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Simulated Effects of Groundwater Withdrawals from the Kirkwood-Cohansey Aquifer System and Piney Point Aquifer, Maurice and Cohansey River Basins, Cumberland County and Vicinity, New Jersey



Scientific Investigations Report 2017–5144

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photo of Maurice River, streamflow-gaging station upstream, right bank, Norma, N.J., December 31, 1943. (Photograph on file at U.S. Geological Survey)

Simulated Effects of Groundwater Withdrawals from the Kirkwood-Cohansey Aquifer System and Piney Point Aquifer, Maurice and Cohansey River Basins, Cumberland County and Vicinity, New Jersey

By Alison D. Gordon and Debra E. Buxton

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New Jersey Department of Environmental Protection

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Conversion Factors

Inch/Pound to SI

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
inch per year per foot [(in/yr)/ft]	83.33	millimeter per year per meter [(mm/yr)/m]

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

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. Negative altitude refers to distance below the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Abbreviations

BWA	Bureau of Water Allocation
CSS	Composite Scaled Sensitivities
ET	Evapotranspiration
GWSI	Groundwater Site Inventory
HUC	Hydrologic Unit Code
NJDEP	New Jersey Department of Environmental Protection
NJPDES	New Jersey Pollutant Discharge Elimination System
RASA	Regional Aquifer-System Analysis
7Q10	7-day 10-year low flow
USGS	U.S. Geological Survey

Simulated Effects of Groundwater Withdrawals from the Kirkwood-Cohansey Aquifer System and Piney Point Aquifer, Maurice and Cohansey River Basins, Cumberland County and vicinity, New Jersey

By Alison D. Gordon and Debra E. Buxton

Abstract

The U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, conducted a study to simulate the effects of withdrawals from the Kirkwood-Cohansey aquifer system on streamflow and groundwater flow and from the Piney Point aquifer on water levels in the Cohansey and Maurice River Basins in Cumberland County and surrounding areas. The aquifer system consists of gravel, sand, silt, and clay sediments of the Cohansey Sand and Kirkwood Formation that dip and thicken to the southeast. The aquifer system is generally an unconfined aquifer, but semi-confined and confined conditions exist within the Cumberland County study area. The Kirkwood-Cohansey aquifer system is present throughout Cumberland County and is the principal source of groundwater for public, domestic, agricultural-irrigation, industrial, and commercial water uses. In 2008, reported groundwater withdrawals from the Kirkwood-Cohansey aquifer system in the study area totaled about 21,700 million gallons—about 36 percent for public supply; about 49 percent for agricultural irrigation; and about 15 percent for industrial, commercial, mining by sand and gravel companies, and non-agricultural irrigation uses. A transient numerical groundwater-flow model of the Kirkwood-Cohansey aquifer system was developed and calibrated by incorporating monthly recharge, base-flow estimates, water-level data, surface-water diversions and discharges, and groundwater withdrawals from 1998 to 2008.

The groundwater-flow model was used to simulate five withdrawal scenarios to observe the effects of additional groundwater withdrawals on the Kirkwood-Cohansey aquifer system and streams. These scenarios include (1) average 1998 to 2008 monthly groundwater withdrawals (baseline scenario); (2) monthly full-allocation groundwater withdrawals, but agricultural-irrigation withdrawals were decreased for October through March; (3) monthly full-allocation groundwater withdrawals; (4) estimated monthly groundwater demand in 2050 at municipal public-supply wells; and (5) estimated 2050 monthly groundwater demand at municipal public-supply wells for which pumping of selected municipal public-supply wells was moved to a deeper part of the Kirkwood-Cohansey aquifer system. The results of the baseline scenario (scenario 1) were used for comparison with the results of scenarios 2–5.

The results of scenarios 2–3 indicate that simulated water-level declines occurred in the Cohansey River Basin when full-allocation groundwater withdrawals were incorporated (scenarios 2 and 3). In scenarios 2 and 3, full-allocation withdrawals in the Cohansey River Basin were approximately 266 and 407 percent greater, respectively, than in the baseline scenario. In scenario 2, the largest decline in simulated water levels was more than 67 ft in June and September of scenario year 11, whereas in scenario 3, simulated water levels declined as much as 90 ft in June and more than 100 ft in September of scenario year 11. These simulated declines occurred in a small area around one pumped well in the Cohansey River Basin. The average decline in simulated water levels for this basin was less than 10 ft for scenario 2 and less than 20 ft for scenario 3. In scenario 2, the Menantico Creek subbasin in the Maurice River Basin had a decrease in base flow during about 29 percent of the 11-year simulation period, and in scenario 3, the decrease occurred during about 71 percent of the 11-year simulation period. In scenario 3, base flow in the Cohansey River Basin was less than the 7-day 10-year low flow in all months of simulation years 7 through 11. Several agricultural-irrigation wells and a number of public-supply wells are within the Cohansey River Basin and the Menantico Creek subbasin.

Three additional scenarios were simulated to evaluate the possible use of the Piney Point aquifer in the Cumberland County study area using the New Jersey Regional Aquifer-System Analysis model, which incorporates all aquifers in the New Jersey Coastal Plain. Various groundwater-withdrawal rates were input to the steady-state New Jersey Regional Aquifer-System Analysis model to assess changes in water levels in the Piney Point aquifer.

The three steady-state scenarios for the New Jersey Regional Aquifer-System Analysis model included the annual average 2004–08 withdrawals for each well in the groundwater-flow model. The results of scenario 6 were used for comparison to the results of scenarios 7 and 8. The groundwater

withdrawals in scenario 7 are the same as in scenario 6, except withdrawals from 50 municipal public-supply wells in the Kirkwood-Cohansey aquifer system that are within the boundary of the Cumberland County study area were increased to estimated 2050 withdrawals. In addition, a municipal public-supply well from nine municipalities in the study area pumping from the Kirkwood-Cohansey aquifer system was assigned the estimated 2050 demand for the Piney Point aquifer instead. The groundwater withdrawals in scenario 8 are the same as in scenario 6, except withdrawals from the municipal public-supply wells in the municipalities of Vineland City, Millville City, and Monroe Township were assigned the full-allocation withdrawals. In addition, the full-allocation withdrawals pumped from one existing municipal public-supply well in each of the three municipalities pumping from the Kirkwood-Cohansey aquifer system were assigned to pump from the Piney Point aquifer instead. The results of the scenarios indicate that the Piney Point aquifer could provide a limited option for public supply in the southeastern part of Cumberland County with constraints on withdrawal rates and the number and proximity of wells additional to those already pumping from the Piney Point aquifer in Bridgeton City and Buena Borough. The transmissivity of the Piney Point aquifer in the Cumberland County study area is about an order of magnitude lower than the average transmissivity of the Kirkwood-Cohansey aquifer system in the study area. This difference in transmissivity may result in deeper cones of depression around the pumped wells in the Piney Point aquifer.

Introduction

The major source of groundwater withdrawals for public, domestic, commercial, industrial, and agricultural uses in the Maurice and Cohansey River Basins is the Kirkwood-Cohansey aquifer system (fig. 1). The Piney Point aquifer underlies the Kirkwood-Cohansey aquifer system throughout most of the study area, but the groundwater withdrawals from this aquifer are substantially less than from the Kirkwood-Cohansey aquifer system.

About 80 percent of annual streamflow in the Cohansey River at Seeley was base flow during water years[1] 1977–88; during water years 1932–94, about 87 percent of annual streamflow was base flow for the Maurice River at Norma streamflow-gaging station (fig. 2) (Charles and others, 2001). Groundwater withdrawals can reduce base flow to streams (Barlow and Leake, 2012). Increasing groundwater withdrawals from the Kirkwood-Cohansey aquifer system is a concern because of potential streamflow depletion and the resulting ecological effects on wetlands and stream habitats. The future water demand for public-supply and irrigation use in the Maurice and Cohansey River Basins can increasingly stress the groundwater and surface-water systems. Annual water use from the Kirkwood-Cohansey aquifer system in the Cohansey and Maurice River Basins in Cumberland County and surrounding areas increased from 10,646 million gallons (Mgal) in 1988 (Charles and others, 2001) to more than 24,000 Mgal in 2008.

The U.S. Geological Survey (USGS), in cooperation with the New Jersey Department of Environmental Protection (NJDEP), conducted a study to assess the effects of withdrawals from the Kirkwood-Cohansey aquifer system on streamflow and groundwater flow and on water levels in the Piney Point aquifer. The study includes the surface-water drainage basins of the Cohansey and Maurice Rivers in the Coastal Plain of New Jersey in Cumberland County and parts of western Atlantic, northwestern Cape May, southern Gloucester and Salem Counties, and a small part of western Camden County (referred to as the "Cumberland County study area") (fig. 1).

The numerical groundwater-flow model was used to simulate groundwater flow for five scenarios. Withdrawals scenarios using this groundwater-flow model are used to assess changes in stream base flow and water levels in the aquifer system. Withdrawal scenarios include (1) monthly groundwater withdrawals averaged from 1998 to 2008; (2) monthly full-allocation withdrawals with decreased agricultural-irrigation withdrawals during October to March; (3) monthly full-allocation groundwater withdrawals; (4) estimated monthly 2050 municipal public-supply demand; and (5) an estimated 2050 municipal public-supply demand alternative that moves withdrawals to a deeper part of the Kirkwood-Cohansey aquifer system.

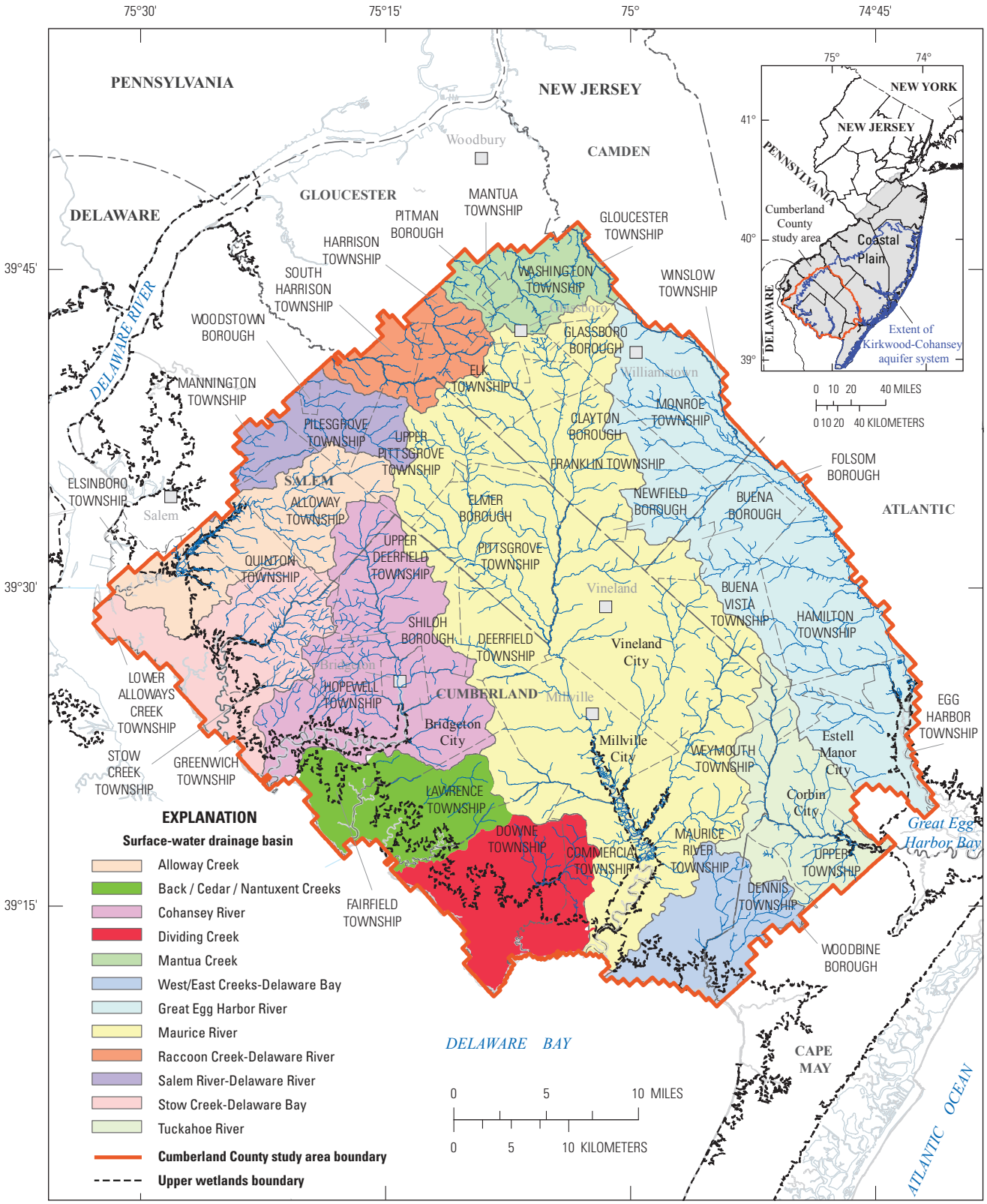
Purpose and Scope

The purpose of this report is to document the development and application of a numerical groundwater-flow model of the Kirkwood-Cohansey aquifer system of the New Jersey Coastal Plain in the Maurice and Cohansey River Basins in Cumberland County and adjacent counties. Groundwater-withdrawal data and estimated base flow and recharge for the period from 1997 to 2008 were used to calibrate the groundwater-flow model.

Results of the Kirkwood-Cohansey groundwater-flow model were used to evaluate the effects of groundwater withdrawals on the aquifer system. Recharge for the period from 1997 to 2008 was used to simulate future groundwater-withdrawal scenarios. The effects of potential future groundwater withdrawals were assessed by simulating five scenarios incorporating full-allocation (maximum permitted withdrawals) or estimated 2050 demand. The effects on water levels and on stream base flow were evaluated.

A regional model of the Coastal Plain aquifer in New Jersey was used to assess the future use of the Piney Point aquifer in Cumberland County and adjacent counties by simulating three scenarios. The effects on water levels in this aquifer were evaluated.

[1] A water year is the 12-month period from October 1 to September 30 and is designated by the year in which it ends.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 1. Location of the Cohansey and Maurice River Basins and surrounding drainage basins, Cumberland County study area, New Jersey.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 2. Cumberland County study area, weather stations, selected streamflow-gaging stations, and line of section in New Jersey.

Description of Study Area

The study area lies within the Coastal Plain Physiographic Province and encompasses Cumberland, western Atlantic, and southern Gloucester and Salem Counties (fig. 1). Small parts of western Camden and northwestern Cape May Counties are also included. Most streams in the study area flow into the Delaware River or Delaware Bay; however, the Tuckahoe and Great Egg Harbor Rivers flow to the Great Egg Harbor Bay (fig. 2). In the northern part of the study area, land surface reaches 140 feet above the National Geodetic Vertical Datum of 1929 (NGVD 29). In the southern and western parts of the study area along the Delaware and Great Egg Harbor Bays, the area is tidal, and altitudes are 5 feet (ft) or less above NGVD 29.

Cumberland County has a substantial agricultural economy and has one of the most progressive nursery and floriculture industries in the United States (Cumberland County New Jersey, 2014). According to the NJDEP land-cover data from 2002, wetlands cover about 30 percent of Cumberland County; about 32 percent is forest, about 12 percent urban or developed, about 19 percent agriculture, and the remaining 7 percent barren land or water (Delaware Valley Regional Planning Commission, 2009). By 2008, about 18 percent of the land of Cumberland County was classified as agricultural (Delaware Valley Regional Planning Commission, 2009).

Previous Investigations

Zapecza (1989) defines the hydrologic units of the New Jersey Coastal Plain, including the Kirkwood-Cohansey aquifer system and describes the subsurface occurrence and configuration of the aquifers and confining units. Sugarman (2001) describes the hydrostratigraphy of the Kirkwood Formation and Cohansey Sand.

Martin (1998) developed a numerical groundwater-flow model of the New Jersey Coastal Plain for the USGS Regional Aquifer-System Analysis (RASA) program. The New Jersey Coastal Plain RASA model was updated by Voronin (2004) by rediscretizing the model grid to a finer cell size and by incorporating a spatially variable recharge rate and updated groundwater-withdrawal data. Cauller and Carleton (2005) developed a numerical groundwater-flow model of the Kirkwood-Cohansey aquifer system, which was used to examine water-management alternatives in the upper Maurice River Basin. Pope and others (2012) developed a numerical groundwater-flow model of the Kirkwood-Cohansey aquifer system and the underlying confined aquifers in the Great Egg Harbor and Mullica River Basins, which was used to examine water-management alternatives in that area.

Rooney (1971) evaluates the groundwater resources of Cumberland County. Studies of the Kirkwood-Cohansey aquifer systems in the Cohansey and Maurice River (Charles and others, 2001), Great Egg Harbor River (Watt and Johnson, 1992), upper Maurice River (Lacombe and Rosman, 1995), and Salem River (Johnson and Charles, 1997) Basins provide information on hydrogeology, water levels, and water quality, along with a surface-water and water-budget analysis.

Well-Numbering System

The well-numbering system used in this report has been used by the USGS in New Jersey since 1978. The well number consists of a county code number and a sequence number assigned to the well in the county. County code numbers used in this report are 01–Atlantic, 07–Cape May, 11–Cumberland, 15–Gloucester, and 33–Salem. For example, well 01-578 is the 578th well inventoried by the USGS in Atlantic County.

Hydrogeology

The following sections describe the hydrogeologic framework of the study area and the hydraulic properties that define groundwater flow in the Kirkwood-Cohansey aquifer system.

Hydrogeologic Framework

The model framework for this study is based on the hydrogeologic framework of the New Jersey Coastal Plain presented in Zapecza (1989). The New Jersey Coastal Plain is a seaward-dipping wedge of unconsolidated sediments that range from Cretaceous to Holocene age (Zapecza, 1989). These sediments consist of alternating layers of sand, gravel, silt, and clay that dip and thicken to the southeast and overlie crystalline bedrock. The sand and gravels compose the aquifers of the New Jersey Coastal Plain, and the clays compose the confining units. A generalized hydrogeologic section of aquifers and confining units in the Coastal Plain of New Jersey that runs from northwest to southeast is shown in figure 3. The geologic and hydrogeologic units of the New Jersey Coastal Plain for this study area are listed in table 1. This study also used stratigraphic data accumulated during the Great Egg Harbor and Mullica River Basins study (Pope and others, 2012).

The Kirkwood-Cohansey aquifer system is present throughout the study area. The aquifer system consists primarily of gravel, sand, silt, and clay sediment of the Cohansey Sand and Kirkwood Formation. In the study area, the aquifer system is composed of the hydraulically connected sediments of the Kirkwood and Cohansey Formations and, depending on location, can include overlying deposits of the Bridgeton Formation, Cape May Formation, and younger Holocene deposits. The Kirkwood-Cohansey aquifer system functions predominantly as an unconfined (water-table) aquifer; however, discontinuous clay units within the aquifer system may create semiconfined to confined conditions locally. Flowing wells have been reported in various locations in Commercial, Downe, Fairfield, and Maurice River Townships and in Millville City (Rooney, 1971).

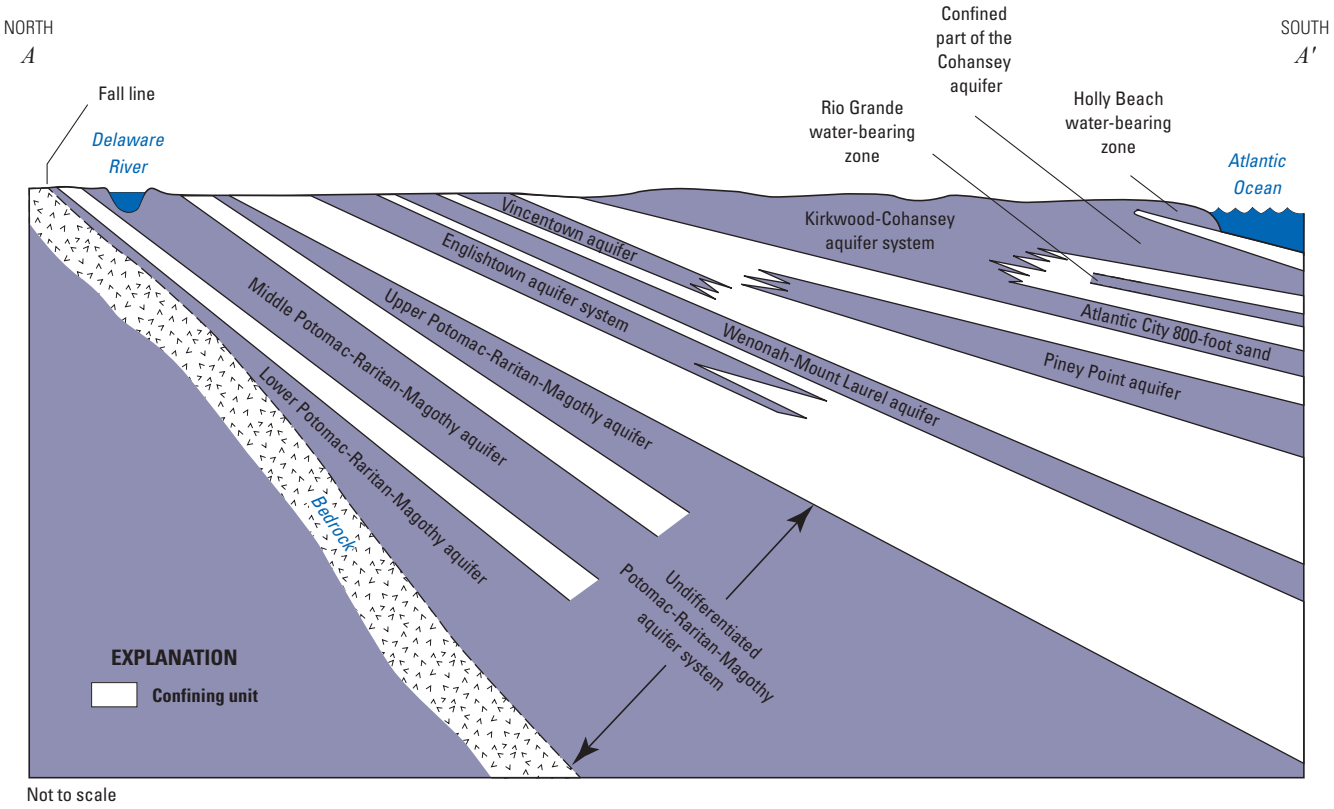


Figure 3. Generalized schematic hydrogeologic section of the New Jersey Coastal Plain. (modified from Martin, 1998) (Line of section shown in figure 2)

Table 1. Geologic and hydrogeologic units of the New Jersey Coastal Plain, Cumberland County study area, New Jersey.

[Modified from Zapecza, 1989, table 2]

System	Series	Geologic unit	Hydrogeologic unit, updip	Hydrogeologic unit, southeastern downdip
Quaternary	Holocene	Alluvial deposits	Kirkwood-Cohansey aquifer system	Kirkwood-Cohansey aquifer system
		Beach sand and swamp deposits		
	Pleistocene	Cape May Formation		
Tertiary	Miocene	Bridgeton Formation		
		Cohansey Sand		
		Kirkwood Formation		Confining unit
				Rio Grande water-bearing zone
				Confining unit
				Atlantic City 800-foot sand
			Composite confining unit	Composite confining unit
	Oligocene	Piney Point Formation	Piney Point aquifer	

The Kirkwood Formation, lower to middle Miocene in age, is a marine unit that forms the basal part of the Kirkwood-Cohansey aquifer system. In the subsurface, in the easternmost part of the model area, thick diatomaceous clay beds with interbedded zones of sand and gravel are dominant; in updip areas, the lithology of the Kirkwood Formation changes to fine- to medium-grained quartz sand and silty sand. Regionally extensive clay beds are present only in the basal part of the formation (Zapecza, 1989). The Cohansey Formation, middle Miocene in age, is a marginal marine deposit composed predominantly of light-colored, medium- to coarse-grained quartz sand with some gravel and silt. Thin interbedded clay layers are common locally. Clay layers as much as 25 ft thick are known to be present within the Cohansey Sand (Hardt and Hilton, 1969; Rosenau and others, 1969); however, these relatively thick clay layers are local in extent (Zapecza, 1989). The Bridgeton Formation of Miocene age is arkosic sand with lenses of fine gravel that were deposited in a fluvial environment. The Bridgeton Formation crops out discontinuously throughout most of the study area, typically at topographic highs. Surficial deposits of the Bridgeton Formation can be as much as 30 to 50 ft thick in parts of Cumberland County (Owens and Minard, 1979). The Kirkwood-Cohansey aquifer system thickens downdip from less than 50 ft near the Kirkwood Formation outcrop area in western Cumberland County to more than 500 ft in eastern Cumberland County. In the extreme eastern part of the Cumberland County, the Kirkwood-Cohansey aquifer system overlies and transitions into the confined aquifers of the Kirkwood Formation, namely the Atlantic City 800-foot sand and the Rio Grande water-bearing zone. Drillers' and geophysical logs of deep wells are not available to define this transition in better detail. The thickness of the Kirkwood-Cohansey aquifer system in this area is determined by the western extent of the confining unit overlying the Atlantic City 800-foot sand. Here the aquifer thickness ranges from less than 200 feet along the western extent of the confining unit to more than 350 feet along the Atlantic Coast. A regional confining unit in the basal part of the Kirkwood Formation averages about 100 feet in thickness throughout the study area and separates the Kirkwood-Cohansey aquifer system and the Atlantic City 800-foot sand from the underlying Piney Point aquifer (Zapecza, 1989).

Aquifer Properties

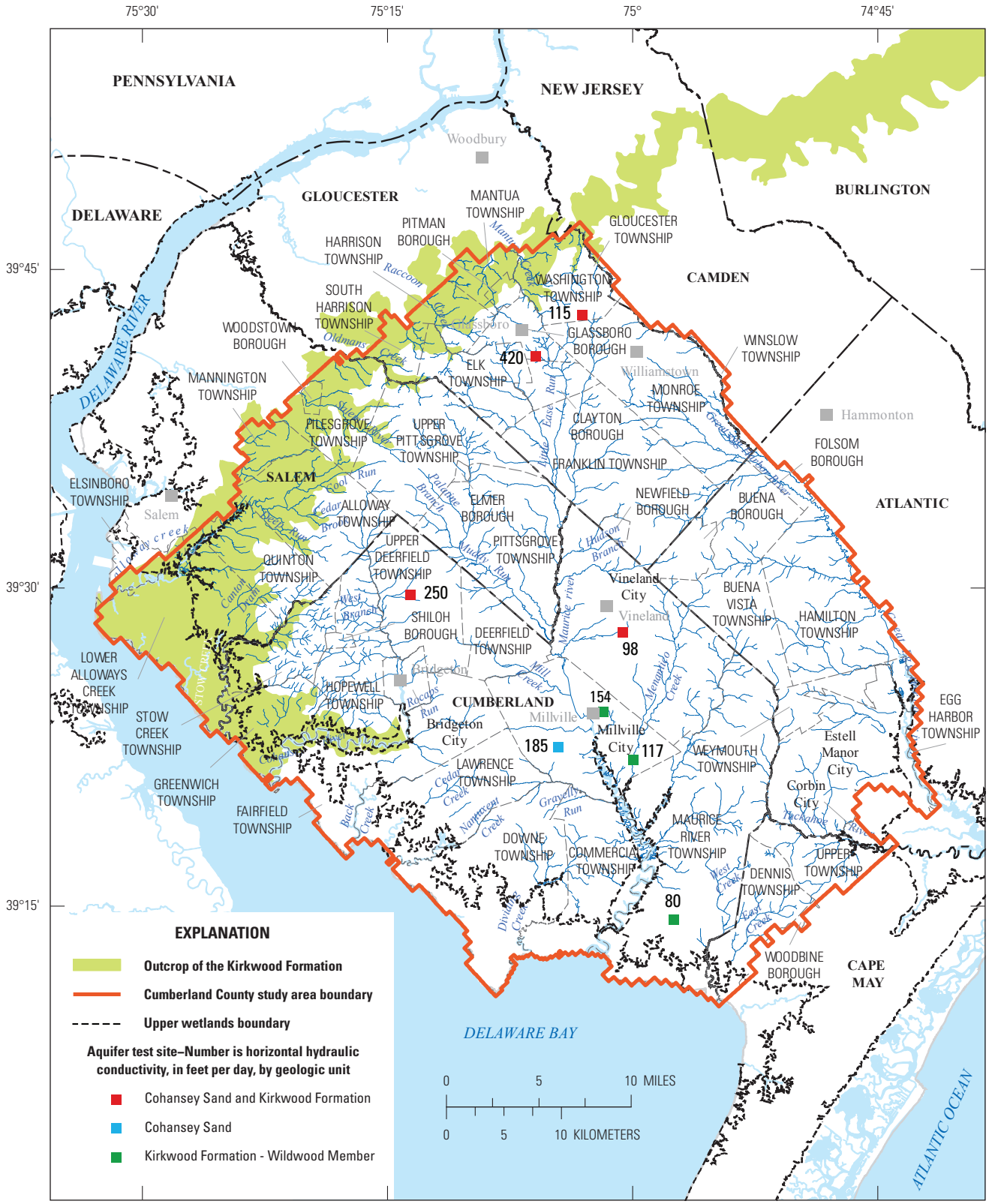
Values of horizontal hydraulic conductivity from aquifer tests conducted for large water-supply wells screened in the Kirkwood-Cohansey aquifer system in the Cumberland County study area were obtained from the New Jersey Geological and Water Survey (NJGWS) hydroparameters database (NJGS DGS02-1) (New Jersey Geological Survey, 2008). The eight aquifer test locations are shown in figure 4. The hydraulic properties of the Kirkwood-Cohansey aquifer system compiled from these aquifer tests conducted between1989 and 1999 indicate that transmissivity values range from about 4,000 to more than 38,000 square feet per day (ft^2/d), and hydraulic conductivity values (transmissivity divided by aquifer thickness) range from 80 to 420 feet per day (ft/d) (New Jersey Geological Survey, 2008). The horizontal hydraulic conductivity data are summarized in table 2 for the eight wells.

Horizontal hydraulic conductivity was also determined from analysis of specific-capacity data from well-acceptance tests that have a well record on file at the USGS New Jersey Water Science Center (fig. 5). Specific capacity is a measure

Table 2. Horizonal hydraulic conductivity of the Kirkwood-Cohansey aquifer system determined from aquifer test data, Cumberland County study area, New Jersey.

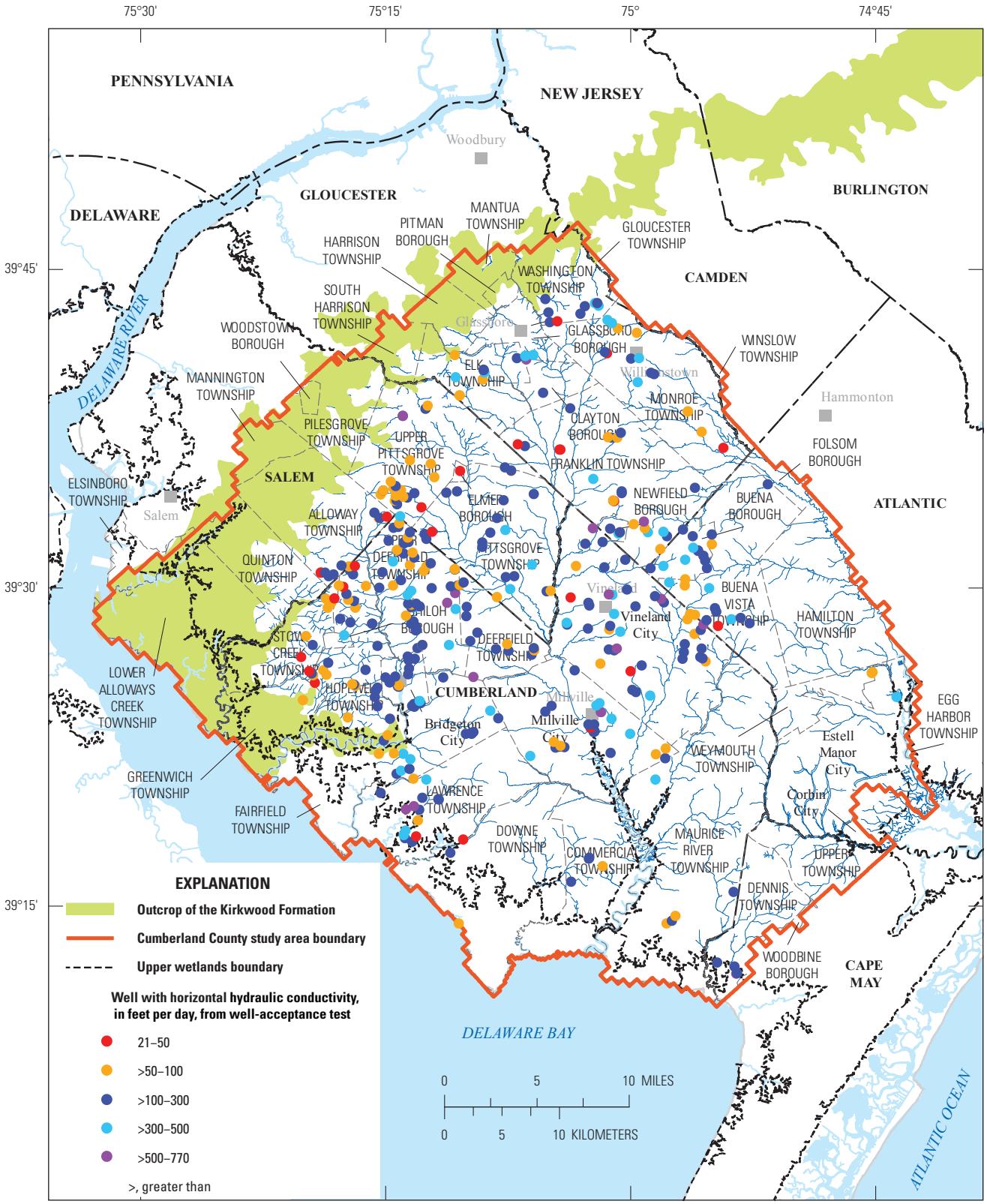
[All wells are in Kirkwood-Cohansey aquifer system; ft/d, feet per day; gal/min, gallons per minute; NJDEP, New Jersey Department of Environmental Protection]

U.S. Geological Survey well number	NJDEP well permit number	Well depth (feet below land surface)	Test date	Pumping rate (gal/min)	Test length (hours)	Hydraulic conductivity (ft/d)	Model layer
11-437	3500001277	150	07/21/1993	538	72	117	3
11-708	3500007632	163	06/22/1988	1001	47	98	4
11-712	3500012630	217	04/20/1992	1022	72	185	5
11-934	3500017509	128	04/07/1992	1200	72	154	3
11-976	3400004438	148	12/12/1993	1170	154	250	3
11-1225	3500020016	270	11/29/1999	1300	72	80	5
15-1361	3100042387	90	11/01/1993	840	72	115	2
15-1385	3100047569	70	03/26/1996	460	72	420	2



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 4. Locations of wells with horizontal hydraulic conductivity determined from aquifer tests conducted on the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 5. Locations of wells with horizontal hydraulic conductivity estimated from specific-capacity data, Cumberland County study area, New Jersey.

of the productivity of a well and is calculated as the pumping rate divided by the resulting drawdown after the well is pumped at the same rate for some period of time (Freeze and Cherry, 1979). Reported specific-capacity data and ancillary information (well diameter, pumping rate and duration, drawdown, and screen lengths) for wells in the study area were retrieved from the USGS Groundwater Site Inventory (GWSI) database in order to estimate values of hydraulic conductivity. The hydraulic conductivity was estimated using a simplified version of the Theis equation derived for the determination of transmissivity from specific capacity; it is given in Heath (1983, p. 61) as

$$K = 308\ Q/sL \quad (1)$$

where K is the hydraulic conductivity, and the factor Q/sL is the specific capacity (Q/s) of the well per foot of well screen (L). The Q/sL factor is given in the well record and it takes into account the length of the well screen. Hydraulic conductivity estimated from the specific-capacity method ranged from about 21 to 770 ft/d at 393 wells in the study area that were pumped at a rate of at least 50 gallons per minute for at least 2 hours. The average horizontal hydraulic conductivity for these wells is about 187 ft/d, although more than 62 percent of these wells have horizontal hydraulic conductivities less than this average. The median horizontal hydraulic conductivity is about 144 ft/d. The distribution of the horizontal hydraulic conductivity values indicates the values are spatially variable.

Some estimates of storage properties in the study area are reported in the literature. Rooney (1971) reports a specific yield of 0.3 from an aquifer test in Deerfield Township in Cumberland County and a storage coefficient of 0.0003 in Elmer Borough in southern Salem County, indicating artesian or semi-artesian conditions. Rhodehamel (1973) and Charles and others (2001) report storage coefficients that range from 0.044 to 0.0001 for seven aquifer tests in the study area.

Groundwater-Flow System

In general, the Kirkwood-Cohansey aquifer system is recharged by precipitation on the outcrop area of the Kirkwood Formation (fig. 5) and the Cohansey Sand that lies southeast of the outcrop area of the Kirkwood Formation. Discharge is to streams, tidal areas along the Delaware Bay, Delaware River and Bay, Great Egg Harbor Bay, pumped wells, and the underlying aquifers, such as the Piney Point aquifer.

Base Flow

Base-flow sites are locations along a stream where discrete measurements were made during low-flow conditions over a period of several years. These discrete data were used with data from nearby long-term streamflow-gaging stations to estimate correlation statistics for the low-flow stations. Monthly base flows from January 1998 to December 2008 were estimated for four streamflow-gaging stations with continuous records using the streamflow partitioning program PART (Rutledge, 1998). The continuous-record streamflow-gaging stations include the Maurice River at Norma (01411500); the Tuckahoe River at Head of River (01411300); and Little Ease (01411456), a tributary of the Maurice River (fig. 6). The Cohansey River at Seeley streamflow-gaging station (01412800) was used as a continuous-record streamflow-gaging station starting August 2003, so this station is also a low-flow partial-record station.

The Maintenance of Variance Extension Type 1 (MOVE1) program was used to estimate the low-flow statistics at partial-record stations (Hirsch, 1982). Three or more streamflow-gaging stations with similar hydrologic characteristics were used as index stations for each partial-record station analysis. Base-flow estimates for the index stations with continuous records of instantaneous streamflow were used to compute low-flow statistics for the low-flow partial-record stations. Daily mean base flows at the index stations were correlated with measured instantaneous base flows at the partial-record stations to produce monthly base flows at the partial-record stations. The correlations between base flows at the index stations and those at the low-flow partial-record stations were used to compute monthly base flows at the 14 low-flow sites. Locations of the continuous-record streamflow-gaging and low-flow partial-record stations are shown in figure 6. The MOVE1 correlation statistics used to compute base flows are listed in table 3. The low-flow correlation equation is used to predict specific discharge statistics for the low-flow partial-record station on the basis of the same discharge statistics measured at the index station. The correlation coefficient is an indication of the accuracy of the predicted discharge. The correlation coefficient is a number from -1.0 to 1.0 that measures the strength of the linear relation between the logarithm (base 10) of the discharge at the low-flow partial-record station and that at the index station. The nearer the correlation coefficient is to 1.0, the more reliable the predicted discharge. The data for equations with a correlation coefficient of 0.75 or greater for a low-flow partial-record station using an index station are listed in table 3.

Summary flow statistics for the 17 streamflow-gaging stations are shown in table 4. The flow statistics in table 4 were determined from the long-term data and from the hydrograph separation program (Rutledge, 1998); the flow statistics for the



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 6. Continuous-record streamflow-gaging and low-flow partial-record stations, Cumberland County study area, New Jersey.

Table 3. MOVE1 correlation data for low-flow partial-record stations, southern New Jersey.

[ft^3/s, cubic feet per second]

Low-flow station number	Station name	Drainage area (square miles)	Number of measure-ments	Index station number	Correlation slope	Correlation exponent	Correlation[1] coefficient	Standard error of estimate (ft^3/s)	Weight
01411442	East Creek near Eldora, NJ	8.10	14	01410000	0.00006	2.715	0.799	141.299	0.298
01411442			14	01411300	0.00892	1.852	0.813	131.389	0.345
01411442			14	01411500	0.00004	2.379	0.823	128.990	0.358
01411445	West Creek near Eldora, NJ	11.90	11	01411000	0.00015	2.542	0.909	87.149	0.434
01411445			11	01411300	0.00175	2.471	0.900	126.499	0.206
01411445			11	01411500	0.00001	2.862	0.917	95.735	0.360
01411680	Palatine Branch at Palatine, NJ	5.39	20	01411456	1.45125	0.598	0.852	48.635	0.162
01411680			21	01411500	0.00779	1.275	0.881	46.795	0.175
01411680			19	01477120	0.11339	1.114	0.872	44.171	0.197
01411800	Maurice River near Millville, NJ	191	19	01411000	3.93661	0.932	0.959	24.864	0.173
01411800			20	01411500	1.67599	0.992	0.993	11.737	0.778
01411850	Mill Creek near Millville, NJ	15.10	20	01411000	0.07633	1.181	0.872	34.275	0.528
01411850			20	01411500	0.04637	1.115	0.866	36.275	0.472
01411955	Gravelly Run at Laurel Lake, NJ	3.19	39	01411000	0.00370	1.392	0.787	71.584	0.255
01411955			40	01411300	0.02089	1.243	0.862	61.024	0.350
01411955			42	01411500	0.00170	1.349	0.855	57.444	0.395
01412005	Menantico Creek at Route 49 at Millville, NJ	26.30	18	01411000	1.15990	0.788	0.927	19.577	0.410
01412005			20	01411500	0.35239	0.933	0.944	22.249	0.317
01412005			17	01477120	1.47126	0.940	0.932	23.981	0.273
01412405	Cohansey River near Beals Mill, NJ	9.44	16	01409500	0.07932	0.971	0.764	27.594	0.307
01412405			18	01411000	0.11001	0.967	0.850	26.961	0.322
01412405			18	01411500	0.10375	0.841	0.867	25.092	0.371
01412500	West Branch Cohansey River at Seeley, NJ	2.58	15	01477120	0.06634	0.763	0.844	26.548	0.256
01412800	Cohansey River at Seeley, NJ	28	95	01411000	1.00984	0.7662	0.7467	36.4684	0.1355
01412800			90	01411500	0.66999	0.7452	0.8283	26.9846	0.2475
01412800			90	01477120	2.14132	0.7634	0.8444	26.5484	0.2557

Table 3. MOVE1 correlation data for low-flow partial-record stations, southern New Jersey.—Continued

[ft^3/s, cubic feet per second]

Low-flow station number	Station name	Drainage area (square miles)	Number of measure-ments	Index station number	Correlation slope	Correlation exponent	Correlation[1] coefficient	Standard error of estimate (ft^3/s)	Weight
01413050	Stow Creek at Jericho, NJ	8.07	14	01411500	0.00725	1.452	0.815	90.662	0.262
01413050			14	01477120	0.13730	1.303	0.880	66.830	0.483
01413050			13	01482500	0.82695	1.123	0.898	92.018	0.255
01413060	Canton Drain near Canton, NJ	2.50	9	01411000	0.01073	1.312	0.931	34.290	0.496
01413060			9	01411500	0.00888	1.143	0.906	41.630	0.336
01413060			9	01482500	0.25523	1.032	0.944	58.890	0.168
01482950	Cedar Brook near Alloway, NJ	3.76	20	01411500	0.00182	1.542	0.871	53.932	0.327
01482950			11	01477120	0.00636	2.085	0.867	61.330	0.253
01482950			8	01482500	0.29388	1.114	0.978	47.618	0.420
01483010	Deep Run near Alloway, NJ	5.30	23	01410000	0.09988	0.968	0.861	32.263	0.183
01483010			22	01411500	0.03139	1.050	0.887	31.419	0.193
01483010			21	01477120	0.15156	1.092	0.852	35.870	0.148

[1]Correlation coefficients greater than 0.75 were chosen for this study. The index station with the best correlation coefficient was used in the study.

Table 4. Streamflow statistics for continuous-record streamflow-gaging and low-flow partial-record stations, Cumberland County study area, New Jersey.

[ft^3/s, cubic feet per second; Type: C, continuous-record streamflow-gaging station; LF, low-flow partial-record station; 7Q10, 7-day average low flow that has 10-precent chance of occurring in a given year (Gillespie and Schopp, 1982)]

Station number	Station name	Drainage area (square miles)	Type[1]	Mean streamflow from 1998 to 2008 (ft^3/s)	7Q10 streamflow[2] (ft^3/s)	Mean base flow from 1998 to 2008 (ft^3/s)	Base flow as a percentage of streamflow	Mean annual streamflow per square mile (ft^3/s)
01411300	Tuckahoe River at Head of River, NJ	30.8	C	36.7	7.2	31	85	1.2
01411456	Little Ease Run near Clayton, NJ	9.77	C	10.1	0.5	7.9	78	1
01411500	Maurice River at Norma, NJ	112	C	152.2	38	140	92	1.4
01411442	East Creek near Eldora, NJ	8.1	LF	10.3	0.5	7	69	1.3
01411445	West Creek near Eldora, NJ	11.9	LF	17.4	0.3	12	68	1.5
01411680	Palatine Branch at Palatine, NJ	5.39	LF	3.3	1	2.6	81	0.6
01411800	Maurice River near Millville, NJ	191	LF	259.6	57	231	89	1.4
01411850	Mill Creek near Millville, NJ	15.1	LF	13.6	2.8	12	87	0.9
01411955	Gravelly Run at Laurel Lake, NJ	3.19	LF	1.7	0.2	1.5	83	0.6
01412005	Menantico Creek at Route 49 at Millville, NJ	26.3	LF	38.3	11	33	86	1.5
01412405	Cohansey River near Beals Mill, NJ	9.44	LF	8.2	2.5	7.4	91	0.9
01412500	West Branch Cohansey River at Seeley, NJ	2.58	LF	1.3	0.4	1.1	85	0.5
01412800	Cohansey River at Seeley, NJ[3]	28	LF	20.9	10	18	86	0.8
01413050	Stow Creek at Jericho, NJ	8.07	LF	18.8	1.3	12	64	2.3
01413060	Canton Drain near Canton, NJ	2.5	LF	4.0	0.5	3.1	77	1.6
01482950	Cedar Brook near Alloway, NJ	3.76	LF	8.4	0.3	6.4	56	3.1
01483010	Deep Run near Alloway, NJ	5.3	LF	4.0	1.9	3.3	80	0.8

[1]For type C, streamflow and base flow estimated from PART program (Rutledge, 1998); for type LF, estimated from MOVE1 program (Hirsch, 1982).

[2]Streamflow from Watson and others, 2005. FlowStat.data online at http://pubs.usgs.gov/sir/2005/5105/pdf/FlowStat-data.pdf.

[3]Station number 01412800, Cohansey River at Seeley, NJ, is also a continuous-record streamflow-gaging station starting August 2003.

partial-record stations were estimated using low-flow correlation. General information about the continuous-record streamflow-gaging and low-flow partial-record stations used in the model calibration and in the analysis of the effects of groundwater withdrawals in the surface-water drainage basins is included in table 4.

Groundwater Withdrawals

The NJDEP Bureau of Water Allocation (BWA) and Well Permitting manages water-allocation permits for withdrawals in New Jersey for users diverting 100,000 gallons per day (gal/d) of water for a period of more than 30 days in a 365 consecutive day period for nonagricultural purposes (New Jersey Department of Environmental Protection, 2015). Water-allocation permits are required for public-supply wells and commercial/industrial wells (5000 and 2000P series, respectively) that divert more than 100,000 gal/d of water. Water-use registrations are required for users who have the capacity to divert more than 100,000 gal/d but divert less than this quantity (10000W series). Diversion limits of 3.1 million gallons per month are assigned for users who divert less than 100,000 gal/d. Agricultural water-usage certifications are required for agricultural users having the capability to divert groundwater and (or) surface water in excess of 100,000 gal/d; agricultural water-usage registrations are required for agricultural users having the capability to divert more than 100,000 gal/d but divert less than this amount (New Jersey Department of Environmental Protection, 2015). For the agricultural users, the series is designated as the first two letters of the New Jersey county followed by a number. The USGS verifies water-use data using a routine of quality-assurance checks, including a comparison of reported annual and monthly withdrawals with the withdrawals allowed by the NJDEP for each permit and a comparison of annual withdrawals with recent yearly average withdrawals for each well. Additional quality-assurance procedures for agricultural withdrawal data were used for this study because of the large volume of agricultural withdrawals within the study area. Paper copies of the agricultural data were collected from NJDEP and checked against the electronic data for the period 1997–2008. For agricultural withdrawal data that were missing or when paper copies were not available, the withdrawals were assigned the value of the most recent year with a reported withdrawal value.

Groundwater withdrawals reported in the Cumberland County study area were primarily used for public supply and agricultural irrigation. Domestic use is not reported to the NJDEP. Domestic groundwater withdrawals are primarily non-consumptive because most of the water is returned to the shallow aquifer.

Monthly groundwater withdrawals in the Cumberland County study area during 1998–2008 are shown in figure 7, which indicates that groundwater withdrawals increased from 1998 to 2008. Over the 11-year period, annual groundwater withdrawals were lowest in 1999 (13,067 Mgal) and were greatest in 2007 (24,641 Mgal). Groundwater withdrawals vary seasonally with greater withdrawals during the summer months, as shown by variations in the average monthly groundwater withdrawals from 1998 to 2008 in figure 8. Mean monthly groundwater use from 1998 to 2008 can be more than 4 times greater for summer (June through August) than for winter (December through February) because of agricultural water use. Groundwater use increased in the spring and summer months and declined steadily through the fall months. The locations of groundwater withdrawals by water-use allocation series from 1997 to 2008 are shown in figure 9. Monthly groundwater withdrawals are not shown in figure 7 for 1997 because when the groundwater-flow model was constructed, the data for 1997 were input for quarterly periods.

Groundwater withdrawals totaled about 21,700 Mgal in 2008. Groundwater withdrawals for public supply accounted for about 36 percent; agricultural irrigation accounted for about 49 percent; and industrial use, commercial use, and non-agricultural irrigation accounted for the remaining 15 percent.

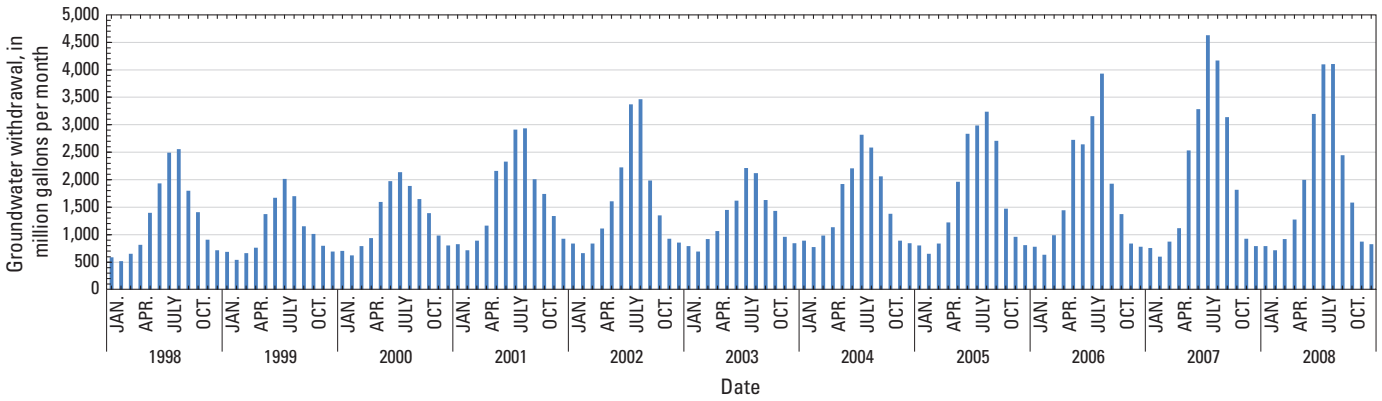


Figure 7. Monthly groundwater withdrawals from the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey, 1998–2008.

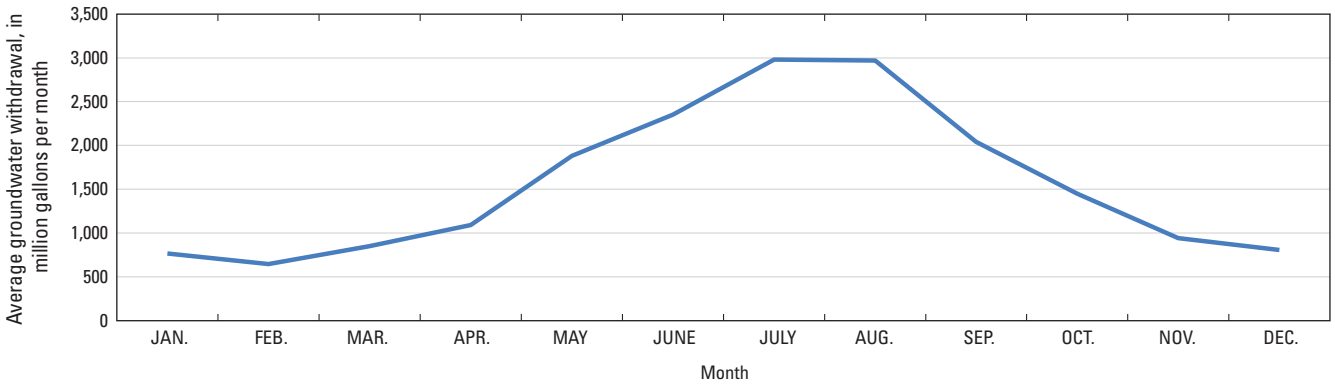


Figure 8. Average monthly groundwater withdrawals from the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey, 1998–2008.

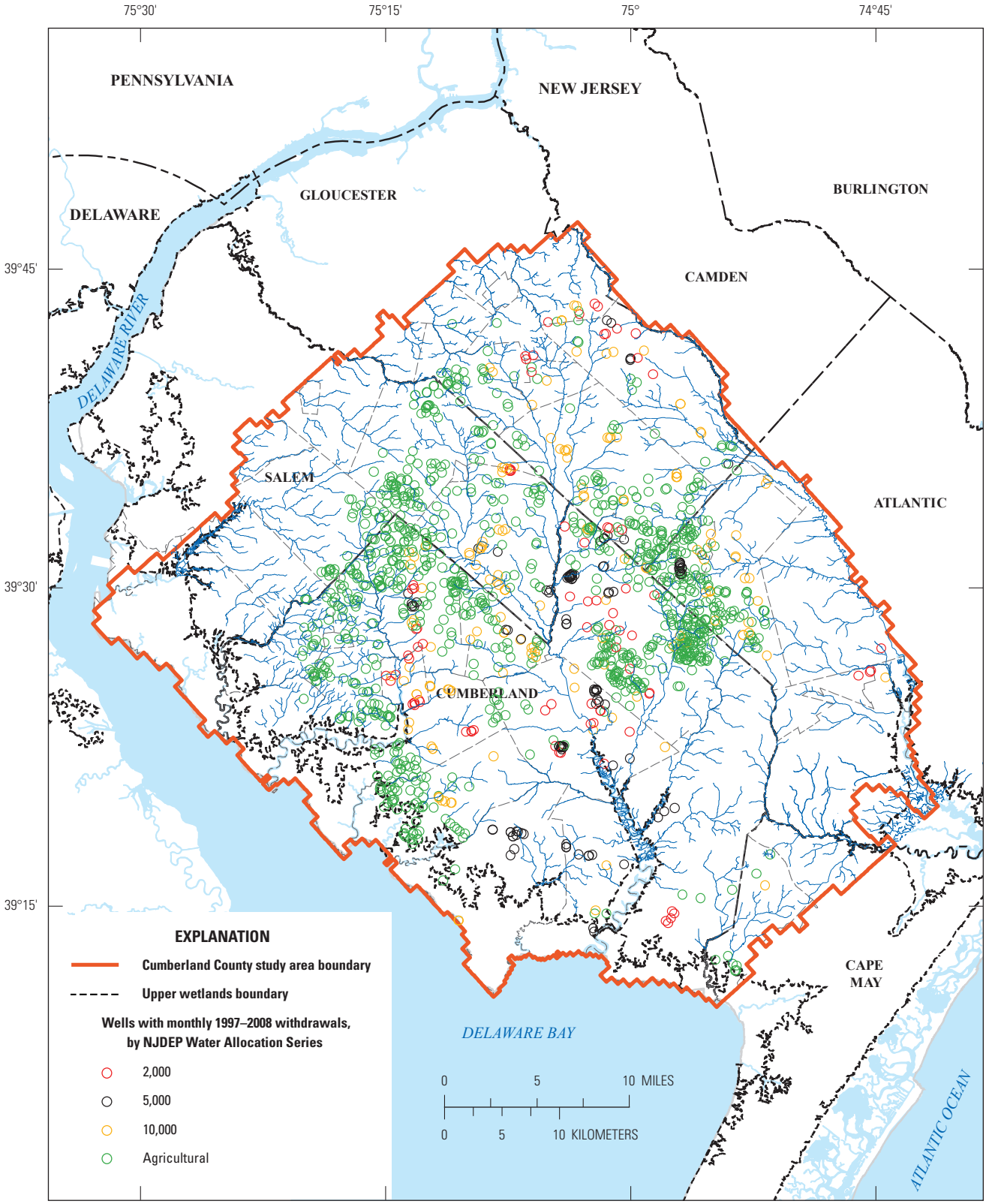
Water-Level Fluctuations and Trends

A map of composite water-table contours is shown in figure 10. The map was created by using water levels measured during several studies of drainage basins where the surficial aquifer is the Kirkwood-Cohansey aquifer system. The water-table map was produced from 741 wells or stream sites located over the drainage basins located within the Cumberland County study area. This composite water table consists of water levels measured April through May 1995 in the Cumberland County area (Charles and others, 2001); fall 1986 in the upper Maurice River Basin (Lacombe and Rosman, 1995); October, November, and December 1993 in the Salem River, and Stow and Alloway Creek Basins (Johnson and Charles, 1997); and April and May 1989 in the Great Egg Harbor River Basin (Watt and Johnson, 1992). The water-level contours produced from each study were matched at each study boundary to produce a seamless water-table map. The drainage basins are shown in figure 1.

The differences between water levels in 35 wells measured in April through May 1995 in the study area (Charles and others, 2001) and water levels in the same wells measured in May or June 2008 are shown in figure 10. A negative difference indicates the 2008 water level is lower than the 1995 water level. Although the water levels were measured during different years, the difference for each well typically is about 1 ft. However, a water level was 9 ft lower in May 2008 compared to April 1995 for a 104-deep agricultural-irrigation well in Deerfield Township (well number 11-283). Total precipitation for April 1995 for the Seabrook Farms weather station near this well was 1.7 inches (in.), and in 2008, the total precipitation was 4.7 in., a difference in precipitation of 3 in. Total precipitation for January through April 1995 for the Seabrook Farms weather station was 9.2 inches (in.), and in 2008, the total precipitation for the same months was 11.9 in., a difference in precipitation of 2.7 in. In addition, daily pumpage is not available for this well or for well number 11-789 (8 ft difference), which is located near a Vineland City supply well.

Hydrographs for six wells in the Maurice and Cohansey River Basins demonstrate the fluctuation in the water levels in these wells over the measurement period (fig. 11). Water levels in the six wells were measured on a periodic basis from January 1998 to December 2008. The water levels indicate that fluctuations of as much as 8.2 ft occurred in well number 15-1054, but typically, monthly fluctuations varied about 4 ft or less (fig. 11). The wells range in depth from 33 ft to 54 ft, except for well 15-372, which is 154 ft deep. Locations of the six wells are shown in figure 12.

Some of these fluctuations may occur because of fluctuations in precipitation during 1998–2008. A detailed analysis of withdrawals from wells near the wells shown in figure 11 and of the precipitation at the Seabrook Farms and Millville Municipal Airport weather stations (fig. 2) was not done; therefore, only general observations about the monthly precipitation and water-level fluctuations at these wells are made. Mean annual precipitation at the Seabrook Farms weather station from 1998 to 2008 was 44.4 inches per year (in/yr) and at the Millville Municipal Airport weather station, 39.1 in/yr. During 1998, precipitation recorded at the Seabrook Farms weather station was 6.6 in/yr less than the 1998–2008 average, and precipitation at the Millville Municipal Airport station was 2.5 in/yr less than the 1998–2008 average. During 2001, precipitation recorded at the Seabrook Farms weather station was 8.3 in/yr less than the 1998–2008 average, and precipitation at the Millville Municipal Airport station was 11.6 in/yr less than the 1998–2008 average. The below average precipitation in 1998 and 2001 is interpreted to be, in part, responsible for the lower water levels during these years. During August 2001–August 2002, precipitation recorded at the Seabrook Farms weather station was 9.2 in/yr less than the 1998–2008 average, and precipitation at the Millville Municipal Airport station was 6.9 in/yr less than the 1998–2008 average. The below average precipitation from August 2001 to August 2002 probably is related to the lower water levels observed during these years (fig. 10). During June 2006–June 2007, precipitation recorded at the Seabrook Farms weather station was 16.2 in/yr more than the 1998–2008 average, and precipitation at the Millville Municipal Airport station was 14.3 in/yr more than the 1998–2008 average. The above average precipitation from June 2006 to June 2007 probably is



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 9. Locations of wells with groundwater withdrawals from the Kirkwood-Cohansey aquifer system, by New Jersey Department of Environmental Protection allocation series, Cumberland County study area, New Jersey, 1997–2008. (NJDEP, New Jersey Department of Environmental Protection)



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 10. Water table for the Kirkwood-Cohansey aquifer system composited from water-level measurements in 1986, 1989, 1993, and 1995, location of wells, and difference between water levels, Cumberland County study area, New Jersey, 1995 and 2008.

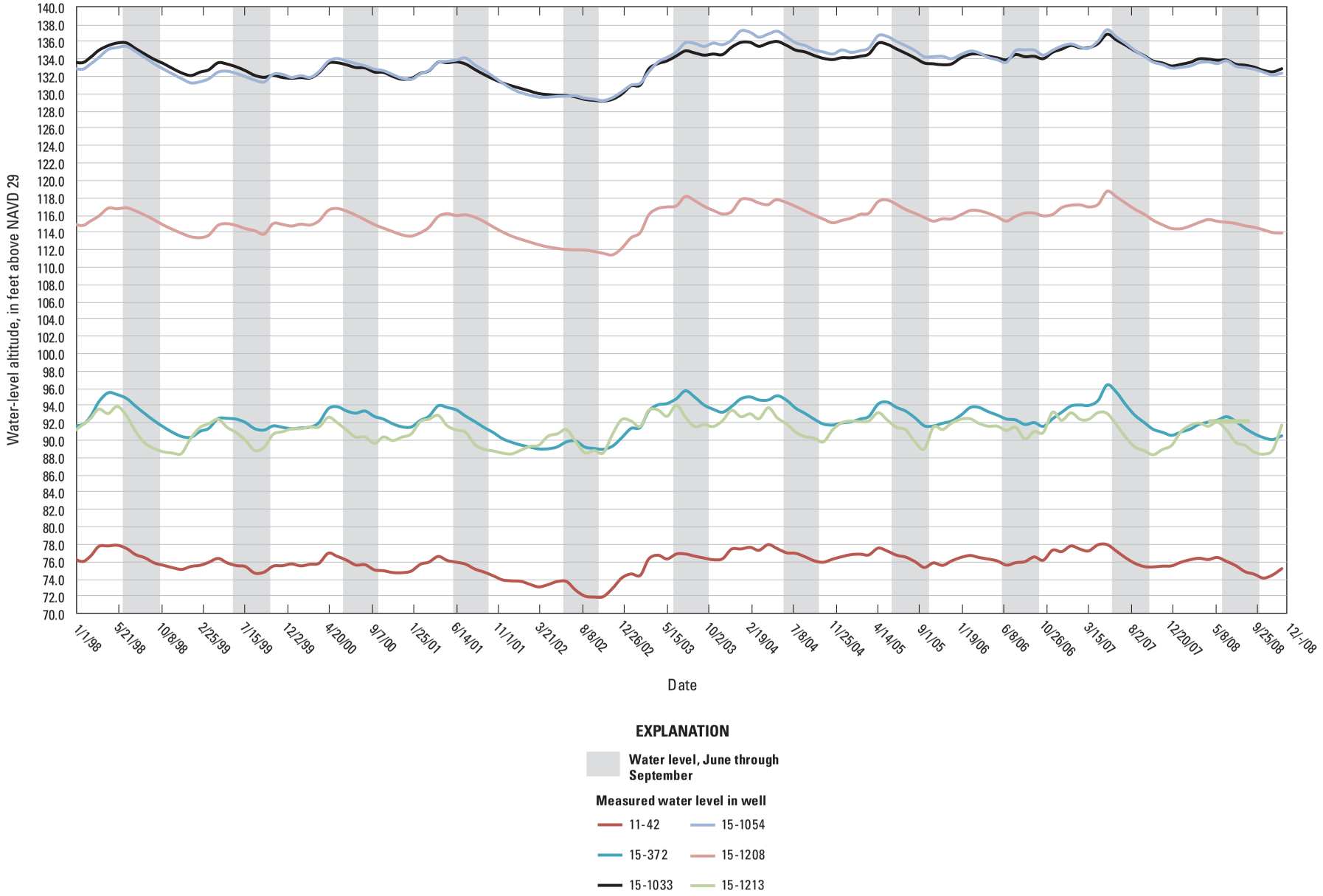
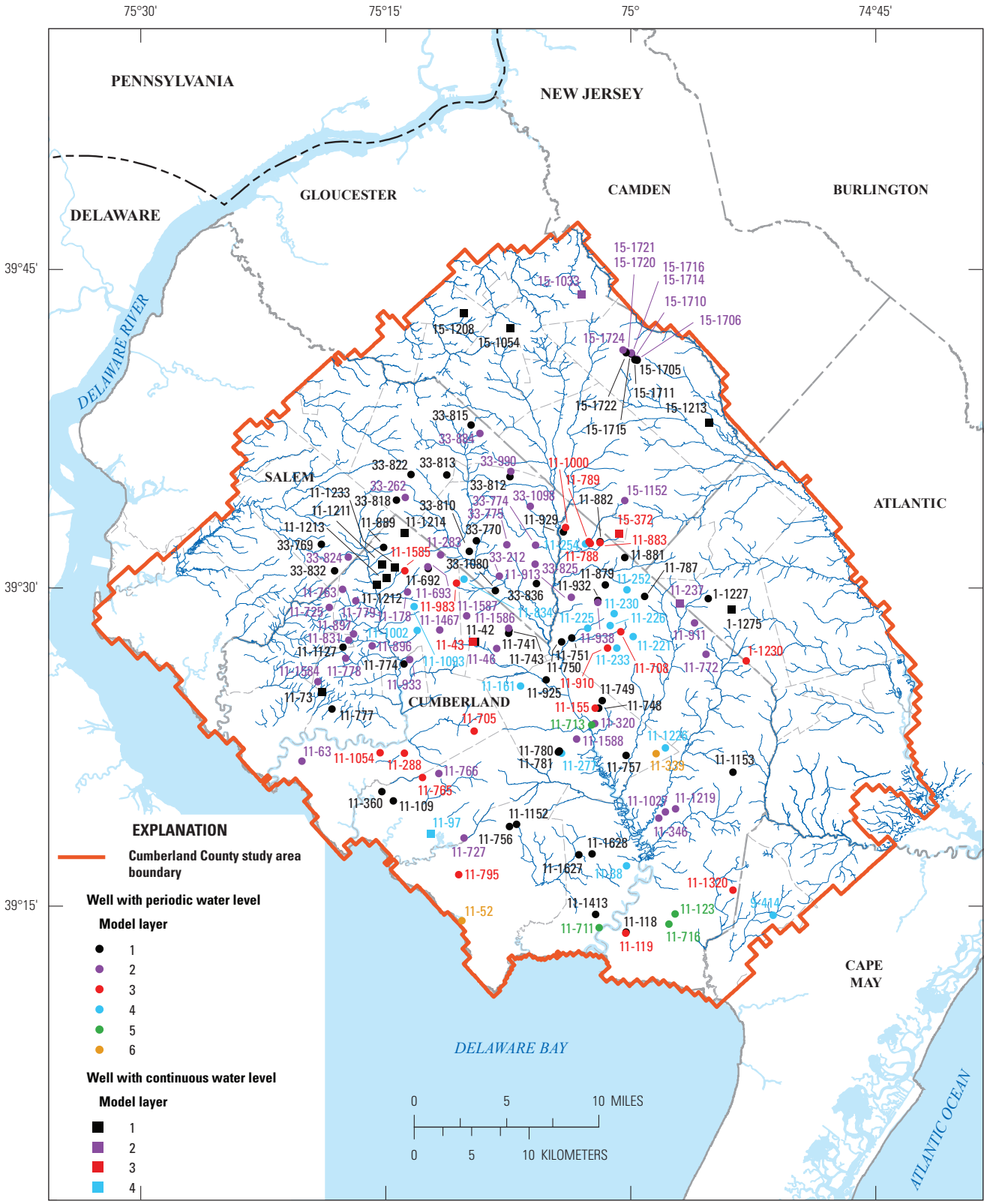


Figure 11. Hydrographs of six selected wells showing periodic water-level measurements, Cumberland County study area, New Jersey, 1998 to 2008.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 12. Locations of wells with periodic water-level measurements, Cumberland County study area, New Jersey, 1998–2008.

related to the higher water levels during these years shown in figure 11.

Rooney (1971) reports 85 percent of evapotranspiration occurs during the growing season from mid-April through mid-October. Rooney (1971) computed evapotranspiration for Shiloh Borough (fig. 2) for 1931 to 1960, using the Thornthwaite and Mather (1955) method. For most years during 1998–2008, water levels were declining during those months (fig. 11). The months from June to September are shaded in figure 11.

Simulation of Groundwater Flow in the Kirkwood-Cohansey Aquifer System

A transient numerical groundwater-flow model was developed to simulate flow in the Kirkwood-Cohansey aquifer system during 1998–2008. The model code used is the USGS modular model MODFLOW-2005 (Harbaugh, 2005). The model is calibrated to water levels and estimated base-flow data for the period 1998–2008. Hydraulic properties and recharge input into the groundwater-flow model were modified during calibration in order to obtain a good fit to the measured water levels and estimated base-flow data. The groundwater-flow model was used to evaluate changes resulting from an increase in groundwater withdrawals under various conditions. Despite the unconfined and semi-confined nature of the Kirkwood-Cohansey aquifer system, significant numerical instabilities associated with solving the nonlinear equations for the unconfined groundwater-flow system made it necessary to model the aquifer system as a specified saturated thickness (Sheets and others, 2015).

Spatial Discretization and Layering

The finite-difference model grid used to represent the Kirkwood-Cohansey aquifer system in the New Jersey Coastal Plain is shown in figure 13*A*. The model area lies almost completely within the study area and encompasses approximately 1,115 square miles (mi^2). The model area is bounded to the north by the outcrop of the Kirkwood Formation, to the west by Delaware Bay, to the east by Big Timber Creek and Great Egg Harbor River, and to the south by surface-water drainage divides. The finite-difference grid consists of 297 rows, 259 columns, and 6 layers. The model grid is aligned to the RASA model (Voronin, 2004), such that boundary conditions for the Kirkwood-Cohansey aquifer system could be easily imported. (The New Jersey RASA model is a finite-difference numerical flow model that simulates groundwater flow in the New Jersey Coastal Plain, and the Cumberland County study area groundwater-flow model nests within the RASA model). The model grid size is variable with the smallest grid spacing of 500 ft by 500 ft in the central area of the model grid, encompassing Cumberland County (fig. 13*A*). The cell size transitions to a maximum height of 3,300 ft with a varying cell width to the southern part of the study area in Atlantic and Cape May Counties and the Delaware Bay, and to a maximum width of 3,960 ft with a varying cell height in the Delaware Bay (fig. 13*A*).

Although the Kirkwood-Cohansey aquifer system is one hydrogeologic unit, dipping and thickening to the southeast in the study area, the aquifer system was separated into layers to evaluate the streams in the top layer and the effect of pumping at different depths in the aquifer system. Most pumped wells are in layers 2 to 4. For the active cells in the model, layer 1 has a thickness of greater than 16 ft to 50 ft. Layers 2, 3, and 4 have a thickness of 50 ft or less, depending on the thickness of the aquifer system in those model cells. Layer 5 has a thickness of 100 ft or less, depending on the thickness of the aquifer system in those model cells. Layer 6 has a thickness of 250 ft or less, depending on the thickness of the aquifer system in those model cells. Although many areas of local clay units are present, the aquifer system is vertically connected because an extensive confining unit is not present in most of Cumberland County. This vertical connection may not be present in the deeper part of the Kirkwood Cohansey aquifer system where it transitions to the confined Kirkwood Formation in the southeastern part of the study area, but this area has not been well defined.

Temporal Discretization

The simulation period for the model is January 1997 through December 2008, and the model has 137 stress periods. Stress period 1 is simulated as steady state to represent January to March (first quarter) conditions in 1997. Stress period 1 was repeated as a transient stress period (stress period 2). Stress periods 2–5 are quarterly 1997 transient stress periods. Stress periods 1–5 provide a reasonable transition period from initial conditions to the monthly transient period. Stress periods 6–137 are transient monthly stress periods that represent January 1998 through December 2008. In the model, distance is in units of feet, and time is in units of seconds.

Hydrologic Boundaries

The boundaries in the model represent lateral flow, recharge, surface-water features, and withdrawals. The boundary that represents the northern limit of the outcrop of the Kirkwood Formation is a no-flow boundary (fig. 13*B*). Delaware and Great Egg Harbor Bays are represented as constant heads in layer 1 with a value of 0.0 to represent sea level (fig. 13*B*). Wetland areas adjacent to Delaware Bay in layer 1 are represented by a constant-head boundary. The wetlands area was obtained from geographic information system (GIS) shapefiles from the NJDEP Office of Information Resources Management Bureau of Geographic Information Systems 2002 Land Use/Land Cover (New Jersey Department of Environmental Protection, 2007). A water level of 0.5 ft was used for

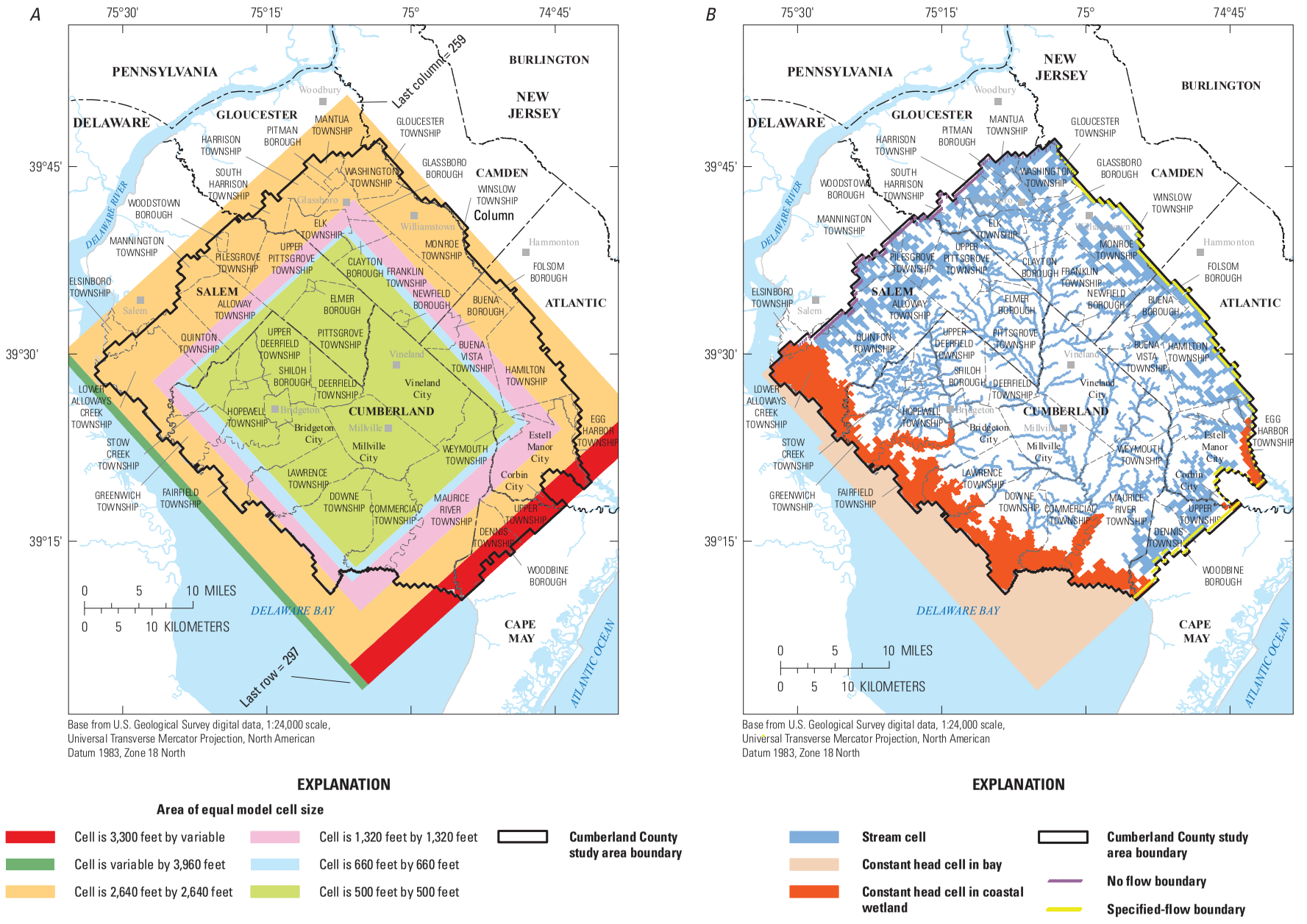


Figure 13. *A*, areas of equal cell size in the model grid and *B*, constant-head, stream, and specified-flow cells of the model for Cumberland County study area, New Jersey.

the constant heads in wetland areas, which is a value greater than that of sea level at the coastline. The wetland areas and the area of Delaware Bay constitute about 10 percent of the modeled area.

The lateral boundary that represents the connection between the Kirkwood-Cohansey aquifer system in the model and the aquifer system outside the model at the eastern boundary and the confined aquifers at the southeastern boundary in the lower layers is a specified-flow boundary using the Flow and Head Boundary package (FHB) of MODFLOW (Leake and Lilly, 1997; fig. 13*B*). The bottom boundary is also a specified-flow boundary that represents the flow from an underlying confined aquifer. The New Jersey Coastal Plain RASA model (Voronin, 2004) was used to provide the lateral and bottom boundary flows.

Monthly groundwater-withdrawal data from 1998 to 2008 were input into the model for stress periods 6–137 using the MODFLOW-2005 WEL package (Harbaugh, 2005). Quarterly withdrawal data for 1997 were input for stress periods 1–5. Monthly and quarterly withdrawal data in million gallons per month were converted to cubic feet per second (ft^3/s) for input into the groundwater-flow model.

Recharge

The Recharge package of MODFLOW-2005 (Harbaugh, 2005) was used to simulate recharge at cells in the topmost layer of the model (layer 1) that represent the outcrop area of the Kirkwood-Cohansey aquifer system in the study area. Recharge data were not input into the model cells in wetland areas or bays. Recharge for 1997–2008 was estimated using a soil-water balance equation that represents long-term precipitation minus long-term evaporation and surface-water runoff. A monthly recharge rate was calculated for January 1998–December 2008 for the model area. For 1997, the same procedure was used, but a quarterly average recharge rate was calculated and input into the model for each quarter of 1997.

The water balance method described in Nicholson and Watt (1997) is used in this study to calculate daily recharge and sum it by month. This indirect approach to recharge estimation is a common method used to account for all water that reaches the land surface as precipitation. A similar method was used to calculate monthly recharge for Ocean County, also located in the New Jersey Coastal Plain east of the study area (Cauller and others, 2016). Equation 2 was used to estimate the daily surplus precipitation (*Daily Surplus PPT*) or the amount of precipitation available for groundwater recharge.

$$Daily\ Surplus\ PPT = Daily\ PPT - Daily\ PET - Daily\ SMD\ (d-1) \quad (2)$$

where

Daily PPT is the daily value of measured precipitation, in inches;

Daily PET is the daily value of estimated potential evapotranspiration, in inches; and

Daily SMD (*d – 1*) is the daily value of soil moisture deficit from the previous day (*d – 1*), in inches.

Estimates of monthly groundwater recharge (*Monthly GW Recharge*) were derived by summing the daily surplus precipitation for each month and subtracting the monthly direct runoff for the same month (equation 3).

$$Monthly\ GW\ Recharge = Monthly\ Surplus\ PPT - Monthly\ DRO \quad (3)$$

where

Monthly Surplus PPT is the monthly total of daily values of remaining precipitation, in inches, and

Monthly DRO is the monthly total of direct runoff, in inches.

Daily precipitation data for each month from 1997 to 2008 were obtained from two weather stations located in the study area, Seabrook Farms and Millville Municipal Airport weather stations (National Oceanic and Atmospheric Administration, 2009). Supplemental data from the Glassboro, Mays Landing, and Woodstown weather stations, which are outside or near the boundary of the study area, were used when data were not available for the Seabrook Farms and Millville Municipal Airport weather stations (National Oceanic and Atmospheric Administration, 2009). All weather stations are shown in figure 2. Average annual precipitation in the study area measured at the Seabrook Farms weather station from 1997 to 2008 was 44.2 in/yr (National Oceanic and Atmospheric Administration, 2009). Average annual precipitation measured at the Millville Municipal Airport weather station from 1997 to 2008, 39.4 in/yr, was lower than that at the Seabrook Farms weather station (National Oceanic and Atmospheric Administration, 2009).

Daily evapotranspiration was interpolated from monthly mean potential evapotranspiration estimated for the Seabrook Farms and Millville Municipal Airport weather stations using the Thornthwaite method (Thornthwaite and Mather, 1957). The soil-moisture deficit was calculated using the daily potential evapotranspiration and the precipitation from the Seabrook Farms or the Millville Municipal Airport weather stations. When soil moisture is less than the maximum soil-moisture capacity, then a soil-moisture deficit exists. Recharge occurs when the deficit is alleviated. In the calculation of monthly recharge, the recharge rate could be underestimated when the sum of total monthly evapotranspiration and the soil-moisture deficit exceeds total monthly precipitation, especially during summer months. To compensate for this situation, recharge must be estimated on a daily basis to account for separate storm events that could produce high rates of infiltration that exceed the sum of evaporation and the soil-moisture deficit for that same period. An initial soil-moisture deficit of zero was assumed for January 1997, and an initial maximum daily soil-moisture deficit of 0.75 inches was assumed, which is the value used in the recharge calculation for the adjacent Great Egg Harbor River and Mullica River Basins by Pope

and others (2012). Monthly surplus precipitation values were calculated using for daily precipitation data and the daily potential evapotranspiration and soil moisture deficit (SMD) values determined for the Seabrook Farms and Millville Municipal Airport weather stations.

Daily recharge was calculated and summed for each month from January 1997 through December 2008 using equation 3 to obtain a monthly recharge value for the Cohansey and Maurice River Basins. Monthly direct runoff (DRO) was estimated for the two major drainage basins in the Cumberland County study area, the Maurice and Cohansey River Basins. Direct runoff was calculated by subtracting base flow from the total flow in the stream using the base flow generated by the PART (Rutledge, 1998) program for the Maurice River Basin and by MOVE1 (Hirsch, 1982) for the Cohansey River Basin. Monthly direct runoff was estimated for the Cohansey River at Seeley streamflow-gaging station (014128000 and for the Maurice River at Norma gaging station (01411500) (fig. 6). The Seabrook Farms weather station is located on the Cohansey River near the Cohansey River at Seeley streamflow-gaging station (fig. 2). The Millville Municipal Airport weather station is located in the Maurice River Basin downstream from the Norma streamflow-gaging station (fig. 2).

For the years 1997 through 2008, the annual recharge calculated using precipitation data from Seabrook Farms weather station in the Cohansey River Basin and direct runoff from the Cohansey River at Seeley streamflow-gaging station ranges from a low of 16.7 in/yr in 2001 to a high of 27.6 in/yr in 1999 with an average of 22.8 in/yr. For the years 1997–2008, the annual recharge calculated using precipitation data from Millville Municipal Airport weather station in the Maurice River Basin and direct runoff from the Maurice River at Norma streamflow-gaging station ranges from 11.8 in/yr in 1998 to 27.4 in/yr in 1997 with an average of 21.8 in/yr. For the years 1997–2008, the average recharge for both sites is 22.3 in/yr. For comparison, monthly groundwater recharge rates used in a groundwater-flow model of the Great Egg Harbor and Mullica River Basins, adjacent to the Cumberland County study area, ranged from 10–15 in/yr in 2001 to 20–25 in/yr in 2005.

Streams

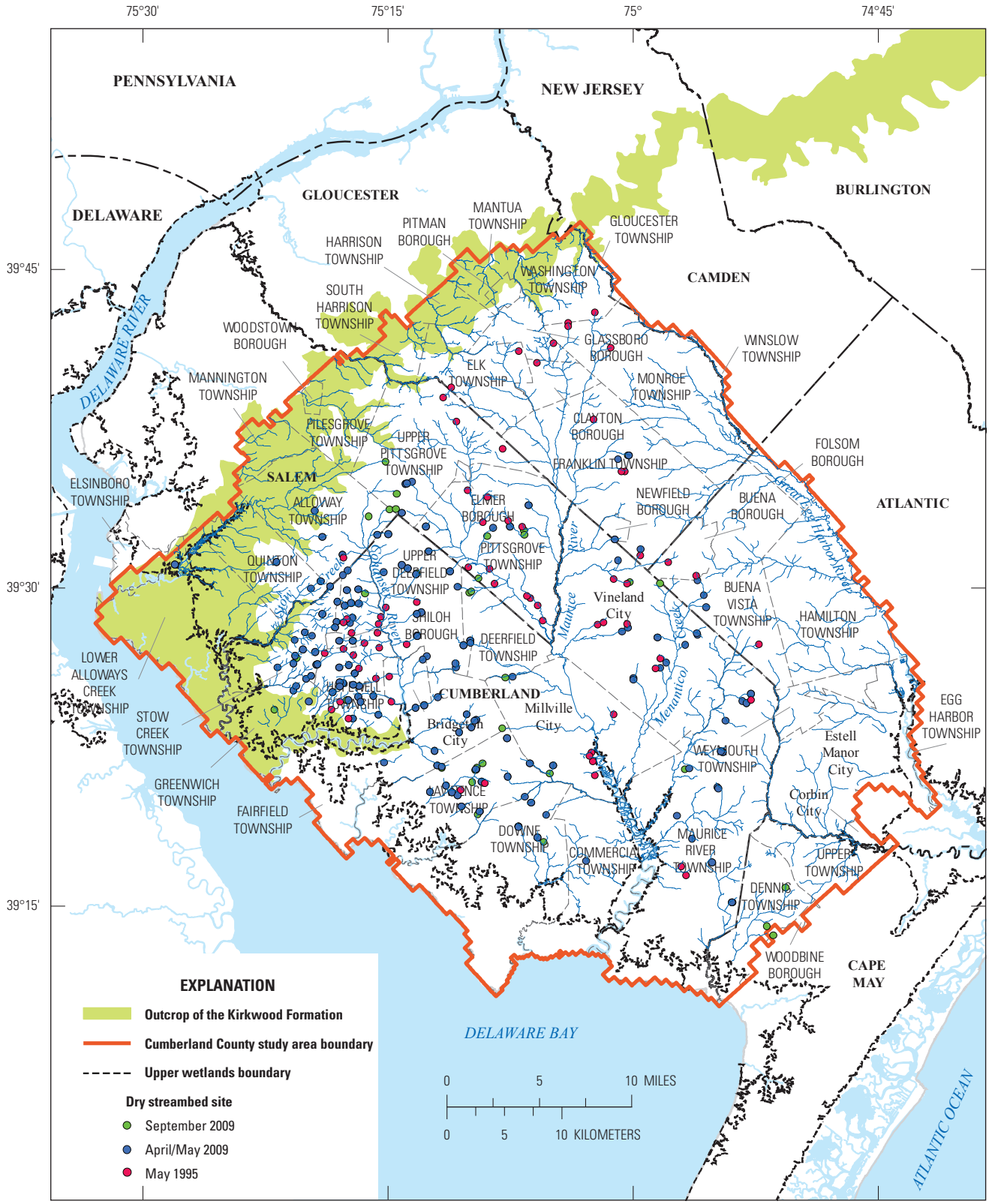
The streamflow-routing package (SFR2) (Niswonger and Prudic, 2009) was used to simulate the interaction between the aquifer and adjoining streams; SFR2 tracks the amount of water within each simulated stream. All streams were simulated in layer 1 of the model. Streams that flow through ponds and lakes that are in hydraulic connection with the aquifer were simulated with SFR2. Streams in the SFR2 package are divided into reaches and segments. A stream reach is a section of stream, and a segment is a group of streams. The model has 1,123 stream segments and 12,581 reaches. The locations of these cells are shown in figure 13.

Stream locations were obtained from the 1:24,000 National Hydrography Dataset (NHD) (U.S. Geological Survey, 2004). The model grid was overlain on the NHD geospatial dataset to identify the location of the streams on the model grid within each appropriate cell. Some smaller tributaries in the outcrop area of the Kirkwood Formation that flow to the Delaware River and some smaller tributaries along the Delaware Bay area were not modeled. The interaction between the groundwater and surface-water systems is controlled by the differences between water levels and stream elevation, or stage, and the hydraulic conductance and thickness of the streambed. The stream elevation in each cell was assigned using digital elevation maps obtained from the National Elevation Database (U.S. Geological Survey, 2006).

Stream depth was calculated using Manning's equation and assuming a rectangular channel. The average widths for the mainstem of the Cohansey and Maurice Rivers and their tributaries and the other streams in the model were retrieved from the USGS National Water Information System database. Stream-channel widths ranged from 5 ft for smaller tributaries up to 80 ft for the lower part of the mainstem of the Maurice River. Stream-channel width was 35 ft for the lower part of the Cohansey River and 50 ft for the lower part of the Great Egg Harbor River (fig. 14). Streambed thickness was set at 2 ft for the mainstem of the upper part of the Cohansey River, the lower part of the Maurice River, and the lower part of Menantico Creek (fig. 6). For all other smaller reaches, a 1-ft streambed thickness was used, except in Stow Creek Basin where a thickness of 0.5 ft was used. The initial hydraulic conductivity of the streambed sediments was 0.1 ft/d on the basis of an initial value similar to that used for a groundwater-flow model of the adjacent Great Egg Harbor River Basin of 0.2 ft/d (Pope and others, 2012).

Start of Flow

Because groundwater withdrawals or surface-water diversions and periods of no precipitation occur, the start of flow of tributaries and streams may be located farther downstream than the mapped location on the topographic maps or shown in the NHD. During April–May and September 2008, observations of start of flow in many tributaries in the study area were recorded and compared with the representation on a USGS topographic map and the NHD. These observations were indicated by following the location of the stream on a topographic map until the streambed became dry. Similar locations were identified as part of a surficial aquifer study conducted in May 1995 and used to contour the water table (Charles and others, 2001). In addition, many of the headwaters of the tributaries can be intermittent but not mapped as such. The information collected during this study and the previous study (Charles and others, 2001) was used to estimate the start of streamflow for some of the smaller streams and tributaries for the SFR2 package. Locations of the May 1995 dry streambed sites from the surficial aquifer study (Charles and others, 2001) and the April/May 2009 and September 2009 dry streambed sites from this study are shown in figure 14.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 14. Dry stream sites for start of flow analysis during May 1995, April through May 2009, and September 2009, Cumberland County study area, New Jersey.

Surface-Water Diversions and Discharges

Monthly discharges to streams (inflows) from 1998 to 2008 were estimated from New Jersey Pollutant Discharge Elimination System (NJPDES) permit data and, in the model, were input into the stream segment and reach on which that point was located. Monthly agricultural surface-water diversions (outflows) from streams from 1998 to 2008 were estimated from a USGS water-use database and input into the segment and reach on which the diversion was located. Surface-water diversions from streams and NJPDES discharges to streams for 1997 were input as estimated average quarterly values. The locations of the surface-water diversions and discharges input into the SFR2 package are shown in figure 15. If simulated streamflow in a reach was insufficient to supply the diversion rate, then the diversion was reduced to the available amount of flow. Total monthly surface-water discharges varied across the study area during the period of the simulation from a low of 7.9 ft^3/s in April 2002 to as much as 18.4 ft^3/s in June 2001. Total monthly surface-water diversions from intakes varied across the study area during the period of the simulation from 0 ft^3/s to as much as 3.5 ft^3/s in July 2007.

There are a few sand-mining operations in the southwestern part of the study area. For these operations, water is pumped to a staging area where the sand settles out, after which the water is returned to the pond. These ponds were not input into the SFR2 package because most of the water used in the mining operation is recycled, and very little is consumed.

Model Input

The Layer-Property Flow package of MODFLOW-2005 (Harbaugh, 2005) was used to input hydraulic parameter values for horizontal hydraulic conductivity, vertical hydraulic conductivity, and storage coefficient. An initial value of horizontal hydraulic conductivity was estimated from the specific-capacity and aquifer-test data. An average value of 150 ft/d was used as the initial value of horizontal hydraulic conductivity for the model. This value was about equal to the median of 147 ft/d determined from the aquifer-test and specific-capacity data. From the initial values, zones of different hydraulic conductivity were determined during the model calibration.

The flow between model cells was simulated in vertical and in horizontal components. In the study area, clay stringers and silty sediments are present locally within the Kirkwood-Cohansey aquifer system and affect the vertical and horizontal movement of groundwater. Small-scale variations in the local geologic framework cannot be represented in the model. The ratio of horizontal to vertical hydraulic conductivity between model layers controls the vertical and horizontal movement of groundwater over large zones. This ratio initially was assumed to be 10:1. Zones of different vertical hydraulic conductivity within the model layers were defined during model calibration to represent differences in the hydrogeologic framework that affect groundwater flow.

There is a lack of information to estimate aquifer storage properties in the study area. An initial storage coefficient value of 0.001 was used and was adjusted during model calibration. This value was based on published values of storage coefficients that ranged from 0.044 to 0.0001 for aquifer tests in the Kirkwood-Cohansey aquifer system near the study area (Rhodehamel, 1973; Charles and others, 2001). Zones for the storage coefficient for the model layers were determined during model calibration. To obtain a specific storage value, the storage coefficient is divided by the layer thickness.

Model Calibration

Model calibration mainly was achieved by a trial-and-error approach. Simulations using UCODE-2005 (Poeter and others, 2005), a universal parameter estimation code, yielded information for identifying sensitive and insensitive parameters during model development. Final calibration was accomplished using the UCODE-2005 parameter sensitivities and manual adjustment of those parameters. During calibration, parameters representing horizontal and vertical hydraulic conductivity, recharge, streambed hydraulic conductivity and storage were modified to best simulate measured water levels and estimated base flows.

Model calibration criteria consisted of matching (1) measured water levels to within less than 10 ft, (2) long-term water-level fluctuations, and (3) estimated base-flow fluctuations and trends. The model calibration was evaluated by comparing differences between simulated and measured or estimated values. The hydrologic parameters in the model were adjusted during model calibration to minimize the differences between simulated and measured or estimated values of (1) water levels in May and June 2008 for 84 wells and in September 2008 for 77 wells, (2) long-term water levels from 1998 to 2008 for 16 wells, and (3) long-term base flows estimated from hydrograph separation or low-flow correlation techniques for 17 streamflow-gaging stations. The wells and surface-water sites were spatially distributed throughout the model area.

Water Levels

Water levels for this study were measured during two synoptic periods—late May and early June 2008, and in September 2008. Water levels in 84 wells were measured in late May and early June, but only 77 of these wells were measured in September. The residuals (simulated minus measured water levels) and water levels for May–June and September 2008 are listed in table 5 (table 5 in back of report). For the May–June residuals, 71 percent of the simulated water levels were within 5 ft of the measured water levels, and 98 percent were within 10 ft. For the September residuals, 66 percent were within 5 ft of the measured water levels, and 91 percent were within 10 ft. Plots of measured water levels in relation to simulated water



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 15. Locations of surface-water diversions and New Jersey Pollutant Discharge Elimination System inflows to streams, Cumberland County study area, New Jersey.

levels are shown in figure 16. The plots show two symbols signifying wells that were surveyed for land-surface altitude and, therefore, have more accurate water-level altitudes and wells that were not surveyed and, therefore, have water-level altitudes that are less accurate. The mean error for the wells in figure 16 is given in table 5; it is less than 2 ft for the June 2008 residuals and less than 0.1 ft for the September 2008 residuals. Spatial clustering of water-level measurements was minimized in this model by using selected wells in such areas.

The simulated water-level contours and residuals for model layer 1 for May through June 2008 are shown in figure 17*A* and for September 2008 in figure 17*B*. The simulated water levels in layers 2–6 are very similar to those for layer 1, so only the simulated water levels in layer 1 are shown. The average residual from the water levels in layer 1 to layers 2 through 5 is 0.1 or less and in layer 6 is less than 0.2. Monthly hydrographs of water levels are plotted for 16 wells in the Kirkwood-Cohansey aquifer system (fig. 18*A*–*C*). The locations of these wells are shown in figure 12. The hydrographs indicate that the simulated water levels match the measured water levels in magnitude and seasonally. The simulated water levels were most affected by horizontal hydraulic conductivity and recharge and, in some of the deeper wells, by vertical hydraulic conductivity.

Base Flows

Groundwater discharge (base flow) is the most significant component of the flow to streams in the Cumberland County study area. Monthly base-flow estimates were used as targets for model calibration and to evaluate the effects of changes in base flow resulting from changes in groundwater withdrawals. A plot of estimated monthly base flow for January 1998–December 2008 in relation to simulated base flow is shown in figure 19. The four symbols in this figure indicate the magnitude of the base flow as (1) greater than 0 to 1 ft^3/s, (2) greater than 1 to 10 ft^3/s, (3) greater than 10 to 100 ft^3/s, and (4) greater than 100 ft^3/s to 450 ft^3/s. Streamflow-gaging stations in wetland areas were not used in the analysis. The wetland area is designated in figure 1 by showing the boundary of its upmost extent.

Simulated base flow matched estimated base flow reasonably well, although the base flows input to the groundwater-flow model are estimates obtained by using hydrograph separation and low-flow correlation techniques. The estimated base flow in the Maurice and Cohansey Rivers and some of the smaller tributaries is variable. Base-flow hydrographs for 17 streamflow-gaging stations are shown in figure 20. The locations of the stations are shown in figure 6. For some of the smaller tributaries, the simulated base flow does not achieve the variability that the estimated base flow shows, for example, simulated base flows in East and West Creeks (streamflow-gaging stations 01411442 and 01411445, respectively) in Cape May County. However, the magnitude of the estimated base flow is generally similar to the simulated base flow. The model did not reproduce some of the higher base flows; however, the trends and fluctuations in the monthly base flow were similar. Because of the variability in estimated base flow, a 3-month average was used at some streamflow-gaging stations to compare the estimated base flow to the simulated base flow to temper some of the variability (Claire Tiedeman, U.S. Geological Survey, oral commun., 2014). These stations include the Maurice River at Norma (01411500); the Tuckahoe River at Head of River (01411300); Little Ease (01411456), a tributary to the Maurice River; and the Cohansey River at Seeley (01412800), which was used as a continuous-record streamflow-gaging station starting August 2003 (fig. 6). A 3-month average was also used for the Maurice River at Millville (01411800) streamflow-gaging station downstream from the Norma station (fig. 6).

Statistics for the monthly base-flow residuals for the continuous-record streamflow-gaging and low-flow partial-record stations with base-flow hydrographs are shown in table 6. The mean error and mean absolute error shown in table 6 for the stations give an indication of the mean difference between the simulated and estimated base flows. The root mean square (RMS) error is the square root of the average of the squared differences. The larger RMS errors are associated with the large flows that occur in the larger drainage basins. The area of the drainage basins is given in table 6.

The simulated base flow for the Cohansey River at Seeley streamflow-gaging station (01412800) is lower than the estimated base flow using the PART program, and the mean error is 3.42 ft^3/s less that the estimated base flow (table 6). However, the fluctuations observed in the simulated base flow follow the fluctuations observed in the estimated base flow, and the lower estimated base flows match the simulated base flows better. The Cohansey River at Seeley station is the only continuous-record streamflow-gaging station in the Cohansey River Basin. Because the period of record for the Seeley gaging station was only 5 years, the base-flow estimates would not be considered a long-term mean base flow. The base-flow estimates for the Cohansey River at Seeley station were used as general estimates of base flow at that gaging station. The average 2004–08 base flow estimated using the PART program is 27.7 ft^3/s.

The estimated and simulated base flows and residuals for June and September 2008 are listed in table 7 for 17 streamflow-gaging stations. Base-flow hydrographs were most affected by recharge and streambed conductivity but also by the horizontal hydraulic conductivity in some areas.

Model Parameters

The Kirkwood-Cohansey aquifer system is represented in all model layers. Different zones of horizontal and vertical hydraulic conductivity and storage were established, differentiating the properties of the aquifer system in each of the six model layers. Final parameter values used in the calibrated model are shown in table 8. Horizontal hydraulic conductivity for the six layers ranged from 40 to 160 ft/d. Zones for the horizontal hydraulic conductivity are shown in figure 21*A*–*B*

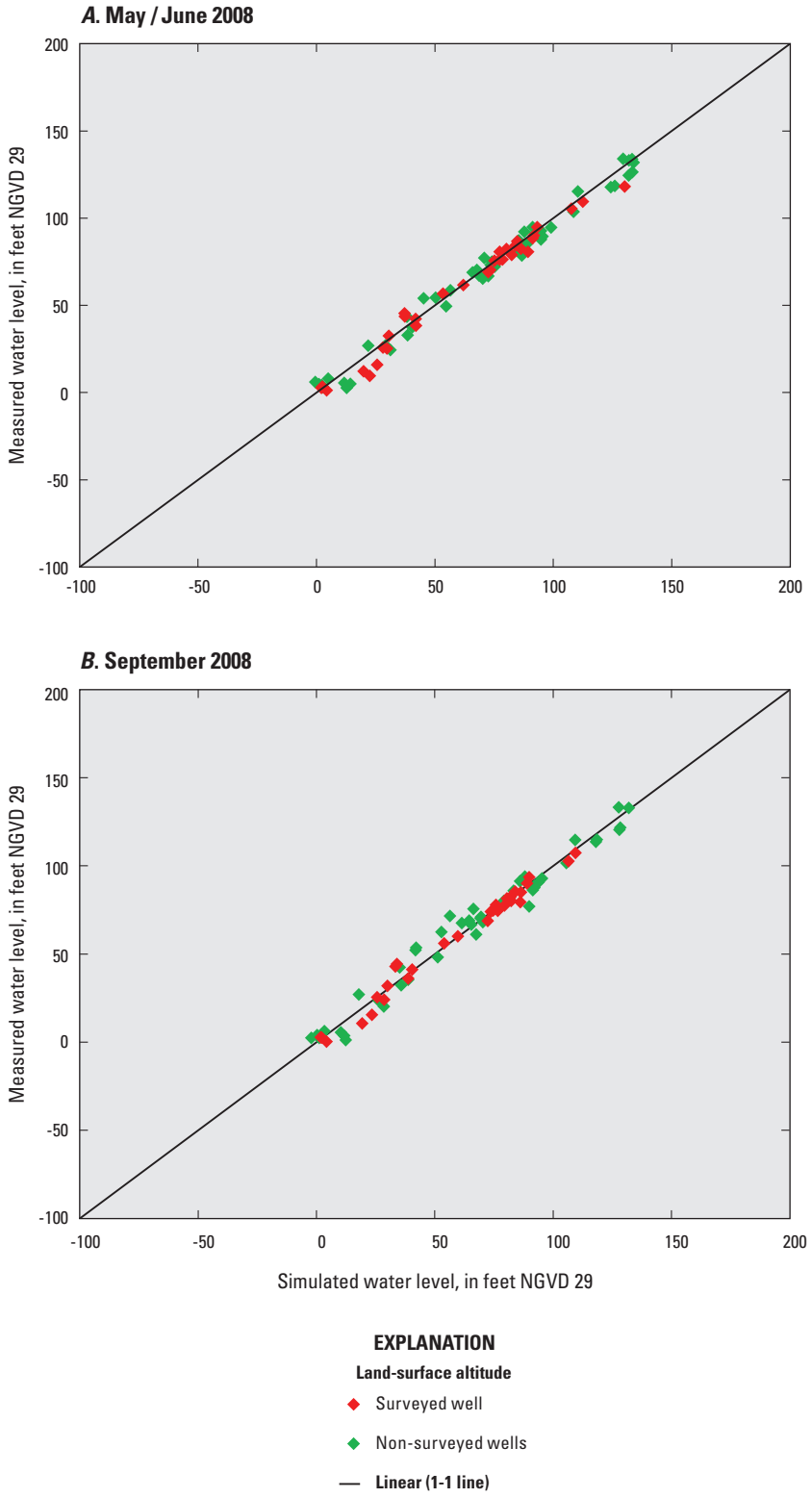
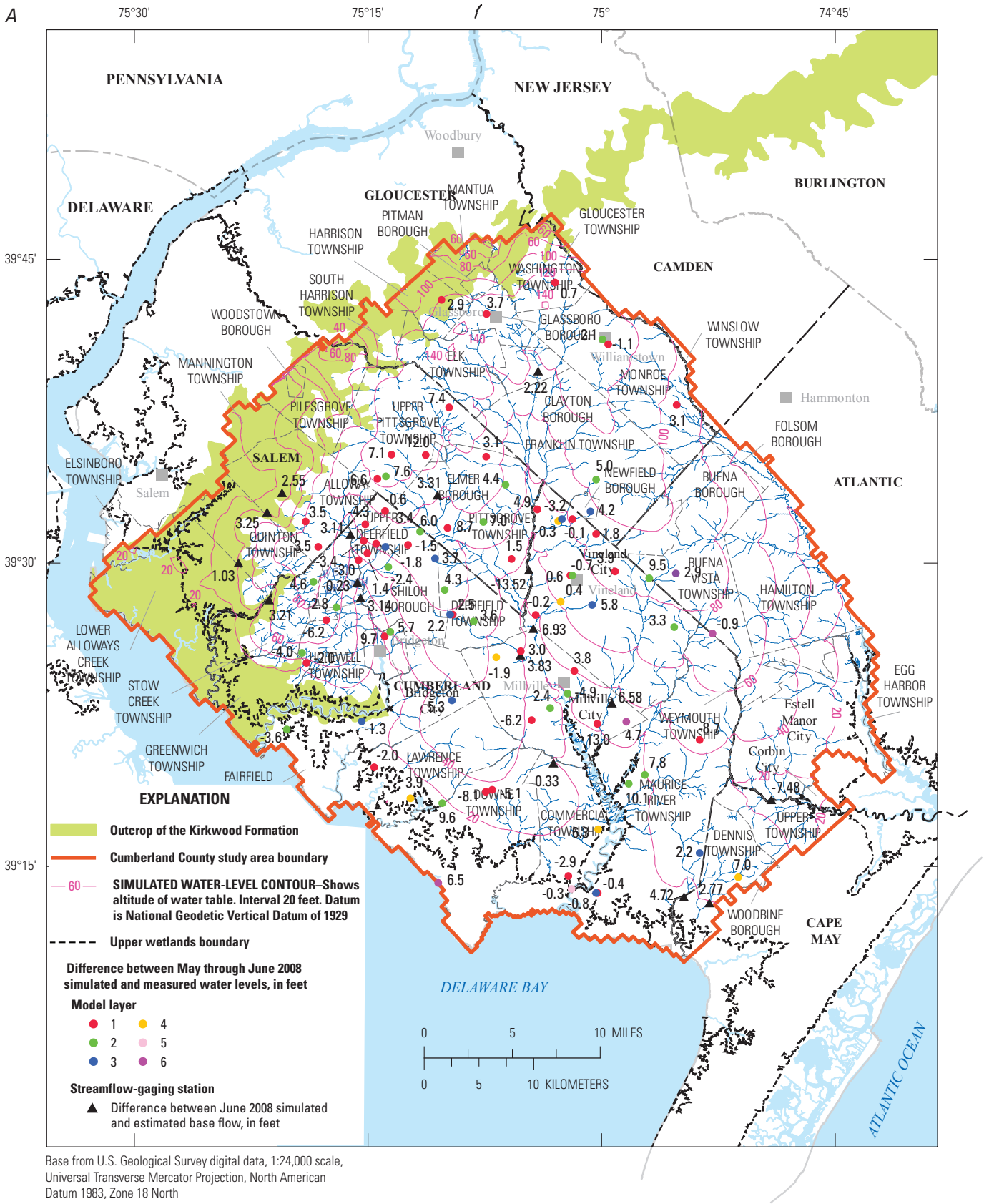
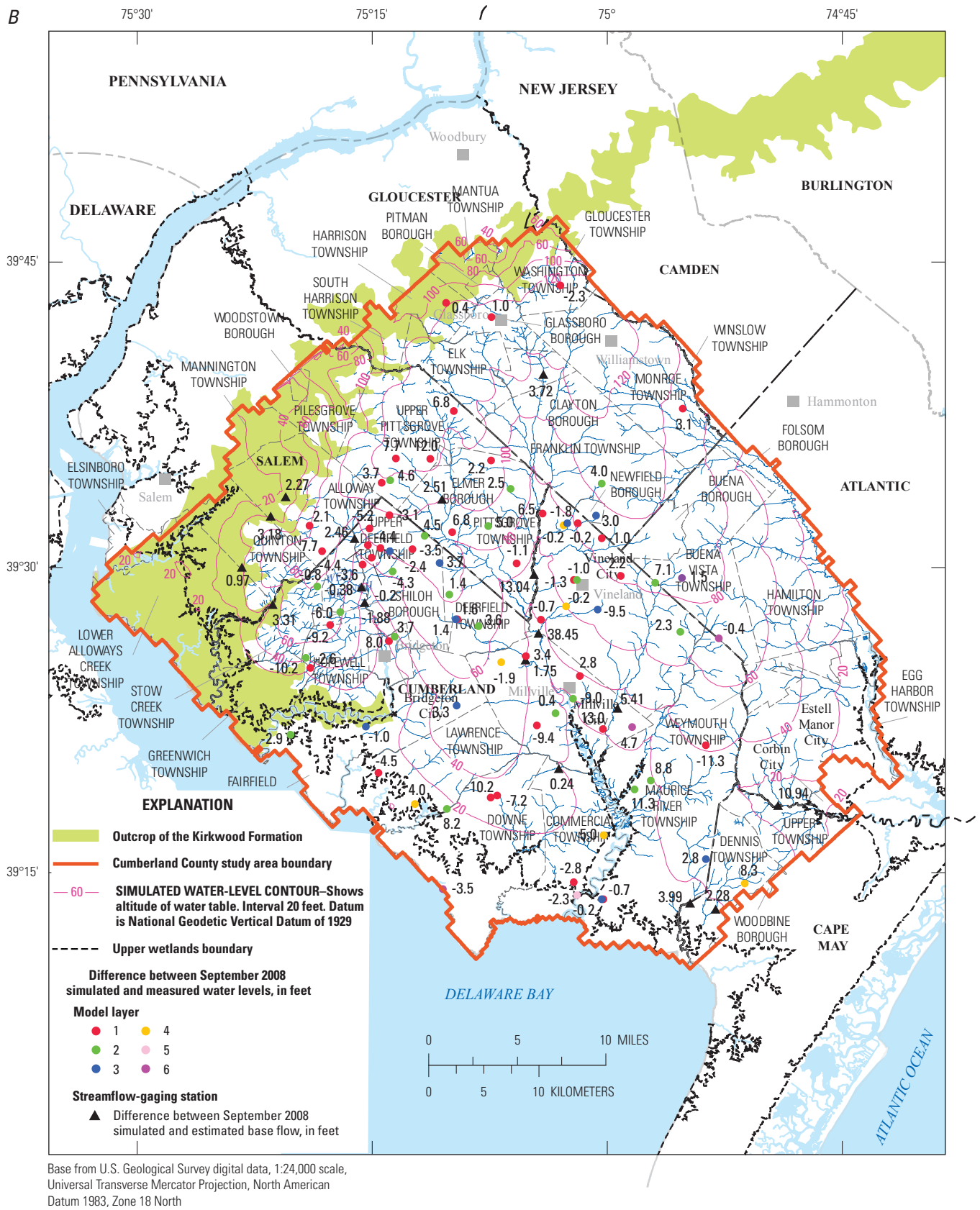


Figure 16. Simulated groundwater levels in relation to measured groundwater levels in *A*, May through June and *B*, September 2008, Cumberland County study area, New Jersey.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 17. Simulated water-level contours for the Kirkwood-Cohansey aquifer system, differences between simulated and measured water levels, and differences between simulated and estimated base flows for *A*, June and *B*, September 2008, Cumberland County study area, New Jersey.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 17. Simulated water-level contours for the Kirkwood-Cohansey aquifer system, differences between simulated and measured water levels, and differences between simulated and estimated base flows for *A*, June and *B*, September 2008, Cumberland County study area, New Jersey.—Continued

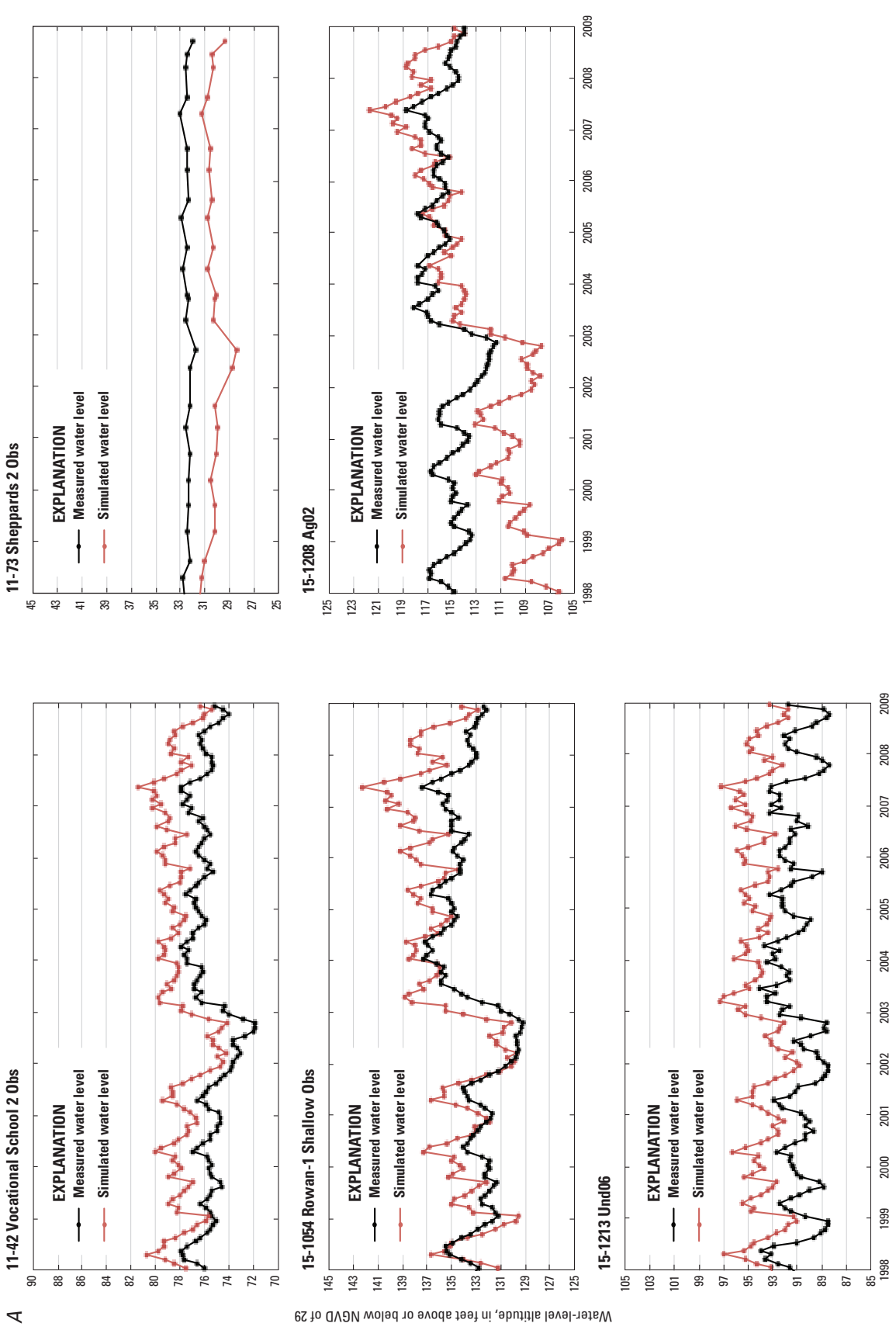


Figure 18. Hydrographs of simulated and measured water levels in selected wells in *A* and *B*, model layer 1 and *C*, model layers 2, 3, or 4, of the groundwater-flow model of the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.

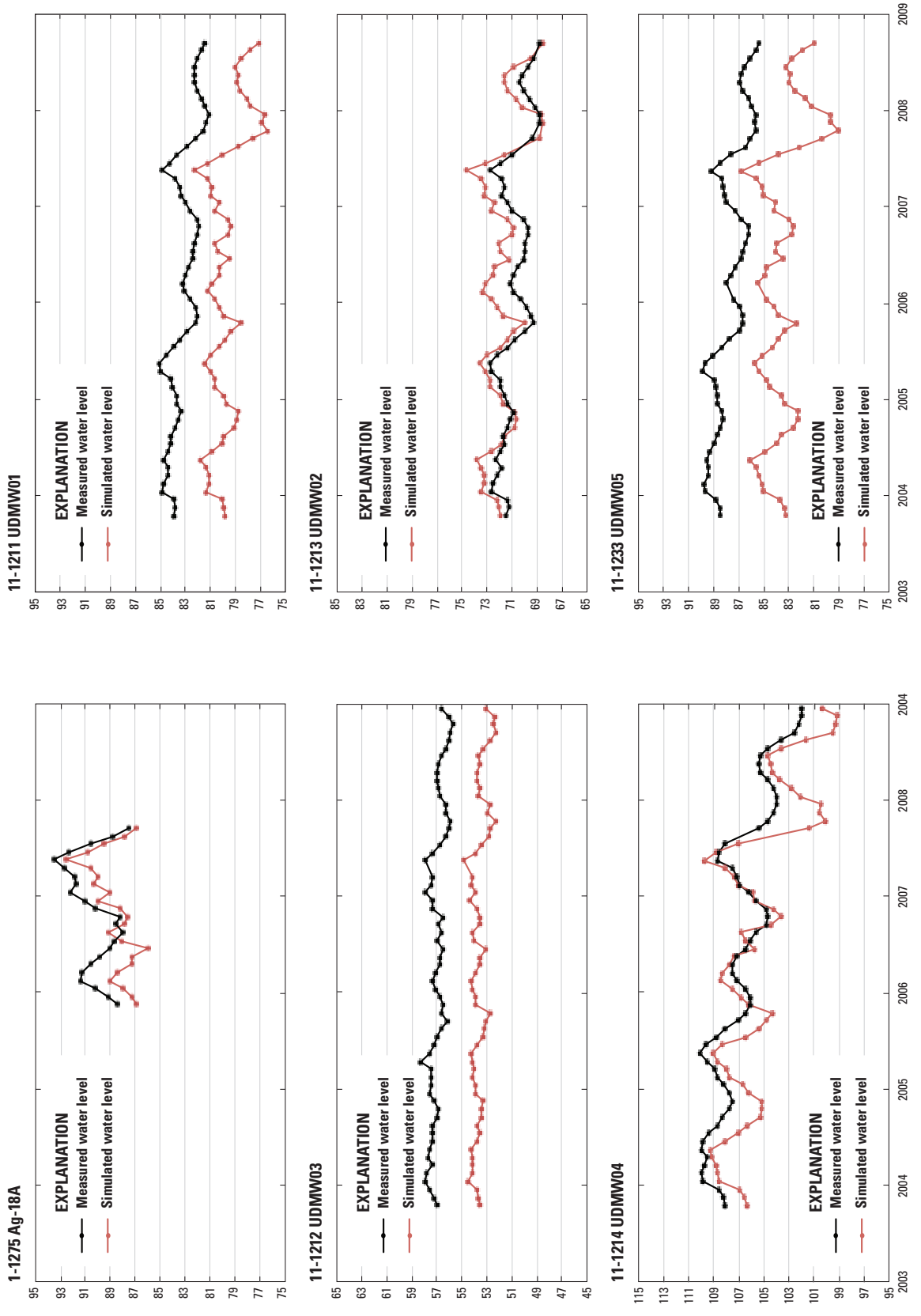


Figure 18. Hydrographs of simulated and measured water levels in selected wells in *A* and *B*, model layer 1 and *C*, model layers 2, 3, or 4, of the groundwater-flow model of the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.—Continued

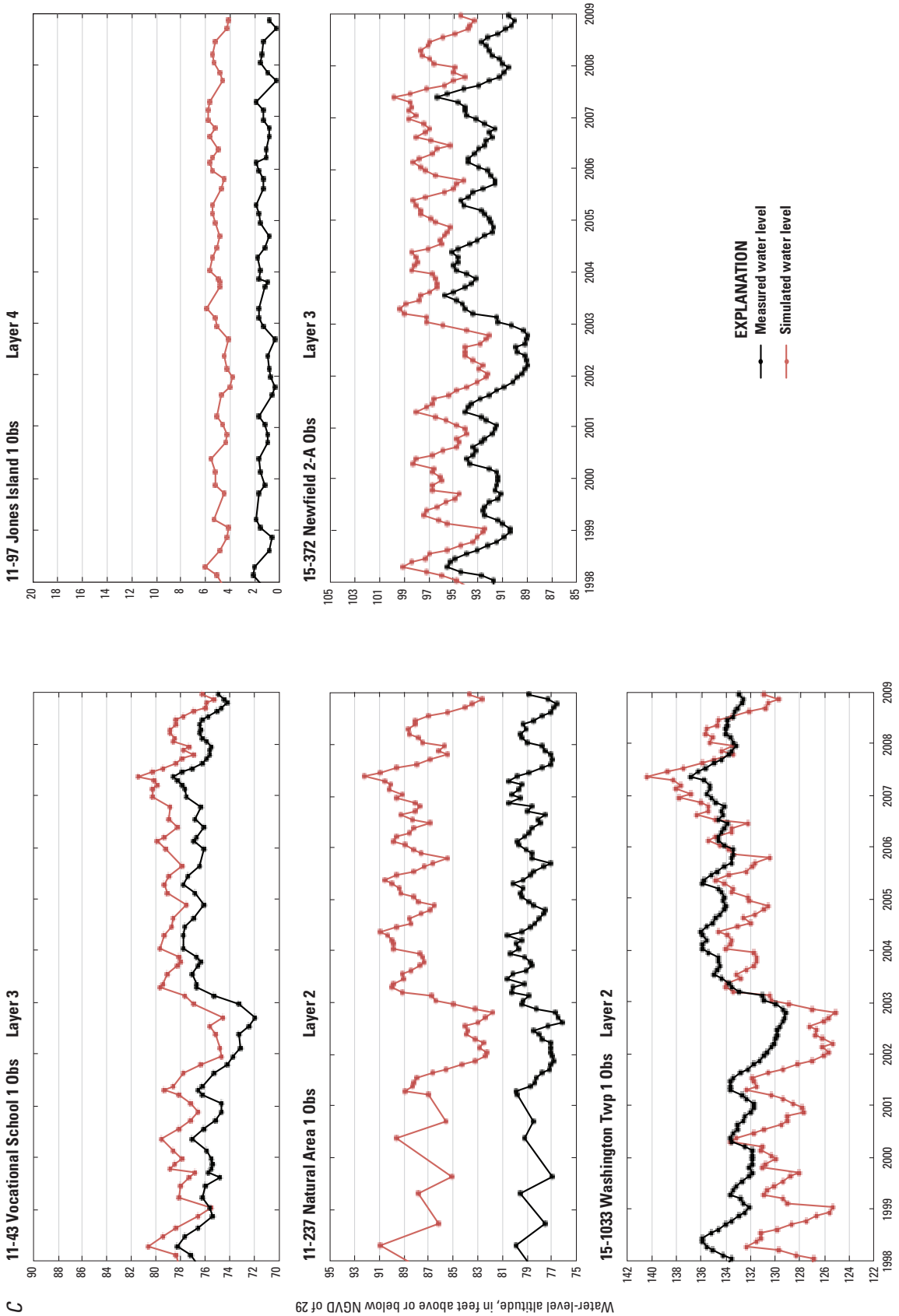


Figure 18. Hydrographs of simulated and measured water levels in selected wells in *A* and *B*, model layer 1 and *C*, model layers 2, 3, or 4, of the groundwater-flow model of the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.—Continued

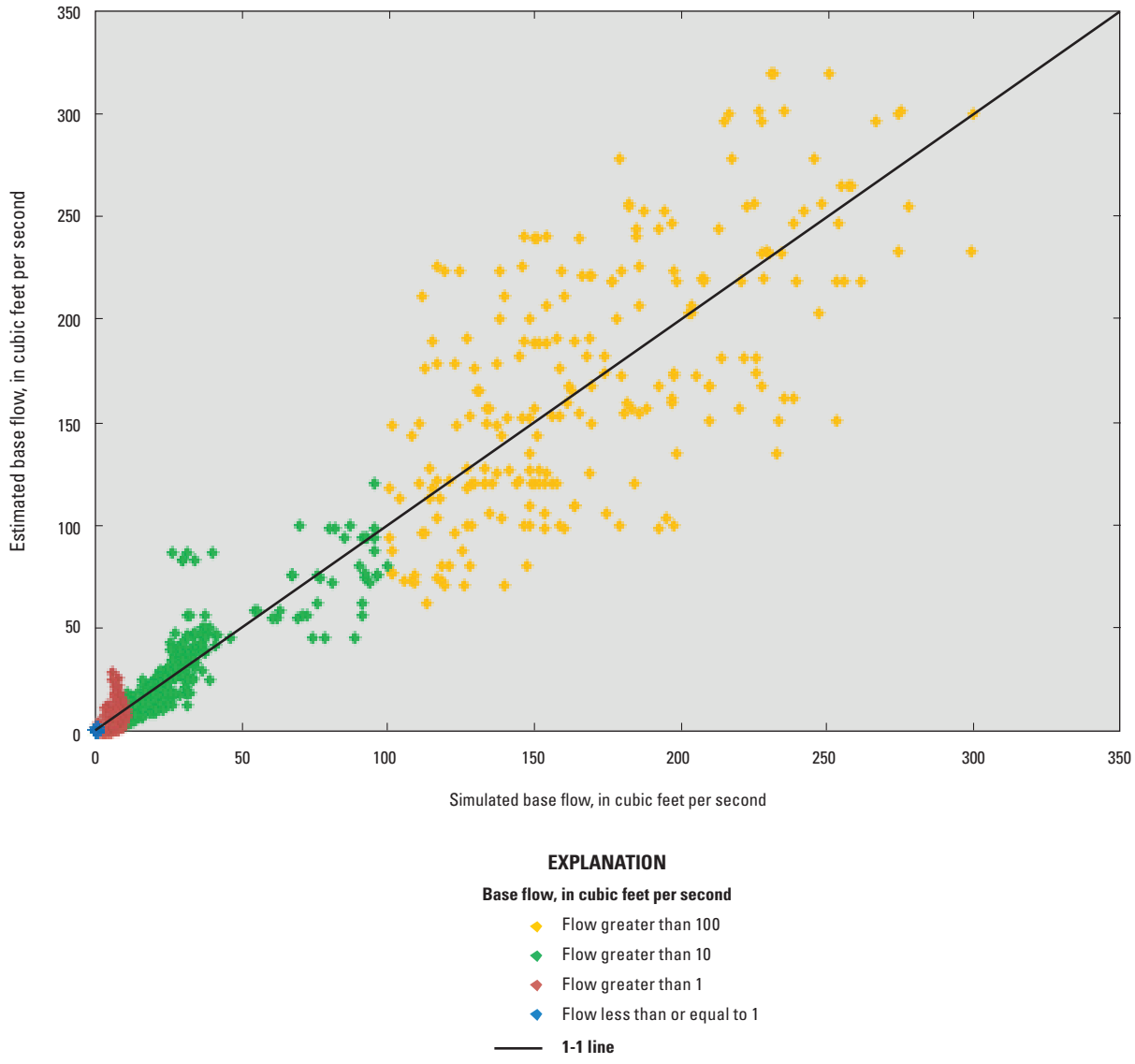


Figure 19. Simulated base flow in relation to estimated base flow at low-flow partial-record stations and continuous-record streamflow-gaging stations, Cumberland County study area, New Jersey.

for model layers 1 and 2 and in figure 22*A–D* for model layers 3 through 6. The horizontal hydraulic conductivity for the zones in layers 1 and 2 ranged from 40 to 83 ft/d, in layers 3 and 4 from 40 to 100 ft/d, and in layers 5 and 6 from 40 to 160 ft/d.

The vertical hydraulic conductivity allows for vertical connection between the model layers. The calibrated vertical hydraulic conductivity for the zones associated with layers 1–6 range from 1 x 10^{-1} to 3.11 ft/d. Zones of vertical hydraulic conductivity between layers 1 and 2 are shown in figure 23 and between layers 3 and 4 in figure 24. The vertical hydraulic conductivity for layers 5 and 6 was not zoned, but was given one value (0.95 ft/d).

Simulation results were sensitive to storage properties in parts of the model, and adjustments were made to the three zones of storage coefficients for layers 1 and 2 on the basis of the response and fluctuations in water levels and streamflow. Storage coefficients for layers 1 and 2 ranged from 4.4 x 10^{-1} to 6.4 x 10^{-1}. Zones in layer 1 and 2 for the storage coefficients are shown in figure 25. A uniform storage coefficient of 5.0 x 10^{-4} was specified for layers 3 and 4, and a uniform storage coefficient of 5.7 x 10^{-3} was specified for layers 5 and 6. The storage coefficient values for layer 1 are less than typical specific yields.

The streams were initially grouped by Hydrologic Unit Code 11 (HUC11) drainage basins but were modified during model calibration to achieve a good fit for estimated

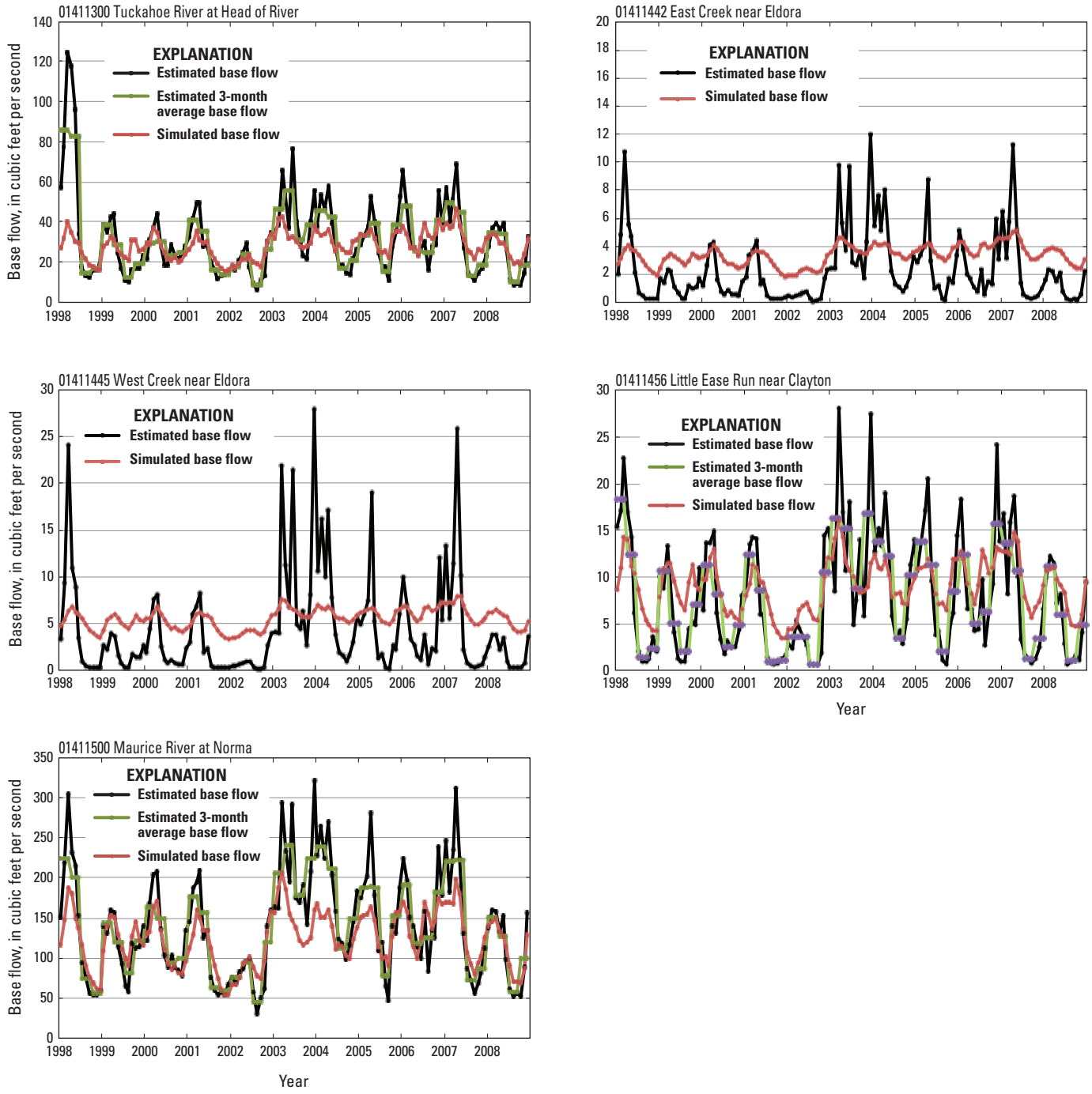


Figure 20. Hydrographs of simulated and estimated base flows at continuous-record and low-flow partial-record streamflow-gaging stations used in model calibration, Cumberland County study area, New Jersey.

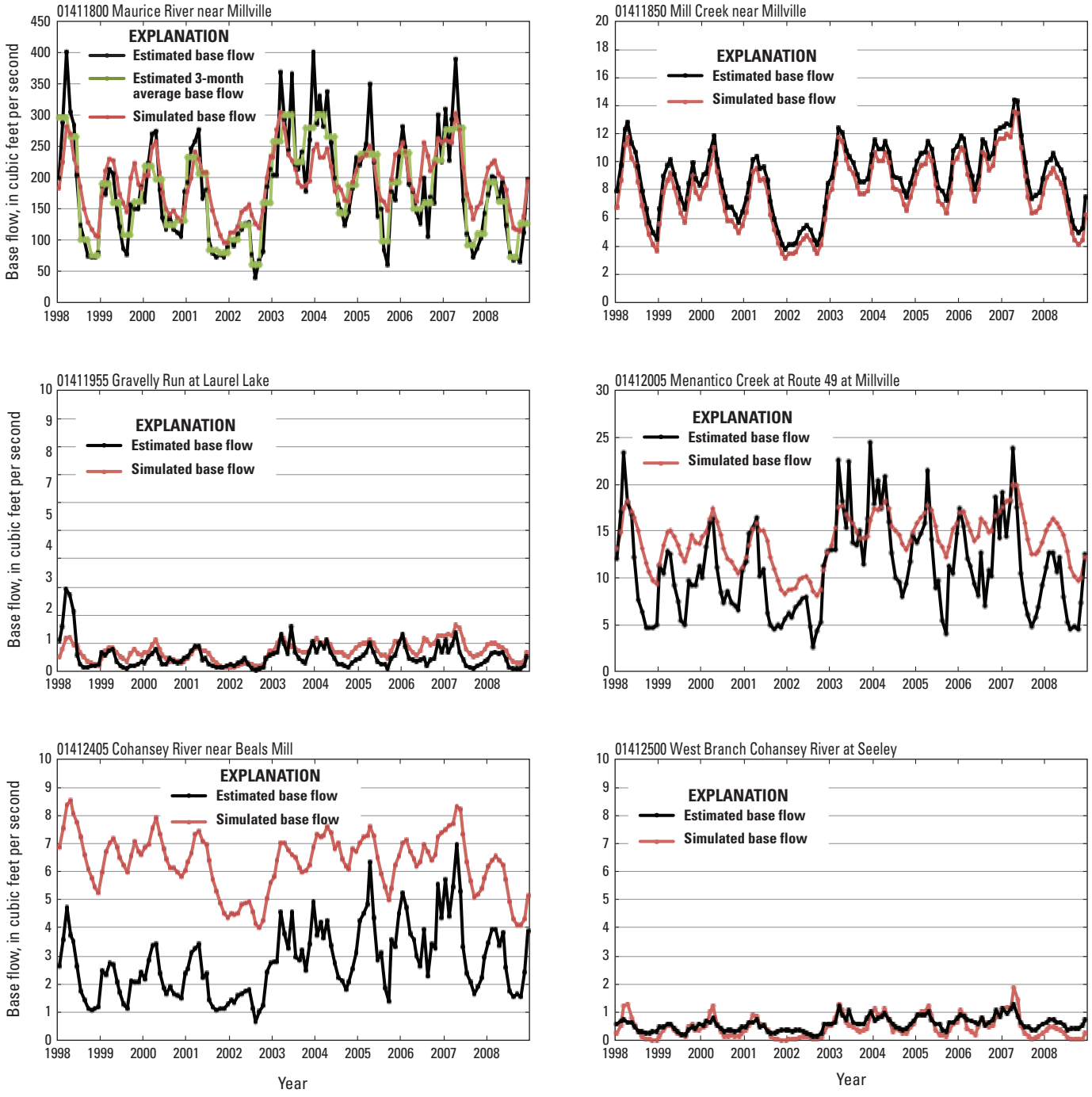


Figure 20. Hydrographs of simulated and estimated base flows at continuous-record and low-flow partial-record streamflow-gaging stations used in model calibration, Cumberland County study area, New Jersey.—Continued

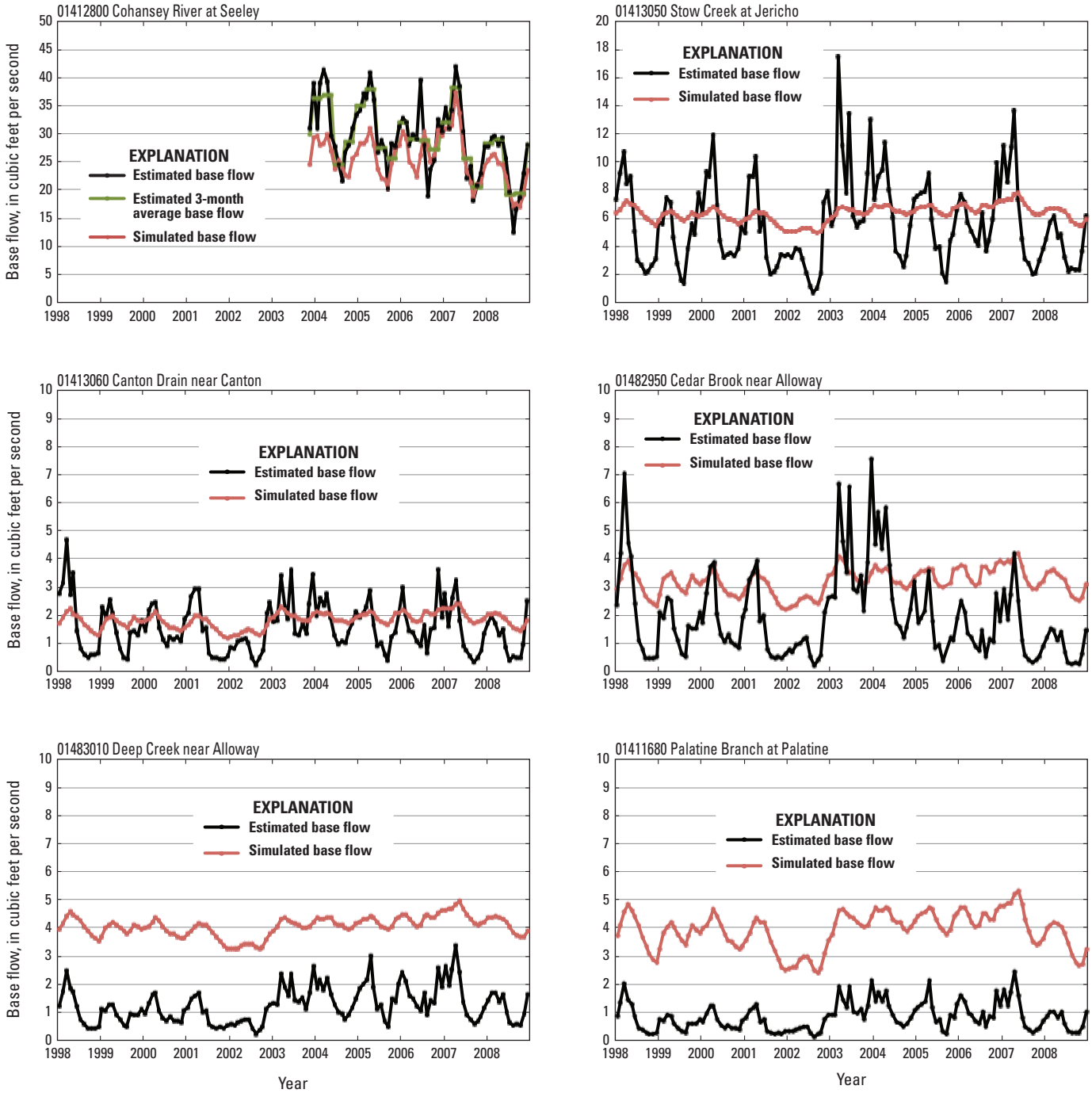


Figure 20. Hydrographs of simulated and estimated base flows at continuous-record and low-flow partial-record streamflow-gaging stations used in model calibration, Cumberland County study area, New Jersey.—Continued

Table 6. Statistics for base-flow residuals at streamflow-gaging stations, Cumberland County study area, New Jersey.

[ft^3/s, cubic foot per second; Type: C, continuous-record streamflow-gaging station; LF, low-flow partial-record station; RMS, Root mean square error]

Station number	Station name	Type	Drainage area, in (square miles)	Mean error (ft^3/s)	Mean absolute error (ft^3/s)	RMS (ft^3/s)
01411300	Tuckahoe River at Head of River NJ	C	30.8	-2.94	9.15	1.63
01411442	East Creek near Eldora, NJ	LF	8.1	1.06	1.96	1.15
01411445	West Creek near Eldora, NJ	LF	11.9	1.26	3.92	1.37
01411456	Little Ease Run near Clayton, NJ	C	9.77	1.06	3.06	1.28
01411500	Maurice River at Norma, NJ	C	112	-15.86	29.63	2.21
01411680	Palatine Branch at Palatine, NJ	LF	5.39	3.12	3.12	1.33
01411800	Maurice River near Millville, NJ	LF	191	14.09	38.81	2.40
01411850	Mill Creek near Millville, NJ	LF	15.1	1.62	2.33	1.19
01411955	Gravelly Run at Laurel Lake, NJ	LF	3.19	0.18	0.31	0.71
01412005	Menantico Creek at Route 49 at Millville, NJ	LF	26.3	2.92	3.71	1.34
01412405	Cohansey River near Beals Mill, NJ	LF	9.44	3.52	3.52	1.36
01412500	West Branch Cohansey River at Seeley, NJ	LF	2.58	-0.10	0.20	0.65
01412800	Cohansey River at Seeley, NJ	LF	28	-3.42	3.85	1.35
01413050	Stow Creek at Jericho, NJ	LF	8.07	0.74	2.35	1.20
01413060	Canton Drain near Canton, NJ	LF	2.5	0.26	0.66	0.88
01482950	Cedar Brook near Alloway, NJ	LF	3.76	1.27	1.62	1.11
01483010	Deep Run near Alloway, NJ	LF	5.3	2.84	2.84	1.30
Average				0.68	6.53	1.32

Table 7. Estimated and simulated base flow at streamflow-gaging stations for June and September 2008, Cumberland County study area, New Jersey.

[ft^3/s, cubic foot per second]

Station number	Station name	Drainage area, in square miles	Estimated[1] base flow June 2008 (ft^3/s)	Simulated base flow June 2008 (ft^3/s)	Residual June 2008 (ft^3/s)	Estimated[1] base flow September 2008 (ft^3/s)	Simulated base flow September 2008 (ft^3/s)	Residual September 2008 (ft^3/s)
01411300	Tuckahoe River at Head of River, NJ[2]	30.80	34.25	26.77	-7.48	9.72	20.66	10.94
01411442	East Creek near Eldora, NJ	8.10	0.70	3.47	2.77	0.19	2.47	2.28
01411445	West Creek near Eldora, NJ	11.90	0.92	5.64	4.72	0.19	4.18	3.99
01411456	Little Ease Run near Clayton, NJ[2]	9.77	5.98	8.20	2.22	0.95	4.67	3.72
01411500	Maurice River at Norma, NJ[2]	112.00	127.79	114.27	-13.52	56.63	69.67	13.04
01411680	Palatine Branch at Palatine, NJ	5.39	0.55	3.86	3.31	0.27	2.78	2.51
01411800	Maurice River near Millville, NJ[2]	191.00	173.03	179.96	6.93	80.10	118.55	38.45
01411850	Mill Creek near Millville, NJ	15.10	3.96	7.79	3.83	2.58	4.33	1.75
01411955	Gravelly Run at Laurel Lake, NJ	3.19	0.42	0.75	0.33	0.11	0.35	0.24
01412005	Menantico Creek at Route 49 at Millville, NJ	26.30	8.02	14.60	6.58	4.80	10.21	5.41
01412405	Cohansey River near Beals Mill, NJ[2]	9.44	2.61	5.72	3.11	1.65	4.11	2.46
01412500	West Branch Cohansey River at Seeley, NJ	2.58	0.50	0.27	-0.23	0.39	0.01	-0.38
01412800	Cohansey River at Seeley, NJ	28.00	19.22	22.36	3.14	19.45	17.57	-1.88
01413050	Stow Creek at Jericho, NJ	8.07	3.29	6.50	3.21	2.35	5.66	3.31
01413060	Canton Drain near Canton, NJ	2.50	0.87	1.90	1.03	0.54	1.51	0.97
01482950	Cedar Brook near Alloway, NJ	3.76	0.70	3.25	2.55	0.30	2.57	2.27
01483010	Deep Run near Alloway, NJ	5.30	0.99	4.24	3.25	0.56	3.74	3.18

[1]Base flow estimates for streamflow-gaging stations are from the hydrograph separation program, PART, and for low-flow partial-record stations are from low-flow correlations using MOVE1.

[2]Estimated base flows are based on a 3-month average.

Table 8. Description of parameters for the calibrated numerical groundwater-flow model, Cumberland County study area, New Jersey.

Parameter	Zone name	Generalized zone location	Value	Unit	Reference figure for zone location	Model layer	Composite scaled sensitivity
Horizontal hydraulic conductivity	KCOH1	Cohansey River Basin	55	feet/day	21A	1	1.04
	KCOH2	Cohansey River Basin	48	feet/day	21B	2	0.56
	KCOH3	Cohansey River Basin	55	feet/day	22A	3	0.23
	KMAU1	Maurice River Basin	55	feet/day	21A	1	1.67
	KMAU2	Maurice River Basin	40	feet/day	21B	2	0.51
	KEGG1	Great Egg Harbor River Basin	56	feet/day	21A	1	0.35
	KEGG2	Great Egg Harbor River Basin	90	feet/day	21B and 22A	2	0.43
	KEGG4	Great Egg Harbor River Basin	100	feet/day	22B	3-4	0.17
	KEGG5	Great Egg Harbor River Basin	40	feet/day	21C and D	5-6	0.21
	KOC1	Kirkwood Formation outcrop	83	feet/day	21A and B	1	0.22
	KBTWN1	Cohansey and Maurice River Basins	65	feet/day	21A	1	0.70
	KBTWN2	Cohansey and Maurice River Basins	60	feet/day	21B	2	0.58
	KMAU3	Maurice River Basin	89	feet/day	22A	3	0.80
	KMAU4	Maurice River Basin	40	feet/day	22B	4	0.32
	KMAU5	Maurice River Basin	160	feet/day	22C	5	1.03
	KMAU6	Maurice River Basin	40	feet/day	22D	6	0.23
	KBAY1	Delaware Bay	60	feet/day	21A, B, and 22A	1-3	0.00
	KBAY5	Delaware Bay	70	feet/day	22B, C, and D	5-6	0.00
Vertical hydraulic conductivity	VKA1	Cohansey River Basin	2.85	feet/day	23A	1	0.02
	VKA12	Cohansey River Basin	3.11	feet/day	23B	2	0.02
	VKA2	Maurice and Great Egg Harbor River Basins	0.99	feet/day	23A	1	0.09
	VKA22	Maurice and Great Egg Harbor River Basins	0.29	feet/day	23B	2	0.33
	VKA4	Model layers 3 and 4	0.52	feet/day	24	3-4	0.16
	VKA5	Delaware Bay tidal	0.10	feet/day	24	3-4	0.22
	VKA56	Model layers 5 and 6	0.95	feet/day	Not shown in a figure	5-6	0.04

Table 8. Description of parameters for the calibrated numerical groundwater-flow model, Cumberland County study area, New Jersey. —Continued

Parameter	Zone name	Generalized zone location	Value	Unit	Reference figure for zone location	Model layer	Composite scaled sensitivity
Streambed hydraulic conductivity	ALLW	Alloway Creek	0.25	feet/day	26	1	0.44
	LwSAL	Lower Salem River	0.27	feet/day	26	1	0.00
	OLD	Oldman Creek	0.83	feet/day	26	1	0.09
	RAC	Raccoon Creek	0.13	feet/day	26	1	1.49
	STO	Stow Creek	0.02	feet/day	26	1	0.50
	UpSAL	Upper Salem River	0.32	feet/day	26	1	0.15
	WOOD	Big Timber Creek	0.53	feet/day	26	1	0.46
	LwCoh	Lower Cohansey River	1.04	feet/day	26	1	0.46
	UpCoh	Upper Cohansey River	14.34	feet/day	26	1	0.10
	LE	Little Ease Run	2.16	feet/day	26	1	0.80
	LwMau	Lower Maurice River	0.21	feet/day	26	1	0.10
	MANA	Manamuskin River	0.78	feet/day	26	1	0.32
	MANT	Mantua Creek	0.25	feet/day	26	1	1.31
	Md1Mau	Middle Maurice River	1.47	feet/day	26	1	0.42
	Md2Mau	Middle Maurice River	8.38	feet/day	26	1	0.06
	MEN	Menantico Creek	0.26	feet/day	26	1	1.00
	MUD	Muddy Run	0.34	feet/day	26	1	0.98
	SCOT	Scotland Run	0.80	feet/day	26	1	0.66
	UpMAU	Upper Maurice River	10.36	feet/day	26	1	0.26
	CDR	Cedar Creek	0.04	feet/day	26	1	0.03
	DIV	Dividing Creek	$2.0x10^{-4}$	feet/day	26	1	0.00
	WES	West Creek	0.25	feet/day	26	1	0.50
	LwGEH	Lower Great Egg Harbor River	1.81	feet/day	26	1	0.05
	MdGEH	Middle Great Egg Harbor RIver	0.69	feet/day	26	1	0.54
	UpGEH	Upper Great Egg Harbor River	0.69	feet/day	26	1	0.27
	TUC	Tuckahoe River	10.36	feet/day	26	1	0.07
Recharge multiplication factor	RECH1	Western Kirkwood Formation outcrop	0.11	dimensionless	27	1	0.12
	RECH2	Cohansey River Basin	1.30	dimensionless	27	1	13.14
	RECH3	Maurice River Basin	1.40	dimensionless	27	1	14.63
	RECH4	Great Egg Harbor Basin	1.45	dimensionless	27	1	12.19
	RECH5	Stow Creek Basin	1.43	dimensionless	27	1	0.85
	RECH6	Eastern Kirkwood Formation Outcrop	0.76	dimensionless	27	1	2.34
Storage coefficient	SS1	Cohansey River Basin	0.0460	dimensionless	25	1-2	3.78
	SS2	Maurice and Great Egg Harbor River Basins	0.0440	dimensionless	25	1-2	0.50
	SS3	Model layers 3 and 4	0.0005	dimensionless	Not shown in a figure	3-4	0.22
	SS4	Southeast area	0.0640	dimensionless	25	1-2	0.22
	SS5	Model layers 5 and 6	0.0057	dimensionless	Not shown in a figure	5-6	0.00

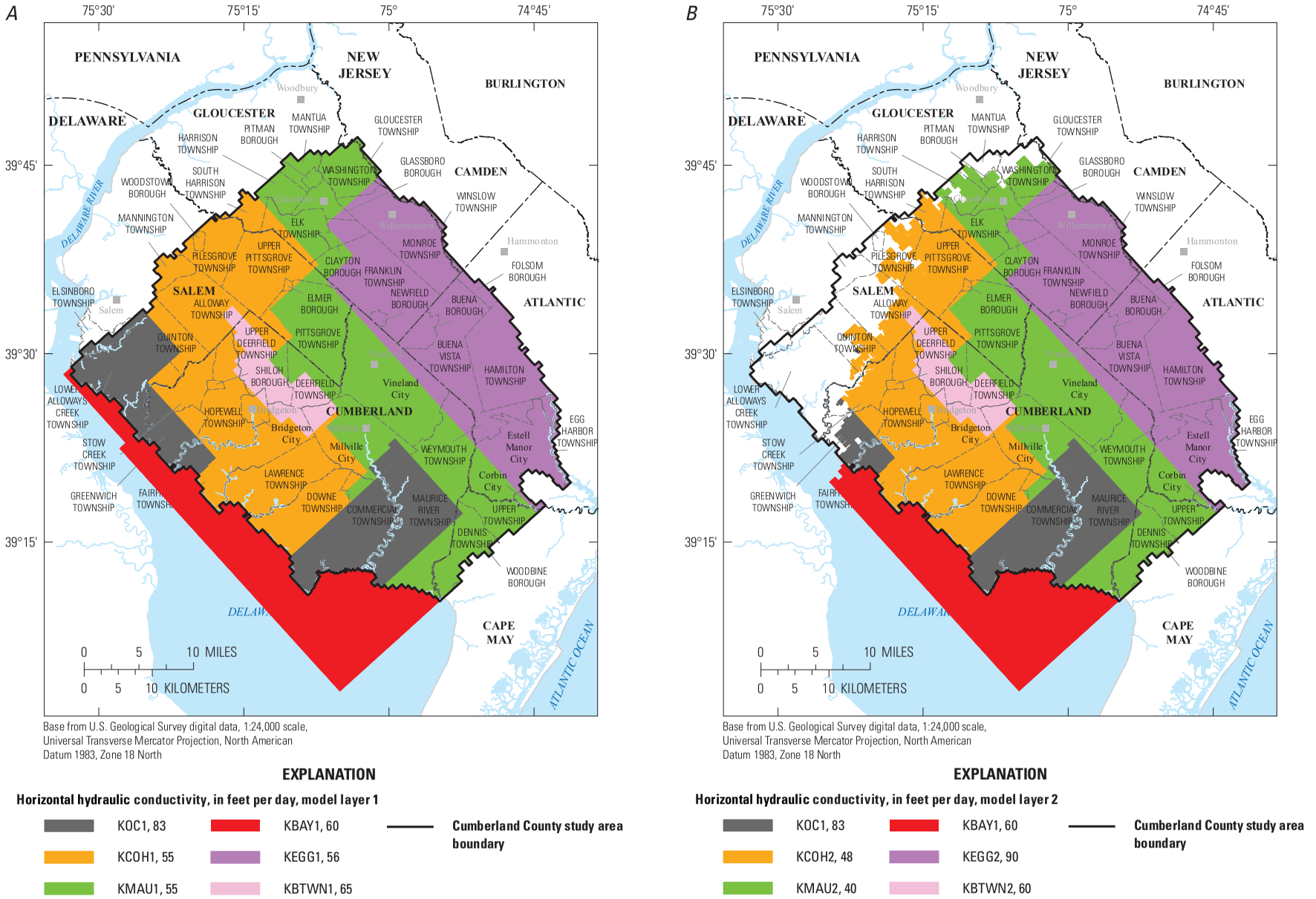


Figure 21. Zones of horizontal hydraulic conductivity in *A*, model layer 1 and *B*, model layer 2 for the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.

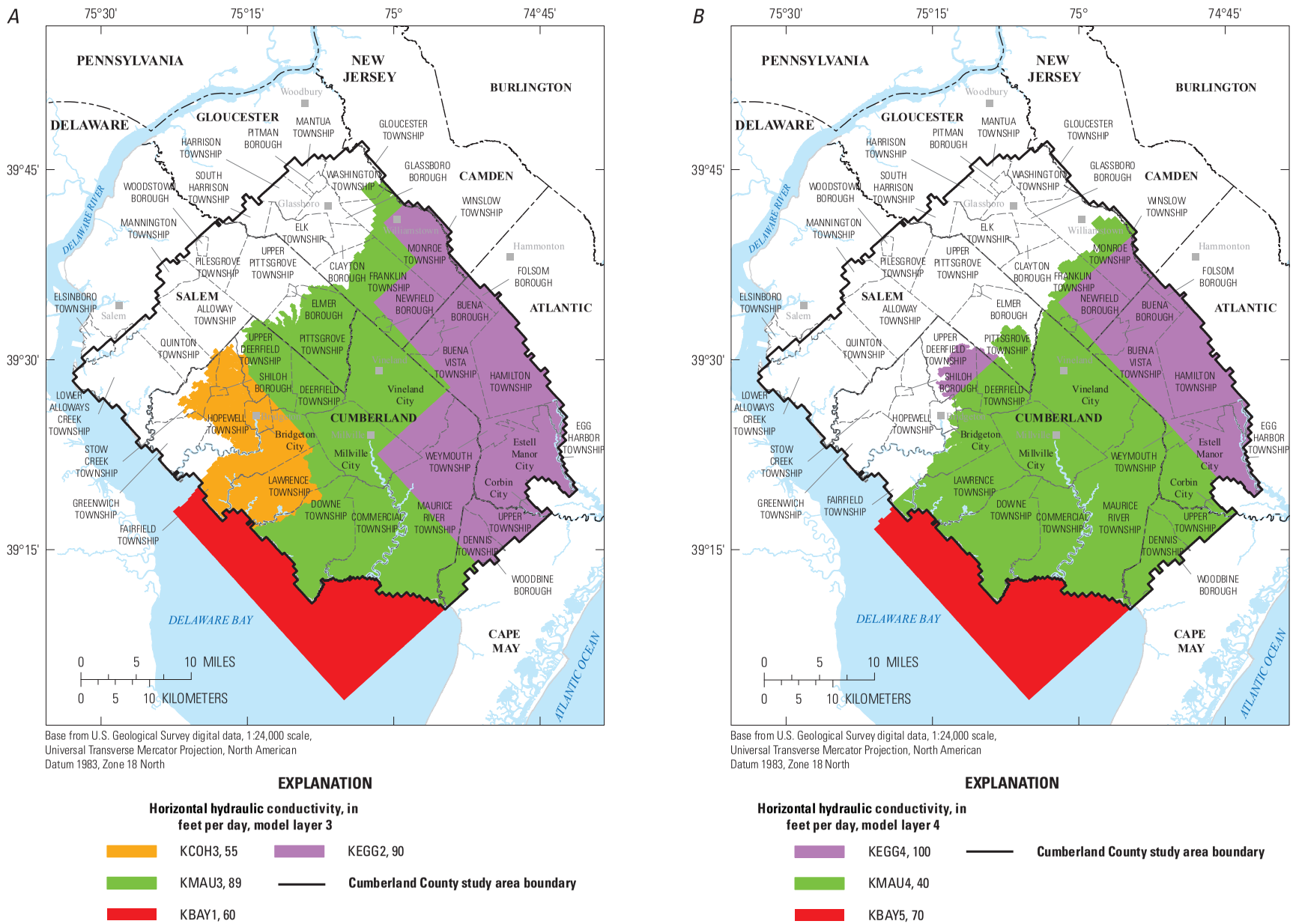


Figure 22. Zones of horizontal hydraulic conductivity in *A*, model layer 3, *B*, model layer 4, *C*, model layer 5, and *D*, model layer 6 in the groundwater-flow model of the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.

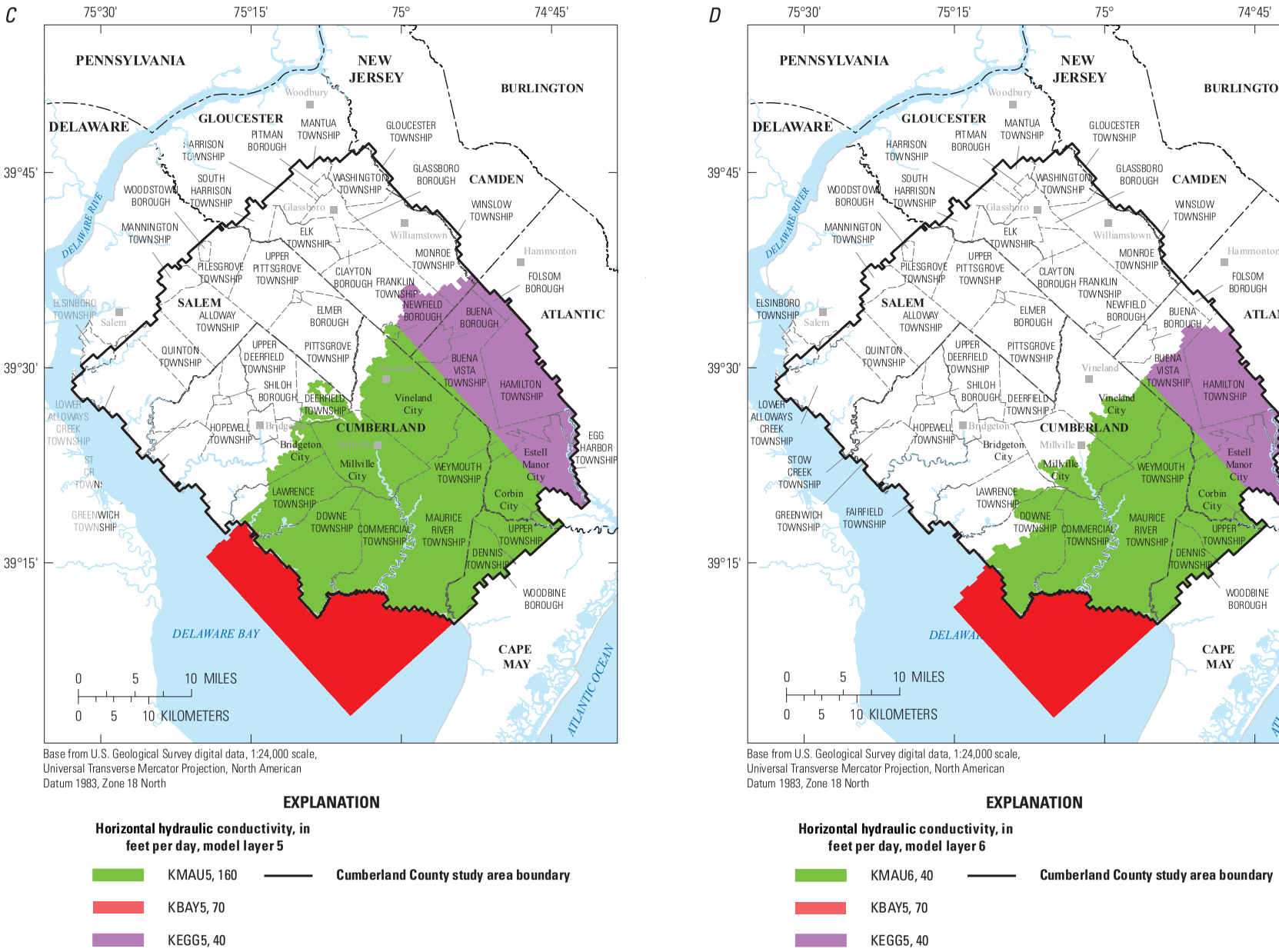


Figure 22. Zones of horizontal hydraulic conductivity in *A*, model layer 3, *B*, model layer 4, *C*, model layer 5, and *D*, model layer 6 in the groundwater-flow model of the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.—Continued

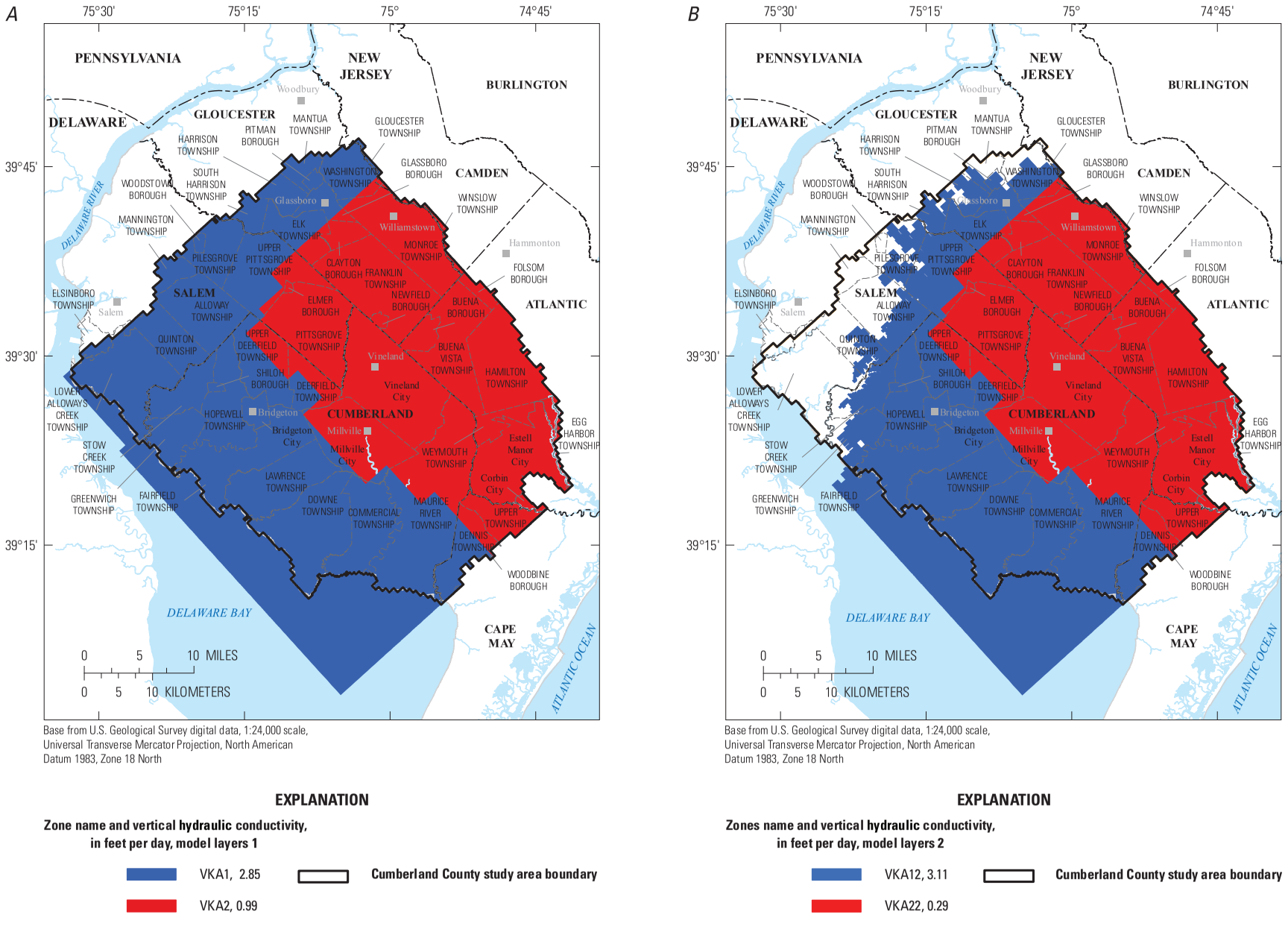
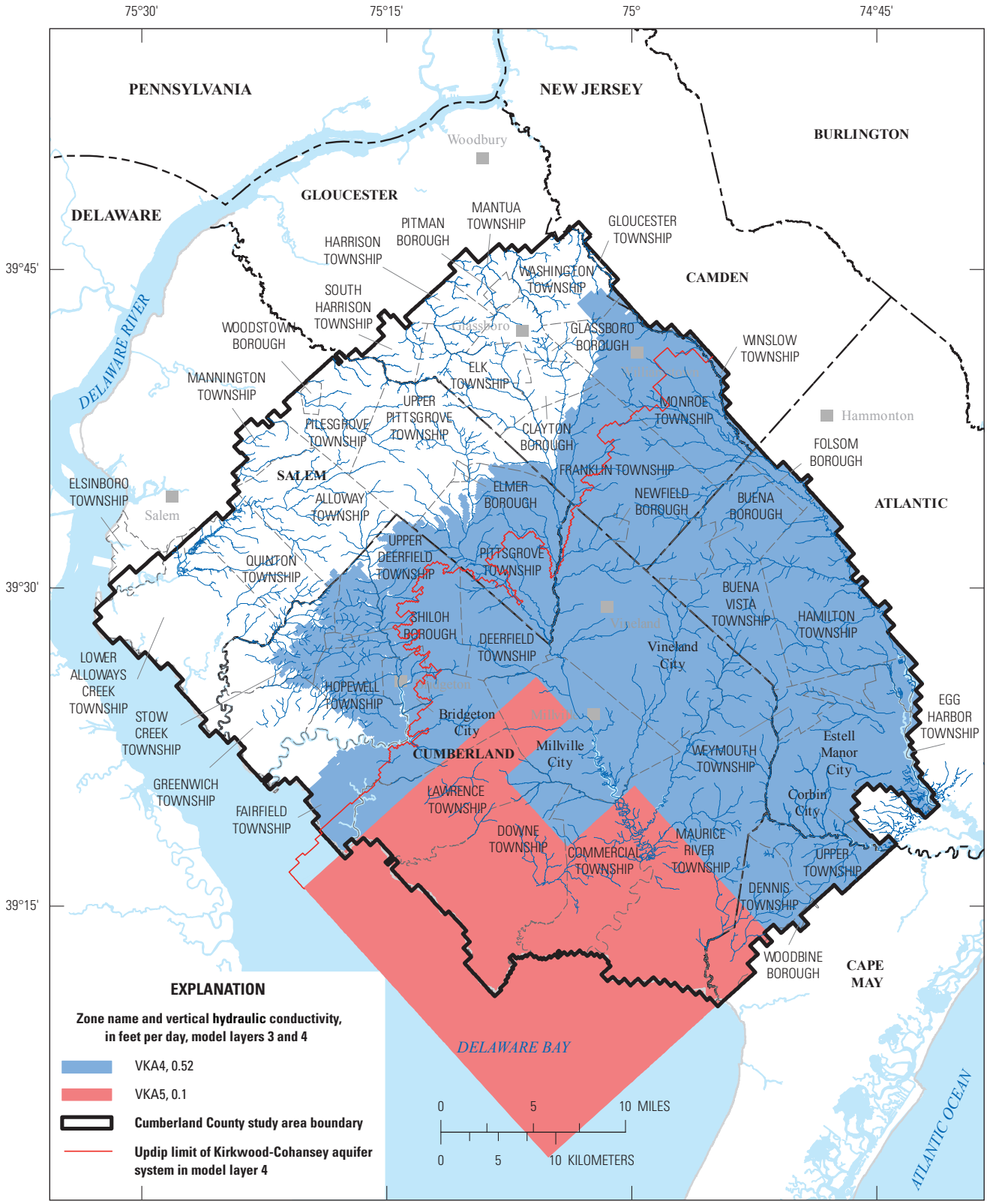
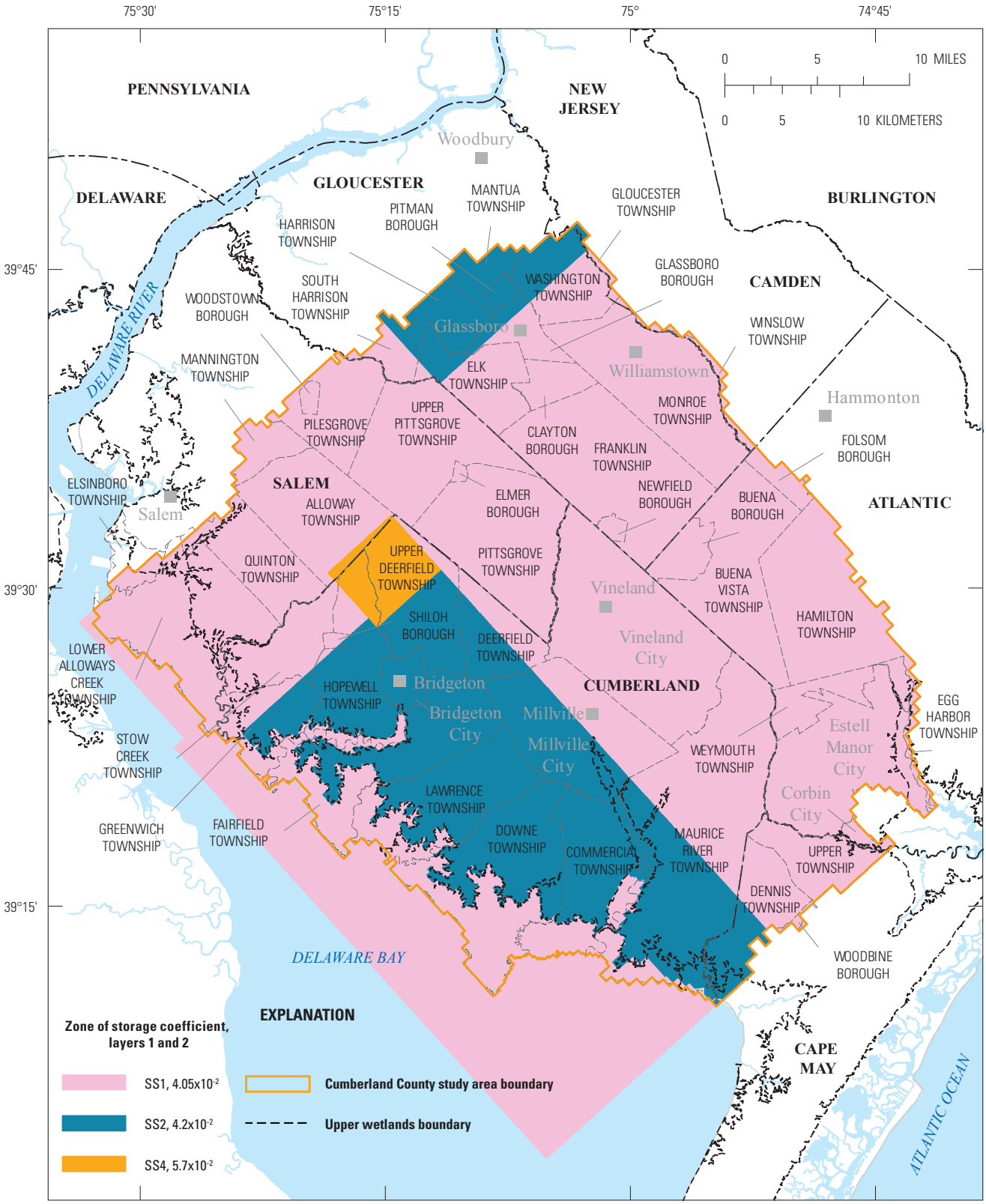


Figure 23. Zones of vertical hydraulic conductivity for *A*, model layer 1 and *B*, model layer 2 in the groundwater-flow model of the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 24. Zones of vertical hydraulic conductivity for model layers 3 and 4 in the groundwater-flow model of the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 25. Zones of storage coefficients in model layers 1 and 2 of the groundwater-flow model of the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.

base flows. Streambed conductivity values for the Maurice River ranged from 2.1 x 10^{-1} to about 1.0 x 10^{1} ft/d (fig. 26). Streambed conductivity values for the Cohansey River were estimated to be 3.0 x 10^{-2} to about 1.4 x 10^{1} ft/d. Streambed hydraulic conductivity values for streams in the outcrop of the Kirkwood Formation ranged from 2.0 x 10^{-2} to 8.3 x 10^{-1} ft/d and for the Great Egg Harbor and Tuckahoe Rivers, from 6.9 x 10^{-1} to about 1.0 x 10^{1} ft/d. Pope and others (2012) used a value of 1 ft/d for riverbed hydraulic conductivity for the Great Egg Harbor River.

Six recharge zones were used to define recharge in the calibrated model. The recharge zones are shown in figure 27. The zones were established to better represent the spatial distribution of recharge in the model. During model calibration, the Cohansey River Basin and the Maurice River Basin were divided into zones on the basis of comparison of fluctuations in monthly recharge with the water levels and monthly estimated base flow from the PART (Rutledge, 1998) or MOVE1 (Hirsch, 1982) analysis; there is overlap in the recharge zones between these two basins. The outcrop of the Kirkwood Formation also was divided into zones—a zone for the tidal Salem River area, a zone for the eastern part of the outcrop, and a zone that overlaps with another recharge zone in the model area. The recharge zone for the Great Egg Harbor River Basin overlaps with a recharge zone for the Maurice River Basin because there were no monthly estimated base flow analyses included for that basin.

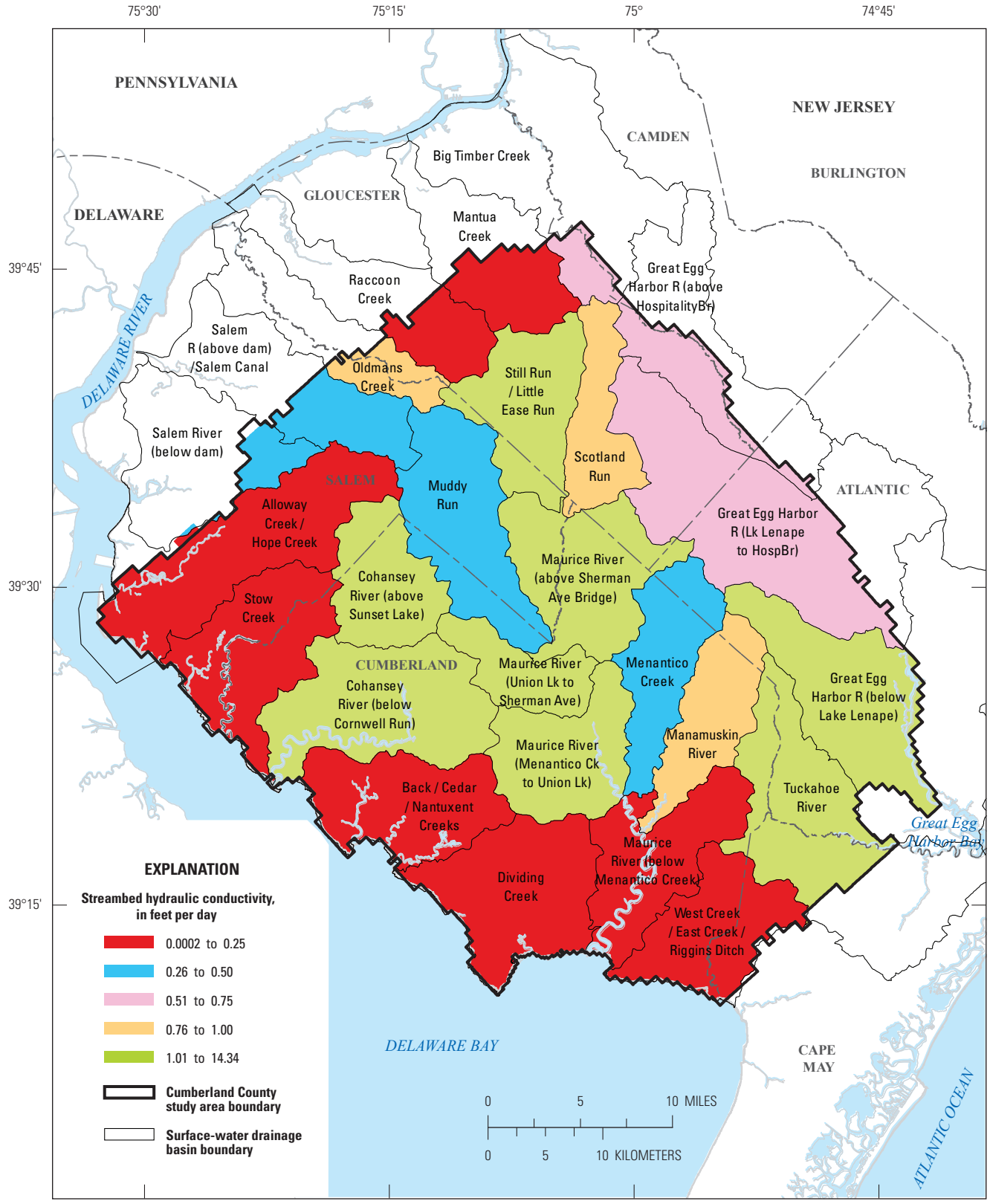
Recharge zones 1, 2, 5, and 6 had monthly recharge rates estimated using precipitation measured at the Seabrook Farms weather station and DRO estimated from MOVE1 analysis of the Cohansey River at Seeley streamflow-gaging station (01412800; fig. 6). Zones 3 and 4 had monthly recharge rates estimated from the precipitation measured at the Millville Municipal Airport weather station and DRO estimated from hydrograph separation of the Maurice River at Norma streamflow-gaging station (01411500; fig. 6). Equation 2, which was used to estimate recharge, allows some months to have zero recharge if the SMD value for that month is greater than precipitation. Months that are in this category were given a recharge value in the model that equaled the lowest estimated monthly recharge rate. Although the Millville Municipal Airport and Seabrook Farms weather stations used to estimate recharge are located within the study area, these two weather stations may not be representative of the eastern part of the study area. However, the Millville Municipal Airport and Seabrook Farms weather stations have records that are more complete for the time of the model simulation than the Glassboro and Mays Landing weather stations, which are on the periphery of the study area. The Millville Municipal Airport and Seabrook Farms weather stations probably monitor local precipitation in the study area more accurately. In addition, DRO values used in the recharge equation for the Maurice River Basin were determined for a long-term continuous-record streamflow-gaging station in the central part of this basin, although the same recharge rates were used for the southern part of the basin. For the Cohansey River Basin recharge zone, the DRO value was calculated using the streamflow and base flow from the low-flow correlation analysis correlated to index stations that have longer periods of discharge measurements than the Cohansey River at Seeley streamflow-gaging station.

Because of these limitations in the estimates of recharge, recharge rates were adjusted during calibration to best match estimated base flows and measured water levels. A recharge multiplier was used to adjust the recharge spatially over the six zones during model calibration (fig. 27). The recharge multiplication factor was lower (less than 1) in recharge zones 1 and 2 in the area of the outcrop of the Kirkwood Formation. Initial recharge estimates were decreased in the Kirkwood Formation outcrop area in the Salem River Basin and the Oldmans, Raccoon, Mantua, and Big Timber Creek drainage basins (fig. 26), and in the lower part of the Maurice River Basin in the tidal area adjacent to the upper wetlands boundary (fig. 4). The Kirkwood Formation contains fine- to medium-grained micaceous sand with clay and silty micaceous clay throughout.

The Cohansey Sand downdip from the Kirkwood Formation outcrop consists of medium to coarse sand, with clay occurring locally (New Jersey Geological Survey, 2009). For some recharge zones in the Cohansey, Maurice, and Great Egg Harbor River Basins where the Cohansey Sand is present, the recharge multiplication factor was increased (greater than 1) to allow greater recharge rates than were estimated. One explanation for the higher recharge rate is there is more irrigation percolation in some areas of the model because crops do not use all the water used for irrigation. Much of this water can seep back into the land. Stanton and others (2013) indicate that their groundwater-flow model for north-central Nebraska simulated water levels and base flow too low in some agricultural areas. They suggest too little simulated recharge or irrigation return flow as one possible explanation, as well as too much simulated irrigation pumpage and recharge areas that were too large areally. Additional recharge ascribed to irrigated agricultural lands was simulated in the groundwater-flow model of Stanton and others (2013). Although return flow was not quantified in the Cumberland County groundwater-flow model, in the areas where many agricultural-irrigation wells are sited in the Cohansey River and Maurice River Basins (fig. 9), the recharge multiplication factor was increased. Additional recharge to the aquifer system also occurs from the return of treated wastewater from septic systems. Many areas adjacent to the municipal areas of Bridgeton, Millville, and Vineland in Cumberland County are without centralized sewer systems and commonly use septic systems.

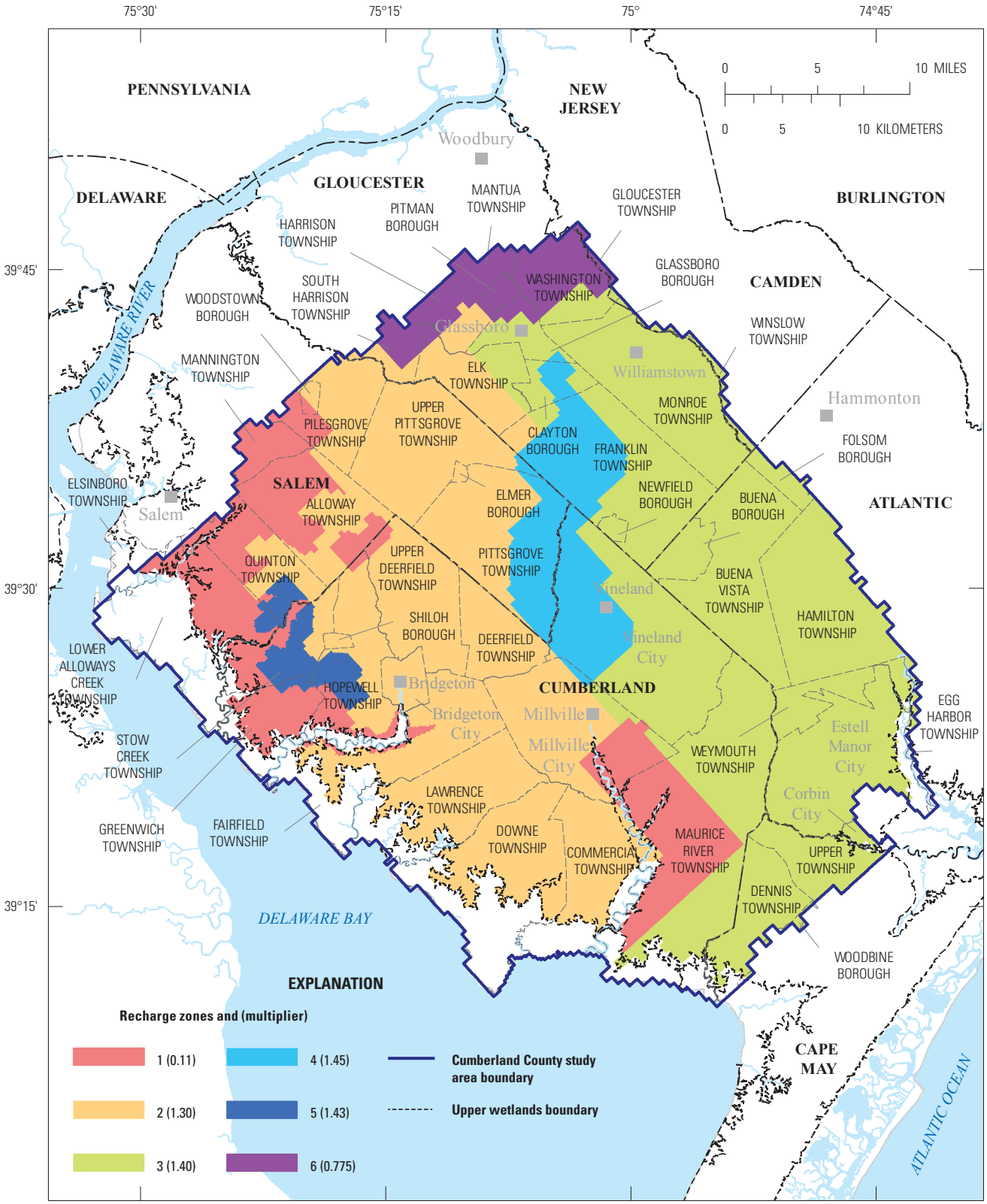
Flow Budgets

A comparison of the June and September 2008 flow-budget components is shown in figure 28. Because the flow-budget components were determined for September 2008, most of the summer irrigation withdrawals and greater ET had already taken place. ET is typically greater during the summer months,



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 26. Zones of streambed hydraulic conductivity for model layer 1 in the groundwater-flow model and surface-water drainage basins, Cumberland County study area, New Jersey.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 27. Recharge zones with multipliers in model layer 1 of the groundwater-flow model, Cumberland County study area, New Jersey.

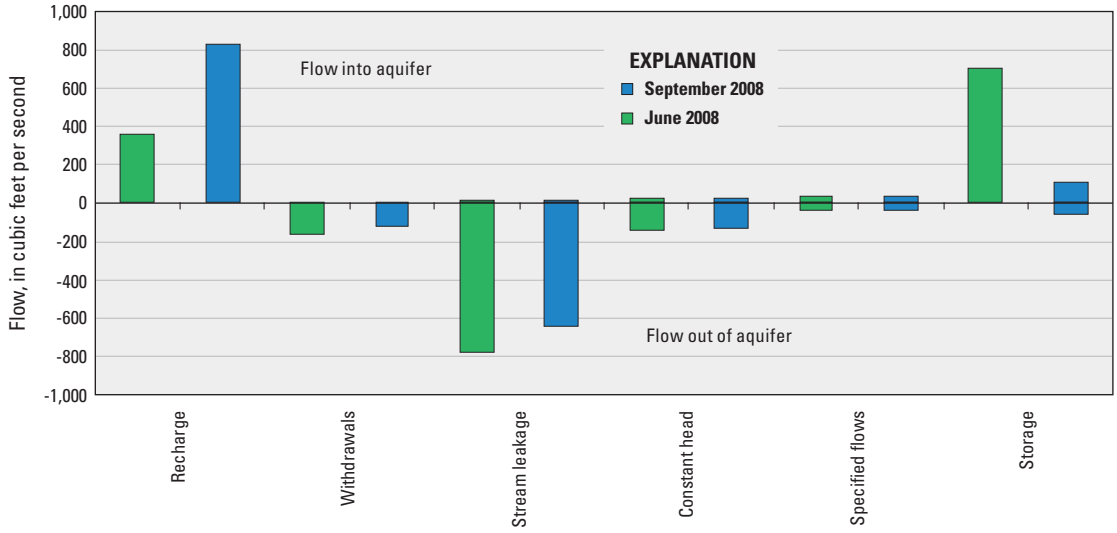


Figure 28. Graphs showing simulated flow budgets for June 2008 and September 2008 for the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey.

affecting recharge to the aquifer. Inflow to the aquifer layer is represented by positive values: negative values indicate flow out of the aquifer layers. Inflow to model layers can include recharge, lateral flow (specified flow) at the eastern boundary of the model, flow from the underlying confined aquifers, water released from storage when water levels decline, and leakage from streams to aquifers resulting from withdrawals. Outflow from model layers includes lateral flow to the aquifer system outside the model area, flow to the underlying aquifers other than the Kirkwood-Cohansey aquifer system, flow to offshore areas of the aquifer, water going into storage when water levels are increasing, leakage to streams, and groundwater withdrawals. Flow into constant heads represents flow to the Delaware or Great Egg Harbor Bays and their adjacent wetlands; flow out of constant heads represents flow to the aquifer.

A comparison of simulated June 2008 and September 2008 budgets indicates that recharge was lower in June 2008 than in September 2008, causing more water to be released from storage into the aquifer in June. During 2008, precipitation was 1.15 in. greater at the Seabrook Farms weather station (fig. 2) and 0.4 in. greater at the Millville Municipal Airport weather station (fig. 2) in June than in September, resulting in greater recharge during the month of September. Groundwater withdrawals were greater in June 2008 because agricultural irrigation increased during the summer growing season months of June, July, and August.

The simulated flow budget for September 2008 indicates that simulated recharge accounted for about 94 percent of inflow to the Kirkwood-Cohansey aquifer system; most of the remainder of the budget inflow is from storage. There is some simulated leakage from the streams to the aquifer system, and a small amount from the constant heads and from specified flow (boundary flows). Simulated groundwater withdrawals account for about 10 percent of outflow from the aquifer system, and simulated outflow to streams accounts for about 78 percent. For much of the remainder of the budget, outflows are to storage and to constant heads (wetlands and bays); a small amount is to specified flows.

The flow budget for the period 1997 to 2008 is shown in figure 29 as recharge, net storage, net base flow, and withdrawals. The specified flows from the model boundaries are small and constant (fig. 28) and are not shown in figure 29. Flow to the constant heads occurs at the wetland areas adjacent to Delaware and Great Egg Harbor Bays. Net flow is towards the bay, but there is a small component of flow from the constant head in the bay to the aquifer in some areas along Delaware Bay. Because the Kirkwood-Cohansey aquifer system interacts with Delaware Bay and tidal areas, salty tidal water is present in some areas and saltwater intrusion is a potential concern in coastal areas (New Jersey Geological Survey, 2009). Figure 9 indicates some agricultural-irrigation wells are adjacent to the wetlands boundary, but the pumpage from these wells is small. The flow budgets indicate that recharge is the major inflow; discharge to streams (net base flow) is the major outflow. Recharge varied monthly and typically was higher in the winter to early spring. Water is released from storage in the summer when recharge is low and water levels decline. Water goes into storage in the winter and spring months when water levels increase. Withdrawals from wells are greater in the summer months for agricultural use, and they follow a pattern similar to that of the storage outflow component. The budget components indicate that flow from the aquifer to the streams (net base flow) follows a pattern that is opposite to that of withdrawals. Therefore, the greater the withdrawals, the less groundwater discharge to streams.

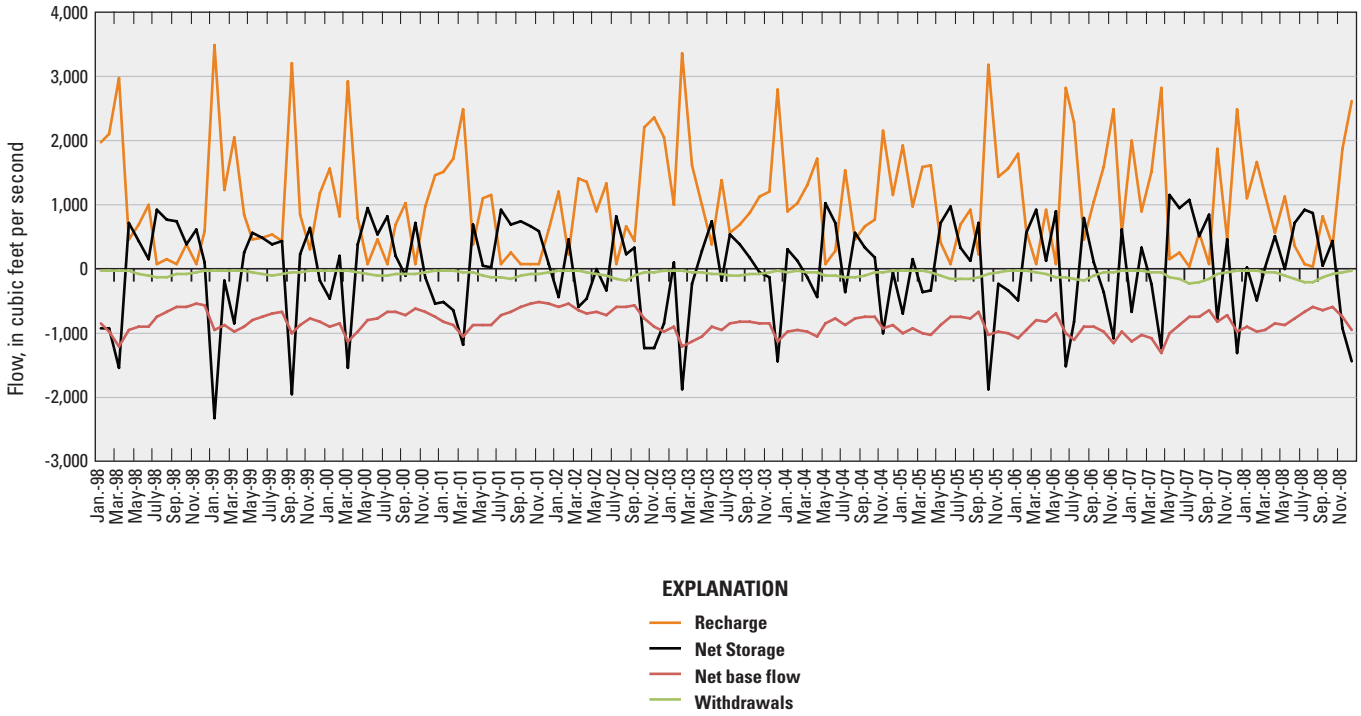


Figure 29. Simulated flow-budget components for the Kirkwood-Cohansey aquifer system, Cumberland County study area, New Jersey, 1998–2008.

Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the relative effects of the various parameters on the sensitivity of the water levels and base flows. The sensitivity of the model parameters was calculated using UCODE-2005 (Poeter and others, 2005). Composite-scaled sensitivities (CSS) were calculated for all 62 parameters in the groundwater-flow model using measured water levels and estimated base flows from 1998 to 2008 to determine which parameters were the most sensitive. The 62 parameters include the recharge multiplication factor, horizontal hydraulic conductivity, vertical hydraulic conductivity, streambed hydraulic conductivity, and storage coefficient (table 8).

Because the water-level measurements and estimated base flows have different units and different orders of magnitude, different error-based weights were assigned to the observations. Weighted residuals represent the fit of the regression relative to the expected accuracy of the observation. For water-level measurements, the standard deviation was used in the error-based weighting; for the base-flow estimates, the variance was used in the error-based weighting. Modifications to the initial weighting approach were used to account for discrepancies in data density between the numbers of water-level measurement and estimated base-flow observations.

Errors in water-level measurements were limited by the accuracy at wells whose locations were not determined using a Global Positioning System (GPS) and by the accuracy of the method used to estimate the elevation of land surface. Some wells have relatively accurate land-surface elevations determined by a land survey (leveled), whereas others have less accurate values interpreted from digital elevation maps or from topographic maps (not leveled). Water-level measurements were divided into one group where the land-surface elevation was surveyed and another group where the land-surface elevation was determined from a topographic map. The two different water-level groups were assigned different error-based weights.

The base flows were estimated by either low-flow correlation methods or hydrograph separation techniques with streamflow discharge measurements at the streamflow-gaging station or an index station. This may contribute more error to the base flow estimate than a calibration using direct or gaged measurements. In addition, errors in streamflow measurements generally are within 5 to 10 percent, based on streamflow and conditions at the time of the measurement (Reed and others, 1999).

Initial weights for the base flow estimates were defined using methods suggested by Hill and Tiedeman (2007) for flow data. Base-flow estimates were divided into categories on the basis of the size of the estimated monthly discharge measurement. The four categories—0.25 to 1 ft^3/s, greater than 1 to 10 ft^3/s, greater than 10 to 100 ft^3/s, and greater than 100 to 450 ft^3/s—were assigned error-based weights. Base flow less than 0.25 ft^3/s was not assigned a weight and was not used in the sensitivity analysis using UCODE-2005. The natural

section control for a streamflow-gaging station is typically less sensitive for discharge of less than about 0.25 ft³/s, resulting in a higher degree of uncertainty in the stage-discharge relation. Base flows of less than 0.25 ft³/s were considered unreliable at the scale of the model and subsequently were not used. As previously mentioned, because of the variability in base flow and streamflow at gaging stations along the mainstem of the Maurice and Cohansey Rivers, a 3-month average was used for the estimated base flow when compared to the simulated base flow (Claire Tiedeman, U.S. Geological Survey, oral commun., 2014).

The CSS values for 35 parameters are shown in figure 30; all other parameters had very small sensitivities and were not included on this graph. The CSS values indicate how sensitive all the water-level measurements or base-flow estimates in the model are to changes in each of the parameters. The parameters with the largest CSS values are the recharge multiplication factor for parts of the Maurice (RECH 3) and Cohansey River (RECH2) Basins. The next four most sensitive parameters are the recharge to the upper part of the Maurice River Basin (RECH4), a storage coefficient for layer 1 (SS1), recharge to a section of the outcrop area (RECH6), and hydraulic conductivity in sections of the Maurice River Basin (KMAU1). Streambed hydraulic conductivity and other horizontal hydraulic conductivities for layer 1 and the lower model layers, and vertical hydraulic conductivity, show similar composite scaled sensitivities.

Model Limitations

All models are based on a limited amount of data and thus are simplifications of the aquifer system and its representation. Limitations result from uncertainty in four aspects of the model, including inadequacies or inaccuracies in (1) conceptualization of the flow system; (2) model discretization and heterogeneity; (3) the methods used to estimate model parameters, sensitivity, and uncertainty; and (4) measurements or estimates used to calibrate the model.

The accuracy of a groundwater-flow model depends on the accuracy of the conceptual model and available data. The necessary simplification of the physical system in groundwater-flow models involves spatial discretization and the representation of physical heterogeneity. For this model, a model cell size is 500 ft by 500 ft where detail is needed in the study area. Because of this discretization, the hydraulic properties and simulated conditions within each cell are reduced to one average value for the entire cell. Although this cell size is adequate for the simulation objectives described in this report, new analyses requiring finer spatial detail would benefit from refinement of the model. The hydrogeologic framework and initial hydraulic property estimates come from sources with their own scale and uncertainty. As previously mentioned, many of the clay units within the Kirkwood-Cohansey aquifer system are of variable extent.

Water-level measurements have a level of accuracy that creates additional uncertainty, affecting limitations to model accuracy. The lack of water-level measurements for the deeper model layers adversely affected determination of parameters and provided an additional source of uncertainty that limits model applicability. Errors that contribute to the uncertainty of a water-level measurement include (1) inaccuracies in the altitude and location of a well and the measurement of a water level and (2) fluctuations introduced by transient stresses. Well-altitude error directly affects the calculation of the water level as referenced to a common datum. The error associated with the potential inaccuracy in well altitude was computed using the altitude accuracy code given in GWSI. The error range varies owing to the precision of measuring methods—GPS surveys and positioning from topographic maps—by ±10 ft for estimates determined from topographic maps having large (20 ft) contour intervals. Measurement instrument errors

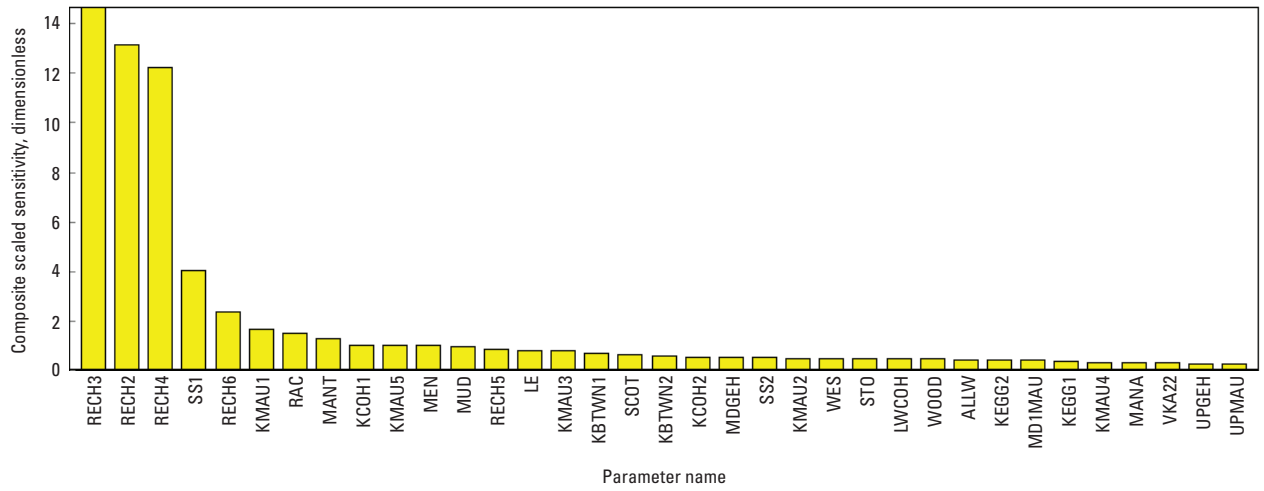


Figure 30. Composite scaled sensitivities of model parameters, Cumberland County study area, New Jersey. (Parameter names appear in table 8.)

result from inaccuracies in the measurement of the depth to water and depend primarily on the device being used to make the measurement. Most water levels were measured using a steel tape or an electric tape; both have a high accuracy of ±0.01 ft. Other factors, such as equipment calibration, can also affect the overall accuracy.

Base flow was estimated using hydrograph separation techniques that have an associated uncertainty contributing more error to the estimation. In addition, their weighting was unrelated to measurable accuracy but was driven by subjective decisions regarding the estimated value. Monthly base flow was estimated for 4 streamflow-gaging stations in the model using the PART program (Rutledge, 1998); monthly base flow for 14 streams and tributaries in the model was estimated using the MOVE1 (Hirsch, 1982) analysis. Variability in discharge is large for many of the smaller streams and the rivers; the very high base flows were not well matched during model calibration for the rivers. A possible explanation may be the interval over which the recharge was calculated for the model, which is monthly. A smaller interval, such as biweekly, may have resulted in better matching for the higher base flows. However, the monthly withdrawal data provided by the NJDEP are not reported at a smaller interval; therefore, monthly recharge values were used. Other limitations regarding recharge were previously discussed in the "Model Calibration" section of the report.

Because boundary flows from the RASA model represent annual flows, the boundary flows of the Cumberland study area may not represent actual seasonal flows. The RASA model was temporally discretized on an annual scale, unlike the monthly scale of the Cumberland study groundwater-flow model. However, model limitations associated with boundary flows are minor because boundary flows are a small part of the overall flow budget.

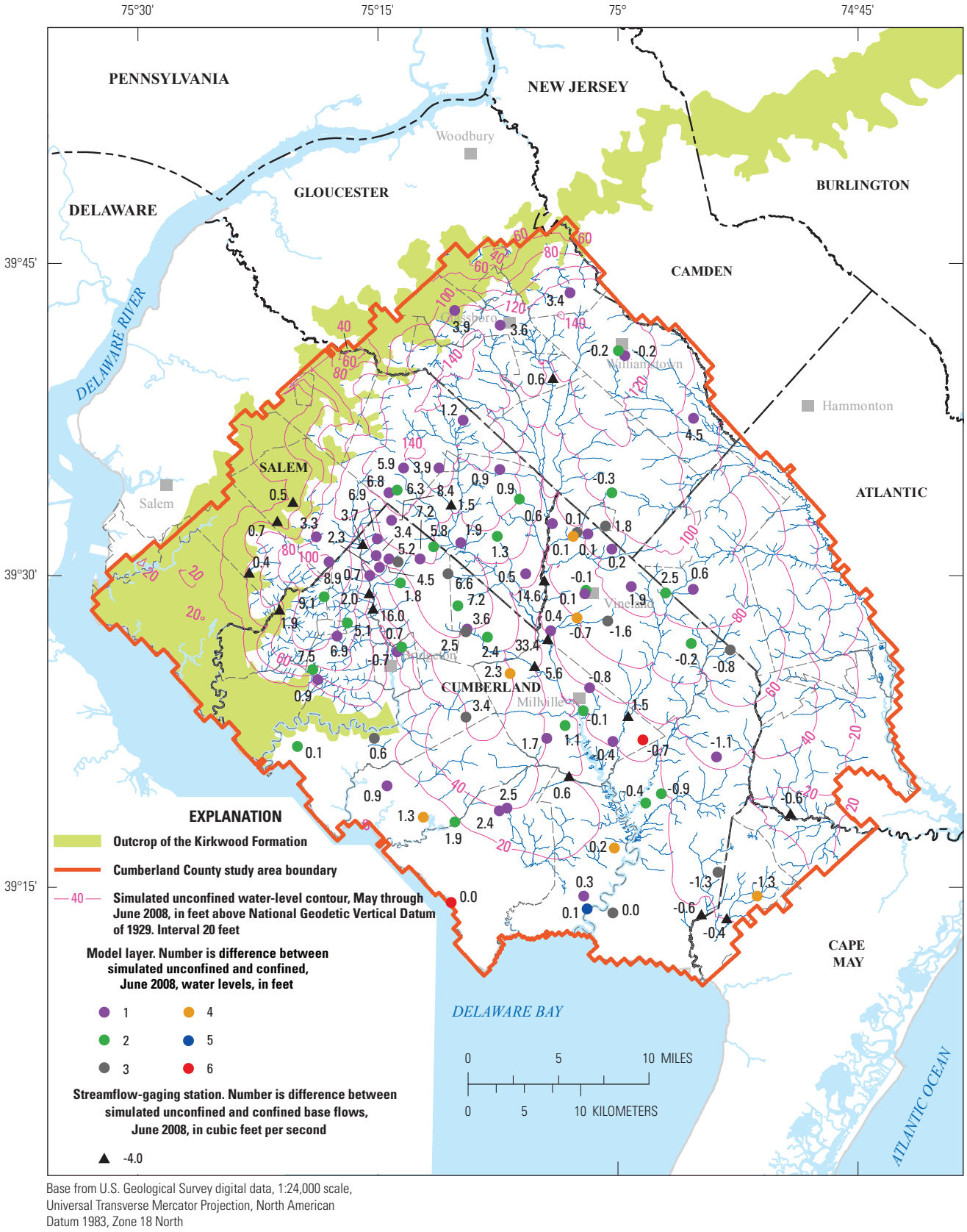
The accuracy of the groundwater withdrawals and surface-water diversions input to the model is difficult to assess because of uncertainties inherent in collecting, recording, and reporting the data for the NJDEP. These inaccuracies can also affect the groundwater discharge to streams in areas if not properly represented. In addition, domestic self-supply groundwater withdrawals were not input into the model. These withdrawals are assumed to be small; for example, in 1994, these withdrawals accounted for about 5 percent of total groundwater withdrawals in Cumberland County (Nawyn, 1997).

As previously mentioned, simulation of the unconfined system resulted in numerical instabilities associated with solving the nonlinear equations that made it necessary to treat the subsurface flow system as confined. The constant-saturated-thickness approximation has been used in numerical simulations to characterize regional-scale groundwater flow during the calibration period. Faunt and others (2011) used this approach in the groundwater-flow model of the Death Valley regional groundwater-flow system where the relevant saturated thickness is generally much greater than the drawdowns. The authors stated that simulated drawdowns are accurate as long as they remain a small fraction of the initial saturated thickness because the transmissivity (thickness multiplied by hydraulic conductivity) of the constant-saturated-thickness system will remain close to that of the unconfined system, and under the assumption of confined flow, changes in parameters such as hydraulic conductivity do not alter the state of the flow system. Cosgrove and others (2006) also found that the confined representation in a MODFLOW model of the unconfined Snake Plain aquifer allowed for a more stable numerical simulation of the aquifer during model calibration. From the specific-capacity data from well-acceptance tests, drawdowns for wells about 50 ft in depth in the Cumberland County study area are about 8 ft or less. The average drawdown for wells with depths greater than 100 ft is about 24 ft. However, in areas where a clay unit is present and confined conditions exist, drawdowns can be greater. Sheets and others (2015) also discuss the issue of large drawdowns and aquifer thickness using a specified thickness approximation approach.

Simulation of Water Levels Using MODFLOW-NWT

A simulation was conducted using the calibrated model parameters and using the MODFLOW-NWT, a package for simulating unconfined groundwater-flow using the Upstream-Weighting (UPW) package of MODFLOW-NWT (analogous to the Layer-Property Flow package of MODFLOW-2005). The results from the calibrated confined model simulation were compared to those of the unconfined simulation using the MODFLOW-NWT package, although the groundwater-flow model was not calibrated using this package. The simulation using MODFLOW-NWT included some convergence problems.

Final parameter values from the confined model (table 8) were input to the MODFLOW-NWT unconfined model. Because the confined model represented the aquifer system under confined conditions, a specific yield value of 0.1 was assumed for specific yield in layer 1. This value is similar to a value used for a groundwater-flow model of the adjacent Great Egg Harbor River Basin of 0.15 (Pope and others, 2012) and is similar to a value used in the Cumberland County groundwater-flow model calculated from the range of storage coefficients divided by the aquifer thickness. Simulated water levels, base flows, and flow budgets were compared and were in reasonable agreement between the confined and unconfined simulations. As an example, the simulated water-level contours from the MODFLOW-NWT model for May through June 2008 are shown in figure 31. The differences between the simulated water levels for the confined aquifer model run and those for the unconfined aquifer model run are shown in figure 31. Figure 17*A* shows the simulated water levels for the June 2008 for the confined simulation. The average difference between the simulated water levels from the unconfined simulation and those from the confined simulation is 2 ft with 65 percent of the wells having a difference of 2 ft or



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 31. Simulated unconfined water-level contours, the difference in simulated water levels between the unconfined and confined aquifers, and the difference in base flows between the unconfined and confined aquifers in the Kirkwood-Cohansey aquifer system for June 2008, Cumberland County study area, New Jersey.

less and 85 percent having a difference of 5 ft or less. For the 17 streamflow-gaging stations, the average difference between the unconfined and confined simulation is 4.7 ft^3/s.

Withdrawal Scenarios Using the Cumberland County Study Area Groundwater-Flow Model

Five withdrawal scenarios were simulated using the calibrated groundwater-flow model of the Cumberland County study. The results of these scenarios are evaluated to assess changes in monthly base flows, water levels, and flow-budget components in the Kirkwood-Cohansey aquifer system compared to a baseline scenario (scenario 1).

Simulations Using the Numerical Groundwater-Flow Model

Scenarios 1 through 5 were simulated using the calibrated groundwater-flow model for the Cumberland County study area to evaluate several withdrawal conditions. The scenarios are summarized in table 9. Scenario 1 represents the monthly average of 1998–2008 groundwater withdrawals. The results of the other four scenarios are compared to results of the scenario 1 (baseline scenario). Scenario 2 incorporates monthly full-allocation groundwater withdrawals, except for the agricultural-irrigation withdrawals. Agricultural-irrigation groundwater withdrawals were modified by decreasing the full-allocation withdrawal to reflect seasonal changes when water-use demand is lower, such as during winter months. Scenario 2 is referred to as an adjusted agriculture full-allocation scenario. Scenario 3 incorporates the monthly full-allocation groundwater withdrawals at all wells. Scenario 4 incorporates estimated increases in municipal public-supply demand in 2050. Scenario 5 incorporates the same withdrawals as scenario 4, except that the withdrawals for several municipal public-supply wells were moved to a deeper model layer to observe the effect on streams. Scenario 5 is a seasonal municipal public-supply alternative scenario. Only existing wells in the Cumberland County study area groundwater-flow model were used in scenarios 1–5. The NJPDES discharges and surface-water diversions input into the SFR2 package (Niswonger and Prudic, 2009) of the model were not changed for the scenarios (fig. 15). Total groundwater withdrawals for scenarios 1–4 are shown in figure 32, by NJDEP permit series. Total groundwater withdrawals for 2008 are also included in this figure for comparison.

The annual precipitation rates from 1998 to 2008 include a wet and dry period. As previously mentioned, mean annual precipitation at the Seabrook Farms and Millville Municipal Airport weather stations from 1998 to 2008 was 44.4 in/yr and 39.1 in/yr, respectively. The period 1998–2008 includes the drier years of 1998 and 2001 and the wetter years of 1999 and 2003. For the years when precipitation was lower than the average, the total precipitation for the Seabrook Farms weather station in 1998 was 37.8 in/yr and in 2001 was 36.1 in/yr; for the Millville Municipal Airport weather station, the total precipitation was 36.5 in/yr in 1998 and 27.5 in/yr in 2001. For the years 1999 and 2003 when precipitation was greater than the average, the total precipitation for the Seabrook Farms weather station was 49.1 in/yr and 55 in/yr, respectively, and for the Millville Municipal Airport weather station it was 41.9 in/yr and 50.8 in/yr, respectively.

The five scenarios pertain to an 11-year hypothetical period during which monthly recharge is equivalent to that estimated for 1998–2008 in the calibrated model. In each of these scenarios, the cycle of withdrawals varies by month. Therefore, these scenarios represent monthly conditions that would have occurred if the withdrawals for the scenarios had occurred during 1998–2008. For discussion of the scenarios

Table 9. General description of withdrawal scenarios for groundwater-flow models, Cumberland County study area, New Jersey.

Scenario number	Withdrawal scenario	Aquifer of interest
Transient scenarios using Cumberland groundwater-flow model		
1	Monthly average 1998–2008 (baseline flow)	Kirkwood-Cohansey aquifer system
2	Monthly adjusted agriculture full allocation	
3	Monthly full allocation	
4	Estimated monthly 2050 municipal public supply	
5	Estimated monthly 2050 municipal public-supply seasonal alternative	
Steady-state scenarios using New Jersey Regional Aquifer System Analysis (RASA) groundwater-flow model		
6	Annual average 2004–08	Piney Point
7	Estimated 2050 municipal public supply	
8	Full allocation for Millville City, Vineland City, and Monroe Township	

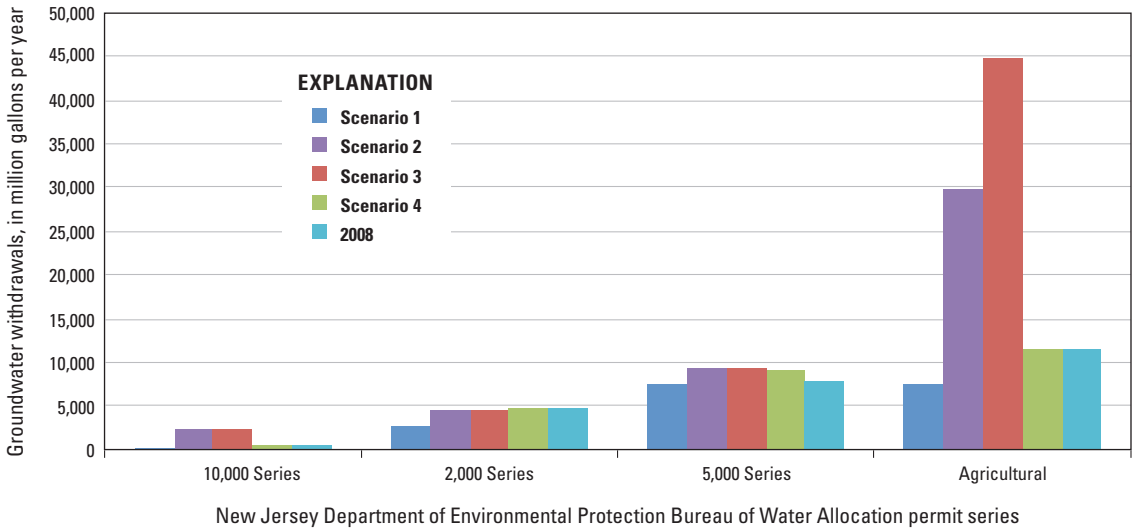


Figure 32. Groundwater withdrawals, by permit series, incorporated in the numerical groundwater-flow model for scenarios 1–4 and 2008, Cumberland County study area, New Jersey.

using the Cumberland County study area groundwater-flow model, the years 1998–2008 are referred to as scenarios years 1 through 11. The scenario year and the recharge year are shown in table 10. Recharge for each year and the ratio of the recharge per year to the largest recharge (2003) are also shown. Recharge and withdrawals for the first 5 stress periods were not changed for scenarios 1–5.

Table 10. Scenario years and recharge per year used for scenarios 1–5, Cumberland County study area, New Jersey.

[Mgal/yr, million gallons per year; ft³/s, cubic foot per second]

Scenario year	Recharge year	Recharge (ft³/s)	Recharge (Mgal/yr)	Recharge ratio[1]
1	1998	10,506	2.48	0.66
3	2000	10,897	2.57	0.68
5	2002	14,142	3.34	0.89
7	2004	12,005	2.83	0.75
9	2006	10,506	2.48	0.66
11	2008	11,684	2.76	0.73

[1] Ratio is recharge for year to largest recharge (2003).

Scenario 1 Average Monthly 1998–2008 Groundwater Withdrawals (Baseline Scenario)

Scenario 1 simulated average withdrawal conditions using withdrawal rates from 1998 to 2008 averaged for each month. The locations of the wells are shown in figure 9. The simulated water-level contours for scenario 1 are shown in figure 33*A* for June and figure 33*B* for September of scenario year 11. The simulated water-level contours form patterns similar to those shown in figure 17*A–B* for June and September of 2008. The simulated budget components—groundwater withdrawals, net storage, and net base flow—are shown in figure 34 for scenarios 1–3. A decrease in base flow is shown in figure 34*A* when withdrawals increase during the summer months. A net decrease in storage (a negative value) is shown in figure 34*B* when water levels decline owing to increased withdrawals and lower recharge because of increased ET, which are typical during the summer months. A net increase in storage (a positive value) is shown in figure 34*B* when water levels are recovering. Monthly groundwater flow to streams (base flow) varied over the 11-year simulation period and ranged from 516.7 ft³/s in November of scenario year 4 to 1,307.3 ft³/s in April of scenario year 10. Monthly groundwater withdrawals varied over the 11-year simulation period, and the average for each month ranged from 34.8 ft³/s in February to 148.1 ft³/s in August. Monthly recharge (not shown in figure 34*A–B*) varied over the 11-year simulation period and is the same monthly recharge as shown in figure 29.

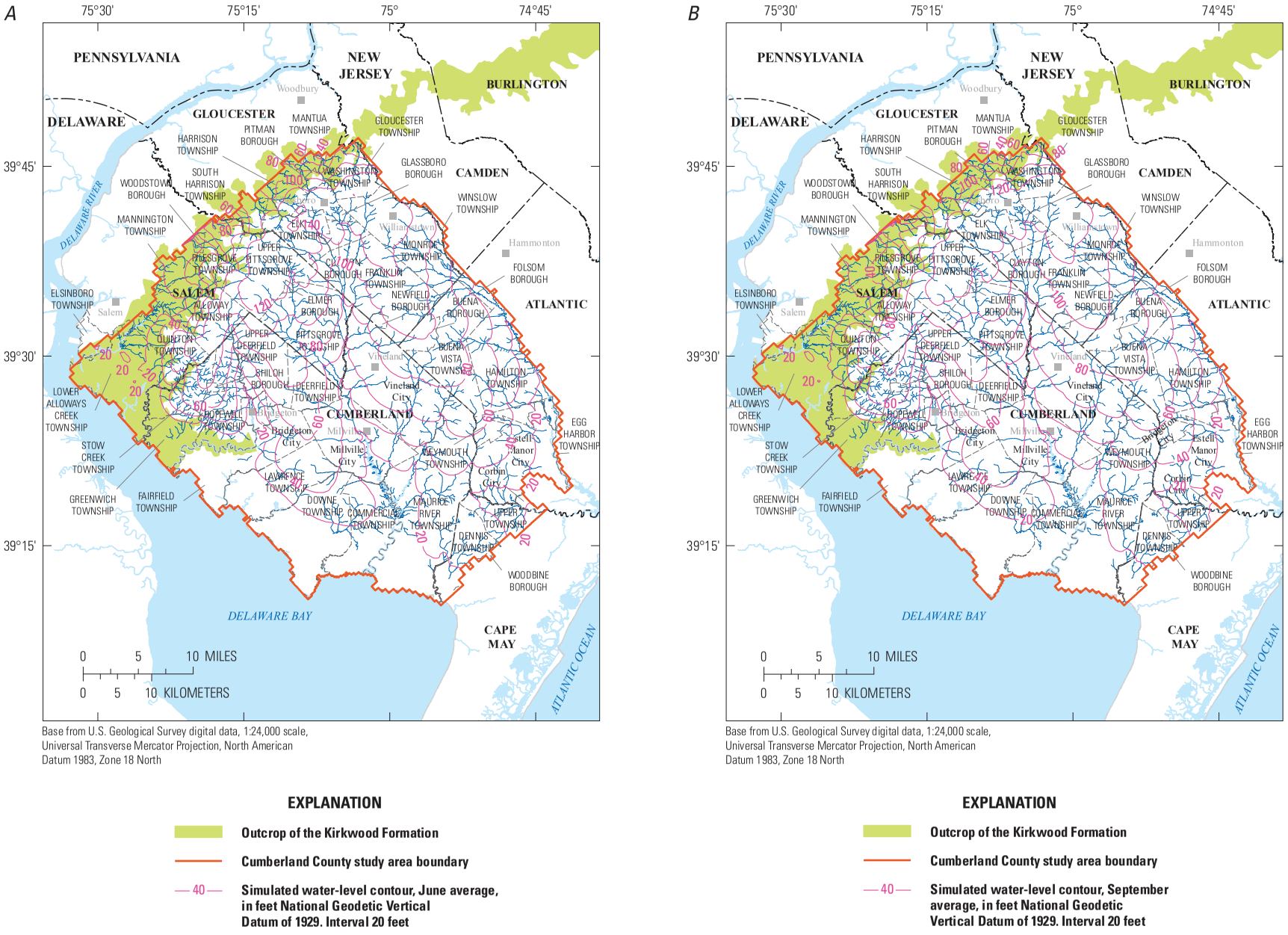


Figure 33. Simulated water-level contours for the Kirkwood-Cohansey aquifer system in scenario 1 for *A*, June and *B*, September in scenario year 11 in model layer 1 of the groundwater-flow model, Cumberland County study area, New Jersey.

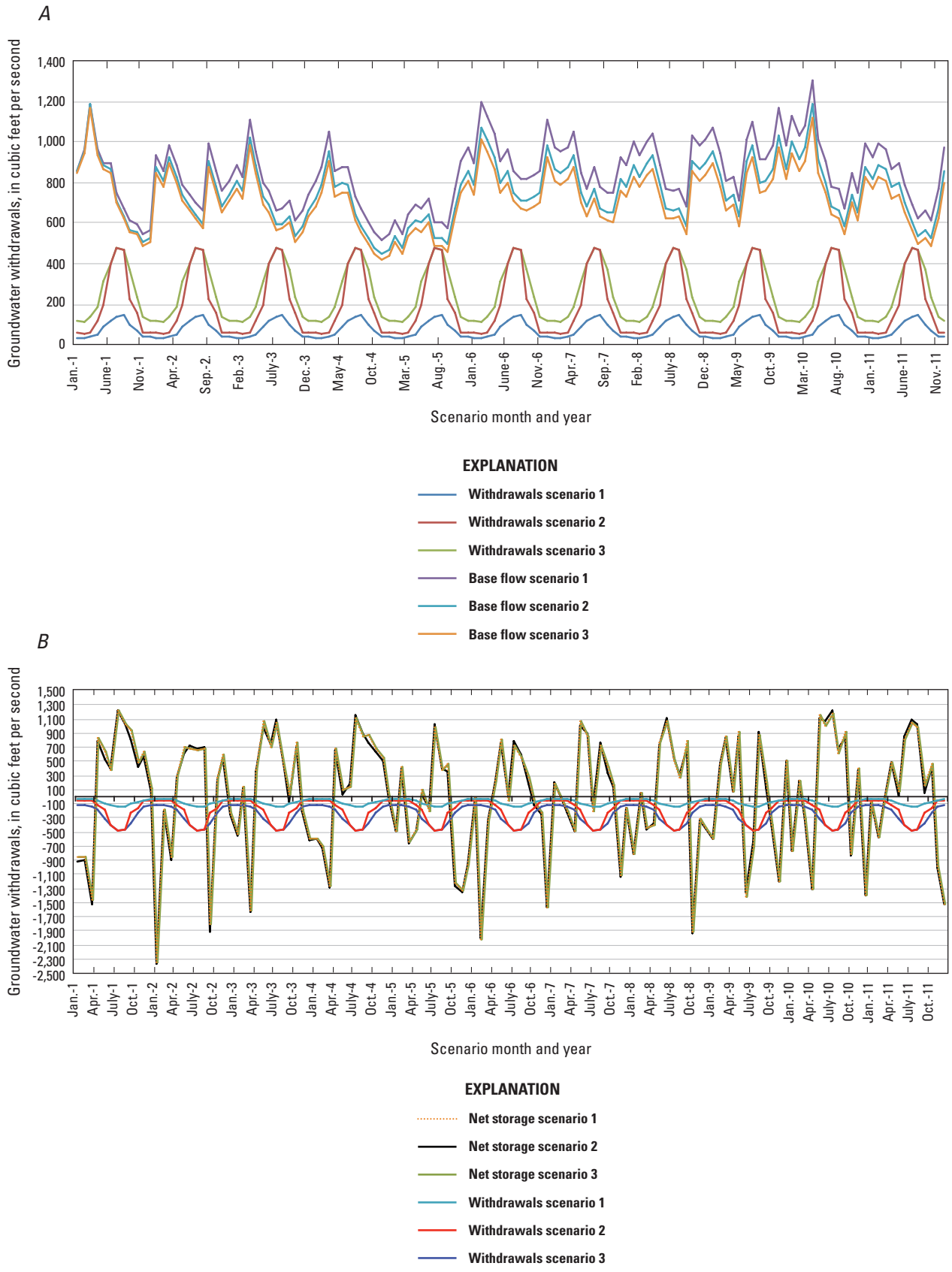


Figure 34. Selected simulated flow-budget components *A*, groundwater withdrawals and net base flow, and *B*, groundwater withdrawals and net storage for scenarios 1–3 of the groundwater-flow model, Cumberland County study area, New Jersey.

Analysis of Simulated Base Flow in the Cohansey and Maurice River Basins

The locations of selected HUC11 drainage basins located in the Cohansey and Maurice River Basins and the Back, Cedar and Nantuxent Creeks Basin are shown in figure 35. Each HUC11 in the Cumberland County study area is designated by the first eight digits of the HUC as 02040206. These digits are followed by a 3-digit number that designates an individual HUC11 in either the Cohansey or Maurice River Basin. The bottom of the watershed (pour point) is the lowest point of the land area where water flows out of the watershed, in this case, the HUC11 (U.S. Environmental Protection Agency, 2015). The pour point for each HUC11 in the Cohansey and Maurice River Basins is shown in figure 35.

The simulated monthly base flows at the pour point for each HUC11 for scenarios 1–5 are shown in figure 36. Simulated monthly base flows for scenarios 2–5 can be compared to the simulated monthly base flows from the baseline scenario (scenario 1) to evaluate months and drainage basins in which base flow decreased. Figure 36 also shows the 7-day 10-year low flow (7Q10) given in Domber and others (2013) for each HUC11. The drought or low-flow statistic traditionally used by New Jersey water-supply planners is the 7Q10. The 7Q10 is a 7-day average low flow that has 10-percent chance of occurring in a given year (Gillespie and Schopp, 1982). The hydrographs in figure 36 indicate that for scenario 1, base flows at the pour points are greater than the 7Q10 value for all HUC11s, except HUC 02040206180 (Menantico Creek). Menantico Creek, which is in the Maurice River Basin, has monthly simulated base flow that is about equal or slightly less than the 7Q10 in November and December of scenario year 4 and January through March and August and September of scenario year 5 (fig. 36*B*).

Total groundwater withdrawals in the Cohansey and Maurice River Basins for scenarios 1–4 and for 2008 are listed in table 11 by NJDEP Bureau of Water Allocation & Well Permitting (BWA) permit type and by HUC11 drainage basin. The total withdrawals for scenario 5 are not shown in the table because they are the same withdrawals as simulated in scenario 4 but in a deeper model layer. Withdrawals in table 11 are in ft^3/s for easier comparison with the 7Q10 and discharge values in the streams. The HUC11 drainage basins in table 11 are shown on figure 35.

Scenario 2 Adjusted Agriculture Full-Allocation

For the adjusted agriculture full-allocation scenario, it was assumed that monthly agricultural-irrigation full-allocation withdrawals would not be pumped over the entire year, but only during the late spring into summer growing months. The maximum permitted withdrawals per water-allocation permit, well registration, or agricultural certification or registration (referred to as "full allocation" in this report) used in these scenarios reflect information listed in NJDEP files as of July 2012. Allocation limits are specified for all water-allocation permits that may include more than one source (wells or surface-water diversions). In some cases, allocation limits are assigned for a group of sources within a permit. Full-allocation rates were estimated for each site (in a group) associated with a BWA permit and having withdrawals from 1998 to 2008. Estimates for each withdrawal site were determined using a USGS computer program that distributes allocation limits among withdrawal sites for a given BWA permit (Mary Chepiga, U.S. Geological Survey, written commun., 2012). Monthly and annual limits were estimated using withdrawal patterns at each site from 1998 to 2008. For each site associated with a BWA permit, the estimated full allocation was based on the percentage of the total withdrawals for the BWA permit such that the summed allocation amount for sites associated with a BWA permit does not exceed the BWA permit monthly or yearly allocation limit.

The monthly agricultural-irrigation groundwater withdrawals averaged from 2004 to 2008 that were used to determine which months to adjust full-allocation withdrawals in scenario 2 are shown in figure 37. Figure 37 shows that the smallest withdrawals occur during January–April and October–December, and the largest withdrawals occur during June–August. Using the information in figure 37, full-allocation withdrawals for agricultural-irrigation wells were input to the groundwater-flow model for June, July, and August. No withdrawals were represented for these wells for November, December, January, February, and March. One-half of the full-allocation withdrawals were input to the model for April, May, September, and October. The locations of agricultural-irrigation wells in the Cumberland County study area for scenarios 2 and 3 are shown in figure 38. Other wells from the 2000P, 10000W, and 5000 BWA permit series were assigned monthly full-allocation withdrawals in this scenario.

The simulated water-level contours for scenario 2 and the change in simulated water levels from the baseline conditions (scenario 1) are shown in figure 39 for June and September of scenario year 11. Full-allocation agricultural-irrigation withdrawals for June were input to the model. In September, withdrawals decrease following the growing season months, so one-half the full allocation was input for September. Simulated water levels in the upper Cohansey River Basin (HUC 02040206080; fig. 35) decreased by more than 67 ft in June and September in scenario year 11 at a pumped well in the upstream part of the basin where the agricultural-irrigation wells are located. Water-level drawdowns in the Cohansey River Basin of as much as 80 ft have been reported for this area. An aquifer test in 1951 in Deerfield Township in the Cohansey River Basin recorded drawdowns of 79 ft (Remson, 1952) where a layer of clay was verified as being present above the pumped well. Total groundwater withdrawals in the Cohansey River Basin were 520 ft^3/s greater in scenario 2 than in scenario 1 (table 11). The average decline in simulated water levels for this drainage basin was less than 10 ft for this scenario.



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 35. Selected Hydrologic Unit Code 11 drainage basins and associated pour points in the Cohansey and Maurice River Basins and the Back, Cedar and Nantuxent Creeks Basin, Cumberland County study area, New Jersey.

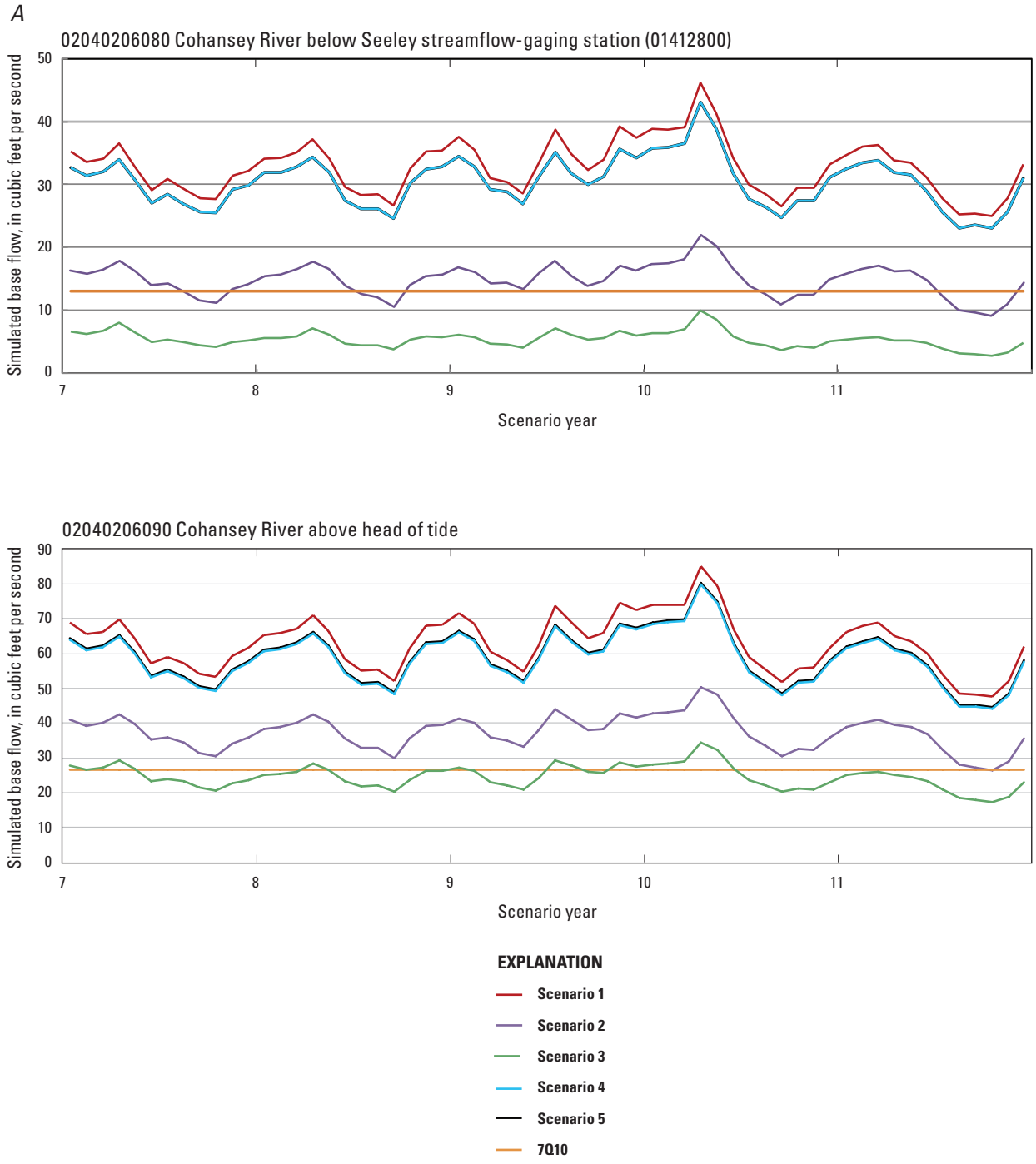


Figure 36. Hydrographs of simulated monthly base flow at pour points in Hydrologic Unit Code 11 drainage basins on the *A*, Cohansey River Basin, *B*, tributaries to the Maurice River Basin, and *C*, the mainstem of the Maurice River for scenarios 1–5 in the groundwater-flow model and the 7-day 10-year low flows, Cumberland County study area, New Jersey. (7Q10, 7-day 10-year low flows)

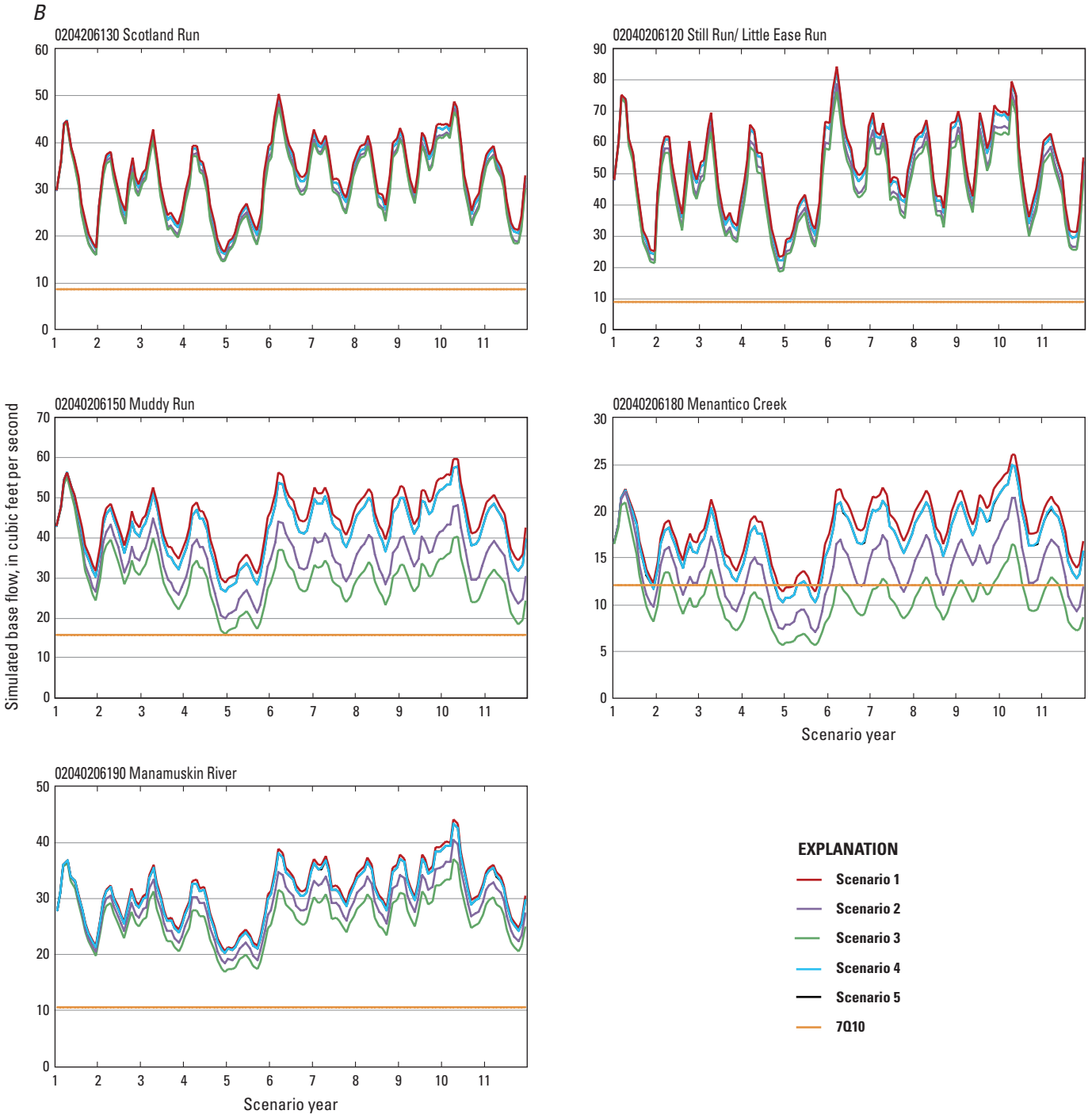


Figure 36. Hydrographs of simulated monthly base flow at pour points in Hydrologic Unit Code 11 drainage basins on the *A*, Cohansey River Basin, *B*, tributaries to the Maurice River Basin, and *C*, the mainstem of the Maurice River for scenarios 1–5 in the groundwater-flow model and the 7-day 10-year low flows, Cumberland County study area, New Jersey. (7Q10, 7-day 10-year low flows) —Continued

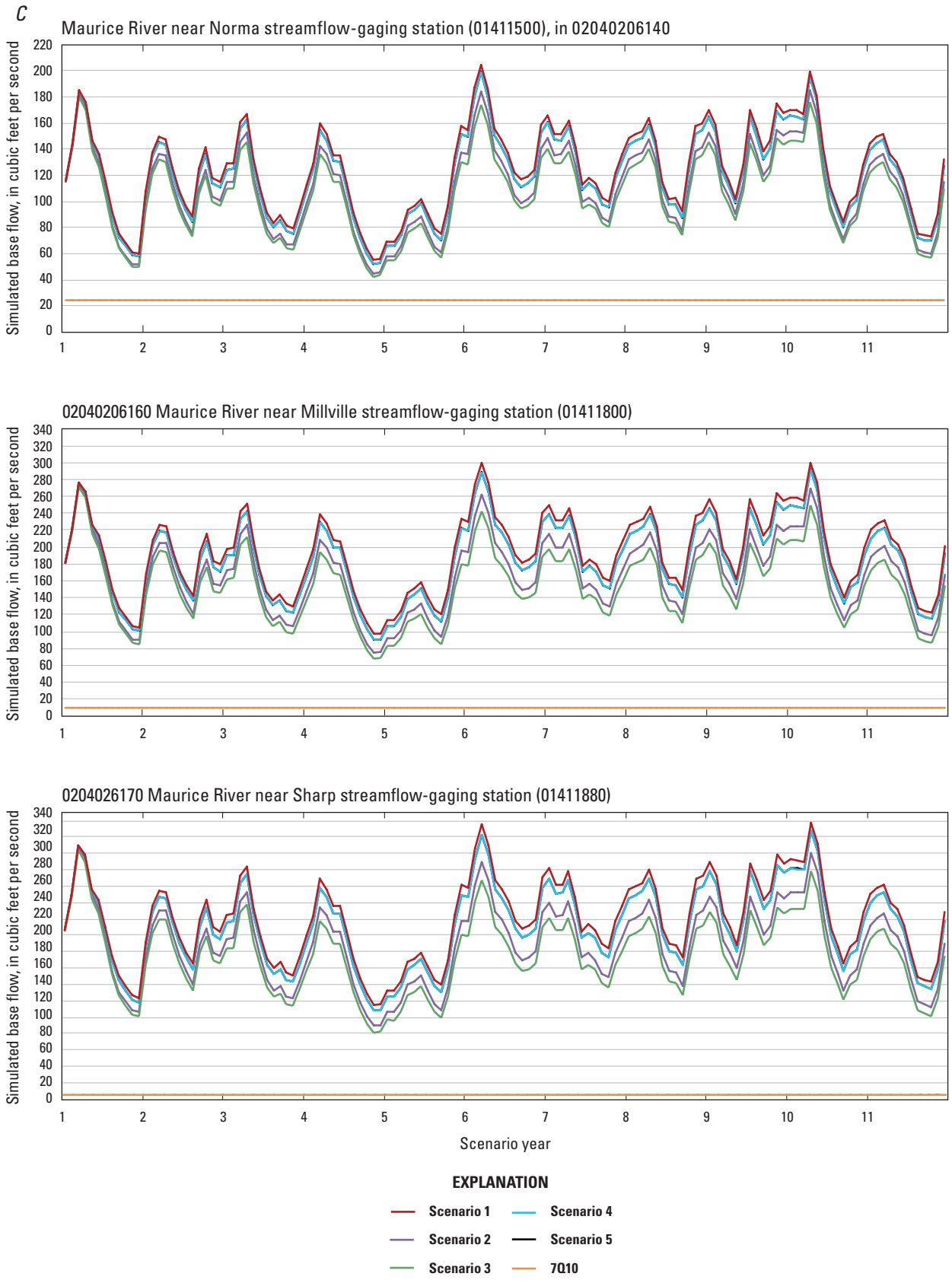


Figure 36. Hydrographs of simulated monthly base flow at pour points in Hydrologic Unit Code 11 drainage basins on the *A*, Cohansey River Basin, *B*, tributaries to the Maurice River Basin, and *C*, the mainstem of the Maurice River for scenarios 1–5 in the groundwater-flow model and the 7-day 10-year low flows, Cumberland County study area, New Jersey. (7Q10, 7-day 10-year low flows)—Continued

Table 11. Groundwater withdrawals for 2008 and scenarios 1–4, by permit type, for selected Hydrologic Unit Code 11 drainage basins in the groundwater-flow model, Cumberland County study area, New Jersey.

[Permit types are from the New Jersey Department of Environmental Protection Bureau of Water Allocation and Wells Permitting. HUC11, Hydrologic Unit Code 11; all withdrawals in cubic feet per second and rounded to nearest integer]

HUC11 number for subbasin	River or Tributary in the Maurice River Basin	10000 Series	2000 Series	5000 Series	Agriculture	Totals
		2008 Withdrawals				
02040206080	Cohansey River	1	63	10	98	172
02040206090	Cohansey River	3	0	48	53	104
02040206100	Back / Cedar / Nantuxent Creeks	1	0	0	33	34
02040206120	Still Run / Little Ease Run	2	0	23	16	41
02040206130	Scotland Run	2	2	30	3	37
02040206140	Maurice River	3	53	133	38	227
02040206150	Muddy Run	2	0	0	105	107
02040206160	Maurice River	1	0	17	10	28
02040206170	Maurice River	0	5	23	17	45
02040206180	Menantico Creek	1	2	33	83	119
02040206190	Manamuskin River	0	1	0	21	22
	Totals	16	126	317	477	936
		Scenario 1 Monthly average 1998–2008 withdrawals (Baseline)				
02040206080	Cohansey River	0	68	6	61	135
02040206090	Cohansey River	2	0	30	25	57
02040206100	Back / Cedar / Nantuxent Creeks	0	0	0	18	18
02040206120	Still Run / Little Ease Run	1	0	14	6	22
02040206130	Scotland Run	2	1	33	1	37
02040206140	Maurice River	2	42	149	25	217
02040206150	Muddy Run	1	0	0	58	59
02040206160	Maurice River	0	0	12	4	16
02040206170	Maurice River	0	7	27	10	45
02040206180	Menantico Creek	1	0	18	61	79
02040206190	Manamuskin River	0	2	0	15	17
	Totals	9	120	289	284	702
		Scenario 2 Adjusted agriculture full-allocation withdrawals				
02040206080	Cohansey River	4	97	10	351	462
02040206090	Cohansey River	17	0	53	170	240
02040206100	Back / Cedar / Nantuxent Creeks	2	0	0	139	141
02040206120	Still Run / Little Ease Run	11	0	25	43	79
02040206130	Scotland Run	10	81	50	9	151
02040206140	Maurice River	12	0	173	87	273
02040206150	Muddy Run	14	0	0	230	244
02040206160	Maurice River	6	0	32	33	70
02040206170	Maurice River	3	33	39	39	114
02040206180	Menantico Creek	6	6	23	164	199
02040206190	Manamuskin River	4	0	0	49	53
	Totals	89	217	405	1314	2026

Table 11. Groundwater withdrawals for 2008 and scenarios 1–4, by permit type, for selected Hydrologic Unit Code 11 drainage basins in the groundwater-flow model, Cumberland County study area, New Jersey.—Continued

[Permit types are from the New Jersey Department of Environmental Protection Bureau of Water Allocation and Wells Permitting. HUC11, Hydrologic Unit Code 11; all withdrawals in cubic feet per second and rounded to nearest integer]

HUC11 number for subbasin	River or Tributary in the Maurice River Basin	10000 Series	2000 Series	5000 Series	Agriculture	Totals
		Scenario 3 Full-allocation withdrawals				
02040206080	Cohansey River	4	97	10	545	656
02040206090	Cohansey River	17	0	53	247	317
02040206100	Back / Cedar / Nantuxent Creeks	2	0	0	197	199
02040206120	Still Run / Little Ease Run	11	0	25	60	97
02040206130	Scotland Run	10	81	50	13	154
02040206140	Maurice River	12	0	173	133	318
02040206150	Muddy Run	14	0	0	334	348
02040206160	Maurice River	6	0	32	51	89
02040206170	Maurice River	3	33	39	54	129
02040206180	Menantico Creek	6	6	23	264	298
02040206190	Manamuskin River	4	0	0	76	80
	Totals	89	217	405	1974	2685
		Scenario 4 2050 Municipal public-supply withdrawals[1]				
02040206080	Cohansey River	1	63	8	98	169
02040206090	Cohansey River	3	0	36	53	91
02040206100	Back / Cedar / Nantuxent Creeks	1	0	0	33	34
02040206120	Still Run / Little Ease Run	2	0	19	16	37
02040206130	Scotland Run	2	2	41	3	48
02040206140	Maurice River	3	53	175	38	269
02040206150	Muddy Run	2	0	0	105	107
02040206160	Maurice River	1	0	14	10	25
02040206170	Maurice River	0	5	32	17	54
02040206180	Menantico Creek	1	2	21	83	107
02040206190	Manamuskin River	0	1	0	21	22
	Totals	16	126	346	477	963

[1]Withdrawals were increased from monthly average 1998–2008 withdrawals to projected 2050 demand for municipal public-supply wells only; simulated 2008 withdrawals were used for all other wells. Values are the same for scenario 5.

The simulated net base flow to streams in scenario 2 and the recharge input for each month in scenario 2 are shown in figure 40. Figure 40 indicates that the monthly recharge is variable and the base flow follows a similar pattern over the 11-year period. The simulated base flow is typically greater when the monthly recharge is greater and less when monthly recharge is lower. Monthly base flow for scenario 2 varies over the 11-year simulation and ranges from 448.2 ft^3/s in September of scenario year 4 to 1,185.7 ft^3/s in April of scenario year 10. The average difference in total simulated base flow is about 86 ft^3/s less in scenario 2 than in scenario 1. The simulated budget components for groundwater withdrawals, net storage, and net base flow are shown in figure 34 for scenario 2.

The simulated monthly base flow at the pour point of each selected HUC11 in the Cohansey and Maurice River Basins and the Back, Cedar and Nantuxent Creeks Basin is shown in figure 36. Simulated base flow is lower than the 7Q10 values in several months (about 27 percent) from scenario year 7 to scenario year 11 for HUC 02040206080 in the Cohansey River Basin. (Scenario years 7 to 11 represent the same period of time represented in the hydrographs in figure 20 for this basin [01412800].) Many agricultural-irrigation wells are located in the upper part of HUC 020406080 and are screened less than 100 ft below land surface. The total increase in groundwater withdrawals from scenario 1 to scenario 2 in this drainage basin for agricultural use is 290 ft^3/s (table 11). Most of the months that show a base-flow value less than the 7Q10 are July

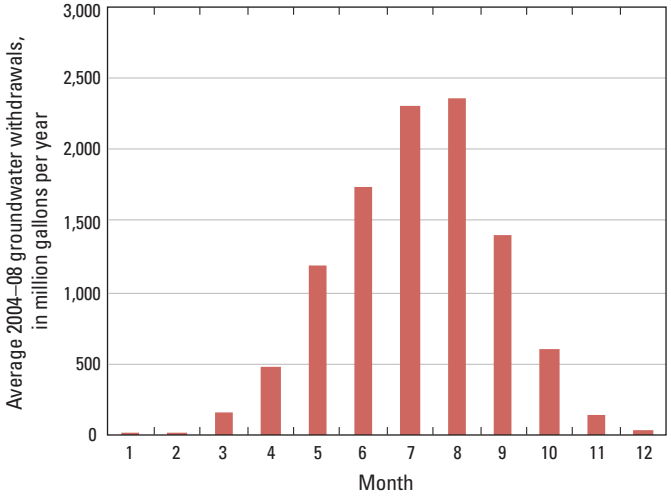


Figure 37. Average monthly full-allocation groundwater withdrawals for agricultural-irrigation use, Cumberland County study area, New Jersey, 2004–08.

through October when agricultural-irrigation withdrawals are at full allocation or at one-half the full-allocation.

The 7Q10 for Menantico Creek in the Maurice River Basin (HUC 02040206180) is greater than the simulated monthly base flow for about 29 percent of the 11-year simulation period (fig. 36*B*), mostly during late summer of scenario year 4, a year of low recharge in the 11-year simulation period (table 10). Vineland City and Millville City and two mobile home parks have public-supply wells sited in this drainage basin. Many agricultural-irrigation wells are sited in the upstream part of this drainage basin; these wells are screened less than 100 ft below land surface. The total increase in agricultural-irrigation groundwater withdrawals from scenario 1 to scenario 2 is 103 ft³/s (table 11).

Scenario 3 Full Allocation

The full-allocation simulation represents withdrawal conditions with all wells pumping at the monthly full-allocation rate. The location of withdrawal wells in scenario 3 are shown in figure 38 and are the same wells as shown in figure 9, except that wells with very small allocations were not included in the model. This exception is the result of the method used to distribute full-allocation withdrawals among groups of wells.

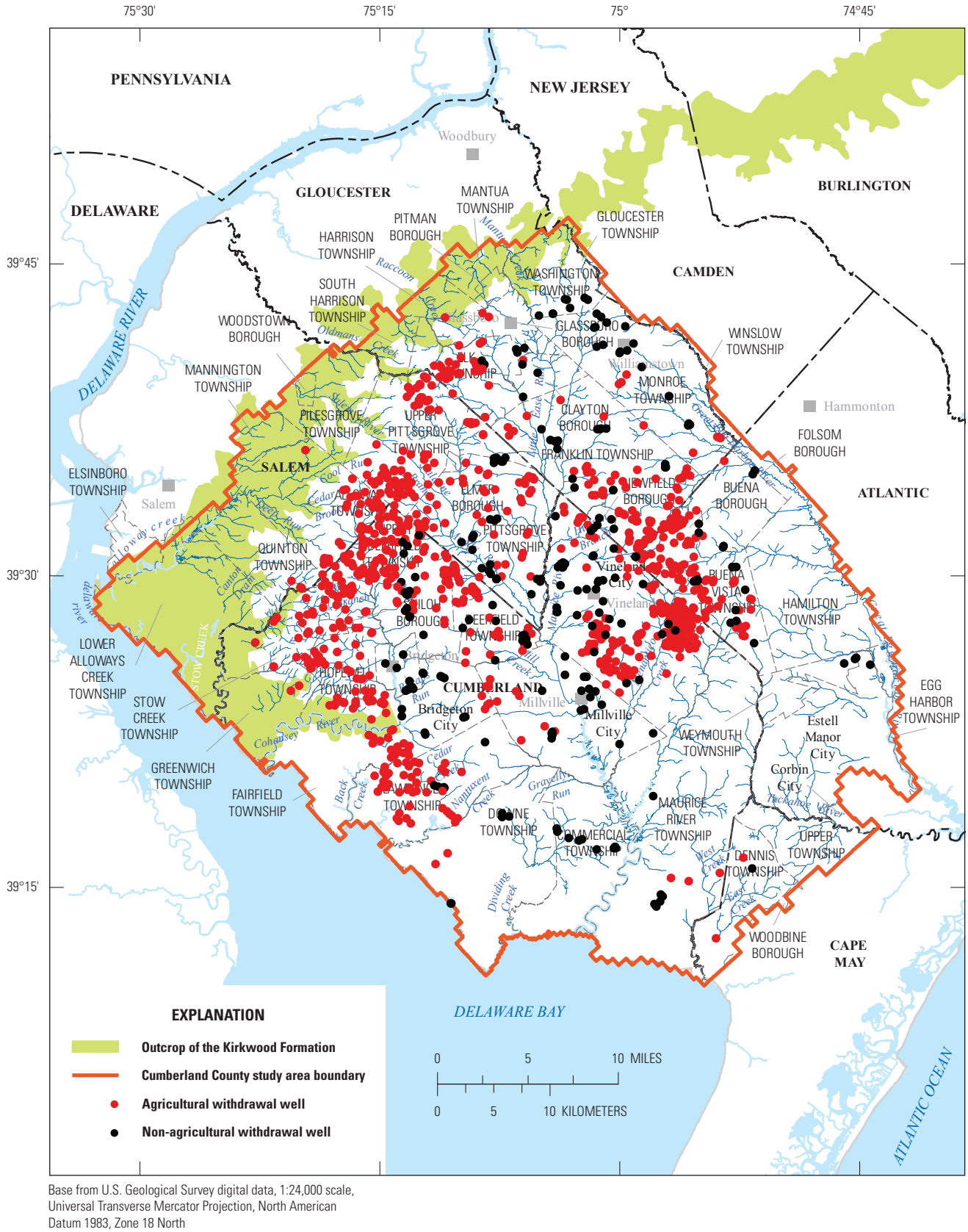
The simulated water-level contours for scenario 3 and the water-level changes from scenario 1 (baseline scenario) to scenario 3 are shown in figure 41 for June and September of scenario year 11. The full-allocation withdrawals affect simulated water levels and simulated base flow to streams, particularly in the Cohansey River Basin. Simulated water levels in small areas of the Cohansey River Basin decreased by more than 90 ft in June and more than 110 ft in September in a small area of the upstream part of the basin where many agricultural-irrigation wells are located. The average decline in simulated water levels for the Cohansey River Basin is less than 20 ft for scenario 3. When compared to scenario 1, simulated water levels declined more than 30 ft in the central western part of Muddy Run (HUC 02040206150) and more than 20 ft in the northeastern part of Menantico Creek (HUC 02040206180) subbasins in June and September of scenario year 11 (fig. 35). A large number of agricultural-irrigation wells are located in these two subbasins.

Total simulated monthly base flow for scenario 3 varied over the 11-year simulation from 420.1 ft³/s in November of scenario year 4 to 1,169.7 ft³/s in March of scenario year 1 (fig. 40). The average difference in total simulated monthly base flow is about 128.4 ft³/s less in scenario 3 than in scenario 1. When simulated base flow in scenario 2 is compared to that of scenario 3 in which all wells are pumping at full-allocation withdrawals in all months, the average difference in simulated monthly base flow is about 41.5 ft³/s greater in scenario 2 than in scenario 3. The simulated budget components—groundwater withdrawals, net storage, and net base flow—for scenario 3 are shown in figure 34. Water is released into the aquifer from storage in the summer when withdrawals are greater and recharge is lower, and water goes into storage in the winter.

The simulated monthly base flow at the pour point of each HUC11 in the Cohansey and Maurice River Basins is shown in figure 36*A–C*. Total groundwater withdrawals in the Cohansey River Basin are 781 ft³/s more in the full-allocation scenario (scenario 3) than in scenario 1 (table 11). Figure 36*A* indicates that simulated base flow in the upper Cohansey River Basin is less than the 7Q10 in all months over a 5-year simulation period (scenario years 7 to 11) for HUC 02040206080. The total increase in agricultural-irrigation groundwater withdrawals from scenario 1 to scenario 3 in this drainage basin is 484 ft³/s (table 11). More than 60 percent of the agricultural-irrigation wells are screened less than 100 ft below land surface in this basin. Figure 36*A* also indicates that simulated base flow in the lower Cohansey River Basin (HUC 02040206090) is less than the 7Q10 for more than one-half of the months during scenario years 7 through 11. The total increase in groundwater withdrawals from scenario 1 to scenario 3 in this drainage basin for agricultural-irrigation withdrawals is 222 ft³/s and for public-supply wells is 23 ft³/s (table 11). The municipal public-supply wells for Bridgeton City and several agricultural-irrigation wells are sited in the downstream part of HUC 02040206090.

Simulated base flow in HUC 020406180 (Menantico Creek) in the Maurice River basin is less than the 7Q10 for about 71 percent of the months over the 11-year simulation period, of which 70 percent of the months are April to November (fig. 36*B*). The total increase in groundwater withdrawals from scenario 1 to scenario 3 in this drainage basin for agricultural-irrigation withdrawals is 203 ft³/s (table 11).

Total groundwater withdrawals from wells located in the Scotland Run (HUC 0204206130) and Still Run/Little Ease Run (HUC 02040206120) subbasins in scenario 3 are 251 ft³/s (table 11). This is an increase of 192 ft³/s more in the Scotland Run and Still Run/Little Ease subbasins compared to scenario 1. In the Muddy Run subbasin (HUC 02040206150),



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 38. Location of withdrawal wells for which withdrawals were input to the groundwater-flow model in scenarios 2 and 3, Cumberland County study area, New Jersey.

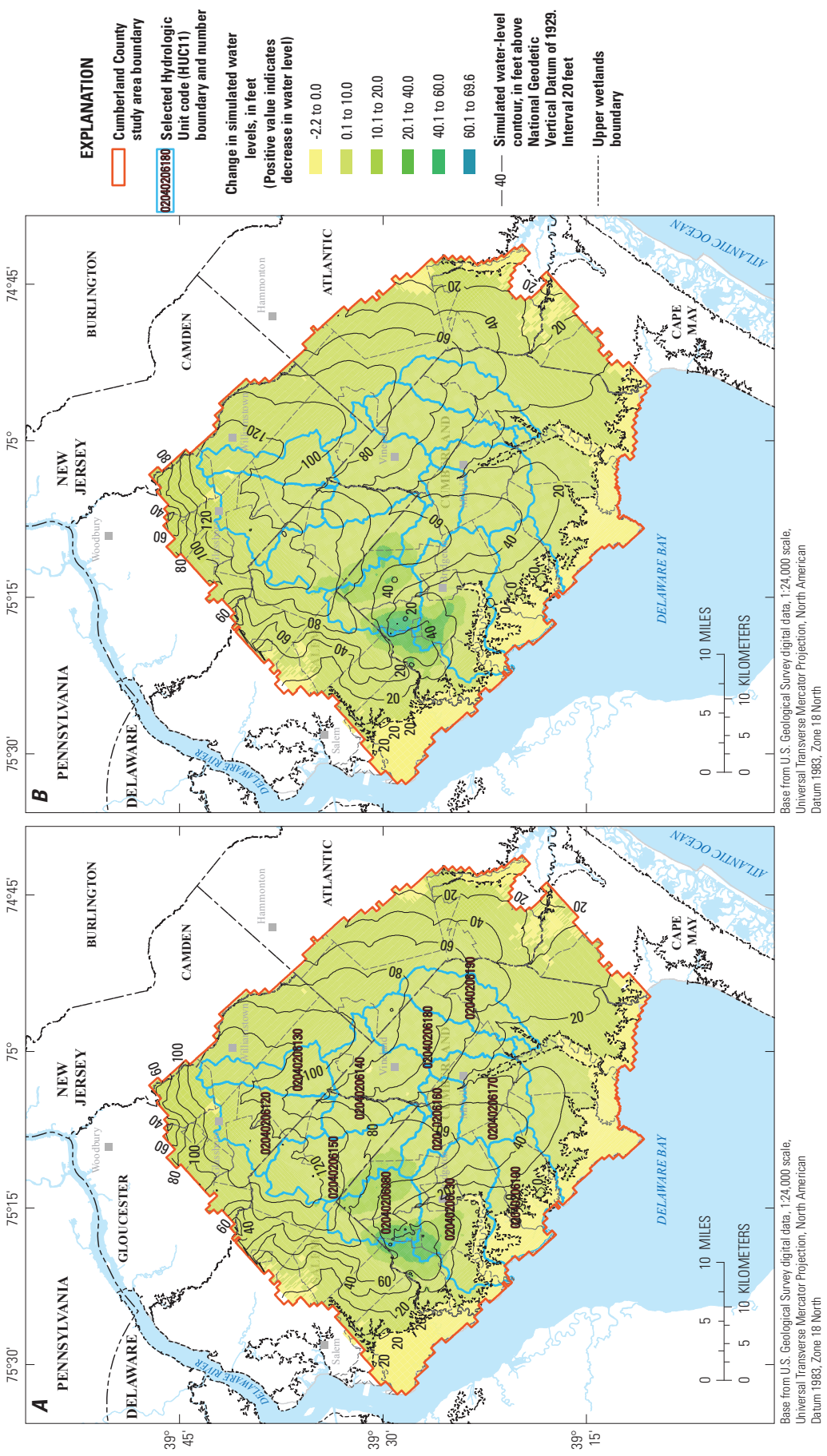


Figure 39. Simulated water-level contours for the Kirkwood-Cohansey aquifer system in scenario 2 for *A*, June and *B*, September in scenario year 11, in model layer 1, and change in simulated water levels from scenario 1 to scenario 2, Cumberland County study area, New Jersey.

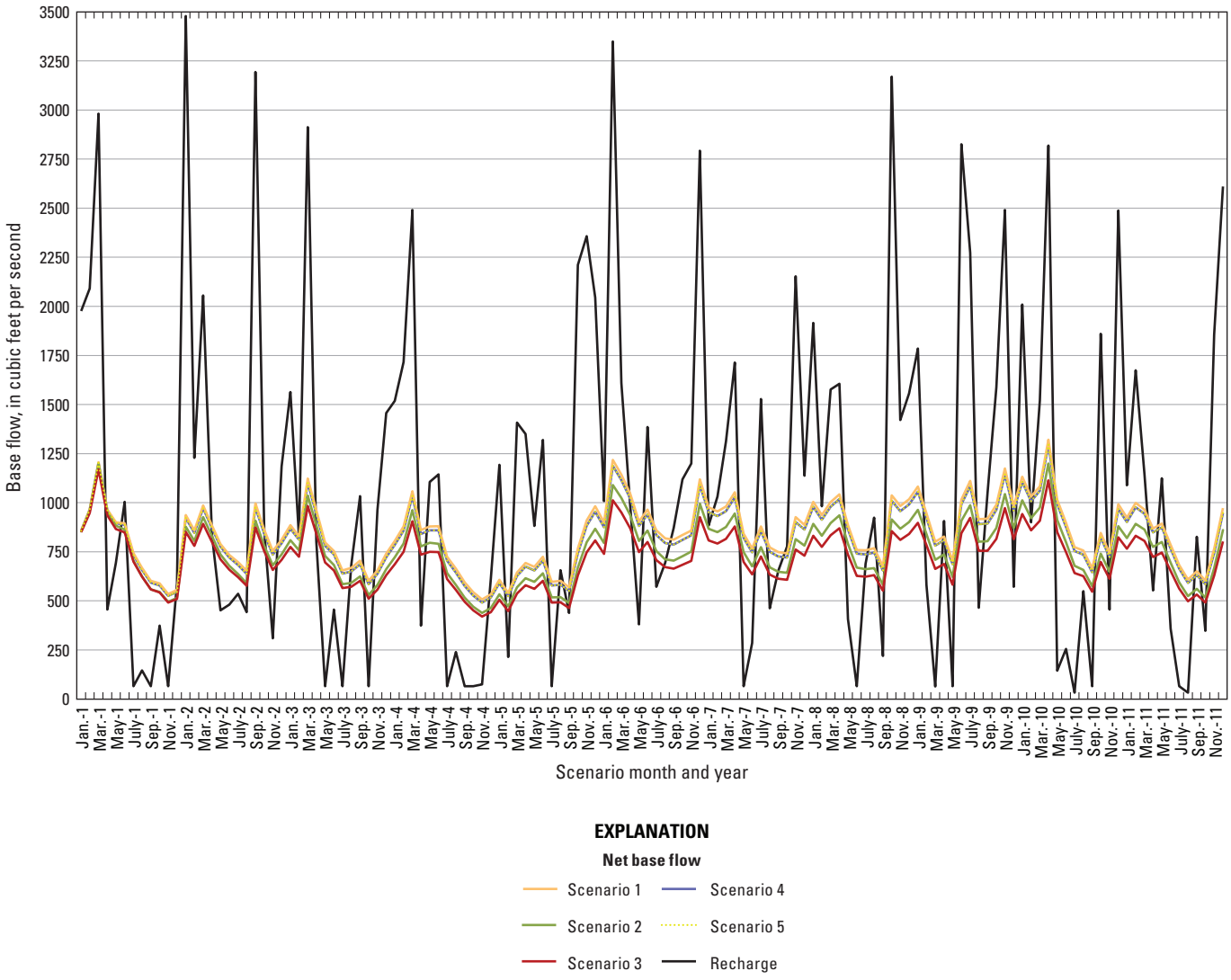


Figure 40. Monthly simulated net base flow and recharge for scenarios 1–5 in the groundwater-flow model, Cumberland County study area, New Jersey.

the increase is 289 ft³/s from scenario 1. In the Scotland Run and Still Run/Little Ease subbasins, the increase is for all categories of wells. In the Muddy Run subbasin, the increase is mostly for agricultural-irrigation wells. However, these three basins do not show base flow less than the 7Q10 for any of the scenarios (fig. 36).

Scenario 4 Projected 2050 Municipal Public-Supply Demand

During 1990–2000, the population of Cumberland County increased by 6.1 percent (New Jersey Department of Labor, 2006) and during 2000–10 by 7.15 percent (CensusViewer, 2012). The U.S. Census Bureau estimates that the population of Cumberland County was 155,544 in 2007, a 6 percent increase from the 2000 population of 146,438 (Delaware Valley Regional Planning Commission, 2009). Municipal population estimates for Cumberland County and the surrounding counties of Atlantic, Cape May, and Salem used in this scenario were developed by the South Jersey Transportation Planning Organization for 2007–30 (South Jersey Transportation Planning Organization, 2006). For each municipality in the study area, a linear projection was used to calculate the change in population over the interval from 2030 to 2050. Municipal population estimates for Gloucester County were developed by the Delaware Valley Regional Planning Commission to 2040 (Delaware Valley Regional Planning Commission, 2013). A linear projection was used to calculate the change in population from 2040 to 2050 for each municipality in the study area in that county. The projected percent increase for 2050 for municipalities in the study area is shown in table 12. The greatest projected increase in population in the study area is in Monroe Township (42 percent)

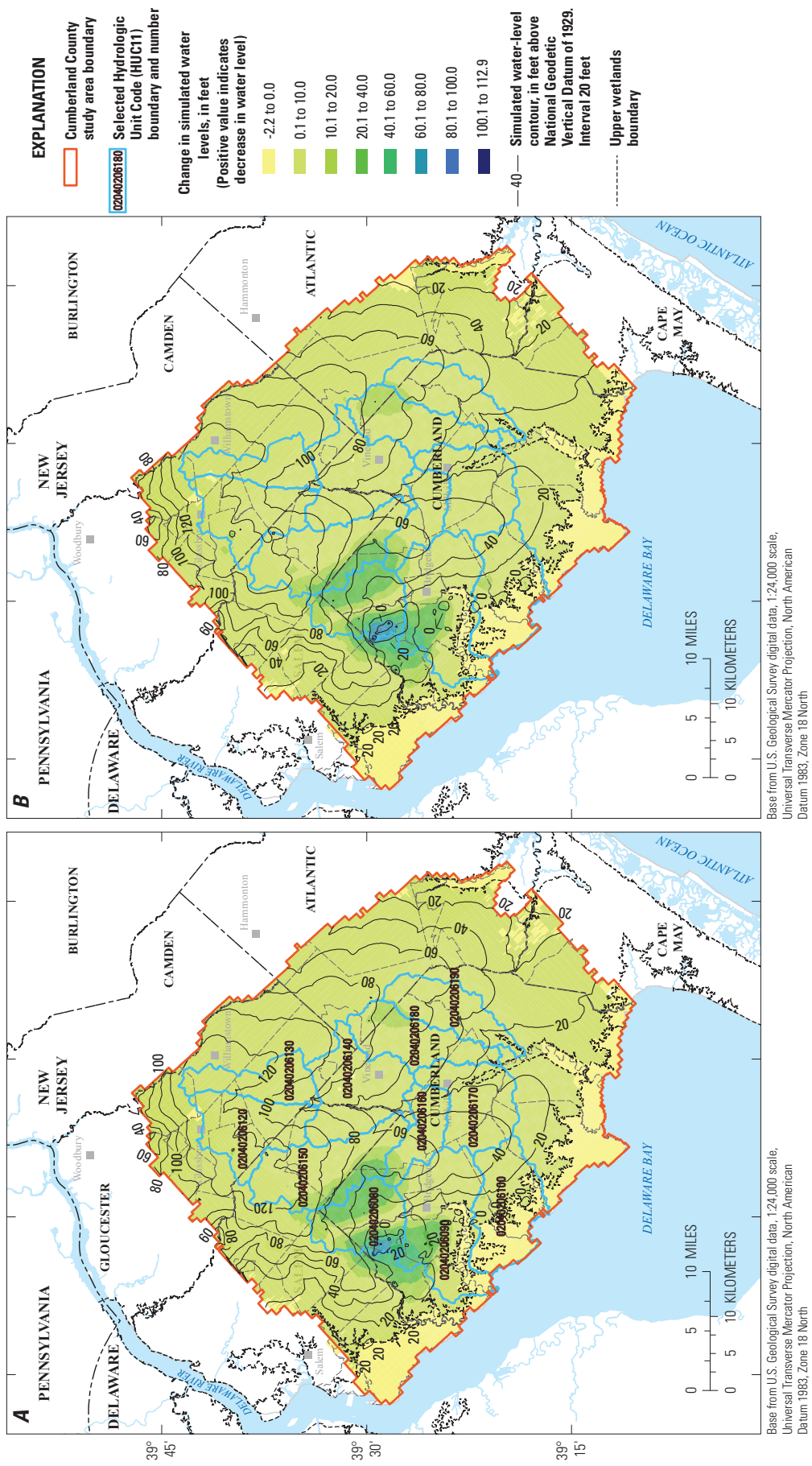


Figure 41. Simulated water-level contours for the Kirkwood-Cohansey aquifer system in scenario 3 for *A*, June and *B*, September in scenario year 11 in model layer 1 of the groundwater-flow model and change in simulated water levels from scenario 1 to scenario 3, Cumberland County study area, New Jersey.

Table 12. Projected percent increase in population from 2008 to 2050 for selected municipalities in the Cumberland County study area, New Jersey.

[NJDEP, New Jersey Department of Environmental Protection]

Municipality	County	NJDEP Bureau of Water Allocation number and wells for municipality	Percent increase in population from 2008 to 2050[1]
Bridgeton City	Cumberland	5032	0.23
Clayton Borough	Gloucester	5244	0.38
Glassboro Borough	Gloucester	5135	0.38
Millville City	Cumberland	5316	0.17
Monroe Township	Gloucester	5161	0.42
Newfield Borough	Gloucester	5147	0.10
Upper Deerfield Township	Cumberland	5376	0.19
Vineland City	Cumberland	5148	0.18
Washington Township	Gloucester	5194	0.17
Weymouth Township	Atlantic	5365	0.18

[1] Percent population increase estimated from South Jersey Transportation Planning Organization (2006) and Delaware Valley Regional Planning Commission (2013).

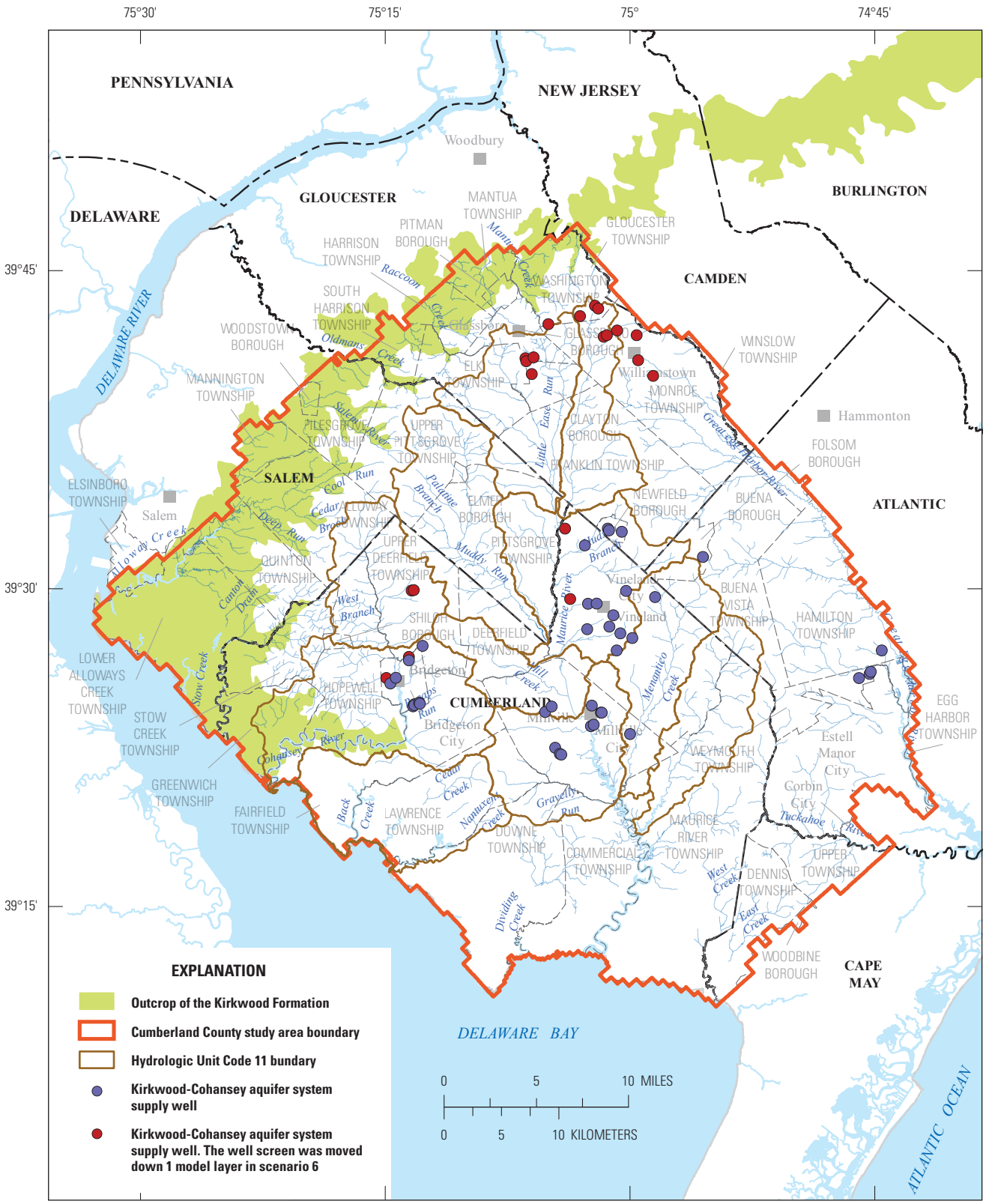
and in Clayton and Glassboro Boroughs (38 percent) in Gloucester County. The projected percent increase in population for each municipality was used to increase the groundwater withdrawals at municipal public-supply wells in the Kirkwood-Cohansey aquifer system from the 2008 monthly rate to the 2050 estimated rate to evaluate the effects of future groundwater withdrawals on these municipalities. The locations of municipal public-supply wells are shown in figure 42. All other wells were assigned the monthly 2008 withdrawals.

The simulated water-level contours for scenarios 4 and 5, and the water-level change from the baseline scenario (scenario 1), are shown in figure 43*A–B* for June and September of scenario year 11. Simulated water levels in the Maurice River Basin generally follow a pattern similar to those in scenario 1 for June and September in scenario year 11, and most areas show a decrease in simulated water levels of about 2 ft or less. In small areas in the upstream part of HUC 02040206080 (upper Cohansey River drainage basin), simulated water levels decreased by about 8 ft in June and September in scenario year 11 and by about 11 ft in June and September of scenario year 11 in HUC 02040206090 (lower Cohansey River drainage basin) where many agricultural-irrigation wells are present. Groundwater withdrawals in the Cohansey River Basin are 69 ft^3/s greater in scenario 4 than in scenario 1. Figure 43 shows water-level recovery in some small areas of the study area because the monthly groundwater withdrawals for June and September in scenario 1 are less than the withdrawals in 2008. (Total groundwater withdrawals in the groundwater-flow model in 2008 were 1,153.9 ft^3/s, whereas the total for scenario 1 was 917.3 ft^3/s).

Selected simulated budget components—groundwater withdrawals, net storage, and base flow—for scenario 4 are shown in figure 44. When the results of scenario 4 are compared to those of scenario 1, the average change in total simulated base flow is about 20.5 ft^3/s less in scenario 4 (fig. 36). Total monthly base flow in scenario 4 varied over the 11-year simulation and ranged from 490.9 ft^3/s in November of scenario year 4 to 1,296 ft^3/s in April of scenario year 10. Total net storage varied over the 11-year simulation from a low of -2,340 ft^3/s in January of scenario year 5 to as much as 1,113 ft^3/s in May of scenario year 10. Water is released into the aquifer from storage in the summer when withdrawals are greater and recharge is lower, and water goes into storage in the winter. A ZONEBUDGET (Harbaugh, 1990) flow-budget analysis indicated that groundwater flow to the wells in the deeper model layers is from vertical flow from the overlying model layer and from horizontal flow within the model layer. Groundwater is being intercepted by withdrawal wells and, therefore, is not available to discharge to streams.

Groundwater withdrawals from wells in the Scotland Run (HUC 0204206130) and Still Run/Little Ease Run (HUC 02040206120) subbasins for scenario 4 (83 ft^3/s; table 11) were 26 ft^3/s greater than those in scenario 1 (table 11). The increase occurred mostly in public-supply and agricultural wells in these two subbasins. For the three drainage basins along the mainstem of the Maurice River (HUCs 02040206140, 02040206160, and 0204006170), groundwater withdrawals in scenario 4 were 70 ft^3/s more than in scenario 1.

For HUC 02040206180 (Menantico Creek), simulated base flow was less than the 7Q10 during 12 months over the 11-year simulation (9 percent) (fig. 36). The groundwater withdrawals from the municipal public-supply wells in Vineland City and Millville City in this HUC11 were increased to 2050 estimates, an increase of 3 ft^3/s from scenario 1. The groundwater withdrawals at the agricultural-irrigation wells located in this HUC11 were increased 22 ft^3/s from those in scenario 1. As previously mentioned, the agricultural-irrigation



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 42. Location of municipal public-supply wells for which measured and estimated withdrawals were input to scenarios 4 and 5 in the groundwater-flow model, Cumberland County study area, New Jersey.

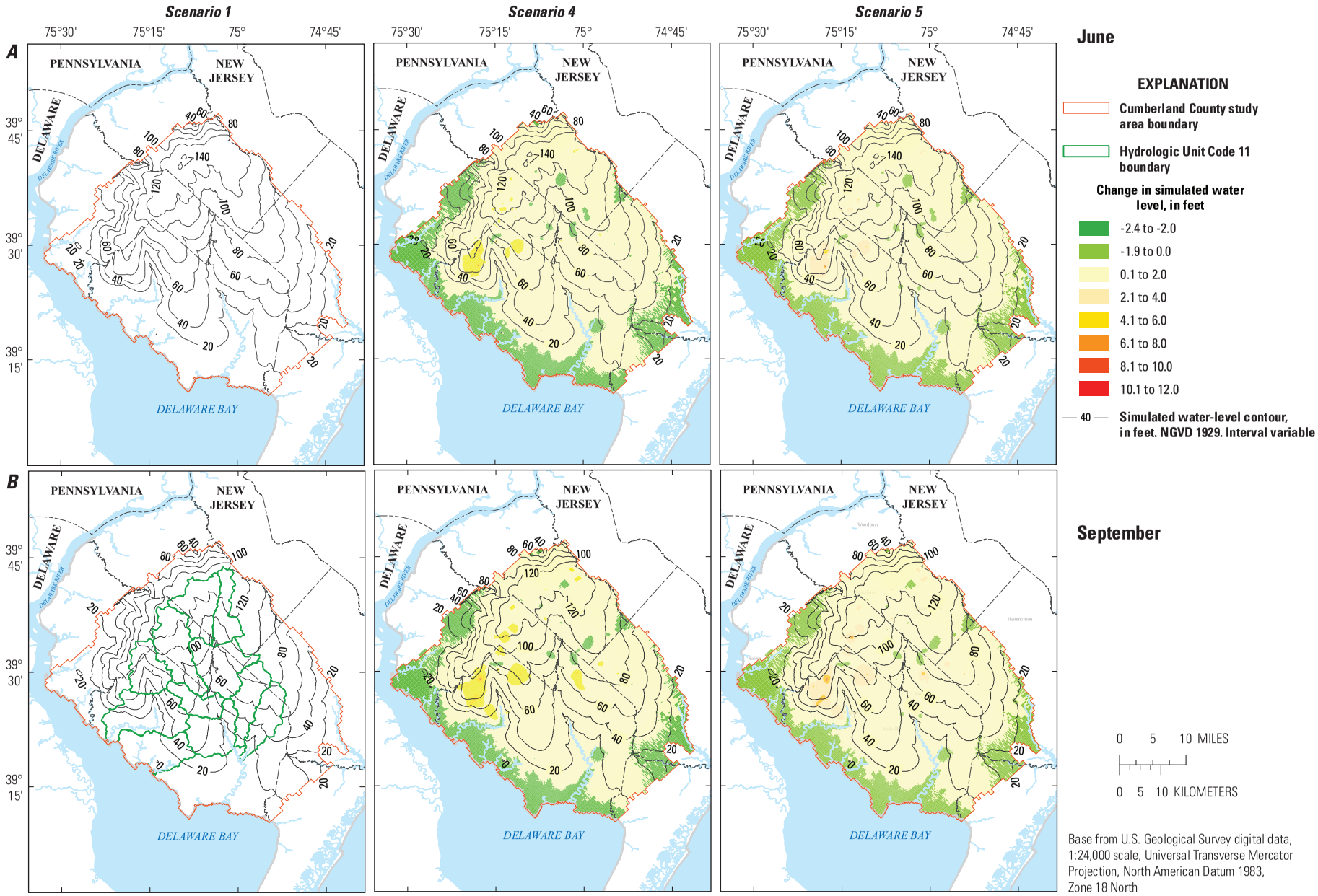


Figure 43. Simulated water-level contours for scenarios 1, 4, and 5 in the groundwater-flow model and changes in the simulated water levels from scenario 1 to scenarios 4 and 5 in the Kirkwood-Cohansey aquifer system for *A*, June and *B*, September in scenario year 11 for model layer 1, Cumberland County study area, New Jersey.

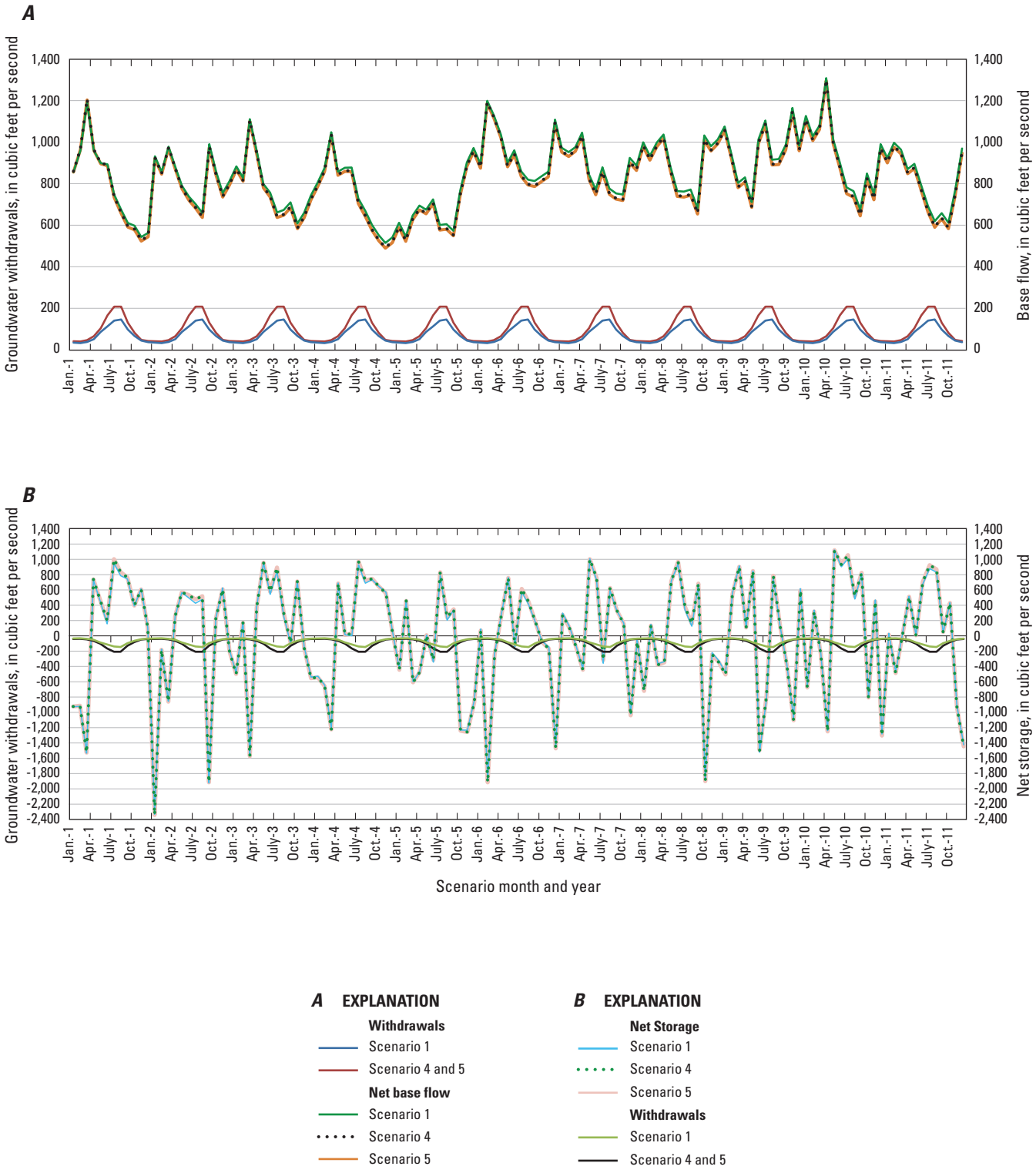


Figure 44. Selected flow-budget components for scenarios 1, 4, and 5 in the groundwater-flow model, by scenario month and year, Cumberland County study area, New Jersey.

groundwater withdrawals increased in scenario 4 because the monthly withdrawals for 2008 were used and were the starting point to increase withdrawals from the municipal public-supply wells, whereas scenario 1 incorporated the monthly average 1998–2008 withdrawals.

Scenario 5 Seasonal Alternative for Projected 2050 Public-Supply Demand

In this scenario, groundwater withdrawals in 2008 from municipal public-supply wells in the study area screened in the Kirkwood-Cohansey aquifer system were increased to the 2050 estimates used in scenario 4; however, the withdrawals at municipal public-supply wells were moved one model layer deeper. This was done to evaluate the effects of pumping from deeper parts of the Kirkwood-Cohansey aquifer system on base flow. All other wells in this scenario were pumped at the monthly groundwater withdrawal amounts for 2008.

The municipal public-supply wells for those municipalities shown in table 11 were assigned to model layers 2–5; one well was assigned to layer 6. The municipal public-supply wells in model layer 2 have a screened interval from 50 to 100 ft below land surface (bls); layer 3, 101–150 ft bls; layer 4, 151–200 ft bls; layer 5, 201–300 ft bls, and layer 6, greater than 301 ft bls. There are 59 municipal public-supply wells represented in the scenario, of which 23 remained in the original model layer because the wells were already in the lowest active model layer. Most of these wells are in Gloucester and Salem Counties and in the upstream part of the Cohansey River Basin (fig. 42). Therefore, 36 municipal public-supply wells in the model represented groundwater withdrawals in the next deeper model layer. Four of these wells are in the Great Egg Harbor River Basin (fig. 1). Twenty-nine wells are in the Still Run/Little Ease (HUC 02040206120) and Scotland Run (HUC 02040206130) subbasins, and the two drainage basins in the Cohansey River Basin (HUCs 02040206080 and 02040206090) (fig. 42). However, 1 well is in HUC 02040206170, and 2 wells are in HUC 02040206160, which are in the Maurice River Basin (fig. 42).

The simulated water-level contours for scenario 5 are shown in figure 43*A–B* for June and September of scenario year 11. Figure 43 also shows the simulated water-level changes from the baseline scenario (scenario 1) to scenario 5 for June and September of scenario year 11. The simulated water levels are similar to those shown in scenario 4 (fig. 43). In small areas of the upper Cohansey River drainage basin (HUC 02040206080), simulated water levels are about 8 ft lower in June and September of scenario year 11 in scenario 5 than in the baseline scenario. In small areas of the lower Cohansey River drainage basin (HUC 02040206090), simulated water levels are about 12 ft lower than simulated baseline scenario water levels in June and September of scenario year 11. Water-level declines occurred at irrigation wells pumped at the 2008 withdrawal rate. The Maurice River Basin shows water-level recoveries of more than 2 ft to more than 5 ft in some areas (indicated by a negative values on fig. 43). The recoveries occurred because the average 1998–2008 withdrawal rates used in scenario 1 are less than the 2008 rates used in scenario 4.

Selected flow-budget components for scenario 5 are shown in figure 44*A–B*. In scenario 5, total monthly base flow varied over the 11-year simulation and ranged from a low of 501.3 ft^3/s in November of scenario year 4 to 1,282.4 ft^3/s in April of scenario year 10. These values are similar to those in scenario 4. When the results for scenario 1 are compared to those for scenario 5, the average difference in simulated monthly base flow is about 19.2 ft^3/s less in scenario 5. When the results for scenario 4 are compared to those for scenario 5, the average difference in simulated monthly base flow is about 0.5 ft^3/s less for scenario 4.

The results for scenario 5 indicate that moving the wells deeper into the aquifer affects simulated water-level declines in the area of those wells and increases groundwater discharge to streams but only by less than 1 ft^3/s. Groundwater discharge to streams is affected either by pumped wells intercepting water so this water does not discharge to a stream or by pumped wells directly pulling water from a stream so the stream becomes a losing stream in the area of the wells. In scenarios 4 and 5, groundwater discharge to wells is being intercepted by pumped wells and therefore is not available to discharge to streams. The municipal public-supply wells in the Cumberland County study area in the baseline scenario were assigned to layers 2 to 6 in the groundwater-flow model. Therefore, in scenario 5, groundwater withdrawals from the 36 municipal public-supply wells were made from a deeper part of the aquifer system, farther below land surface by 50 ft or more. A flow-budget analysis of model results using the ZONEBUDGET program (Harbaugh, 1990) indicates that groundwater flow to the wells in the deeper model layers is from vertical flow from overlying model layers and from horizontal flow in the aquifer layer.

Hydrographs of the HUC11 drainage basins in figure 36 show that simulated monthly base flow in the Cohansey River Basin in scenario 5 is similar to simulated monthly base flow in scenario 4. Of the 16 municipal public-supply wells in the Cohansey River Basin (HUCs 02040206080 and 02040206090), 8 wells were not moved down to the next layer. For the Maurice River Basin, simulated monthly base flows at the Maurice River at Norma streamflow-gaging station (01411500) in HUC 02040206140 and the next downstream drainage basin, HUC 02040206170, were similar to simulated base flows in scenario 4.

For Menantico Creek in the Maurice River Basin (HUC 020406180) simulated base flow was lower during 12 nonconsecutive months (9 percent of the simulation period) of scenario years 4 and 5 (fig. 36). Municipal public-supply wells for Vineland City and Millville City are in the Menantico Creek subbasin.

Simulations Using the New Jersey RASA Numerical Groundwater-Flow Model

The Kirkwood-Cohansey aquifer system in the study area is underlain by the Piney Point aquifer, except for northernmost part where the outcrop of the Kirkwood Formation is present (fig. 45). Because the Piney Point aquifer was not modeled in the groundwater-flow model of the Cumberland study area, the RASA groundwater-flow model (Voronin, 2004) was used for scenarios 6–8. These simulations provide general information on the manner in which water levels in the confined Piney Point aquifer in the Cumberland County study area may change when groundwater withdrawals are increased. The RASA groundwater-flow model is described in Voronin (2004). The three steady-state scenarios are summarized in.

New Jersey Steady-State RASA Model

As part of this study, the finite-difference numerical flow model developed for the USGS RASA program for the New Jersey Coastal Plain was used to simulated flow in the Piney Point aquifer. The RASA numerical groundwater-flow model simulated flow in 10 New Jersey Coastal Plain aquifers, including the Piney Point aquifer. The New Jersey Coastal Plain was discretized vertically into 10 aquifers and 9 intervening confining units (Zapecza, 1989; Martin, 1998). The RASA model grid consists of 135 rows and 245 columns with a cell size of 0.25 mi² in the northern and southwestern Coastal Plain, 0.31 mi² in the southeastern Coastal Plain, and up to 3.16 mi² in offshore areas (Voronin, 2004). Average annual groundwater withdrawals were used to represent withdrawal conditions from 1968 to 1998. The RASA model grid boundary and the updip limit of the Piney Point aquifer in the Cumberland County study area are shown in figure 45. A more detailed description of the RASA model for the New Jersey Coastal Plain is provided in Martin (1998) and Voronin (2004). The RASA model has been used by the USGS to simulate water-supply scenarios for New Jersey (Watt and Voronin, 2006; Gordon, 2007; Spitz and DePaul, 2008). Minor changes previously were made to the vertical conductance of the Vincentown-Manasquan confining unit of the regional New Jersey Coastal Plain RASA model by Watt and Voronin (2006) to improve the representation of the hydrogeology of two minor confined aquifers, and the model was updated to include 1999–2003 average annual withdrawal data.

The RASA model was modified for this study to include annual groundwater withdrawals averaged from 2004 to 2008. In addition, transmissivity of the Piney Point aquifer in the RASA model was decreased to 500 ft²/d, which is about one-half the previous value, only in the Cumberland County study area where the aquifer is present. In addition, boundary flows in the Piney Point aquifer were increased by 20 percent in a small number of model cells across Delaware Bay to allow representation of increased groundwater withdrawals in Delaware and southern New Jersey. This was done to better match the 2008 synoptic water-level measurements in wells screened in the Piney Point aquifer in the Cumberland County study area (DePaul and Rosman, 2015). The inset in figure 45 shows the updip limit of the Piney Point aquifer in Delaware (Lacombe and Rosman, 2001). No other boundary flows were changed. No additional calibration or sensitivity analysis was done.

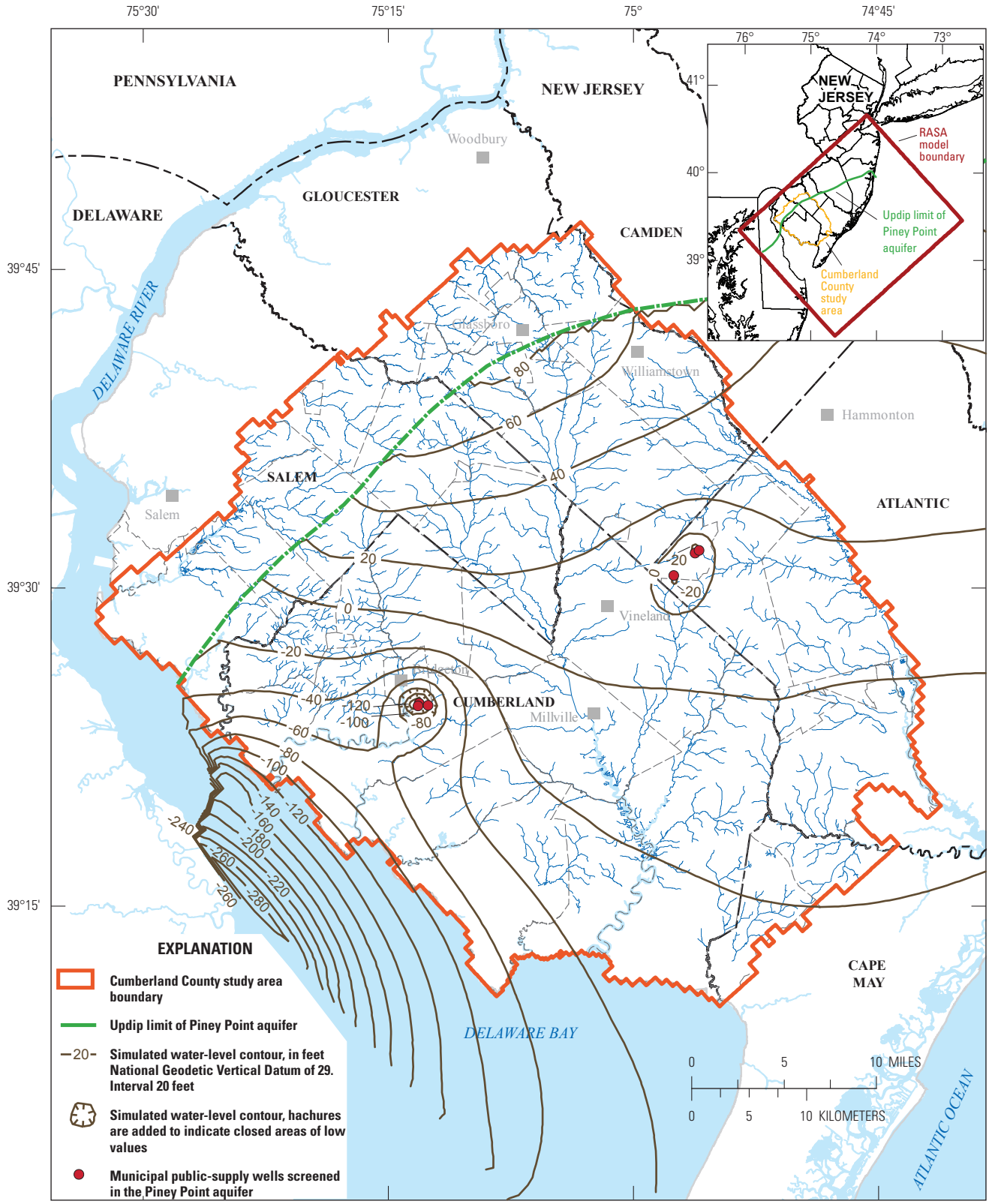
In this study, simulations were conducted with the modification to the RASA model in order to evaluate the effects of increased groundwater withdrawals on water levels in the Piney Point aquifer in the Cumberland County study area. Many verification simulations were conducted with different modifications to transmissivity and boundary flows in the Piney Point aquifer in order to best simulate the 2008 measured water levels for that aquifer (DePaul and Rosman, 2015).

There are some limitations using the RASA model for scenarios 6–8. Local-scale hydrologic features are not represented in the model. The use of an estimated parameter for transmissivity and the use of averaged annual values for groundwater withdrawals may lead to inaccuracies in the simulations. The simulated water levels for the regional flow system are considered reasonable because the area of influence is regional in extent and withdrawals made in 2008 from this aquifer in the Cumberland County study area are small in comparison to all other groundwater withdrawals from the New Jersey Coastal Plain aquifers. The effects of additional groundwater withdrawals on local water levels and flow are uncertain, but the simulations for scenarios 6–8 provide a reasonable estimate of simulated water-level declines.

Scenario 6 Average Annual 2004–08 Groundwater Withdrawals

This scenario is a steady-state simulation that incorporates the average annual withdrawals from 2004 to 2008 from aquifers in the New Jersey Coastal Plain. Groundwater withdrawals from most wells in the Cumberland study area groundwater-flow model are included in the RASA groundwater-flow model; however, the regional RASA model does not include the detail of agricultural-irrigation wells and many smaller users that are represented in the Cumberland County study area groundwater-flow model. These wells were given a RASA model grid location and added to layer 2 of the RASA model, which represents the Kirkwood-Cohansey aquifer system.

The simulated water levels for scenario 6 are shown in figure 45. Also shown are the six public-supply wells (3 in Buena Borough and 3 in Bridgeton City), which are represented as pumping from the Piney Point aquifer in the RASA model within the boundary of the Cumberland County study area. The groundwater withdrawal data for these wells are listed in table 13. The simulated water levels at the center of the cone of depression are more than 120 ft below NGVD 29



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 45. Simulated water-level contours for the Piney Point aquifer using the RASA model under average 2004–08 withdrawal conditions, Cumberland County study area, New Jersey.

Table 13. Groundwater withdrawals from wells in the Piney Point aquifer for scenarios 6–8 in the RASA model, by municipality, in the Cumberland County study area, New Jersey.

[Mgal/yr, million gallons per year; N/A, not applicable; NJDEP, New Jersey Department of Environmental Protection; RASA, Regional Aquifer System Analysis]

Municipality	County	NJDEP Bureau of Water Allocation permit number	Number of wells pumping from the Piney Point aquifer	Number of pumped wells moved from the Kirkwood-Cohansey aquifer system to the Piney Point aquifer	Total withdrawals (Mgal/yr)	Approximate largest decline in simulated water level from baseline scenario (feet)
Scenario 6 Baseline						
Bridgeton City	Cumberland	5032	3	0	363.7	N/A
Buena Borough	Atlantic	5275	3	0	200.2	N/A
Scenario 7 Estimated 2050 public-supply demand						
Bridgeton City	Cumberland	5032	3	1	388.2	40
Glassboro Borough	Gloucester	5135	0	1	44.4	50
Buena Borough	Atlantic	5275	3	0	200.2	20
Clayton Borough	Gloucester	5244	0	1	127.4	50
Millville City	Cumberland	5316	0	1	282.2	130
Monroe Township	Gloucester	5161	0	1	114.5	70
Newfield Borough	Gloucester	5147	0	1	48.6	40
Upper Deerfield Township	Cumberland	5376	0	1	197.6	70
Vineland City	Cumberland	5148	0	1	267.7	100
Weymouth Township	Atlantic	5365	0	1	22.7	20
Scenario 8 Full allocation						
Bridgeton City	Cumberland	5032	3	0	363.7	20
Buena Borough	Atlantic	5275	3	0	200.2	40
Millville City	Cumberland	5316	0	2	483.8	170
Monroe Township[1]	Gloucester	5161	0	1	235.8	110
Vineland City	Cumberland	5148	0	1	484.6	190

[1]The total full-allocation withdrawal for the well in Monroe Township is 283 Mgal/yr. The remainder of the withdrawals, 47.2 Mgal/yr, was input for a well in the Kirkwood-Cohansey aquifer system.

at two of the Piney Point wells located in Bridgeton City; the simulated water levels are more than 100 ft below NGVD 29 at the third Bridgeton City well in the Piney Point aquifer. The simulated water levels at the center of the two cones of depression in Buena Borough are about 20 ft below NGVD 29 in the area around the three Piney Point wells.

Scenario 7 Projected 2050 Demand for Municipal Public Supply

Scenario 7 is a steady-state scenario, which investigates the possible future use of the Piney Point aquifer in the Cumberland County study area. The groundwater withdrawals in this scenario are the same as in scenario 6, except for the withdrawals from 50 municipal public-supply wells in the Kirkwood-Cohansey aquifer system (layer 2) in the RASA model that are within the boundary of the Cumberland County study area. For these 50 public-supply wells, the average annual 2004–08 groundwater withdrawals used in scenario 6 were increased to annual 2050 withdrawals by using the percentages shown in table 12, depending on the municipality in which the wells are located. In addition, groundwater withdrawals in nine public-supply wells screened in the Kirkwood-Cohansey aquifer system in the RASA model (1 well each for 9 of the 10 municipalities in table 12) were moved to the Piney Point aquifer (for example, from RASA model layer 2 [scenario 6] to layer 4 [scenario 7].) Therefore, for these nine wells, only the model layer (aquifer) was changed. (Layer 3 of the RASA model is the confined Kirkwood aquifer and is present east of the Cumberland County study area groundwater-flow model (see figure 3). One municipality listed in table 12, Washington Township in Gloucester County, is north of the northwestern extent of the Piney Point aquifer; therefore, those municipal public-supply wells could not be moved to the Piney Point aquifer, and withdrawals were represented as being in the Kirkwood-Cohansey aquifer system. The groundwater withdrawals from the Piney Point aquifer for those wells are listed in table 13. All other wells in the RASA groundwater-flow model were pumped at the average annual 2004–08 withdrawal rates input in scenario 6.

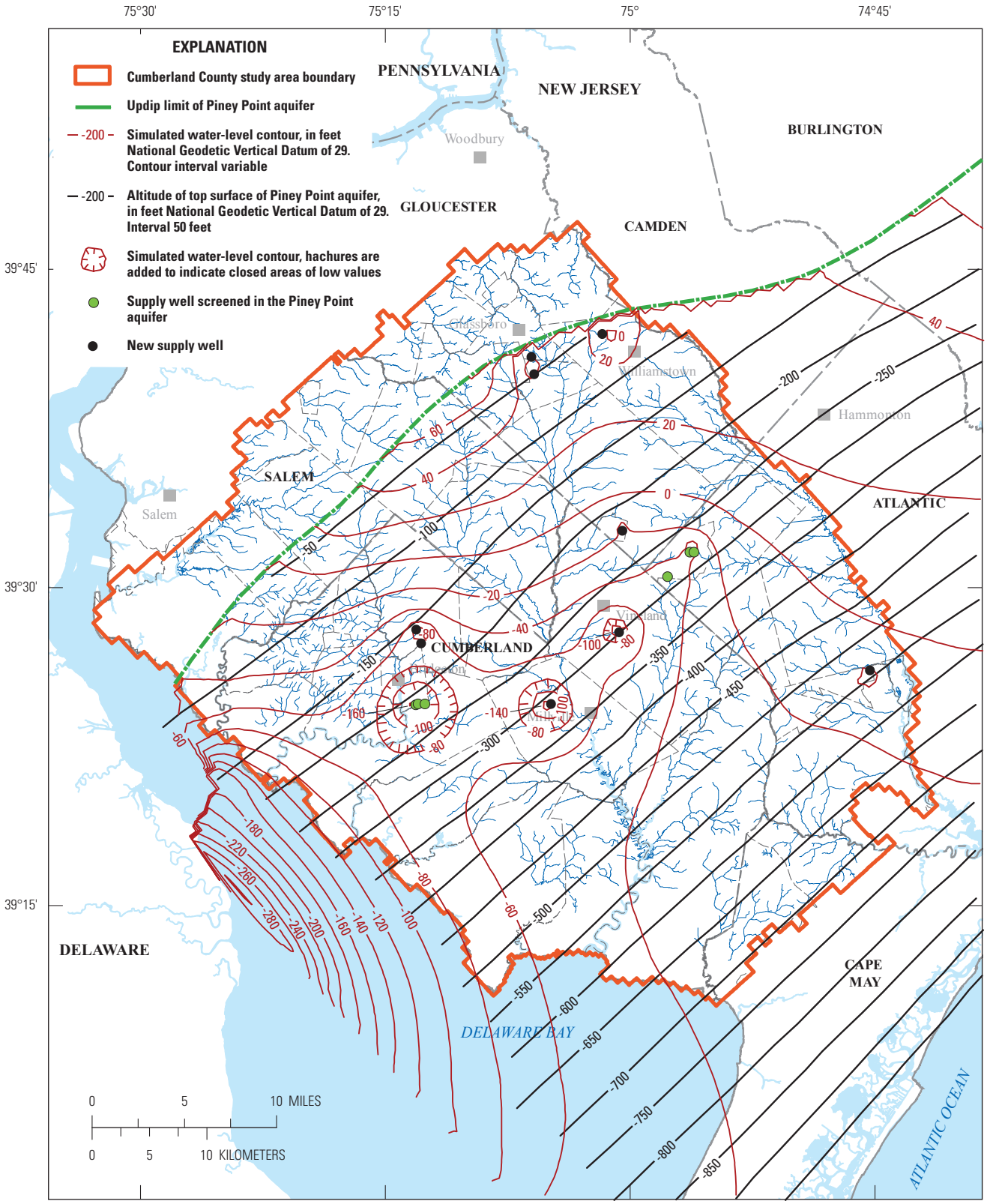
Because optimization of groundwater withdrawals from the Piney Point aquifer was not within the scope of this study, multiple simulations were run using different combinations of moving withdrawals from a public-supply well from each municipality pumping from the Kirkwood-Cohansey aquifer system to pump from the Piney Point aquifer instead. Therefore, the location of the pumping well in the model was not changed. The results of only one of these simulations are presented in this report.

During the well selection process, the geohydrologic location of the public-supply wells and aquifer thickness were used as a selection criteria. The aquifer is thickest in western Cumberland County, more than 200 ft thick (Martin, 1998). As previously mentioned in scenario 6, Bridgeton City and Buena Borough use the Piney Point aquifer for public supply, so groundwater withdrawals moved to the Piney Point aquifer had to be located away from the Bridgeton City and Buena Borough wells to limit the effects of new pumping on the existing pumped wells in those two municipalities (fig. 46). The selected location and distance from the updip limit of the aquifer and from existing Piney Point aquifer pumped wells were based, in part, on the magnitude of the withdrawals from the hypothetical well. Figure 46 shows the altitude of the top of the Piney Point aquifer as given Zapecza (1989). Because of the low transmissivity incorporated in the model of the Piney Point aquifer in the study area, a public-supply well pumped at the estimated 2050 withdrawal rate could cause the simulated water level to fall below the top of the altitude of the aquifer, which can cause drying up of wells, land subsidence, and increased pumping costs. The average transmissivity of the Piney Point aquifer in the Cumberland County study area simulated by the RASA model is 500 ft^2/d, which is less than the average transmissivity of the Kirkwood-Cohansey aquifer system of 4,500 ft^2/d (Voronin, 2004) in the Cumberland County study area. To prevent this problem from occurring in a simulation, a particular combination of withdrawals from all the wells pumping from the Piney Point aquifer in the study area was identified from the multiple simulations run for scenario 7. Additionally, future use of the Piney Point aquifer in the Cumberland County study area for public supply would need to consider increased groundwater withdrawals from the Piney Point aquifer at pumped wells across Delaware Bay in Delaware. The location of the groundwater divide in the Piney Point aquifer could not be determined from the limited number of water levels measured in wells screened in the Piney Point aquifer in the Cumberland County study area and in Delaware during the 2008 New Jersey Coastal Plain synoptic (DePaul and Rosman, 2015).

The simulated water levels for the selected well locations used in scenario 7 are shown in figure 46. Declines in simulated water levels are observed at the nine Piney Point wells that represented the estimated 2050 groundwater withdrawals. The simulation resulted in cones of depression around the pumped wells. The largest decline in simulated water level is shown in table 13.

Scenario 8 Full-Allocation Groundwater Withdrawals for Public-Supply Wells in Millville City, Vineland City, and Monroe Township

Scenario 8 is a steady-state simulation that investigates the use of the Piney Point aquifer in the study area under annual full-allocation groundwater withdrawals for three municipalities. The groundwater withdrawals in this scenario are the same as in scenario 6, except for the withdrawals from the municipal public-supply wells in the Kirkwood-Cohansey aquifer system in Millville City, Vineland City, and Monroe Township which were increased to annual full-allocation withdrawals. In addition, the full-allocation withdrawals from the Kirkwood-Cohansey aquifer system in one public-supply well



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 46. Simulated water-level contours in the Piney Point aquifer for scenario 7 of the RASA model and altitude of the top of the Piney Point aquifer, Cumberland County study area, New Jersey. (Piney Point aquifer altitudes from Zapecza, 1989)

in each of the three municipalities was moved to the deeper Piney Point aquifer; therefore, following the same method used in scenario 7, for these three wells, only the model layer was changed. Multiple simulations were run using different combinations of public-supply wells moved to the Piney Point aquifer, but the results of only one of these simulations is presented in this report. The groundwater withdrawals used for these wells in scenario 8 are listed in table 13. The same criteria used in scenario 7 for well selection was used for this scenario.

The simulated water-level contours from scenario 8 are shown in figure 47. Monroe Township is near the northwestern extent of the Piney Point aquifer; therefore, only the public-supply wells in this township located farther downdip from the northwestern extent or that had smaller full-allocation rates could be used in the simulation without causing simulated water levels to drop below the top of the Piney Point aquifer. The two wells farthest from the updip limit of the aquifer had the largest allocation limits; therefore, two other wells were chosen (fig. 47). The well chosen to represent pumping from the Piney Point aquifer in this scenario could not be pumped at the full allocation limit (1.2 ft^3/s) because the full allocation caused the simulated water level to drop almost to the altitude of the top of the Piney Point aquifer. Therefore, this well was given an allocation of 1.0 ft^3/s, and the remainder of the allocation (0.2 ft^3/s) was assigned to a well pumping from the Kirkwood-Cohansey aquifer system in Monroe Township. A cone of depression was simulated near the well in the Piney Point aquifer. The simulated water levels are about 40 ft below NGVD 29, about 110 ft lower than the simulated water levels from scenario 6. The simulated water levels from scenario 8 are about 10 ft above the altitude of the top of the Piney Point aquifer in this area.

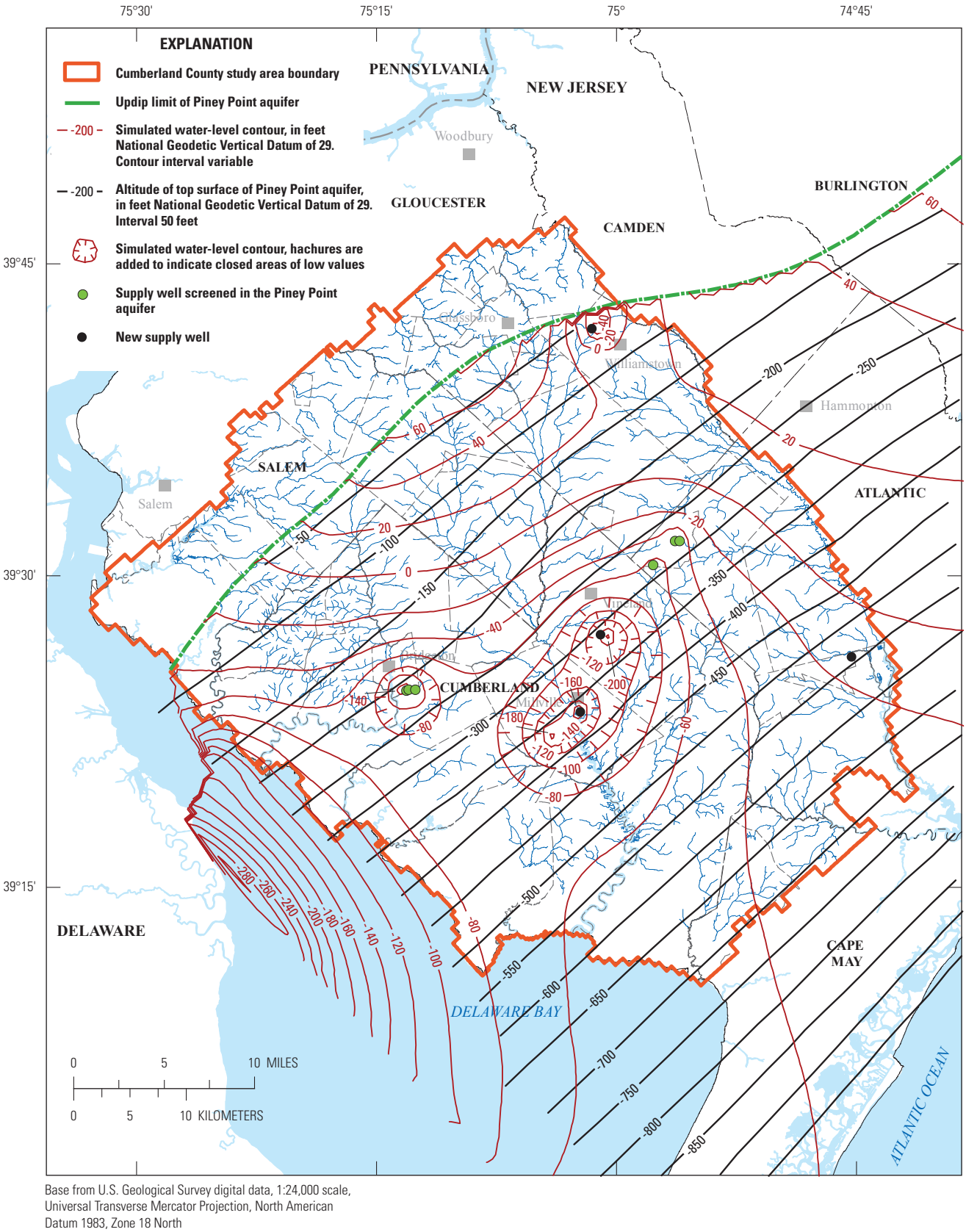
A cone of depression centered on a public-supply well moved to the Piney Point aquifer from the Kirkwood-Cohansey aquifer system in Vineland City is about 200 ft below NGVD 29, about 190 ft lower than the simulated water levels in scenario 6. When compared to the simulated water levels for scenario 6, simulated water levels for scenario 8 were more than 40 ft lower in the Buena Borough well nearest to the Vineland City well and about 20 ft lower in the other two Buena Borough wells farther away from the Vineland City well.

A cone of depression is centered on two public-supply wells in Millville City moved to the Piney Point aquifer from the Kirkwood-Cohansey aquifer system. The water level was more than 180 ft below NGVD 29 for one well and about 160 ft below NGVD 29 for the other well, a decline of less than 170 ft and about 150 ft, respectively, from the simulated water levels in scenario 6. The center of a cone of depression near Bridgeton City in scenario 6 showed a 20 ft decline in simulated water levels as a result of the additional pumping of the two wells in Millville City.

The results of scenarios 7 and 8 indicate that the withdrawal rate and location of additional pumping in the Piney Point aquifer in the study area need further evaluation. The simulated water levels from scenarios 7 and 8 indicate that the additional pumping from the Piney Point aquifer did not result in a drop in simulated water levels below the top of the Piney Point aquifer for that particular set of withdrawals rates and well locations. Additionally, future use of the Piney Point aquifer in the Cumberland County study area for public supply would need to consider the effects of increased withdrawals at pumping wells screened in the Piney Point aquifer across Delaware Bay in Delaware.



Photograph of agricultural-irrigation well in Cumberland County (Provided by Robert Rosman, U.S. Geological Survey)



Base from U.S. Geological Survey digital data, 1:24,000 scale, Universal Transverse Mercator Projection, North American Datum 1983, Zone 18 North

Figure 47. Simulated water-level contours in the Piney Point aquifer for scenario 8 of the RASA model and altitude of the top of the Piney Point aquifer, Cumberland County study area, New Jersey. (Piney Point aquifer altitudes from Zapecza, 1989)

Summary and Conclusions

The U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, conducted an investigation of the groundwater/surface-water interactions and the effects of withdrawals from the Kirkwood-Cohansey aquifer system in the Maurice and Cohansey River Basins in Cumberland County and adjacent counties. The major resource for groundwater withdrawals in the Maurice and Cohansey River Basins is the Kirkwood-Cohansey aquifer system. This aquifer system is present throughout Cumberland County and is the principal source of groundwater for public and domestic supply and agricultural-irrigation, industrial, and commercial water use in Cumberland County, which has a substantial agricultural economy. The aquifer system is generally unconfined, but semi-confined and confined conditions exist within the Cumberland County study area. Although many areas of local clay units are present, the aquifer system is vertically connected because an extensive confining unit is not present in most of Cumberland County. The aquifer system consists of gravel, sand, silt, and clay sediments of the Cohansey Sand and Kirkwood Formation. Many of the clay units within the Kirkwood-Cohansey aquifer system are of variable extent. The Kirkwood-Cohansey aquifer system thickens downdip from its northern extent near the outcrop area of the Kirkwood Formation in southern Salem and central Gloucester Counties to more than 500 feet (ft) in southeastern Cumberland County.

This investigation involved the development of a numerical ground-water flow model to simulate the effects of groundwater withdrawals from the Kirkwood-Cohansey aquifer system on base flow in the Cohansey and Maurice River Basins. The groundwater system in the Cohansey and Maurice River Basins supplies about 80 percent or more of annual streamflow as base flow. Increasing groundwater withdrawals from the Kirkwood-Cohansey aquifer system is a concern because of potential streamflow depletion, resulting from lower base flow owing to increased withdrawals in the basins.

A transient numerical groundwater-flow model of the Kirkwood-Cohansey aquifer system was constructed and calibrated; the model incorporated monthly recharge, groundwater withdrawals, and surface-water diversions from 1998 to 2008. The Kirkwood-Cohansey aquifer system was represented in the model by six layers. Base flow for each stream and river in the model was represented using the Streamflow-Routing Package of MODFLOW to simulate base flow. Hydraulic conductivity in the groundwater-flow model ranged from 40 to 160 feet per day (ft/d).

The recharge rates input to the groundwater-flow model represent long-term precipitation minus long-term evaporation and surface-water runoff. A monthly recharge rate was calculated for each month from January 1998 to December 2008 from the monthly soil moisture deficit and the average direct runoff for the Cohansey River and the Maurice River Basins. The simulated flow budgets for the entire simulation period, 1997–2008, indicate that the major inflow to the Kirkwood-Cohansey aquifer system is recharge that eventually discharges to streams when not diverted to wells or diverted from the streams for irrigation. Hydrographs of base flow of the Cohansey and Maurice Rivers indicate that monthly discharge is variable.

In 2008, reported groundwater withdrawals from the Kirkwood-Cohansey aquifer system in the study area totaled about 21,700 million gallons; about 36 percent was used for public supply, about 49 percent for agricultural-irrigation use, and the remaining 15 percent for industrial, commercial, mining by sand and gravel companies, and non-agricultural irrigation use. Seasonal variations in withdrawals in the study area were observed for each year; generally, greater withdrawals occurred during the summer months for irrigation water use. Withdrawals from 1998 to 2008 in the summer months (June–August) generally were more than 4 times those in the winter (December–February). The simulated flow budget for 2008 indicated that groundwater withdrawals accounted for about 10 percent of outflow from the aquifer system, and outflow to streams accounted for about 77 percent of the budget.

Five withdrawal scenarios were simulated using the numerical groundwater-flow model of the Cumberland County study area. The scenarios represented an 11-year period. Monthly recharge values from the numerical groundwater-flow model were used, and the groundwater withdrawals, by month, were varied, depending on the withdrawal scenario. The results of these scenarios were evaluated to assess changes in base flow, water levels, and flow budgets for the Kirkwood-Cohansey aquifer system compared to a baseline simulation (scenario 1). Scenario 1 incorporated averaged 1998–2008 monthly groundwater withdrawals and this scenario was used as a baseline for comparison to the results of scenarios 2–5.

In scenario 2, full-allocation groundwater withdrawals at agricultural-irrigation wells were input for June, July, and August. No groundwater withdrawals were input for November, December, January, February, and March, and 50 percent of the full-allocation groundwater withdrawals was input for April, May, September, and October for each agricultural-irrigation well. For all other types of wells, full-allocation withdrawals were used. In scenario 2, simulated water levels in the Cohansey River Basin decreased by more than 67 ft in June of scenario year 11 in the upstream part of the basin where many agricultural-irrigation wells are located. In scenario 3, simulated water levels in a small part of the Cohansey River Basin decreased by more than 100 ft in September of scenario year 11.

In scenario 2, the simulated monthly base flow is lower than the 7-day 10-year (7Q10) low flow for about 27 percent of the months during scenario years 7–10 for Hydrologic Unit Code 11 (HUC) 02040206080 in the upper Cohansey River Basin. Many agricultural-irrigation wells are in the upper part this basin. During July–October, when agricultural-irrigation wells were pumped at full allocation or at one-half the full-allocation rates, simulated base flow generally was less than the 7Q10. For Menantico Creek in the Maurice River Basin (HUC 02040206180), the 7Q10 is greater than the simulated

monthly base flow for about 29 percent of the months over the 11-year simulation period. Many agricultural-irrigation wells are sited in the upstream part of this HUC, and these wells are screened at less than 100 ft below land surface.

In scenario 3, the simulated base flow in the upper Cohansey River Basin is less than the 7Q10 in all months during scenario years 7–11 for HUC 02040206080. The simulated monthly base flow in the lower Cohansey River drainage basin (HUC 02040206090) is less than the 7Q10 for more than one-half the months during scenario years 7–10. Several agricultural-irrigation wells are in the western part of the lower Cohansey River Basin. Simulated monthly base flow for Menantico Creek in the Maurice River Basin (HUC 02040206180) is less than the 7Q10 for about 71 percent of the months during the 11-year simulation period. Several agricultural-irrigation wells are in the upstream part of HUC 02040206180.

Scenarios 4 and 5 had similar characteristics. In scenario 4, estimated municipal public-supply demand was increased for 2050 in 10 municipalities in the Cumberland County study area. In scenario 5, municipal public-supply well withdrawals from scenario 4 were used, except that withdrawals from 36 of the municipal public-supply wells came from a deeper part of the aquifer; this was done to observe the effects on the streams. The results of scenarios 4 and 5 indicate that, for Menantico Creek, simulated monthly base flow is less than the 7Q10 during 12 months (9 percent of the 11-year simulation period). The results of scenario 5, in which 36 municipal public-supply wells were pumped from a deeper part of the aquifer, indicate that the average difference in base flow is about 0.5 cubic feet per second (ft^3/s) more in this scenario than in scenario 4. The municipal public-supply wells have screened intervals greater than 50 ft below land surface. The groundwater discharge to streams in scenarios 4 and 5 is similar because groundwater was intercepted by pumped wells and, therefore, was not available for discharge to streams.

Three additional scenarios (scenarios 6–8) were simulated to evaluate the possible use of the Piney Point aquifer in the Cumberland County study area by using a previously existing numerical groundwater-flow model, the New Jersey Regional Aquifer-System Analysis (RASA) model, because the Piney Point aquifer was not represented in the Cumberland County study area groundwater-flow model. The withdrawal scenarios were used to assess changes in water levels in the Piney Point aquifer and evaluate the possible use of the Piney Point aquifer for water supply.

In scenario 6, average annual 2004–08 withdrawals for all aquifers were input to the RASA model; the results were used for comparison to the results of scenarios 7 and 8. Scenario 7 incorporated the withdrawals from the Kirkwood-Cohansey aquifer system used in scenario 6, except annual withdrawals were increased to 2050 rates at municipal public-supply wells; scenario 8 incorporated the withdrawals from the Kirkwood-Cohansey aquifer system used in scenario 6, except annual full-allocation withdrawals were incorporated at the municipal public-supply wells in Vineland City, Millville City, and in Monroe Township. Additionally for scenario 7, an existing municipal public-supply well from each municipality in the study area pumping in 2008 from the Kirkwood-Cohansey aquifer system was represented as pumping from the Piney Point aquifer instead. In scenario 8, existing municipal public-supply wells—one each from Vineland City, Millville City, and Monroe Township—with pumping in 2008 from the Kirkwood-Cohansey aquifer system were represented as pumping from the Piney Point aquifer instead. The results of scenarios 6–8 indicate that the Piney Point aquifer could be a limited option for public supply in the southeastern areas of the Cumberland County study area with constraints on withdrawal rates, the number of wells, and the proximity of proposed wells to the wells already pumping from the aquifer in Buena Borough and Bridgeton City. The transmissivity of the Piney Point aquifer used in the RASA model of the Cumberland County study area is 500 square feet per day (ft^2/d), which is lower than the average transmissivity of 4,500 ft^2/d in the Kirkwood-Cohansey aquifer system in the study area. This difference in transmissivity may result in deeper cones of depression around the pumped wells completed in the Piney Point aquifer. Monitoring of the water levels in the Piney Point aquifer in the Cumberland County study area and in Delaware is needed to better evaluate the use of this aquifer as an additional source of public supply in the study area.

Population growth and economic growth from agriculture in the Cohansey River Basin necessitates monitoring of discharge in the Maurice and Cohansey River drainage basins and some of the tributaries to evaluate future groundwater withdrawals in the study area. Therefore monitoring of streamflow is needed to evaluate the effects of additional withdrawals in these two basins. The population in the Cohansey River Basin is expected to increase by approximately 20 percent by 2050. Since 2004, the Cohansey River streamflow-gaging station at Seeley (01412800) has been a continuous-record streamflow-gaging station. Because of the large number of agricultural-irrigation groundwater withdrawals in the upper part of the Cohansey River Basin and the municipal public-supply groundwater withdrawals for Bridgeton City and Upper Deerfield Township, a long-term period of discharge data is needed to evaluate base flow and runoff components of streamflow in the basin. Because of the many agricultural-irrigation and the municipal public-supply wells in the Menantico Creek subbasin (HUC 02040206180), monitoring of streamflow also is needed to evaluate the effects of withdrawals in the subbasin.

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Table 5. Description of wells with simulated and measured groundwater levels and residuals for May through June and September 2008, Cumberland County study area, New Jersey.

[All wells are screened in the Kirkwood-Cohansey aquifer system. Simulated and measured water levels are in feet above the National Geodetic Vertical Datum of 1929 (NGVD 29); NJDEP, New Jersey Department of Environmental Protection; –, no data; <, less than]

U.S. Geological Survey well number	NJDEP well permit number	Well use	Altitude of land surface (feet, NGVD 29)	Well depth, (feet below land surface)	Model layer	May through June 2008			September 2008		
						Measured water-level altitude	Simulated water-level altitude	Residual	Measured water-level altitude	Simulated water-level altitude	Residual
1-1227	3500006406	Observation	108.7	41	1	88.4	91.3	2.9	84.9	86.4	1.5
1-1230	3500013994	Withdrawal	90	120	3	75.1	74.2	-0.9	71.5	71.1	-0.4
9-414	3500001234	Withdrawal	34	176	4	24.3	31.3	7.0	20.3	28.5	8.3
11-38	3500000984	Withdrawal	10	205	4	5.5	11.8	6.3	5.5	10.5	5.0
11-42	3500001145	Observation	81.77	47	1	76.0	78.5	2.5	74.5	76.1	1.6
11-43	3500001146	Observation	82.14	138	3	76.3	78.4	2.2	74.7	76.1	1.4
11-46	3500000874	Withdrawal	85	83	2	69.0	72.6	3.6	–	–	–
11-52	3500001299	Withdrawal	8	303	6	-6.0	0.5	6.5	3.9	0.3	-3.5
11-63	3400000846	Observation	8	72	2	4.7	1.0	-3.6	3.5	0.6	-2.9
11-73	–	Observation	37.35	40	1	32.4	30.4	-2.0	31.9	29.3	-2.6
11-97	3400000845	Observation	10.1	171	4	1.3	5.2	3.9	0.2	4.2	4.0
11-109	3400000084	Withdrawal	10	49	1	4.2	2.2	-2.0	2.4	-2.1	-4.5
11-118	3400001148	Observation	6.22	41	1	2.6	2.2	-0.4	2.7	1.9	-0.7
11-119	–	Observation	5.98	135	3	3.4	2.6	-0.8	2.5	2.3	-0.2
11-161	3500001144	Observation	80	176	4	58.5	56.6	-1.9	–	–	–
11-178	–	Withdrawal	90	91	2	70.2	67.8	-2.4	68.9	64.6	-4.3
11-225	3500000962	Withdrawal	68.7	181	4	61.6	62.0	0.4	60.0	59.8	-0.2
11-237	3500001165	Observation	88	81	2	78.5	88.0	9.5	76.9	84.0	7.1
11-254	3100005227	Withdrawal	90	160	4	75.6	75.2	-0.3	73.9	73.7	-0.2
11-283	3500001206	Withdrawal	98	104	2	89.4	95.4	6.0	87.6	92.1	4.5
11-320	3500002522	Withdrawal	30	106	2	26.9	21.9	-4.9	27.0	18.0	-9.0
11-339	3500002992	Test	48	385	6	25.2	29.9	4.7	24.0	28.7	4.7

Table 5. Description of wells with simulated and measured groundwater levels and residuals for May through June and September 2008, Cumberland County study area, New Jersey.—Continued

[All wells are screened in the Kirkwood-Cohansey aquifer system. Simulated and measured water levels are in feet above the National Geodetic Vertical Datum of 1929 (NGVD 29); NJDEP, New Jersey Department of Environmental Protection; –, no data; <, less than]

U.S. Geological Survey well number	NJDEP well permit number	Well use	Altitude of land surface (feet, NGVD 29)	Well depth, (feet below land surface)	Model layer	May through June 2008			September 2008		
						Measured water-level altitude	Simulated water-level altitude	Residual	Measured water-level altitude	Simulated water-level altitude	Residual
11-346	3500003763	Withdrawal	15	104	2	2.7	12.8	10.1	1.1	12.4	11.3
11-692	3400003742	Observation	119.62	38	1	94.8	93.3	-1.5	93.5	90.0	-3.5
11-705	3500010445	Withdrawal	72	120	3	49.4	54.7	5.3	48.1	51.3	3.3
11-708	3500007632	Withdrawal	80	163	3	66.8	72.6	5.8	62.4	52.9	-9.5
11-711	3500003083	Withdrawal	5	230	5	3.0	2.6	-0.3	4.5	2.2	-2.3
11-725	3400000493	Withdrawal	127	67	2	80.8	85.3	4.6	80.0	79.2	-0.8
11-727	3500008387	Withdrawal	10	122	2	4.9	14.4	9.6	3.6	11.8	8.2
11-749	3500011442	Observation	51.98	28	1	38.2	42.1	3.8	36.0	38.8	2.8
11-750	3500006839	Observation	52.37	28	1	42.2	42.0	-0.2	41.1	40.4	-0.7
11-756	3500001675	Observation	70.08	32	1	45.3	37.2	-8.1	44.2	34.1	-10.2
11-757	3500007323	Observation	20.7	30	1	9.5	22.5	13.0	–	–	–
11-772	3500013268	Withdrawal	99	95	2	72.1	75.4	3.3	68.1	70.4	2.3
11-774	3500010555	Observation	46.59	40	1	15.9	25.6	9.7	15.5	23.5	8.0
11-780	3500015647	Observation	66.8	35	1	43.6	37.4	-6.2	42.8	33.5	-9.4
11-787	3500012333	Observation	98.72	25	1	82.5	86.4	3.9	80.1	82.3	2.2
11-789	3100026185	Observation	85.5	158	3	80.6	77.4	-3.2	77.7	75.9	-1.8
11-881	3500014194	Observation	106.87	25	1	90.0	91.8	1.8	90.0	89.0	-1.0
11-882	3100035435	Observation	91.71	20	1	84.1	84.0	-0.1	82.1	81.9	-0.2
11-889	3400005530	Observation	122	39	1	92.1	87.8	-4.3	91.3	86.1	-5.2
11-897	3400000540	Withdrawal	112	78	2	68.8	66.0	-2.8	67.4	61.4	-6.0
11-925	3500017101	Observation	50	26	1	37.5	40.5	3.0	35.3	38.8	3.4
11-929	3100050480	Observation	70	12	1	65.4	70.3	4.9	61.1	67.6	6.5

Table 5. Description of wells with simulated and measured groundwater levels and residuals for May through June and September 2008, Cumberland County study area, New Jersey.—Continued

[All wells are screened in the Kirkwood-Cohansey aquifer system. Simulated and measured water levels are in feet above the National Geodetic Vertical Datum of 1929 (NGVD 29); NJDEP, New Jersey Department of Environmental Protection; –, no data; <, less than]

U.S. Geological Survey well number	NJDEP well permit number	Well use	Altitude of land surface (feet, NGVD 29)	Well depth, (feet below land surface)	Model layer	May through June 2008			September 2008		
						Measured water-level altitude	Simulated water-level altitude	Residual	Measured water-level altitude	Simulated water-level altitude	Residual
11-932	3500017426	Observation	90	22	1	73.3	73.9	0.6	70.9	69.6	-1.3
11-933	3400005096	Withdrawal	76	110	2	32.8	38.5	5.7	32.2	35.9	3.7
11-938	3500017867	Observation	90	56	2	73.0	73.7	0.7	70.3	69.3	-1.0
11-983	3500005667	Withdrawal	105	150	3	85.3	89.0	3.7	–	–	–
11-1054	3400002615	Withdrawal	10	120	3	3.5	2.2	-1.3	2.3	1.2	-1.0
11-1127	3400005702	Observation	95	24	1	77.0	70.9	-6.2	75.6	66.4	-9.2
11-1152	3500020734	Observation	50	12	1	43.4	38.3	-5.1	42.4	35.2	-7.2
11-1153	3500021049	Observation	83	32	1	54.0	45.3	-8.7	53.4	42.1	-11.3
11-1211	3400007097	Observation	103.62	27	1	82.3	78.9	-3.4	81.4	77.1	-4.4
11-1212	3400007098	Observation	73.66	25	1	56.7	53.6	-3.0	55.9	52.3	-3.6
11-1213	3400007099	Observation	96.87	35	1	70.2	71.6	1.4	68.8	68.5	-0.2
11-1214	3000016691	Observation	139.64	44	1	105.3	104.7	-0.6	102.6	99.5	-3.1
11-1219	3500004102	Withdrawal	20.5	86	2	12.1	19.9	7.8	10.6	19.4	8.8
11-1233	3400007181	Observation	112.87	35	1	86.6	83.2	-3.4	85.3	80.9	-4.4
11-1320	3500016814	Withdrawal	40	145	3	27.0	29.2	2.2	23.5	26.3	2.8
11-1413	3500011622	Withdrawal	10	30	1	7.9	4.9	-2.9	6.2	3.4	-2.8
11-1584	3400007957	Withdrawal	109	90	2	54.3	50.3	-4.0	52.1	41.8	-10.2
11-1585	3400008127	Withdrawal	110	107	3	87.2	85.4	-1.8	85.8	83.3	-2.4
11-1587	3500026629	Withdrawal	105	90	2	81.7	86.0	4.3	80.4	81.8	1.4
11-1588	3500004550	Observation	70.74	60	2	25.7	28.1	2.4	25.4	25.7	0.4
15-372	3100006092	Withdrawal	113	154	3	92.7	97.0	4.2	90.8	93.8	3.0
15-1033	3100031399	Observation	150	54	1	133.9	134.6	0.7	133.1	130.8	-2.3

Table 5. Description of wells with simulated and measured groundwater levels and residuals for May through June and September 2008, Cumberland County study area, New Jersey.—Continued

[All wells are screened in the Kirkwood-Cohansey aquifer system. Simulated and measured water levels are in feet above the National Geodetic Vertical Datum of 1929 (NGVD 29); NJDEP, New Jersey Department of Environmental Protection; –, no data; <, less than]

U.S. Geological Survey well number	NJDEP well permit number	Well use	Altitude of land surface (feet, NGVD 29)	Well depth, (feet below land surface)	Model layer	May through June 2008			September 2008		
						Measured water-level altitude	Simulated water-level altitude	Residual	Measured water-level altitude	Simulated water-level altitude	Residual
15-1054	3100033949	Observation	153.9	36	1	133.8	137.5	3.7	132.8	133.8	1.0
15-1152	3100024323	Withdrawal	112	100	2	103.6	108.6	5.0	101.6	105.6	4.0
15-1208	3100049627	Observation	140	33	1	115.2	118.0	2.9	114.6	115.0	0.4
15-1213	3100049658	Observation	97	15	1	91.2	94.3	3.1	88.6	91.8	3.1
15-1705	–	Observation	160	40	1	133.0	132.0	-1.1	–	–	–
15-1716	3100075223	Observation	146	85	2	131.9	133.9	2.1	–	–	–
33-262	3000001292	Withdrawal	132	93	2	118.4	126.0	7.6	113.5	118.2	4.6
33-769	3400002326	Observation	92.6	20	1	78.9	82.4	3.5	77.4	79.5	2.1
33-775	3100025124	Withdrawal	115	75	2	87.7	94.8	7.0	86.2	91.2	5.0
33-810	3500010749	Observation	105.95	39	1	80.7	89.3	8.7	79.4	86.2	6.8
33-812	3100018825	Observation	118.02	24	1	109.4	112.5	3.1	107.2	109.4	2.2
33-813	3100034186	Observation	142.18	35	1	118.1	130.1	12.0	–	–	–
33-815	3100039698	Observation	135	21	1	124.5	131.9	7.4	121.6	128.4	6.8
33-818	3000011704	Observation	140	32	1	117.7	124.3	6.6	114.8	118.5	3.7
33-822	3000011772	Observation	150	31	1	126.3	133.4	7.1	120.3	128.0	7.7
33-832	3400005531	Observation	120	34	1	94.8	91.3	-3.5	93.8	88.0	-5.8
33-836	3500017396	Observation	88	29	1	67.1	68.6	1.5	66.6	65.5	-1.1
33-1098	3100074321	Withdrawal	103	90	2	94.7	99.0	4.4	92.9	95.4	2.5
				Mean error				1.9			<0.1
				Mean absolute error				4.1			4.0
				Root mean square error				5.0			5.0

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