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Simulated Effects of Groundwater Withdrawals From the Kirkwood-Cohansey Aquifer System, the Rio Grande Water-Bearing Zone, the Atlantic City 800-Foot Sand Unit, and the Piney Point Aquifer, Ocean County and Vicinity, New Jersey

By Stephen J. Cauller, Lois M. Voronin, and Mary M. Chepiga

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Contents

Acknowledgments iv

Abstract 1

Introduction 4

Purpose and Scope 6

Previous Investigations 7

Well Numbering System 8

Description of Study Area 9

Land Use 9

Population 10

Hydrogeologic Framework 11

Groundwater Withdrawals 14

Simulation of Groundwater Flow 15

Model Discretization 16

Boundary Conditions 19

Recharge 21

Hydrologic Properties 23

Transient Calibration 24

Sensitivity Analysis 30

Model Limitations 32

Simulated Effects of Groundwater Withdrawals 34

No-Withdrawal Conditions 37

Post-Development Withdrawal Conditions 39

Maximum-Allocation Withdrawal Conditions 46

Simulated Groundwater Flow Paths and Travel Time 51

Scenario 1 53

Scenario 2 55

Groundwater Flow to Saltwater Boundaries 57

Summary and Conclusions 58

References Cited 67

Figures

**Figure 1.** Map showing location of study area and major roads in New Jersey. 5

**Figure 2.** Map showing location of townships, Ocean County study area, New Jersey. 5

**Figure 3.** Diagrammatic section through the Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, Atlantic City 800-foot sand, Piney Point and Vincentown aquifers, illustrating the relation between model layers and aquifers, Ocean County study area, New Jersey. Line of section is shown in figure 1. 5

**Figure 4.** Map showing location of surface-water basins, Ocean County study area, New Jersey. 9

**Figure 5.** Maps showing land use in the Ocean County study area, New Jersey, in: *A*, 1973; and *B*, 2007. 10

**Figure 6.** Maps showing extent of hydrogeologic units, Ocean County study area, New Jersey: *A*, unconfined Kirkwood-Cohansey and Vincentown aquifers; *B*, Rio Grande water-bearing zone; *C*, Atlantic City 800-foot sand; and *D*, confined Piney Point and Vincentown aquifers . 13

**Figure 7.** Map showing location of groundwater-withdrawal wells screened in the Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, Atlantic City 800-foot sand, Piney Point aquifer, and Vincentown aquifer, Ocean County study area, New Jersey, with withdrawal records for 2000 to 2003. 15

**Figure 8.** Graphs showing reported annual groundwater withdrawals by: *A*, water allocation permit series: and *B*, aquifer, Ocean County study area, New Jersey, 2000 to 2003. (NJDEP, New Jersey Department of Environmental Protection) 15

**Figure 9.** Variably spaced model grid, lateral boundaries, and representation of water bodies in the Ocean County study area, New Jersey. 17

**Figure 10.** Graph showing monthly and annual simulated recharge, 2000 to 2003, Ocean County study area, N.J. 24

**Figure 11.** Maps showing simulated October 2003 and composite measured water tables of the: A, Kirkwood-Cohansey aquifer system; *B*, Rio Grande water-bearing zone; *C*, Atlantic City 800-foot sand, upper sand unit; *D*, Atlantic City 800-foot sand, lower sand unit; and *E*, Piney Point aquifer, Ocean County study area, New Jersey. Average water-level residuals for 2000 to 2003 are shown for each well screened in the aquifer with multiple water-level measurements. 26

**Figure 12.** Map showing location of selected observation wells with periodic water-level measurements, Ocean County study area, New Jersey. 28

**Figure 13.** Hydrographs of simulated and measured water levels at selected observation wells screened in: *A to F*, the Kirkwood Cohansey aquifer system; and, *G to H*, Rio Grande water-bearing zone, Ocean County study area, New Jersey, 2000 to 2003. 28

**Figure 14.** Hydrographs of simulated and measured water levels at selected observation wells screened in: *A to C*, the Atlantic City 800-foot sand; and, *D to F*, Piney Point aquifer, Ocean County study area, New Jersey, 2000 to 2003. 28

**Figure 15.** Map showing location of selected streamflow-gaging stations in the Ocean County study area, New Jersey. 29

**Figure 16.** Graphs showing estimated monthly and simulated monthly base flow from January 2000 to December 2003 at streamflow-gaging stations: *A*, North Branch Metedeconk River near Lakewood (01408120): *B*, South Branch Metedeconk River near Lakewood (01408150): *C*, Toms River near Toms River (01408500): *D*, Wrangel Brook at Mule Road near Toms River (01408592): *E*, Cedar Creek at Lanoka Harbor (01409000): and *F*, North Branch Forked River near Forked River (01409050), New Jersey. 29

**Figure 17.** Graphs showing estimated monthly and simulated monthly base flow from January 2000 to December 2003 at streamflow-gaging stations: *A*, Oyster Creek near Waretown (01409100); *B*, Mill Creek near Manahawkin (01409150); *C*, Cedar Run near Manahawkin (01409250); *D*, Westecunk Creek at Stafford Forge (01409280); *E*, East Branch Bass River near New Gretna (01410150); and *F*, Oswego River at Harrisville (01410000), New Jersey. 29

**Figure 18.** Graph showing composite scaled sensitivity values, Ocean County study area, New Jersey. 32

**Figure 19.** Maps showing location of parameter value zones in the model, Ocean County study area, New Jersey. 32

**Figure 20.** Graphs showing groundwater-flow budgets for during selected stress periods under no-withdrawal conditions: *A*, the Kirkwood-Cohansey aquifer system, *B*, Rio Grande water-bearing zone, *C*, Atlantic City 800-foot sand, and *D*, Piney Point aquifer, Ocean County study area. 38

**Figure 21.** Graphs showing simulated water levels in selected observation wells screened in the unconfined Kirkwood-Cohansey aquifer system, wells *A*, 29–141, *B*, 29–1060, *C*, 29–513, *D*, 29–17 and in the Rio Grande water-bearing zone, wells *E*, 29–775, and *F*, 29–1621, during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey. 38

**Figure 22.** Graphs showing simulated water levels in selected observation wells screened in the Atlantic City 800-foot sand, wells *A*, 29–9, *B*, 29–457, *C*, 29–936, *D*, 29–464, and *E*, 29–814, during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey. 39

**Figure 23.** Graphs showing simulated water levels in selected observation wells screened in the Piney Point aquifer, wells *A*, 29–2, *B*, 29–425, *C*, 29–582, and *D*, 29–1210, during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey. 39

**Figure 24.** Graphs showing groundwater-flow budgets for the *A*, Kirkwood-Cohansey aquifer system, *B*, Rio Grande water-bearing zone, *C*, Atlantic City 800-foot sand, and *D*, Piney Point aquifer, during post-development withdrawal conditions, Ocean County study area, New Jersey. 39

**Figure 25.** Maps showing simulated potentiometric surfaces of the Rio Grande water-bearing zone, stress periods 73 (August 2002) and 80 (March 2003), during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey. 43

**Figure 26.** Maps showing simulated drawdown of potentiometric surfaces of: *A*, the Rio Grande water-bearing zone;, *B*, the Atlantic City 800-foot sand, upper sand unit; *C*, the Atlantic City 800-foot sand, lower sand unit; and *D*, the Piney Point aquifer from no-withdrawal to postdevelopment withdrawal conditions, stress period 73 (August 2002) in the Ocean County study area, New Jersey. 44

**Figure 27.** Maps showing simulated potentiometric surfaces of the Atlantic City 800-foot sand, upper sand unit, stress periods 73 (August 2002) and 80 (March 2003), during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey. 45

**Figure 28.** Maps showing simulated potentiometric surfaces of the Piney Point aquifer, stress periods 73 (August 2002 recharge) and 80 (March 2003 recharge), during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey. 45

**Figure 29.** Graphs showing groundwater-flow budgets for: *A*, the Kirkwood-Cohansey aquifer system; *B*, Rio Grande water-bearing zone; *C*, Atlantic City 800-foot sand; and *D*, Piney Point aquifer during maximum-allocation withdrawal conditions, Ocean County study area, New Jersey. 47

**Figure 30.** Graphs showing monthly base flow during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions at streamflow-gaging stations: *A*, North Branch Metedeconk River near Lakewood, N.J. (01408120); *B*, South Branch Metedeconk River near Lakewood, N.J. (01408150); *C*, Toms River near Toms River, N.J. (01408500); *D*, Wrangel Brook at Mule Road near Toms River, N.J. (01408592); *E*, Cedar Creek at Lanoka Harbor, N.J. (01409000); and *F*, North Branch Forked River near Forked River, N.J. (01409050), Ocean County study area, New Jersey. 47

**Figure 31.** Graphs showing monthly base flow during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions at streamflow-gaging stations: *A*, Oyster Creek near Waretown, N.J. (01409100); *B*, Mill Creek near Manahawkin, N.J. (01409150); *C*, Cedar Run near Manahawkin, N.J. (01409250); *D*, Westecunk Creek at Stafford Forge, N.J. (01409280); *E*, East Branch Bass River near New Gretna, N.J. (01410150); and *F*, Oswego River at Harrisville, N.J. (01410000), Ocean County study area, New Jersey. 48

**Figure 32.** Maps showing simulated drawdown of: *A*, the Rio Grande water-bearing zone potentiometric surface; *B*, the Atlantic City 800-foot sand, upper sand unit, potentiometric surface; *C*, the Atlantic City 800-foot sand, lower sand unit, potentiometric surface; and *D*, the Piney Point aquifer potentiometric surface as a result of maximum-allocation withdrawals, stress period 73 (August 2002), Ocean County study area, New Jersey. 50

**Figure 33.** Map showing locations of selected wells screened in the Kirkwood-Cohansey aquifer system proximal to the coastline and production wells screened in the Rio Grande water-bearing zone or in the Atlantic City 800-foot sand, used in particle-tracking analysis, Ocean County study area, New Jersey. 53

**Figure 34.** Map showing flow paths from point of recharge to point of discharge and travel time of particles that discharge to near-shore wells screened in the unconfined Kirkwood-Cohansey aquifer system, postdevelopment conditions scenario, Ocean County study area, New Jersey. 54

**Figure 35.** Map showing flow paths from point of recharge to point of discharge and travel time of particles that discharge to near-shore wells screened in the Rio Grande water-bearing zone and Atlantic City 800-foot sand, postdevelopment conditions scenario, Ocean County study area, New Jersey. 55

**Figure 36.** Map showing flow paths from point of recharge to point of discharge and travel time of particles that discharge to near-shore wells screened in the unconfined Kirkwood-Cohansey aquifer system, maximum allocation conditions scenario, Ocean County study area, New Jersey. 56

**Figure 37.** Map showing flow paths from point of recharge to point of discharge and travel time of particles that discharge to wells screened in the Rio Grande water-bearing zone or the Atlantic City 800-foot sand, maximum- allocation conditions scenario, Ocean County study area, New Jersey. 57

**Figure 38.** Maps showing groundwater flow into, or out of, constant head cells in the Barnegat Bay-Little Egg Harbor, Great Bay, Atlantic Ocean, and coastal wetlands for *A*, postdevelopment withdrawal conditions, and *B*, maximum-allocation withdrawal conditions, Ocean County study area, New Jersey. 58

Tables

**Table 1.** Land use in the Ocean County study area, New Jersey. 11

**Table 2.** Stratigraphic and hydrogeologic units, Ocean County study area, New Jersey. 15

**Table 3.** New Jersey Department of Environmental Protection water allocation permit series. 16

**Table 4.** Groundwater model layers and their representation in hydrogeologic units in the Ocean County study area, New Jersey. 22

**Table 5.** Published hydraulic properties of aquifers and confining units in the Coastal Plain of New Jersey. 25

**Table 6.** Hydraulic properties used in groundwater-flow model simulations for the Ocean County study area, New Jersey. 25

**Table 7.** Average difference between simulated and measured water levels in selected wells, Ocean County study area, New Jersey, January 2000 to December 2003. 26

**Table 8.** Simulated and estimated mean monthly base flow at selected streamflow-gaging stations, Ocean County study area, New Jersey, for January 2000 to December 2003. 31

**Table 9.** Time period, groundwater-withdrawal rate, groundwater discharge to streams, and recharge rate simulated in the groundwater-flow model. 31

**Table 10.** Calibrated model parameter values and composite scaled sensitivities, Ocean County study area, New Jersey. 32

**Table 11.** Simulated base-flow reductions at selected streamflow-gaging stations from no-withdrawal to postdevelopment withdrawal conditions and from no-withdrawal to maximum-allocation withdrawal conditions, Ocean County study area, New Jersey. 41

**Table 12.** Estimated base flow to streams that flow into the Barnegat Bay-Little Egg Harbor estuary, Ocean County study area, New Jersey. 42

**Table 13.** Simulated water levels during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions at selected wells, stress periods 73 (August 2002) and 80 (March 2003), Ocean County study area, New Jersey. 43

Conversion Factors and Datum

Inch/Pound to International System of Units

|  |  |  |
| --- | --- | --- |
| Multiply | By | To obtain |
| Length | | |
| inch (in.) | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| Area | | |
| square mile (mi2) | 2.590 | square kilometer (km2) |
| acre | 0.4047 | hectare (ha) |
| Volume | | |
| gallon (gal) | 3.785 | liter (L) |
| gallon (gal) | 0.003785 | cubic meter (m3) |
| million gallons (Mgal) | 3,785 | cubic meter (m3) |
| Flow rate | | |
| cubic foot per second (ft3/s) | 0.02832 | cubic meter per second (m3/s) |
| gallon per day (gal/d) | 0.003785 | cubic meter per day (m3/d) |

Datum

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.

Abbreviations

CSS composite scaled sensitivities

FHB1 Flow and Head Boundary Package

GIRAS Geographic Information and Retrieval Analysis System

NJDEP New Jersey Department of Environmental Protection

NJGWS New Jersey Geological and Water Survey

RASA Regional Aquifer System Analysis model

USGS U.S. Geological Survey

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# Abstract

Rapid population growth in Ocean County, New Jersey, since the 1930s, coupled with the conversion of forested land to urban land, has placed increasing demands upon the freshwater resources in this area. A study was undertaken to examine the effects of groundwater withdrawals in Ocean County and vicinity from four primary aquifers—the unconfined Kirkwood-Cohansey aquifer system, the deep confined Rio Grande water-bearing zone, the Atlantic City 800-foot sand, and the Piney Point aquifer. A three-dimensional groundwater flow model of the Ocean County study area was developed to simulate the groundwater flow system. The influence of groundwater withdrawals in the Ocean County study area on the flow system was evaluated using transient groundwater-flow model simulations that incorporate three different withdrawal schemes—no-withdrawal conditions, postdevelopment withdrawal conditions, and maximum-allocation withdrawal conditions. Simulation of no-withdrawal conditions excluded all groundwater withdrawals. Postdevelopment conditions included reported monthly withdrawals at all production wells from January 2000 through December 2003, and maximum-allocation withdrawal conditions included the maximum withdrawal allowed by New Jersey Department of Environmental Protection permits at each well. Particle tracking analysis using results from steady-state model simulations of postdevelopment groundwater withdrawal conditions (average annual 2000 to 2003) and average maximum-allocation groundwater withdrawal conditions delineated particle flow paths from production wells to the point of recharge, and estimated particle travel times.

Compared with no-withdrawal conditions, postdevelopment withdrawal conditions reduced the amount of groundwater flow out of the Kirkwood-Cohansey aquifer system into streams, increased the net flow of water into other layers, reduced net flow into or out of storage, and reduced flow from the Kirkwood-Cohansey aquifer system to constant head cells.

Freshwater discharging to the Barnegat Bay-Little Egg Harbor estuary from streams and groundwater is essential to maintaining the ecology of the bay. Examination of selected stress periods indicates that simulated base flow in streams flowing into the Barnegat Bay-Little Egg Harbor estuary is reduced by as much as 49 cubic feet per second from postdevelopment withdrawal conditions when compared with no-withdrawal conditions.

The effects of seasonal changes in recharge to and groundwater withdrawals from the groundwater flow system were evaluated by examining water levels in the major confined aquifers in the Ocean County study area during periods of relatively low recharge and high withdrawals as well as of high recharge and low withdrawals. The simulated potentiometric surface of the Rio Grande water-bearing zone and the Atlantic City 800-foot sand during stress periods 73 and 80 indicates substantial declines from no-withdrawal conditions to postdevelopment conditions as a result of groundwater withdrawals. Cones of depression located in Toms River Township, Seaside Heights and Seaside Park Boroughs, and Barnegat Light Borough developed in the potentiometric surface of the Piney Point aquifer in response to groundwater withdrawals.

Maximum-allocation withdrawals decreased flow out of the Kirkwood-Cohansey aquifer system to constant head cells, increased the flow out of the aquifer system to adjacent and lower layers, and reduced groundwater discharge to streams when compared with postdevelopment withdrawal conditions. Increases in withdrawals from the Rio Grande water-bearing zone, the Atlantic City 800-foot sand, and the Piney Point aquifer result in increased simulated net groundwater flow into these aquifers. Examination of selected stress periods indicated a base-flow reduction from postdevelopment to maximum-allocation conditions of 25 to 29 cubic feet per second in all streams that drain into the Barnegat Bay-Little Egg Harbor. Potentiometric surfaces of the Rio Grande water-bearing zone, Atlantic City 800-foot sand, and the Piney Point aquifer during stress periods 73 and 80 of simulated maximum-allocation withdrawal conditions indicated the expansion of several cones of depression that developed during postdevelopment withdrawals.

Simulation of average postdevelopment groundwater withdrawals indicated to what extent the groundwater-flow system was susceptible to potential saltwater intrusion into near-shore wells. Travel time from recharge to discharge location ranged from 11 to more than 50,700 years in near-shore Kirkwood-Cohansey aquifer system wells. Travel time along flow paths to wells screened in the Rio Grande water-bearing zone and the Atlantic City 800-foot sand from recharge to discharge point ranged from nearly 530 years to greater than 3.73 million years. Particle tracking indicated that most wells screened in these aquifers derived a large part of their recharge from the Oswego River Basin. A small portion of flow originated either beneath Barnegat Bay or to the east beneath the Atlantic Ocean.

Simulation of average maximum-allocation withdrawal conditions indicated that wells screened in the Kirkwood-Cohansey aquifer system in Seaside Heights Borough, in Island Beach State Park (Lacey Township), and in Ship Bottom Borough have particle travel times from 140 to 12,000 years and flow paths that originated under Barnegat Bay or the Atlantic Ocean. Wells completed in the Rio Grande water-bearing zone and Atlantic City 800-foot sand in the communities of Harvey Cedars Borough south through Beach Haven Borough derived their water from a combination of areas beneath Barnegat Bay, the Atlantic Ocean, and the mainland. Travel time along flow paths that start beneath either Barnegat Bay or the Atlantic Ocean ranged from 2,300 to more than 134,000 years.

# Introduction

The southernmost part of Monmouth County and the northern half of Ocean County, New Jersey, have experienced rapid population growth and subsequent residential and commercial land development during the period of 1930 to 2000, particularly in areas close to the shoreline; Ocean County experienced the largest percent change in population (1,445 percent) of all the counties in the State (Ocean County Department of Planning, 2006). The conversion of undeveloped land to residential use was followed by the development of a burgeoning infrastructure to support the needs of the community, including the development of transportation corridors, commercial strip malls, shopping centers, pockets of industrial land, and various commercial endeavors. Groundwater withdrawals from the Kirkwood-Cohansey aquifer system, the Rio Grande water-bearing zone, the Atlantic City 800-foot sand, and the Piney Point and Vincentown aquifers in this area increased from an estimated 606 million gallons in 1930 (Zapecza and others, 1987) to more than 14 billion gallons in 2003 in order to serve the needs of the growing population.

Conversion of undeveloped land to residential use has accelerated in the southern half of Ocean County, especially along the Garden State Parkway corridor and east to the coast (fig. 1). From 1997 to 2007, in the southern half of Ocean County, Barnegat, Ocean, and Stafford Townships and Little Egg Harbor (fig. 2) experienced some of the highest rates of population growth in the county, ranging from 34 to nearly 54 percent (Ocean County Department of Planning, 2009). As the population grew, demands placed on the available supply of freshwater also increased. The barrier island beach communities experienced a large seasonal population increase and high water demand during the summer months. Several communities in northern Ocean County increased their groundwater withdrawals from the confined Piney Point aquifer, and several southern communities increased their withdrawals from confined parts of the Kirkwood-Cohansey aquifer system, the Rio Grande water-bearing zone, and the Atlantic City 800-foot sand (fig. 3).

1. Map showing location of study area and major roads in New Jersey.
2. Map showing location of townships, Ocean County study area, New Jersey.
3. Diagrammatic section through the Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, Atlantic City 800-foot sand, Piney Point and Vincentown aquifers, illustrating the relation between model layers and aquifers, Ocean County study area, New Jersey. Line of section is shown in figure 1. SE, southeast; NW, northwest.

In the study area, streamflow is the main source of freshwater flow into the Barnegat Bay-Little Egg Harbor estuary. Direct precipitation and subsurface groundwater flow are secondary sources of freshwater. Groundwater flow to streams, or base flow, is a major component of freshwater flow in streams that drain the New Jersey Coastal Plain. Withdrawals of groundwater in the study area reduce the quantity of both groundwater discharge to streams that flow into the bay and groundwater discharge directly into the bay. This reduction has potential implications for the salinity of the bay water, the flora and fauna supported in the bay ecosystem, and the overall health of the estuary.

Water-supply wells located near the shore or on the barrier islands tend to be susceptible to saltwater intrusion because of their proximity to salty water either in the Barnegat Bay-Little Egg Harbor or the Atlantic Ocean. Production wells screened in the confined Rio Grande water-bearing zone and Atlantic City 800-foot sand may be susceptible to sources of saltwater either downdip in the aquifer or updip where confinement ends.

## Purpose and Scope

The U.S. Geological Survey (USGS), in cooperation with the New Jersey Department of Environmental Protection (NJDEP) and the Barnegat Bay Partnership, studied the effects of 2000–2003 annual and maximum-allocation groundwater withdrawals from the Kirkwood-Cohansey aquifer system, the Rio Grande water-bearing zone, the Atlantic City 800-foot sand, and the Piney Point aquifer on the freshwater supply in Ocean County and vicinity (referred to as the study area). As of 2003, groundwater withdrawals had created cones of depression in the potentiometric surfaces of the Rio Grande water-bearing zone, the Atlantic City 800-foot sand, and the Piney Point aquifer in parts of the study area. The effects of maximum-allocation groundwater withdrawals were evaluated by quantifying changes to the simulated potentiometric surfaces of the confined aquifers compared with simulated no-withdrawal and post development surfaces.

This report documents the results of groundwater-flow simulations for aquifers in the Atlantic coastal basins of central New Jersey. The report focuses primarily on the basins in Ocean County that drain into Barnegat Bay and Little Egg Harbor. Aquifers included in this study are the unconfined, surficial Kirkwood-Cohansey aquifer system; the deeper, confined parts of the Kirkwood Formation, which includes the Rio Grande water-bearing zone and the Atlantic City 800-foot sand; the Piney Point aquifer; and the Vincentown aquifer in the northwestern part of the study area. Groundwater flow through the Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, Atlantic City 800-foot sand, and the Piney Point aquifer is simulated. Groundwater flow to streams and ultimately to the Barnegat Bay-Little Egg Harbor estuary is estimated. This report presents the results of simulations that represent no groundwater withdrawals, postdevelopment (2000 to 2003) groundwater withdrawals, and maximum-allocation groundwater withdrawals. Particle-tracking analysis is used to assess the vulnerability of near-shore wells screened in the unconfined Kirkwood-Cohansey aquifer system to saltwater intrusion from the salty bay or ocean. Sources of water to wells in both unconfined and confined aquifers and travel times based on particle-tracking analysis are used to assess the susceptibility of selected wells to saltwater intrusion.

## Previous Investigations

Isphording (1970) characterized the stratigraphy of the Kirkwood Formation . Sugarman (2001) presented he geology and stratigraphic relations of the Kirkwood and Cohansey Formations . Nemickas and Carswell (1976) described the stratigraphic relation and geology of the lower Kirkwood Formation and the Piney Point aquifer. Owens and others (1998) described and mapped the bedrock geology of central and southern New Jersey. Newell and others (2000) presented detailed descriptions and mapping of the surficial sedimentary deposits of central and southern New Jersey.

Zapecza (1989) presented a comprehensive study of the hydrogeologic framework of the New Jersey Coastal Plain and mapped the subsurface extent and stratigraphic relations of all the aquifers and confining units. A series of maps of the potentiometric surface of the confined aquifers in the New Jersey Coastal Plain, produced at 5-year increments, illustrated changes in the hydrologic system during 1988, 1993, 1998, and 2003 (Rosman and others, 1995; Lacombe and Rosman, 1997; Lacombe and Rosman, 2001; dePaul and others, 2009) The geology and groundwater resources of Ocean County were documented by Anderson and Appel (1969). The hydrology of the unconfined Kirkwood-Cohansey aquifer system in the Metedeconk River and Toms River Basins in the northern part of Ocean County was described by Watt and others (1994), and the hydrology of the Atlantic coastal basins and Mullica River Basin in the southern part of the Ocean County study area was described by Gordon (2004) and Johnson and Watt (1996), respectively. The geology and hydrology of the Mullica River Basin were documented by Rhodehamal (1973).

Several groundwater flow models were developed and documented for the coastal plain aquifers in New Jersey or parts of specific aquifers that extend into Ocean County. The Regional Aquifer System Analysis (RASA) model encompassed all the aquifers and confining units of the New Jersey Coastal Plain, which includes the Ocean County study area (Martin, 1998; Voronin, 2005). McAuley and others (2001) developed a groundwater-flow model of the Atlantic City 800-foot sand which extends approximately from the middle of Ocean County south through Cape May County. Nicholson and Watt (1997) developed a groundwater-flow model of the unconfined Kirkwood-Cohansey aquifer system in the Metedeconk River and Toms River Basins in the northern half of Ocean County. The model was used to evaluate the effects of increased groundwater withdrawals from the Kirkwood-Cohansey aquifer system on water levels in the surficial Kirkwood-Cohansey aquifer system and on base flow in the Metedeconk River and Toms River.

## 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. The county codes used in this report are 05 for Monmouth County, 25 for Burlington County, and 29 for Ocean County. For example, well 29–928 is the 928th well inventoried in Ocean County.

# Description of Study Area

The study area extends from the southern part of Monmouth County to the southern boundary of Ocean County; it includes parts of Freehold, Howell, and Wall Townships and encompasses nearly all of Ocean County. The southwestern part of the study area includes eastern Burlington County, primarily Bass River Township (fig. 2). The eastern boundary extends approximately 5.5 miles east of the barrier islands into the Atlantic Ocean. The study area includes all or parts of more than 30 surface-water basins that drain into the Atlantic Ocean or Barnegat Bay and Little Egg Harbor to the east (fig. 4), the Mullica River and Great Bay to the south, or the Delaware River to the west (fig. 1).

1. Map showing location of surface-water basins, Ocean County study area, New Jersey.

## Land Use

Land-use and land-cover data, identified as Geographic Information and Retrieval Analysis System (GIRAS), were produced by the USGS with Landsat satellite imagery for New Jersey from the late 1960s to early 1970s. These images were manually interpreted into land-use polygons and paneled into 1:250,000 scale quadrangles. Production of this data is documented in Fegeas and others (1983). This dataset was used to determine land use for the study area in 1973 (fig. 5). The NJDEP generated and released land-use datasets for the entirety of New Jersey for 1986, 1995, 2002, and 2007. The NJDEP datasets were produced at different scales, reflecting improvements in digital imaging and processing over time. The 1986 land use maps were produced at a scale of 1:24,000, whereas the 1995, 2002, and 2007 land-use maps were produced at a scale of 1:12,000. Different data resolutions and reclassification of some land parcels over time account for some differences among land-use datasets developed for different years. However, general changes in land use in the study area were evident by the comparison of the land-use data from 1973 with those of 2007 (fig. 5).

1. Maps showing land use in the Ocean County study area, New Jersey, in A, 1973 and B, 2007.

A large part of the study area is designated as the Pinelands by NJDEP (fig. 2). Also known as the Pine Barrens, the Pinelands is largely undeveloped land that comprises 251,708 acres of the study area. A comparison of land-use summaries (table 1) indicates that conversion of forest, agriculture, and barren land to new urban land proceeded steadily from 1973 to 2007 outside the Pinelands. The largest decreases in acreage occurred to forested land, followed by agricultural land and barren land. A comparison of 1986 data with 2007 data indicates that nearly all of the combined loss of forest, agricultural, and barren land resulted from conversion to urban land. In 1973, urban land accounted for about 14.9 percent of all land use (excluding water). By 2007, urban land had increased to about 24.1 percent of all land use (excluding water), an increase of 47,329 acres.

A much lower acreage of wetlands was noted in the GIRAS data than in the NJDEP datasets (table 1). This difference was attributed to poor resolution of wetlands on aerial photographs at a scale of 1:250,000. Differences in acreage of water bodies between the 1973 GIRAS dataset and more recent NJDEP datasets resulted from different accounting methods; specifically, the surface area of the Barnegat Bay and Little Egg Harbor was accounted for in the NJDEP datasets, but not in the GIRAS. Therefore, net changes for water and wetlands from 1973 to 2007 were not calculated in table 1.

1. Land use in the Ocean County study area, New Jersey.

## Population

The population of Ocean County grew from 33,069 in 1930 to 510,916 in 2000 (Ocean County Department of Planning, 2009). The 2008 population was estimated at 569,111 (U.S. Census Bureau, 2009). Development in the county occurred along the coastal beaches and along the north-south transportation corridor formed by the Garden State Parkway and U.S. Route 9 (fig. 1). Land development west of the Garden State Parkway occurred along several east-west transportation corridors, including State Routes 526, 70, and 37 in the northern part of the county and State Route 72 in the southern part of the county. The largest total increases in population by municipality from 1930 to 2000 occurred in Toms River (85,736), Brick (74,947), Lakewood (52,483), Jackson (41,097), Berkeley (39,180), and Manchester (37,919) Townships, and Point Pleasant Borough (17,248) in the northern part of the county and Lacey (24,654) and Stafford (21,493) Townships in the central and southern part of the county (Ocean County Department of Planning, 2009).

Population increased by 20 percent for all of Ocean County between 1994 and 2004, from 461,152 to 553,251. Municipalities that exceeded the county-wide growth rate were Stafford (58.9 percent), Barnegat (41.1 percent), Little Egg Harbor (36.5 percent), and Ocean Townships (29 percent), and Surf City Borough (34.1 percent) in the southern half of the county, and Jackson (39.4 percent), Lakewood (31.4 percent) and Plumsted (22.3 percent) Townships, in the northern part of the county (Ocean County Department of Planning, 2006). Trends in population growth indicate which areas may experience a measureable effect on water resources in the future from continued development.

## Hydrogeologic Framework

The hydrogeologic framework described in this report is based on a prior study by Zapecza (1989) and additional hydrogeologic interpretations by the New Jersey Geological and Water Survey (NJGWS) of the NJDEP (L.G. Mullikin, New Jersey Geological and Water Survey, written commun., 2001). The unconsolidated sediments described in this study range in age from Holocene deposits 10,000 years before present) to the upper Paleocene Vincentown Formation (65.5 million years before present) (table 2). Pleistocene deposits of colluvium and alluvium in the subsurface and on the land surface have been mapped in detail by Newell and others (2000).

1. Correlation chart showing the stratigraphic and hydrogeologic units in Ocean County, New Jersey. Geologic nomenclature is from Owens and others (1998) and Newell and others (2000); hydrologic nomenclature is from Zapecza (2989) and New Jersey Geological and Water Survey (L.G. Mullikin, New Jersey Geological and Water Survey, written commun., 2001). The composite confining hydrologic unit includes geologic units older than the Paleocene units shown on the chart that are not included on the chart.

In the southern part of the study area, small pockets of the Bridgeton Formation, arkosic sand with larger clasts, have been mapped at the surface. The unconsolidated middle Miocene Cohansey Formation consists of fine to coarse-grained sand and clay and underlies the surficial deposits throughout the study area. Underlying the Cohansey Formation is the lower to middle Miocene Kirkwood Formation. The Kirkwood Formation has been mapped and subdivided into four members. These members, from youngest to oldest, are the Belleplain, Wildwood, Shiloh Marl, and Lower. The Kirkwood Formation, Cohansey Formation, and overlying undifferentiated sediments compose a seaward-dipping wedge of gravel, sand, silt, and clay that forms the unconfined Kirkwood-Cohansey aquifer system in the study area (fig. 6A). Where the layers of sediment thicken downdip in a southeasterly direction (fig. 3), the Kirkwood Formation contains a massive diatomaceous clay unit that confines the Rio Grande water-bearing zone and the Atlantic City 800-foot sand. Sugarman (2001) referred to this confining bed and the Rio Grande water-bearing zone are referred to as the Wildwood-Belleplain confining unit. The confining unit overlying the Rio Grande water-bearing zone extends southwest from just north of Barnegat Inlet in Island Beach State Park through the eastern mainland of Lacey, Ocean, Barnegat, Stafford, Eagleswood, Little Egg Harbor, and Bass River Townships (figs. 2 and 6B). A semiconfined zone, mapped by the NJGWS (L.G. Mullikin, New Jersey Geological and Water Survey, written commun., 2001), extends updip from 2 to 5 miles north and west of this designation. The thickness of the Rio Grande water-bearing zone ranges from 20 to 60 feet.

The confining unit above the Atlantic City 800-foot sand extends from approximately 4 miles north of Barnegat Inlet southwest through Bass River Township (figs. 2 and 6C). The semiconfined zone parallels the zone of confinement and extends from approximately 10 miles north of this designation in Lavallette Borough to 5 miles north and west in Bass River Township (L.G. Mullikin, New Jersey Geological and Water Survey, written commun., 2001). The Atlantic City 800-foot sand is divided into, and mapped as, upper and lower sand units separated by a leaky confining bed (Sugarman, 2001). From the top of the upper sand to the bottom of the lower sand, the Atlantic City 800-foot sand is from 40 to 160 feet thick in this area.

1. Maps showing extent of hydrogeologic units, Ocean County study area, New Jersey. A, Unconfined Kirkwood-Cohansey and Vincentown aquifers; B, Rio Grande water-bearing zone; C, Atlantic City 800-foot sand; and D, confined Piney Point and Vincentown aquifers.

The Lower Member of the Kirkwood Formation contains a basal clay unit that forms the top of the composite confining bed (Zapecza, 1989) and confines the Piney Point aquifer, which exists only in the subsurface. The Piney Point aquifer consists of parts of the upper Oligocene Atlantic City Formation, the lower Oligocene Sewell Point Formation (not identified in the study area), the upper Eocene Absecon Inlet Formation, and the upper to middle Eocene Shark River Formation. The NJGWS mapped distinct units in the Piney Point aquifer, including upper and lower sand units with an intervening confining unit (L.G. Mullikin, New Jersey Geological and Water Survey, written commun., 2001). The upper sand extends approximately from the boundary of Manchester Township with Lacey and Berkeley Townships northeast to the Manasquan River near the boundary of Brick Township and Point Pleasant Borough (figs. 2 and 6D). The upper sand unit ranges in thickness from 40 to 220 feet. The extent of the lower sand is similar to the upper sand unit except in the western part of the study area where its northernmost extent is approximately 10 miles south of the upper sand. The thickness of the lower sand ranges from 20 feet to a maximum of 100 feet at Island Beach State Park. The lower sand unit is correlative with the Shark River Formation. Very few water-supply wells are known to tap this horizon. The Piney Point aquifer is used for water supply in the Toms River area and in Barnegat Light Borough (figs. 2 and 6D).

The lower Eocene Manasquan Formation stratigraphically underlies the Piney Point aquifer and confines the underlying upper Paleocene Vincentown aquifer. The Vincentown aquifer is in hydrologic contact with the Kirkwood-Cohansey aquifer system at the northwestern edge of the study area, where the Vincentown aquifer crops out adjacent to the western limit of the Kirkwood-Cohansey aquifer system (fig. 6A). The Vincentown aquifer extends for several miles downdip to the east where it becomes confined and truncates in the subsurface as it grades into finer-grained silts and clays. The confining unit overlying the Vincentown aquifer, which does not crop out in the study area, includes sediments of the Manasquan Formation and the basal Kirkwood-Cohansey aquifer system (Zapecza, 1989). The subsurface contact between the Kirkwood-Cohansey and the Vincentown aquifers in the study area is not well mapped, due primarily to the Vincentown aquifer’s limited extent and the sparse distribution of wells that traverse this zone. The easternmost extent of the Vincentown aquifer approximately parallels the boundary of Manchester Township with Plumsted and Jackson Townships northeast to the Manasquan River (fig. 4) near the border with Wall and Brick Townships. The Vincentown aquifer ranges in thickness from 20 to 100 feet, where confined.

## Groundwater Withdrawals

The NJDEP Bureau of Water Supply requires well owners to report monthly withdrawals for all wells within the State that have a pump capable of extracting 70 gallons per minute or greater. Owners of private domestic wells are not required to report water use, therefore, domestic self-supply is not included in this study. The NJDEP maintains records for all reported water-use wells, categorized by type of water use and pump capacity (table 3) Wells in the 5000, 2000P, and 10000W permit series are metered, but wells with an agricultural certification are not. Withdrawals from wells with agricultural certification are estimated. Withdrawal estimates for unmetered agricultural wells are generally based on pump capacity multiplied by the number of hours the pump operated. Monthly water-use records with reported values for 2000 to 2003, compiled by the NJDEP, were used to calculate annual withdrawals from the 682 wells screened in the Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, Atlantic City 800-foot sand, Piney Point aquifer, and Vincentown aquifer in the Ocean County study area (fig. 7). Groundwater withdrawals in the Ocean County study area from the aquifers studied, increased from approximately 12.5 billion gallons in 2000 to more than 14 billion gallons per year from 2001 to 2003 (fig. 8). Withdrawals from the Kirkwood-Cohansey aquifer system range from 8.6 to 10.3 billion gallons per year and exceed the combined withdrawals from the other aquifers investigated in the Ocean County study area.

1. New Jersey Department of Environmental Protection water allocation permit series.
2. Map showing location of groundwater-withdrawal wells screened in the Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, Atlantic City 800-foot sand, Piney Point aquifer, and Vincentown aquifer, Ocean County study area, New Jersey, with withdrawal records for 2000 to 2003.
3. Graphs showing reported annual groundwater withdrawals by: A, water allocation permit series and B, aquifer, Ocean County study area, New Jersey, from 2000 to 2003. NJDEP, New Jersey Department of Environmental Protection.

# Simulation of Groundwater Flow

A three-dimensional groundwater-flow model of the Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, Atlantic City 800-foot sand, Piney Point aquifer, and Vincentown aquifer was developed by creating a mathematical representation of the regional hydrogeologic framework and flow system. The USGS modular finite-difference, groundwater-flow model, MODFLOW-2000, was used in this study (Harbaugh and others, 2000). The model code was designed and developed for use with packages that add functionality to the core program. Several MODFLOW packages, including the Basic (BA6), Discretization (DIS), Layer Property Flow (LPF), Recharge (RCH), Well (WEL), River (RIV), Drain (DRN), Flow and Head Boundary (FHB1), Zone (ZONE), Multiplier (MULT), Sensitivity (SEN), and Observation (OBS), were used to represent the flow system in the Ocean County study area. The FHB1 package is documented in Leake and Lilly (1997).

Hydraulic properties used in the model were initially estimated from aquifer tests and published hydrogeologic and modeling studies of the aquifers of interest. Initial values were revised during model calibration. The following sections describe the groundwater-flow model in detail and include the model discretization, model stresses, boundary conditions, and calibration evaluation.

## Model Discretization

The study area was discretized into a variably spaced model grid that was rotated 6 degrees from north. The model grid approximately parallelled the coastline of northern Ocean County and had a uniform spacing of 800 feet (ft), west to east, and 800 ft, north to south, over the land mass. Grid-cell dimensions increased to the east over the Atlantic Ocean to a maximum of 2,400 ft, west to east, and remained at 800 ft, north to south (fig. 9). There are 196 columns and 344 rows. The number of cells per layer is 67,424. The areal extent of the entire model grid is approximately 1,732 square miles and the active area of the model is 1,185 square miles.

1. Variably spaced model grid, lateral boundaries, and representation of water bodies in the Ocean County study area, New Jersey.

The vertical dimension of the hydrogeologic framework included in this investigation, extended from land surface through the subsurface to the bottom boundary of either the Vincentown aquifer or the lower sand of the Piney Point aquifer with underlying clay units. The groundwater-flow system was divided into 11 model layers, on the basis of the framework of the New Jersey Coastal Plain by the USGS (Zapecza, 1989) and on the updated hydrogeologic framework interpretations of Ocean County by the NJGWS (L.G. Mullikin, written commun., 2001). Contours of the top of hydrogeologic units provided by the NJGWS formed the basis for most of the model layers, particularly the top surface of each aquifer. The interpretation of the bottom of the unconfined Kirkwood-Cohansey aquifer system coincident with the top of the confining unit overlying the Rio Grande water-bearing zone by Zapecza (1989) was used to delineate the top of model layer 2. All model layers were extrapolated to be continuous throughout the area of active model cells. Where hydrogeologic units were interpreted to pinch out in the subsurface, the model layer thickness and hydraulic properties were set to represent flow properties of a different lithology (fig. 3).

Hydrostratigraphic interpretations of the Ocean County study area by NJGWS indicated subsurface zones of reduced permeability updip (northwest) from the confined Rio Grande water-bearing zone and the Atlantic City 800-foot sand (L.G. Mullikin, New Jersey Geological and Water Survey, written commun., 2001). In plan view, the semiconfined zones represented a transition from the clay units overlying the Rio Grande water-bearing zone and the Atlantic City 800-foot sand to the undifferentiated sands of the Kirkwood-Cohansey aquifer system (fig. 6). In vertical section, the semiconfined zones represented a gradational zone of sands and clays between the unconfined Cohansey Formation and the Kirkwood Formation sand, and the confined part of the Kirkwood Formation to the southeast (fig. 3). Vertical discretization of model layers 2 through 7 included these semiconfined zones, which extend several miles northwest of the Rio Grande water-bearing zone and Atlantic City 800-foot sand. In this report, potentiometric-surface maps of the Rio Grande water-bearing zone and Atlantic City 800-foot sand (model layers 3, 5, and 7) included this area. Wells within these semiconfined zones that contain a well screen within layers 1 to 7 were considered screened in the undifferentiated Kirkwood-Cohansey aquifer system. The aquifer designation of each well was derived from the USGS Ground Water Site Inventory (GWSI) database. Aquifer designations were based upon geologic maps, aquifer thickness, screen depth and either a driller’s log or a geophysical log of the bore hole or well, if available. Three deep wells (29–937, 29–1039, and 29–1133) in the Kirkwood-Cohansey aquifer system in Toms River Borough are screened in model layer 9 (table 4) and within the mapped updip limit of the Piney Point aquifer. Measured water levels in the 3 wells indicated a hydrologic connection with the Kirkwood-Cohansey aquifer system. These wells were identified as withdrawing water from the Kirkwood-Cohansey aquifer due to thin or inconsistent clays above the screen zone. At these locations model layers 1 to 9 were interpreted as the Kirkwood-Cohansey aquifer system.

1. Groundwater model layers and their representation in hydrogeologic units in the Ocean County study area, New Jersey

Streams, ponds, and lakes were simulated using a combination of the MODFLOW River Package and Drain Package. All surface-water features in the groundwater-flow model were derived from the geographical representation of their extent in the USGS 1:24,000 scale National Hydrography Dataset (NHD)—a feature-based database that interconnects and uniquely identifies the stream segments or reaches that make up the surface-water drainage system throughout the country.

Time in the groundwater-flow model was set to units of seconds. The simulation period of the model was from January 2000 through December 2003; a total of 89 stress periods were used. The first five stress periods were steady-state initial conditions, representing average recharge and withdrawal conditions from January 1 through December 31, 2000, repeated five times. Stress periods 6 through 41 were transient stress periods representing year 2000 monthly stresses, repeated three times. This created a transition from steady-state average 2000 conditions to the transient period used for model calibration. The calibration period extended from stress period 42 through 89 which were each 1 month in duration, and represented January 1, 2000, through December 31, 2003.

## Boundary Conditions

The top boundary of the flow model is the free surface of the water table (fig.3). Land areas were represented by variable head cells with groundwater recharge applied to the top surface. Where land surface is beneath Barnegat Bay, Little Egg Harbor, Great Bay, or the Atlantic Ocean, the top boundary was represented by constant head cells. Additional areas of constant head cells include small sedge islands, primarily in Little Egg Harbor, and shoreline land masses that are large coastal wetland areas (fig. 3). Streams and inland wetland areas were represented as specified-head boundaries, using either the RIV or DRN package.

The FHB1 package provides a way to apply specified heads, or specified flow at boundary cells from a larger-scale model, such as RASA. The RASA model (Voronin, 2005) was revised to include a model layer representing the Rio Grande water-bearing zone (Daryll Pope, U.S. Geological Survey, written commun., 2008). Model simulations of no-withdrawal and recent withdrawal conditions were made using the revised RASA model. Flows generated by these simulations were used at corresponding cells as input to the FHB1 Package to incorporate flow at lateral and bottom model boundaries.

The bottom boundary of the model is a flow boundary representing the movement of water at the bottom contact of a confined aquifer with an underlying clay unit within the composite confining unit (table 2). The bottom boundary in the northern part of the study area is between the base of the Vincentown aquifer and the top of the Hornerstown Formation. Farther to the southeast, the bottom boundary is the contact between the bottom of the lower sand of the Piney Point aquifer and the top of the Manasquan Formation. Flow at the bottom boundary was simulated with the FHB1 Package.

The lateral flow boundaries of the study area are coincident with a variety of hydrologic features. The northwestern boundary corresponds to the northwestern extent of the Vincentown aquifer. The northeastern boundary is the center of the main branch of the Manasquan River, and the southern boundary is the center of the main channel of Wading River, Mullica River, and Great Bay. The eastern boundary is approximately 5.5 miles east of the barrier island in the Atlantic Ocean. The western boundary from south to north corresponds to the basin boundary of Oswego River and subbasin divides within the Mount Misery Brook, Pole Bridge Branch, and Jumping Brook Basins, and a portion of Lahaway Creek. The FHB1 Package was used to incorporate boundary flow in model layers 1 and 3 for no-withdrawal conditions dependent upon the cell-by-cell budget determination at corresponding cell faces in the RASA model. Published prepumping heads (Zapecza and others, 1987) were used to specify boundary heads for layers 5, 7, 9 and 11 (Atlantic City 800-foot sand, Piney Point and Vincentown aquifers) for no-withdrawal conditions. Simulated boundary flows derived from the revised RASA model were used for layers 1 and 3 of the Ocean County study area model because published prepumping heads for the Rio Grande (model layer 3) do not exist. The FHB1 Package was used to incorporate boundary flows from the RASA model in model layers 1, 3, 5, 7, 9, and 11 for the years of 2000 to 2003.

All streams and lakes were represented in the groundwater-flow model using the RIV package. Ponds and upland wetland areas disconnected from stream reaches were represented in the groundwater-flow model using the DRN package. Barnegat Bay-Little Egg Harbor, Great Bay, and any low-lying islands in the bay were represented as constant head cells with a water level of 0 feet. Wetland areas in the southern part of the study area were represented in the NHD by interconnected channels adjacent to the shoreline and generally had an altitude of 5 feet or less. These areas were simulated as constant head cells. Groundwater withdrawals were simulated in the groundwater flow model using the WEL package.

## Recharge

In the groundwater-flow model, recharge to the unconfined surficial aquifer was represented as a flux across the water table, simulated as a volume of water applied to the top area of each model cell in layer 1 per unit of time. Researchers have used a variety of methods to estimate recharge in the New Jersey Coastal Plain, including water-budget analysis that accounts for soil type and land use (Charles and others, 1993) and calculations of unsaturated flow using moisture-content data (Baehr and others, 2003). Watt and others (1994) used a water-budget analysis to estimate recharge in the Metedeconk River Basin and the Toms River Basin with precipitation and discharge data from 1980 through 1989. Watt and others (1994) estimated an annual recharge rate of 15.45 inches per year (in/yr) in the Metedeconk River Basin and 19.4 in/yr in the Toms River Basin. Nicholson and Watt (1997) estimated different recharge rates on the basis of geology of the underlying sediments and the percentage of urban land use in the Metedeconk River and Toms River Basins. In that study, recharge of 13.4 to 17.3 in/yr was estimated for urban land, and 16.8 to 21.6 in/yr was estimated for non-urban land. Gordon (2004) conducted an investigation of water resources in the southern part of Ocean County that includes Cedar Creek, Forked River, Oyster Creek, Mill Creek, Cedar Run, Dinner Point Creek, Westecunk Creek, and Tuckerton Creek Basins. Gordon (2004) estimated a recharge rate of 17.5 in/yr. The NJGWS used land use, land cover, soil and climate data to derive and map estimates of groundwater recharge throughout New Jersey (New Jersey Geological and Water Survey, 2005). Groundwater recharge rates are generated at a resolution of 1 acre or greater for all parcels of land in New Jersey. Using the NJGWS method, two distinct areas of different recharge rates were produced, whereas water-budget methods generate a uniform rate over the entire Ocean County study area that varies with time. Annual recharge in the Ocean County study area varies from no recharge in wetland areas to 18 in/yr in upland areas, using the NJGWS methodology.

A monthly recharge rate was estimated for 1990 to 2003 in the Ocean County study area using a modified water balance method that incorporates the effect of land use by factoring spatially uniform estimated monthly rates with the spatially variable annual recharge data. The water balance method described in Nicholson and Watt (1997) was used in this study to calculate daily recharge and sum it by month; the method was modified slightly so that infiltration values are not time lagged. Calculation of recharge, a multistep process, is presented in equations 1 and 2. Equation 1 estimates 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), (1)

where

Daily PPT = daily value of measured precipitation, in inches;

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

Daily SMD (d – 1) = 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 2).

Monthly GW Recharge = Monthly Surplus PPT – Monthly DRO, (2)

where

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

Monthly DRO = monthly total of direct runoff, in inches.

Precipitation, direct runoff, and potential evapotranspiration vary spatially between the northern and southern parts of the Ocean County study area. In general, the north has higher precipitation, higher direct runoff, and lower potential evapotranspiration rates than the south. These differences were the basis for using two recharge zones with different time-dependent values in each zone. Monthly values for each recharge zone were averaged to determine a 14-year monthly average. The monthly values were divided by the 14-year monthly average to establish a monthly rate multiplier for use with the NJGWS groundwater recharge data.

Average yearly recharge in the NJGWS geospatial recharge data was assigned to each model cell. Recharge is set to zero at cells that simulate groundwater-discharge areas, such as wetlands. The average yearly recharge for each model cell was converted to a monthly value and multiplied by the monthly rate multiplier to calculate monthly recharge per model cell. These values were increased by a multiplication factor during model calibration to provide a better match between measured and simulated base-flow values. For the years 2000 through 2003, the simulated annual recharge for all model cells in layer 1 ranges from a low of 12.42 in/yr in 2001 to a high of 21.20 in/yr in 2002 (fig. 10).

1. Graph showing monthly and annual simulated recharge, 2000 to 2003, Ocean County study area, New Jresey.

## Hydrologic Properties

Previous hydrologic investigations of the New Jersey Coastal Plain reported values of horizontal and vertical hydraulic conductivity, specific yield, and storage coefficient for the Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, Atlantic City 800-foot sand, and Piney Point and Vincentown aquifers; vertical hydraulic conductivity was reported for the intervening confining units (table 5). The calibrated flow model applied published hydraulic parameter values to each hydrogeologic unit (table 6).

Streambed hydraulic conductivity of 0.35 feet per day (ft/d) and drain hydraulic conductivity of 0.25 (ft/d) were used to calculate the conductance of river and drain cells. These values are similar to those used in a simulation of the water table in the Mullica River Basin, New Jersey (Harbaugh and Tilley, 1984). Streambed thickness is estimated at 3 feet. The river conductance for each cell was calculated as a product of the area within a cell, the streambed hydraulic conductivity, and the streambed thickness.

1. Published hydraulic properties of aquifers and confining units in the Coastal Plain of New Jersey.
2. Hydraulic properties used in groundwater-flow model simulations for the Ocean County study area, New Jersey.

## Transient Calibration

When evaluating the adequacy of model calibration, Reilly and Harbaugh (2004) state that “a reasonable representation of the conceptual model and sources of water is more important than blindly minimizing the discrepancy between simulated and observed heads.” For this model, several types of data are used for comparison of measured and simulated values to support the representation of the conceptual model, including water levels, ground-water discharge to streams and regional flow budgets.

Hydrologic properties are adjusted during model calibration to minimize the differences between simulated and measured values of one or more of the following: (1) estimated base flow at 12 streamflow-gaging stations, (2) water levels in 63 selected wells, (3) potentiometric surfaces in October 2003, and (4) water levels in 14 selected observation wells for which long-term hydrographs are available. Potentiometric-surface maps of all confined aquifers in the New Jersey Coastal Plain, generated from measurements of groundwater level during October to December 2003 (dePaul and others, 2009), were used in this analysis.

Initial values of specific yield for the unconfined Kirkwood-Cohansey aquifer system (layer 1) and the unconfined part of the Vincentown aquifer are set to published values and adjusted during model calibration by comparing measured water levels at wells screened in the unconfined aquifer to simulated heads in the respective model layer. Storage is a source of water to groundwater-withdrawal wells, and the amount of water available from storage varies from aquifer to aquifer. Hydrographs of simulated and measured water levels are compared for wells screened within each respective aquifer. Initial published values of specific storage are adjusted for each model layer to minimize the difference between simulated heads and periodic water-level measurements at observation or withdrawal wells.

The average difference (simulated water level minus measured water level or residual), average absolute difference, and the root mean square error between simulated and measured water levels at 63 wells that had more than one water-level measurement during January 2000 to December 2003 are used to evaluate model calibration (table 7). The root mean square error for 631 water-level measurements within the study area is 13.0 feet, indicative of a reasonable fit between simulated and measured water levels. Seventy-eight percent of the simulated water levels are within11 feet of the measured water levels. Wells that had a water-level residual greater than 9 feet include public-supply wells and observation wells near public-supply wells where substantial withdrawals occur. The average of the residual for each layer ranges from -13.2 to 6.2 feet. The average absolute difference residual for each layer ranges from 4.7 to 13.2 feet.

1. Average difference between simulated and measured water levels from January 2000 to December 2003 in selected wells, Ocean County study area, New Jersey.

The October 2003 simulated water table of the Kirkwood-Cohansey aquifer system closely approximates the measured composite water table (fig. 11A). The absolute values of the average water-level residuals for wells screened in the Kirkwood-Cohansey aquifer system are 11 feet or less at 23 of 28 wells, and the average of residuals is -4.6 feet (table 7). Relatively large residuals are indicated at five wells, of which, four are affected by groundwater withdrawals.

1. Maps showing simulated October 2003 and composite measured water tables of the A, Kirkwood-Cohansey aquifer system; B, Rio Grande water-bearing zone; C, Atlantic City 800-foot sand, upper sand unit; D, Atlantic City 800-foot sand, lower sand unit; and E, Piney Point aquifer, Ocean County study area, New Jersey. Average water-level residuals from 2000 to 2003 are shown for each well screened in the aquifer with multiple water-level measurements. NGVD 29, National Geodetic Vertical Datum of 1929.

The October 2003 simulated and measured potentiometric surfaces of the Rio Grande water-bearing zone along with the average 2000 to 2003 water-level residuals are based on data from only two public-supply wells screened in the aquifer (fig. 11B). Hydrologic data for the Rio Grande water-bearing zone in the Ocean County study area are limited as a result of the minor geographic extent of the water-bearing zone in the southeastern part of the county. The average residual at the two public-supply wells is -13.2 feet.

The October 2003 simulated potentiometric surface of the upper and lower sand units of the Atlantic City 800-foot sand are very similar (figs. 11C and D). Most of the wells screened in the Atlantic City 800-foot sand are public-supply wells located on Long Beach Island and are subject to high withdrawal demand. Measured water levels in these wells are affected by pumping conditions at or near each well. Residuals at 12 of 13 wells are 9 feet or less (table 7). The average of residuals in the Atlantic City 800-foot sand is -3 feet. Simulated water levels are within 5 feet of the measured 2003 potentiometric surface near the cone of depression in the southern part of the barrier island.

The October 2003 simulated potentiometric surface closely approximates the measured potentiometric surface of the Piney Point aquifer (fig. 11E). The depths of two cones of depression centered near Barnegat Light Borough and Seaside Park, New Jersey, are accurately simulated. Simulated water levels for 14 of the 18 observation wells screened in the Piney Point aquifer are within 14 feet of measured water levels (table 7). Average water level residuals are greater than 14 feet at several public-supply wells and at observation well 29–1675. Well 29–1675 with a residual of 20 feet is located near observation wells 29–1217 and 29–585 where simulated water levels are within 6 feet of measured water levels.

More emphasis is placed on closely matching measured water levels at selected observation wells (fig. 12) than at public-supply wells during calibration. All of the simulated water levels at these selected observation wells screened in the Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, Atlantic City 800-foot sand, and the Piney Point aquifer are within 11 feet of measured water levels at the observation wells (figs. 13 and 14). Simulated water levels also reflect monthly, seasonal, and long-term trends in measured water levels.

1. Map showing location of selected observation wells with periodic water-level measurements, Ocean County study area, New Jersey.
2. Hydrographs of simulated and measured water levels at selected observation wells screened in: A to F, the Kirkwood Cohansey aquifer system; and, G to H, Rio Grande water-bearing zone, Ocean County study area, New Jersey, 2000 to 2003.
3. Hydrographs of simulated and measured water levels at selected observation wells screened in: A to C, the Atlantic City 800-foot sand; and, D to F, Piney Point aquifer, Ocean County study area, New Jersey, 2000 to 2003.

Base flow was estimated for 12 streamflow-gaging stations located within the Ocean County study area (fig. 15). Five streamflow-gaging stations are equipped with instrumentation that records continuous streamflow, and seven streamflow-gaging stations are sites at which periodic streamflow measurements are made during low-flow conditions. Base flow estimates from streamflow measurements at continuous record stations are based on hydrograph separation methods described by Rutledge (1993). Base flow estimates for periodic-record stations are based on developing correlations with index stations and using the estimated base flow for the index station in the correlation equation. Simulated base flow values are calculated by summing the flow to drain cells (used to represent wetlands adjacent to stream reaches) and the flow to river cells upstream from each streamflow-gaging station location in the model.

1. Map showing location of selected streamflow-gaging stations in the Ocean County study area, New Jersey.

Calibration to monthly base flow was achieved by varying values of model parameters within a plausible range to achieve a reasonable match in base flow while not adversely affecting simulated groundwater levels in the unconfined part of the groundwater-flow model. Model parameters that were adjusted include streambed conductance, horizontal and vertical conductivity of model layers 1 and 2, and specific yield. Recharge rates were changed during calibration by modifying the recharge multiplier, thereby keeping the areal variability based on the NJGWS recharge data.

Streamflow-gaging stations are used as calibration points because measured streamflow is from distinct areas of the Barnegat Bay-Little Egg Harbor watershed or other subbasins in the study area. Base-flow separations and low-flow correlations are used to estimate average monthly base flow over a 48-month period (January 2000 to December 2003) at five continuous-record stations and seven low-flow partial-record stations (table 8). Simulated base flow is the summation of flow out of drain and river cells (figs. 16 and 17). Residual values indicate a reasonable match between simulated and estimated base flow at the streamflow-gaging stations listed (table 8).

1. Graphs showing estimated monthly and simulated monthly base flow from January 2000 to December 2003 at streamflow-gaging stations: A, North Branch Metedeconk River near Lakewood (01408120): B, South Branch Metedeconk River near Lakewood (01408150): C, Toms River near Toms River (01408500): D, Wrangel Brook at Mule Road near Toms River (01408592): E, Cedar Creek at Lanoka Harbor (01409000): and F, North Branch Forked River near Forked River (01409050), New Jersey.
2. Graphs showing estimated monthly and simulated monthly base flow from January 2000 to December 2003 at streamflow-gaging stations: A, Oyster Creek near Waretown (01409100); B, Mill Creek near Manahawkin (01409150); C, Cedar Run near Manahawkin (01409250); D, Westecunk Creek at Stafford Forge (01409280); E, East Branch Bass River near New Gretna (01410150); and F, Oswego River at Harrisville (01410000), New Jersey.

In general, simulated base flow follows the same temporal pattern as estimated base flow at each gaging station. However, during certain months simulated base-flow peaks are lower than estimated peaks, and simulated lows are higher than estimated lows at certain streamflow-gaging stations (figs. 16 and 17). The mean difference and mean absolute difference between simulated and estimated mean monthly base flows are generally small when compared with mean monthly base flows at each streamflow-gaging station. Larger differences occur at 01409250 Cedar Run (fig. 17C) near Manahawkin, N.J., where measured flow is from a very small basin, than from relatively large basins (?). Comparing mean differences between simulated and estimated base flow indicates that simulated base flows are underestimated in the southern portion of the Ocean County study area (Oyster Creek basin to Westecunk Creek basin). Precipitation and recharge in 2000 is less than in1998 to 1999 and preliminary model development that simulated 1998 through 2003 demonstrated higher simulated monthly base flow during 2000 when the transient simulation included those years, than during 1998 to 1999. Increasing the recharge multiplier in the southern portion of the Ocean County study area would increase base flow in these streams; however, emphasis in the calibration was placed upon simulating reasonable yearly recharge rates (table 9).

1. Simulated and estimated mean monthly base flow at selected streamflow-gaging stations, Ocean County study area, New Jersey, for January 2000 to December 2003.
2. Time period, groundwater-withdrawal rate, groundwater discharge to streams, and recharge rate simulated in the groundwater-flow model.

## Sensitivity Analysis

The model calibration demonstrates that the groundwater-flow model defined by its combination of boundary conditions, boundary flows and heads, hydrologic unit definition, geometry and hydraulic parameters reasonably reproduces the measured water table, base flows, and potentiometric surfaces of the aquifer system for the Ocean County study area. The purpose of sensitivity analysis is to quantify the uncertainty in the calibrated model due to uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions (Anderson and Woessner, 1991). The objective is to determine how readily and excessively water-level altitudes are affected by a change in hydrologic parameters in the calibrated model. A sensitivity analysis was conducted for the groundwater-flow model using UCODE-2005 (Poeter and others, 2005). The composite scaled sensitivities (CSS) are used to evaluate the sensitivity of the simulated model parameters and determine if there is sufficient information in the calibration data to estimate a parameter (Hill and Tiedeman, 2007).

CSS are calculated for 115 parameters as part of the model sensitivity analysis (table 10). A weighting factor for the observation value is not used in the calculation of the CSS. Hill and Tiedeman (2007) state that it is likely that a parameter-estimation routine will not be able to estimate those parameters whose CSS values are less than about 0.01 times the largest value which is 27 for this model. Forty-two of the 115 parameters estimated in this study are considered sensitive (CSS values greater than 0.27), indicating they are reasonably estimated by model calibration (fig. 18). The most sensitive parameters (CSS greater than 2.0) are rech\_north (recharge in the northern part of the study area); rech\_south (recharge in the southern part of the study area); hk716 (horizontal hydraulic conductivity, layer 7, Atlantic city 800-foot lower sand unit); riverbedk (streambed hydraulic conductivity); hk715 (horizontal hydraulic conductivity, layer 7, Atlantic city 800-foot - lower sand unit); hk37 (horizontal hydraulic conductivity, layer 3, Rio Grande water-bearing zone); hk511 (horizontal hydraulic conductivity, layer 5, Atlantic city 800-foot upper sand unit); hk921 (horizontal hydraulic conductivity, layer 9, Piney Point Aquifer - upper sand unit); drainK (streambed hydraulic conductivity); hk15 (horizontal hydraulic conductivity, layer 1, Kirkwood-Cohansey aquifer system); hk512 (horizontal hydraulic conductivity, layer 5, Atlantic city 800-foot upper sand unit); vk818 (vertical hydraulic conductivity, layer 8, confining unit above Piney Point Aquifer); hk920 (horizontal hydraulic conductivity, layer 9, Piney Point Aquifer upper sand unit); hk1126 (horizontal hydraulic conductivity, layer 11, Piney Point Aquifer lower sand unit); hk48 (horizontal hydraulic conductivity, layer 4–7, Kirkwood-Cohansey aquifer system); and hk922 (horizontal hydraulic conductivity, layer 9, Piney Point Aquifer upper sand unit).

1. Graph showing composite scaled sensitivity values, Ocean County study area, New Jersey.
2. Maps showing location of parameter value zones in the model, Ocean County study area, New Jersey.
3. Calibrated model parameter values and composite scaled sensitivities, Ocean County study area, New Jersey.

## Model Limitations

The groundwater-flow model developed for this study is an approximation of a dynamic, real-world groundwater-flow system that covers 1,185 square miles of land and water, extends at the deepest point to nearly 1,000 feet below land surface, and represents five different aquifers. The flow model is constructed by dividing the area of study into discrete model cells that are primarily 800 feet by 800 feet in plan view and of variable thickness. Because of the number of model cells in each model layer (67,424), the number of model layers (11), and the limited data available that describe the hydrologic properties of each layer, the hydrologic parameters in the flow model are generalized and, therefore, do not reflect the total variability that exists in the actual flow system.

The vertical discretization of the hydrogeologic framework into model layers is based on available interpretations of the stratigraphy in the Ocean County study area. The delineation of the contact between the Vincentown aquifer and the Kirkwood-Cohansey aquifer system in the northwestern part of the study area is not well known. In particular, the area where the Vincentown aquifer becomes confined, the extent and the character of the confining bed have not been mapped in detail because of the limited number of available well logs in this area. The Vincentown aquifer in this area is not very extensive, and its use for public supply is small. As a result of these constraints, detailed analysis of the Vincentown aquifer is not a goal of this study. The lower sand unit of the Piney Point aquifer (L.G. Mullikin, New Jersey Geological and Water Survey, written commun., 2001) contains very few water supply wells and detailed analysis of its hydrologic properties is lacking. Model simulation results focus on the upper sand unit of the Piney Point aquifer.

The study area partially or entirely encompasses more than 30 distinct surface-water basins with extensive surface-water features (fig. 4). The model cell size (800 ft by 800 ft) provides an accurate representation of surface-water features without generating more than 1 million model cells in the 11 layer model which provides for reasonable model development and run times. A finer discretization of the study area would enhance the resolution of surface-water features by isolating individual stream reaches in more model cells. Improved resolution of surface-water features in the groundwater-flow model could provide more detail in simulated base flows.

The specified flow boundaries of the Ocean County study area model are derived from the New Jersey RASA model and are affected by limitations of that model. The RASA model has a larger grid discretization than the Ocean County study area model. Model cells over land surface in the RASA model range in area from 6.25 to 9.375 square miles (mi2), whereas the area of corresponding cells in the Ocean County study area model is 0.0229 mi2. The RASA model has a coarser time discretization than the Ocean County study area model and uses annual time steps; therefore, boundary flows into the Ocean County study area may not represent seasonal changes in these flows. The simulation of no-withdrawal conditions uses boundary heads for several confined aquifers. The boundary heads are derived from published contour maps of pre-pumping heads. The accuracy of pre-pumping groundwater levels are influenced by spatial (lack of numerous, evenly spaced wells at which water levels were recorded) and time-scale (some measurements made after 1900) issues and are considered estimates of the pre-pumping potentiometric surfaces (Zapecza and others, 1987).

# Simulated Effects of Groundwater Withdrawals

The effect of groundwater withdrawals on the groundwater-flow system in the Ocean County study area is evaluated based on three distinct groundwater-model simulations conditions that incorporate different withdrawal schemes or conditions: no-withdrawal conditions, postdevelopment withdrawal conditions, and maximum-allocation withdrawal conditions. No-withdrawal conditions are simulated using monthly recharge values estimated by model calibration, but groundwater withdrawals are excluded from the simulation. This simulation uses prevailing hydrologic conditions without withdrawals to provide a basis for comparison of conditions that may have existed prior to extensive development and use of the groundwater resource. Postdevelopment conditions are simulated using reported monthly groundwater withdrawals at production wells from January 2000 through December 2003 and monthly recharge rates estimated by model calibration. Maximum-allocation withdrawals are used to simulate a worst-case scenario in which all the wells in the study area extract the maximum-allocation withdrawal per monitoring period allowed by NJDEP Bureau of Water Allocation permits. To simulate these conditions, input to the flow model is designed so that all groundwater withdrawals occur at existing wells, and monthly recharge rates used in postdevelopment simulations are incorporated. These simulations allow direct comparison of the response of the groundwater-flow system to different withdrawal conditions.

Monthly allocations for individual wells in the Ocean County study area are estimated on the basis of 2006 permit allocations provided by the NJDEP Bureau of Water Supply and historical withdrawal data. Monthly well allocations are derived from the monthly percentage of a permit allocation attributed to the well on the basis of recorded withdrawals for all wells listed in a permit. Withdrawals from 1987 through 2006 are used to define the monthly percentage of the permit allocations apportioned to each well. Estimated allocations for wells listed under multiple permit allocations are based on the smallest permit allocation that pertains to that well. The sum of the estimated monthly well allocations for each month for all wells governed by the same permit is the highest combination of individual well withdrawals that do not exceed the monthly maximum allocation. The monthly sum of the estimated monthly well allocations for all wells in a permit is the highest combination of individual withdrawals that do not exceed the yearly allocation.

In general, permit allocations with high monthly maximum allocations and no yearly allocations result in excessively high estimated monthly well allocations. For public supply (5000) and industrial (2000P) permit series, wells with no yearly or no monthly maximum allocation are assigned an allocation on the basis of the average ratio of defined yearly allocation limits to defined monthly maximum-allocation limits for all permits within the respective series. For example, the ratio of yearly maximum to monthly maximum-allocation limits for wells used in this study is 7.4 for public supply withdrawal permits and 6.0 for industrial withdrawal permits. For small volume withdrawal permits (10000W series), estimated monthly maximum allocations are assumed to be 1.033 million gallons times the number of withdrawal wells in the permit, and the yearly maximum permit allocations are assumed to be 12.4 million gallons times the number of withdrawal wells on the permit. For agricultural permits pertaining to row crops, estimated monthly maximum allocations for June, July, and August are set to the monthly maximum permit allocation; for May, to one-half the monthly maximum allocation; and for the remaining months, to zero. For agricultural permits pertaining to withdrawals for containerized plants and blueberries, estimated yearly allocations are estimated to be 8 times the maximum monthly allocation assigned by the NJDEP.

Groundwater withdrawals from the shallow Kirkwood-Cohansey aquifer system causes a reduction in base flow in the streams in the study area. Groundwater flow that normally discharges to surface-water features under non-withdrawal conditions is diverted to supply wells. Results from stress periods 64, 73, 77, 80, and 87, which simulate monthly recharge conditions similar to November 2001, August 2002, December 2002, March 2003 and October 2003, respectively, are examined in detail to illustrate how the flow system responds to these conditions. Stress period 64 (November 2001 recharge) is a time of zero recharge following two months of low recharge. Stress period 73 (August 2002 recharge) is a month of slightly low recharge following four months of low recharge, and stress period 77 (December 2002 recharge) is a month of high recharge preceded by two months of high recharge. Stress period 80 (March 2003 recharge) is a month of slightly high recharge following five months of high recharge, and stress period 87 (October 2003 recharge) has average recharge proceeded by three months of low to average recharge in the study area. The following discussion examines simulations of three different withdrawal conditions and their effect on base-flow values at streamflow-gaging stations on streams that drain into the Barnegat Bay-Little Egg Harbor estuary or Great Bay.

The effects of seasonal changes in recharge to, and groundwater withdrawals from, the groundwater flow system is evaluated by examining water levels in the major confined aquifers in the Ocean County study area for August 2002 and March 2003 recharge conditions. May 2002 to August 2002 is a period with low simulated water levels and base flow, in part due to average estimated monthly groundwater recharge of 0.9 inch. Evapotranspiration is high and groundwater withdrawals typically increase during the summer; groundwater levels usually reach the lowest point of the year in late summer or early fall. Evapotranspiration decreases from October through March due to cooler temperatures and diminished plant growth and respiration. As a result, March 2003 is a period with relatively high water levels and base flow. The average estimated monthly groundwater recharge for October 2002 through March 2003 is 2.7 inches (table 9), nearly double the average estimated monthly recharge of 1.4 inches for 2000 through 2003 in the Ocean County study area. Stress period 73 (August 2002 recharge) and stress period 80 (March 2003 recharge) represent contrasts in recharge and withdrawals during the simulation period (fig. 16) and are used in the following discussion to illustrate the response of water levels to these conditions.

## No-Withdrawal Conditions

A groundwater budget of flow into, and out of, the Kirkwood-Cohansey aquifer system during five stress periods can be used to illustrate how the groundwater-flow system responds to natural conditions without groundwater withdrawals (fig. 20A). Analysis of stress period 64 (November 2001 recharge), stress period 73 (August 2002 recharge), stress period 77 (December 2002 recharge), stress period 80 (March 2003 recharge), and stress period 87 (October 2003 recharge) indicates that the largest and most variable component of water entering the groundwater-flow system is recharge (0 to 2,290 cubic feet per second [ft3/s]), followed by net flow into storage (27 to 602 ft3/s). The largest component of groundwater flow out of the Kirkwood-Cohansey aquifer system, 484 to 1,086 ft3/s flows to all streams, represented as drain and river cells in the model (fig. 20A). Water in the Kirkwood-Cohansey aquifer system enters storage during high recharge conditions (net flow of 1,043 ft3/s in stress period 77), flows out to wetlands and the ocean that are represented as constant head cells in the model (107 to 136 ft3/s) and out to adjacent aquifers (9 to 27 ft3/s) during the examined stress periods. Simulation of no-withdrawal conditions indicates that flow is less than 1 ft3/s into and out of the Rio Grande water-bearing zone and the Atlantic City 800-foot sand for selected stress periods and less than 2.5 ft3/s into and out of the Piney Point aquifer in the Ocean County study area (figs. 20B, C, and D). Groundwater flow to streams, which subsequently discharges into the Barnegat Bay-Little Egg Harbor estuary, ranges from 326 to 759 ft3/s per stress period due to the simulated conditions.

1. Graphs showing groundwater-flow budgets for during selected stress periods under no-withdrawal conditions: A, the Kirkwood-Cohansey aquifer system, B, Rio Grande water-bearing zone, C, Atlantic City 800-foot sand, and D, Piney Point aquifer, Ocean County study area.

Wells 29–141, 29–1060, and 29–513 (figs. 21A, B, and C, respectively) are screened in the unconfined Kirkwood-Cohansey aquifer system; simulated water levels in these wells respond to variable recharge under the conditions of no-withdrawal that are depicted. Simulated water levels in wells screened in confined aquifers show little response to variations in recharge (figs. 21E and F, 22A–E, and 23A, C, and D), except at observation well 29–425, screened in the Piney Point aquifer (fig. 23B). This well is located in the west-central part of the study area close to the updip boundary of the aquifer. Water levels from no-withdrawal conditions range from 119 to 121 feet. The updip area of the Piney Point aquifer appears to be more affected by fluctuations in the water table than downdip areas. The confining unit overlying the Piney Point aquifer in the updip area may contain sediments that are more transmissive than those in the downdip area [?], and as a result, the Piney Point aquifer might have a hydraulic connection with the overlying water table.

1. Graphs showing simulated water levels in selected observation wells screened in the unconfined Kirkwood-Cohansey aquifer system, wells A, 29–141, B, 29–1060, C, 29–513, D, 29–17 and in the Rio Grande water-bearing zone, wells E, 29–775, and F, 29–1621, during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey.
2. Graphs showing simulated water levels in selected observation wells screened in the Atlantic City 800-foot sand, wells A, 29–9, B, 29–457, C, 29–936, D, 29–464, and E, 29–814, during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey.
3. Graphs showing simulated water levels in selected observation wells screened in the Piney Point aquifer, wells A, 29–2, B, 29–425, C, 29–582, and D, 29–1210, during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey.

## Postdevelopment Withdrawal Conditions

Postdevelopment withdrawal conditions from 2000 to 2003 are simulated using monthly groundwater withdrawals from wells in the Ocean County study area for aquifers during postdevelopment withdrawal conditions for stress periods 64, 73, 77, 80 and 87 (with November 2001, August 2002, December 2002, March 2003, and October 2003 recharge, respectively; fig. 24). Because of the withdrawals (24 to 42 ft3/s), less groundwater flows out of the Kirkwood-Cohansey aquifer system into streams (437 to 1,025 ft3/s combined net flux) than for the no-withdrawal simulation. Simulated flow out of the Kirkwood-Cohansey aquifer system to constant head cells ranges from 99 to 129 ft3/s (fig. 24A). Net flow out of the Kirkwood-Cohansey aquifer system to adjacent layers ranges from 33 to 49 ft3/s, an increase from no-withdrawal conditions.

1. Graphs showing groundwater-flow budgets for the A, Kirkwood-Cohansey aquifer system, B, Rio Grande water-bearing zone, C, Atlantic City 800-foot sand, and D, Piney Point aquifer, during postdevelopment withdrawal conditions, Ocean County study area, New Jersey.

Groundwater withdrawals from the Kirkwood-Cohansey aquifer system (24 to 42 ft3/s) and the Rio Grande water-bearing zone (0 to 0.7 ft3/s) cause net flow into the Rio Grande water-bearing zone from adjacent layers (0.3 to 0.7 ft3/s) (fig. 24B). Groundwater withdrawals from the Atlantic City 800-foot sand (12 to 30 ft3/s) caused flow into this aquifer from other layers (15 to 21 ft3/s) (fig. 24C). The net inflow to the Rio Grande water-bearing zone and Atlantic City 800-foot sand in this simulation reflects a change in flow direction from no-withdrawal conditions, where flow is generally out to other layers. Withdrawals from the Piney Point aquifer during postdevelopment withdrawal conditions (3.7 to 7.5 ft3/s) resulted in increased net groundwater flow into the aquifer from other layers (3.8 to 4.7 ft3/s) (fig. 24D). Groundwater withdrawals from all confined aquifers are largest during stress period 73 (August 2002 recharge), of the five stress periods examined, which causes the largest in flow from storage and other layers in the confined aquifers.

Simulated groundwater withdrawals from the Kirkwood-Cohansey aquifer system cause a reduction in base flow that is evaluated by comparing base flow at streamflow-gaging stations from the no-withdrawal simulation to base flow at the same stations during a simulation of postdevelopment withdrawal conditions. Simulated postdevelopment withdrawals cause base-flow reductions at all simulated streamflow-gaging stations locations in the Ocean County study area with 6 of the 12 stations having average simulated reductions of less than 1 ft3/s (table 11). The smallest reduction in simulated base flow from no-withdrawal to postdevelopment withdrawal conditions occurs at streamflow-gaging station Cedar Run near Manahawkin, N.J. (01409250), which decreases by a minimum of 0.03 ft3/s and a maximum of 0.11 ft3/s. Larger base-flow reductions than those simulated for Cedar Run occurred at streamflow-gaging stations Wrangel Brook at Mule Road near Toms River, N.J. (01408592); South Branch Metedeconk River near Lakewood, N.J. (01408150); Toms River near Toms River, N.J. (01408500); Cedar Creek at Lanoka Harbor, N.J. (01409000); and Oswego River at Harrisville, N.J. (01410000). The largest reduction in base flow between the two simulations occurs at the simulated location of Toms River near Toms River, N.J. (01408500) streamflow-gaging station, which has a minimum decrease of 6.8 and a maximum of 9.5 ft3/s.

The percent reduction in base flow from no-withdrawal to postdevelopment withdrawal conditions indicates that all streamflow-gaging stations had less than a 9-percent reduction. Streamflow-gaging stations Wrangel Brook at Mule Road near Toms River, N.J. (01408592) and North Branch Metedeconk River near Lakewood, N.J. (01408120) in the northern part of the study area had the highest percent and highest average percent reductions in base flows, whereas Cedar Creek at Lanoka Harbor, N.J. (01409000), and Oswego River at Harrisville, N.J. (01410000), in the central and southern part of the study area, respectively, had the lowest percent reductions.

1. Simulated base-flow reductions at selected streamflow-gaging stations from no-withdrawal to postdevelopment withdrawal conditions and from no-withdrawal to maximum-allocation withdrawal conditions, Ocean County study area, New Jersey.

During extended periods of little or no precipitation, streamflow in the Coastal Plain of New Jersey can be entirely from base flow.. During periods of normal precipitation, the total amount of streamflow at any point in a stream includes both base flow and overland flow from storms. The total base-flow rate in streams that drain into the Barnegat Bay-Little Egg Harbor estuary is calculated for each model simulation (table 12). The amount of base flow that reaches Barnegat Bay-Little Egg Harbor estuary is dependent on the amount of precipitation that falls on the land surface and ultimately recharges the surficial aquifer and the amount of groundwater withdrawn from the shallow aquifer system, as well as the location of streams and drains that influence the directions of flow within the unconfined and confined aquifers. Of the stress periods examined, stress period 77 (December 2002 recharge) had a high rate of simulated recharge to the aquifer and the highest amount of simulated base flow out of the aquifer to streams that flow into the Barnegat Bay-Little Egg Harbor estuary.

Results of simulated base flow to streams that flow into the Barnegat Bay-Little Egg Harbor estuary indicate that for stress period 64 (November 2001 recharge), postdevelopment withdrawal conditions, base flow from all streams that flow into the Barnegat Bay-Little Egg Harbor estuary (287 ft3/s) is less than half of base flow (710 ft3/s) for stress period 77 (December 2002 recharge) as a result of much lower seasonal recharge rates and larger withdrawals (table 12). Results of comparing the simulation of postdevelopment withdrawal conditions with no-withdrawal conditions indicate there is 39 ft3/s (12 percent) less base flow reaching the Barnegat Bay-Little Egg Harbor estuary during stress period 64 (November 2001 recharge) and 49 ft3/s (6.4 percent) less during stress period 77 (December 2002 recharge) due to groundwater withdrawals than during the no-withdrawal simulations.

1. Estimated base flow to streams that flow into the Barnegat Bay-Little Egg Harbor estuary, Ocean County study area, New Jersey.

Simulated water levels from postdevelopment withdrawal conditions at wells 29–141, 29–513, 29–1060 and 29–17, screened in the Kirkwood-Cohansey aquifer system are less than 1 ft lower than they would be based on no-withdrawal conditions alone (fig. 21). Simulated water levels in well 29–17 are 12.04 and 11.72 feet lower during stress periods 73 and 80 (August 2002 and March 2003 recharge, respectively), than they would be under no-withdrawal conditions (table 13). Wells 29–141, 29–513 and 29–1060 are screened 50 feet or less below the land surface. The small response in groundwater levels at these wells is typical of wells completed in the shallow, unconfined water-table aquifer. Well 29–17 is screened 377 feet below land surface, and the groundwater-level response in this well is indicative of semiconfined conditions at depth.

1. Simulated water levels during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions at selected wells, stress periods 73 (August 2002) and 80 (March 2003), Ocean County study area, New Jersey.

The simulated potentiometric surfaces of the Rio Grande water-bearing zone (fig. 25) during stress periods 73 (August 2002 recharge) and 80 (March 2003 recharge), examined at wells 29–775 and 29–1621 (table 13), indicate substantial declines from no-withdrawal conditions to postdevelopment conditions as a result of groundwater withdrawals. Simulated groundwater levels in these wells declined approximately 39 to 150 feet in stress period 73 (August 2002 recharge) and 28 to 37 feet in stress period 80 (March 2003 recharge). Groundwater levels in the Rio Grande water-bearing zone exhibit larger seasonal fluctuations in areas closer to the center of the cone of depression in the southern part of Long Beach Island (fig. 25) as reflected in the simulated hydrograph for well 29–1621 (fig. 21F). The simulated change in water levels due to seasonal withdrawals at this well are sometimes as great as 100 feet over the course of a year.

1. Maps showing simulated potentiometric surfaces of the Rio Grande water-bearing zone, stress periods 73 (August 2002) and 80 (March 2003), during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey.

Regional water levels in the Rio Grande water-bearing zone simulated for postdevelopment withdrawal conditions range from an altitude of -40 to -60 feet during stress period 73 (August 2002 recharge) to -10 to -20 feet during stress period 80 to at the southern end of Long Beach Island (fig. 25). Drawdown of no-withdrawal potentiometric surfaces to postdevelopment potentiometric surfaces are illustrated for the confined aquifers during stress period 73 (August 2002 recharge) and represent maximum differences due to seasonal lows in water levels (fig. 26). Regional drawdown of the Rio Grande water-bearing zone potentiometric surface along Long Beach Island ranges from 20 feet near the northern part of the barrier island to 60 to 80 feet near the southern end. Drawdowns at well 29–1621 in Holgate are larger than elsewhere.

1. Maps showing simulated drawdown of potentiometric surfaces of: A, the Rio Grande water-bearing zone;, B, the Atlantic City 800-foot sand, upper sand unit; C, the Atlantic City 800-foot sand, lower sand unit; and D, the Piney Point aquifer from no-withdrawal to postdevelopment withdrawal conditions, stress period 73 (August 2002) in the Ocean County study area, New Jersey.

During postdevelopment withdrawal conditions, seasonal variations in water levels in the upper and lower sand units vary as much as 20 to 30 feet (fig. 22; table 13). The simulated postdevelopment potentiometric surface of the upper sand of the Atlantic City 800-foot sand during stress periods 73 (August 2002 recharge) and 80 (March 2003 recharge) are very similar in the upper and lower sand units (fig. 27). During no-withdrawal conditions, stress periods 73 and 80, the potentiometric surface is at an altitude of 20 feet in Barnegat Light Borough. In response to large groundwater withdrawals from this aquifer in Atlantic County (18 to 24 million gallons per day, 1978–2003), a cone of depression centered developed near Margate City, N.J., (dePaul and others, 2009). Measured water levels in the Atlantic City 800-foot sand within the center of the cone of depression, just north of Margate City are at an altitude of -90 feet in 2003 (dePaul and others, 2009). The northern edge of this regional cone of depression extends into Ocean County at an altitude of -20 feet just south of Barnegat Light Borough. Simulated postdevelopment water levels during stress period 87 (October 2003 recharge) are very similar to mapped 2003 water levels (dePaul and others, 2009; fig. 12C). Regional water levels in the Atlantic City 800-ft sand, simulated for postdevelopment withdrawal conditions, range from -20 feet at Surf City Borough to the southern end of Long Beach Island during stress period 80, to -40 feet at Surf City Borough south to Beach Haven Borough during stress period 73 (fig. 27). Simulation of postdevelopment withdrawals from the Atlantic City 800-foot sand indicates regional drawdowns ranging from 20 to 80 feet (figs. 26B and C) from simulated no-withdrawal water levels during stress period 73. Simulated regional drawdown of the Atlantic City 800-ft sand potentiometric surface ranges from 60 to 80 feet centered on the Long Beach Island communities of Surf City, Ship Bottom, and Beach Haven Boroughs and Long Beach Township, with larger drawdowns simulated at withdrawal wells (figs. 26B and C).

1. Maps showing simulated potentiometric surfaces of the Atlantic City 800-foot sand, upper sand unit, stress periods 73 (August 2002) and 80 (March 2003), during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey.

The differences between no-withdrawal and postdevelopment simulated water levels for wells 29–2, 29–425, 29–582, and 29–1210, screened in the Piney Point aquifer, range from less than 1 foot to 73 feet at these wells during stress periods 73 (August 2002 recharge) and 80 (March 2003 recharge). The center of the cone of depression in the potentiometric surface of the Piney Point aquifer is located in Barnegat Light Borough (figs. 2 and 28) near well 29–2 (fig. 23A). Well 29–1210, located south of the center of the cone of depression in Barnegat Light Borough (fig. 23D), exhibits a smaller decline of approximately 40 feet, in water levels. Simulated water levels in well 29–425, located in the northwest part of the study area, far from the cones of depression centered in Barnegat Light and Seaside Park Boroughs (figs. 23B and 28) does not experience declining water levels.

1. Maps showing simulated potentiometric surfaces of the Piney Point aquifer, stress periods 73 (August 2002 recharge) and 80 (March 2003 recharge), during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions, Ocean County study area, New Jersey.

The simulated potentiometric surface of the Piney Point aquifer during stress periods 73 (August 2002 recharge) and 80 (March 2003 recharge) from no-withdrawal conditions in the Piney Point aquifer are at an altitude of approximately 20 feet on much of Long Beach Island (fig. 28). Cones of depression located in Toms River Township, Seaside Heights and Seaside Park Boroughs, and Barnegat Light Borough developed in the aquifer in response to postdevelopment groundwater withdrawals. Regional water levels in the Piney Point aquifer simulated for postdevelopment withdrawal conditions are at an altitude of -20 feet in the barrier island communities of southern Long Beach Township, Barnegat Light and Seaside Park Boroughs and the mainland communities of Berkeley Township, Ocean Gate Borough and Toms River Township during stress period 80. Lower water levels are simulated at individual withdrawal wells. (Water levels lower than -20 feet are simulated at individual withdrawal wells [table 13].)During stress period 73, the cones of depression expand and deepen, particularly in Barnegat Light Borough and the bay side of Toms River Township, Berkeley Township and the barrier island communities of Seaside Park Borough north to Lavallette Borough. As a result of postdevelopment withdrawals, the simulated potentiometric surface of the Piney Point aquifer exhibits regional drawdowns ranging from 40 to 60 feet in Little Egg Harbor Township, Tuckerton and Beach Haven Boroughs, southern Long Beach Township, Barnegat Light Borough and the northern communities of Berkeley Township, Ocean Gate Borough, Toms River Township, Seaside Heights and Seaside Park Boroughs during stress period 73. Individual wells may exhibit larger drawdowns than are simulated regionally (fig. 26D),

## Maximum-Allocation Withdrawal Conditions

Simulations of maximum–allocation withdrawal conditions incorporate maximum permitted monthly withdrawals at all large volume withdrawal wells in the study area for the 2000 to 2003 analysis period. Maximum-allocation withdrawals in all aquifers are greater than postdevelopment withdrawals (fig. 29).

Analysis of selected stress periods indicates that groundwater withdrawals (45 to 63 ft3/s) during simulations of maximum–allocation withdrawal conditions affected net flow to constant head cells (94 to 124 ft3/s) and increased the net flow out of the Kirkwood-Cohansey aquifer system to the lower confined aquifers (52 to 70 ft3/s). Net flow out to drain and river cells (404 to 985 ft3/s) is reduced from postdevelopment flows. Increased withdrawals from the Rio Grande water-bearing zone in this simulation (0.6 to 1.5 ft3/s) are supported by a net increase of flow from other layers (0.9 to 1.5 ft3/s). Increased withdrawals from the Atlantic City 800-foot sand (22 to 43 ft3/s) produced more net flow into the aquifer from other layers (27 to 33 ft3/s). The Piney Point aquifer had more net flow into the aquifer from other layers (7.2 to 8 ft3/s) during the maximum–allocation withdrawal simulation than during postdevelopment withdrawal conditions.

1. Graphs showing groundwater-flow budgets for: A, the Kirkwood-Cohansey aquifer system; B, Rio Grande water-bearing zone; C, Atlantic City 800-foot sand; and D, Piney Point aquifer during maximum-allocation withdrawal conditions, Ocean County study area, New Jersey.

Comparison of simulations of no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions reveals the effect of these conditions on base flow in streams in the Ocean County study area. Simulations of maximum-allocation withdrawals indicate that lower base-flows than those simulated for postdevelopment withdrawals occur at all streamflow-gaging stations, except Wrangel Brook at Mule Road near Toms River, N.J. (01408592) (figs. 30 and 31; table 11).

1. Graphs showing monthly base flow during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions at streamflow-gaging stations: A, North Branch Metedeconk River near Lakewood, N.J. (01408120); B, South Branch Metedeconk River near Lakewood, N.J. (01408150); C, Toms River near Toms River, N.J. (01408500); D, Wrangel Brook at Mule Road near Toms River, N.J. (01408592); E, Cedar Creek at Lanoka Harbor, N.J. (01409000); and F, North Branch Forked River near Forked River, N.J. (01409050), Ocean County study area, New Jersey.
2. Graphs showing monthly base flow during no-withdrawal, postdevelopment withdrawal, and maximum-allocation withdrawal conditions at streamflow-gaging stations: A, Oyster Creek near Waretown, N.J. (01409100); B, Mill Creek near Manahawkin, N.J. (01409150); C, Cedar Run near Manahawkin, N.J. (01409250); D, Westecunk Creek at Stafford Forge, N.J. (01409280); E, East Branch Bass River near New Gretna, N.J. (01410150); and F, Oswego River at Harrisville, N.J. (01410000), Ocean County study area, New Jersey.

A comparison of base flow from simulations of no-withdrawal and maximum-allocation conditions reveals as much as a 20-percent reduction in base flow at individual streamflow-gaging stations from maximum-allocation withdrawals (table 11). The largest reduction in simulated base flow at streamflow-gaging stations due to maximum-allocation groundwater withdrawals occurs in the Toms River Basin. Simulated base flow in the Toms River at streamflow-gaging station Toms River near Toms River, N.J. (01408500) decreases by 15 to 20 ft3/s from no-withdrawal conditions to maximum-allocation withdrawal conditions. This is the largest stream basin in the study area and is one of the most developed areas of Ocean County. These factors, combined with a large number of wells screened in the unconfined Kirkwood-Cohansey aquifer system, produced the large base-flow decline. Streamflow-gaging station Mill Creek near Manahawkin, N.J. (01409150), had the largest percent reduction in base flow between the two simulations, ranging from 11 to 20 percent. Three of the 12 streamflow-gaging stations in the Ocean County study area had average base-flow reductions of less than 1 ft3/s from no-withdrawal to maximum-allocation conditions (table 11). The smallest average reduction in simulated base flow from no-withdrawal conditions to maximum-allocation withdrawal conditions (0.18 ft3/s) occurred at Cedar Run near Manahawkin, N.J. (01409250); the drainage basin of this stream is one of the smallest, least developed stream basins in the study area and contains few production wells.

In order to avoid tidal fluctuations, streamflow-gaging stations are located less than 8 miles upstream from the area where their streams discharge into the Barnegat Bay-Little Egg Harbor estuary. Gages are located primarily on relatively large stream reaches; numerous streams or reaches that flow into the Barnegat Bay-Little Egg Harbor are ungaged. The combined effect of withdrawals on both gaged and ungaged streams is summarized by the total base-flow reduction to the Barnegat Bay-Little Egg Harbor estuary (table 12). Compared with the no-withdrawal simulation, maximum-allocation withdrawals reduce the total simulated base flow to the Barnegat Bay-Little Egg Harbor estuary by 64 ft3/s (20 percent) during stress period 64 (November 2001 recharge) and by 78 ft3/s (10 percent) during stress period 77 (December 2002 recharge).

Simulated maximum-allocation groundwater levels at wells 29–141, 29–513, and 29–1060, screened in the Kirkwood-Cohansey aquifer system, had additional drawdown ranging from less than 1 foot to approximately 11 feet (table 13) from postdevelopment water levels. Simulated postdevelopment water levels in well 29–17, located in Barnegat Light Borough, decrease an additional 20 feet from those simulated under maximum-allocation withdrawal conditions (fig. 21D; table 13).

Analysis of simulation results of maximum-allocation withdrawal conditions indicate water levels decrease substantially from simulated no-withdrawal water levels in the Rio Grande water-bearing zone (fig. 25). Regional water levels in the Rio Grande water-bearing zone range from an altitude of -30 feet in Harvey Cedars Borough to -60 feet in Little Egg Harbor Township and Beach Haven Borough during stress period 80 of simulated maximum-allocation withdrawal conditions. The simulated cone of depression centered at Holgate deepens during stress period 73 with a regional water level altitude of -80 feet in Little Egg Harbor Township and Beach Haven Borough. Regional drawdowns of the no-withdrawal potentiometric surface in the Rio Grande water-bearing zone range from 0 to 20 feet near the northern extent of the aquifer to 100 to 120 feet in the southern coastal communities from maximum-allocation withdrawal conditions during stress period 73 (fig. 32A). Simulate drawdown at public-supply well 29–1621 in Holgate is larger than the regional drawdown (fig. 32A; table 13).

1. Maps showing simulated drawdown of: A, the Rio Grande water-bearing zone potentiometric surface; B, the Atlantic City 800-foot sand, upper sand unit, potentiometric surface; C, the Atlantic City 800-foot sand, lower sand unit, potentiometric surface; and D, the Piney Point aquifer potentiometric surface as a result of maximum-allocation withdrawals, stress period 73 (August 2002), Ocean County study area, New Jersey.

Regional water levels in the Atlantic City 800-ft sand, upper sand unit, simulated for maximum-allocation withdrawal conditions, range from an altitude of -20 feet at the southern end of Island Beach State Park in Ocean Township, to -80 feet at Surf City Borough and extend through the southern end of Long Beach Island and Little Egg Harbor Township during stress period 80 (fig. 27). During stress period 73 the cone of depression expands further inland and deepens to -100 feet at Surf City Borough south to Beach Haven Township (fig. 27). Drawdown from no-withdrawal groundwater levels in the Atlantic City 800-foot sand aquifer, upper and lower sand units, resulting from maximum-allocation withdrawals indicate a large area of water-level declines. Simulation of maximum-allocation withdrawals during stress period 73 indicates regional drawdowns from simulated no-withdrawal water levels in the Atlantic City 800-foot sand of 100 to 120 feet centered along Long Beach Island, and as much as 120 to 140 feet in the center of the cone of depression (figs. 32B and C).

Initial simulated no-withdrawal groundwater levels in the Piney Point aquifer on Long Beach Island are near an altitude of 20 feet (fig. 28). The simulated maximum-allocation potentiometric surfaces of the Piney Point aquifer during stress periods 73 and 80 indicate the expansion of several cones of depression that developed during postdevelopment withdrawals. The progression of a regional depression in the potentiometric surface of the Piney Point aquifer that parallels the coast is best noted by examining the -20-ft contour for both stress periods. The -20-ft contour extends in the north from Lavallette Borough and Toms River Township south and westward through all of the bay-side communities, including Little Egg Harbor and Bass River Townships at the southern boundary (fig. 28). The potentiometric surface of the Piney Point aquifer for both stress periods appear to be similar with the exception of additional drawdowns at several withdrawal wells during stress period 73. Analysis of stress period 73 indicates that 80 to 100 feet of drawdown of the simulated no-withdrawal Piney Point potentiometric surface occurred in the communities of Berkeley and Toms River Townships, Seaside Heights, Seaside Park and Barnegat Light Boroughs, and southward from Surf City Borough and Stafford Township; as a result of maximum-allocation withdrawals, larger drawdowns occur at withdrawal wells than at the regional potentiometric surfaces (fig. 32D).

# Simulated Groundwater Flow Paths and Travel Time

Production wells located on the mainland or the barrier island that are close to the shoreline may be susceptible to saltwater intrusion from recharge that originates beneath the Atlantic Ocean or beneath Barnegat Bay-Little Egg Harbor. To evaluate the vulnerability of these wells to saltwater intrusion, MODFLOW simulations are analyzed using the particle-tracking code MODPATH (Pollock, 1994) to determine the source and travel time of water flowing to the production wells. Two steady-state groundwater-flow models that simulate postdevelopment and maximum-allocation withdrawal conditions are described in this section. For the postdevelopment withdrawal conditions (scenario 1), annual average groundwater withdrawals from 2000 to 2003 are used. Annual average maximum-allocation groundwater withdrawals are used to simulate maximum-allocation conditions (scenario 2). Groundwater withdrawals are simulated with the MODFLOW Well package. Both steady-state groundwater-flow models incorporated annual average recharge in the Ocean County study area for 2000 to 2003. MODPATH estimates groundwater flow paths, travel times, and recharge locations of the groundwater-flow system in the study area. Simulated heads for each model layer and cell by cell budget files derived from individual MODFLOW simulations are input to MODPATH to calculate particle paths and travel times.

The effective porosity of each model layer is used in the calculation of travel time. Effective porosity is set to 0.30 for the unconfined Kirkwood-Cohansey aquifer system and from 0.35 to 0.40 for all confining units and confined aquifers. These porosities are typical for the type of geologic materials that compose the aquifers and confining units located in the study area (Freeze and Cherry, 1979) and are similar to values used in other studies of the unconfined Kirkwood-Cohansey aquifer system (Kaufman and others, 2001) and the Atlantic City 800-foot sand in the New Jersey Coastal Plain (Voronin and others, 1996).

Particles of water are simulated as originating within cells that represent the screened interval of wells in the Kirkwood-Cohansey aquifer system, the Rio Grande water-bearing zone, or Atlantic City 800-foot sand; the particles are tracked backward to the point where they entered the simulated aquifer system. The wells used in this analysis are chosen from the USGS GWSI database. Wells are restricted to withdrawal wells with screen intervals in the aquifers and model layers of interest. For the Kirkwood-Cohansey aquifer system, only the model cells that contain an existing well within 1 mile of the shoreline are selected (fig. 33). An internal array of 27 particles is used for each cell where particles originated. This analysis is useful for determining the probable recharge area for water withdrawn from each well. Particles that enter a cell that behaves as a weak sink are allowed to pass through the cell.

1. Map showing locations of selected wells screened in the Kirkwood-Cohansey aquifer system proximal to the coastline and production wells screened in the Rio Grande water-bearing zone or in the Atlantic City 800-foot sand, used in particle-tracking analysis, Ocean County study area, New Jersey.

The Barnegat Bay-Little Egg Harbor estuary, Great Bay, Atlantic Ocean, and coastal wetlands on the barrier island and mainland are important hydrologic boundaries. Groundwater withdrawals could reverse the direction of flow, with the possible effects of reducing freshwater discharge to tidal systems, thus affecting the [coastal wetland?] ecosystem, and inducing saltwater into freshwater aquifers, thus damaging the drinking-water resource. To show areas of simulated groundwater discharge into the bay from the groundwater system and areas of recharge to the aquifer beneath the bay or ocean, the net value of flow for each constant-head model cell in layer 1 is mapped. The pattern and quantity of flow from or to constant head boundaries show where groundwater withdrawals from wells in near-shore areas affect groundwater flow to and from the saltwater boundaries.

## **Scenario 1**

For scenario1, average postdevelopment hydrologic stresses are simulated by incorporating average recharge and withdrawals for the years 2000 through 2003. This approach identifies which wells may be susceptible to saltwater intrusion from recharge of salty water originating in Barnegat Bay-Little Egg Harbor or the Atlantic Ocean. Flow to near-shore Kirkwood-Cohansey aquifer system wells is determined using MODPATH to track particles backward from the model layer of each well screen to their origin at the water table or point of recharge. The travel time for each flow path is determined by MODPATH, which provides an approximate age of groundwater at a particular well. The same approach is used to track particles backward from the model layer of the well screen for wells that withdraw water from the Rio Grande water-bearing zone and the Atlantic City 800-foot sand.

Travel times of most flow paths to Kirkwood-Cohansey aquifer system wells, range from 11 years to nearly 50,700 years (fig. 34). A flow path that originates at the model boundary in the ocean east of Seaside Heights Borough has a travel time greater than 1.35 million years. Most near-shore wells screened in the Kirkwood-Cohansey aquifer system derive water from updip sources inland. However, wells located on Island Beach, particularly in the community of Seaside Heights Borough, have some flow paths that start beneath Barnegat Bay or the Atlantic Ocean and are susceptible to saltwater intrusion. Travel times of the shortest flow paths to wells on Island Beach indicate that it could take slightly less than 350 years for water entering the aquifer system in this area to reach these wells. Other flow paths to these wells have travel times that are substantially longer than 350 years; for example, as much as 10,400 years in Seaside Heights Borough. Wells located on the barrier island portion of Berkeley and Toms River Townships have flow paths that do not extend past the island. Wells located in Island Beach State Park, within Lacey Township, have flow paths that extend inland to central Berkeley Township, indicating that the wells are not susceptible to saltwater intrusion. Travel times of flow to these wells range from approximately 4,700 to 7,800 years.

1. Map showing flow paths from point of recharge to point of discharge and travel time of particles that discharge to near-shore wells screened in the unconfined Kirkwood-Cohansey aquifer system, postdevelopment conditions scenario, Ocean County study area, New Jersey.

Flow paths from recharge areas to wells screened in the Rio Grande water-bearing zone and Atlantic City 800-foot sand (fig. 35) have longer travel times than flow paths to wells in the Kirkwood-Cohansey aquifer system; the Rio Grande water-bearing zone and Atlantic City 800-foot sand aquifers are greater in depth than the Kirkwood-Cohansey aquifer system and flow paths in the Rio Grande water-bearing zone and Atlantic City 800-foot sand aquifers typically traverse low permeability hydrogeologic units that greatly retard the velocity of flow—two circumstances that may substantially affect travel times. Travel times along flow paths from point of recharge to production wells range from nearly 530 to greater than 3.73 million years.

1. Map showing flow paths from point of recharge to point of discharge and travel time of particles that discharge to near-shore wells screened in the Rio Grande water-bearing zone and Atlantic City 800-foot sand, postdevelopment conditions scenario, Ocean County study area, New Jersey.

Most of the wells screened in the Rio Grande water-bearing zone and the Atlantic City 800-foot sand derive a large amount of their recharge from the Oswego River Basin area (figs. 4 and 35). Wells located on the barrier island have several flow paths that originate beneath Barnegat Bay and several that originate offshore, east of the well or beneath the ocean adjacent to the eastern boundary of the study area. Travel time of the flow paths that originate beneath Barnegat Bay-Little Egg Harbor or offshore of the southern part of Long Beach Island are estimated to be between nearly 19,000 and 517,000 years. Flow paths that end at the study area boundary would likely extend eastward if the boundary extended farther out in the ocean than it does in these model simulations. Travel times for these paths are estimated to be between nearly 2,900 years to 3.73 million years; however, they originate in model layer 5 or 9 and are not in contact with present-day saline ocean water. This analysis indicates that, under postdevelopment pumping regimes, the water quality in these wells is not likely to be affected by saltwater intrusion in the foreseeable future. In addition, the salinity and age of water derived from these wells would consist of a blend of fresh and salty sources.

## Scenario 2

For scenario 2, average maximum-allocation withdrawal conditions are simulated for each well, coupled with average yearly recharge during the period 2000 to 2003. Flows to near-shore Kirkwood-Cohansey aquifer system wells and to deeper confined Rio Grande water-bearing zone and Atlantic City 800-foot sand wells are determined by tracking particles backward from wells to the points where water entered the groundwater-flow system (fig. 36). Scenario 2 illustrates how groundwater withdrawals greater than the postdevelopment withdrawals simulated in scenario 1 affect the flow of water to shallow near-shore and to relatively deep confined wells along the coast in the Ocean County study area. This approach indicates which wells may be susceptible to saltwater intrusion by deriving some of their recharge from salty water; the approach also yields estimates of the travel times of particles that are withdrawn at each well.

Results of scenario 2 indicate that wells screened in the Kirkwood-Cohansey aquifer system in Seaside Heights Borough and in the Island Beach State Park area of Lacey Township have flow paths that start beneath the Barnegat Bay or the Atlantic Ocean (fig. 36). The travel time from recharge to discharge point for these particles is estimated to be approximately 400 to 12,000 years. This indicates that these wells are potentially susceptible to saltwater intrusion from maximum-allocation groundwater withdrawals. A well in Ship Bottom Borough is also susceptible to an influx of saltwater along flow paths with travel times of approximately 140 to 7,400 years. Wells located on the mainland have flow paths that originate farther inland and, thus, are not susceptible to saltwater intrusion.



Wells screened in the Rio Grande water-bearing zone or Atlantic City 800-foot sand have longer flow paths and travel times (fig. 37) than wells screened in the shallower Kirkwood-Cohansey aquifer system (fig. 36). Most particles that flow to the confined wells on the mainland originate in the Oswego River Basin. Travel times of water entering all Rio Grande water-bearing zone and Atlantic City 800-foot sand wells range from more than 400 to 268,000 years. Wells located in the communities of Harvey Cedars Borough, Surf City Borough, Ship Bottom Borough, Long Beach Township, and Beach Haven Borough on Long Beach Island have flow paths that originate in a combination of areas beneath the Barnegat Bay-Little Egg Harbor or the Atlantic Ocean, and on the mainland. Travel times of particles that start beneath either the Barnegat Bay-Little Egg Harbor or the Atlantic Ocean range from approximately 2,300 to more than 134,000 years.

1. Map showing flow paths from point of recharge to point of discharge and travel time of particles that discharge to wells screened in the Rio Grande water-bearing zone or the Atlantic City 800-foot sand, maximum- allocation conditions scenario, Ocean County study area, New Jersey.

## Groundwater Flow to Saltwater Boundaries

Flow from the groundwater system into and out of Barnegat Bay-Little Egg Harbor serves to maintain the ecosystem of the estuary and to determine the potential for saltwater intrusion into the groundwater system. The net flux of bay water into, or groundwater out of, the groundwater-flow system beneath the Barnegat Bay-Little Egg Harbor and the Atlantic Ocean is determined using budget analysis of flow to constant head cells that represent this area. Results of simulations of postdevelopment and maximum allocation conditions are used to examine the effects of groundwater withdrawals on the flow of groundwater beneath the Barnegat Bay-Little Egg Harbor and the Atlantic Ocean.

Constant head cells represent all or portions of the Atlantic Ocean, Barnegat Bay-Little Egg Harbor, Great Bay, and low-lying coastal and bay swamps and wetlands in the groundwater-flow model. For postdevelopment groundwater withdrawals, a large number of constant head cells have net flow away from the cell (area is shown in blue in fig. 38A). Flow is out of constant head cells to adjacent variable head cells beneath layer 1, indicating predominantly downward flow. A large part of the Barnegat Bay-Little Egg Harbor and coastal wetlands have a net flux out of the constant head cells, particularly in the southern half of the Ocean County study area. The area of downward flow encompasses most of the Atlantic Ocean, as represented in the flow model, except for cells immediately adjacent to the barrier island in the northern half of the study area and an area adjacent to the northeastern boundary (area is shown in green in fig. 38A?). Although water flows away from most cells, the total flux into all constant head cells (saline water bodies) is 113.7 ft3/s. Flow values indicate that downward flow out of individual constant head cells tends to be very small; lateral or upward flow into constant head cells is larger than the flow out of the cells.

Maximum-allocation groundwater withdrawals affect the quantity of groundwater discharging directly into Barnegat Bay. In this simulation, the number of constant head cells with flows into the cells and their total area in the Barnegat Bay-Little Egg Harbor estuary are considerably less than postdevelopment conditions. Groundwater discharging to the estuary is restricted to a small area south of the mouth of Toms River with additional cells adjacent to the barrier island (fig. 38B). The total flux into all of the constant head cells in this simulation decreased by 5.1 to 108.6 ft3/s. The reduction in flow to constant head cells is attributed to additional groundwater withdrawals in this simulation.

1. Maps showing groundwater flow into, or out of, constant head cells in the Barnegat Bay-Little Egg Harbor, Great Bay, Atlantic Ocean, and coastal wetlands for A, postdevelopment withdrawal conditions, and B, maximum-allocation withdrawal conditions, Ocean County study area, New Jersey.

# Summary

Between 1930 and 2000. Ocean County was the fastest growing area of New Jersey. The population of Ocean County increased from 33,000 in 1930 to more than 510,000 in 2000. As the population increased, rapid development of the land led to a conversion of undeveloped/barren, forested, and agricultural land to urban land. These changes placed additional stresses on the surface-water and groundwater resources in the area. Large withdrawals of surface water and groundwater to supply the needs of the population affected the freshwater supply in a number of ways, including reduced streamflow, base flow, and total flow of freshwater into the Barnegat Bay-Little Egg Harbor estuary. These reductions have implications for the health of marine plant and animal life. Groundwater withdrawals from the unconfined Kirkwood-Cohansey aquifer system, the confined Rio Grande water-bearing zone, the Atlantic City 800-foot sand, and the Piney Point aquifer in the Ocean County study area exceeded 14 billion gallons per year from 2001 to 2003. Withdrawals created regional cones of depression in the confined aquifers. As of 2008, cones of depression were present in the Piney Point aquifer near the population center of Toms River Township and in the Rio Grande water-bearing zone, the Atlantic City 800-foot sand, and the Piney Point aquifers underlying several boroughs on the barrier island(s) where a large summer population places high demands on the freshwater supply.

As a result of increasing demand for freshwater in the Ocean County study area, a study was conducted by the U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, to determine the effects of postdevelopment and maximum-allocation groundwater withdrawals on groundwater flow in the Kirkwood-Cohansey aquifer system, the confined Rio Grande water-bearing zone, the Atlantic City 800-foot (ft) sand, and the Piney Point aquifer. The quantity of freshwater discharging into the Barnegat Bay-Little Egg Harbor estuary was also evaluated.

A three-dimensional groundwater-flow model of the surficial, unconfined Kirkwood-Cohansey aquifer system, the underlying, confined Rio Grande water-bearing zone, the Atlantic City 800-foot sand, the Piney Point aquifer, and the Vincentown aquifer was developed to represent the regional groundwater-flow system in the Ocean County study area. The area was discretized into a grid of 67,424 model cells per layer. The stratigraphy and orientation of aquifers and confining units were represented in the model by 11 vertical layers. The groundwater-flow model was designed with five steady-state stress periods, using 2,000 average conditions as initial conditions, followed by 84 transient stress periods representing monthly conditions. The final 48 monthly stress periods of the transient simulation represented January 2000 through December 2003 conditions. The transient model was used to quantify changes to the water budget, potentiometric surfaces of the confined aquifers, and reduction in base flow in the Ocean County study area resulting from various groundwater-withdrawal scenarios. A steady-state model of 2000 to 2003 yearly average conditions was developed to estimate particle flow paths and travel time of water to near-shore wells.

Simulated base flow, water budgets, and groundwater levels during five selected stress periods (64, 73, 77, 80, and 87) that simulate monthly hydrologic conditions representative of November 2001, August and December 2002, and March and October 2003 were used to compare and contrast three distinct groundwater withdrawal scenarios—no-withdrawal conditions, postdevelopment withdrawal conditions, and maximum-allocation withdrawal conditions. Examination of these stress periods illustrated how the groundwater flow system responded to varying seasonal recharge and different withdrawal schemes.

During no-withdrawal conditions, the largest and most variable component of water entering the groundwater-flow system was recharge (0 to 2,290 cubic feet per second [ft3/s]), followed by net flow into storage (27 to 602 ft3/s). The largest component of groundwater flow out of the Kirkwood-Cohansey aquifer system entered streams, with net flow ranging from 484 to 1,086 ft3/s. Water in the Kirkwood-Cohansey aquifer system entered storage during high recharge conditions (net flow of 1,043 ft3/s in stress period 77), flowed out to constant head cells (107 to 136 ft3/s), and also flowed out to adjacent layers in the model (9 to 27 ft3/s) during the examined stress periods. Groundwater flow out to streams, which subsequently discharged into the Barnegat Bay-Little Egg Harbor estuary, ranged from 326 to 759 ft3/s per stress period based on the simulated conditions.

Compared with simulated no-withdrawal conditions, postdevelopment withdrawals reduced groundwater flow out of the Kirkwood-Cohansey aquifer system into streams (437 to 1,025 ft3/s combined net flow) that drain predominantly into the Barnegat Bay-Little Egg Harbor estuary. Simulated flow out of the Kirkwood-Cohansey aquifer system to constant head cells ranged from 99 to 129 ft3/s. Net flow out of the Kirkwood-Cohansey aquifer system to adjacent layers ranged from 33 to 49 ft3/s, an increase from no-withdrawal conditions.

Groundwater withdrawals from the Kirkwood-Cohansey (24 to 42 ft3/s) and the Rio Grande water-bearing zone (0 to 0.7 ft3/s) produced net flow into the Rio Grande water-bearing zone from adjacent layers (0.3 to 0.7 ft3/s). Groundwater withdrawals from the Atlantic City 800-foot sand (12 to 30 ft3/s) created flow into this aquifer from other layers (15 to 21 ft3/s). Withdrawals from the Piney Point aquifer during postdevelopment withdrawal conditions (3.7 to 7.5 ft3/s) resulted in increased net groundwater flow into the aquifer from other layers (3.8 to 4.7 ft3/s). Groundwater withdrawals from all confined aquifers were largest during stress period 73 (August 2002 recharge) which caused the largest in flow from storage and other layers in the confined aquifers of the five stress periods examined.

Postdevelopment withdrawal conditions caused base-flow reductions at all streamflow-gaging stations in the Ocean County study area; 6 of the 12 stations had reductions of less than 1 ft3/s. The largest reduction in base flow between the two simulations occurred at streamflow-gaging station Toms River near Toms River, N.J. (01408500) which had a minimum decrease of 6.8 and a maximum of 9.5 ft3/s. The percent reduction in base flow from no-withdrawal to postdevelopment withdrawal conditions was less than 9 percent at all streamflow-gaging stations.

Simulation of postdevelopment withdrawal conditions indicated that during stress period 64 (November 2001 recharge), base flow from all streams that flow into the Barnegat Bay-Little Egg Harbor estuary (287 ft3/s) was less than half of base flow simulated for stress period 77 (December 2002 recharge) (710 ft3/s) as a result of a much lower recharge rate and larger withdrawals. When compared with no-withdrawal conditions, postdevelopment withdrawal conditions, resulted in reductions in base flow reaching the Barnegat Bay-Little Egg Harbor estuary of 39 ft3/s (12 percent) during stress period 64 (November 2001 recharge), and 49 ft3/s (6.4 percent) during stress period 77 (December 2002 recharge).

The simulated potentiometric surface of the Rio Grande water-bearing zone during stress periods 73 and 80 declined substantially as a result of the change from no-withdrawal conditions to postdevelopment conditions. Groundwater levels in the Rio Grande water-bearing zone exhibited larger seasonal fluctuations in areas close to the center of the cone of depression in the southern part of Long Beach Island than in other areas. Regional water levels in the Rio Grande water-bearing zone at the southern end of Long Beach Island that were simulated for postdevelopment withdrawal conditions ranged from an altitude of -10 to -20 feet during stress period 80 to -40 to -60 feet during stress period 73. Water level altitudes at withdrawal wells were not as low as the regional water levels. Simulated seasonal variations in water levels in the Atlantic City 800-ft sand, upper and lower sand units, varied as much as 20 to 30 feet. Regional water levels in the Atlantic City 800-ft sand, simulated for postdevelopment withdrawal conditions, ranged from -20 feet (at Surf City Borough to the southern end of Long Beach Island during stress period 80) to -40 feet (at Surf City Borough south to Beach Haven Township during stress period 73).

In Toms River Township, Seaside Heights, Seaside Park, and Barnegat Light Boroughs, cones of depression developed in the potentiometric surface of the Piney Point aquifer in response to groundwater withdrawals. Regional postdevelopment water levels in the Piney Point aquifer during stress period 80 were at an altitude of -20 feet in the barrier island communities of southern Long Beach Township, Barnegat Light and Seaside Park Boroughs and the mainland communities of Berkeley Township, Ocean Gate Borough, and Toms River Township. Simulated water levels were lower at individual withdrawal wells than they were regionally. During stress period 73, the cones of depression expanded and deepened, particularly in Barnegat Light Borough and the bay side of Toms River Township, Berkeley Township and from the barrier island community of Seaside Park Borough north to Lavallette Borough.

Analysis of selected stress periods indicated that under maximum-allocation withdrawal conditions, groundwater withdrawals from the Kirkwood-Cohansey aquifer system (45 to 63 ft3/s) decreased net flow to constant head cells (94 to 124 ft3/s) and increased the net flow out of the surficial aquifer system to the lower confined aquifers (52 to 70 ft3/s). Simulated net flow out to drain and river cells (404 to 985 ft3/s) was less than postdevelopment flows. Increased withdrawals from the Rio Grande water-bearing zone in this simulation (0.6 to 1.5 ft3/s) were supported by a net increase of flow from other layers (0.9 to 1.5 ft3/s). Increased withdrawals from the Atlantic City 800-foot sand (22 to 43 ft3/s) produced more net flow into the aquifer from other layers (27 to 33 ft3/s). The Piney Point aquifer had more net flow into the aquifer from other layers (7.2 to 8 ft3/s) than during postdevelopment withdrawal conditions.

A comparison of base flow from simulations of no-withdrawal and maximum-allocation withdrawal conditions indicated as much as a 20-percent reduction in base flow at individual streamflow-gaging stations would be caused by maximum-allocation withdrawals. The largest reduction in simulated base flow at streamflow-gaging stations occurred in the Toms River Basin (15 to 20 ft3/s). When compared with no-withdrawal conditions, maximum-allocation withdrawals reduced the total simulated base flow to the Barnegat Bay-Little Egg Harbor estuary by 64 ft3/s (20 percent), during stress period 64 (November 2001 recharge) and by 78 ft3/s, (10 percent) during stress period 77 (December 2002 recharge).

Maximum-allocation withdrawal water levels decreased substantially from simulated no-withdrawal water levels in the Rio Grande water-bearing zone. Regional water levels in the Rio Grande water-bearing zone ranged from an altitude of -30 feet in Harvey Cedars Borough to -60 feet in Little Egg Harbor Township and Beach Haven Borough during stress period 80 of the simulated conditions. The cone of depression in the Rio Grande water-bearing zone potentiometric surface, centered at Holgate, deepened during stress period 73 (August 2002 recharge) with a regional water level altitude of -80 feet in Little Egg Harbor Township and Beach Haven Borough.

Regional water levels in the Atlantic City 800-ft sand, upper sand unit, from simulated maximum-allocation withdrawal conditions, ranged from an altitude of -20 feet at the southern end of Island Beach State Park in Ocean Township, to -80 feet at Surf City Borough and extend through the southern end of Long Beach Island and Little Egg Harbor Township during stress period 80 (March 2003 recharge). A cone of depression in the Atlantic City 800-ft sand expands further inland during stress period 73 (August 2002 recharge) and deepens to -100 feet at Surf City Borough south to Beach Haven Township.

The simulated maximum-allocation withdrawal potentiometric surfaces of the Piney Point aquifer during stress periods 73 and 80 indicate the expansion of several cones of depression that develop during postdevelopment withdrawals. The -20 ft contour of the Piney Point potentiometric surface extends in the north from Lavallette Borough and Toms River Township south and westward through all of the bay-side communities, including Little Egg Harbor and Bass River Townships at the southern boundary. The potentiometric surfaces of the Piney Point aquifer for both stress periods appear to be similar with the exception of additional drawdowns at several withdrawal wells during stress period 73.

Simulation of average yearly postdevelopment (2000 to 2003) withdrawal conditions indicated how stresses on the groundwater-flow system affected near-shore wells by inducing saltwater to flow towards, and ultimately into, production wells. Particle tracking was used to estimate groundwater-flow paths and travel times through, and location of recharge to, the groundwater flow system. The vulnerability of wells to saltwater intrusion was assessed by tracking particles of water from the screen interval of production wells in the Kirkwood-Cohansey aquifer system, Rio Grande water-bearing zone, or Atlantic City 800-foot sand, backward to the point where particles entered the simulated aquifer system. In this simulation, travel time of most flow paths to Kirkwood-Cohansey aquifer system wells, ranged from 11 years to nearly 50,700 years. A flow path that originated at the model boundary in the ocean had a travel time greater than 1.35 million years. Most near-shore wells screened in the Kirkwood-Cohansey aquifer system derived water from updip sources inland. However, wells located on Island Beach, particularly in the community of Seaside Heights Borough, had some flow paths that started beneath Barnegat Bay or the Atlantic Ocean and were susceptible to saltwater intrusion. Travel times of the shortest flow paths to wells on Island Beach indicated that it could take slightly less than 350 years for water entering the aquifer system in this area to reach these wells. Flow paths to wells in Seaside Heights Borough had travel times that are as much as 10,400 years. Wells located in Island Beach State Park, Lacey Township had flow paths that extended inland to central Berkeley Township, indicating that the wells were not susceptible to saltwater intrusion. Travel time of flow to these wells ranged from approximately 4,700 to 7,800 years.

Flow paths from recharge areas to wells screened in the Rio Grande water-bearing zone and Atlantic City 800-foot sand had longer travel times because the aquifers were deeper than [other aquifers?] and because flow paths typically traverse low permeability hydrogeologic units. Travel times along flow paths from point of recharge to production wells in these aquifers ranged from nearly 530 to greater than 3.73 million years. Most wells screened in the Rio Grande water-bearing zone and the Atlantic City 800-foot sand derived a large amount of their recharge from the Oswego River Basin area. Travel time of the flow paths that originated beneath the Barnegat Bay-Little Egg Harbor or offshore of the southern part of Long Beach island were estimated to be between nearly 19,000 and 517,000 years. Under postdevelopment pumping regimes the water quality in these wells was not likely to be affected by saltwater intrusion in the foreseeable future.

Results of average yearly maximum-allocation withdrawal conditions indicated how maximum-allocation stresses on the groundwater-flow system could induce saltwater toward and potentially into near-shore production wells. This simulation indicated that wells screened in the Kirkwood-Cohansey aquifer system in Seaside Heights Borough and in Island Beach State Park, Lacey Township had flow paths that started beneath the Barnegat Bay or the Atlantic Ocean. The travel time from recharge to discharge point for these particles was estimated to be approximately 400 to 12,000 years. A well in Ship Bottom Borough was also susceptible to an influx of saltwater along flow paths with travel times of approximately 140 to 7,400 years. Wells located on the mainland had flow paths that originated farther inland and are not susceptible to saltwater intrusion. Most particles that flowed to the confined wells on the mainland originated in the Oswego River Basin. Travel times of water entering all Rio Grande water-bearing zone and Atlantic City 800-foot sand wells ranged from more than 400 to 268,000 years. Wells located in the communities of Harvey Cedars Borough, Surf City Borough, Ship Bottom Borough, Long Beach Township, and Beach Haven Borough on Long Beach Island had flow paths that originated in a combination of areas beneath the Barnegat Bay-Little Egg Harbor or the Atlantic Ocean, and on the mainland. Travel times of particles that started beneath either the Barnegat Bay-Little Egg Harbor or the Atlantic Ocean ranged from approximately 2,300 to more than 134,000 years.

Freshwater discharging to the Barnegat Bay-Little Egg Harbor estuary from both streams and direct groundwater flow is essential to maintaining the ecology of the bay. Average postdevelopment withdrawal and maximum-allocation withdrawal simulations provide a comparison of the net flux of groundwater discharging from the groundwater-flow system into the estuary. For average postdevelopment withdrawal conditions, a large number of constant head cells had net flow away from the cell to adjacent variable head cells beneath layer 1, indicating predominantly downward flow. This occurred in a large part of the Barnegat Bay-Little Egg Harbor and coastal wetlands, particularly in the southern half of the Ocean County study area. Although water flowed away from most constant head cells, the net flux to saltwater boundaries (constant head cells beneath the estuary) was 113.7 ft3/s. Flow values indicated that downward flow out of individual constant head cells tended to be very small; in particular, smaller than lateral or upward flow into constant head cells In the average maximum-allocation withdrawal simulation, the number of constant head cells with flow into the cell and their total area in the Barnegat Bay-Little Egg Harbor estuary was considerably less than average postdevelopment withdrawal conditions. Groundwater discharging to the estuary was restricted to a small area south of the mouth of Toms River with additional cells adjacent to the barrier island. The net flux into all constant head cells decreased by 5.1 ft3/s in this simulation.

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