SS_Par10	1.61 E–07	10	SS_Par12OC	5.58 E–03	12
SS_Par11	6.17 E–04	11	SS_Par13OC	7.27 E–05	13
SS_Par12	5.64 E–07	12	SS_Par14OC	4.76 E–03	14
SS_Par13	4.21 E–08	13	SS_Par15OC	1.33 E–04	15
SS_Par14	1.29 E–05	14	SS_Par16OC	4.00 E–01	16
SS_Par15	2.53 E–08	15	SS_Par17OC	1.79 E–06	17
SS_Par16	4.49 E–07	16	SS_Par18OC	1.50 E–01	18
SS_Par17	1.62 E–06	17	SS_Par19oc	2.37 E–05	19
SS_Par17up	1.00 E–07	17	SS_Par19O2	1.51 E–02	19
SS_Par18	5.15 E–07	18	SS_Par20OC	1.50 E–01	20
SS_Par19	9.50 E–05	19	SS_Par21OC	9.43 E–02	21
SS_Par20	3.26 E–07	21			
SS_Par21	2.88 E–07	21			

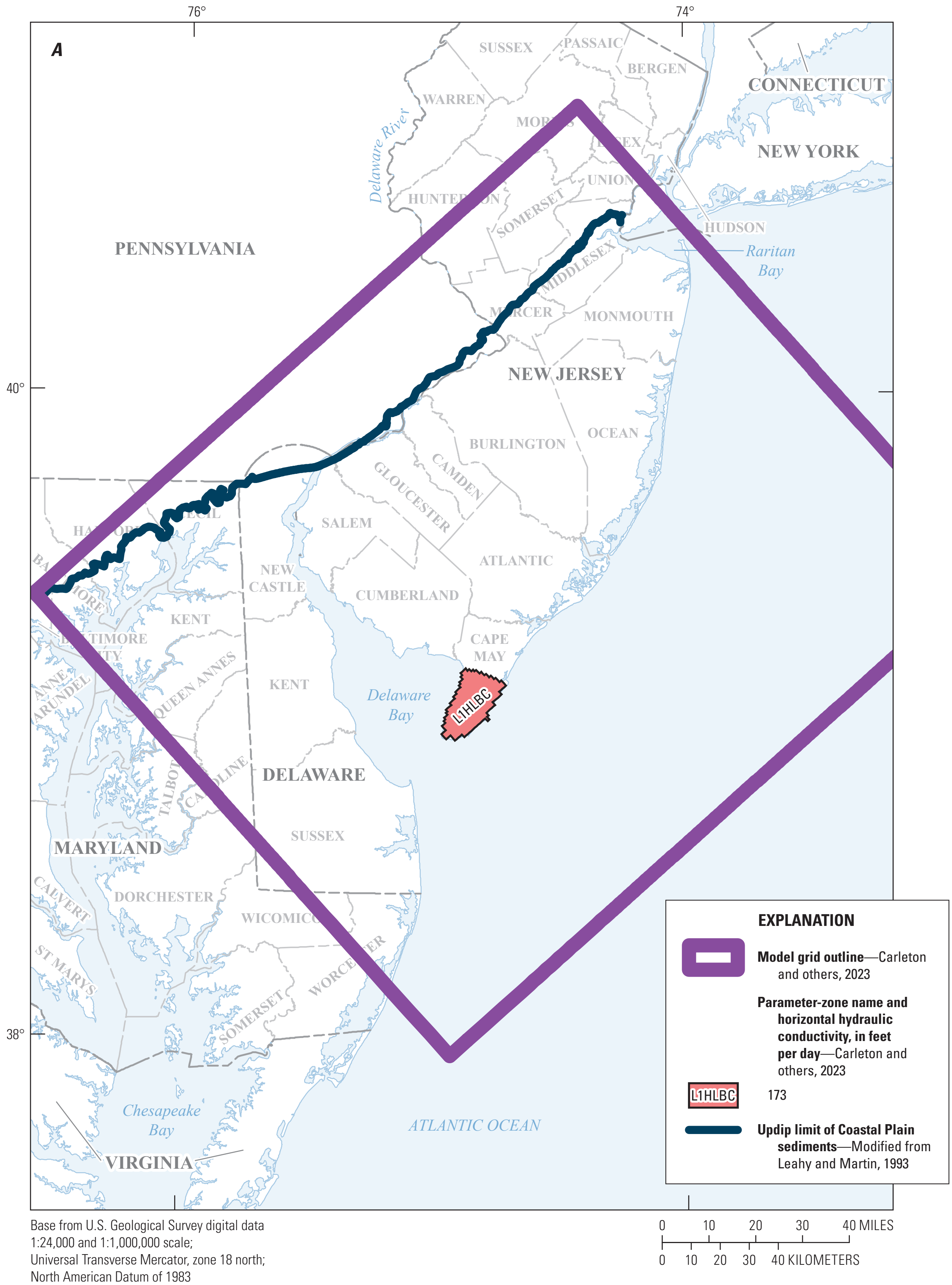


Figure 9. Maps showing *A*, horizontal hydraulic conductivity zones of model layer 1 and *B*, vertical hydraulic conductivity zones of model layer 2, in the New Jersey Coastal Plain groundwater-flow model.

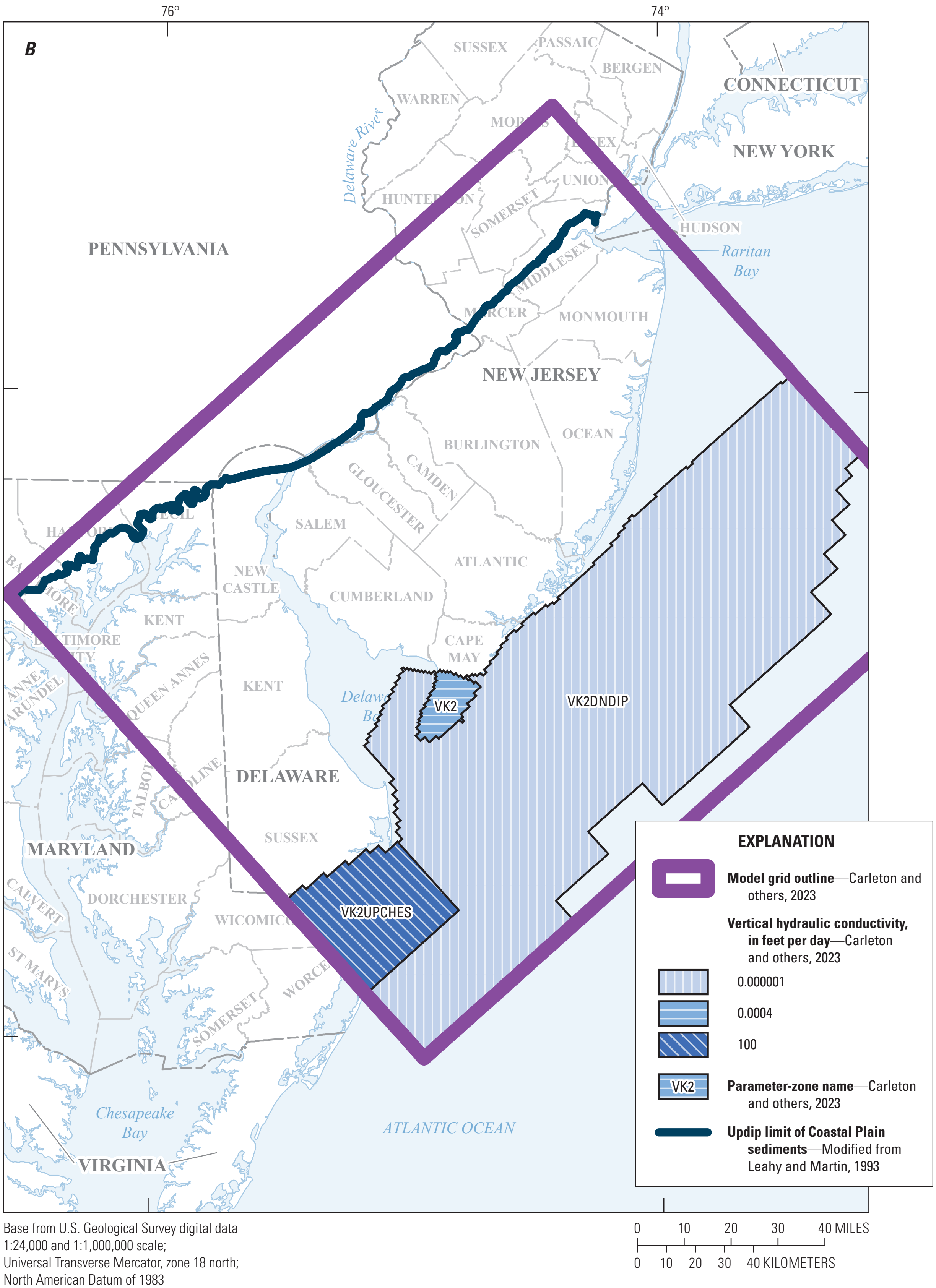


Figure 9.—Continued

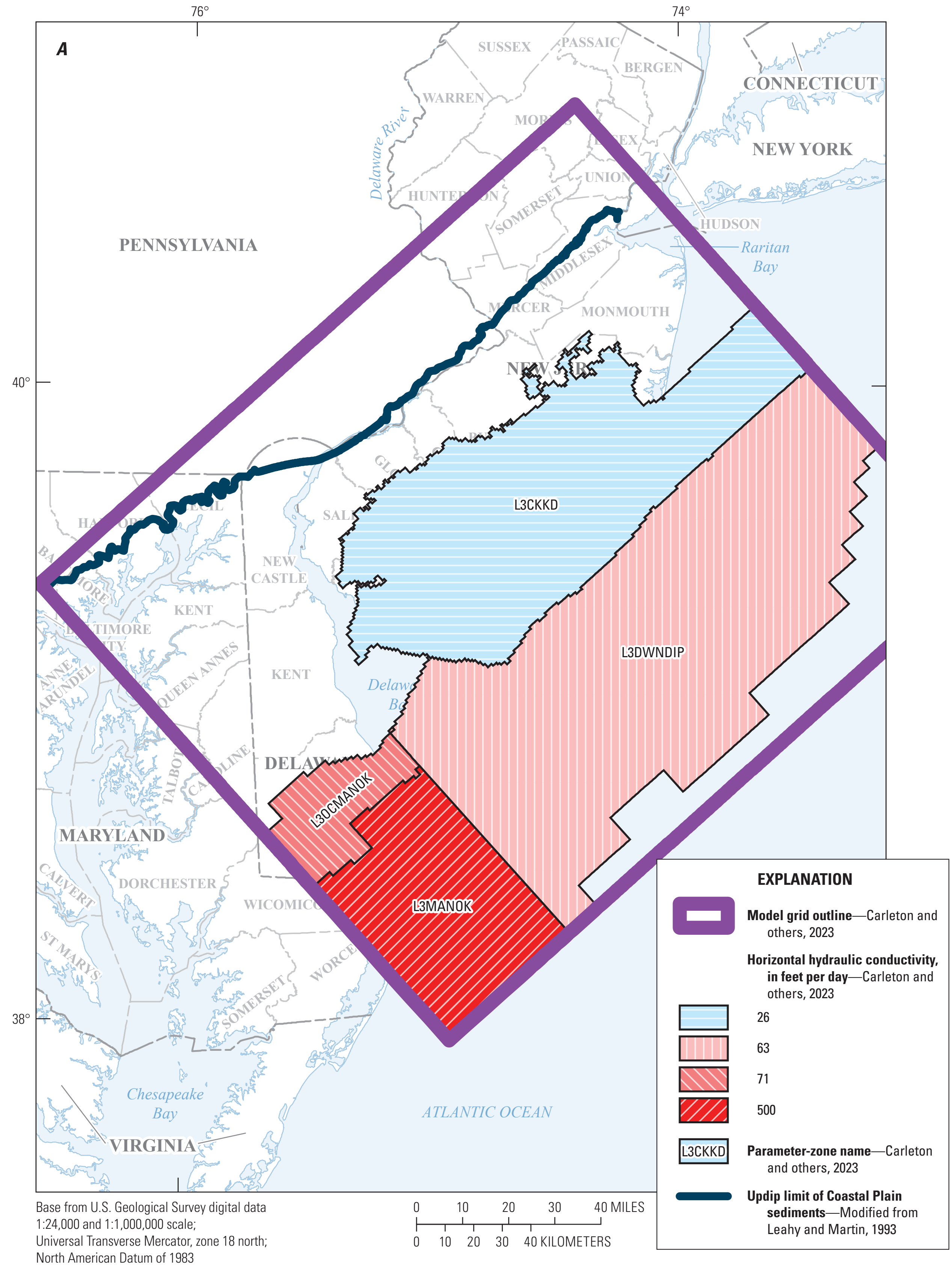


Figure 10. Maps showing *A*, horizontal hydraulic conductivity zones of model layer 3 and *B*, vertical hydraulic conductivity zones of model layer 4, in the New Jersey Coastal Plain groundwater-flow model.

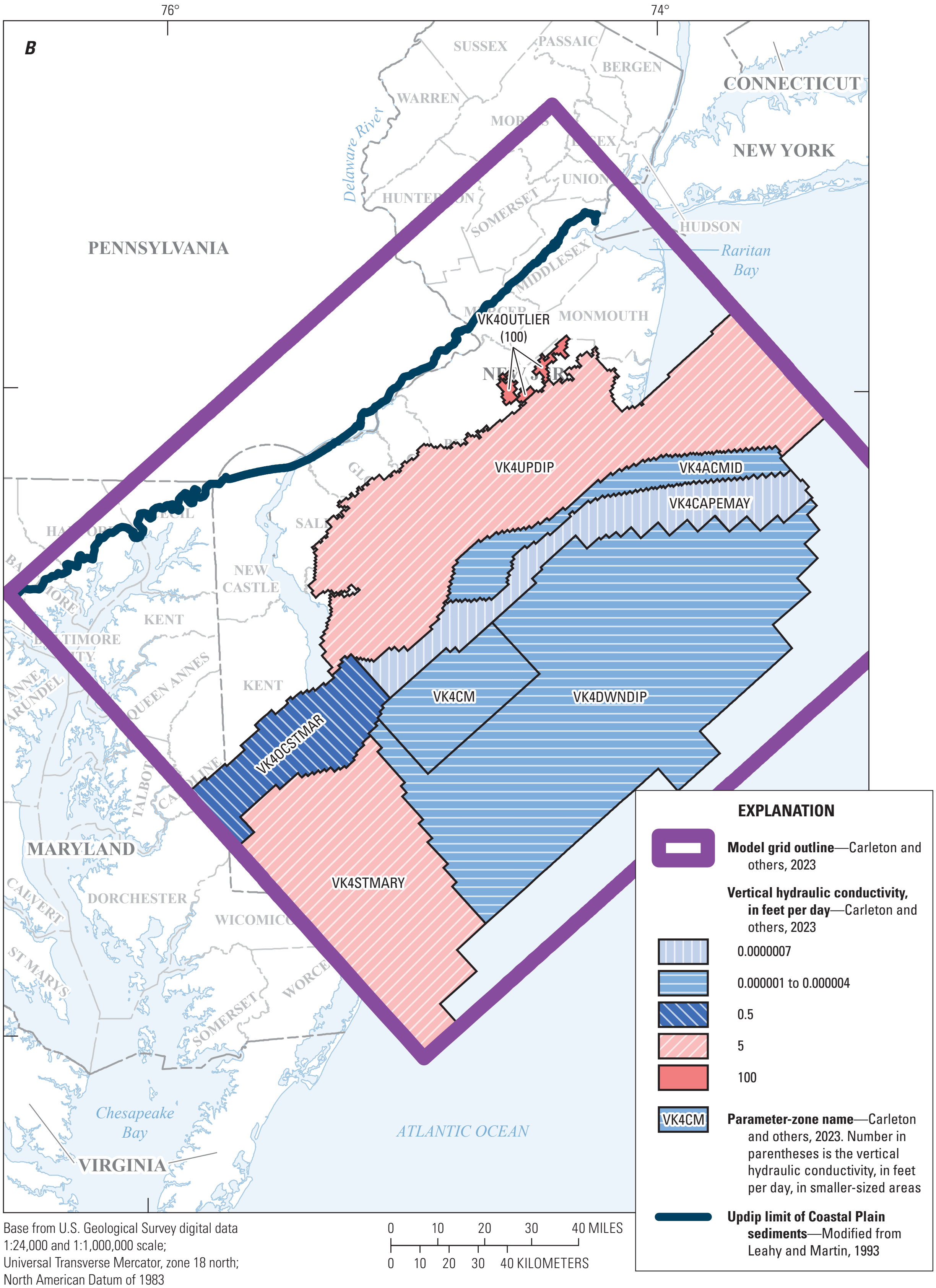


Figure 10.—Continued

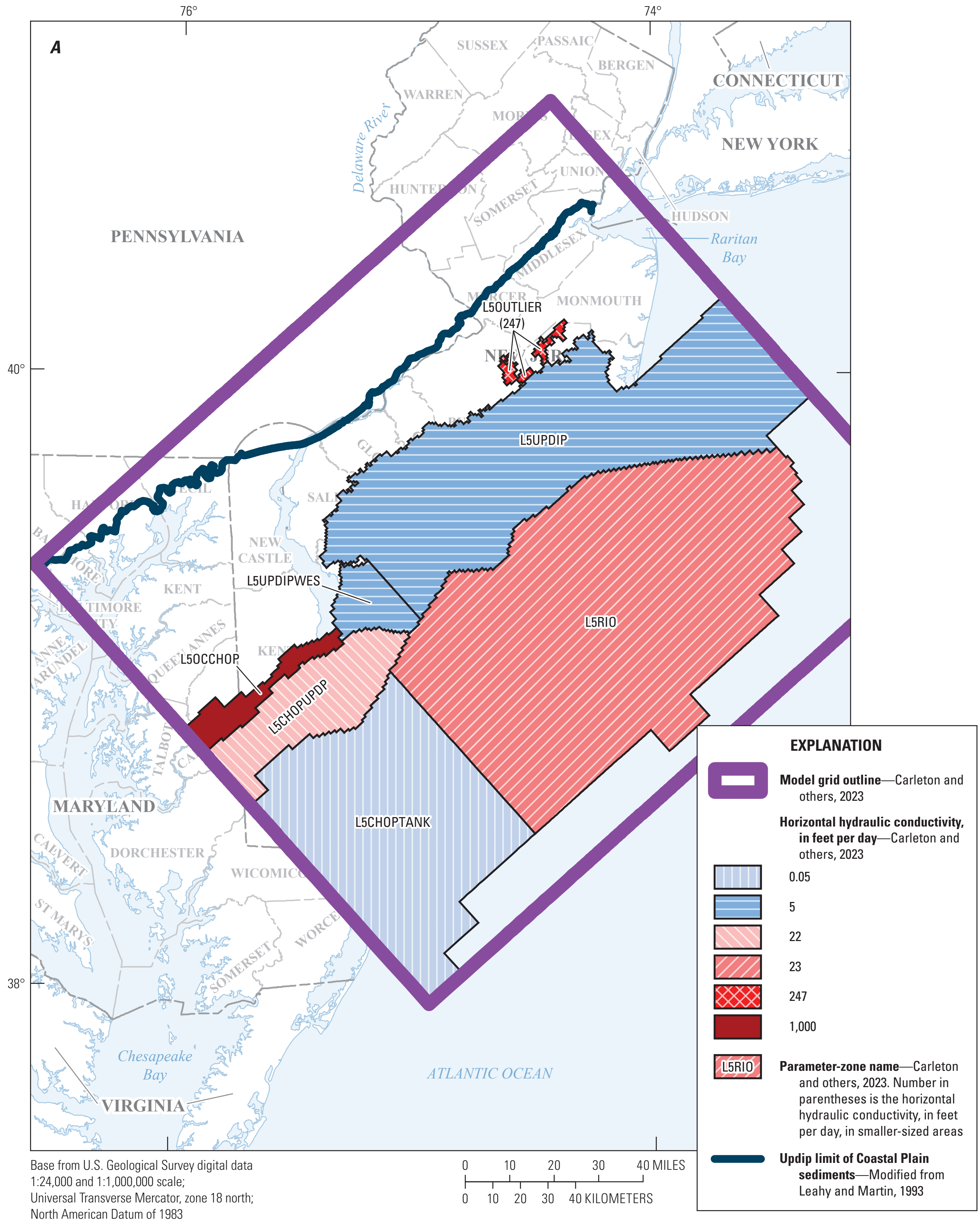
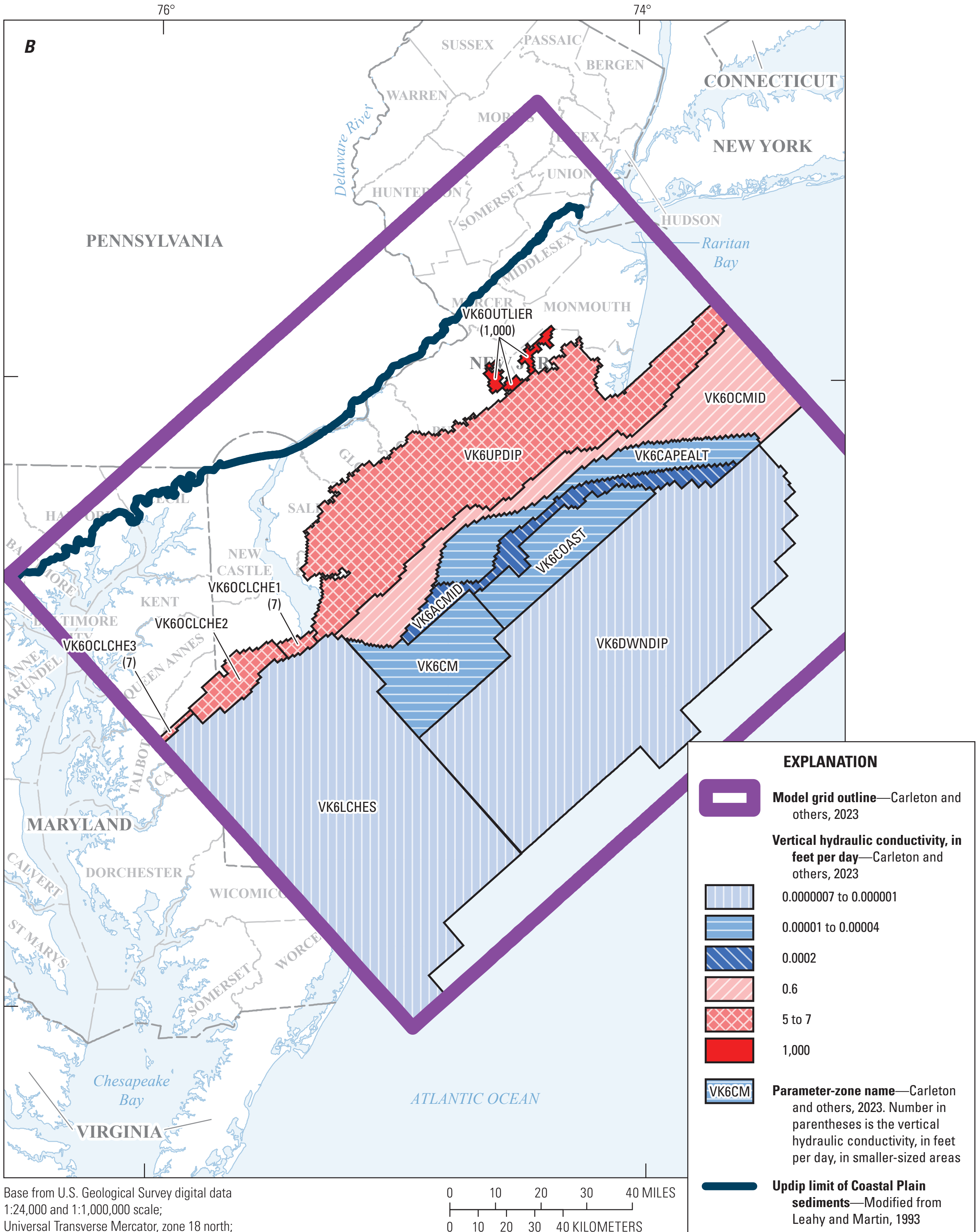
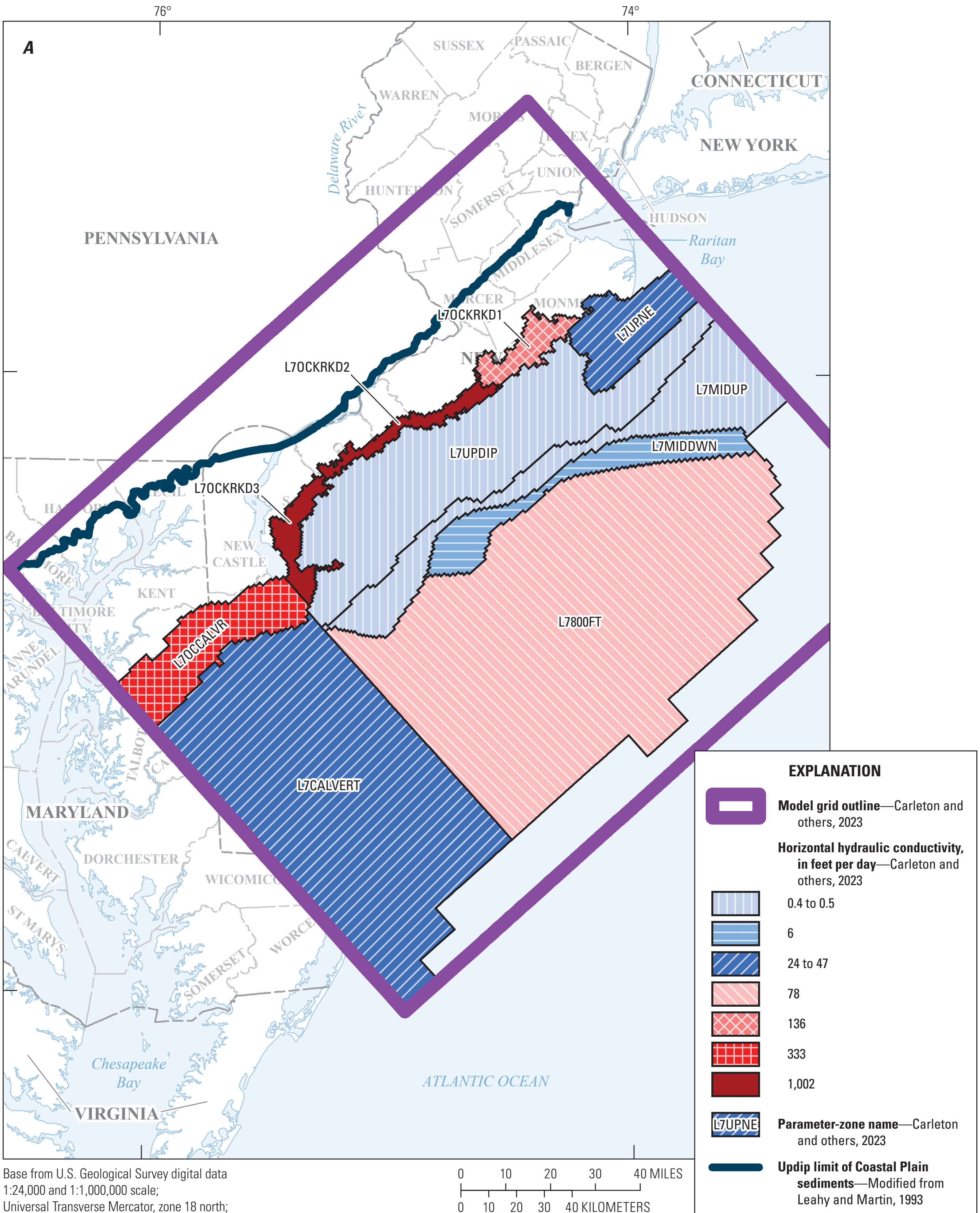


Figure 11. Maps showing *A*, horizontal hydraulic conductivity zones of model layer 5 and *B*, vertical hydraulic conductivity zones of model layer 6, in the New Jersey Coastal Plain groundwater-flow model.



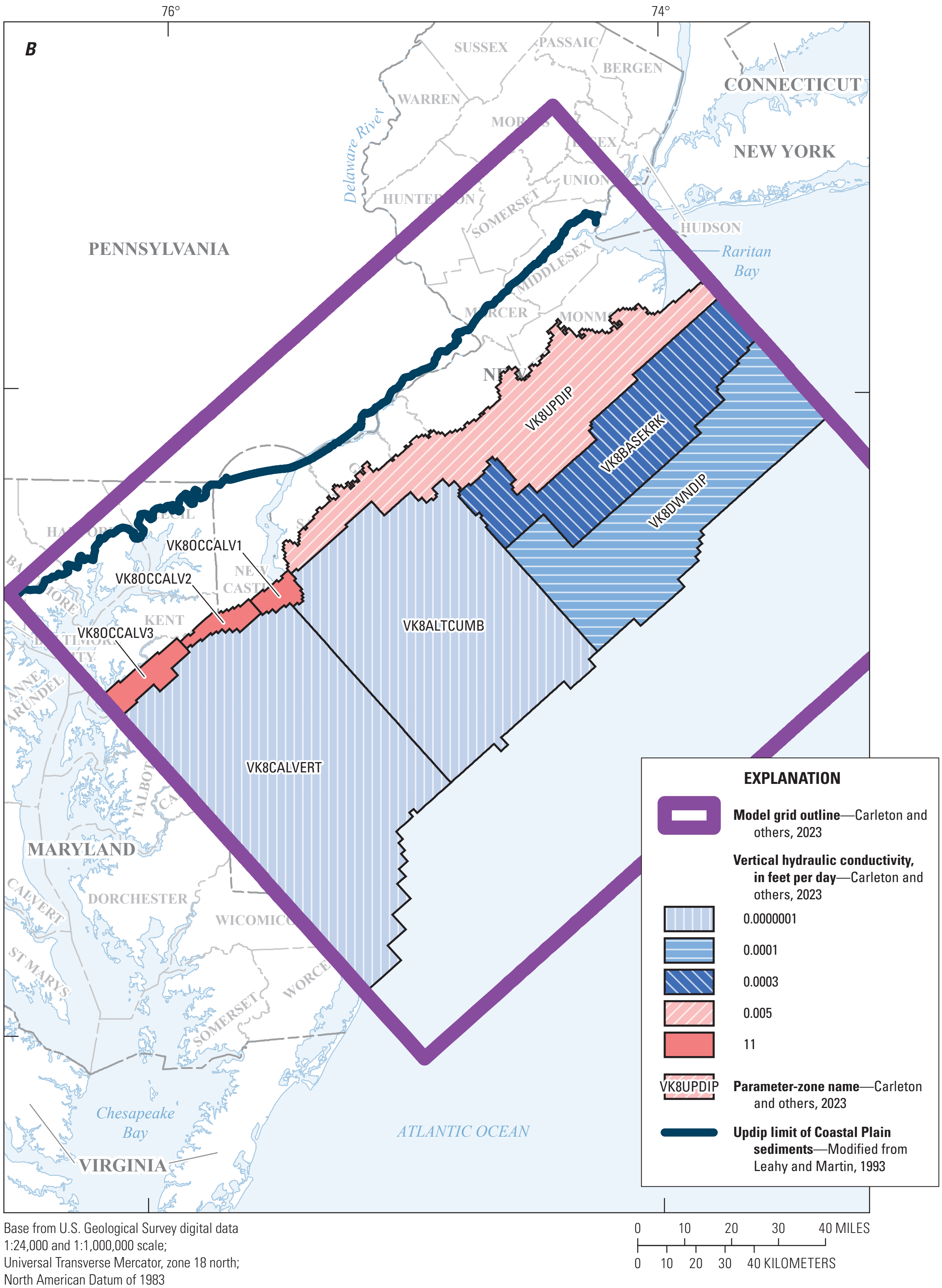
Base from U.S. Geological Survey digital data 1:24,000 and 1:1,000,000 scale;
Universal Transverse Mercator, zone 18 north;
North American Datum of 1983

Figure 11.—Continued



Base from U.S. Geological Survey digital data 1:24,000 and 1:1,000,000 scale;
Universal Transverse Mercator, zone 18 north;
North American Datum of 1983

Figure 12. Maps showing *A*, horizontal hydraulic conductivity zones of model layer 7 and *B*, vertical hydraulic conductivity zones of model layer 8, in the New Jersey Coastal Plain groundwater-flow model.



Base from U.S. Geological Survey digital data
1:24,000 and 1:1,000,000 scale;
Universal Transverse Mercator, zone 18 north;
North American Datum of 1983

Figure 12.—Continued

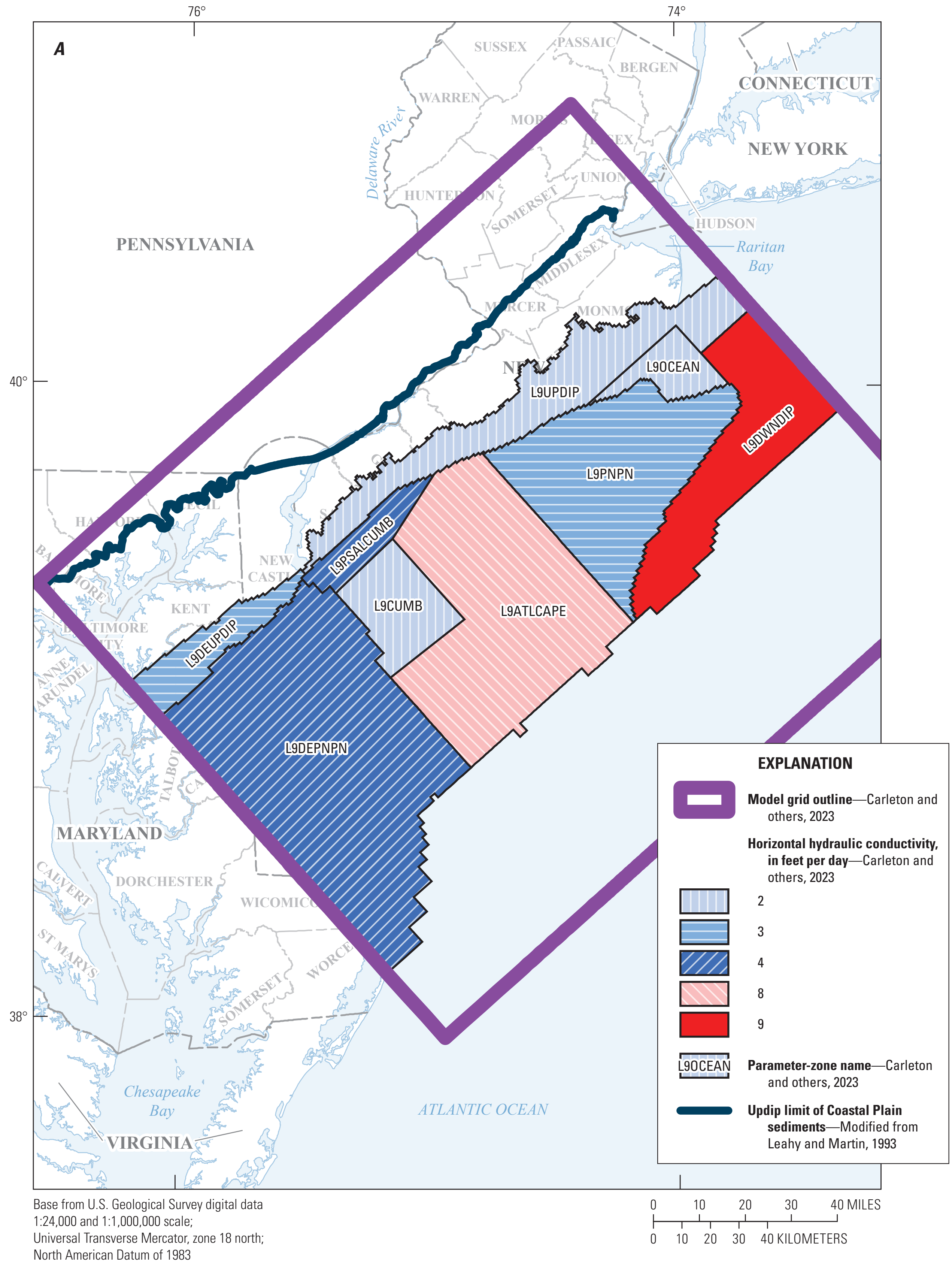
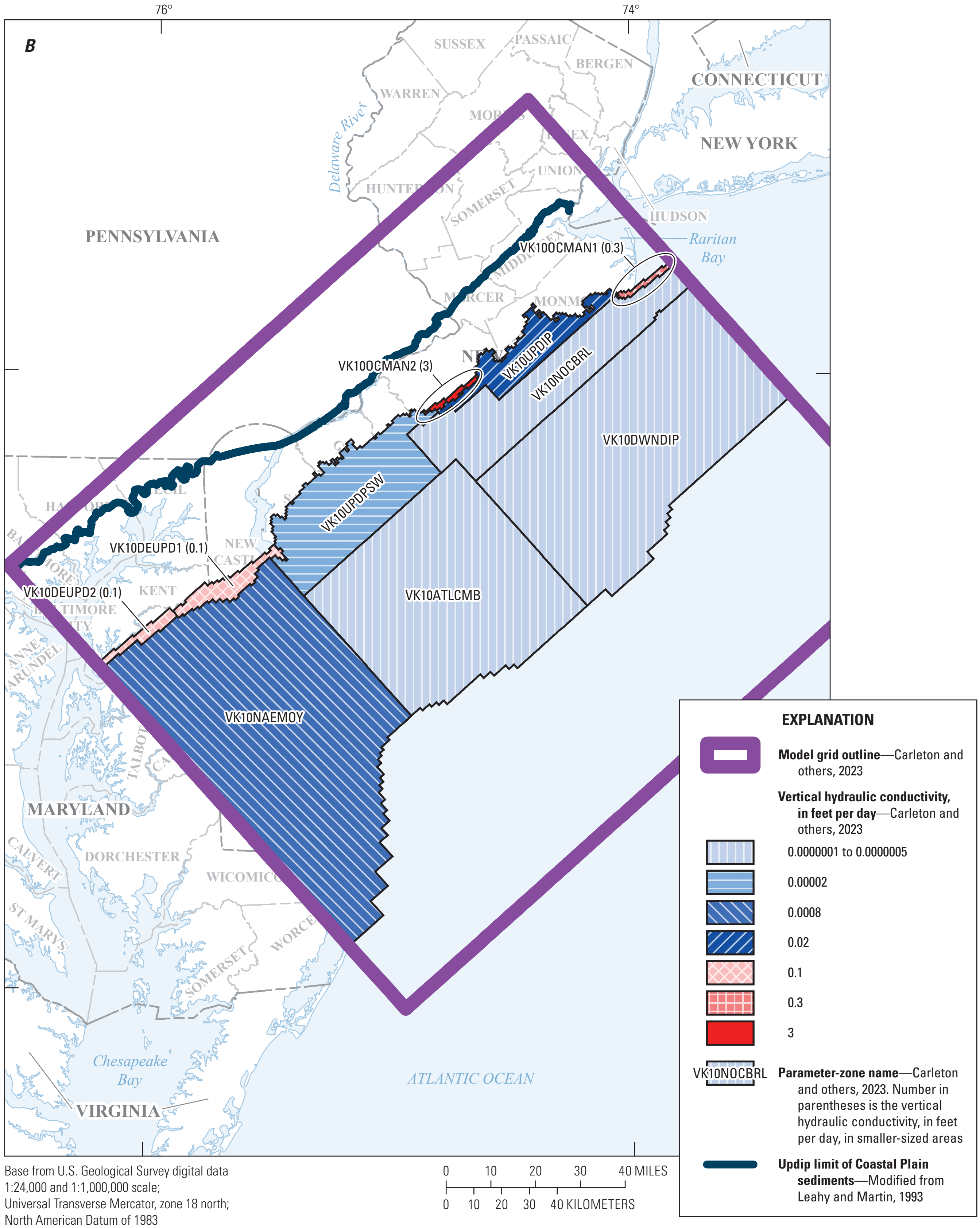


Figure 13. Maps showing *A*, horizontal hydraulic conductivity zones of model layer 9 and *B*, vertical hydraulic conductivity zones of model layer 10, in the New Jersey Coastal Plain groundwater-flow model.



Base from U.S. Geological Survey digital data 1:24,000 and 1:1,000,000 scale;
Universal Transverse Mercator, zone 18 north;
North American Datum of 1983

Figure 13.—Continued

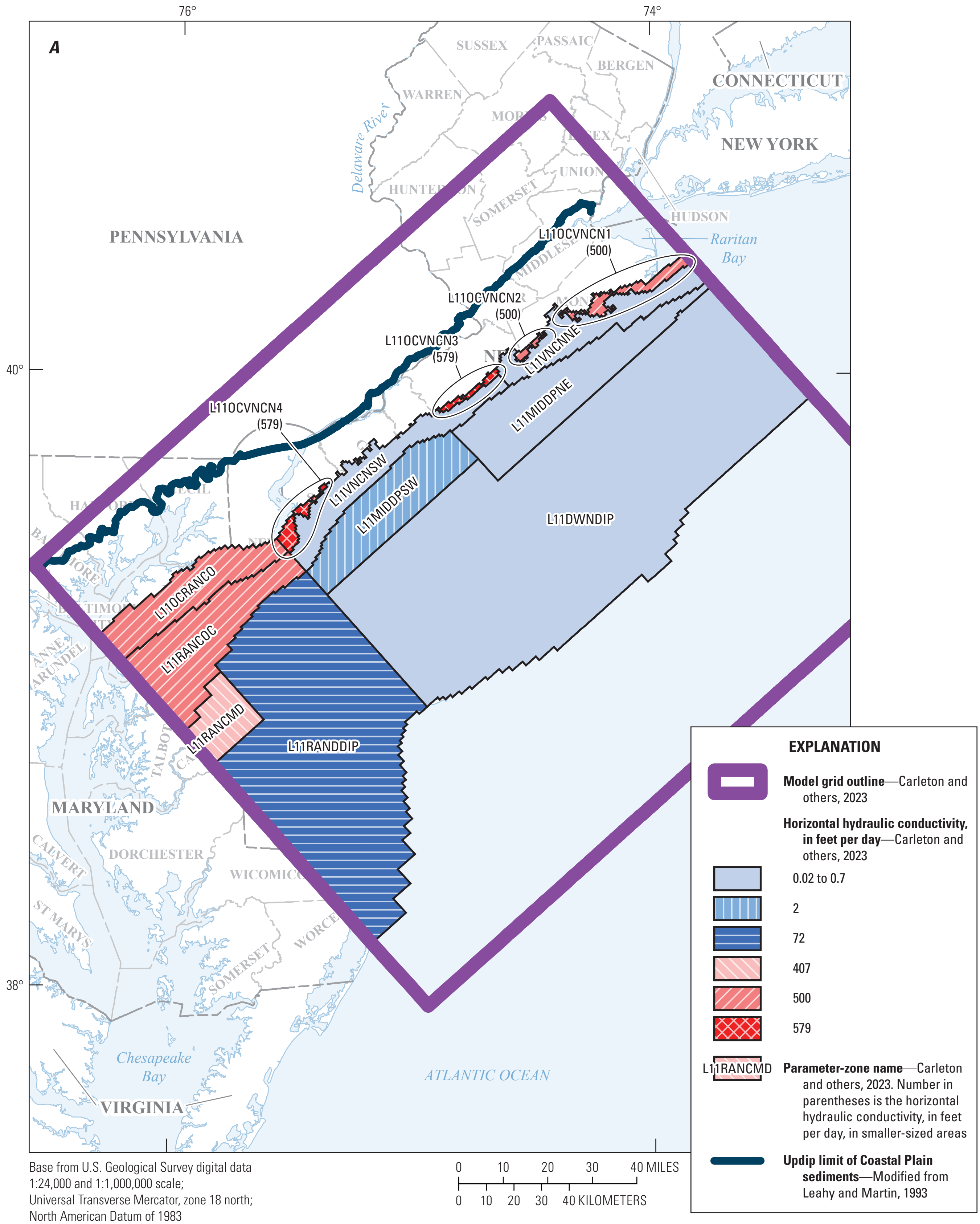


Figure 14. Maps showing *A*, horizontal hydraulic conductivity zones of model layer 11 and *B*, vertical hydraulic conductivity zones of model layer 12, in the New Jersey Coastal Plain groundwater-flow model.

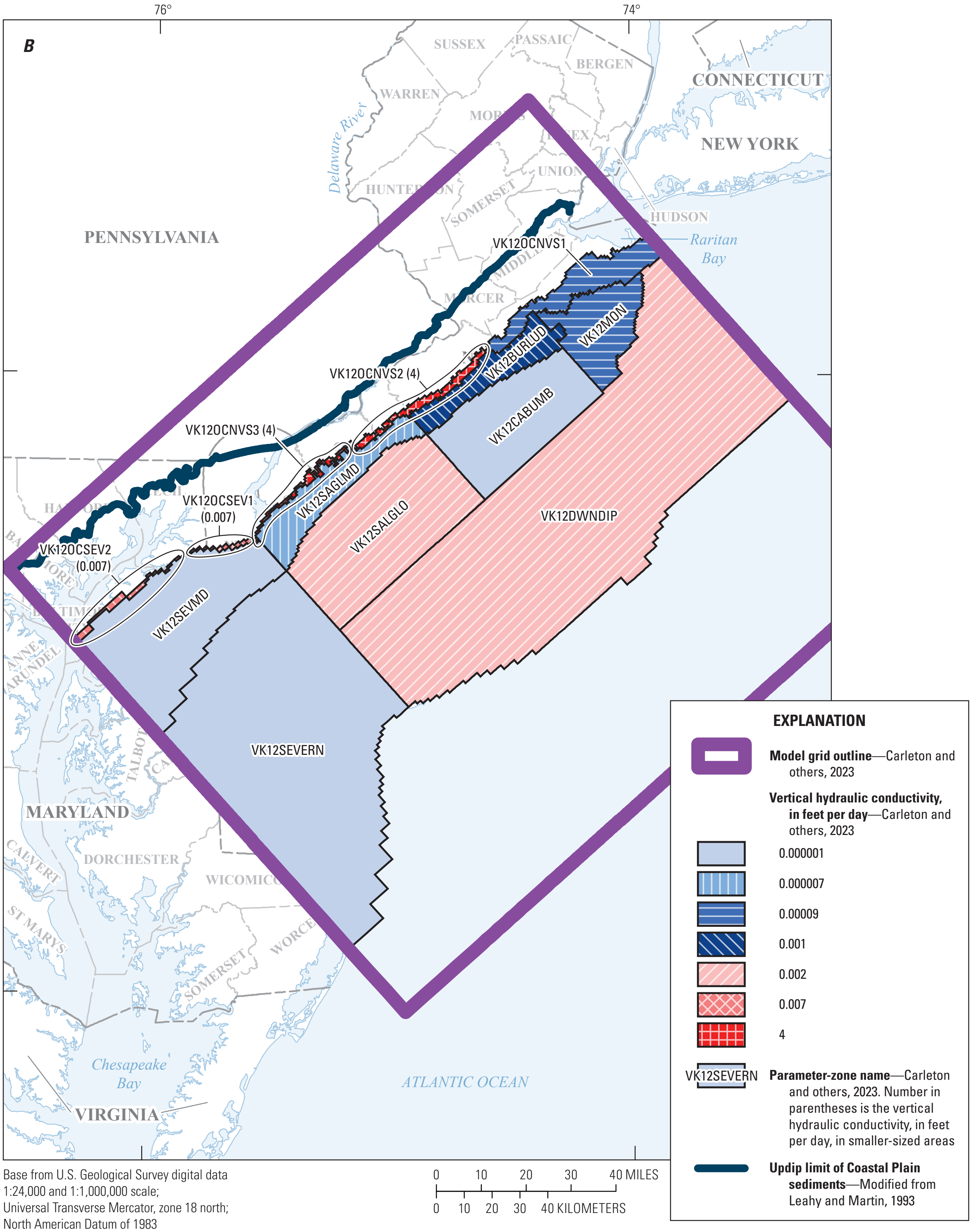
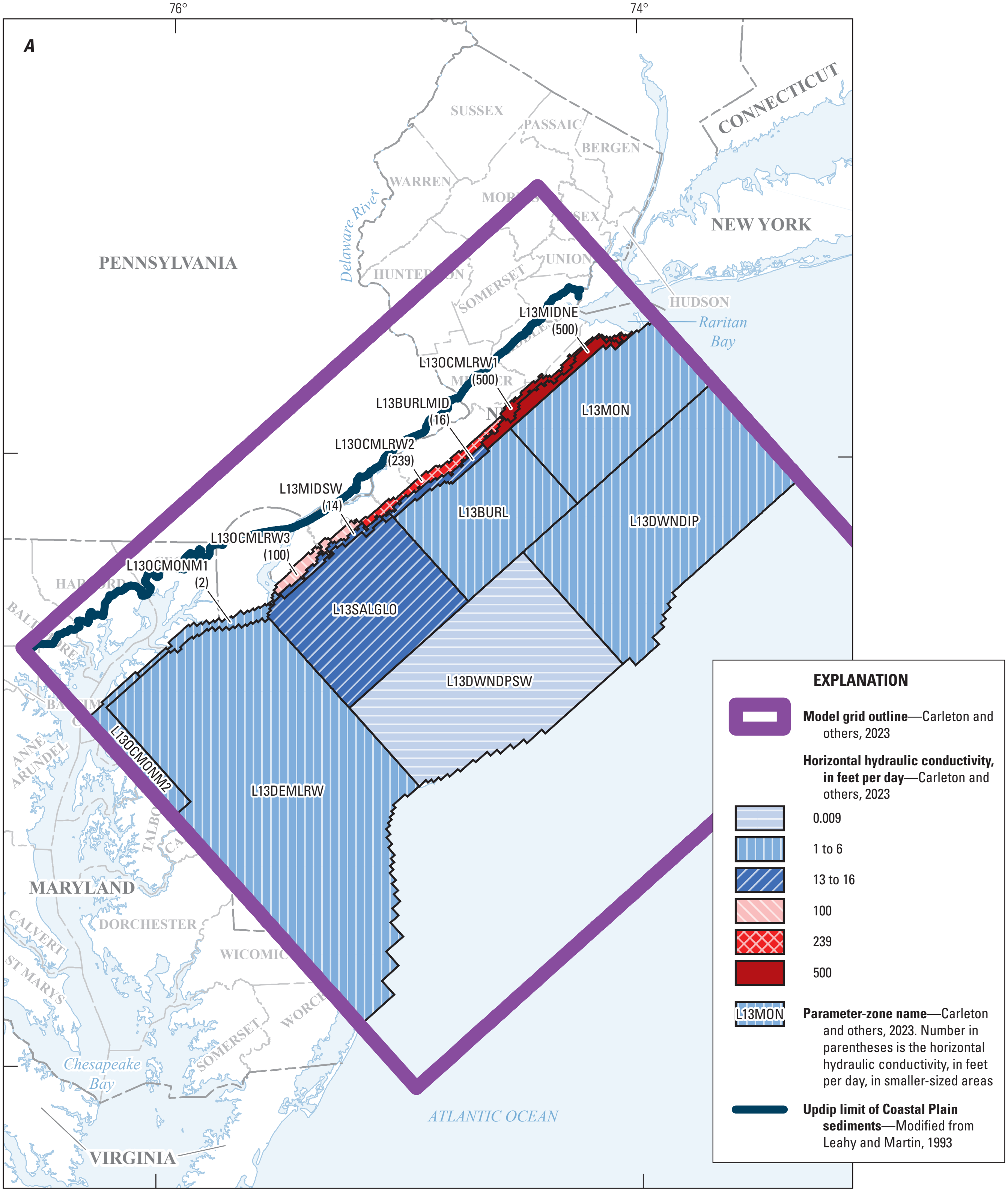


Figure 14.—Continued



Base from U.S. Geological Survey digital data
1:24,000 and 1:1,000,000 scale;
Universal Transverse Mercator, zone 18 north;
North American Datum of 1983

Figure 15. Maps showing *A*, horizontal hydraulic conductivity zones of model layer 13 and *B*, vertical hydraulic conductivity zones of model layer 14, in the New Jersey Coastal Plain groundwater-flow model.

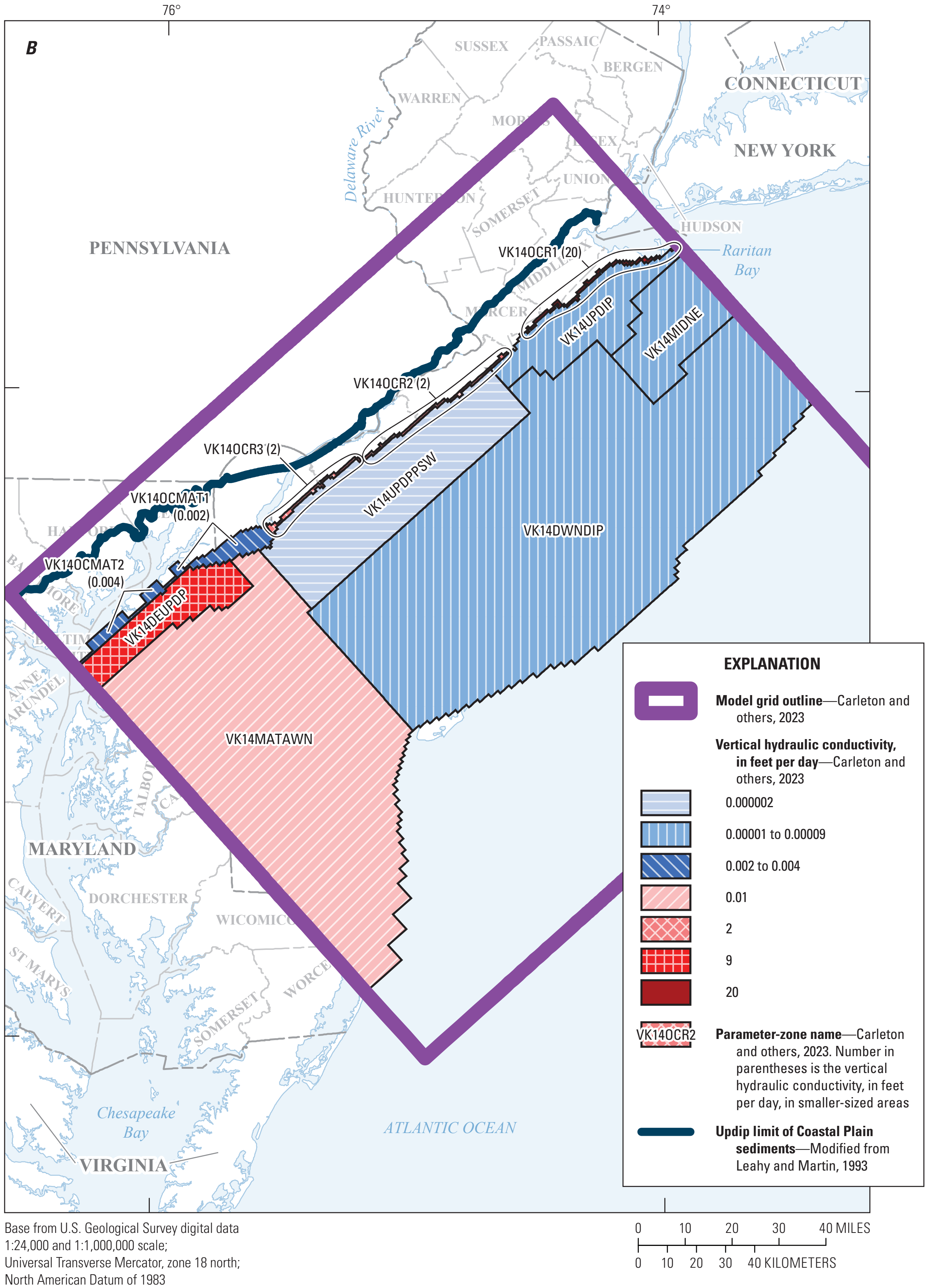


Figure 15.—Continued

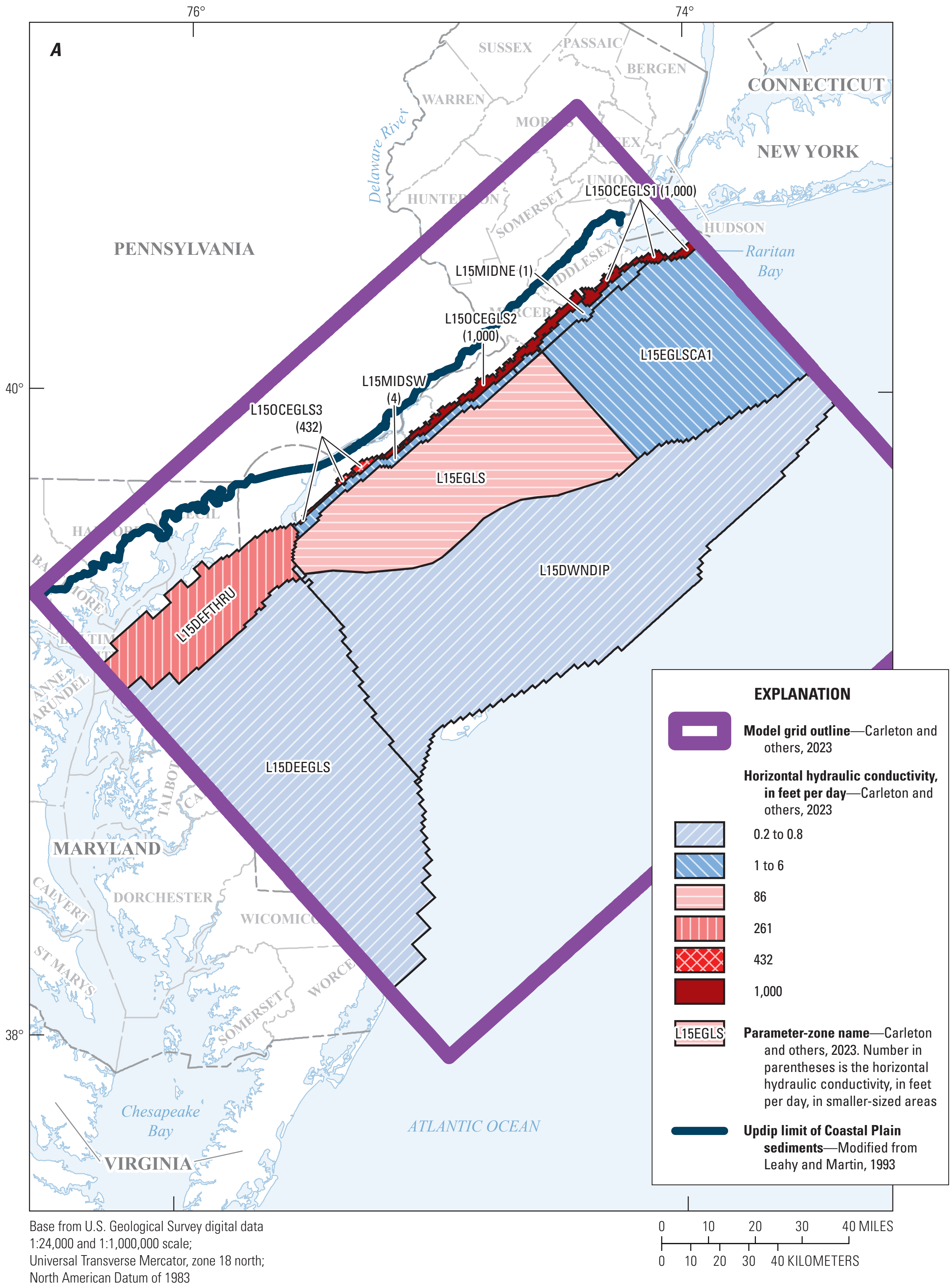


Figure 16. Maps showing *A*, horizontal hydraulic conductivity zones of model layer 15 and *B*, vertical hydraulic conductivity zones of model layer 16, in the New Jersey Coastal Plain groundwater-flow model.

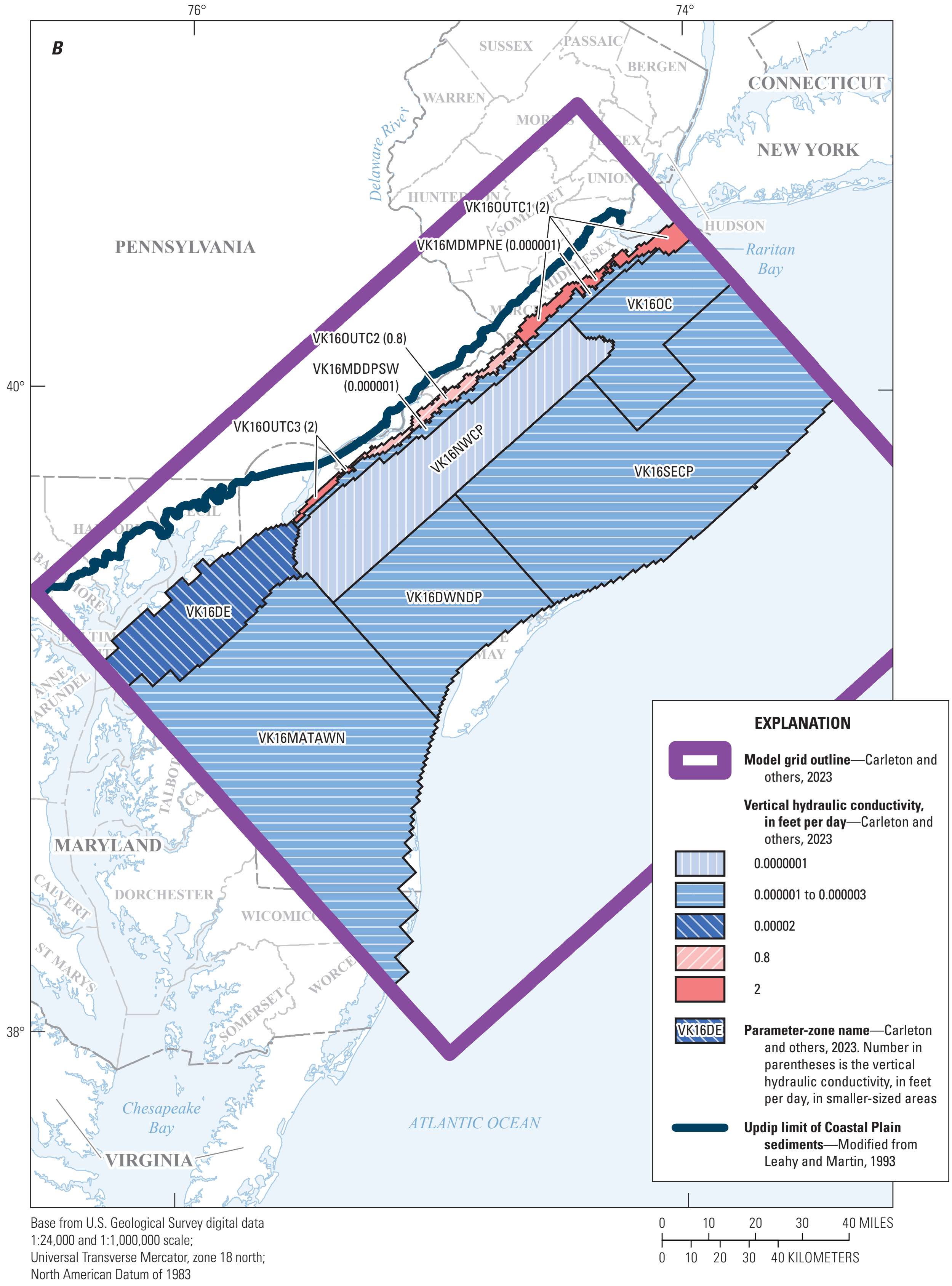


Figure 16.—Continued

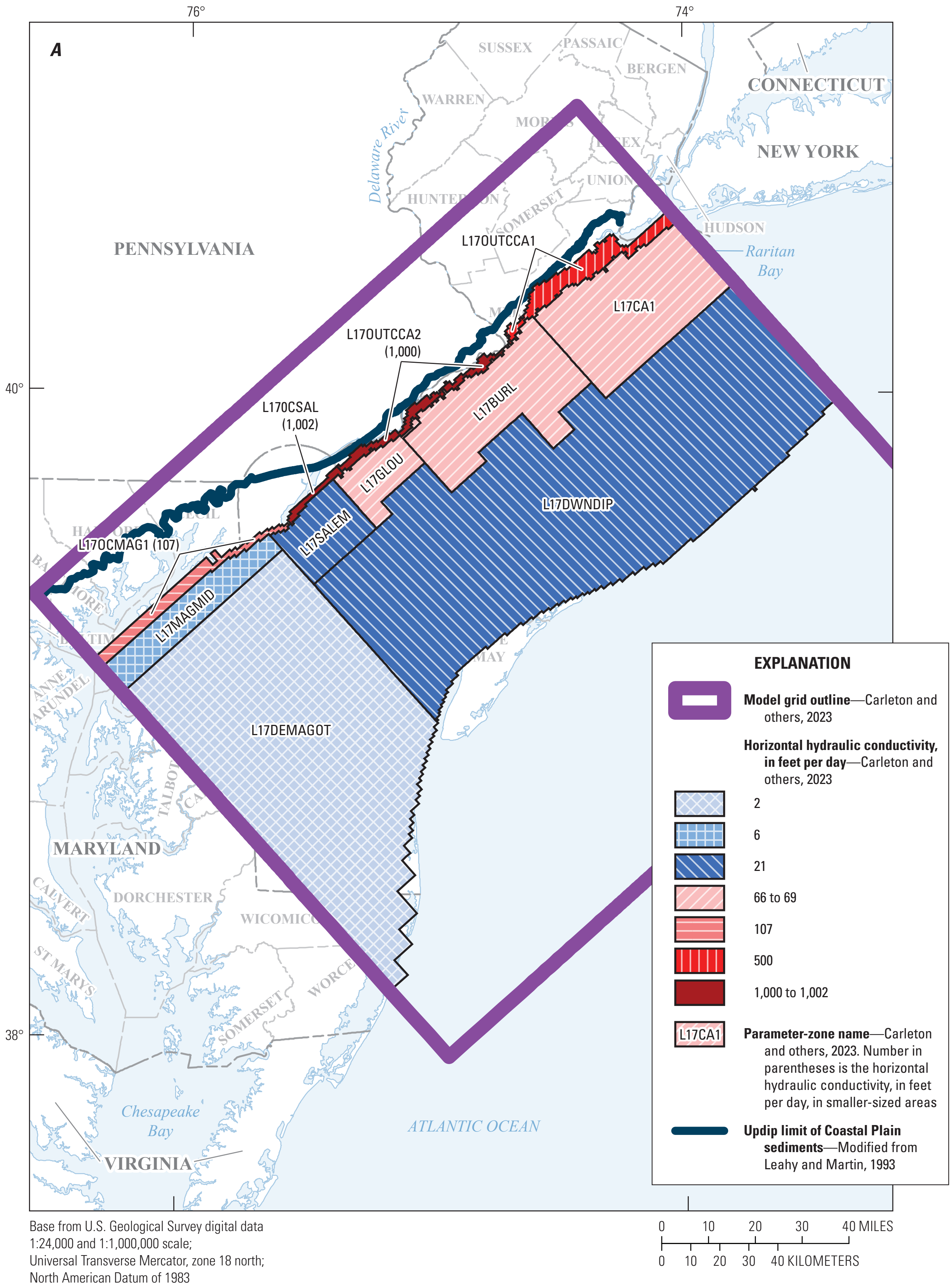


Figure 17. Maps showing *A*, horizontal hydraulic conductivity zones of model layer 17 and *B*, vertical hydraulic conductivity zones of model layer 18, in the New Jersey Coastal Plain groundwater-flow model.

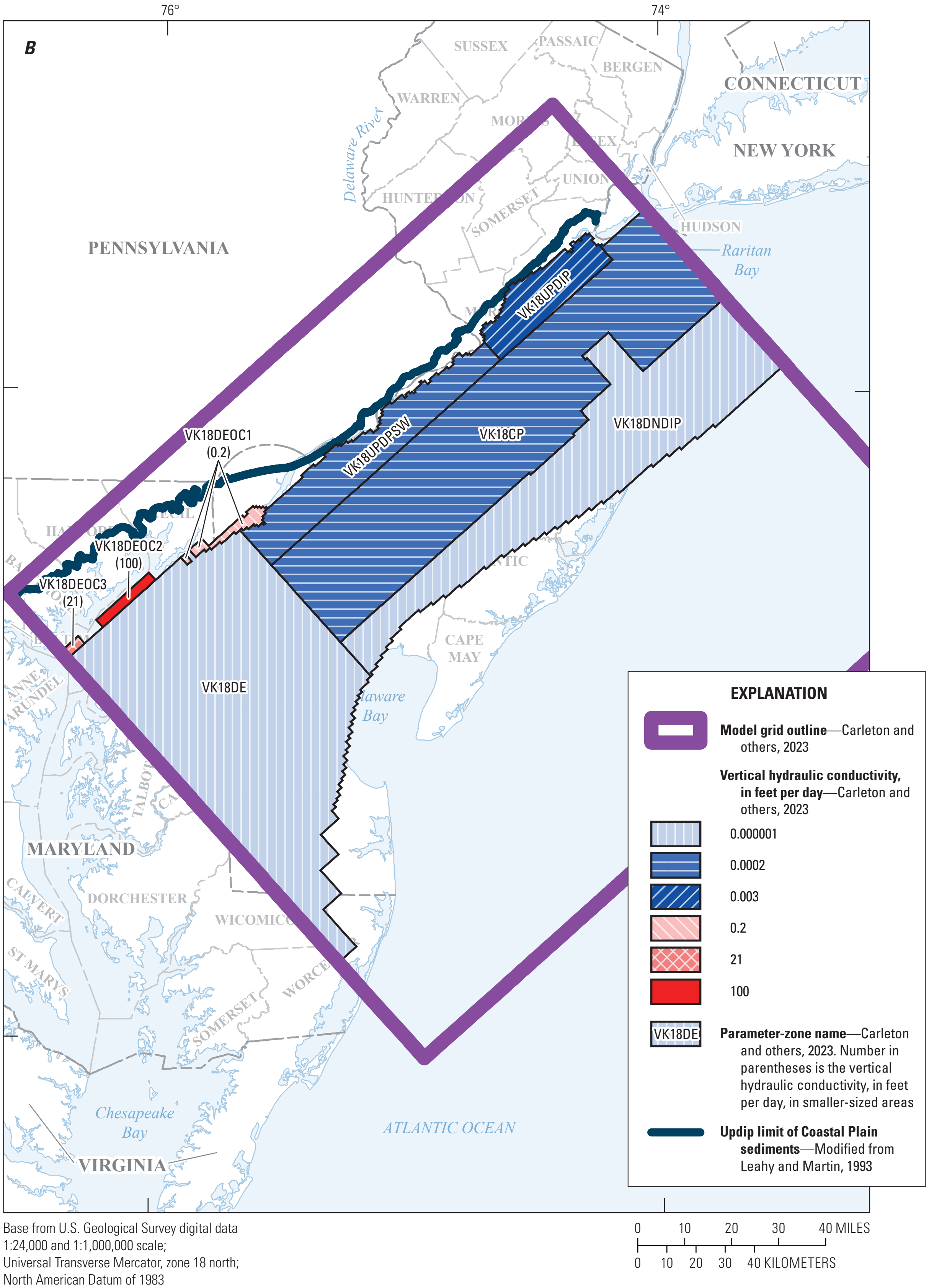


Figure 17.—Continued

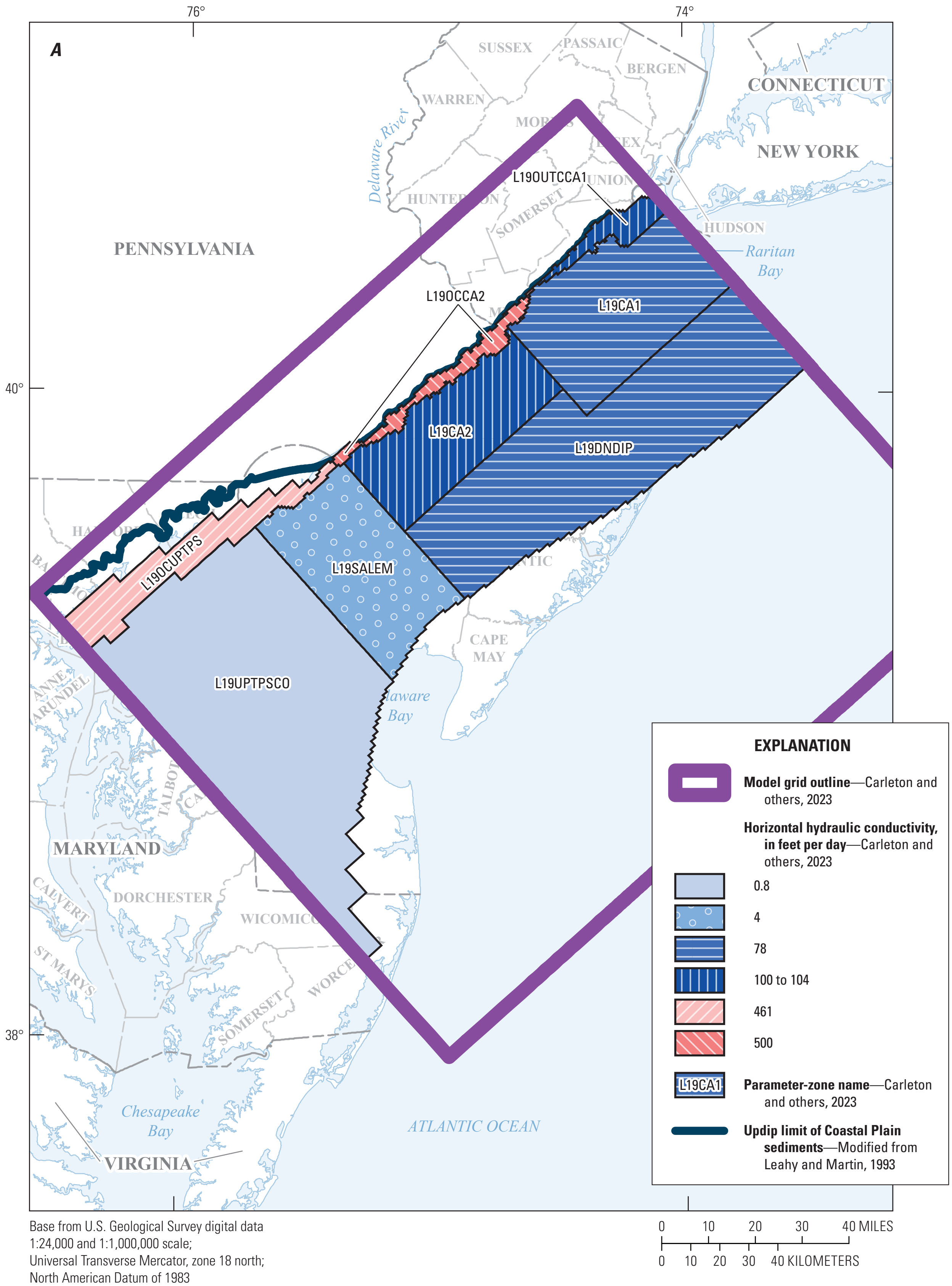


Figure 18. Maps showing *A,* horizontal hydraulic conductivity zones of model layer 19 and *B*, vertical hydraulic conductivity zones of model layer 20, in the New Jersey Coastal Plain groundwater-flow model.

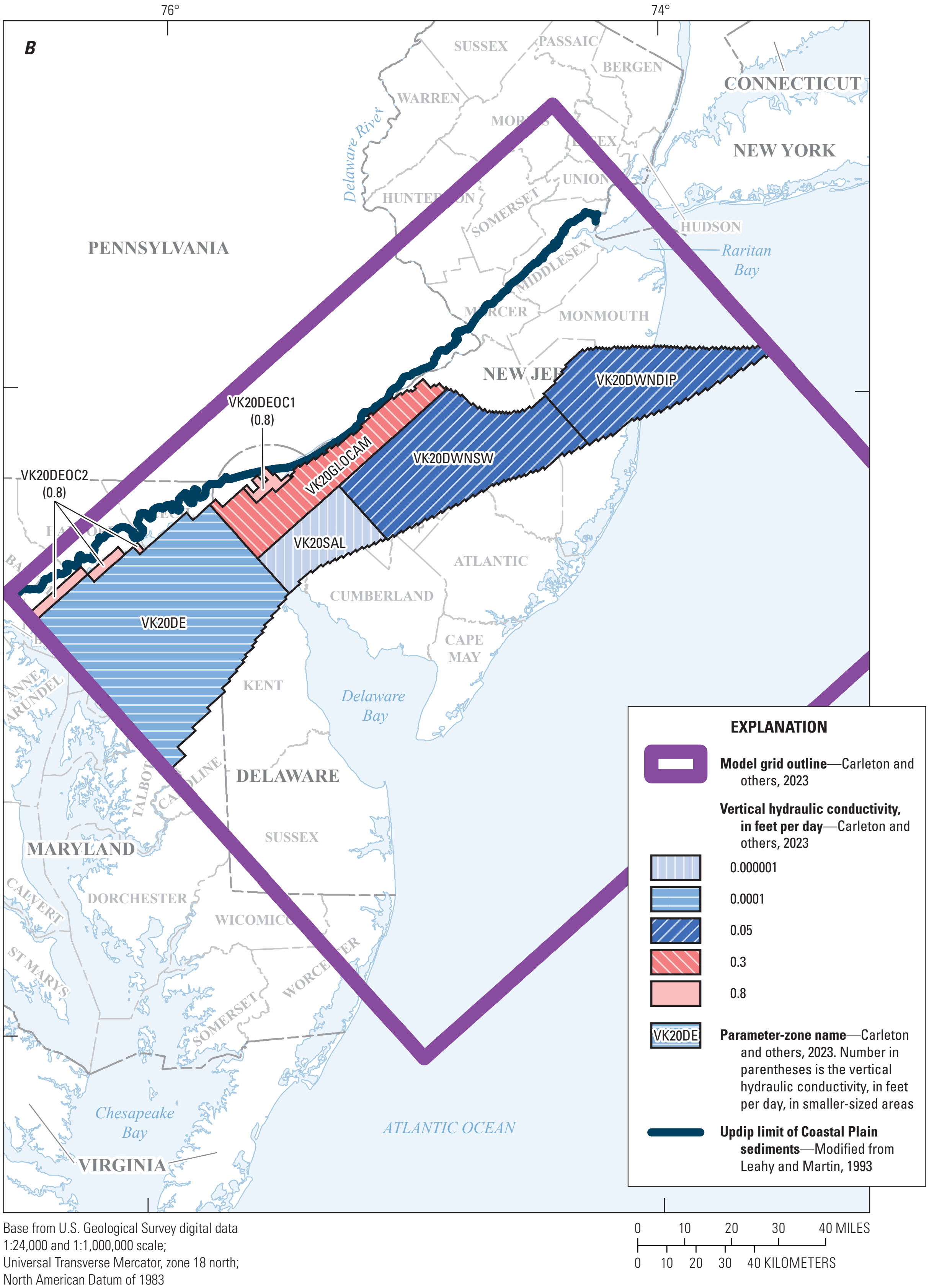


Figure 18.—Continued

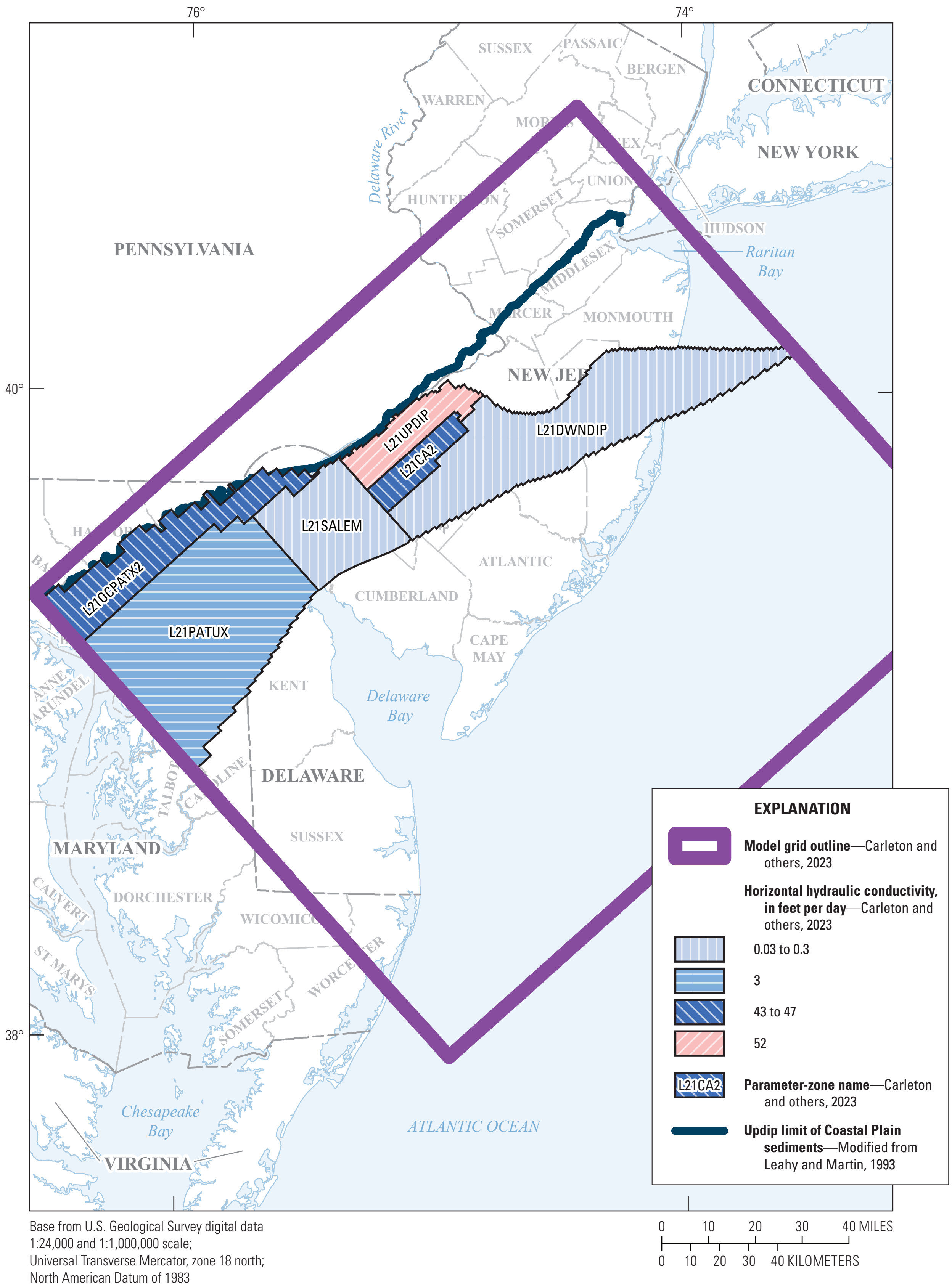


Figure 19. Map showing horizontal hydraulic conductivity zones of model layer 21 in the New Jersey Coastal Plain groundwater-flow model.

for these properties, these data were considered secondary to the calibration of the regional-scale Coastal Plain model. During model calibration, simulation results indicated the model was insensitive to the riverbed-conductance parameter. Additionally, the comparison of simulated to estimated base flows was reasonable when a single streambed-conductance parameter for drain cells was used; therefore, neither parameter was subdivided to represent smaller or local areas for the river or drain cells. This process is described further in the "Parameter Sensitivity and Correlation" and "Parameter Estimation and Residual Analysis" sections below.

Two parameters were used to vary the recharge rates in the model calibration. One parameter was used for New Jersey and another parameter was used for recharge in Delaware and Maryland. The recharge parameter for New Jersey is a multiplier applied equally to the recharge value estimated for each model cell by using the Soil-Water-Balance model (described in the "Recharge" section earlier in this report). The recharge parameter was increased from an initial value of 1.0 to a final value of 1.2 to provide a reasonable match between simulated and estimated base flow in the 47 New Jersey surface-water basins (fig. 8).

Parameter Sensitivity and Correlation

A sensitivity analysis of the calibrated model was conducted to evaluate the relative effects of the various parameters on the match between simulated and observed water levels and simulated and estimated base flows. The sensitivity analysis is used to identify which parameters in the model, when modified, improve model results. Parameters which are least sensitive, when modified, have little effect on model results. The sensitivity of model parameters was calculated by using the parameter-estimation software UCODE–2014 (Poeter and others, 2014). Parameter sensitivities were calculated two ways: by using base-flow observations only and by using water-level observations only. This section discusses composite scaled sensitivities (CSS) and parameter correlation coefficients. The CSS values show how sensitive water-level and base-flow observations in the model are to changes in each of the parameters.

According to composite-scaled sensitivity analysis, the parameters most sensitive to base-flow observations (excluding recharge) are primarily streambed conductance, horizontal hydraulic conductivity, and storage in zones in the outcrop areas of several model layers (fig. 20). Recharge is the dominant parameter with respect to base-flow observations, and the recharge multiplier parameter was adjusted manually such that average simulated base flow equaled the estimated base flow of the New Jersey Coastal Plain of about 16 inches per year (in/yr), a value determined from surficial-aquifer studies completed in surface-water basins in the New Jersey Coastal Plain during 1992–2003 (Watt and Johnson, 1992; Watt and others, 1994; Lacombe and Rosman, 1995; Johnson and Watt, 1996; Johnson and Charles, 1997; Charles and others, 2001; Watt and others, 2003; Gordon, 2004). The streambed-conductance parameter for the drains (DRN_Par1) is ranked the 4th most sensitive parameter to base-flow observations (fig. 20). As indicated above, there is only one

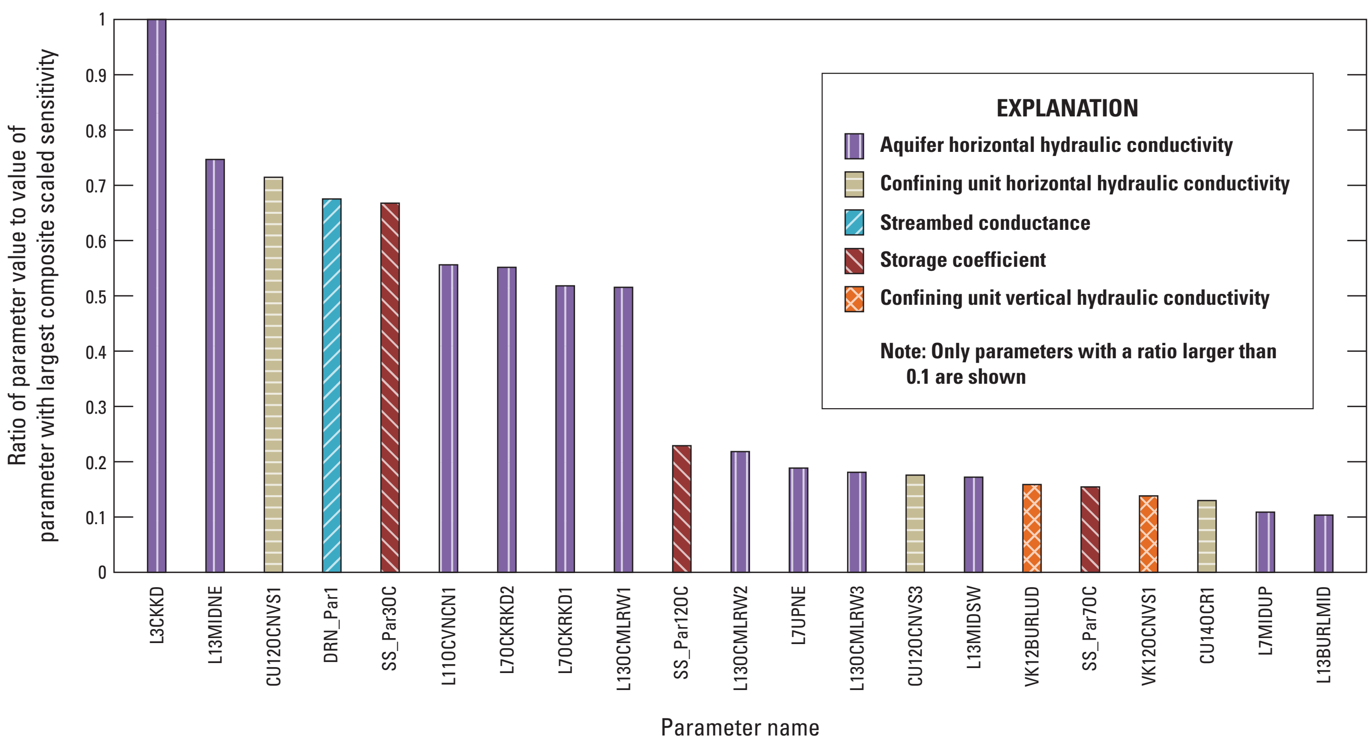


Figure 20. Graph showing composite scaled sensitivities of model parameters derived from base-flow observations for the New Jersey Coastal Plain groundwater-flow model.

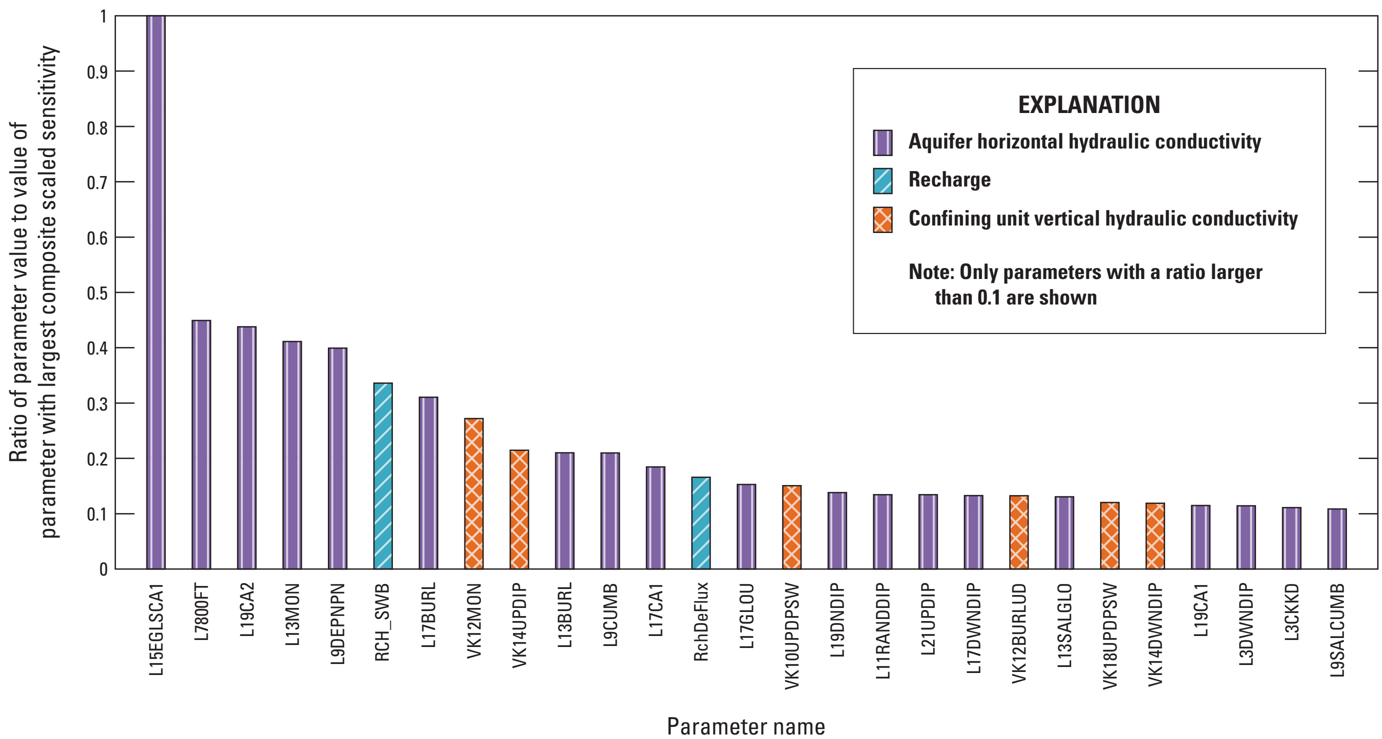


Figure 21. Graph showing composite scaled sensitivities of model parameters derived from water-level observations for the New Jersey Coastal Plain groundwater-flow model.

parameter for streambed conductance and any change to that parameter is applied to all streams uniformly rather than to individual streams. When the streambed conductance was decreased, groundwater levels tended to increase but the location or timing of discharge to base flow did not necessarily change. The 21 most sensitive parameters (fig. 20) other than streambed conductance (DRN_Par1) are in, or laterally or vertically adjacent to, an outcrop area.

Results of the CSS analysis indicate that the parameters most sensitive to water-level observations are recharge, and horizontal and vertical hydraulic conductivity (fig. 21); riverbed and general-head-boundary conductances are insensitive. Of the 27 most sensitive parameters (including the two recharge parameters (RCH_SWB and RchDeFlux), 19 (70 percent) are horizontal hydraulic conductivity, and 6 (22 percent) are vertical hydraulic conductivity.

Six pairs of the 130 most sensitive horizontal and vertical hydraulic conductivity parameters are correlated when recharge is excluded and only head observations are included in the parameter estimation (fig. 22). Most of the correlations are between vertically adjacent zones (for example, layers 20 and 21 in Delaware [figs. 18*B* and 19]) or horizontal and vertical hydraulic conductivity of the same zone (for example, layer 11 in northwestern Ocean County and northeastern Burlington County [fig. 14*A*]). Four of the six pairs are parameter zones in Delaware and three of the six pairs are parameter zones in outcrop areas. Although the parameters were correlated, each correlated parameter was allowed to be estimated separately. There is not sufficient

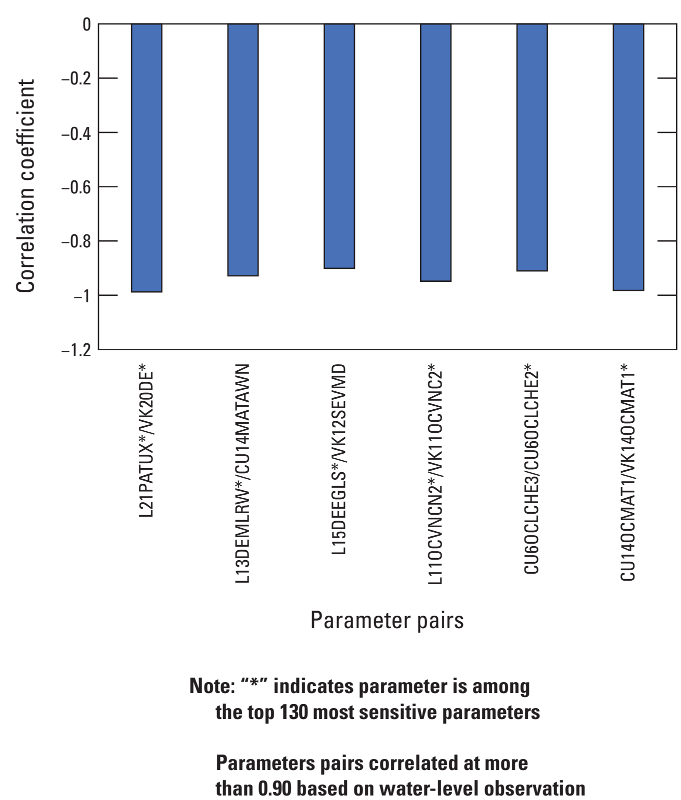


Figure 22. Graph showing model parameter pairs in the New Jersey Coastal Plain groundwater-flow model with greater than 90 percent correlation.

water-level data in the parameter zones to resolve the negative correlation between the horizontal hydraulic conductivity and (or) vertical hydraulic conductivity of each of the correlated parameter pairs.

Parameter Estimation and Residual Analysis

The parameters used in the New Jersey Coastal Plain model were tested and adjusted in an iterative calibration process. Initial parameter-estimation runs with UCODE–2014 (Poeter and others, 2014) were conducted by using all observations (water-level and base-flow). Results indicated that matching water levels in the aquifers would be less likely if base-flow observations were included. The challenge of adjusting the weights of base-flow observations to avoid their having too little or too great an effect on water levels was judged to be not effective because of the single streambed parameter for drains and the relative coarseness of the representation of the stream network in the DRN package. Therefore, after some adjustments were made to sensitive parameters to obtain an initial optimal calibration with all observations, parameter-estimation runs were done by using only base-flow observations. The recharge multiplier had the greatest effect on simulated base flows; once the recharge multiplier was held constant, the model response was generally more sensitive to parameters in the outcrop areas of aquifers and confining units. Subsequent parameter-estimation runs were done by using only water-level observations. For these runs, the parameters that were sensitive to drain (base-flow) observations, but not to water-level observations, typically remained at the value determined in the previous parameter-estimation runs in which only drain observations were used.

The number of simulated and water-level observations from wells in New Jersey used in the NJCP groundwater-flow model each total 4,243. The total includes 2,361 water-level observations from 392 wells, 920 historical water-level trends for 29 wells during 1980–2013, 210 observations of vertical gradients in 33 pairs of nested wells, and 752 observations of changes in water levels over time calculated for 134 wells. When plotted against each other (fig. 23), these values are clustered around the 1:1 correlation line where the observed water levels have a range of 411 ft and more than 96 percent of the simulated water levels fall within +/− 10 percent of the total range during 1980–2013. The residuals (simulated minus observed water level) are within + or – 10 feet for 58 percent of the water-level observations for New Jersey, and within + or – 20 feet for 84 percent. The average water-level residual is 1.5 ft; the minimum; first, second, and third quartile; and maximum residuals are −127.4, −5.5, 1.6, 10.4, and 179.4 ft, respectively.

Calibration of Stream Base Flows

The simulated average annual base flows and estimated annual average base flows for the period of record for 47 surface-water basins are shown in figure 24. Hydrographs of simulated average annual base flows at continuous- and partial-record gaging stations during the period of record available for 1980–2013 generally match estimated average annual base flows and are shown in figures 25 and 26, respectively. Although the annual variations are not well correlated and simulated flows are higher than estimated base flow in some basins and lower in others, the overall difference between simulated and estimated average base flow was reasonably matched for most basins (figs. 25 and 26).

The residual (simulated average annual base flow minus estimated annual average base flow) for each of the 47 surface-water basins in New Jersey also is shown in table 10. Simulated average annual base flows in 37 of the 47 surface-water basins (79 percent) are within 50 percent of the estimated average annual base flows and simulated average base flows in 25 basins (53 percent) are within 25 percent. Estimated average annual base flow ranges from 0.8 to 171.7 cubic feet per second (ft^3/s) and simulated average base flows range from 0.0 to 149.7 (ft^3/s). The largest percent residuals in the table generally are associated with the small streamflows in basins with drainage areas 20 mi^2 or less (7 of 20 surface-water basins (30 percent)). In some instances, simulated average base flow is lower than estimated base flow in the surface-water basins in updip basins (fig. 24), and simulated average base flow is higher than estimated base flow in adjacent downdip basins. For example, simulated average base flow at the Toms River continuous-record gaging station (01408500) is −34.9 ft^3/s (20 percent) less than estimated average annual base flow, whereas simulated average base flow at gaging stations in the adjacent basin of Crosswicks Creek (01464500) is 26.0 ft^3/s (31 percent), respectively, greater than the estimated value. Simulated base flow from this model and the previous RASA model (Voronin, 2004) are compared during model calibration to ensure that the level of calibration was maintained or improved. Voronin (2004) reports that simulated average base flows at the gaging stations at Toms River (01408500) and North Branch Rancocas Creek (0146700) are within about 10 percent of estimated values for 1926–96 and 1921–96, respectively. Simulated average base flows at Toms River (01408500) and North Branch Rancocas Creek (01467000) in this report are within −20 and 8 percent of estimated values, respectively, for 1980–2013. Similarly, Voronin (2004) reports that simulated average base flow of Raccoon Creek (01477120) is within 31 percent of the estimated value for 1966–92; simulated average base flow for this station in this report, however, is within 22 percent of that estimated for 1980–2013.

Calibration of Water Levels

During model calibration, simulated water levels were compared to water levels measured in the seven quinquennial New Jersey Coastal Plain synoptic studies conducted in 1983, 1988, 1993, 1998, 2003, 2008, and 2013 to ensure that the cones of depression and flow directions were simulated accurately. Discussion of simulated water levels in this report is limited to 2013 groundwater-flow conditions. Maps of the

2013 potentiometric surface for the confined aquifers in the New Jersey Coastal Plain (Cauller and Gordon, 2021) and the simulated water levels for the major aquifers in the New Jersey Coastal Plain and the confined aquifers in Delaware and residuals at wells measured in those aquifers in 2013 are shown in this section. As previously mentioned in the “Model Development” section, if the aquifer does not extend across a model layer in the MODFLOW-2005 finite difference solution method, but instead pinches out, the absent area of the aquifer is represented in the model by a thin layer that allows for the hydraulic connection between underlying and overlying model layers. These aquifers include the downdip areas of the Vincentown and lower PRM aquifers, and the Englishtown aquifer system, (model layers 11, 21, and 15, respectively), and the updip areas of the Rio Grande water-bearing zone, Atlantic 800-foot sand, and Piney Point aquifer (model layers 5, 7, and 9). Therefore, the simulated water levels for the part of a model layer representing the aquifer area only are shown on the figures for these aquifers. The residuals are the simulated water level minus the measured (observed) water level at the well and the root mean square error (RMSE) statistic of the residuals for each aquifer is computed. The RMSE is the standard deviation of the residuals. Hydrographs of water levels also were used to calibrate the model. The

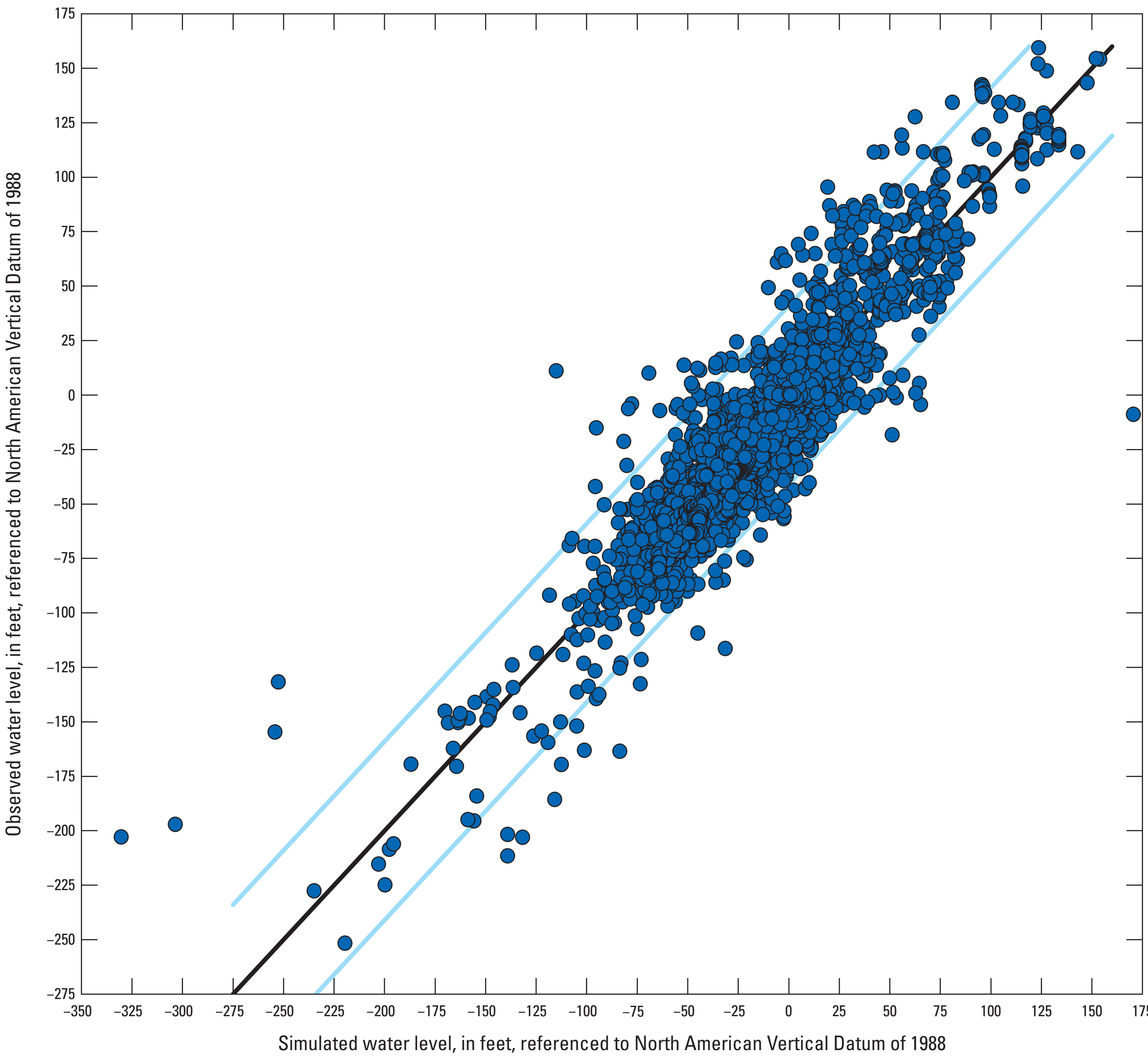


Figure 23. Graph showing simulated and observed water levels in wells in New Jersey used in calibration for the New Jersey Coastal Plain groundwater-flow model, 1980–2013.

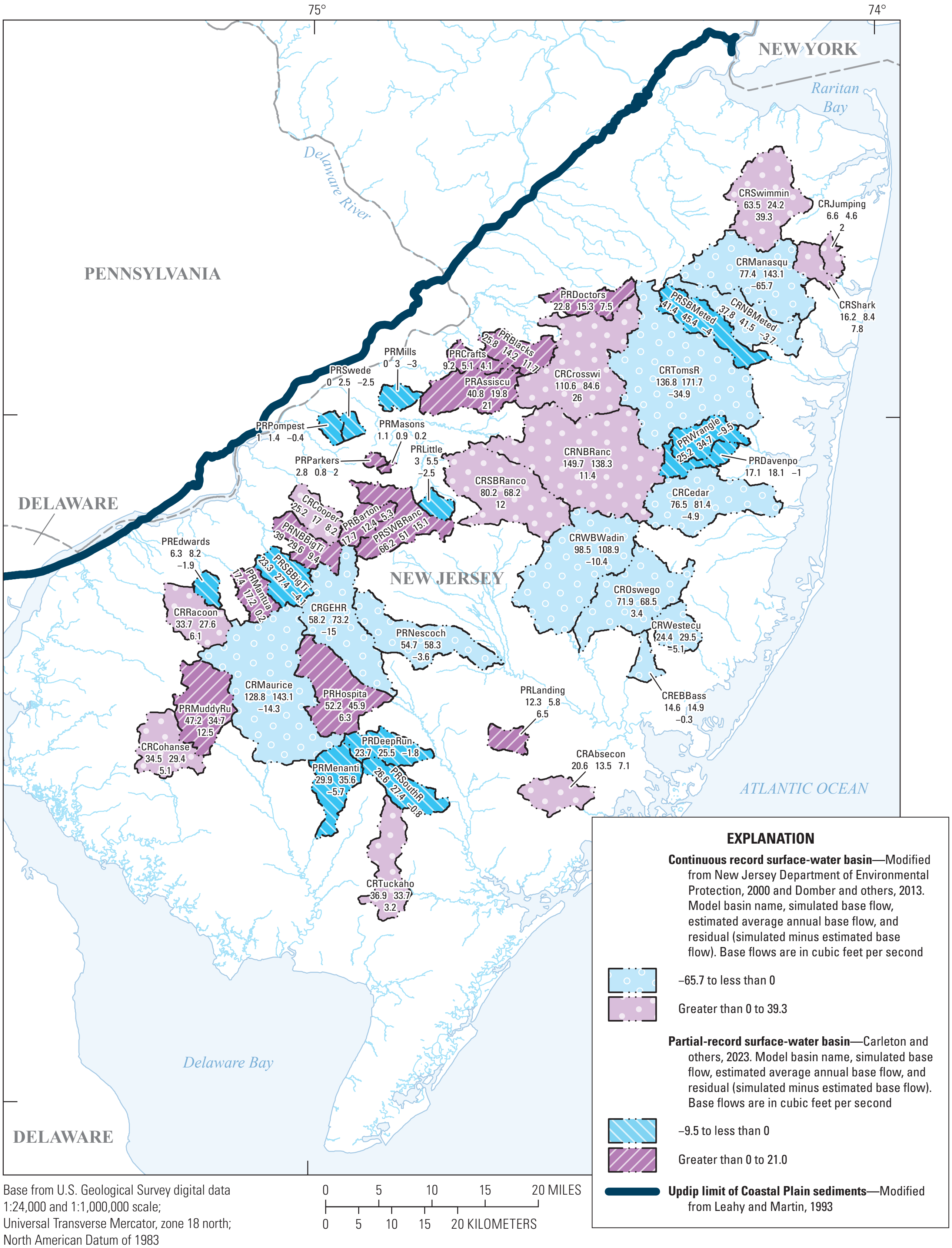


Figure 24. Map showing simulated average and estimated average annual base flow for the period of record for selected surface-water basins in the New Jersey Coastal Plain.

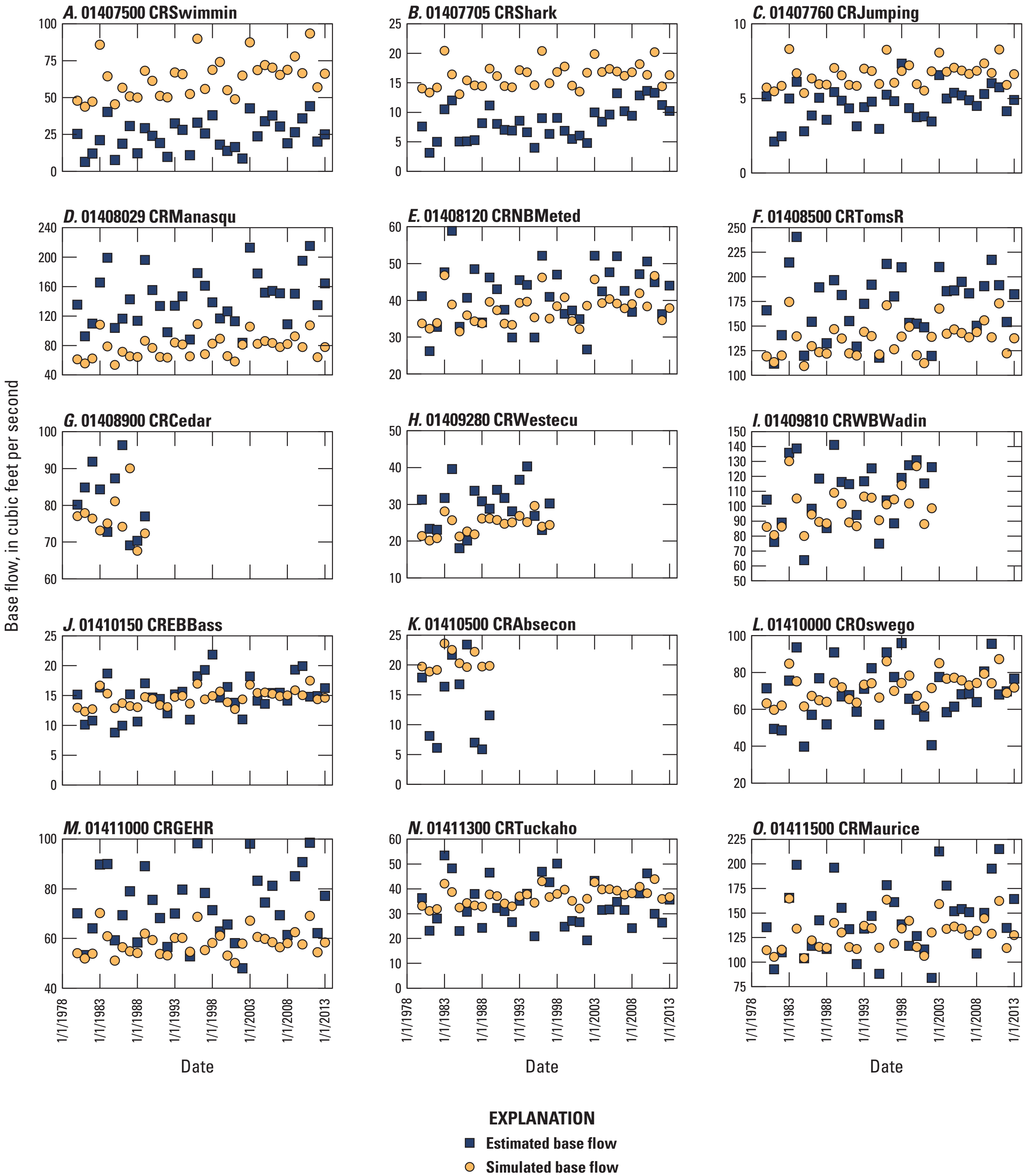


Figure 25. Hydrographs of simulated and estimated annual base flow for selected continuous-record gaging stations in the New Jersey Coastal Plain, 1980–2013.

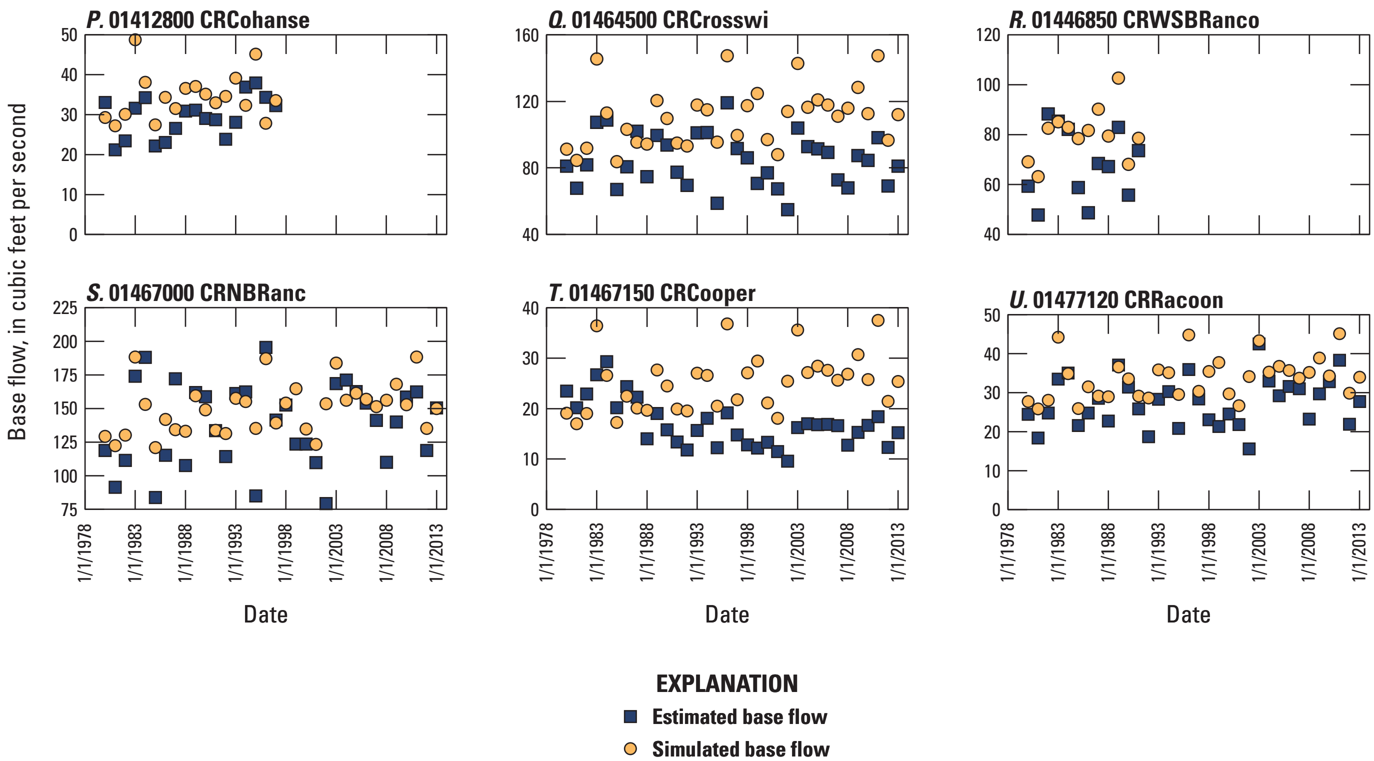


Figure 25.—Continued

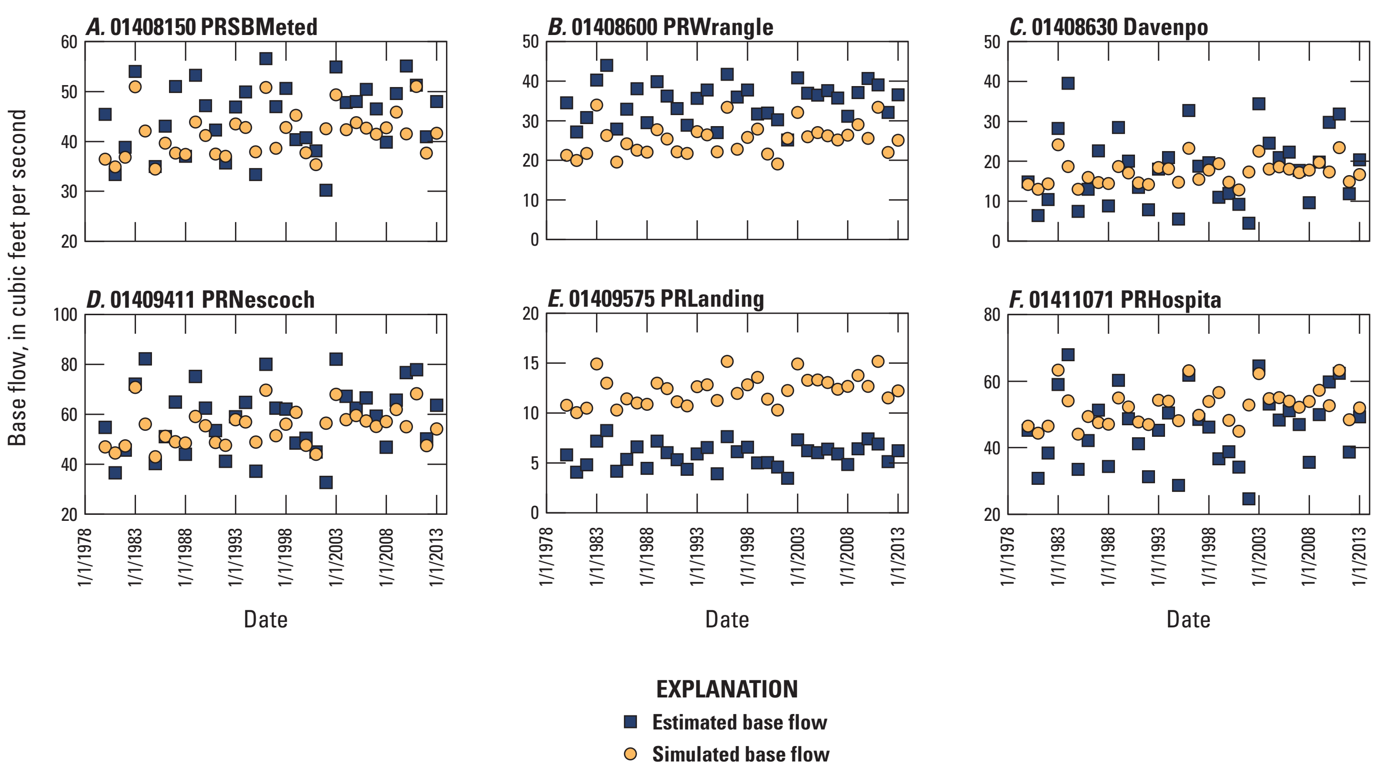


Figure 26. Hydrographs of simulated and estimated annual base flow for selected partial-record gaging stations in the New Jersey Coastal Plain, 1980–2013.

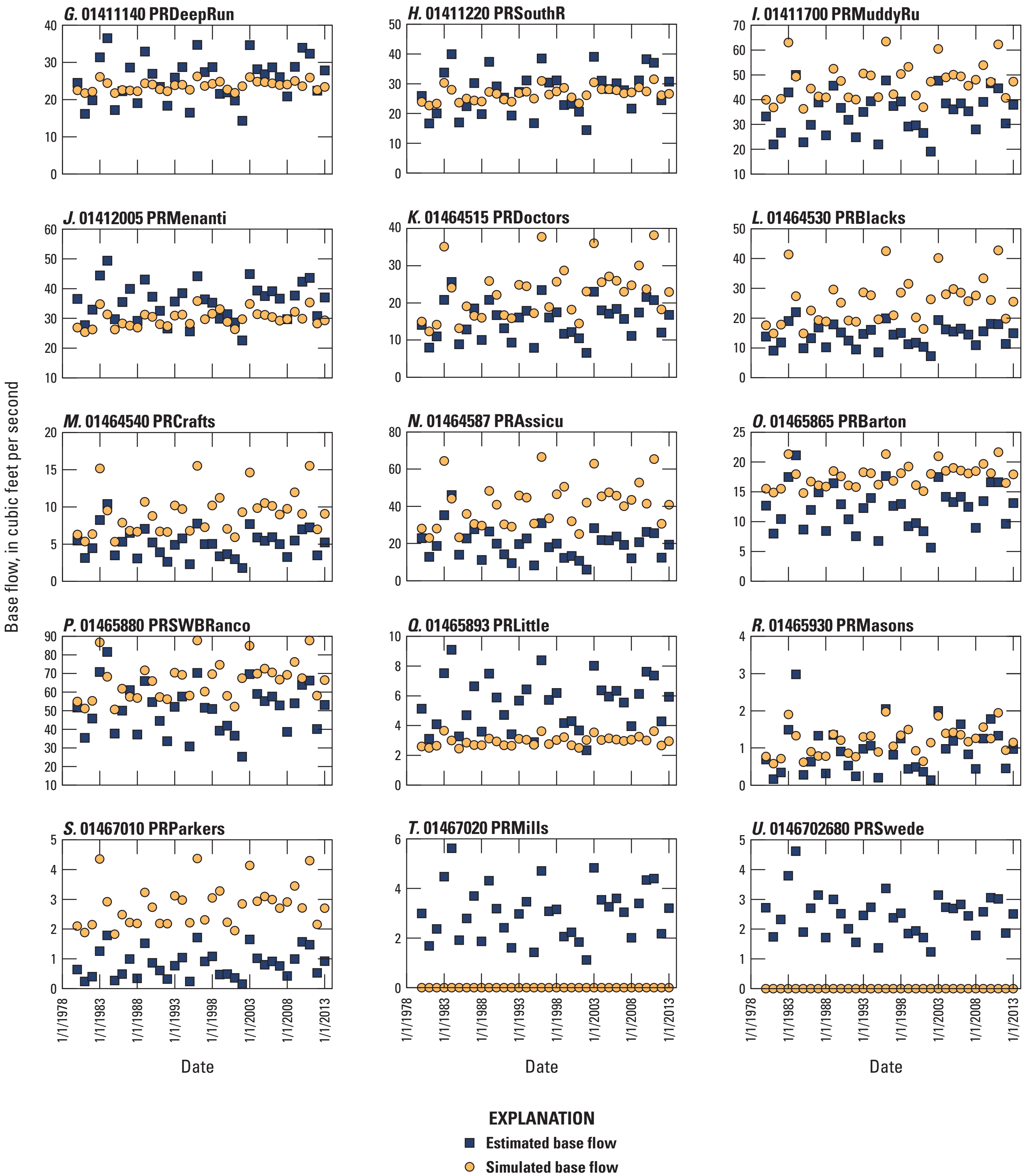


Figure 26.—Continued

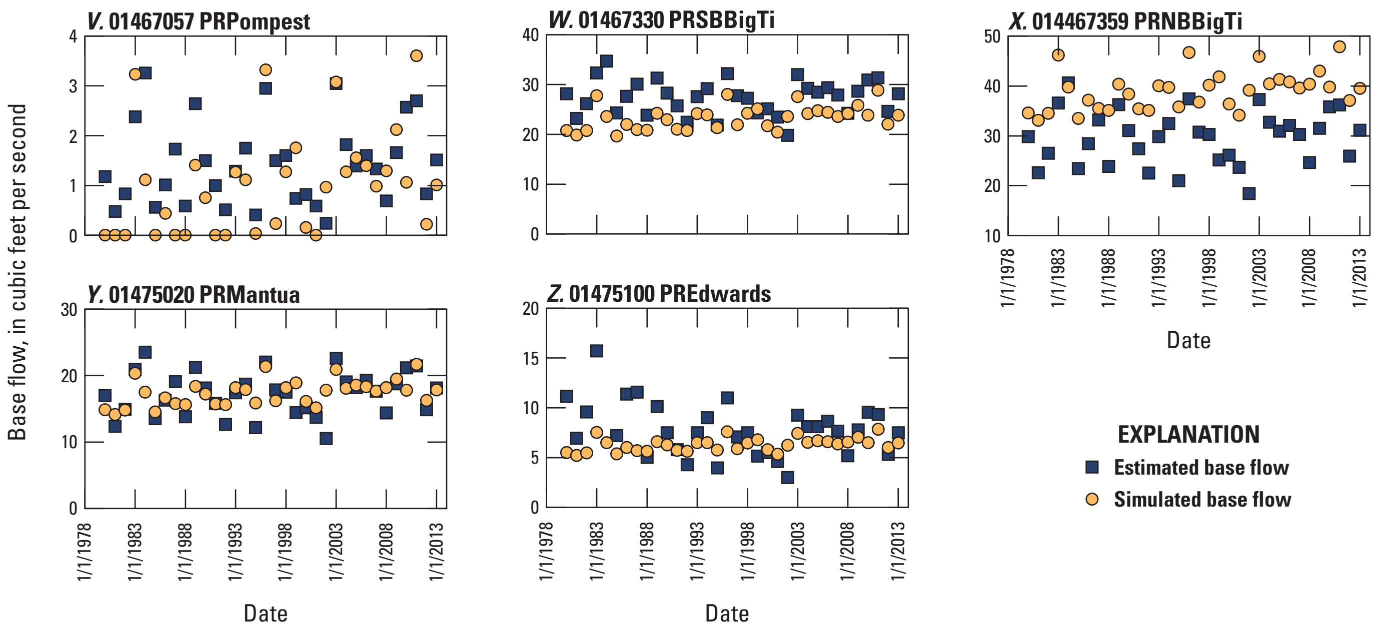


Figure 26.—Continued

Table 10. Simulated average and estimated average annual base flow for the period of record at selected continuous and partial-record streamflow-gaging stations in the New Jersey Coastal Plain.

[ft³/s, cubic feet per second; NJ, New Jersey]

Station number	Station name	Drainage area (square miles)	Model station identifier	Simulated average annual base flow (ft³/s)	Estimated average annual base flow (ft³/s)	Residual (ft³/s)	Percent residual
	Surface-water basin with continuous streamflow-gaging station						
01407500	Swimming River near Red Bank NJ	49.2	CRSwimmin	63.5	24.2	39.3	162
01407705	Shark River near Neptune City NJ	9.96	CRShark	16.2	8.4	7.8	93
01407760	Jumping Brook near Neptune City NJ	6.46	CRJumping	6.6	4.6	2.0	43
01408029	Manasquan River near Allenwood NJ	63.3	CRManasqu	77.4	143.1	−65.7	−46
01408120	North Branch Metedeconk River near Lakewood NJ	34.9	CRNBMeted	37.8	41.5	−3.7	−9
01408500	Toms River near Toms River NJ	123	CRTomsR	136.8	171.7	−34.9	−20
01408900	Cedar Creek near Lanoka Harbor NJ	53.1	CRCedar	76.5	81.4	−4.9	−6
01409280	Westecunk Creek at Stafford Forge NJ	15.8	CRWestecu	24.4	29.5	−5.1	−17
01409810	West Branch Wading River near Jenkins NJ	84.1	CRWBWadin	98.5	108.9	−10.4	−10
01410150	East Branch Bass River near New Gretna NJ	8.11	CREBBass	14.6	14.9	−0.3	−2
01410500	Absecon Creek at Absecon NJ	17.9	CRAbsecon	20.6	13.5	7.1	53
01410000	Oswego River at Harrisville NJ	72.5	CROswego	71.9	68.5	3.4	5
01411000	Great Egg Harbor River at Folsom NJ	57.1	CRGEHR	58.2	73.2	−15.0	−21
01411300	Tuckahoe River at Head of River NJ	30.8	CRTuckaho	36.9	33.7	3.2	9
01411500	Maurice River at Norma NJ	112	CRMaurice	128.8	143.1	−14.3	−10
01412800	Cohansey River at Seeley NJ	28	CRCohanse	34.5	29.4	5.1	17
01464500	Crosswicks Creek at Extonville NJ	81.5	CRCrosswi	110.6	84.6	26.0	31

Table 10. Simulated average and estimated average annual base flow for the period of record at selected continuous and partial-record streamflow-gaging stations in the New Jersey Coastal Plain.—Continued

[ft^3/s, cubic feet per second; NJ, New Jersey]

Station number	Station name	Drainage area (square miles)	Model station identifier	Simulated average annual base flow (ft^3/s)	Estimated average annual base flow (ft^3/s)	Residual (ft^3/s)	Percent residual
	Surface-water basin with continuous streamflow-gaging station—Continued						
01465850	South Branch Rancocas Creek at Vincentown NJ	64.5	CRSBRanco	80.2	68.2	12.0	18
01467000	North Branch Rancocas Creek at Pemberton NJ	118	CRNBRanc	149.7	138.3	11.4	8
01467150	Cooper River at Haddonfield NJ	17	CRCooper	25.2	17.0	8.2	48
01477120	Raccoon Creek near Swedesboro NJ	26.9	CRRacoon	33.7	27.6	6.1	22
	Surface-water basin with partial record streamflow-gaging station						
01408150	South Branch Metedeconk River near Lakewood NJ	27.4	PRSBMeted	41.4	45.4	−4.0	−9
01408600	Wrangle Brook near Toms River NJ	19.4	PRWrangle	25.2	34.7	−9.5	−27
01408630	Davenport Branch near Toms River NJ	12.3	PRDavenpo	17.1	18.1	−1.0	−6
01409411	Nescochague Creek at Pleasant Mills NJ	43.6	PRNescoch	54.7	58.3	−3.6	−6
01409575	Landing Creek at Phila Ave at Egg Harbor City NJ	8.3	PRLanding	12.3	5.8	6.5	112
01411071	Hospitality Branch at RR bridge near Folsom NJ	44.9	PRHospita	52.2	45.9	6.3	14
01411140	Deep Run at Weymouth NJ	20.0	PRDeepRun	23.7	25.5	−1.8	−7
01411220	South River near Belcoville NJ	20.4	PRSouthR	26.6	27.4	−0.8	−3
01411700	Muddy Run at Centerton NJ	37.7	PRMuddyRu	47.2	34.7	12.5	36
01412005	Menantico Creek at Route 49 at Millville NJ	26.4	PRMenanti	29.9	35.6	−5.7	−16
01464515	Doctors Creek at Allentown NJ	17.5	PRDoctors	22.8	15.3	7.5	49
01464530	Blacks Creek at Mansfield Square NJ	19.6	PRBlacks	25.8	14.2	11.6	82
01464540	Crafts Creek at Hedding NJ	10.5	PRCrafts	9.2	5.1	4.1	80
01464587	Assiscunk Creek at Jacksonville NJ	32.4	PRAssiscu	40.8	19.8	21.0	106
01465865	Barton Run at Tuckerton Road near Medford NJ	12.8	PRBarton	17.7	12.4	5.3	43
01465880	Southwest Branch Rancocas Creek at Medford NJ	47.1	PRSWBRanc	66.2	51.1	15.1	30
01465893	Little Creek at Chairville NJ	6.4	PRLittle	3.0	5.5	−2.5	−45
01465930	Masons Creek near Springville NJ	1.1	PRMasons	1.1	0.9	0.2	22
01467010	Parkers Creek near Mount Laurel NJ	2.5	PRParkers	2.8	0.8	2.0	250
01467020	Mill Creek at Willingboro NJ	7.8	PRMills	0.0	3.0	−3.0	−100
0146702680	Swede Run at Conrow Road at Delran NJ	4.5	PRSwede	0.0	2.5	−2.5	−100
01467057	Pompeston Creek at Cinnaminson NJ	5.8	PRPompest	1.0	1.4	−0.4	−29
01467330	South Branch Big Timber Creek at Blackwood NJ	20.8	PRSBBigTi	23.3	27.4	−4.1	−15
01467359	North Branch Big Timber Creek at Glendora NJ	18.6	PRNBBigTi	39.0	29.6	9.4	32
01475020	Mantua Creek at Sewell NJ	14.5	PRMantua	17.4	17.2	0.2	2
01475100	Edwards Run near Mantua NJ	6.4	PREdwards	6.3	8.2	−1.9	−23

hydrographs were compared to simulation results from Voronin (2004) to ensure that the updated model maintained or improved the level of calibration achieved with the previous model.

Calibration of Water Levels in the Holly Beach Water-Bearing Zone

Simulated water-level contours in the Holly Beach water-bearing zone (model layer 1, Cape May County) are shown in figure 27. The Holly Beach water-bearing zone is a minor aquifer in New Jersey; the observed water levels shown in Lacombe and Carleton (2002) were used to visually compare to the simulated water-level contours.

Calibration of Water Levels in the Confined Cohansey Aquifer and Unconfined Kirkwood-Cohansey Aquifer System

Simulated water-level contours in the unconfined Kirkwood-Cohansey aquifer shown in the updip area of model layer 3 closely match the observed water-table contours in general direction and slope (fig. 28). The observed water-table contours are an aggregate of data from multiple surficial-aquifer studies in the following surface-water basins of the New Jersey Coastal Plain: Great Egg Harbor River Basin (Watt and Johnson, 1992); Toms River, Metedeconk River, and Kettle Creek Basins (Watt and others, 1994); upper Maurice River Basin (Lacombe and Rosman, 1995); Mullica River Basin (Johnson and Watt, 1996); Salem River and Raccoon, Oldmans, Alloway, and Stow Creek Basins (Johnson and Charles, 1997); and Rancocas, Crosswicks, Assunpink, Blacks, and Crafts Creek Basins (Watt and others, 2003). The aggregated (observed) water-table contours are shown only in the areas where a surficial-aquifer study was completed before 2004. In Cape May County, New Jersey, as well as in Sussex County, Delaware, groundwater is confined.

The updip limit of the confined Cohansey aquifer in Cape May County is shown in figure 29. The simulated water-level contours in the confined Cohansey aquifer in New Jersey and the potentiometric surface of the 2013 New Jersey Coastal Plain water-level synoptic study (Cauller and Gordon, 2021) for this aquifer also are shown in figure 29. Simulated water levels in the confined part of the Cohansey aquifer (model layer 3, Cape May County) generally match observed water levels (table 11). The average water-level residual (simulated minus observed) for 17 observation points in Cape May County for the confined Cohansey aquifer is −0.2 ft and the root mean square error (RMSE) is 3.3 ft. The simulated water levels for the Upper Chesapeake aquifer in Delaware and the average water-level residual for four wells measured in Delaware in 2013 (table 11) also are shown in figure 29.

The hydrographs of simulated and observed water levels for well 090049 (fig. 30) are similar, with minima, maxima, and averages for the observed water levels of –21, –8, and –13 ft, respectively, for the observed water levels and –19, –7, and –11 ft, respectively, for the simulated water levels. Simulated water levels are, on average, 2 ft greater than observed. The hydrographs of simulated and observed water levels for well 090080 in south-central Cape May County (fig. 31) are similar, with minima, maxima, and averages for the observed water levels of –11, –1, and –6 ft, respectively, for the observed water levels and –18, –0.5, and –8 ft, respectively, for the simulated water levels.

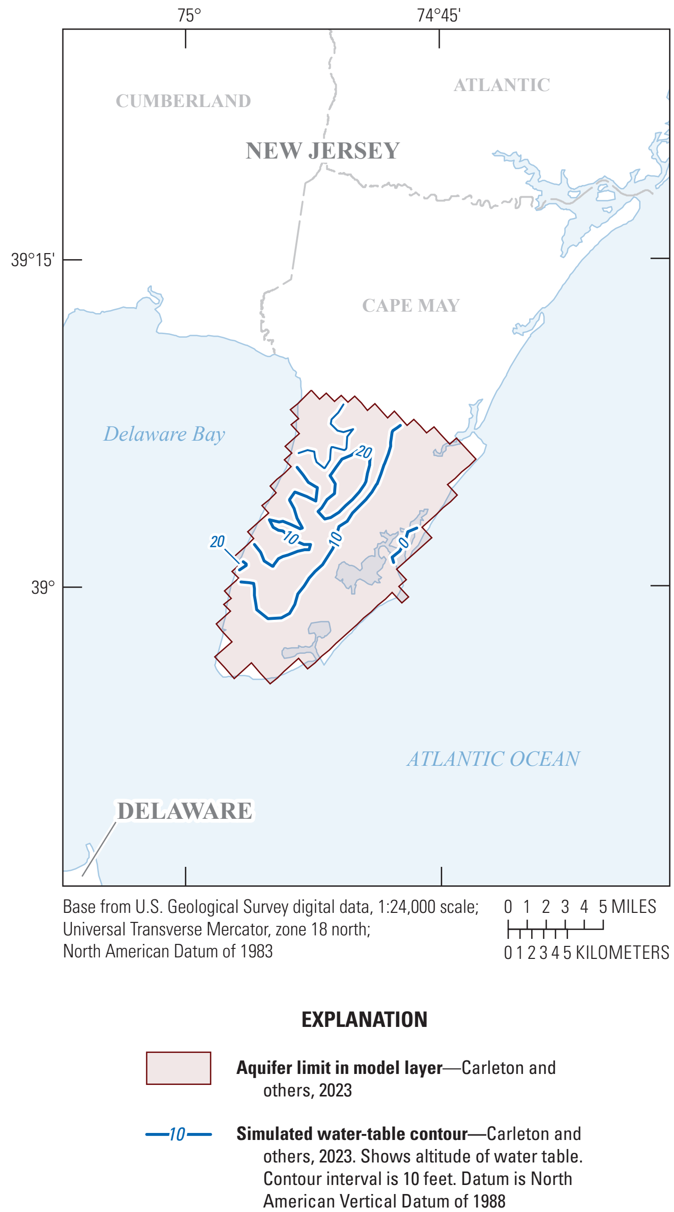


Figure 27. Map showing simulated water-level contours for the Holly Beach water-bearing zone, Cape May County, New Jersey, 2013.

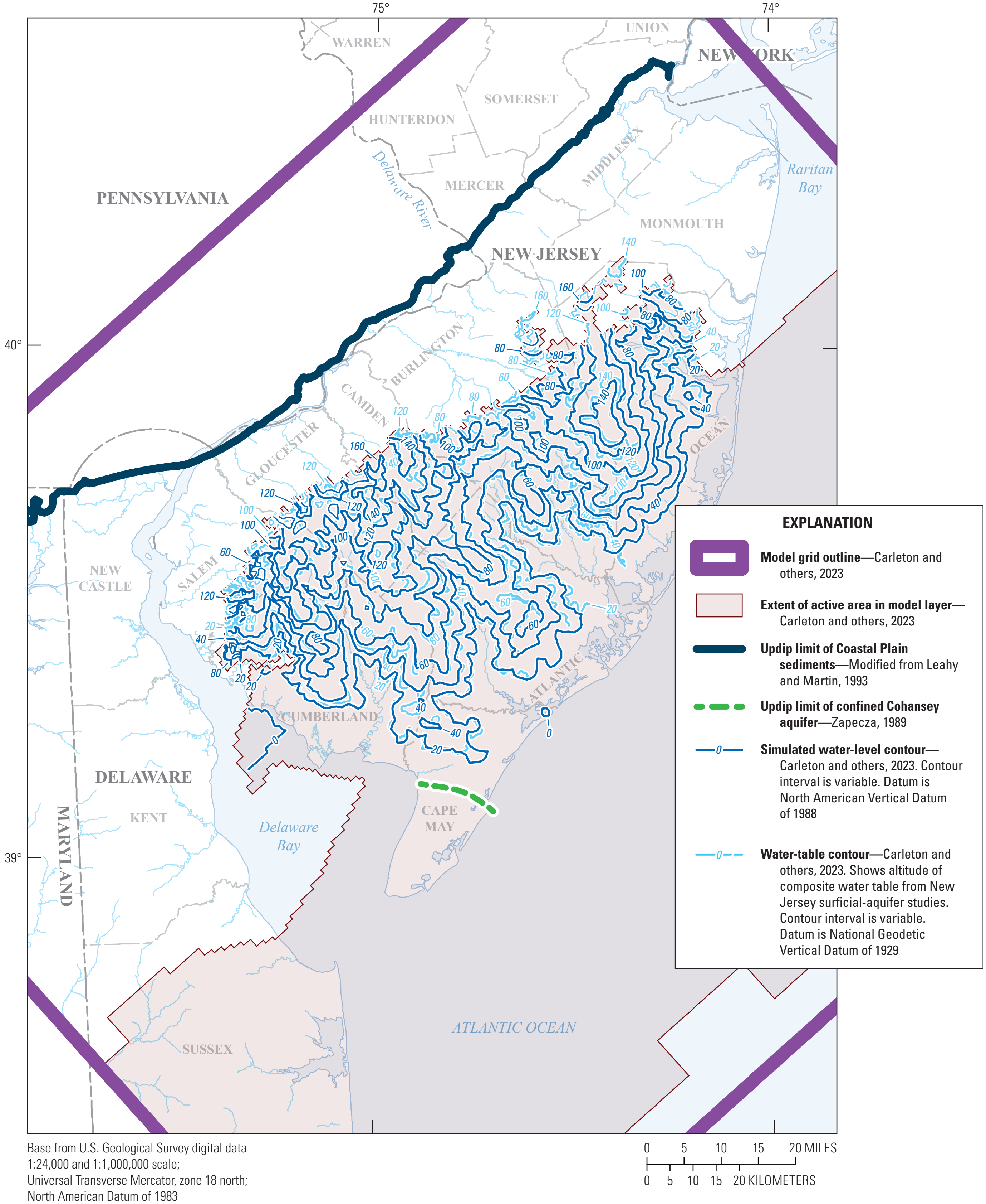
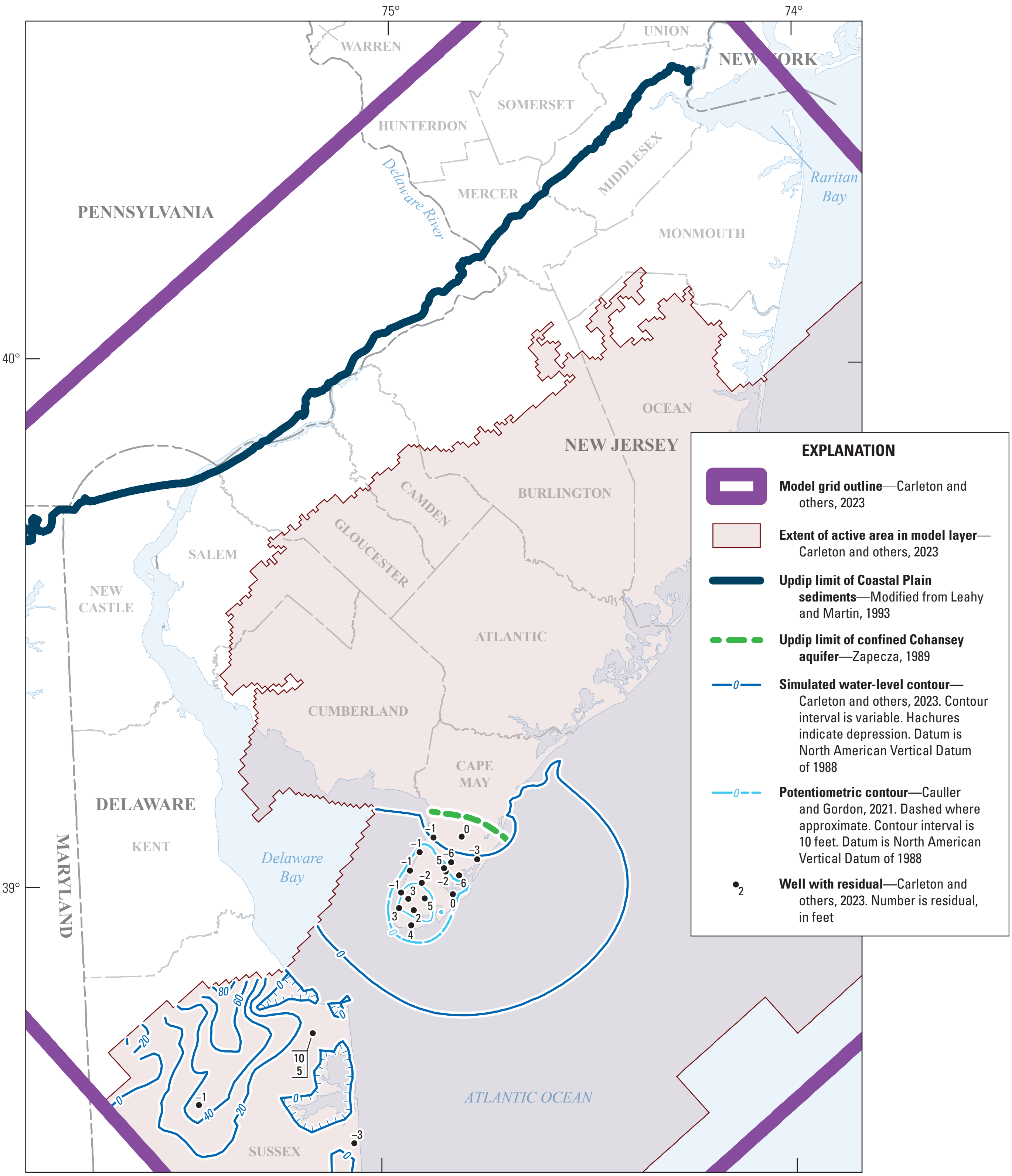


Figure 28. Map showing simulated and composite observed water-table contours for the unconfined Kirkwood-Cohansey aquifer system in New Jersey.



Base from U.S. Geological Survey digital data
1:24,000 and 1:1,000,000 scale;
Universal Transverse Mercator, zone 18 north;
North American Datum of 1983

0 5 10 15 20 MILES
0 5 10 15 20 KILOMETERS

Figure 29. Map showing simulated water-level contours and 2013 potentiometric surface of, and residuals for selected wells in, the confined Cohansey aquifer, Cape May County, New Jersey, and simulated water-level contours for the Upper Chesapeake aquifer, Delaware.

Table 11. Simulated and observed water-level observations and residuals for wells open to the confined Cohansey aquifer, Cape May County, New Jersey, and the Upper Chesapeake aquifer, Delaware, 2013.

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
New Jersey wells				
WLOb090048_7	090048	−10.36	–8.09	2.27
WLOb090049_7	090049	−10.42	–7.54	2.88
WLOb090054_7	090054	–13.90	–11.12	2.78
WLOb090060_7	090060	–9.06	–10.98	–1.92
WLOb090080_7	090080	–1.89	–4.02	–2.13
WLOb090089_7	090089	–2.60	–3.62	–1.02
WLOb090099_7	090099	3.55	3.06	–0.49
WLOb090150_7	090150	–8.89	–5.04	3.85
WLOb090187_6	090187	–5.95	–7.15	–1.20
WLOb090210_6	090210	–7.42	8.87	–1.45
WLOb090219_5	090219	1.41	0.28	–1.13
WLOb090292_6	090292	2.71	–0.31	–3.02
WLOb090315_3	090315	4.54	–1.91	–6.45
WLOb090354_5	090354	3.10	–2.42	–5.52
WLOb090358_4	090358	–1.14	3.73	4.87
WLOb090366_4	090366	–3.52	–3.59	–0.07
WLOb090395_5	090395	–12.91	–7.91	5.00
Delaware wells				
WLObOh2502_6	Oh2502	–4.80	5.54	10.34
WLObOh2503_6	Oh2503	1.00	5.55	4.55
WLObPe5403_5	Pe5403	44.95	43.68	–1.27
WLObQj4104_6	Qj4104	3.63	0.25	–3.38

Calibration of Water Levels in the Rio Grande Water-Bearing Zone

Simulated water-level contours and the potentiometric surface of the 2013 New Jersey Coastal Plain water-level synoptic study (Cauller and Gordon, 2021) in the Rio Grande water-bearing zone (model layer 5, parts of Ocean, Atlantic, and Cape May Counties) are shown in figure 32. The 2013 simulated water levels are an average 7 ft lower than the observed water levels at six wells in Cape May County and are 35 ft lower than the observed water levels at three wells in Ocean County. The simulated 2013 potentiometric contours indicate a cone of depression along the shoreline of Cape May and Atlantic Counties caused by drawdowns in the underlying Atlantic City 800-foot sand; a cone of depression also is observed in the simulated water-level contours. The differences between the simulated and observed water levels for 10 observation points in New Jersey are listed in table 12. The average water-level residual (simulated minus observed) for the 10 observation points (figs. 32 and 33) is −16 ft and the RMSE is 24 ft. The minimum; first, second, and third quartile; and maximum residuals are −45, −31, −13, 0, and 5 ft, respectively.

Calibration of Water Levels in the Atlantic City 800-Foot Sand

Simulated water-level contours in the Atlantic City 800-foot sand (model layer 7, parts of Cape May, Atlantic, and Ocean Counties) generally match the 2013 potentiometric surface in coastal Atlantic and Cape May Counties (fig. 34). The simulated water-level contours are similar in shape to the 2013 potentiometric surface (Cauller and Gordon, 2021), although the gradient of the simulated contours is less steep than that of the water-level contours drawn from measurements made in updip central Atlantic County. The simulated water levels are within 10 ft of observed levels in 13 of 34 wells (38 percent) in New Jersey and within 15 ft of observed levels in 24 of 34 wells (71 percent) (figs. 34 and 35 and table 13). The 2013 simulated water levels are an average 8 ft higher than the observed water levels at 13 wells in Cape May County and are an average 13 ft lower than the observed water levels at 14 wells in Atlantic County. The simulated water levels are an average 11 ft lower than observed levels at 7 wells in Ocean County. The average water-level residual (simulated minus observed) for 34 wells in Cape May, Atlantic, and Ocean Counties is −4 ft and the RMSE is 21 ft. The minimum; first, second, and third quartile; and maximum residuals are −57, −12, 3, 12, and 17 ft, respectively. The simulated water levels for the Calvert aquifer system in Delaware and the average water-level residual for one well measured in Delaware in 2013 (table 13) also are shown in figure 34.

The hydrographs of wells 010180 and 010578, in northeastern and southeastern Atlantic County, respectively (fig. 36), show the same trend and amplitude as the observed water levels, but the simulated water levels are, on average, 1 ft lower and 12 ft higher, respectively, than the observed. The hydrographs of simulated and observed water levels for well 010180 (fig. 36*A*) are similar, with minima, maxima, and average for the observed water levels of –57, –35, and –47 ft, respectively, for the observed water levels and –60, –36, and –48 ft, respectively, for the simulated water levels. The hydrographs of simulated and observed water levels for well 010158 (fig. 36*B*) are similar, with minima, maxima, and average for the observed water levels of –71, –49, and –60 ft, respectively, and –60, –38, and –48 ft, respectively, for the simulated water levels. The hydrograph for well 010578 (fig. 36*B*) shows simulated water levels that are closer to and more closely match the trend in the observed water levels than those simulated by Voronin (2004) for 1990–98.

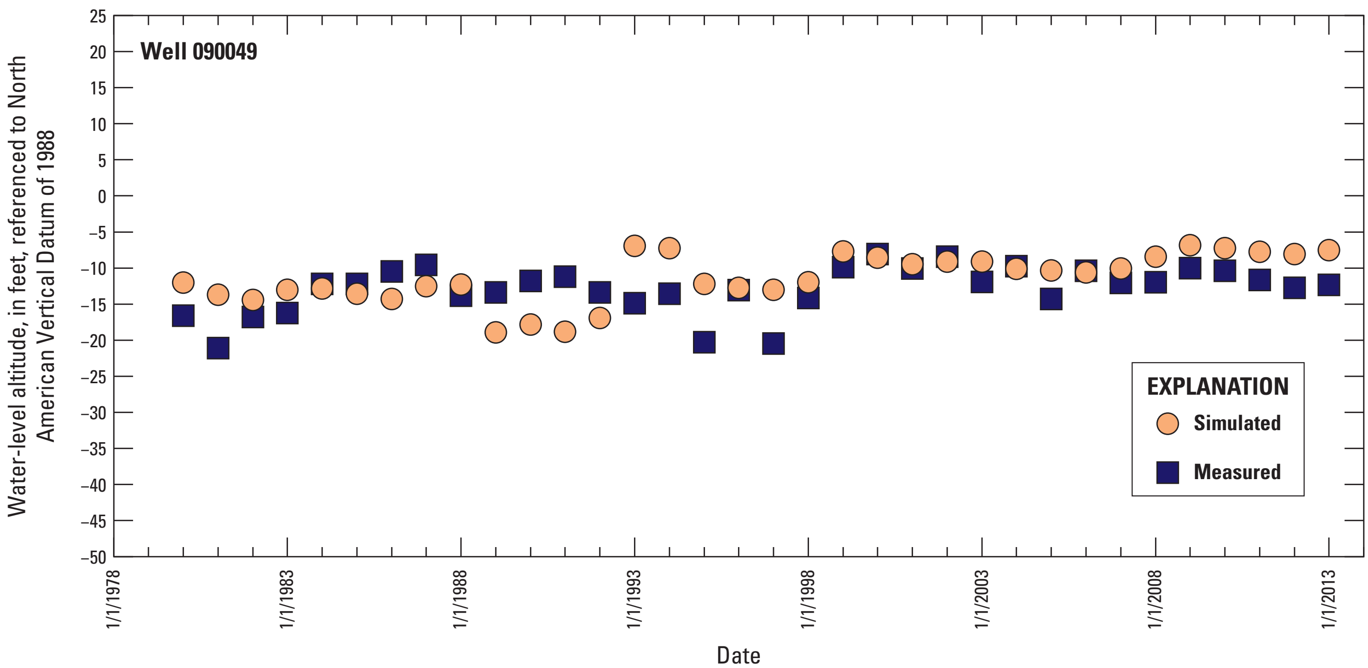


Figure 30. Hydrograph of simulated and observed water levels in well 090049 open to the confined Cohansey aquifer, New Jersey, 1980–2013.

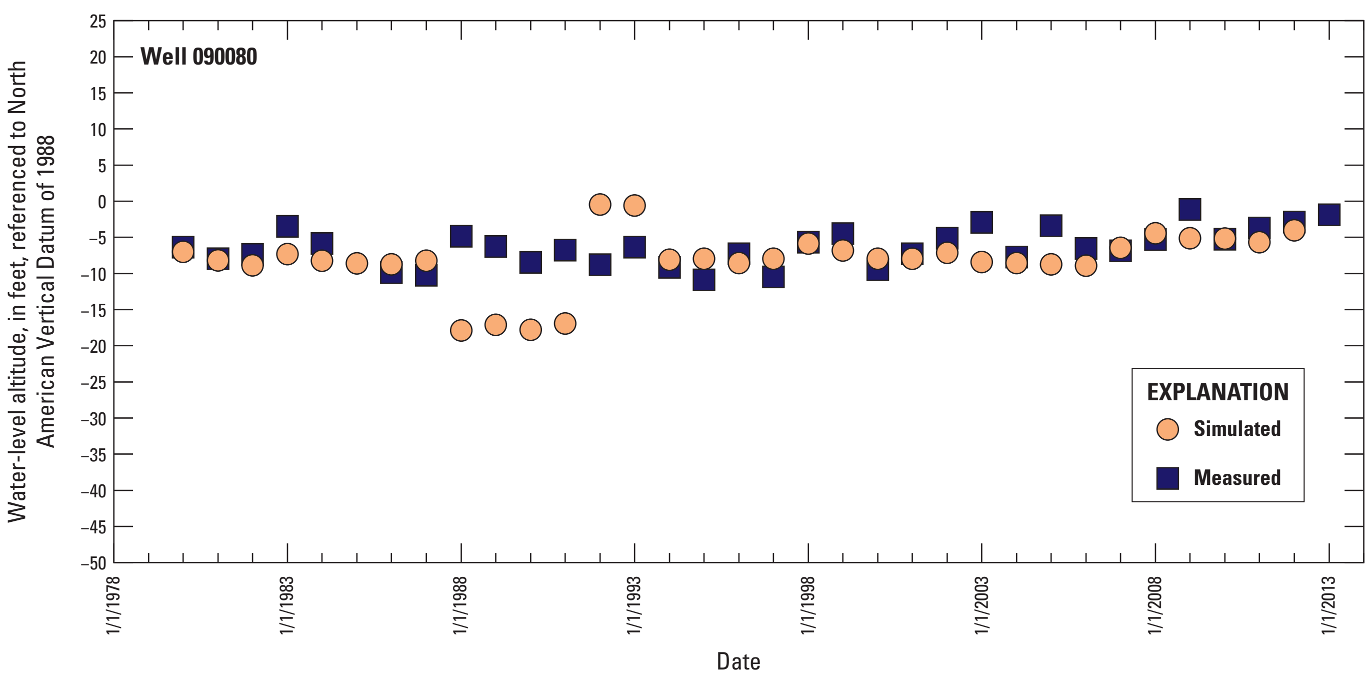


Figure 31. Hydrograph of simulated and observed water levels in well 090080 open to the confined Cohansey aquifer, New Jersey, 1980–2013.

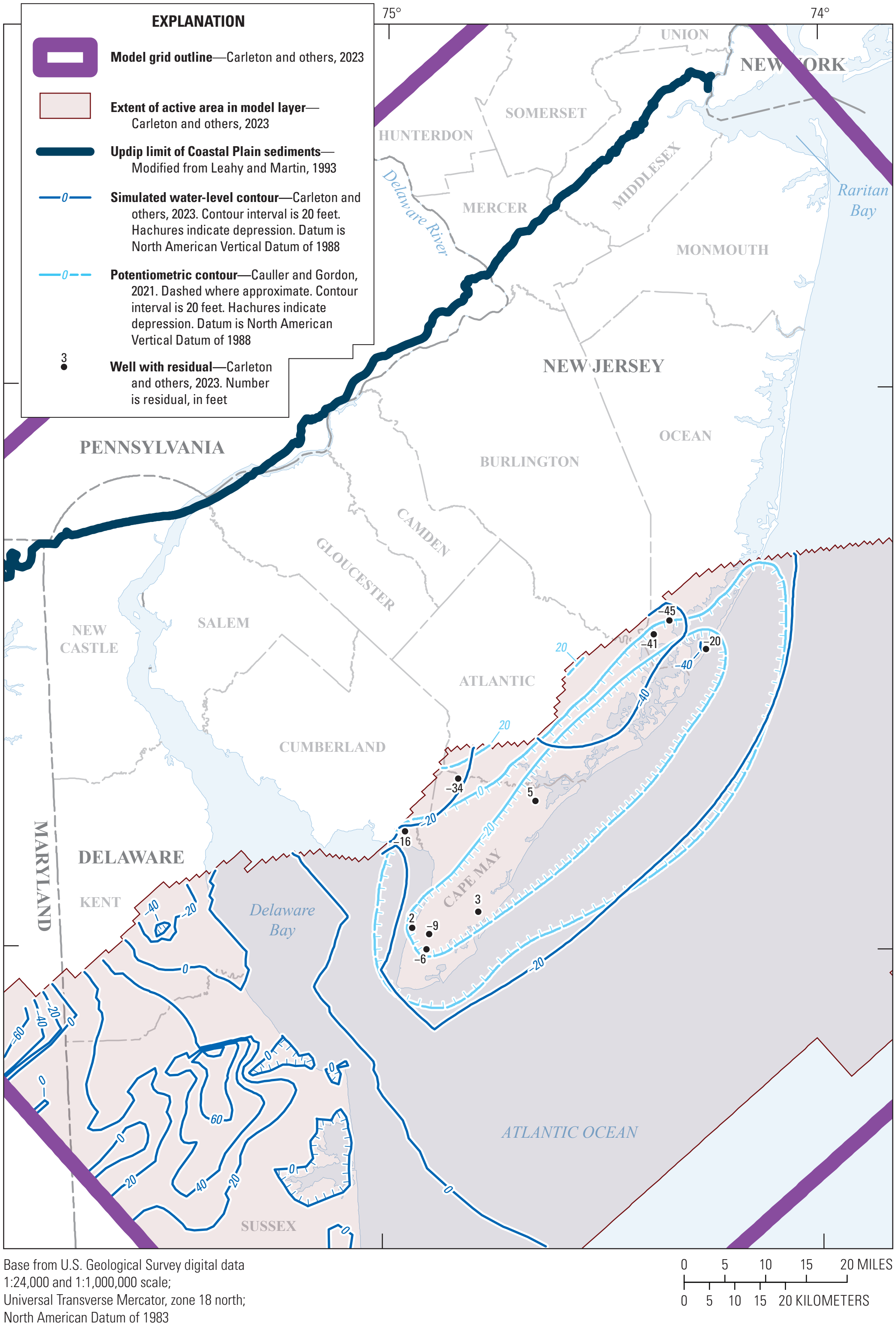


Figure 32. Map showing simulated water-level contours and 2013 potentiometric surface for, and residuals for selected wells in, the Rio Grande water-bearing zone, New Jersey and simulated water-level contours for the Lower Chesapeake aquifer, Delaware.

Table 12. Simulated and observed water-level observations and residuals for wells open to the Rio Grande water-bearing zone, New Jersey, 2013.

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
WLOb090071_6	090071	–23.19	–32.57	−9.38
WLOb090149_6	090149	16.14	–18.08	–34.22
WLOb090304_4	090304	–20.83	–26.83	–6.00
WLOb090305_3	090305	–27.34	–24.39	2.95
WLOb090526_3	090526	–26.40	–24.72	1.68
WLOb090629_2	090629	–32.47	–27.70	4.77
WLOb110737_4	110737	–4.39	–20.29	–15.90
WLOb290775_6	290775	–1.97	–42.86	–40.89
WLOb290813_5	290813	0.01	–44.54	–44.55
WLOb291621_3	291621	–22.80	–42.43	–19.63

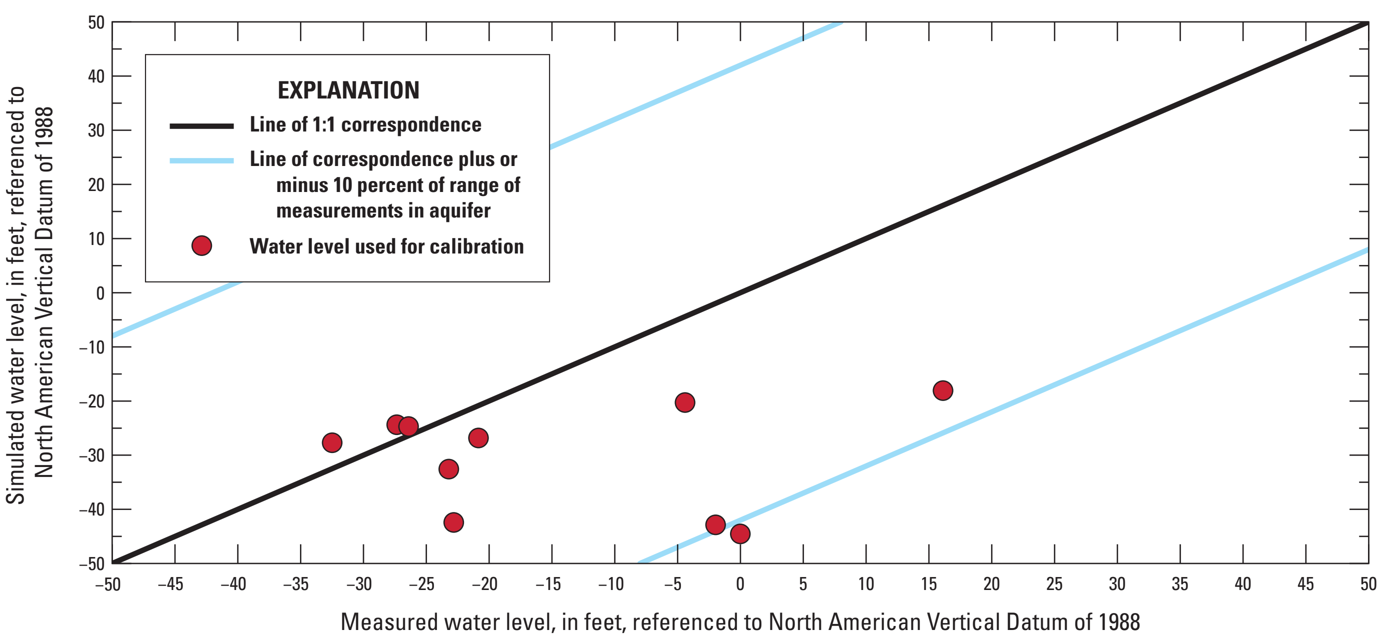


Figure 33. Graph showing simulated and observed water levels in wells open to the Rio Grande water-bearing zone, Cape May, Atlantic, and Ocean Counties, New Jersey, 2013.

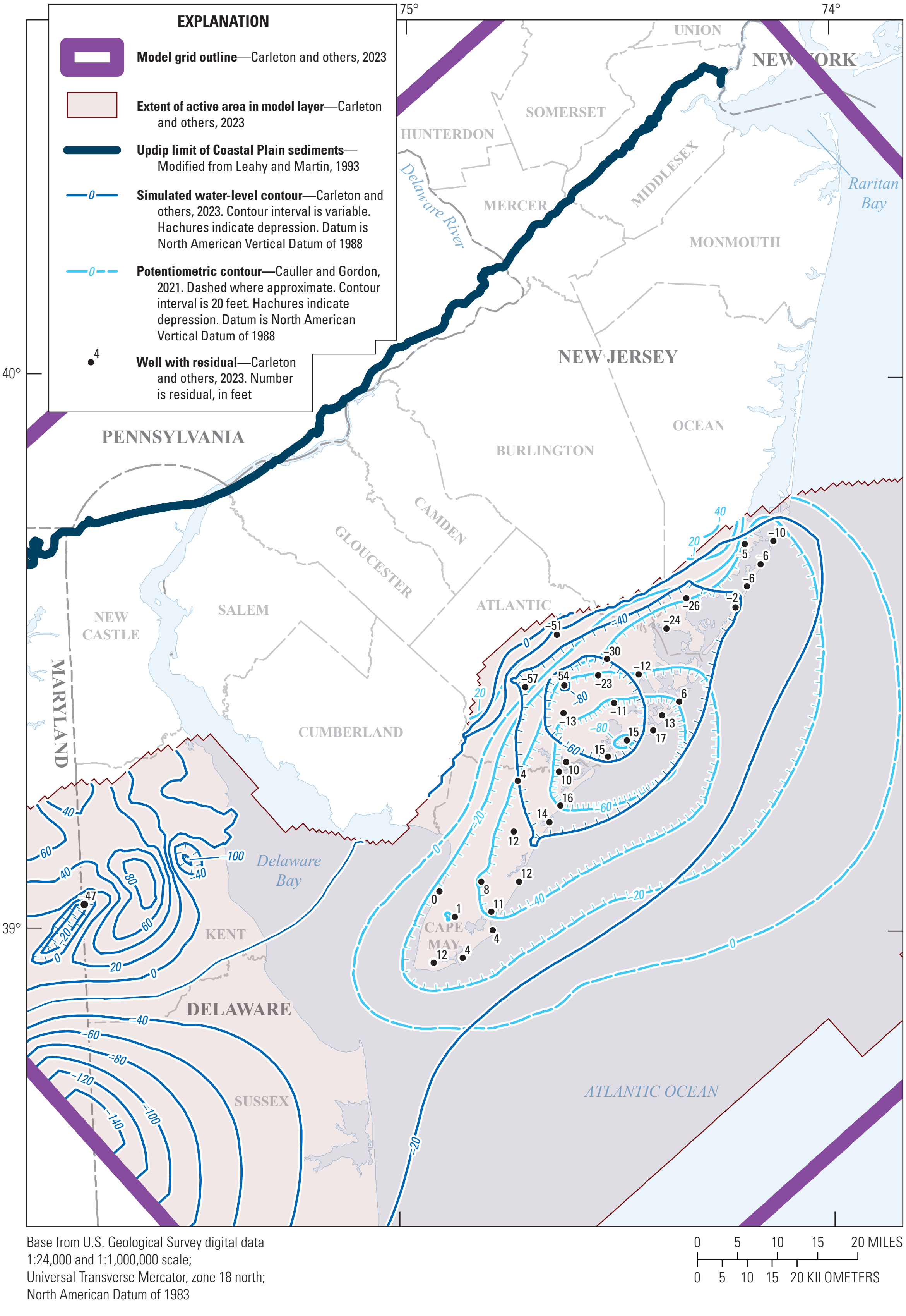


Figure 34. Map showing simulated water–level contours and 2013 potentiometric surface for, and residuals for selected wells in, the Atlantic City 800-foot sand, New Jersey and the simulated water-level contours for, and residuals for a selected well in, the Calvert aquifer system, Delaware.

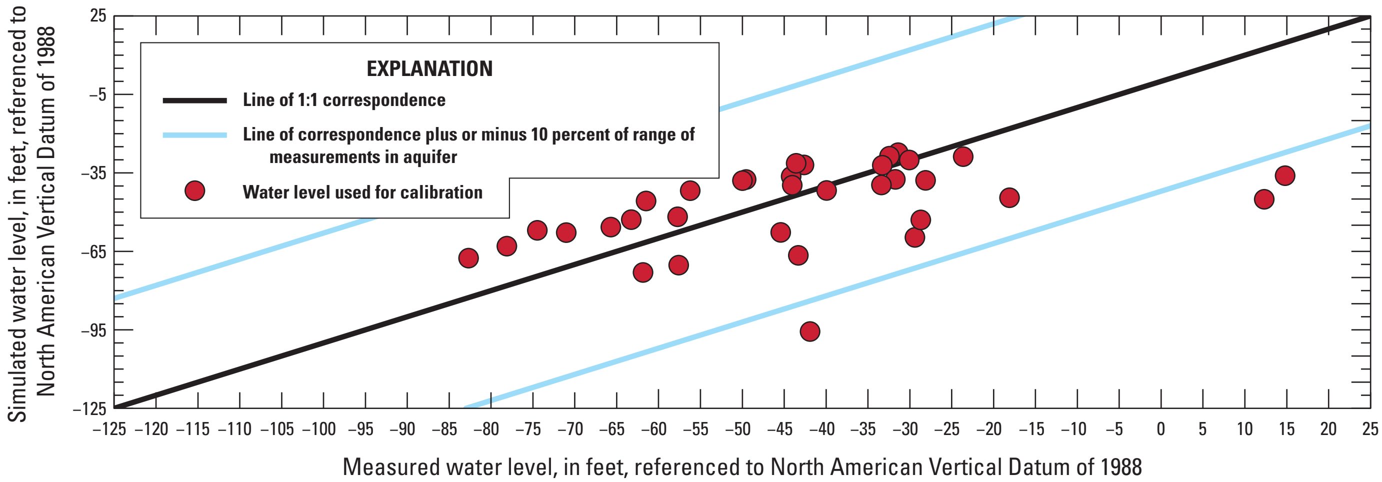


Figure 35. Graph showing simulated and observed water levels for wells open to the Atlantic City 800-foot sand, Cape May, Atlantic, and Ocean Counties, New Jersey, 2013.

Table 13. Simulated and observed water-level observations and residuals for wells open to the Atlantic City 800-foot sand, New Jersey, and the Calvert aquifer system, Delaware, 2013.

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
		New Jersey wells		
WLOb010037_7	010037	−74.45	−56.98	17.47
WLOb010039_7	010039	−71.02	−57.85	13.17
WLOb010180_7	010180	−45.40	−57.76	−12.36
WLOb010367_7	010367	−78.10	−63.01	15.09
WLOb010578_7	010578	−65.68	−55.73	9.95
WLOb010600_7	010600	−82.67	−67.60	15.07
WLOb010650_6	010650	12.33	−45.09	−57.42
WLOb010704_6	010704	−57.58	−70.29	−12.71
WLOb010706_6	010706	−29.39	−59.66	−30.27
WLOb010967_5	010967	−57.71	−51.79	5.92
WLOb011220_4	011220	−41.90	−95.65	−53.75
WLOb011252_3	011252	14.81	−36.07	−50.88
WLOb011253_4	011253	−43.30	−66.53	−23.23
WLOb011456_2	011456	−61.83	−73.09	−11.26
WLOb090004_7	090004	−49.54	−37.53	12.01
WLOb090079_5	090079	−42.63	−31.97	10.66
WLOb090092_7	090092	−44.16	−36.36	7.80
WLOb090106_7	090106	−61.48	−45.74	15.74
WLOb090136_7	090136	−56.20	−41.81	14.39
WLOb090144_7	090144	−63.25	−52.88	10.37
WLOb090185_5	090185	−44.03	−39.73	4.30
WLOb090302_5	090302	−31.37	−27.28	4.09
WLOb090306_5	090306	−30.05	−30.08	−0.03
WLOb090337_5	090337	−32.42	−28.62	3.80
WLOb090423_5	090423	−33.28	−32.08	1.20
WLOb090479_4	090479	−43.56	−31.35	12.21
WLOb090527_2	090527	−49.98	−37.96	12.02
WLOb290112_7	290112	−28.12	−37.85	−9.73
WLOb290457_5	290457	−39.93	−41.72	−1.79
WLOb290561_7	290561	−31.73	−37.48	−5.75
WLOb290597_5	290597	−18.08	−44.521	−26.43

Table 13. Simulated and observed water-level observations and residuals for wells open to the Atlantic City 800-foot sand, New Jersey, and the Calvert aquifer system, Delaware, 2013.—Continued

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
New Jersey wells—Continued				
WLOb290598_6	290598	−23.62	−28.78	−5.16
WLOb290814_5	290814	−28.67	−52.98	−24.31
WLOb290936_6	290936	−33.37	−39.62	−6.25
Delaware well				
WLObKb3102_7	Kb3102	27.67	−19.81	−47.48

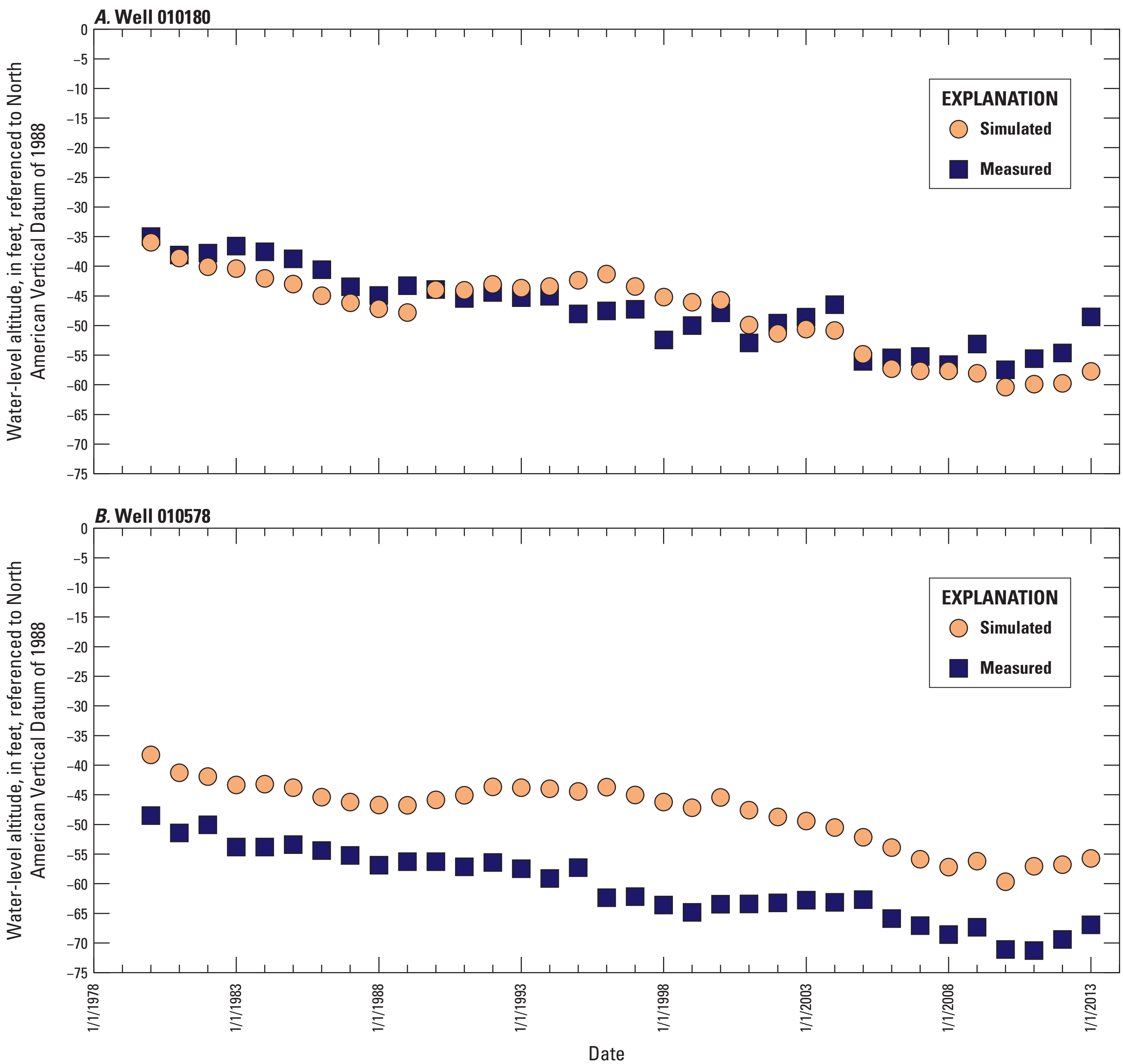


Figure 36. Hydrographs of simulated and observed water levels in wells *A*, 010180 and *B*, 010578, open to the Atlantic City 800-foot sand, New Jersey, 1980–2013.

Calibration of Water Levels in the Piney Point Aquifer

Simulated water-level contours in the Piney Point aquifer (model layer 9, primarily in Ocean, Atlantic, Burlington, Gloucester, and Cumberland Counties, New Jersey, and Kent County in Delaware) are generally similar in shape to the 2013 potentiometric surface (Cauller and Gordon, 2021) (fig. 37), including the contours defining cones of depression in Kent County in Delaware and Cumberland and Ocean Counties in New Jersey. The simulated water levels extend farther updip in Burlington and Ocean Counties than the 2013 potentiometric surface because the updip limit of the Piney Point aquifer in the new hydrogeologic framework used in this groundwater-flow model used new well information from that area which was not available at the time of the previous framework developed by Zapecza, (1989). However, the 2013 potentiometric surface used the updip limit of the Piney Point aquifer which was based on the earlier hydrogeologic framework presented in Zapecza, (1989) for that aquifer. Available Piney Point aquifer withdrawal data indicate anomalously low rates in 2004, 2008, and 2010, likely resulting from missing data for wells with reported withdrawals in other years. Therefore, the 2007 withdrawal rates were substituted for 2004, 2008, and 2010 withdrawals for wells with presumed missing data. The average water-level residuals (simulated minus observed) are shown in table 14 and figures 37 and 38 for 26 wells in New Jersey. The average water-level residual for 26 wells in Cumberland, Atlantic, Gloucester, Camden, Burlington, and Ocean Counties in New Jersey is 9 ft and the RMSE is 23 ft. The minimum; first, second, and third quartile; and maximum residuals are –22, –2, 4, 16, and 80 ft, respectively. The simulated water levels are within 10 ft of observed water levels for 14 of the 26 wells (54 percent) in New Jersey and within 20 ft of observed levels in 19 of 26 wells (73 percent) (figures 37 and 38 and table 14). The average water-level residuals also are shown in table 14 and figure 37 for four wells in Delaware.

Hydrographs for two wells screened in the Piney Point aquifer are shown in figure 39. Simulated water levels in well 050676, located in an area in southeastern Burlington County where withdrawals are minimal, have the same flat trend but a smaller amplitude than observed water levels and are, on average, 16 ft greater than observed water levels (fig. 39*A*). The water levels simulated for this well by Voronin (2004) also show a smaller amplitude than observed water levels and are 5 to 10 ft lower than the observed water levels during 1980–98. The simulated water levels in well 110096 in Cumberland County have the same decreasing trend and amplitude as the observed water levels (associated with increased nearby withdrawals), but the simulated water levels are on average 9 ft greater than observed water levels (fig. 39*B*). The water levels simulated for this well by Voronin (2004) show a pattern similar to that of the simulated water levels shown in figure 39*B* for 1980–98.

Calibration of Water Levels in the Vincentown Aquifer

Simulated water level contours in the Vincentown aquifer (model layer 11, present primarily in Burlington, Gloucester, Monmouth, Ocean, and Salem Counties) generally match the 2013 potentiometric surface (Cauller and Gordon, 2021) (fig. 40). The differences between the simulated and observed water levels are shown in table 15 and in figures 40 and 41 for wells measured in New Jersey in 2013. The average water-level residual (simulated minus observed) for nine wells in Burlington, Gloucester, Monmouth, Ocean, and Salem Counties is −2 ft and the RMSE is 11 ft. The minimum; first, second, and third quartile; and maximum residuals are −9, −6, −2, 8, and 29 ft, respectively. The simulated water levels are within 10 ft of observed water levels for seven of the nine wells (89 percent) in New Jersey. The simulated water levels for the Rancocas aquifer in Delaware and the average water-level residual for one well measured in Delaware in 2013 (table 15) also are shown in figure 40.

Hydrographs of simulated and observed water levels in wells 250636 and 290139 in Monmouth and Ocean Counties, respectively, show that simulated water levels are an average of 2 ft and about 3 ft lower than observed water levels, respectively, and have the same flat trend and similar amplitude (fig. 42). The hydrograph for well 290139 in Voronin (2004) is similar to the hydrograph shown in figure 42*B* for 1980–98, whereas the hydrograph for well 250636 (fig. 42*A*) in Voronin (2004) shows simulated water levels that are 20 to 25 ft lower than observed water levels during 1980–98.

Calibration of Water Levels in the Wenonah-Mount Laurel Aquifer

Simulated water-level contours in the Wenonah-Mount Laurel aquifer (model layer 13, Monmouth, Ocean, Burlington, Camden, Gloucester, and Salem Counties) generally match the 2013 potentiometric surface (Cauller and Gordon, 2021), but the simulated water levels are lower in updip areas of Monmouth County and central Gloucester County (fig. 43). The simulated water-level contours generally are similar in shape to the 2013 potentiometric surface over much of the extent of the aquifer and the simulated water levels are within 10 or 20 ft of the water levels that were measured at the cones of depression associated with pumping centers in coastal Ocean and Monmouth Counties and western Burlington and central Camden Counties. The differences between the simulated and observed water levels for wells measured in New Jersey in 2013 are shown in table 16 and in figures 43 and 44. The average water-level residual (simulated minus observed) for 48 wells in Salem, Gloucester, Camden, Burlington, Ocean, and Monmouth Counties is −8 ft and the RMSE is 23 ft. The minimum; first, second, and third quartiles;

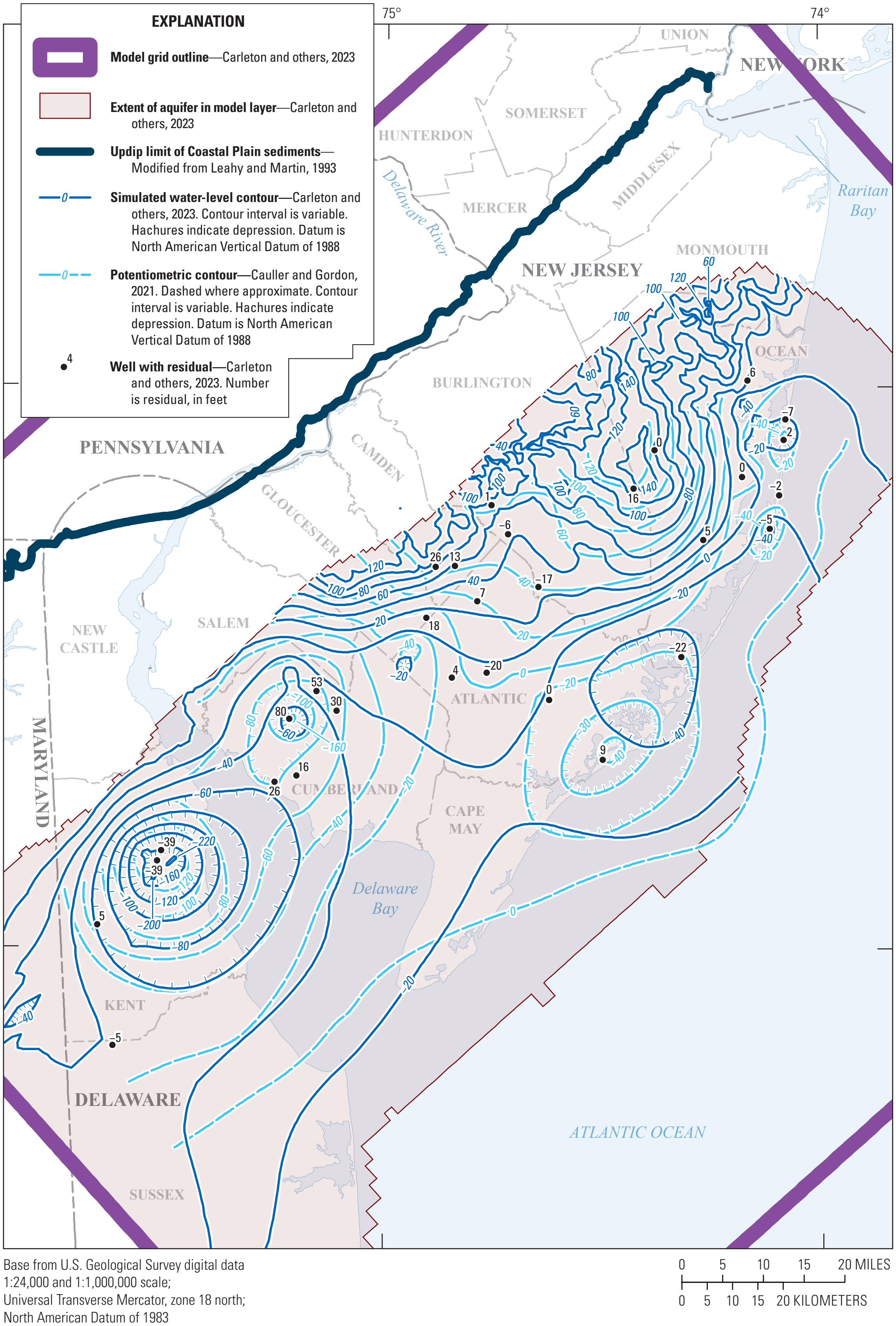


Figure 37. Map showing simulated water–level contours and the 2013 potentiometric surface for, and residuals for selected wells in, the Piney Point aquifer, New Jersey and Delaware.

Table 14. Simulated and observed water-level observations and residuals for wells open to the Piney Point aquifer, New Jersey and Delaware, 2013.

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
New Jersey wells				
WLOb010270_7	010270	19.94	27.27	7.33
WLOb010700_6	010700	16.95	−3.29	−20.24
WLOb010713_6	010713	−11.40	−7.58	3.82
WLOb010834_6	010834	−40.26	−31.66	8.60
WLOb011219_5	011219	−22.84	−22.45	0.39
WLOb050407_7	050407	48.88	42.40	−6.48
WLOb050488_7	050488	41.21	23.80	−17.41
WLOb050676_7	050676	117.76	133.69	15.93
WLOb050800_7	050800	72.73	73.46	0.73
WLOb071147_2	071147	52.25	78.15	25.90
WLOb071280_2	071280	42.17	55.07	12.90
WLOb110044_7	110044	−84.94	−32.29	52.65
WLOb110092_7	110092	−81.79	−55.56	26.21
WLOb110096_7	110096	−68.59	−52.58	16.01
WLOb110163_7	110163	−62.21	−32.37	29.84
WLOb111220_3	111220	−163.51	−83.62	79.89
WLOb151592_2	151592	−6.85	11.62	18.47
WLOb290018_7	290018	−4.61	−6.59	−1.98
WLOb290023_5	290023	−37.08	−34.82	2.26
WLOb290425_5	290425	117.25	117.25	0.00
WLOb290537_7	290537	−15.57	−22.21	−6.64
WLOb290585_6	290585	9.38	9.29	−0.09
WLOb290607_7	290607	−47.39	−52.11	−4.72
WLOb290739_7	290739	13.30	18.84	5.54
WLOb291210_4	291210	−20.48	−42.62	−22.14
WLOb291579_3	291579	23.62	28.14	4.52
Delaware wells				
WLObId5501_7	Id5501	−124.39	−163.76	−39.37
WLObJd1415_6	Jd1415	−140.00	−179.04	−39.04
WLObKc3101_5	Kc3101	−66.81	−61.66	5.15
WLObNc1303_6	Nc1303	−36.71	−41.91	−5.20

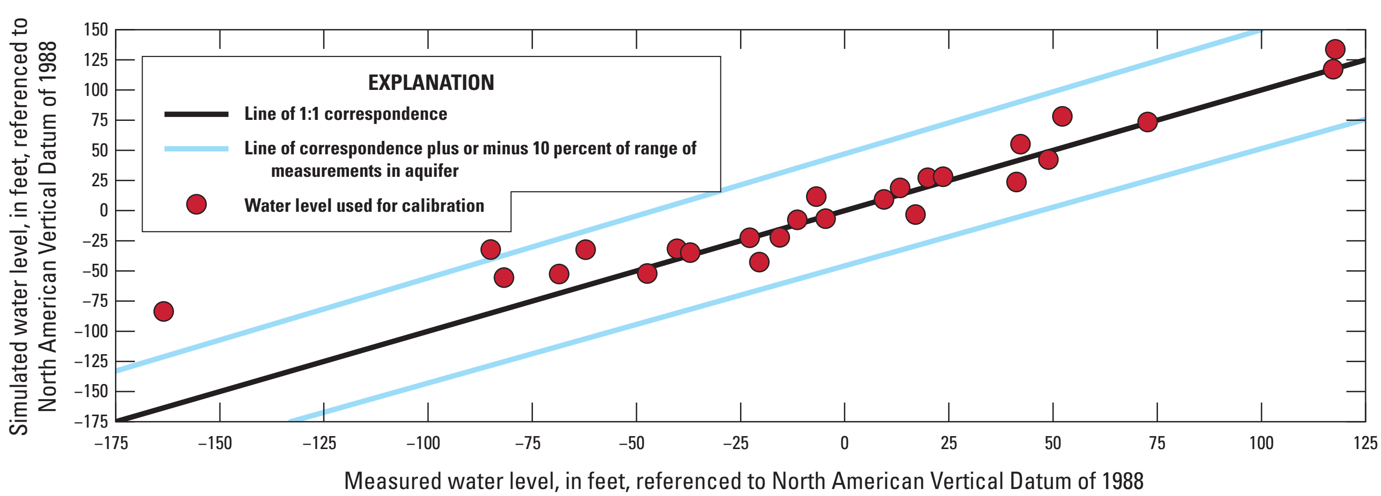


Figure 38. Graph showing simulated and observed water levels for selected wells open to the Piney Point aquifer, New Jersey and Delaware, 2013.

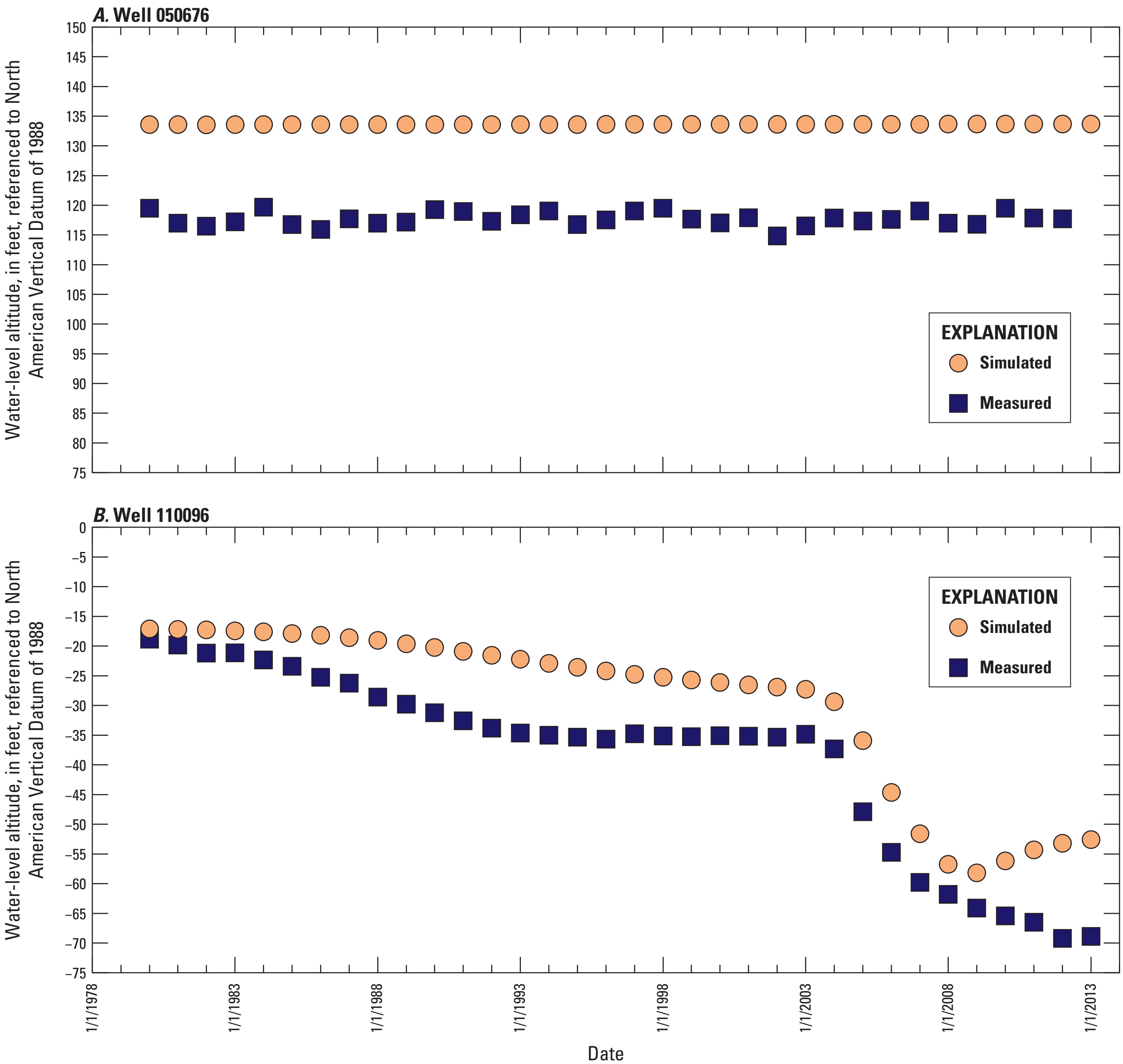
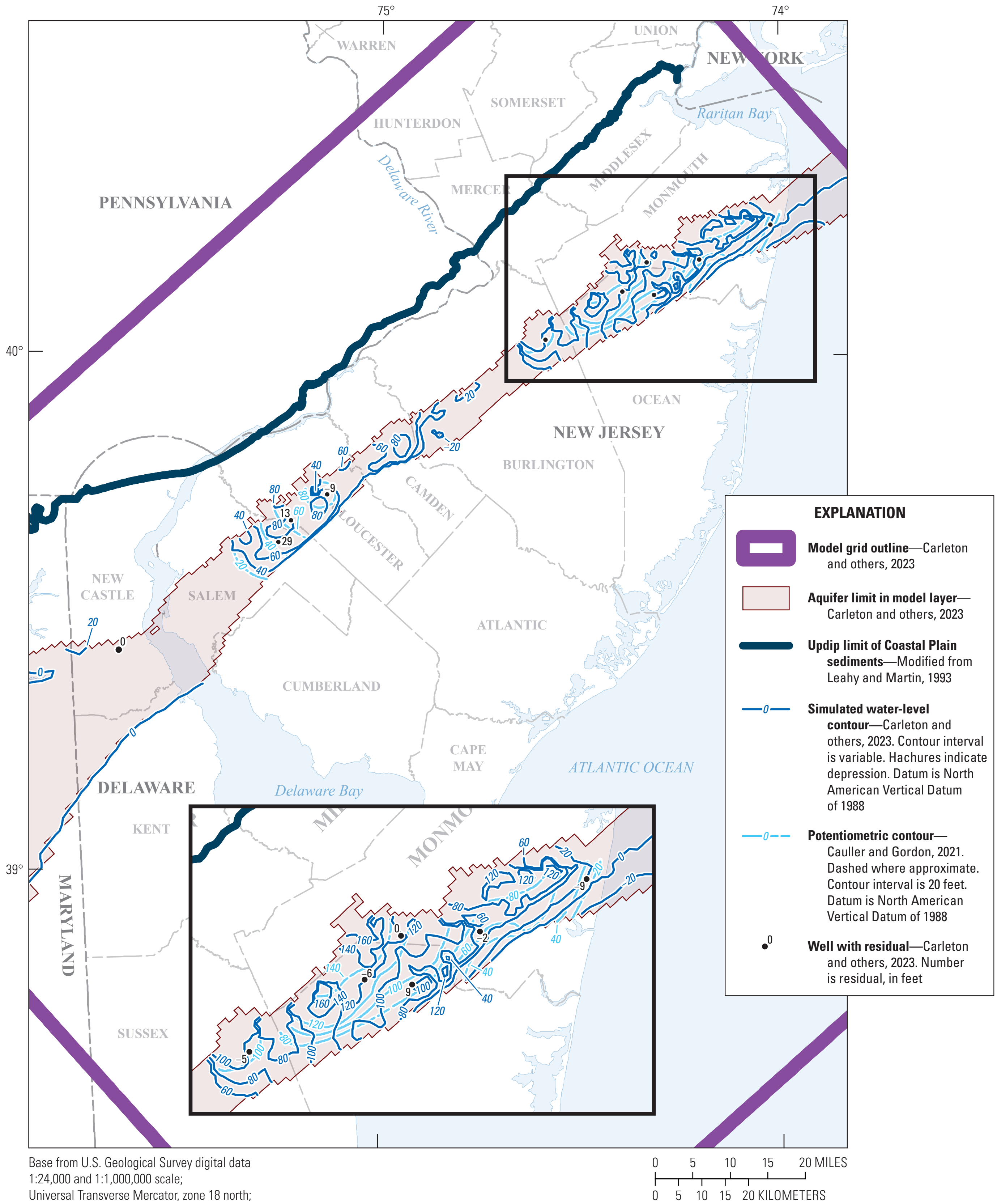


Figure 39. Hydrographs of simulated and observed water levels in wells *A*, 050676 and *B*, 110096, open to the Piney Point aquifer, New Jersey, 1980–2013.



Base from U.S. Geological Survey digital data 1:24,000 and 1:1,000,000 scale;
Universal Transverse Mercator, zone 18 north;
North American Datum of 1983

Figure 40. Map showing simulated water-level contours and the 2013 potentiometric surface for, and residuals for selected wells in, the Vincentown aquifer, New Jersey and the simulated water-level contours for, and residual for a selected well in, the Rancocas aquifer, Delaware.

Table 15. Simulated and observed water-level observations and residuals for wells open to the Vincentown aquifer, New Jersey, and the Rancocas aquifer, Delaware, 2013.

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
		New Jersey wells		
WLOb051250_4	051250	101.02	96.22	−4.80
WLOb151005_5	151005	68.42	81.03	12.61
WLOb151360_4	151360	81.15	72.54	−8.61
WLOb250636_6	250636	70.70	68.32	−2.38
WLOb250717_4	250717	123.79	123.37	-0.42
WLOb250788_4	250788	28.65	19.39	-9.26
WLOb290230_5	290230	125.46	119.67	−5.79
WLOb290658_5	290658	90.93	99.51	8.58
WLOb330292_3	330292	45.19	74.31	29.12
		Delaware well		
WLObFc5128_4	Fc5128	11.38	11.17	−0.21

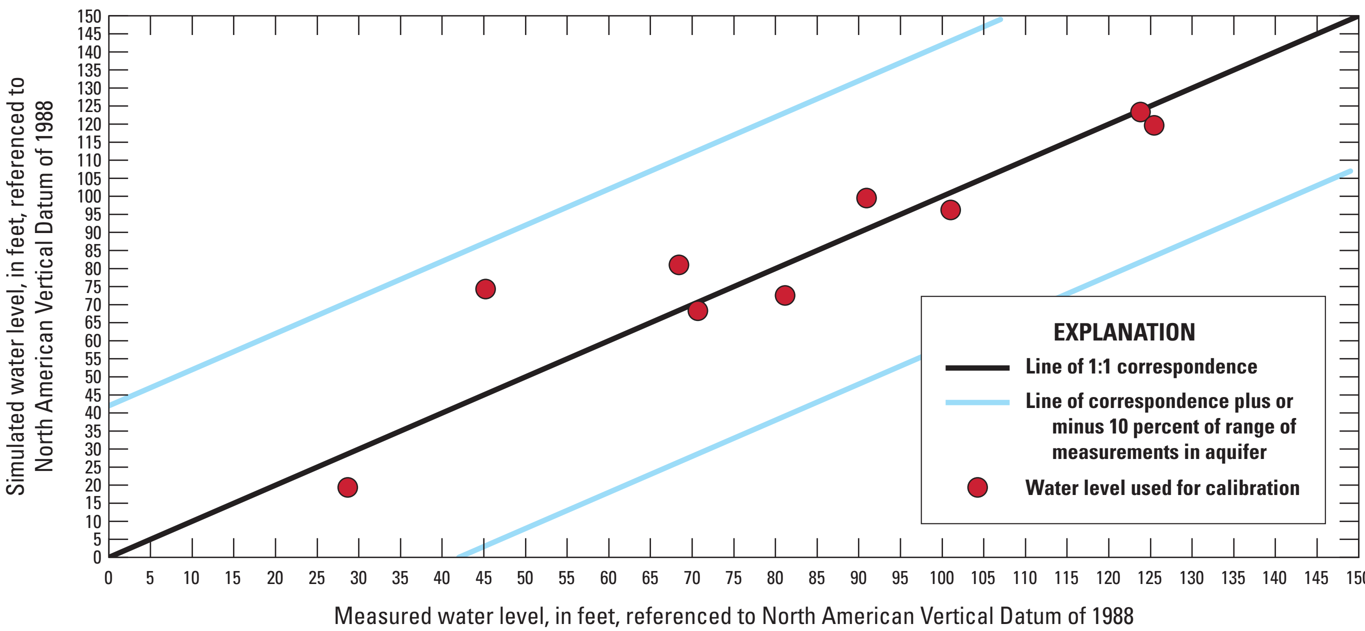


Figure 41. Graph showing simulated and observed water levels open to the Vincentown aquifer, New Jersey, 2013.

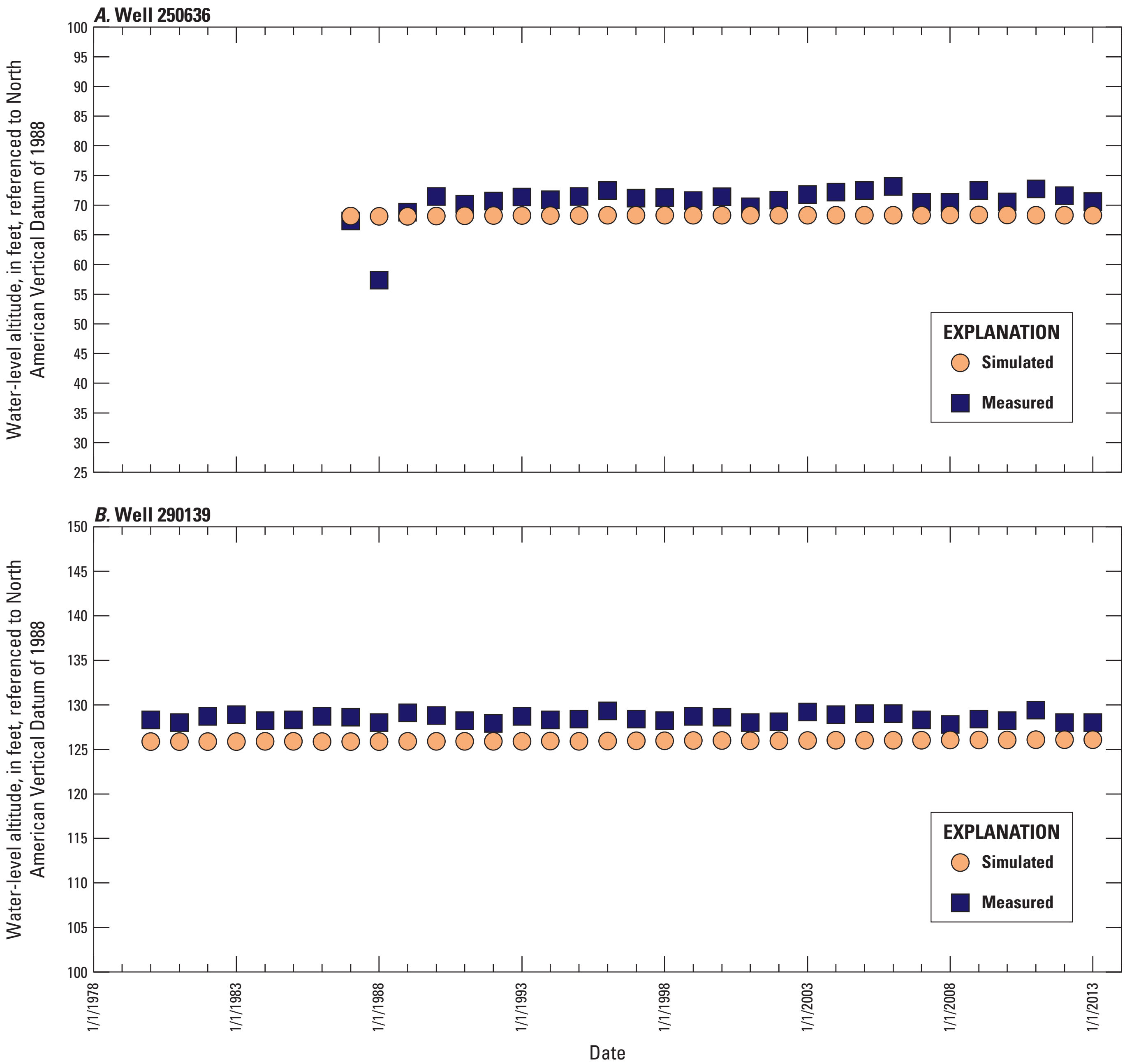
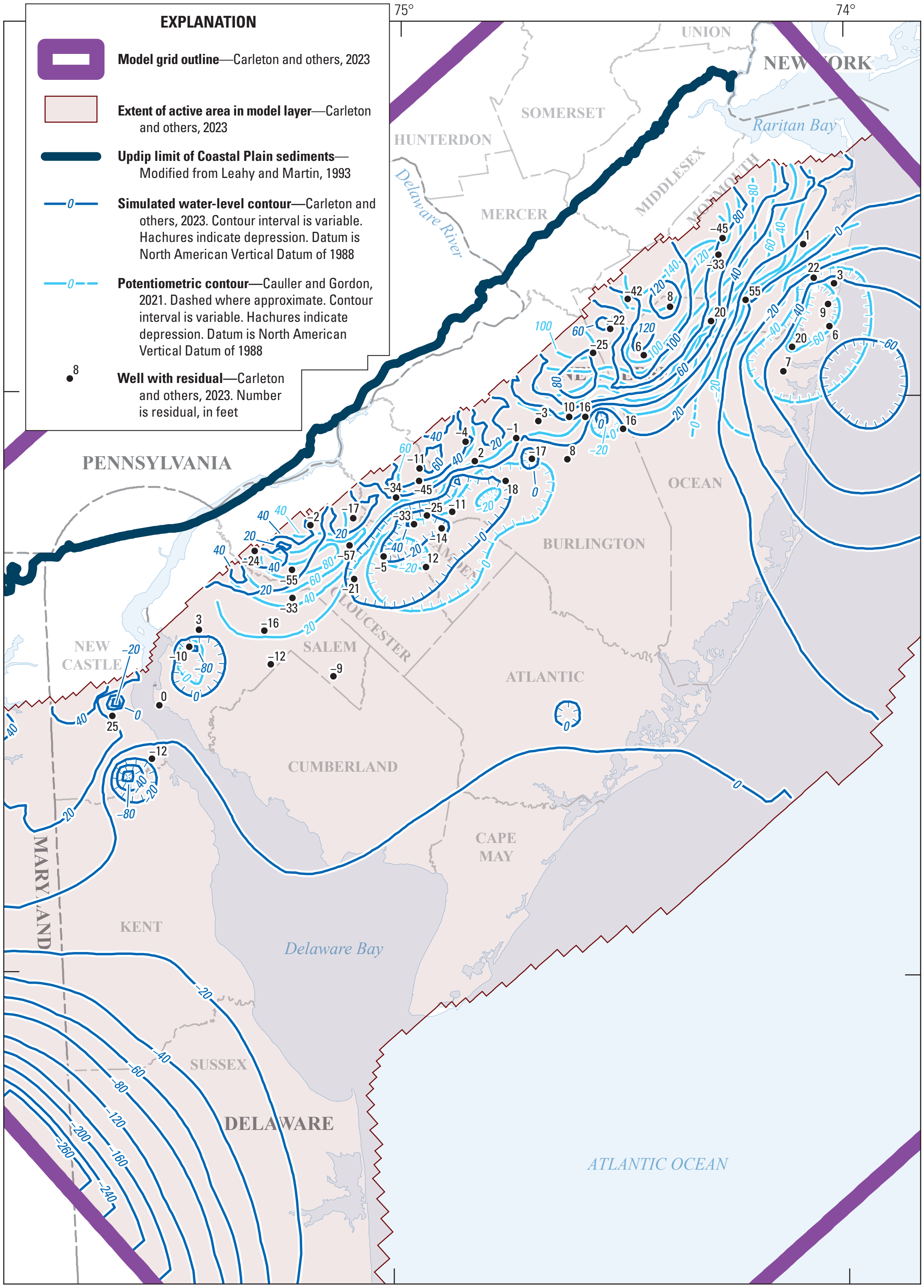


Figure 42. Hydrographs of simulated and observed water levels in wells, *A*, 250636, and *B*, 290139, open to the Vincentown aquifer, New Jersey, 1980–2013.



Base from U.S. Geological Survey digital data
1:24,000 and 1:1,000,000 scale;
Universal Transverse Mercator, zone 18 north;
North American Datum of 1983

0 5 10 15 20 MILES
0 5 10 15 20 KILOMETERS

Figure 43. Map showing simulated water-level contours and the 2013 potentiometric surface for, and residuals for selected wells in, the Wenonah-Mount Laurel aquifer, New Jersey and simulated water-level contours for, and residuals for selected wells in, the Mount Laurel aquifer, Delaware.

Table 16. Simulated and observed water-level observations and residuals for wells open to the Wenonah-Mount Laurel aquifer, New Jersey, and the Mount Laurel aquifer, Delaware, 2013.

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
New Jersey wells				
WLOb050257_7	050257	47.50	43.57	–3.93
WLOb050359_7	050359	26.95	24.31	–2.64
WLOb050365_7	050365	14.56	30.15	15.59
WLOb050427_7	050427	1.61	–14.93	–16.54
WLOb050695_7	050695	7.27	15.02	7.75
WLOb050720_6	050720	–16.40	1.71	18.11
WLOb050744_7	050744	2.44	18.42	15.98
WLOb051086_4	051086	34.43	44.04	9.61
WLOb051155_5	051155	23.73	25.70	1.97
WLOb051166_5	051166	99.60	74.70	–24.90
WLOb051178_5	051178	21.62	21.02	-0.60
WLOb051387_4	051387	−1.42	–12.42	–11.00
WLOb070022_6	070022	9.51	–15.53	–25.04
WLOb070118_7	070118	67.39	56.49	–10.90
WLOb070308_7	070308	46.9	13.34	–33.56
WLOb070391_7	070391	−3.95	–37.21	–33.26
WLOb070421_7	070421	85.67	40.59	–45.08
WLOb070449_6	070449	−22.10	–35.86	–13.76
WLOb070478_7	070478	−20.58	–8.31	12.27
WLOb150687_6	150687	20.66	18.97	–1.69
WLOb150910_6	150910	82.82	27.39	–55.43
WLOb150953_6	150953	55.67	38.67	–17.00
WLOb151009_6	151009	64.28	6.90	–57.38
WLOb151060_5	151060	13.46	–7.61	–21.07
WLOb151104_5	151104	80.29	56.06	–24.23
WLOb151384_3	151384	−20.06	–24.69	–4.63
WLOb250014_7	250014	−54.47	–51.47	3.04
WLOb250088_6	250088	109.86	76.62	–33.24
WLOb250095_5	250095	140.62	95.55	–45.07
WLOb250168_6	250168	−1.23	53.34	54.57
WLOb250335_7	250335	−51.05	–28.76	22.29
WLOb250353_7	250353	14.08	15.09	1.01
WLOb250391_7	250391	−62.21	–53.42	8.79
WLOb250396_7	250396	84.72	62.54	–22.18
WLOb250405_7	250405	138.12	95.72	–42.40
WLOb250486_6	250486	−61.92	–55.63	6.29
WLOb290031_7	290031	−55.36	–48.34	7.02
WLOb290049_7	290049	−66.43	–46.60	19.83
WLOb290140_7	290140	109.52	115.31	5.79
WLOb290699_7	290699	120.17	127.76	7.59
WLOb290783_7	290783	46.95	67.11	20.16

Table 16. Simulated and observed water-level observations and residuals for wells open to the Wenonah-Mount Laurel aquifer, New Jersey, and the Mount Laurel aquifer, Delaware, 2013.—Continued

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
New Jersey wells—Continued				
WLOb330002_7	330002	16.70	4.21	–12.49
WLOb330020_7	330020	23.06	7.16	–15.90
WLOb330050_7	330050	4.51	7.64	3.13
WLOb330252_7	330252	−1.17	–11.25	–10.08
WLOb330842_4	330842	14.32	5.03	–9.29
WLOb330904_3	330904	48.11	14.84	–33.27
WLOb330938_4	330938	2.11	1.63	–0.48
Delaware wells				
WLObFc4211_4	Fc4211	−7.67	17.53	25.20
WLObGd3304_7	Gd3304	−0.67	–12.90	–12.23

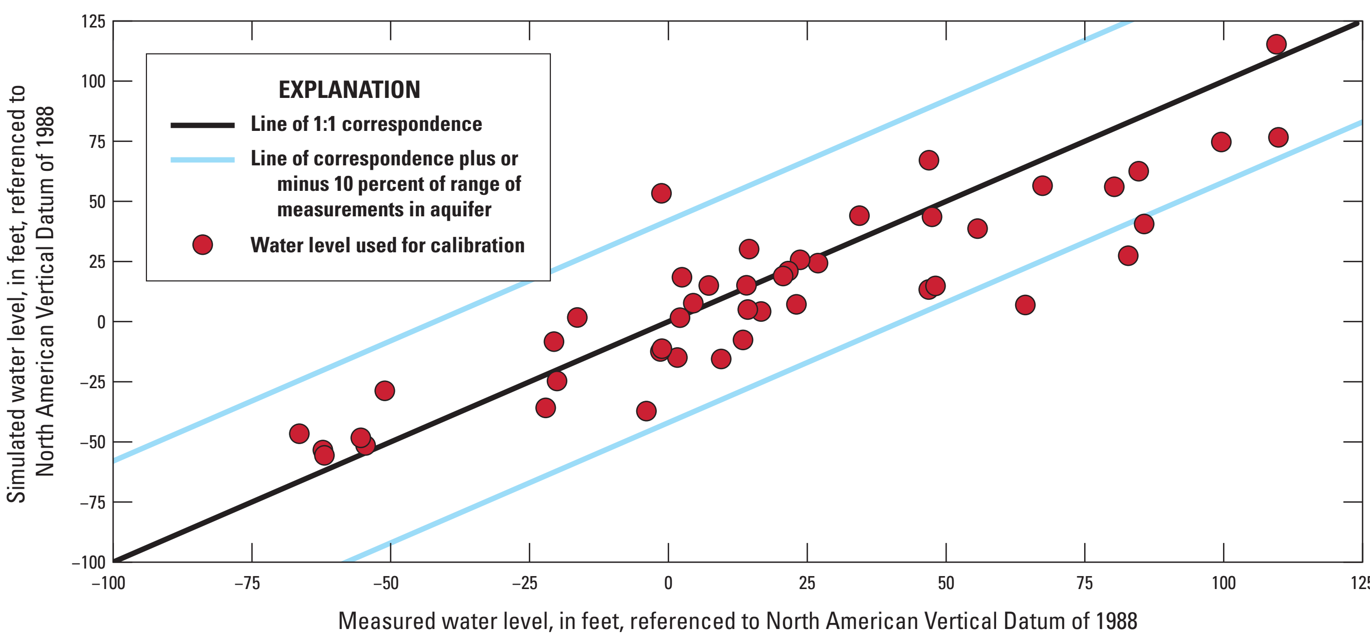


Figure 44. Graph showing simulated and observed water levels for selected wells open to the Wenonah-Mount Laurel aquifer, New Jersey, 2013.

and maximum residuals are –57, –23, –4, 7, and 55 ft, respectively. The simulated water levels are within 10 ft of observed water levels for 19 of the 48 wells (40 percent) and within 20 ft of observed water levels for 33 of the 48 wells (69 percent) in New Jersey. The simulated water levels for the Mount Laurel aquifer in Delaware and the average water-level residual for two wells measured in Delaware in 2013 (table 16) also are shown in figure 43.

The hydrographs of selected wells screened in the Wenonah-Mount Laurel aquifer are shown in figure 45. The hydrograph for well 070478 in Camden County indicates simulated water levels have a similar trend as observed water levels but a smaller amplitude and are lower from 1980 to 1992, but higher from 1993 to 2013, with an average difference of 8 ft (fig. 45*A*). These trends are also observed in the hydrograph shown in Voronin (2004) for this well during 1980–98. The hydrographs of simulated water levels for wells 250353 (fig. 45*B*) and 250637 (fig. 45*C*) in Monmouth County have the same trend and amplitude as observed water levels in those wells but with an average residual of 0.3 and 10 ft lower, respectively, than the observed water levels. Water levels in well 250353 simulated by Voronin (2004) show a smaller amplitude than the observed water levels, and the simulated water levels in well 250637 are about 10 ft lower than those observed during 1980–98. The hydrograph for well 290140 in Ocean County indicates that the simulated water levels have the same trend and amplitude as the observed water levels, and are, on average, within 3 ft of the observed water levels (fig. 45*D*). Simulated water levels in well 330020 in Salem County have the same trend and amplitude as observed water levels but are an average of 12 ft lower than them (fig. 45*E*).

Calibration of Water Levels in the Englishtown Aquifer System

Simulated water-level contours in the Englishtown aquifer system (model layer 15, Monmouth, Ocean, Burlington, Camden, Gloucester, and Salem Counties) generally match the 2013 potentiometric surface (Cauller and Gordon, 2021) but the simulated water levels are lower in parts of northern Camden and Burlington Counties and near a pumping center in updip Monmouth County (fig. 46). The simulated contours and 2013 potentiometric surface generally have the same minima in the cones of depression in coastal southern Monmouth County and central northern Ocean County, but the cones differ in shape, partly as a result of simulated residuals and (or) of interpretation of the limited water-level data in areas used to develop the potentiometric contours. The differences between the simulated and observed water levels for wells measured in 2013 are shown in table 17 and figures 46 and 47. The average water-level residual (simulated minus observed) for 39 wells in New Jersey is −5 ft and the RMSE is 17 ft. The minimum; first, second, and third quartile; and maximum residuals are −41, −13, −1, 6, and 28 ft, respectively. The simulated water levels are within 10 ft of observed water levels for 23 of the 39 wells (59 percent) and within 15 ft of observed water levels for 29 of the 39 wells (74 percent) in New Jersey.

The hydrographs of selected wells screened in the Englishtown aquifer system are shown in figure 48. The hydrograph for well 050259 in Burlington County shows that simulated water levels have the same trend and amplitude as observed water levels but are an average of 1 ft lower than observed water levels (fig. 48*A*). In comparison, the hydrograph in Voronin (2004) for well 050259 shows simulated water levels that are 5 to 10 ft higher than the observed water levels during 1980–98. The simulated water levels in the hydrographs for wells 250429 and 250638 in Monmouth County show the same trend of the recovering observed water levels in the 1990s and the amplitudes of the simulated water levels are similar to those of the observed water levels but are an average of –4 and –12 ft, respectively, lower than them (figs. 48*B* and 48*C*). In comparison, the hydrographs in Voronin (2004) for these two wells show simulated water levels that follow a similar pattern as those simulated by the current updated model but a smaller amplitude than observed water levels during 1980–98. Simulated water levels in well 290138 in Ocean County have the same trend and amplitude as observed water levels but are an average of 18 ft lower than them (fig. 48*D*). The hydrograph for this well in Voronin (2004) shows simulated water levels that are 10 to 15 ft higher than observed water levels during 1980–98.

Calibration of Water Levels in the Upper Potomac-Raritan-Magothy Aquifer

Simulated water-level contours in the upper Potomac-Raritan-Magothy aquifer (model layer 17, Middlesex, Mercer, Monmouth, Ocean, Burlington, Camden, Gloucester, and Salem Counties) closely match the 2013 potentiometric surface (Cauller and Gordon, 2021) (fig. 49). The simulated contours and 2013 potentiometric surface are similar in shape and the contours correspond well in the areas of the major cones of depression in central Camden and Ocean Counties. The differences (residuals) between the simulated and observed water levels for wells measured in New Jersey in 2013 are shown in table 18 and in figures 49 and 50. The average water-level residual for 88 wells in New Jersey is 9 ft and the RMSE is 14 ft. The minimum; first, second, and third quartile; and maximum residuals for New Jersey wells are −17, 2, 24, 15, and 35 ft, respectively. The simulated water levels are within 10 ft of observed water levels for 46 of the 88 wells (52 percent) and within 15 ft of observed water levels for 64 of the 88 wells (73 percent) in New Jersey. The simulated water levels for the Magothy aquifer in Delaware and the average water-level residual for four wells measured in Delaware in 2013 (table 18) also are shown in figure 49.

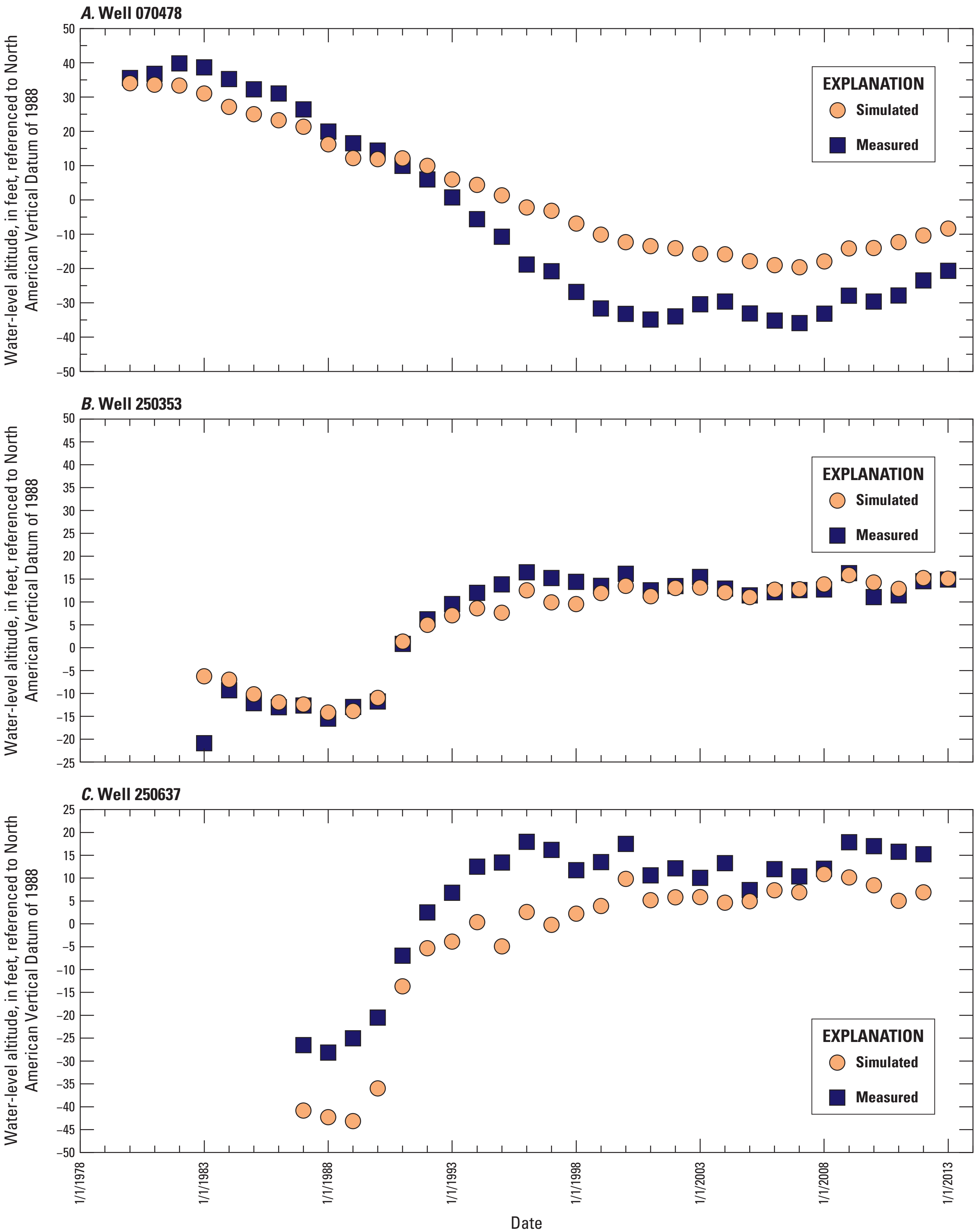


Figure 45. Hydrographs of simulated and observed water levels for wells *A*, 070478, *B*, 250353, *C*, 250637, *D*, 290140, and *E*, 330020, open to the Wenonah-Mount Laurel aquifer, New Jersey, 1980–2013.

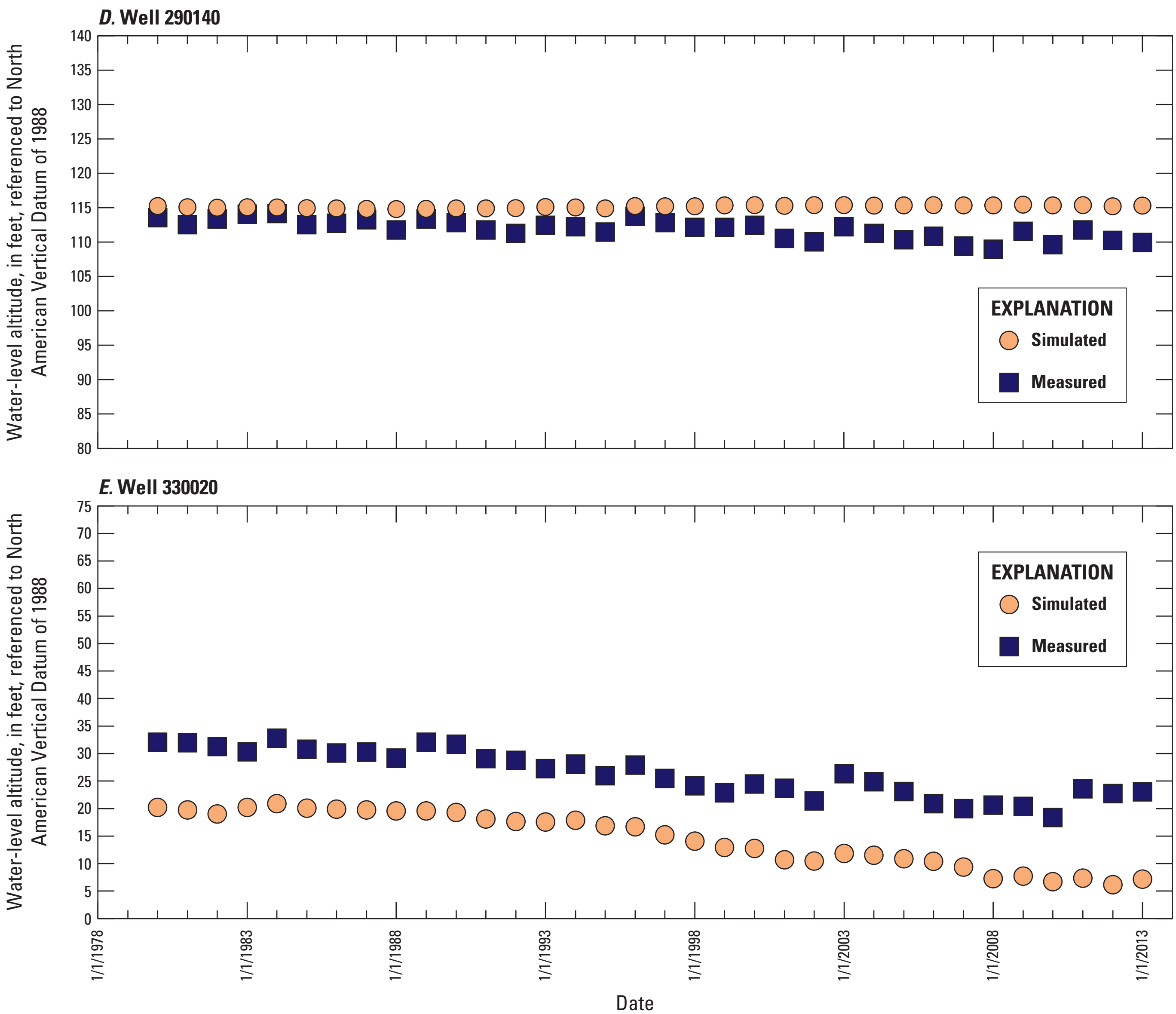


Figure 45.—Continued

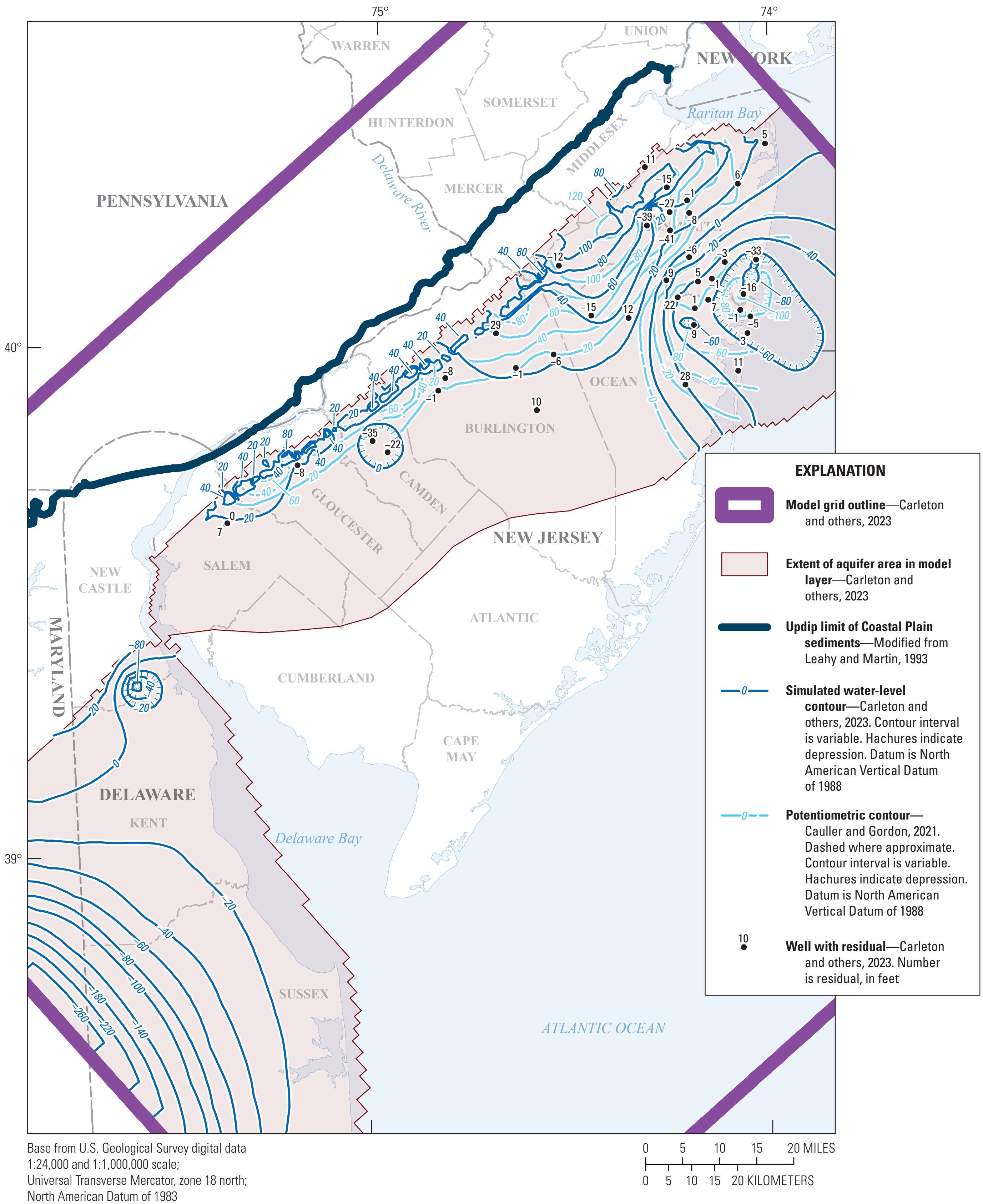


Figure 46. Map showing simulated water-level contours and 2013 potentiometric surface for, and residuals for selected wells in, the Englishtown aquifer system, New Jersey and simulated water-level contours for the Matawan aquifer, Delaware.

Table 17. Simulated and observed water-level observations and residuals for wells open to the Englishtown aquifer system, New Jersey, 2013.

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
WLOb050197_7	050197	24.36	16.38	–7.98
WLOb050259_7	050259	16.46	15.67	–0.79
WLOb050375_7	050375	21.41	20.61	–0.80
WLOb050437_7	050437	58.71	29.25	–29.46
WLOb050754_7	050754	27.98	22.14	–5.84
WLOb051390_4	051390	5.79	15.68	9.89
WLOb070166_7	070166	16.63	–5.17	–21.80
WLOb070672_6	070672	19.68	–15.25	–34.93
WLOb150676_6	150676	28.70	20.26	–8.44
WLOb230104_6	230104	70.93	81.88	–10.95
WLOb250016_7	250016	–52.57	–85.96	–33.39
WLOb250030_7	250030	–65.22	–81.57	–16.35
WLOb250046_6	250046	41.39	40.49	–0.90
WLOb250080_7	250080	63.76	23.13	–40.63
WLOb250096_7	250096	59.02	32.13	–26.89
WLOb250162_7	250162	–47.36	–41.91	5.45
WLOb250250_7	250250	87.67	72.98	–14.69
WLOb250408_6	250408	102.07	90.41	–11.66
WLOb250429_7	250429	–48.47	–49.54	–1.07
WLOb250441_7	250441	–48.70	–51.57	–2.87
WLOb250638_6	250638	–3.19	–9.28	–6.09
WLOb250697_6	250697	12.64	18.88	6.24
WLOb250704_6	250704	89.15	50.44	–38.71
WLOb250710_6	250710	–65.61	–58.17	7.44
WLOb250715_5	250715	2.71	7.70	4.99
WLOb250733_4	250733	36.71	28.40	–8.31
WLOb290005_7	290005	–70.05	–74.95	–4.90
WLOb290138_7	290138	60.03	45.28	–14.75
WLOb290236_7	290236	–16.64	–7.32	9.32
WLOb290433_7	290433	–70.86	–62.34	8.52
WLOb290441_7	290441	–54.46	–53.23	1.23
WLOb290450_7	290450	–65.93	–43.49	22.44
WLOb290452_6	290452	–58.70	–47.40	11.30
WLOb290503_7	290503	–67.18	–64.53	–2.65
WLOb290530_6	290530	–75.50	–76.49	–0.99
WLOb290534_7	290534	–47.42	–19.70	27.72
WLOb290938_6	290938	15.12	27.40	12.28
WLOb330168_4	330168	16.30	15.89	–0.41
WLOb330581_5	330581	12.03	18.67	6.64

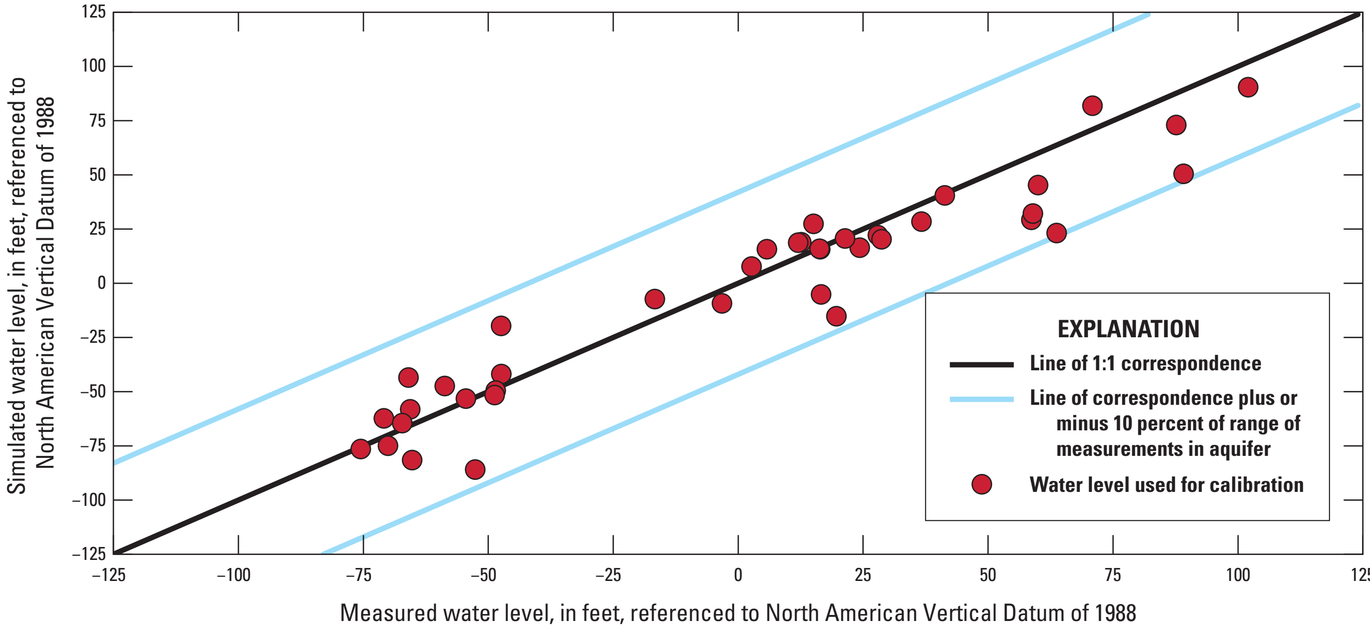


Figure 47. Graph showing simulated and observed water-levels for selected wells open to the Englishtown aquifer system, New Jersey, 2013.

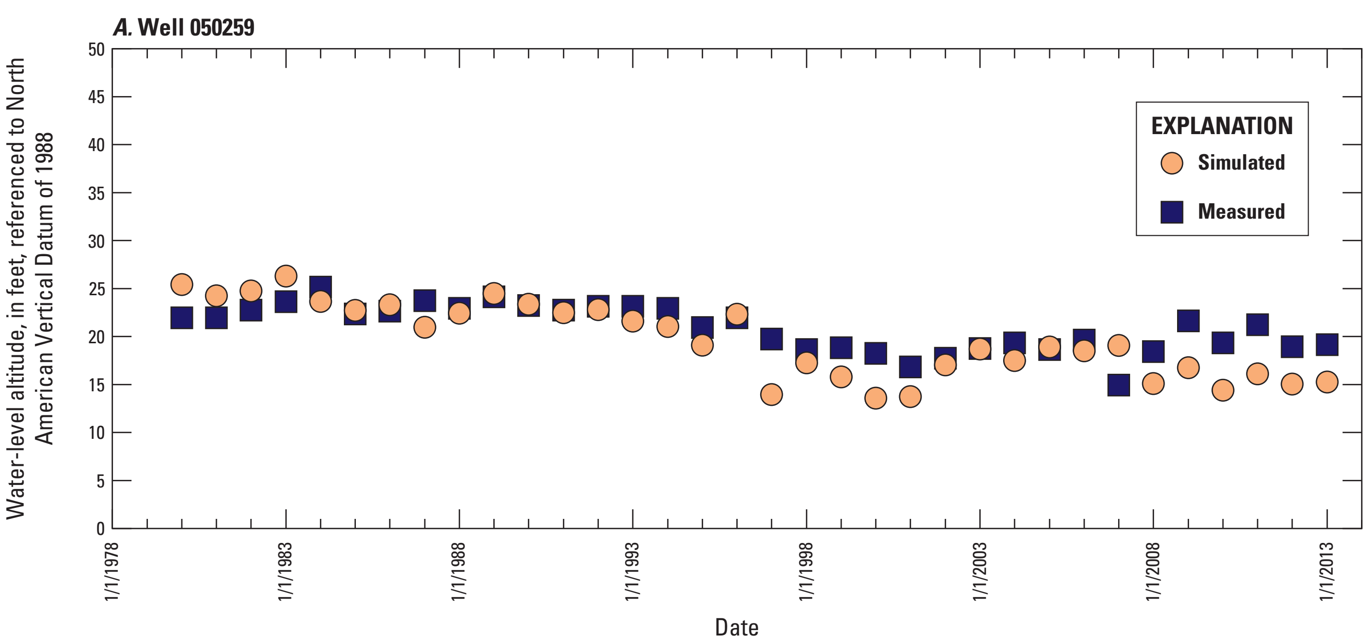


Figure 48. Hydrographs of simulated and observed water levels in wells *A*, 050259, *B*, 250429, *C*, 250638, and *D*, 290138, open to the Englishtown aquifer system, New Jersey, 1980–2013.

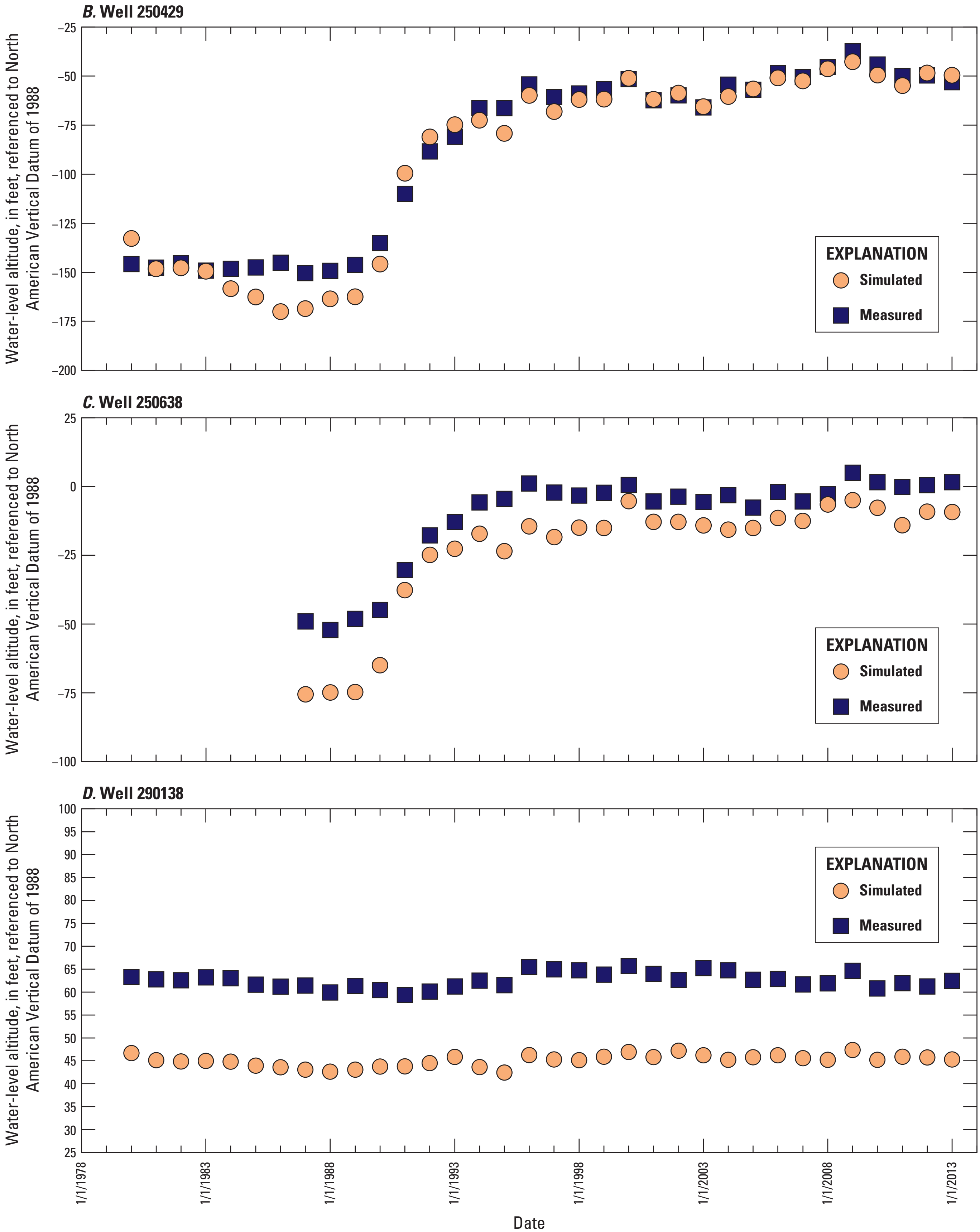


Figure 48.—Continued

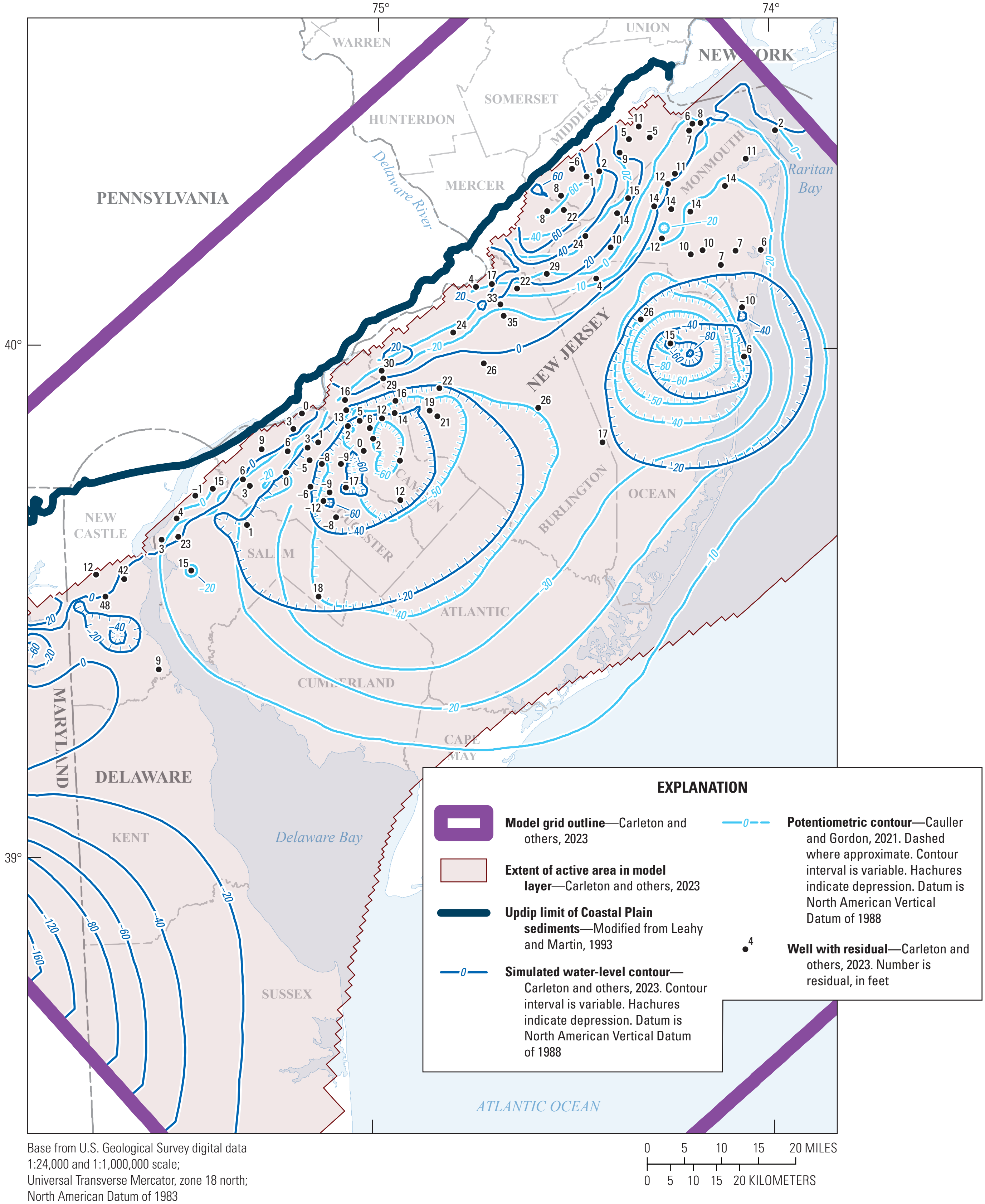


Figure 49. Map showing simulated water-level contours and 2013 potentiometric surface for, and residuals for selected wells in, the upper Potomac-Raritan-Magothy aquifer, New Jersey and simulated water-level contours for, and residuals for selected wells in, the Magothy aquifer, Delaware.

Table 18. Simulated and observed water-level observations and residuals for wells open to the upper Potomac-Raritan-Magothy aquifer, New Jersey, and the Magothy aquifer, Delaware, 2013.

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
New Jersey wells				
WLOb050116_7	050116	−5.52	16.75	22.27
WLOb050167_7	050167	−56.3	−37.20	19.10
WLOb050207_6	050207	−24.25	11.10	35.35
WLOb050212_7	050212	−16.55	16.13	32.68
WLOb050218_7	050218	1.22	5.03	3.81
WLOb050229_7	050229	−28.96	−0.05	28.91
WLOb050249_7	050249	–57.00	−36.16	20.84
WLOb050258_7	050258	–44.32	−21.98	22.34
WLOb050728_7	050728	−31.46	−5.08	26.38
WLOb050729_4	050729	−21.45	8.46	29.91
WLOb050731_7	050731	0.16	16.67	16.51
WLOb050745_7	050745	–12.73	10.80	23.53
WLOb051389_4	051389	–38.56	−12.23	26.33
WLOb051391_4	051391	–35.25	−18.44	16.81
WLOb070015_6	070015	−58.03	−51.07	6.96
WLOb070115_7	070115	−56.40	−44.14	12.26
WLOb070117_7	070117	−53.64	−39.45	14.19
WLOb070131_7	070131	−48.95	−32.95	16.00
WLOb070252_7	070252	−56.59	−56.70	−0.11
WLOb070285_7	070285	−34.89	−21.84	13.05
WLOb070311_7	070311	−59.63	−57.38	2.25
WLOb070316_7	070316	−50.98	−46.20	4.78
WLOb070322_7	070322	−23.86	−8.35	15.51
WLOb070404_7	070404	−49.28	−46.91	2.37
WLOb070410_7	070410	−56.76	−50.56	6.20
WLOb070477_7	070477	−55.38	−43.74	11.64
WLOb150003_7	150003	−44.56	−52.36	−7.80
WLOb150008_6	150008	−36.66	−44.50	−7.84
WLOb150028_7	150028	−15.32	−8.83	6.49
WLOb150060_7	150060	−44.13	−56.04	−11.91
WLOb150063_7	150063	−44.95	−54.28	−9.33
WLOb150127_6	150127	−33.17	−39.08	−5.91
WLOb150248_6	150248	−48.66	−65.99	−17.33
WLOb150276_6	150276	−27.57	−24.37	3.20
WLOb150303_7	150303	−1.30	1.22	2.52
WLOb150330_7	150330	−30.10	−29.34	0.76
WLOb150339_7	150339	−14.10	−10.65	3.45
WLOb150346_7	150346	−20.57	−20.70	−0.13
WLOb150433_7	150433	−47.79	−57.06	−9.27
WLOb150728_6	150728	−4.59	4.55	9.14
WLOb150741_6	150741	−27.10	−31.98	−4.88

Table 18. Simulated and observed water-level observations and residuals for wells open to the upper Potomac-Raritan-Magothy aquifer, New Jersey, and the Magothy aquifer, Delaware, 2013.—Continued

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
New Jersey wells—Continued				
WLOb150779_6	150779	0.98	1.04	0.06
WLOb151483_4	151483	−10.63	−4.20	6.43
WLOb210019_7	210019	64.57	72.58	8.01
WLOb210084_7	210084	52.26	74.45	22.19
WLOb230098_7	230098	43.37	45.23	1.86
WLOb230109_7	230109	4.27	13.00	8.73
WLOb230180_7	230180	3.41	8.50	5.09
WLOb230182_7	230182	14.68	10.04	−4.64
WLOb230228_7	230228	61.12	59.76	−1.36
WLOb230292_7	230292	73.71	67.80	−5.91
WLOb230351_7	230351	18.93	7.44	−11.49
WLOb230508_7	230508	64.33	72.57	8.24
WLOb250013_7	250013	−22.36	−16.16	6.20
WLOb250037_7	250037	−21.58	−7.22	14.36
WLOb250056_7	250056	7.76	22.90	15.14
WLOb250062_7	250062	−24.51	−14.57	9.94
WLOb250097_7	250097	−17.88	−3.66	14.22
WLOb250103_7	250103	−11.39	2.57	13.96
WLOb250197_7	250197	−5.13	1.84	6.97
WLOb250206_7	250206	−5.40	0.51	5.91
WLOb250218_6	250218	11.94	26.09	14.15
WLOb250259_7	250259	−9.39	1.25	10.64
WLOb250316_7	250316	–2.52	−0.98	1.54
WLOb250322_7	250322	6.64	16.64	10.00
WLOb250436_7	250436	–25.39	−18.29	7.10
WLOb250459_7	250459	–18.24	−7.17	11.07
WLOb250500_6	250500	–1.15	27.45	28.60
WLOb250509_7	250509	13.24	37.19	23.95
WLOb250550_6	250550	–18.38	−6.81	11.57
WLOb250567_6	250567	–6.98	1.47	8.45
WLOb250639_6	250639	–23.85	−14.07	9.78
WLOb250721_4	250721	–23.65	−17.05	6.60
WLOb250724_5	250724	–13.21	−0.84	12.37
WLOb250729_5	250729	–22.79	−8.93	13.86
WLOb290070_7	290070	–36.55	−42.30	−5.75
WLOb290134_7	290134	–50.85	−24.37	26.48
WLOb290238_6	290238	2.00	6.47	4.47
WLOb290531_6	290531	–29.78	−40.02	−10.24
WLOb291040_5	291040	–84.17	−69.63	14.54
WLOb330076_7	330076	–0.61	14.61	15.22
WLOb330111_7	330111	−20.54	2.20	22.74

Table 18. Simulated and observed water-level observations and residuals for wells open to the upper Potomac-Raritan-Magothy aquifer, New Jersey, and the Magothy aquifer, Delaware, 2013.—Continued

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
New Jersey wells—Continued				
WLOb330253_7	330253	−27.91	−13.38	14.53
WLOb330342_7	330342	−6.35	5.48	−0.87
WLOb330355_7	330355	−22.32	−21.64	0.68
WLOb330671_5	330671	−3.15	1.03	4.18
WLOb330841_4	330841	−40.08	−22.05	18.03
WLOb330953_3	330953	−0.11	3.34	3.45
Delaware wells				
WLObEb2322_6	Eb2322	33.84	46.32	12.48
WLObEb5509_2	Eb5509	−49.49	−1.00	48.49
WLObEc3203_6	Ec3203	−47.87	−6.33	41.54
WLObGd3305_7	Gd3305	−22.58	−13.59	8.99

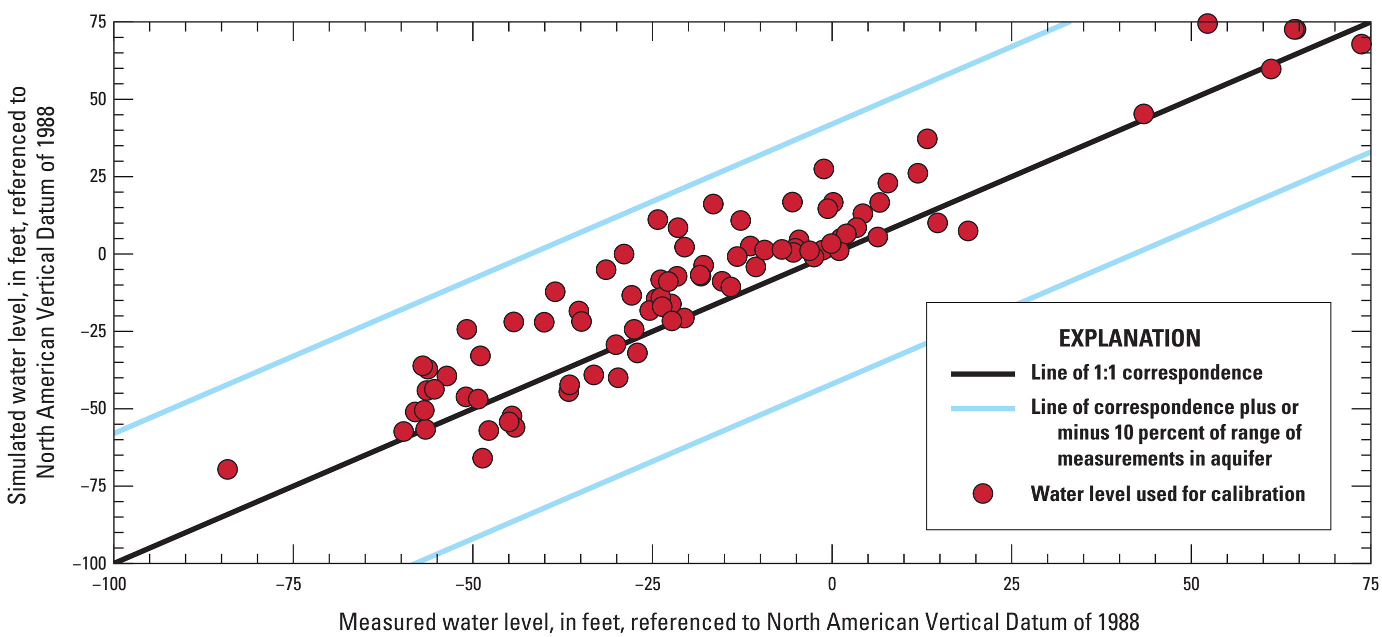


Figure 50. Graph showing simulated and observed water-levels for selected wells open to the upper Potomac-Raritan-Magothy aquifer, New Jersey, 2013.

The hydrographs of four selected wells screened in the upper Potomac-Raritan-Magothy aquifer are shown in figure 51. Simulated water levels in wells 050258, 070477, 150728, and 250639 in Burlington, Camden, Gloucester, and Monmouth Counties, respectively, have the same trend and amplitude as observed water levels but are an average of 24, 11, 11, and 6 ft higher than them, respectively. The hydrographs for these four wells in Voronin (2004) show simulated water levels in wells 050258, 070477, and 150728 that are 5 to 15, 15 to 25, and 5 to 10 ft higher, respectively, than the observed water levels during 1980–98; the hydrograph for well 290639 shows simulated water levels within 15 ft of observed water levels, but with smaller amplitude.

Calibration of Water Levels in the Middle Potomac-Raritan-Magothy Aquifer

Simulated water-level contours in the middle Potomac-Raritan-Magothy aquifer (model layer 19, Middlesex, Mercer, Monmouth, Ocean, Burlington, Camden, Gloucester, and Salem Counties) generally match the 2013 potentiometric surface (Cauller and Gordon, 2021) (fig. 52). The simulated contours and 2013 potentiometric surface are similar in shape and correspond well in the areas of the major cones of depression in central Camden County and north-central Ocean County. The differences between the simulated and observed water levels for wells measured in New Jersey in 2013 are shown in table 19 and in figures 52 and 53. The average water-level residual (simulated minus observed) for 73 wells in New Jersey is 1 ft and the RMSE is 9 ft. The minimum; first, second, and third quartile; and maximum residuals are −22, −4, −0.1, 7, and 24 ft, respectively. The simulated water levels are within 10 ft of observed water levels for 57 of the 73 wells (78 percent) and within 15 ft of observed water levels for 68 of the 73 wells (93 percent) in New Jersey. The simulated water levels for the Potomac-Patapsco aquifer in Delaware and the average water-level residual for three wells measured in Delaware in 2013 (table 19) also are shown in figure 52.

The hydrographs of five wells screened in the Middle Potomac-Raritan-Magothy aquifer are shown in figure 54. The simulated water levels in wells 050063, 050261, 150713, 330187, and 330251, located in Burlington (2 wells), Gloucester (1 well), and Salem (2 wells) Counties, respectively, have the same trend and amplitude as the observed water levels but are an average of −5, 10, −5, 2, and 15 ft higher or lower, respectively, than them. In comparison, the hydrographs for wells 150713, 330187, and 330251 in Voronin (2004) show simulated water levels that are 0 to 5, 10 to 15, and 0 to 10 ft higher, respectively, than observed water levels during 1980–98, and simulated water levels in well 050261 that are 5 to 10 ft lower prior to 1984 and 5 to 10 ft higher during 1992–98 than observed water levels.

Calibration of Water Levels in the Lower Potomac-Raritan-Magothy Aquifer

Simulated water-level contours in the lower Potomac-Raritan-Magothy aquifer (model layer 21, Burlington, Camden, Gloucester, and Salem Counties) generally match the 2013 potentiometric surface (Cauller and Gordon, 2021) (fig. 55). The simulated water-level contours are similar in shape, and the location of the major cone of depression in central Camden County and the location of the major cone of depression in Salem County that results from withdrawals in Delaware, corresponds closely to the location of the two simulated cones of depression. The differences between the simulated and observed water levels for wells measured in New Jersey in 2013 are shown in table 20 and in figures 55 and 56. The average water-level residual (simulated minus observed) for 39 wells in New Jersey is −4 ft and the RMSE is 13 ft. The minimum; first, second, and third quartile; and maximum residuals are −25, −13, −3, 3, and 29 ft, respectively. The simulated water levels are within 10 ft of observed water levels for 25 of the 39 wells (64 percent) and within 15 ft of observed water levels for 31 of the 39 wells (79 percent) in New Jersey. The simulated water levels for the Potomac-Patuxent aquifer in Delaware and the average water-level residual for five wells measured in Delaware in 2013 (table 20) also are shown in figure 55.

The hydrographs of three selected wells screened in the Lower Potomac-Raritan-Magothy aquifer are shown in figure 57. Simulated water levels in wells 050262, 070412, and 150712, located in Burlington, Camden, and Gloucester Counties, respectively, have the same trend and amplitude as observed water levels and are an average of 10, 8, and −2 ft higher than observed water levels, respectively. The hydrograph for well 050262 in Voronin (2004) shows simulated water levels that range from 15 to 20 ft lower before 1984 and 0 ft to 10 ft higher during 1990–98 than observed water levels, and the hydrograph for well 150712 shows simulated water levels that are 5 to 10 ft higher than observed water levels during 1980–98.

Average Simulated Water Levels in Critical Areas 1 and 2, 1980–2013

The State of New Jersey instituted a program in the late 1980s to reduce groundwater withdrawals in two designated Critical Areas in which water levels in certain aquifers used for water supply had declined substantially. Restrictions on groundwater withdrawals in Critical Area 2 apply only to the aquifers of the PRM aquifer system and were initiated in 1996. Critical Area 1 restrictions were implemented in 1989, however compliance by most purveyors was deferred until 1991 because access to alternate water supplies was

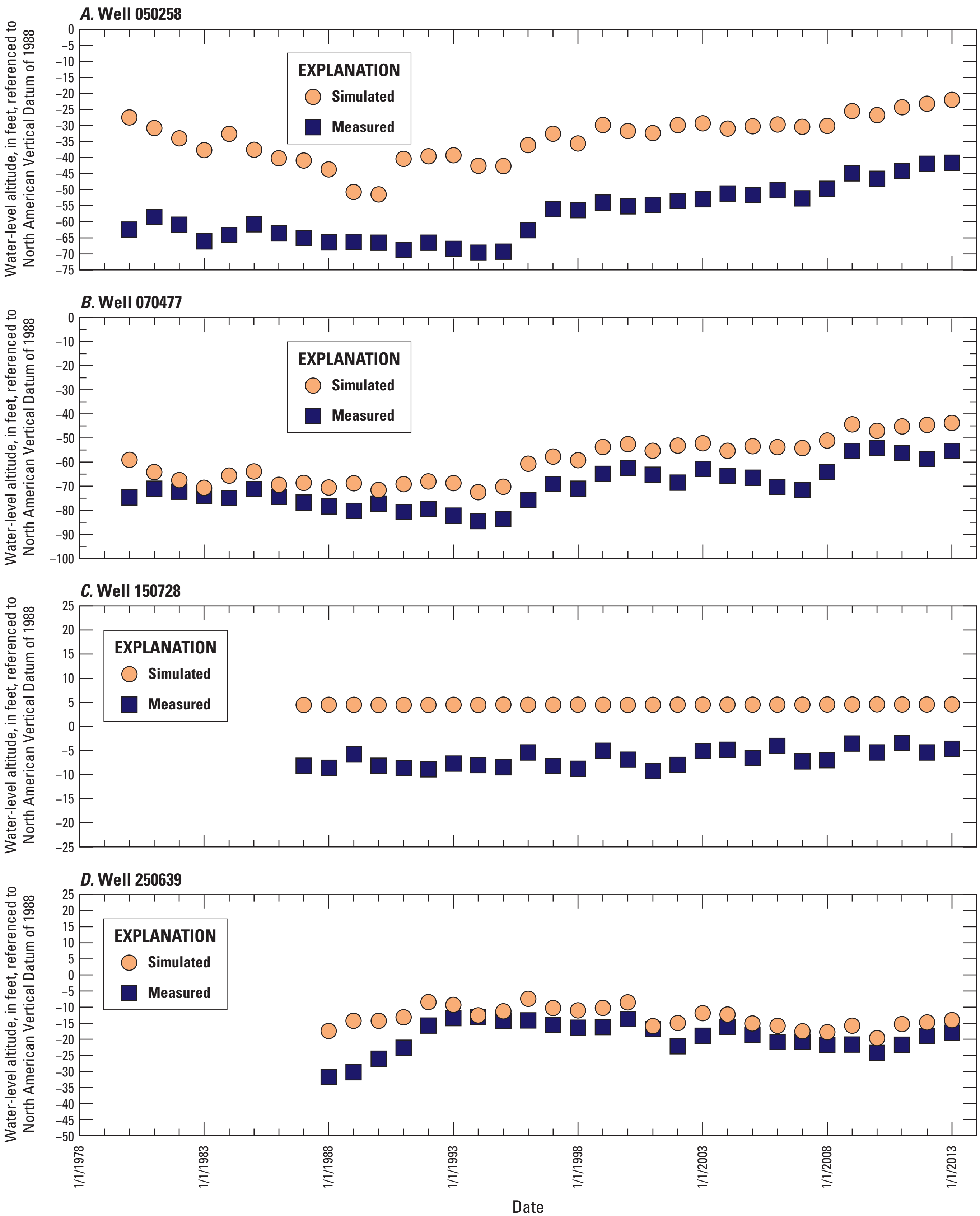


Figure 51. Hydrographs of simulated and observed water levels in wells *A*, 050258, *B*, 070477, *C*, 150728, and *D*, 250639, open to the upper Potomac-Raritan-Magothy aquifer, New Jersey, 1980

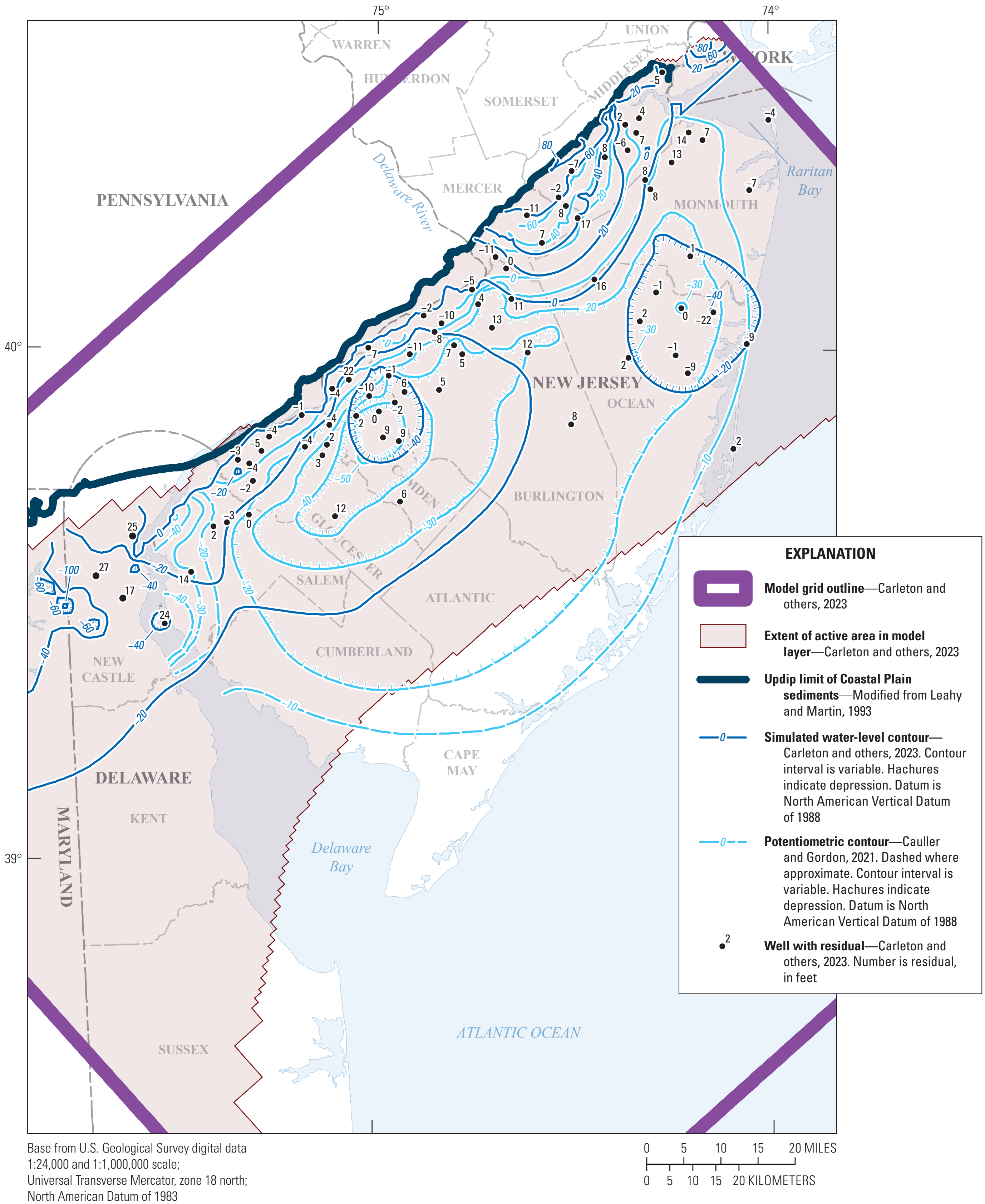


Figure 52. Map showing simulated water-level contours and the 2013 potentiometric surface for, and residuals for selected wells in, the middle Potomac-Raritan-Magothy aquifer, New Jersey, and the simulated water-level contours for, and residuals for selected wells in, the Potomac-Patapsco aquifer, Delaware.

Table 19. Simulated and observed water-level observations and residuals for wells open to the middle Potomac-Raritan-Magothy aquifer, New Jersey, and the Potomac-Patapsco aquifer, Delaware, 2013.

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
New Jersey wells				
WLOb050063_7	050063	−12.09	−19.65	−7.56
WLOb050070_4	050070	−5.18	−15.18	−10.00
WLOb050087_7	050087	−1.4	−3.86	−2.46
WLOb050114_7	050114	−12.8	−1.78	11.02
WLOb050122_7	050122	11.08	10.95	−0.13
WLOb050214_6	050214	−16.55	−12.88	3.67
WLOb050261_7	050261	−38.18	−33.01	5.17
WLOb050265_6	050265	−40.22	−41.51	−1.29
WLOb050284_6	050284	−16.30	−27.42	−11.12
WLOb050290_7	050290	−30.74	−25.46	5.28
WLOb050330_7	050330	−30.36	−18.37	11.99
WLOb050440_7	050440	−28.51	−15.42	13.09
WLOb050634_7	050634	−33.98	−27.27	6.71
WLOb050683_7	050683	−25.58	−17.23	8.35
WLOb050749_7	050749	−49.80	−43.55	6.25
WLOb050801_7	050801	0.10	−6.59	−6.69
WLOb051172_4	051172	4.31	−0.96	−5.27
WLOb070048_6	070048	−5.98	−9.72	−3.74
WLOb070124_7	070124	−53.01	−53.31	−0.30
WLOb070132_6	070132	−49.47	−51.66	−2.19
WLOb070142_6	070142	−35.86	−46.13	−10.27
WLOb070186_7	070186	−56.69	−47.60	9.09
WLOb070413_7	070413	−52.77	−44.12	8.65
WLOb070476_7	070476	−38.29	−32.44	5.85
WLOb070734_4	070734	−50.12	−48.36	1.76
WLOb070986_4	070986	−11.85	−33.50	−21.65
WLOb150024_6	150024	−23.60	−27.25	−3.65
WLOb150236_7	150236	−14.34	−16.58	−2.24
WLOb150374_7	150374	−33.62	−31.50	2.12
WLOb150415_7	150415	−20.24	−23.82	−3.58
WLOb150585_6	150585	−0.64	−3.77	−3.13
WLOb150616_6	150616	−5.31	−9.67	−4.36
WLOb150679_6	150679	−1.50	−5.98	−4.48
WLOb150713_6	150713	−4.67	−9.31	−4.64
WLOb150780_6	150780	0.54	−0.18	−0.72
WLOb150998_5	150998	−42.38	−29.90	12.48
WLOb151036_5	151036	−35.56	−32.26	3.30
WLOb210012_7	210012	21.18	38.03	16.85
WLOb210022_7	210022	47.64	55.26	7.62
WLOb210043_7	210043	7.20	−4.12	−11.32
WLOb210101_7	210101	40.88	48.24	7.36
WLOb210120_6	210120	68.42	57.09	−11.33
WLOb230009_7	230009	62.86	60.84	−2.02
WLOb230097_7	230097	26.14	33.93	7.79
WLOb230132_7	230132	9.96	3.93	-6.03
WLOb230194_7	230194	−2.84	4.42	7.26
WLOb230291_7	230291	68.84	61.36	−7.48
WLOb230439_7	230439	1.92	3.80	1.88
WLOb230482_7	230482	8.96	3.58	−5.38
WLOb231160_6	231160	0.41	4.30	3.89
WLOb250153_7	250153	−16.84	−9.94	6.90
WLOb250230_7	250230	−9.04	−0.91	8.13
WLOb250247_7	250247	−12.96	−544	7.52
WLOb250272_7	250272	−21.78	−8.69	13.09

Table 19. Simulated and observed water-level observations and residuals for wells open to the middle Potomac-Raritan-Magothy aquifer, New Jersey, and the Potomac-Patapsco aquifer, Delaware, 2013.—Continued

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
New Jersey wells—Continued				
WLOb250320_7	250320	0.84	−3.44	−4.28
WLOb250495_6	250495	−2.06	−8.80	−6.74
WLOb250562_3	250562	−17.09	−3.53	13.56
WLOb250635_6	250635	−22.77	−21.77	1.00
WLOb290019_7	290019	−5.62	−3.20	2.42
WLOb290047_7	290047	−20.95	−43.11	−22.16
WLOb290085_7	290085	−24.05	−25.834	−1.29
WLOb290132_7	290132	−23.91	−21.58	2.33
WLOb290440_7	290440	−30.90	−31.27	−0.37
WLOb290490_7	290490	−22.20	−20.20	2.00
WLOb290576_7	290576	−26.48	−27.18	−0.70
WLOb290581_7	290581	−14.25	2.13	16.38
WLOb290626_7	290626	−23.34	−32.12	−8.78
WLOb291113_4	291113	−11.18	−20.15	-8.97
WLOb330065_6	330065	−17.44	−14.95	2.49
WLOb330166_6	330166	−15.84	−19.02	−3.18
WLOb330187_7	330187	−24.33	−24.62	−0.29
WLOb330251_7	330251	−31.64	−18.10	13.54
WLOb330934_4	330934	−71.43	−47.856	23.87
Delaware wells				
WLObDc3406_7	Dc3406	−30.61	−5.43	25.18
WLObEb2324_6	Eb2324	−59.60	−32.55	27.05
WLObEc5224_2	Ec5224	−51.41	−34.53	16.88

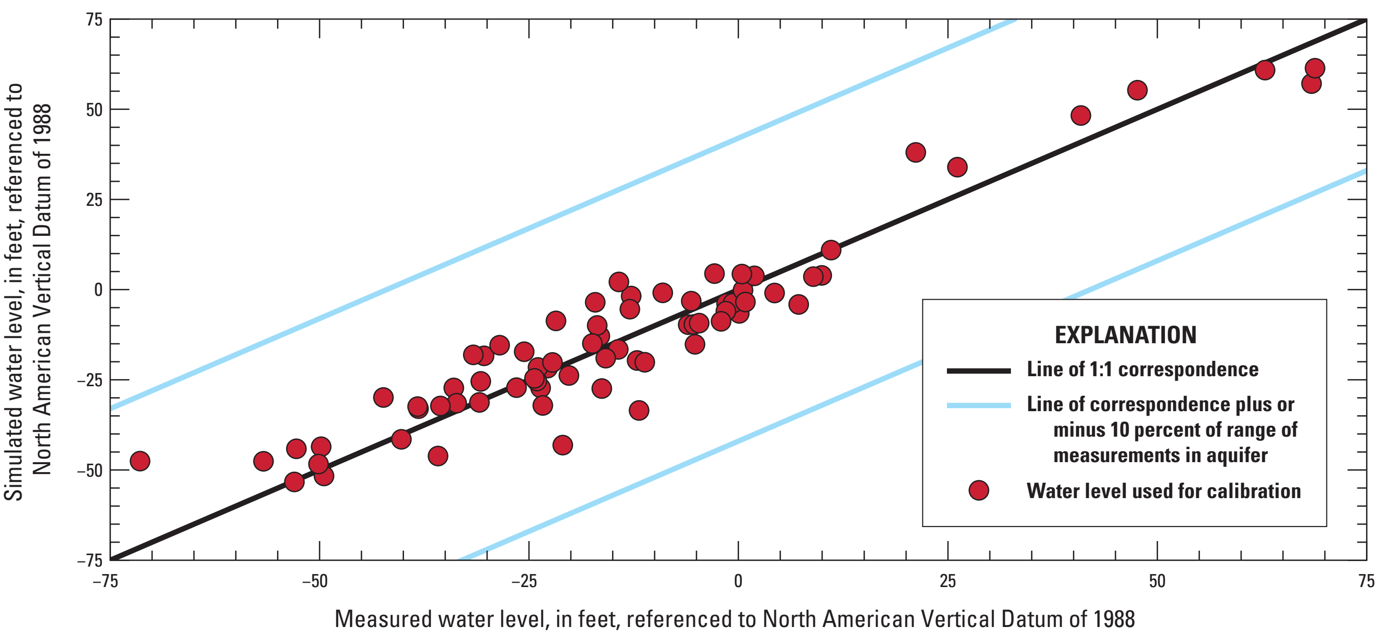


Figure 53. Graph showing simulated and observed water-levels for selected wells open to the middle Potomac-Raritan-Magothy aquifer, New Jersey, 2013.

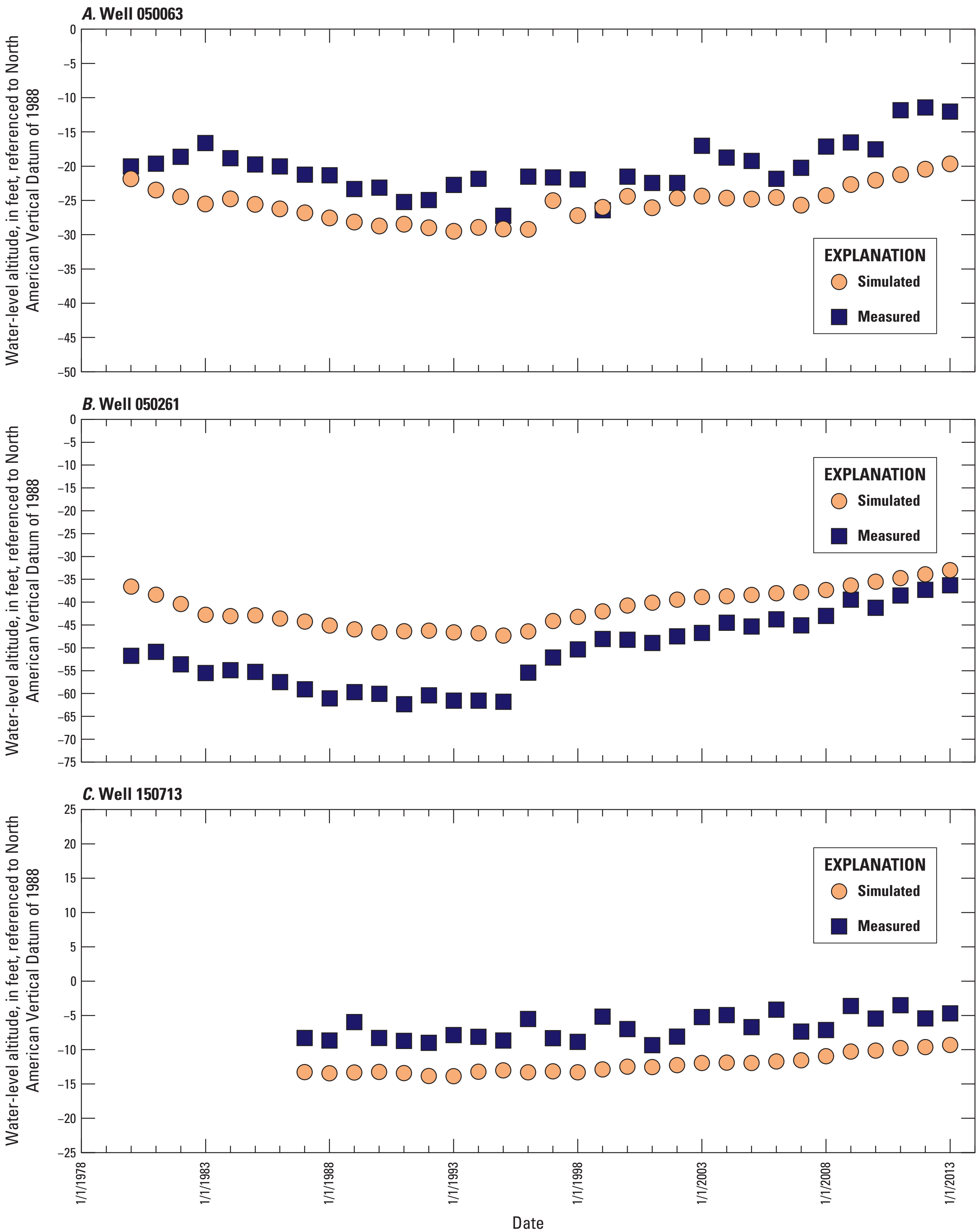


Figure 54. Hydrographs of simulated and observed water levels in wells *A*, 050063, *B*, 050261, *C*, 150713, *D*, 330187, and *E*, 330251, open to the middle Potomac-Raritan-Magothy aquifer, New Jersey, 1980–2013.

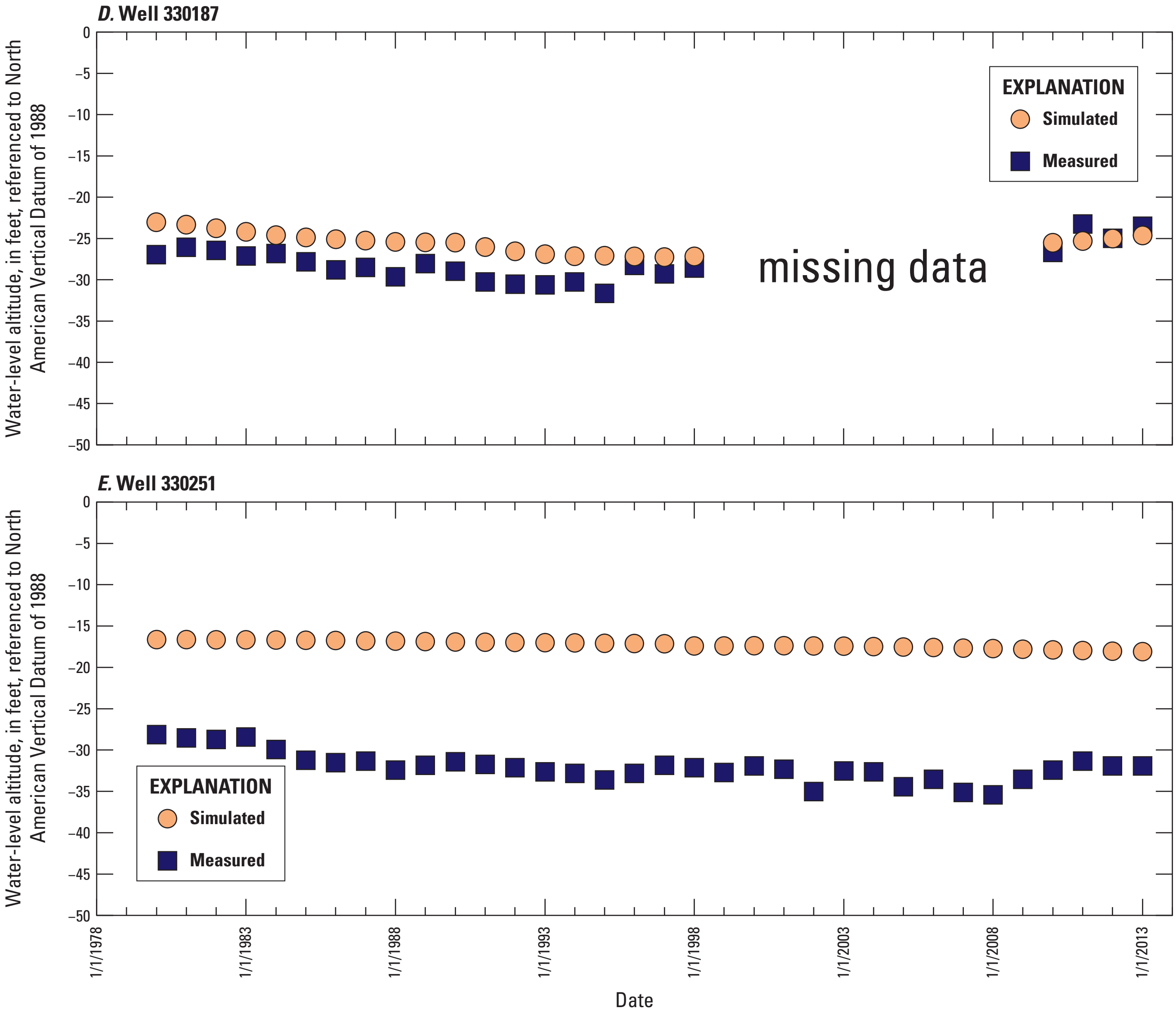


Figure 54.—Continued

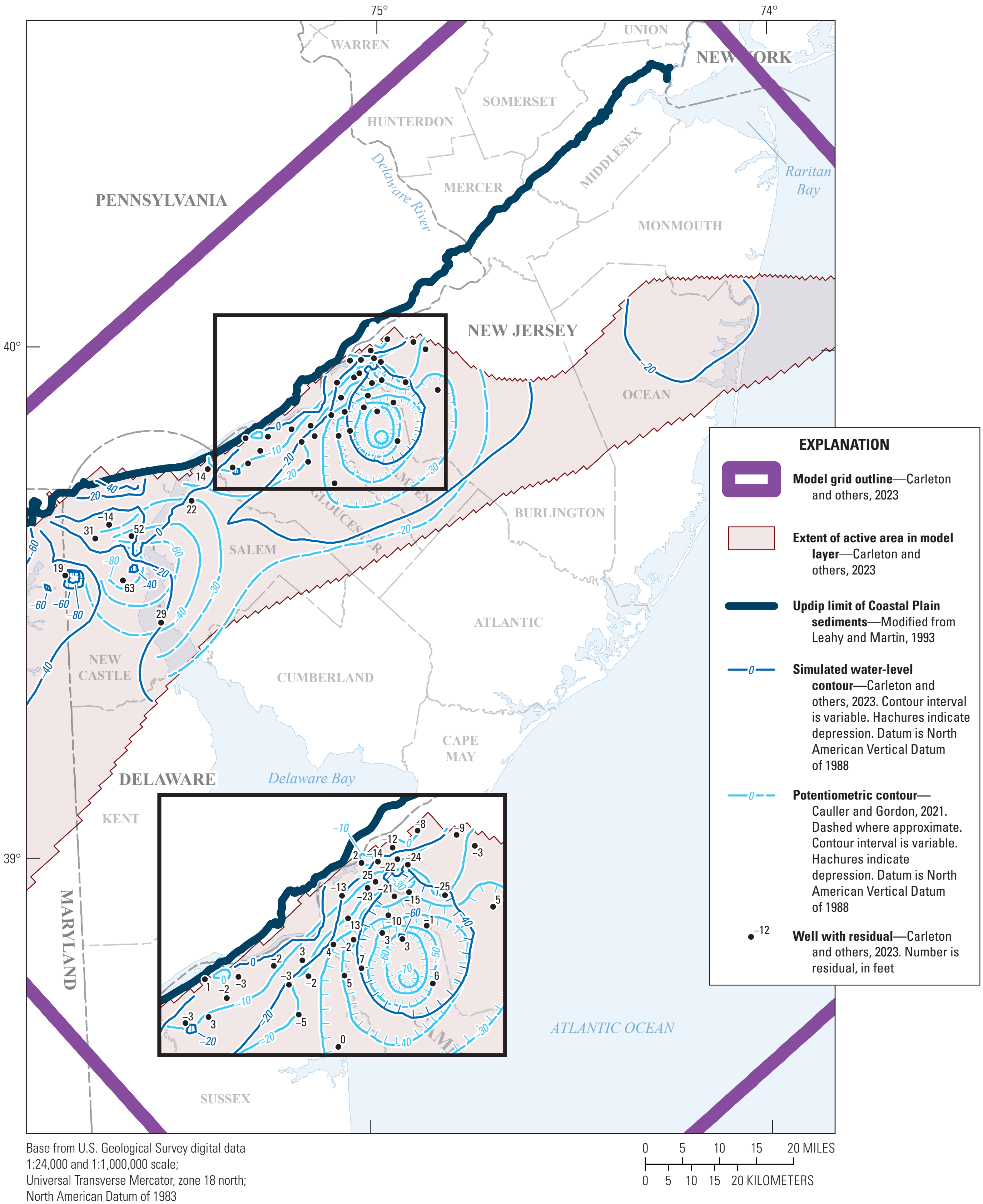


Figure 55. Map showing simulated water-level contours and the 2013 potentiometric surface for, and residuals for selected wells in, the lower Potomac-Raritan-Magothy aquifer, New Jersey and simulated water-level contours for, and residuals for selected wells in, and the Potomac-Patuxent aquifer, Delaware.

Table 20. Simulated and observed water-level observations and residuals for wells open to the lower Potomac-Raritan-Magothy aquifer, New Jersey, and the Potomac-Patuxent aquifer, Delaware, 2013.

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
		New Jersey wells		
WLOb050123_7	050123	−5.83	−28.14	−22.31
WLOb050130_7	050130	−1.29	−13.36	−12.07
WLOb050146_5	050146	2.10	−5.66	−7.76
WLOb050228_7	050228	−28.46	−42.99	−14.53
WLOb050262_7	050262	−38.01	−33.28	4.73
WLOb050274_7	050274	−15.74	−38.40	−23.66
WLOb050645_7	050645	−25.22	−27.78	−2.56
WLOb050648_7	050648	−16.67	−25.62	−8.95
WLOb050823_7	050823	−18.96	−43.59	−24.63
WLOb070012_7	070012	−29.68	−25.26	4.42
WLOb070121_6	070121	−64.73	−61.97	2.76
WLOb070130_7	070130	−48.40	−49.85	−1.45
WLOb070144_7	070144	−37.15	−47.01	−9.86
WLOb070163_7	070163	−25.47	−46.45	−20.98
WLOb070172_6	070172	−18.63	−31.57	−12.94
WLOb070273_7	070273	−47.35	−40.63	6.72
WLOb070283_7	070283	−35.14	−36.99	−1.85
WLOb070302_7	070302	−51.34	−54.05	−2.71
WLOb070320_7	070320	−14.18	−37.06	−22.88
WLOb070335_7	070335	−11.86	−37.04	−25.18
WLOb070368_5	070368	−7.10	−5.49	1.61
WLOb070372_6	070372	−8.97	−23.08	−14.11
WLOb070412_7	070412	−50.88	−45.26	5.62
WLOb070541_7	070541	−7.13	−20.18	−13.05
WLOb150139_7	150139	−9.04	−12.00	−2.96
WLOb150282_6	150282	−19.42	−22.00	−2.58
WLOb150308_7	150308	−6.56	−8.15	−1.59
WLOb150312_7	150312	−17.20	−14.60	2.60
WLOb150331_7	150331	−24.42	−26.18	−1.76
WLOb150398_5	150398	−1.08	0.37	0.71
WLOb150615_6	150615	−12.23	−9.68	2.55
WLOb150671_6	150671	−40.60	−35.19	5.41
WLOb150678_6	150678	−3.49	−6.06	−2.57
WLOb150712_6	150712	−7.51	−9.30	−1.79
WLOb150742_6	150742	−21.92	−27.06	−5.14
WLOb151004_6	151004	−32.67	−32.65	0.02
WLOb330086_7	330086	−13.57	0.14	13.71
WLOb330335_5	330335	−29.44	−7.38	22.06
WLOb330458_6	330458	−49.16	−20.58	28.58

Table 20. Simulated and observed water-level observations and residuals for wells open to the lower Potomac-Raritan-Magothy aquifer, New Jersey, and the Potomac-Patuxent aquifer, Delaware, 2013.—Continued

[USGS, U.S. Geological Survey; residual, simulated water level minus observed water level]

Model well number	USGS well number	Observed water level (feet)	Simulated water level (feet)	Residual (feet)
		Delaware wells		
WLObDb1505_7	Db1505	8.06	−6.08	−14.14
WLObDb3317_7	Db3317	−46.42	−15.00	31.42
WLObDc3405_7	Dc3405	−57.95	−5.67	52.28
WLObEa2407_3	Ea2407	−82.21	−62.82	19.39
WLObEc3207_7	Ec3207	−98.45	−35.74	62.71

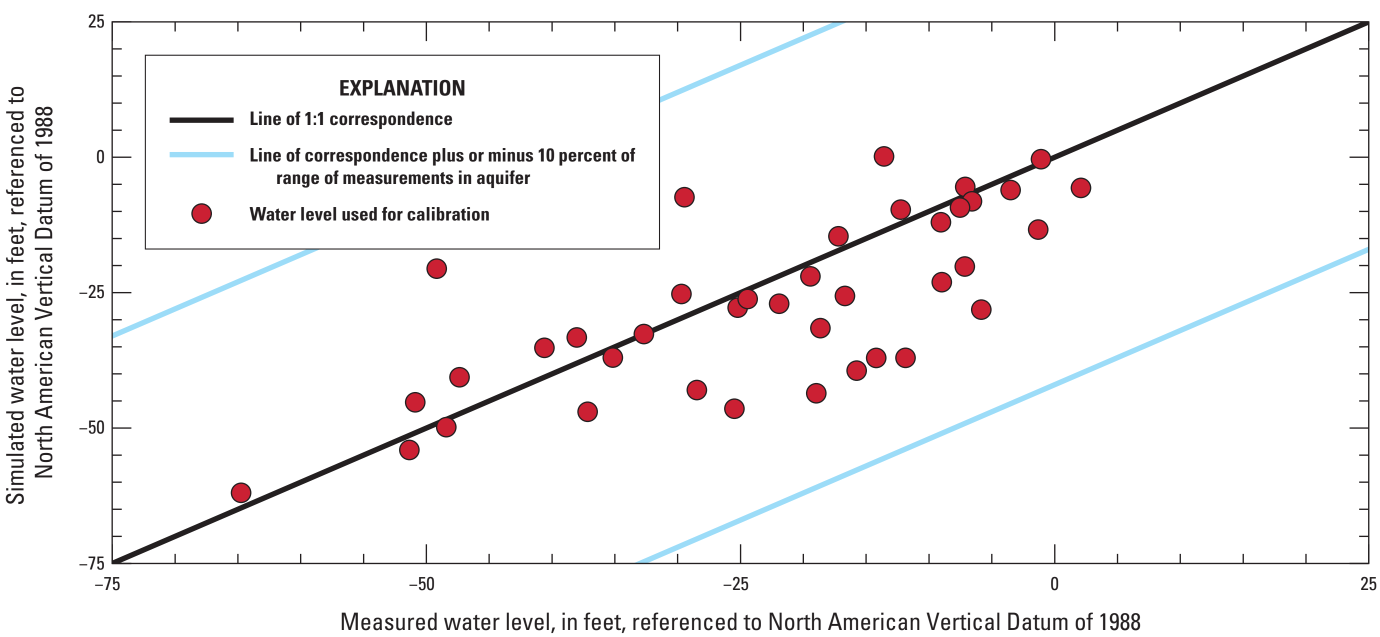


Figure 56. Graph showing simulated and observed water-levels for selected wells open to the lower Potomac-Raritan-Magothy aquifer, New Jersey, 2013.

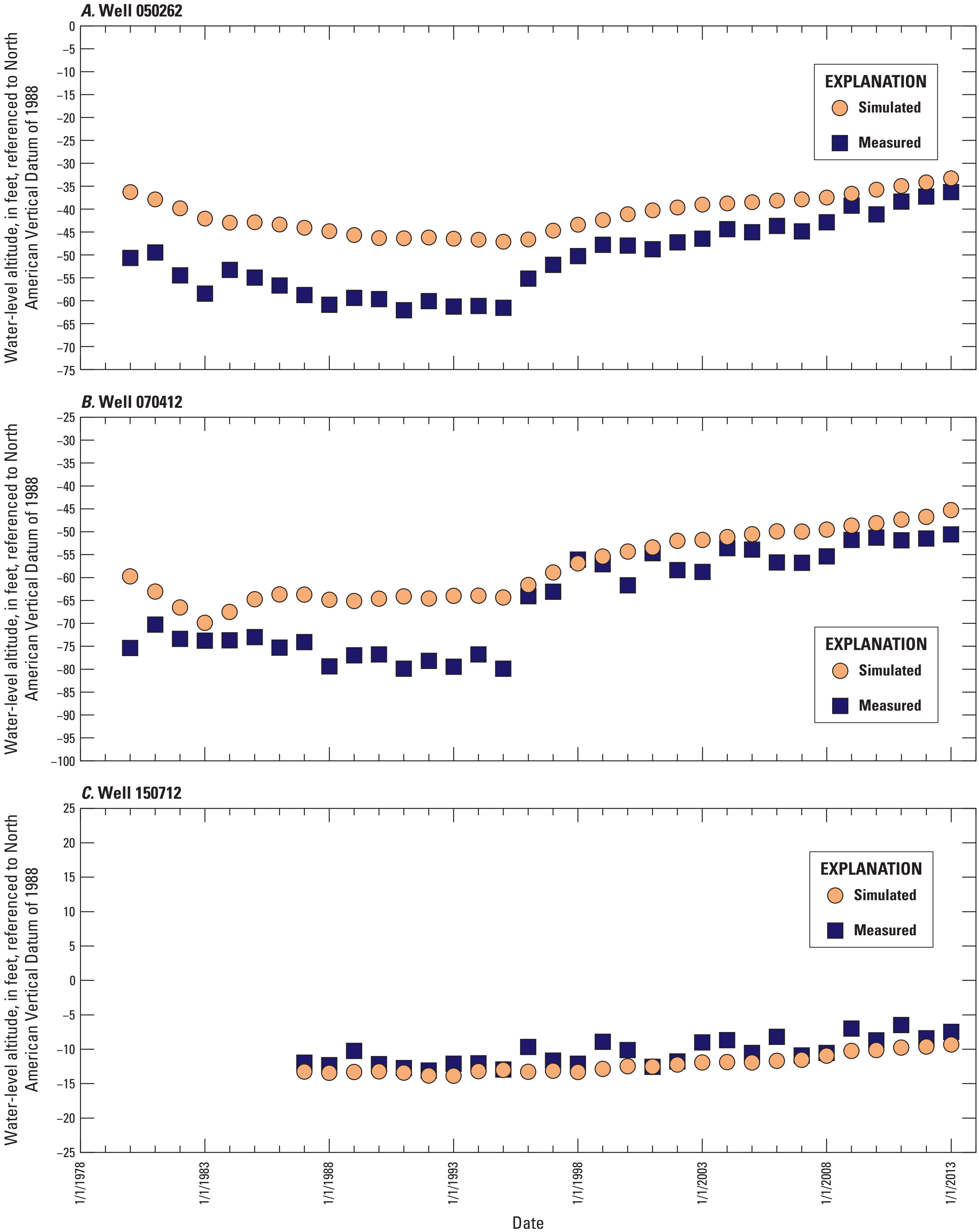


Figure 57. Hydrographs of simulated and observed water levels in wells *A*, 050262, *B*, 070412, and *C*, 150712, open to the lower Potomac-Raritan-Magothy aquifer, New Jersey, 1980–2013.

not initially available. The potentiometric surface in 2013 indicates that water levels generally recovered in the Critical Areas during 1983–2013, particularly at the center of the regional cones of depression measured in the Critical Areas in 1983 (Gordon and others, 2021). Trends in the average simulated water levels and withdrawals for the period 1980–2013 are shown by aquifer in figures 58 and 59. Figure 58*A* shows the decrease in simulated groundwater withdrawals in Critical Area 1, generally after the mid-1990s, from the Englishtown aquifer system, Wenonah-Mount Laurel aquifer, and the upper and middle PRM aquifer and a general recovery in average simulated water levels (fig. 58*B*), particularly in the Englishtown aquifer system and the Wenonah-Mount Laurel aquifer, resulting from the decrease in groundwater withdrawals from those aquifers. The average simulated water levels in the upper PRM aquifer show a decline after 2004, however, the average simulated water levels show a recovery after 2010. Figure 59*A* shows a decrease in groundwater withdrawals from the upper, middle, and lower PRM aquifers in Critical Area 2 generally after 1996 and the subsequent recovery in average simulated water levels in those aquifers is shown in figure 59*B*. These figures show the withdrawal data in cubic feet per second (the units used for withdrawal data in the New Jersey Coastal Plain groundwater-flow model) together with the water levels simulated with the model for the Critical Area aquifers.

Model Limitations

The purpose of the New Jersey Coastal Plain groundwater-flow model is to represent the interactions of groundwater flow in and simulated water levels in 11 major aquifers in the groundwater-flow system of the New Jersey Coastal Plain. In the model, grid-cell dimensions are smaller in the onshore part of New Jersey than in offshore areas, Delaware, and Maryland. The smaller grid-cell dimensions were used to improve the accuracy of the flow simulation in the aquifers in New Jersey and are adequate for a regional representation of the groundwater-flow system. However, spatial and temporal discretization in the model require simplifications of the groundwater-flow system. Although detailed groundwater/surface-water interactions cannot be evaluated in some areas, the model cell size is adequate for a regional representation of streams in New Jersey. However, because land-surface elevation and hydraulic parameters are assigned values that represent an average over an entire model cell, they may not accurately represent parameters for the streams.

The model simulates the groundwater-flow system using average annual withdrawals and estimated annual recharge rates. The water-level calibration attempts to reproduce water levels measured in late fall of the seven quinquennial New Jersey Coastal Plain water-level synoptic studies (1983, 1988, 1993, 1998, 2003, 2008, and 2013) to represent an approximation of average annual water-level conditions. Water levels that result from seasonal variations in groundwater withdrawals or recharge rates are not simulated and this may introduce inaccuracies in matching observed and simulated water levels and base flows. Although permitted withdrawals from public-supply, industrial, commercial, and agricultural wells are simulated in the model, domestic-self supply wells are not included in the withdrawal dataset; these wells are typically open to the shallower aquifers, potentially affecting base flow to the simulated streams or water levels in the aquifers that crop out.

The unconfined surficial aquifer in Delaware and eastern Maryland was not included in the model hydrogeologic framework; however, the effects of withdrawals from the surficial aquifer are assumed to be controlled by local streams and not to affect water levels in New Jersey. Recharge to the surficial aquifer in this area was input as fluxes to the model layer. The model is based on a 21-layer hydrogeologic framework, because the framework used to represent the groundwater-flow system is regionalized, local clay units or heterogeneities that affect the groundwater-flow system may not represented.

Summary

The U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, updated a previously published regional groundwater-flow model of the New Jersey Coastal Plain by incorporating a revised hydrogeologic framework of the New Jersey Coastal Plain and groundwater withdrawals from 1980 to 2013, updating groundwater recharge based on a soil-water balance budget, and extending the model into Delaware to address the effects of withdrawals from aquifers that extend into that state.

The three-dimensional transient groundwater-flow model was developed by using the numerical code MODFLOW–2005. The model was constructed by using hydrogeologic information about and estimated hydraulic properties of 11 separate aquifers and 10 intervening confining units to represent the groundwater-flow system. The finite-difference grid consists of 145 rows, 245 columns, and 21 layers. The model extends from the updip limit of the Coastal Plain sediments in New Jersey, Delaware, and Maryland, downdip to the boundary between freshwater and saltwater in each aquifer.

The model was calibrated by using the parameter-estimation code UCODE–2014 as well as manual calibration techniques. Seven categories of parameters were adjusted: horizontal and vertical hydraulic conductivity, storage coefficient, riverbed conductance for the Delaware River, streambed conductance for the other streams in the model area, general-head-boundary conductance, and recharge, resulting in a total of 422 parameters. Model calibration consisted of matching data for 1980 to 2013 that include 3,453 water levels measured during 1983–2013 in 440 wells

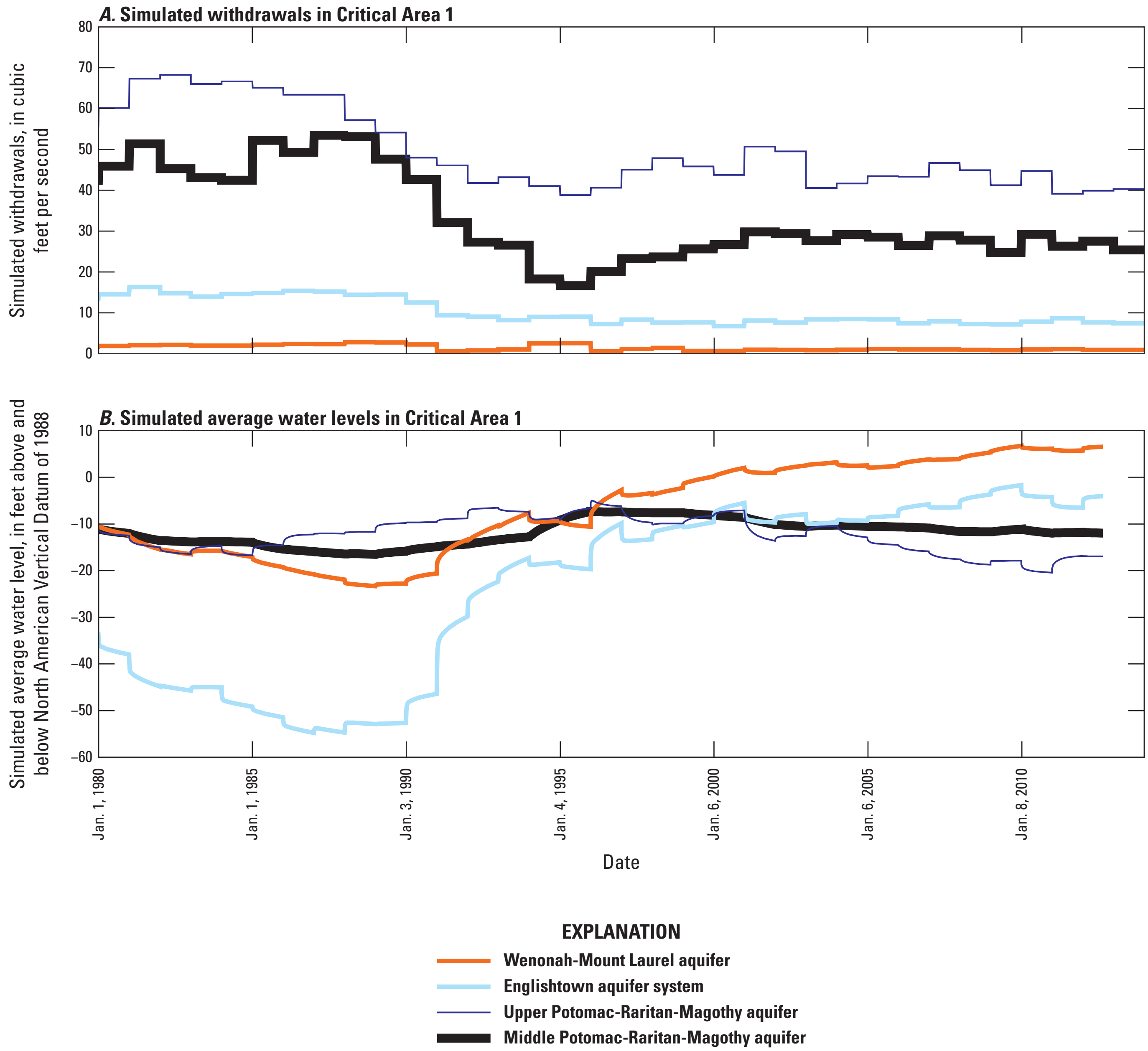


Figure 58. Graphs showing *A*, simulated withdrawals and *B*, simulated average water levels in Critical Area 1 for the Wenonah-Mount Laurel aquifer, Englishtown aquifer system, upper Potomac-Raritan-Magothy aquifer, and middle Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, 1980–2013.

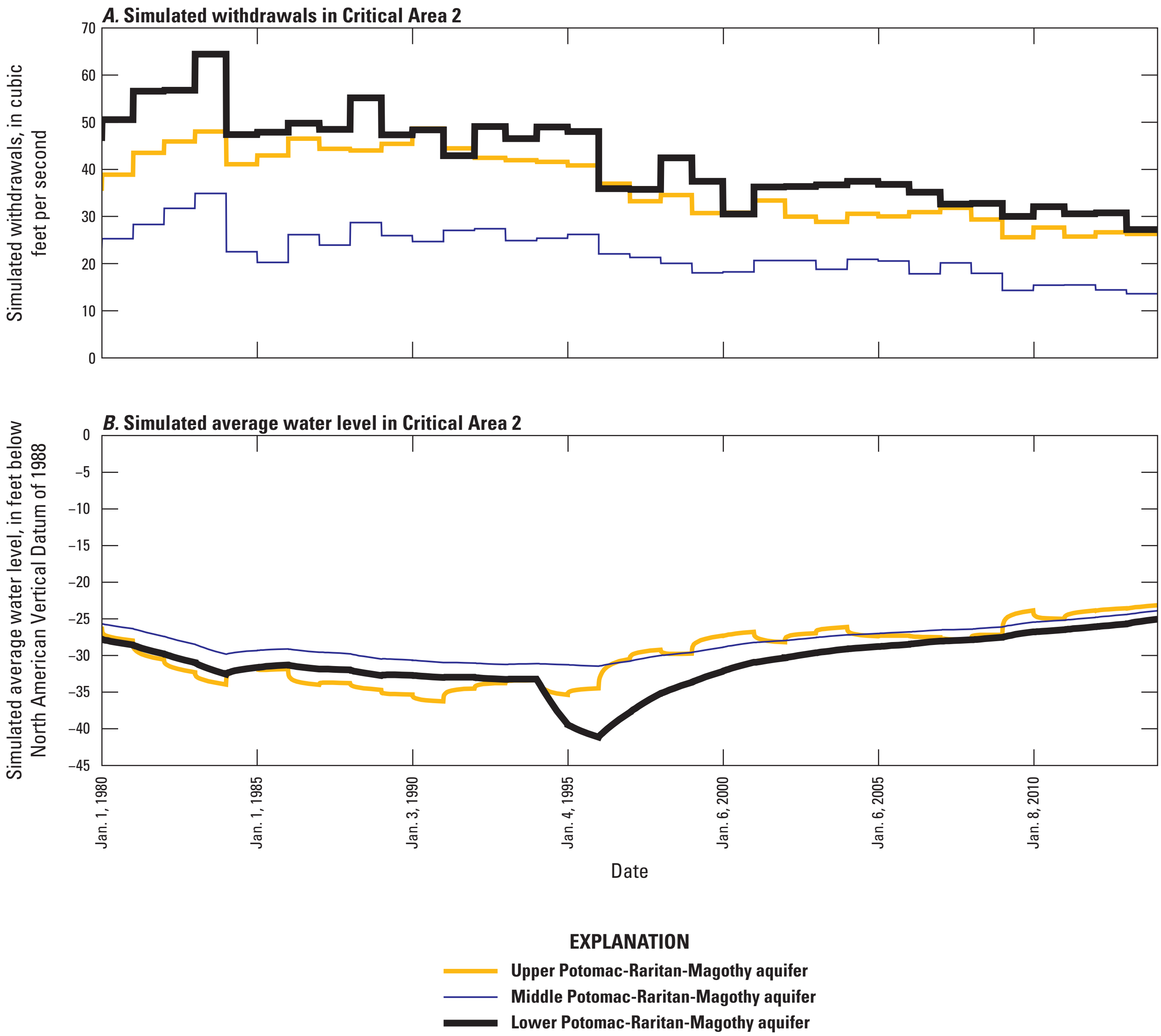


Figure 59. Graphs showing *A*, simulated withdrawals and *B*, simulated average water levels in Critical Area 2 for the upper Potomac-Raritan-Magothy aquifer, middle Potomac-Raritan-Magothy aquifer, and lower Potomac-Raritan-Magothy aquifer, New Jersey Coastal Plain, 1980–2013.

in New Jersey and Delaware, which includes trends in water levels for 29 wells in New Jersey during 1980–2013 presented in time-series hydrographs, and historical base-flow measurements made during 1980–2013 in 47 surface-water basins in New Jersey. Observations of vertical gradients were calculated for 33 pairs of nested observation wells in New Jersey, for a total of 210 observations. Changes in water levels over time were calculated for 138 wells, 134 wells in New Jersey and four wells in Delaware, where water levels had varied substantially (approximately 10 ft) over the 30-year span of synoptic water-level measurements, for a total of 767 observations.

The simulated water levels for the New Jersey Coastal Plain aquifers were compared to water-level measurements made during 1980–2013. The average water-level residual (simulated minus observed water level) for 4,243 water-level observations for New Jersey is 1.5 ft. The simulated water-level contours for the confined aquifers for 2013 were compared to potentiometric surfaces produced from water levels measured during 2013. Simulated water levels generally matched the 2013 potentiometric surfaces of the confined aquifers in the areas of large withdrawals, most of the simulated water levels are within 10 to 15 ft of the observed water levels. Hydrographs of 29 wells in the New Jersey coastal Plain aquifers with long-term water level measurements from 1980 to 2013 show that simulated water levels reasonably match the magnitude and seasonal variation of the observed water levels. Hydrographs of base-flow for the 47 streamgaging stations indicate that most of the simulated and observed data match reasonably well.

The sensitivity of simulated water levels to the model parameters was calculated with UCODE-2014. Composite scaled sensitivities were calculated for the 422 parameters by using the water level and base-flow observations. Parameters most sensitive to water-level observations include recharge and horizontal hydraulic conductivity, and vertical hydraulic conductivity. Recharge is the dominant parameter with respect to base-flow observations, but streambed conductance, horizontal hydraulic conductivity and storage parameters are also sensitive in and near outcrop areas in some aquifers.

Several limitations are associated with the ability of the New Jersey Coastal Plain groundwater-flow model to simulate the regional groundwater-flow system of the New Jersey Coastal Plain. The model simulates the groundwater-flow system using average annual withdrawals and estimated annual recharge rates. Spatial discretization in the model requires simplifications of the groundwater-flow system that may prevent the model from representing smaller scale hydrologic features. Temporal discretization in the model may limit the accuracy of simulated water levels that result from seasonal variations in groundwater withdrawals or recharge rates that are not simulated, thereby introducing inaccuracies in matching observed and simulated water levels and base flows. Although the model is based on a 21-layer hydrogeologic framework, because the framework used to represent the groundwater-flow system is regionalized, local clay units or heterogeneities that affect the groundwater-flow system may not be represented.

The groundwater-flow model of the New Jersey Coastal Plain must be updated periodically to maintain its usefulness as a tool for managing water resources and evaluating water-resource-development alternatives because of changing hydrologic stresses, changing and increasingly complex water-management needs, and updated knowledge of hydrologic conditions. The conversion from a quasi- to a fully three-dimensional model will allow for potential future uses such as particle tracking and simulation of variable-density flow that were not possible with earlier versions of the model. The addition of annual recharge estimates derived by using the U.S. Geological Survey Soil-Water Balance model (SWB) resulted in a spatially and temporally finer discretization. These updates will support the application of this model as a tool to evaluate regional effects of changes in groundwater withdrawals on water levels and the effects of potential water-management strategies in the New Jersey Coastal Plain. This current revision further improves the accuracy of the model and enhances its usefulness for evaluating alternative water-management alternatives under recent conditions.

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Appendix 1. Soil-Water Balance Methodology

Introduction

Soil-water balance (SWB) models estimate potential groundwater recharge by simulating the physical process of the movement of water as it enters the soil and moves downward to the water table (Masterson and others, 2015). The method allocates the water from precipitation among surface runoff, evapotranspiration, and infiltration.

The SWB model used in this investigation to estimate recharge is based on a modified Thornthwaite-Mather (Thornthwaite and Mather, 1957) approach that incorporates spatially distributed land-use cover data, soils properties, and daily meteorological data and produces model output of detailed spatial and temporal variability of recharge and evapotranspiration across the study area (Westenbroek and others, 2010). The SWB model calculates the distribution of soil-water budget components by using gridded datasets for hydrologic soil groups, land-use classification, and available soil-water capacity. The SWB model also uses tabular daily precipitation and temperature data as input. The Thornthwaite and Mather (1957) method is used to estimate evapotranspiration in the SWB model. Land-cover classification, hydrologic soil group, available water capacity, evapotranspiration estimates, and daily precipitation and temperature are inputs to the SWB model used to calculate the water-budget components. Model output was generated for each year from 1980 to 2013.

The SWB model used to estimate recharge in this study consists of 108,240 grid cells equally spaced (at 0.62 miles (1 kilometer)) across a study area that includes the New Jersey Coastal Plain, Delaware, part of southeastern Pennsylvania, and the eastern part of Maryland (fig. 1.1). The grid consists of 328 rows and 330 columns and is oriented north-south.

Model Input Requirements

Meteorological data needed for the model include daily precipitation, minimum daily temperature, and maximum daily temperature. The SWB model also requires the following gridded dataset to calculate a cell-by-cell recharge: land-cover data, hydrologic soil group, and available water capacity. The gridded land-use and soils data were converted to ASCII format for use in the SWB model by using ArcGIS methods.

Daily Climate Data

Precipitation in inches and maximum and minimum temperature in degrees Fahrenheit were input for the years 1980 through 2013. The daily mean, maximum, and minimum air temperatures are used to determine whether precipitation takes the form of rain or snow. Daily minimum temperature, maximum temperature, and precipitation tabular data were obtained from the USGS Geo Data Portal (GDP) (U.S. Geological Survey Geo Data Portal, 2017) for the study area shown in the grid in figure 1.1. Mean annual precipitation for 1980 through 2013 ranged from 38.4 inches per year (in/yr) in 2001 to 63.4 in/yr in 2011, with an average of 48.4 in/yr. For comparison, mean annual precipitation for the area that encompasses the New Jersey Coastal Plain from 1980 through 2013 is 44.4 in/yr (Office of the New Jersey State Climatologist, 2021).

Land Cover

The SWB model requires land-cover data to calculate net recharge to the groundwater-flow system. Grids of land-cover classifications were developed from the National Land Cover Database (NLCD) for 1992, 2001, and 2011 (U.S. Geological Survey, 2008; 2014a; 2014b, respectively). The NLCD is a raster dataset with a spatial resolution of 30 meters (approximately 98.4 feet). Land-use cover in the study area in 1992 was primarily agricultural (32 percent), forest (27 percent), and developed (13 percent); in 2001, agricultural (27 percent), forest (22 percent), and developed (18 percent); and in 2011, agricultural (26 percent), forest (22 percent), and developed (19 percent) (U.S. Geological Survey, 2008; 2014a; and 2014b, respectively). The NLCD dataset includes 16 land-cover classifications for 2001 and 2011, and 13 land-cover classifications for 1992. The 1992 NLCD was used in the SWB program to estimate recharge for 1980 through 1999, the 2001 NLCD was used to estimate recharge from 2000 through 2006, and the 2011 NLCD was used to estimate recharge from 2007 to 2013. The 1992 land-cover classification codes for wetland and residential areas were modified in 2001; therefore, some modifications were made in wetland and residential areas to accommodate this code change. Figure 1.2 shows the land-cover classification for the New Jersey Coastal Plain and Delaware for 2011. Recharge is not calculated where the land-cover type of a cell has been identified as “Open_water_land_use” in the input control file or where the soil-water capacity is near zero (Westenbroek and others, 2010).

Hydrologic Soil Groups

Soil data were obtained for each county in the study area from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database (Natural Resources Conservation Service, 2014). The SSURGO digital maps at the county scale were merged and converted to a 1-kilometer-square (0.386 miles-square) grid. The data on

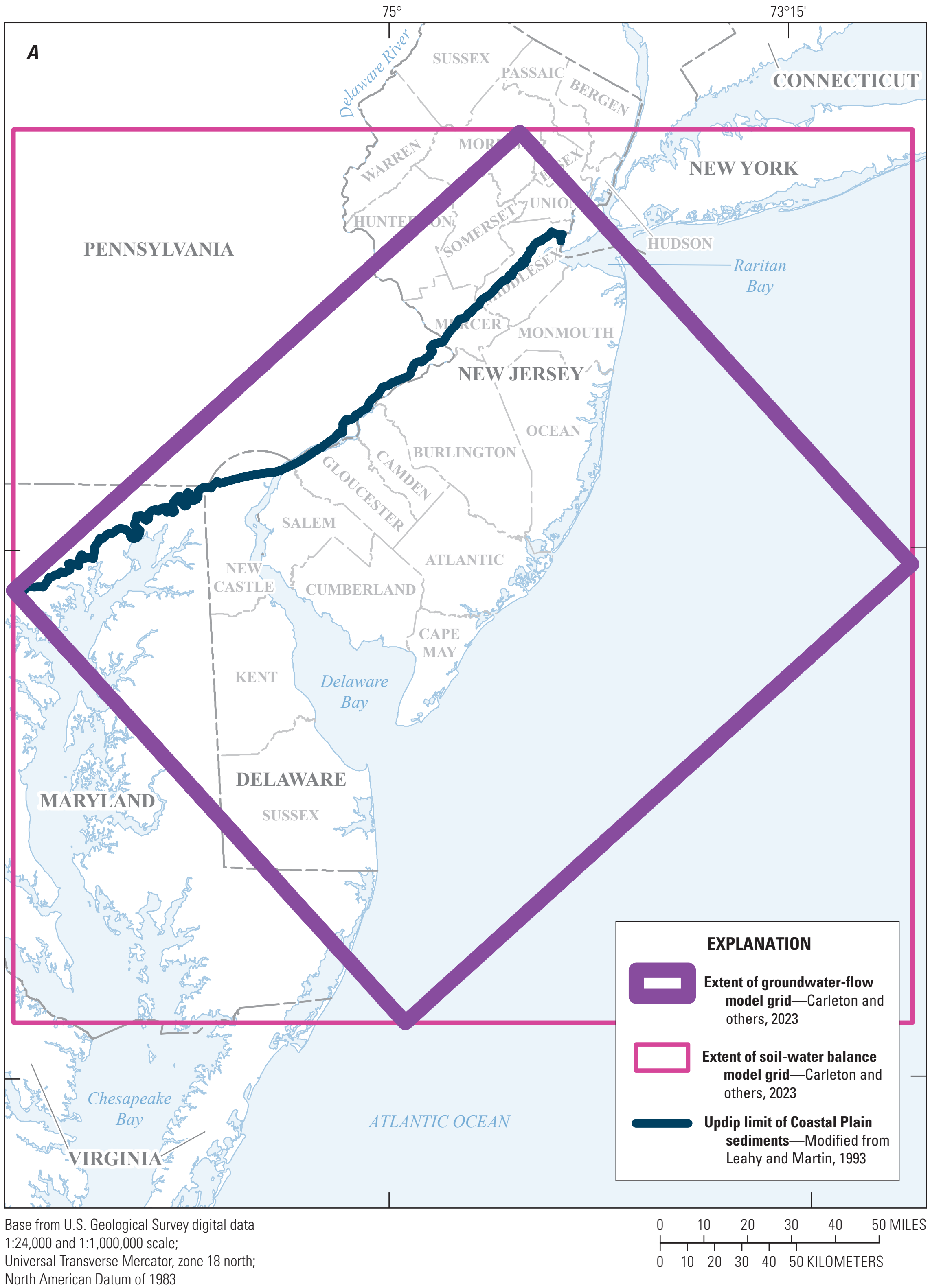

Figure 1.1. Maps showing *A*, location of soil-water balance (SWB) model grid for the New Jersey Coastal Plain groundwater-flow model study area; and *B*, Example of cells in the SWB model grid in Atlantic County, New Jersey.

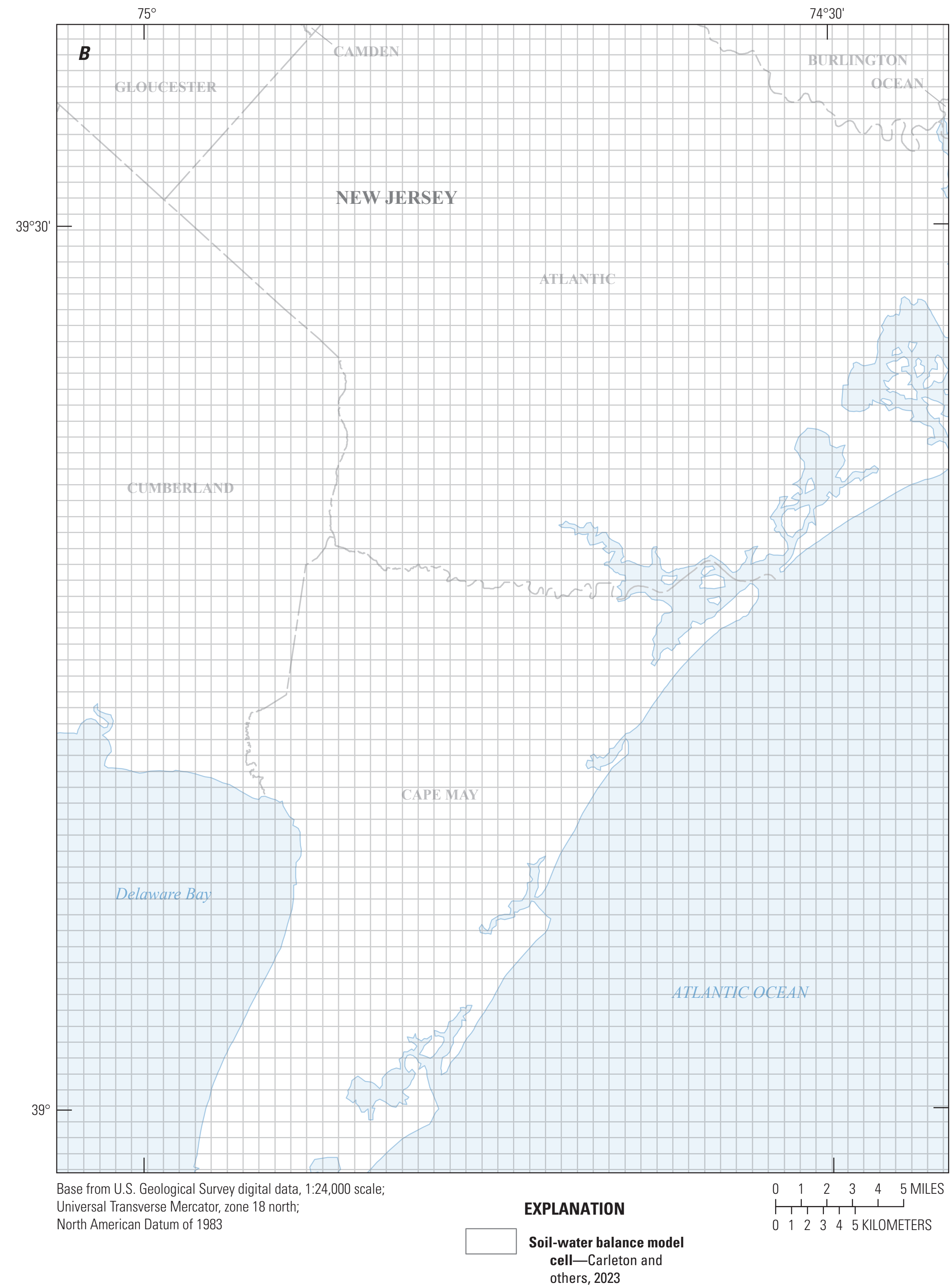

Figure 1.1.—Continued

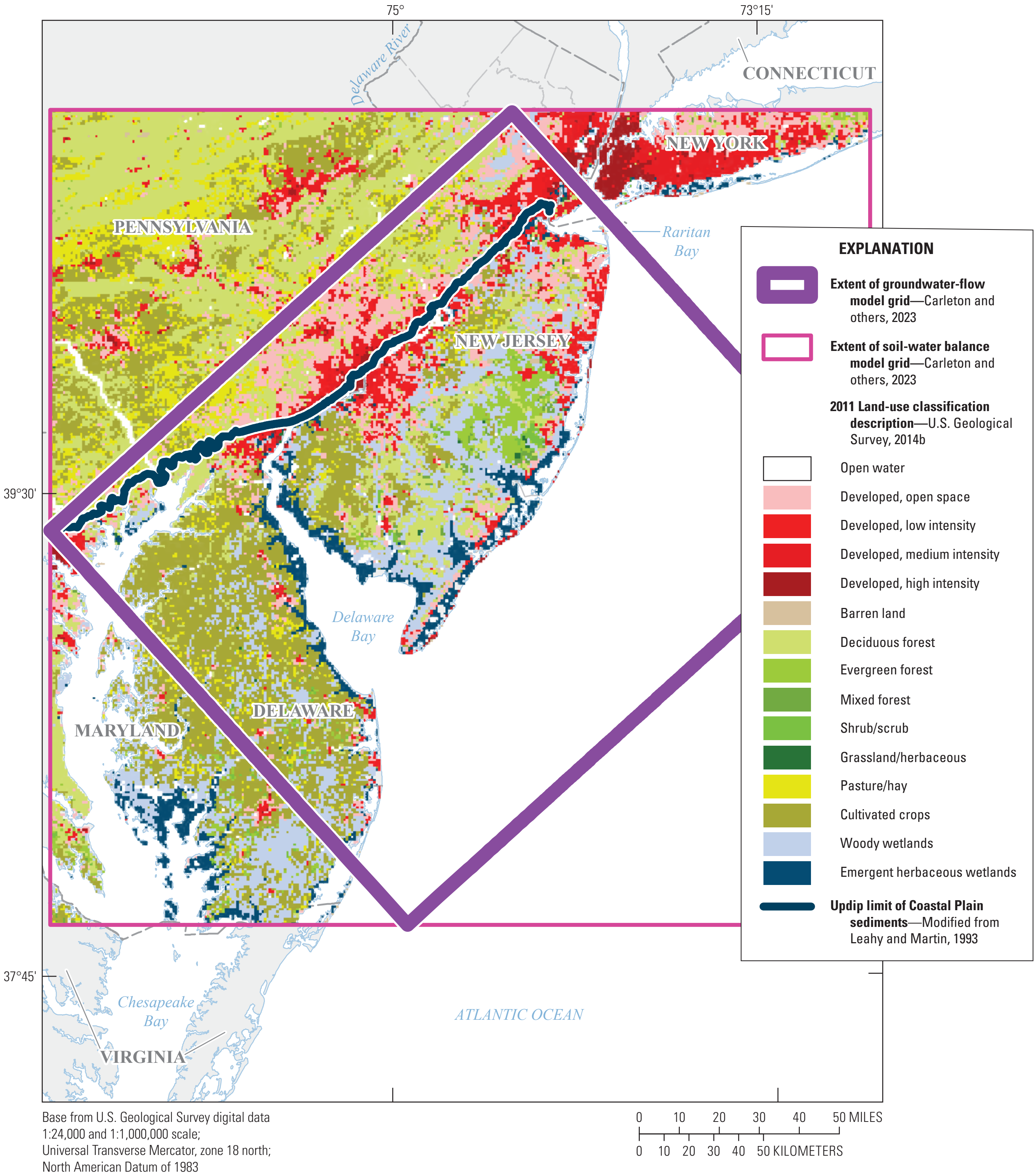

Figure 1.2. Map showing land-use classification in New Jersey Coastal Plain groundwater-flow model study area, 2011.

hydrologic soils groups provided in the NRCS soil (SSURGO) datasets (Natural Resources Conservation Service, 2014) were used to define gridded datasets of hydrologic soils to be used as input to the SWB model. Hydrologic soils within the United States are classified in the U.S. Department of Agriculture NRCS National Engineering Handbook for Hydrology (Natural Resources Conservation Service, 2009) into four major groups. Each group is assigned a letter designation (A–D) that describes soils with similar physical and runoff characteristics. The designation focuses on the soil's capacity for infiltration. Soils designated group A have a high capacity for infiltration (greater than 0.30 inch per hour (in/hr)) and low runoff potential, whereas those designated group D have low infiltration capacity (less than 0.05 in/hr) and high runoff potential (Cronshey and others, 1986). Group B soils have moderate infiltration capacity and low runoff potential and group C soils have low infiltration capacity and moderately high runoff potential. Most soils are group A in Burlington and Ocean Counties (in the Pineland Preservation area of New Jersey) and group B in the western part of the New Jersey Coastal Plain. The hydrologic soil groups in the SWB study area are shown in figure 1.3. In Delaware, group B is found primarily in the interior of the state and group C is found primarily in the northern and southern parts. Group D soils are found along streams and in coastal areas of New Jersey and Delaware (fig. 1.3). A hydrologic soil group category was assigned to every SWB model grid cell and the same values were used throughout the 1980-2013 time period.

Available Water Capacity

Available water capacity (AWC) is the amount of water that a soil can store that is available for use by plants (Natural Resources Conservation Service, 1998). An AWC value was assigned to every SWB model grid cell and these values were unchanged from 1980–2013. Estimated AWC values for 14 soil-texture groups are provided in Westenbroek and others (2010). These AWC values are expressed in units of inches of water per foot of soil thickness. The original source of these values is Thornthwaite and Mather (1957). The AWC grid input to the SWB model was created by assigning values from Westenbroek and others (2010) for each soil-texture group from the SSURGO soil-survey data (Natural Resources Conservation Service, 2014).

Lookup Tables

The SWB model requires two lookup tables to assign properties related to soils and land use to model cells. The first lookup table is used to assign, root-zone depths, runoff curve numbers, interception storage values, and maximum recharge to each combination of hydrologic soil group and land-use/land-cover type (Westenbroek and others, 2010). Root-zone depth is needed in the recharge calculation because of its effect on water flow and transpiration. Root-zone depth values, in feet, were modified from those determined for New Jersey by the NRCS (Natural Resources Conservation Service, 2007). The runoff-curve number is an empirical parameter developed by the U.S. Department of Agriculture Soil Conservation Service (SCS) (since 1994, the NRCS) that is used to estimate rainfall runoff or infiltration (Hjelmfelt, 1991). The SWB model applies runoff-curve numbers to the combination of hydrologic soil groups and land-cover types listed in the lookup table. Curve-number information was obtained primarily from the NRCS (Natural Resources Conservation Service, 2004).

Interception storage values represent water that is trapped by vegetation or evaporated from plant surfaces (Westenbroek and others, 2010). Precipitation must exceed interception for any water to reach the soil surface. Interception storage values in the SWB model are specified for each land-cover type and for growing and nongrowing (dormant) seasons. A value of 0.0835 was used for all land-cover types during the growing season except land-use types designated open water, barren land, and emergent herbaceous wetland land-cover types, which were assigned a value of zero (Tillman, 2015). Maximum daily recharge rates are used to limit the maximum amount of recharge in any cell to a reasonable value. Maximum recharge rates were input to the SWB model modified from values given in Westenbroek and others (2010).

The second lookup table is an extended version of the Thornthwaite-Mather soil-water retention tables that describe the ability of various soils to hold water (Thornthwaite and Mather, 1957). The ability of soil to hold water is strongly related to particle size; water molecules hold more tightly to clay than to coarse materials, such as sand. The soil-water retention tables are provided with the SWB model (Westenbroek and others, 2010).

Comparison of Recharge Estimates for New Jersey Coastal Plain Groundwater-Flow Models

In the Regional Aquifer System Analysis (RASA) model of the New Jersey Coastal Plain (Martin, 1998), a constant recharge rate of 20 in/yr was used. Recharge values in the rediscretized RASA model (Voronin, 2004) ranged from 0.01 in/yr in the outcrop areas of the confining units in updip areas to 20 in/yr in the outcrop areas of the unconfined Kirkwood-Cohansey aquifer system in downdip areas; however, recharge was not varied annually. The values used by Voronin (2004) were based on long-term averages reported in surficial-aquifer studies completed in the late 1980s to late 1990s in several surface-water basins in the New Jersey Coastal Plain as well as on regional estimates. The recharge rates reported in the surficial-aquifer studies ranged from 12.5 to 19.4 in/yr (Watt and Johnson, 1992; Watt and others, 1994; Lacombe and Rosman, 1995; Johnson and Watt, 1996; Johnson and Charles, 1997; Charles and others, 2001; Watt and others, 2003). These values were calculated by using water-budget equations determined for each

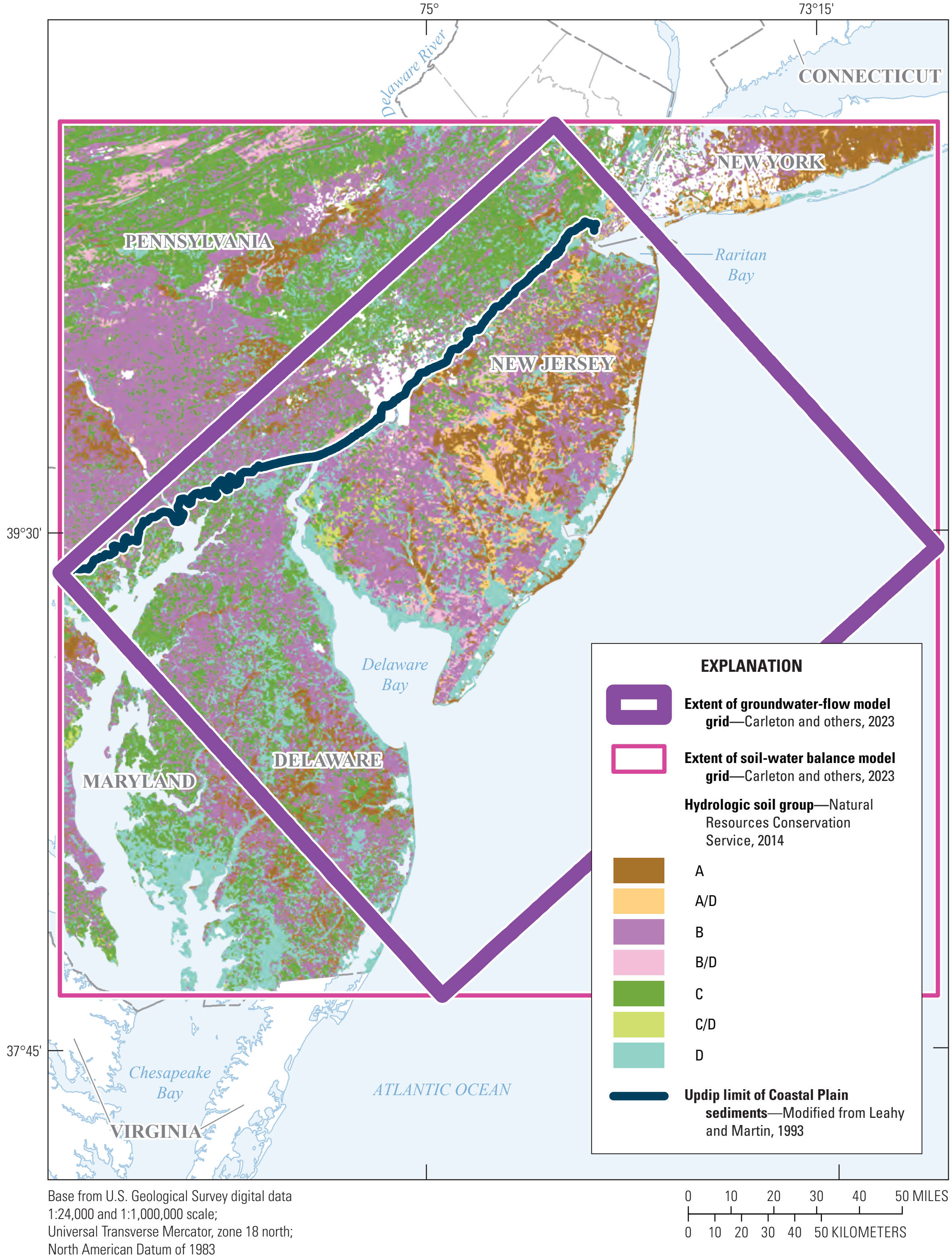

Figure 1.3. Map showing hydrologic soil groups in the New Jersey Coastal Plain groundwater-flow model study area.

individual New Jersey Coastal Plain basin studied, and do not incorporate land use or soil cover in the determination of the recharge estimates.

Because the recharge determined by using the SWB method is a function of land use, soil type, and AWC, estimated recharge varied spatially. Recharge also varied annually and was calculated for each year from 1980 through 2013. Results of the SWB model indicate that the average recharge rate in the study area varied from a minimum of 7.9 in/yr in 1985 to a maximum of 26.2 in/yr in 1996 and averaged 15.4 in/yr in the study area.

A SWB model also was developed for the North Atlantic Coastal Plain (NACP) groundwater-flow model for 2005–09 (Masterson and others, 2015). Results of the NACP SWB model indicate that the average recharge rate for the NACP study area varied from a minimum of 4.2 to a maximum of 37.6 in/yr, and averaged 13.9 in/yr, The SWB model developed for the New Jersey Coastal Plain (NJCP) groundwater-flow model simulated conditions over a longer annual period, 34 years (1980–2013), and the study area was smaller, occupying only part of the NACP study area. For example, the SWB program for the NJCP groundwater-flow model calculated an average groundwater recharge rate for 2013 of 15.3 in/yr, and recharge varied from a minimum of 5.8 to a maximum of 23.3 in/yr (fig. 1.4) for land-use categories not designated as a water body.

Limitations

The SWB method provides an improved understanding of the effects of climate, land use, and soil type on infiltration at the regional scale, but some uncertainties and limitations are acknowledged. Although recharge rates vary over the study area, the SWB model does not account for lag time. Recharge in the model is assumed to be instantaneous within the daily time step, whereas actual recharge is less rapid. Travel times to the water table are affected by infiltration capacity and root-zone dynamics at the time of recharge, as well as the amount of the recharge.

Maximum infiltration rates, root-zone depth, and curve-number values input to the first lookup table are subject to parameter uncertainties. In addition, parameters input to the SWB model are generalized across a model cell, although these parameters can vary locally across the model cell. This limitation may have resulted in a bias in gridded average weighted results for land use, soil, and precipitation in some areas.

Recharge was adjusted during model calibration (described in the Model Calibration section of this report) by using only one recharge parameter for New Jersey in the parameter-estimation calibration process. The use of only one parameter zone for New Jersey in the groundwater-flow model in this study likely affected the accuracy of recharge estimates in areas where local variations occur.

Recharge from wastewater return flow was not simulated in the SWB model. The omission of return flow may have affected estimates of recharge in areas of the NJCP with domestic wells where sewers are absent.

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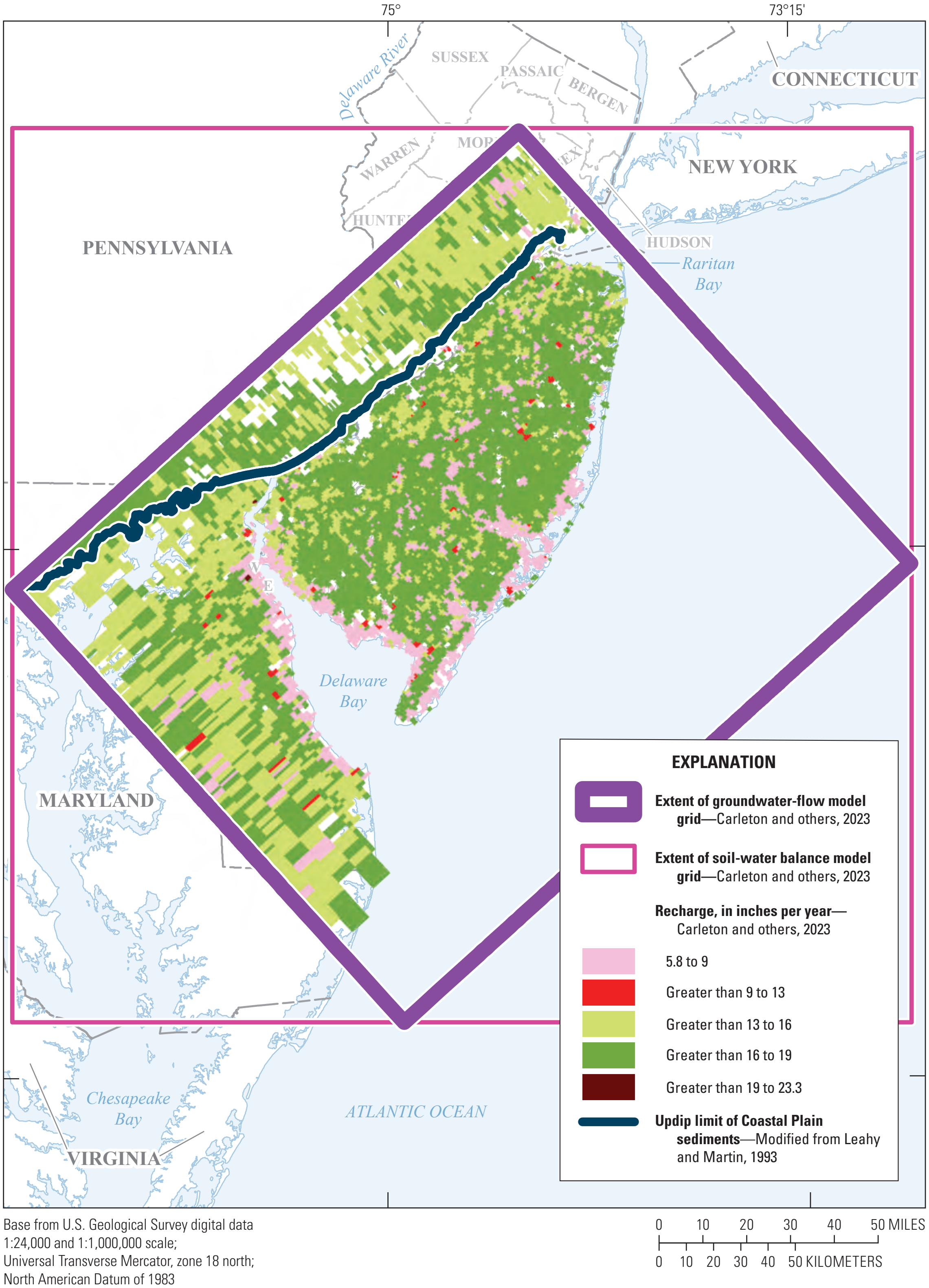

Figure 1.4. Maps showing recharge in the New Jersey Coastal Plain groundwater-flow model in 2013.

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Publishing support provided by the Baltimore Publishing Service Center.

Gordon and Carleton—**Updates to the Regional Groundwater-Flow Model of the New Jersey Coastal Plain, 1980–2013**—SIR 2023–5066

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20235066