Prepared in cooperation with the Barnegat Bay Partnership

Simulated Groundwater Flow Paths, Travel Time, and Advective Transport of Nitrogen in the Kirkwood-Cohansey Aquifer System, Barnegat Bay–Little Egg Harbor Watershed, New Jersey

Scientific Investigations Report 2016–5169

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

Cover: Photo of southern shore of Toms River, looking to the east. (Photograph provided by Stephen Cauller, U.S. Geological Survey)

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.59	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

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.

Simulated Groundwater Flow Paths, Travel Time, and Advective Transport of Nitrogen in the Kirkwood-Cohansey Aquifer System, Barnegat Bay–Little Egg Harbor Watershed, New Jersey

By Lois M. Voronin and Stephen J. Cauller

Abstract

Elevated concentrations of nitrogen in groundwater that discharges to surface-water bodies can degrade surface-water quality and habitats in the New Jersey Coastal Plain. An analysis of groundwater flow in the Kirkwood-Cohansey aquifer system and deeper confined aquifers that underlie the Barnegat Bay–Little Egg Harbor (BB-LEH) watershed and estuary was conducted by using groundwater-flow simulation, in conjunction with a particle-tracking routine, to provide estimates of groundwater flow paths and travel times to streams and the BB-LEH estuary.

Water-quality data from the Ambient Groundwater Quality Monitoring Network, a long-term monitoring network of wells distributed throughout New Jersey, were used to estimate the initial nitrogen concentration in recharge for five different land-use classes—agricultural cropland or pasture, agricultural orchard or vineyard, urban non-residential, urban residential, and undeveloped. Land use at the point of recharge within the watershed was determined using a geographic information system (GIS). Flow path starting locations were plotted on land-use maps for 1930, 1973, 1986, 1997, and 2002. Information on the land use at the time and location of recharge, time of travel to the discharge location, and the point of discharge were determined for each simulated flow path. Particle-tracking analysis provided the link from the point of recharge, along the particle flow path, to the point of discharge, and the particle travel time. The travel time of each simulated particle established the recharge year. Land use during the year of recharge was used to define the nitrogen concentration associated with each flow path. The recharge-weighted average nitrogen concentration for all flow paths that discharge to the Toms River upstream from streamflow-gaging station 01408500 or to the BB-LEH estuary was calculated.

Groundwater input into the Barnegat Bay–Little Egg Harbor estuary from two main sources— indirect discharge from base flow to streams that eventually flow into the bay and groundwater discharge directly into the estuary and adjoining coastal wetlands— is summarized by quantity, travel time, and estimated nitrogen concentration. Simulated average groundwater discharge to streams in the watershed that flow into the BB-LEH estuary is approximately 400 million gallons per day. Particle-tracking results indicate that the travel time of 56 percent of this discharge is less than 7 years. Fourteen percent of the groundwater discharge to the streams in the BB-LEH watershed has a travel time of less than 7 years and originates in urban land. Analysis of flow-path simulations indicate that approximately 13 percent of the total groundwater flow through the study area discharges directly to the estuary and adjoining coastal wetlands (approximately 64 million gallons per day). The travel time of 19 percent of this discharge is less than 7 years. Ten percent of this discharge (1 percent of the total groundwater flow through the study area) originates in urban areas and has a travel time of less than 7 years. Groundwater that discharges to the streams that flow into the BB-LEH, in general, has shorter travel times, and a higher percentage of it originates in urban areas than does direct groundwater discharge to the Barnegat Bay–Little Egg Harbor estuary.

The simulated average nitrogen concentration in groundwater that discharges to the Toms River, upstream from streamflow-gaging station 01408500 was computed and compared to summary concentrations determined from analysis of multiple surface-water samples. The nitrogen concentration in groundwater that discharges directly to the estuary and adjoining coastal wetlands is a current data gap. The particle tracking methodology used in this study provides an estimate of this concentration.

Introduction

In the Atlantic coastal watersheds of south-central New Jersey, groundwater plays an essential role in both water supply and the health of surface water and estuarine ecosystems. Communities in this area rely heavily on groundwater from the unconfined Kirkwood-Cohansey aquifer system for water supply. Water demand continues to increase to meet the needs of increasing permanent and seasonal populations. Groundwater discharge to streams accounts for a substantial portion of the streamflow in the area. Streamflow accounts for most of the freshwater input to the Barnegat Bay–Little Egg Harbor (BB–LEH) estuary (Hunchak-Kariouk and Nicholson, 2001). Groundwater discharge to surface water is an important contaminant transport pathway that can result in degraded surface-water quality and degraded surface-water habitats in the New Jersey Coastal Plain (Modica and others, 1998). Elevated concentrations of nutrients and other contaminants have been identified in shallow groundwater in the area (Hunchak-Kariouk and Nicholson, 2001; Nicholson and others, 2003), and groundwater discharge to streams and direct groundwater discharge to the BB–LEH estuary may contribute substantial contaminant loads. The estuary is a eutrophic system that is vulnerable to water-quality degradation as a result of relatively low freshwater inflow, long water residence times, and considerable development (Kennish, 2001; Kennish and others, 2007).

The current population and continuing growth in south-central New Jersey directly affects the quantity and quality of the freshwater supply and the health of river and estuarine resources. The quantity and quality of groundwater withdrawn by production wells or discharging to surface-water bodies are interrelated issues in the BB-LEH watershed. Prior studies (Modica and others, 1998; Hunchak-Kariouk, 1999; Phillips and Lindsey, 2003 and Kauffman and others, 2001) have shown that actions undertaken to reduce contaminant inputs to groundwater may not result in immediately observable benefits to the BB-LEH estuary because subsurface travel times can range from days to hundreds of years.

This study conducted by the U. S. Geological Survey (USGS), in cooperation with the Barnegat Bay Partnership, evaluated groundwater flow in the Kirkwood-Cohansey aquifer system that underlies the BB–LEH watershed. A groundwater-flow model of Ocean County, developed by the USGS (Cauller and others, 2016), was used in conjunction with the particle-tracking computer program MODPATH (Pollock, 1994) to estimate groundwater flow paths, travel times, and the subsurface transport of nitrogen to streams and to the BB-LEH estuary. An assessment was made of the quantity of, and the potential nitrogen concentration in, groundwater that flows directly into the BB–LEH estuary or adjoining coastal wetlands and groundwater that discharges to streams that eventually flow into the estuary.

Purpose and Scope

The purpose of this study was to delineate groundwater flow paths and travel times to the BB-LEH estuary and streams within the BB–LEH watershed. This report presents the results of a three-dimensional numerical simulation of the unconfined groundwater-flow system in the BB–LEH watershed of southern New Jersey. A previously published groundwater-flow model (Cauller and others, 2016) was used in conjunction with a particle-tracking routine to delineate particle flow paths, the discharge location of each particle, and the travel time along flow paths. Advective transport of nitrogen through the Kirkwood-Cohansey aquifer system to base flow entering the Toms River is evaluated by comparing the recharge-weighted average nitrogen concentration (2000–03) to the median nitrogen concentration of multiple samples collected during 1987–2008 at a long-term streamflow-gaging station. The recharge-weighted average nitrogen concentrations in groundwater discharge to the BB–LEH estuary are presented, and results of the simulation are shown in illustrations.

Previous Investigations

Voronin (2004) simulated groundwater flow in the New Jersey Coastal Plain. The groundwater-flow model provided regional estimates of aquifer transmissivity and confining-unit vertical leakance of the unconsolidated groundwater-flow system. Nicholson and Watt (1997) simulated groundwater flow in the unconfined Kirkwood-Cohansey aquifer system in the Toms River, Metedeconk River, and Kettle Creek Basins in the northern part of the BB–LEH watershed. Simulation results indicate that groundwater withdrawals through the 1980s reduced average base flow in some streams from predevelopment conditions. In addition, withdrawals changed flow patterns in the unconfined Kirkwood-Cohansey aquifer system and caused average water-level declines of up to 20 feet near pumping centers. Rice and Szabo (1997) simulated groundwater flow paths and travel times along three vertical sections of the unconfined Kirkwood-Cohansey aquifer system in southwestern New Jersey. Conceptual models of the distribution of nitrate and radium concentrations and groundwater age were determined from simulation results. Modica and others (1998) used a groundwater-flow model and particle-tracking analysis of the Kirkwood-Cohansey aquifer system in the Cohansey River Basin to determine the source and travel time of groundwater flow to streams. Patterns of nitrogen concentration were correlated with the age of groundwater entering the stream channel.

Hunchak-Kariouk (1999) analyzed chemical constituents, including nutrients, in surface-water samples from four tributaries to the Toms River and evaluated the effects of land use on the water quality in the tributaries. Hunchak-Kariouk determined that nonpoint-source contributions from groundwater and storm runoff to the Toms River are influenced by the type and intensity of development and historical land use in the contributing drainage area and are modified by instream biological and chemical processes. Hunchak-Kariouk and Nicholson (2001) summarized available water-quality data and hydrologic conditions in the BB-LEH watershed and related these conditions to land use/land cover. These data provided the basis for identifying potential contaminants of concern and for estimating nutrient loading to the estuary. Wieben and Baker (2009) compiled the most recent data available on nitrogen in the BB-LEH watershed and updated the previous estimates by Hunchak-Kariouk (1999) and Hunchak-Kariouk and Nicholson (2001) of nitrogen loading to the Barnegat Bay. Wieben and Baker (2009) concluded that the most substantial pathways for delivery of nitrogen to the bay are surface water [431,000 kilograms as nitrogen per year (Kg N/yr)], atmospheric deposition (141,000 Kg N/yr), and direct groundwater discharge (78,000 Kg N/yr).

Kauffman and others (2001) used a groundwater-flow model and particle-tracking analysis to simulate the effects of land use and travel time on the distribution of nitrate in the Kirkwood-Cohansey aquifer system and to determine nitrate concentration trends in three streams in Gloucester County, New Jersey. This study demonstrates the type of evaluation possible using groundwater flow-path analysis.

Studies conducted in the Chesapeake Bay area of Maryland and Virginia illustrates the role of groundwater in nutrient loads. Although the Chesapeake Bay watershed includes areas that overlie fractured rocks, it also includes areas with Coastal Plain sediments that are similar to those in the BB-LEH watershed. Regulatory statutes related to the Clean Water Act list the Chesapeake Bay as impaired by excess nutrients. In the mid-1980s, the Chesapeake Bay Program began efforts to reduce nutrient input to the Chesapeake Bay. Studies of the Chesapeake Bay watershed by Bachman and others (1998), Phillips and others (1999), and Phillips and Lindsey (2003) determined the source and type of nutrients impairing the Chesapeake Bay. These studies concluded that more than one-half of annual streamflow in the Chesapeake Bay watershed originated as groundwater and base flow with a median age of 10 years contained elevated nitrogen concentrations (Phillips and Lindsey, 2003).

The U.S. Environmental Protection Agency (EPA) established the Chesapeake Bay Total Maximum Daily Load (TMDL) with accountability measures to initiate actions to restore clean water in the Chesapeake Bay and the region's streams, creeks, and rivers. The TMDL sets Chesapeake Bay watershed limits of 185.9 million pounds of nitrogen, 12.5 million pounds of phosphorus, and 6.45 billion pounds of sediment per year— a 25 percent reduction in nitrogen, 24 percent reduction in phosphorus, and 20 percent reduction in sediment.

Description of Study Area

The study area (fig. 1) encompasses the BB–LEH watershed and is located predominantly within Ocean County, New Jersey. The study area is 648 square miles, including the BB–LEH estuary, with 41 surface-water basins (including several unnamed basins) that drain into either Barnegat Bay or Little Egg Harbor. Surface-water basins range in area from 0.01 to 191 square miles.

Land-Use Data

Aerial photographs taken in the early 1930s of the BB–LEH watershed were obtained from the New Jersey Department of Environmental Protection (NJDEP) and converted into digital land-use maps at a 1:24,000 scale by the USGS using a Level 1 Anderson land-use and land-cover classification method (Anderson and others, 1976). Land-use and land-cover data for the Nation, referred to as GIRAS (Geographic Information and Retrieval Analysis System), were produced by the USGS using Landsat satellite imagery from the late 1960s to early 1970s. These images were manually interpreted into land-use polygons and paneled into 1:250,000 scale quadrangles (Fegeas, and others, 1983). This dataset provided 1973 land use for the study area. The NJDEP generated and released land-use datasets for the entirety of New Jersey for 1986 (New Jersey Department of Environmental Protection, 1998), 1995 (New Jersey Department of Environmental Protection, 2000) and 2002 (New Jersey Department of Environmental Protection, 2007). The 1986, 1995 and 2002 land-use maps were produced at scales of 1:24,000, 1:12,000 and 1:2,400, respectively.

Land-use analysis for 1930 to 2002 indicates the effects of urbanization in the BB-LEH watershed (fig. 2). Decreases in acreage of forest (88,465 acres) and agricultural land (29,226 acres) was offset by increases of 71,587 acres of urban land, wetlands (40,398 acres), and water (5,137 acres). The 1930 land-use dataset was derived from black and white aerial photographs making accurate identification of wetlands and water problematic. The increase in wetlands and water, evident in 2002, is likely due to improvements in imagery and image processing over more than 70 years.

Photo of forest vegetation native to the New Jersey Pinelands, Manchester Township. (Photograph provided by Stephen Cauller, U.S. Geological Survey)

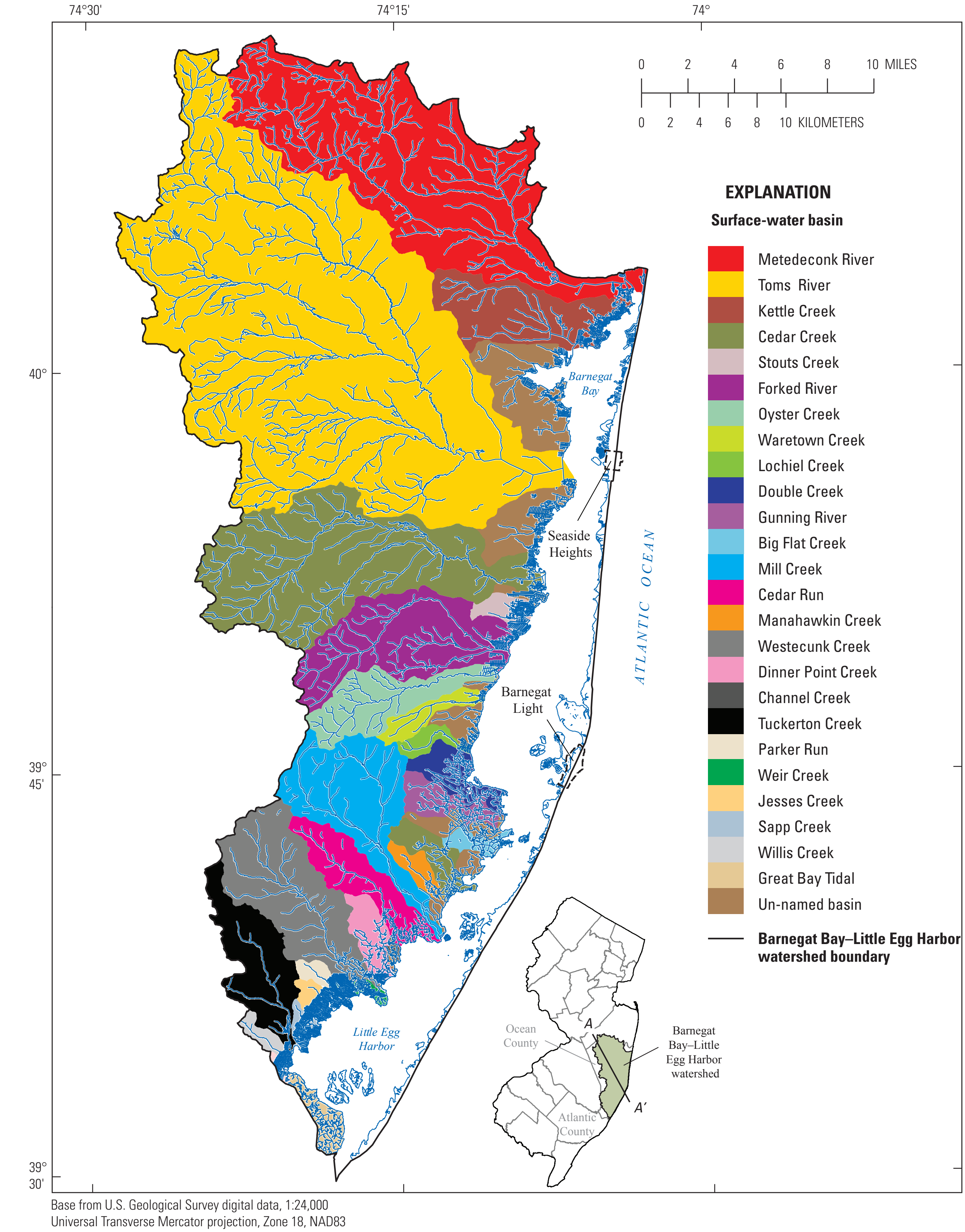

Figure 1. Location of basins in the Barnegat Bay–Little Egg Harbor watershed, N.J.

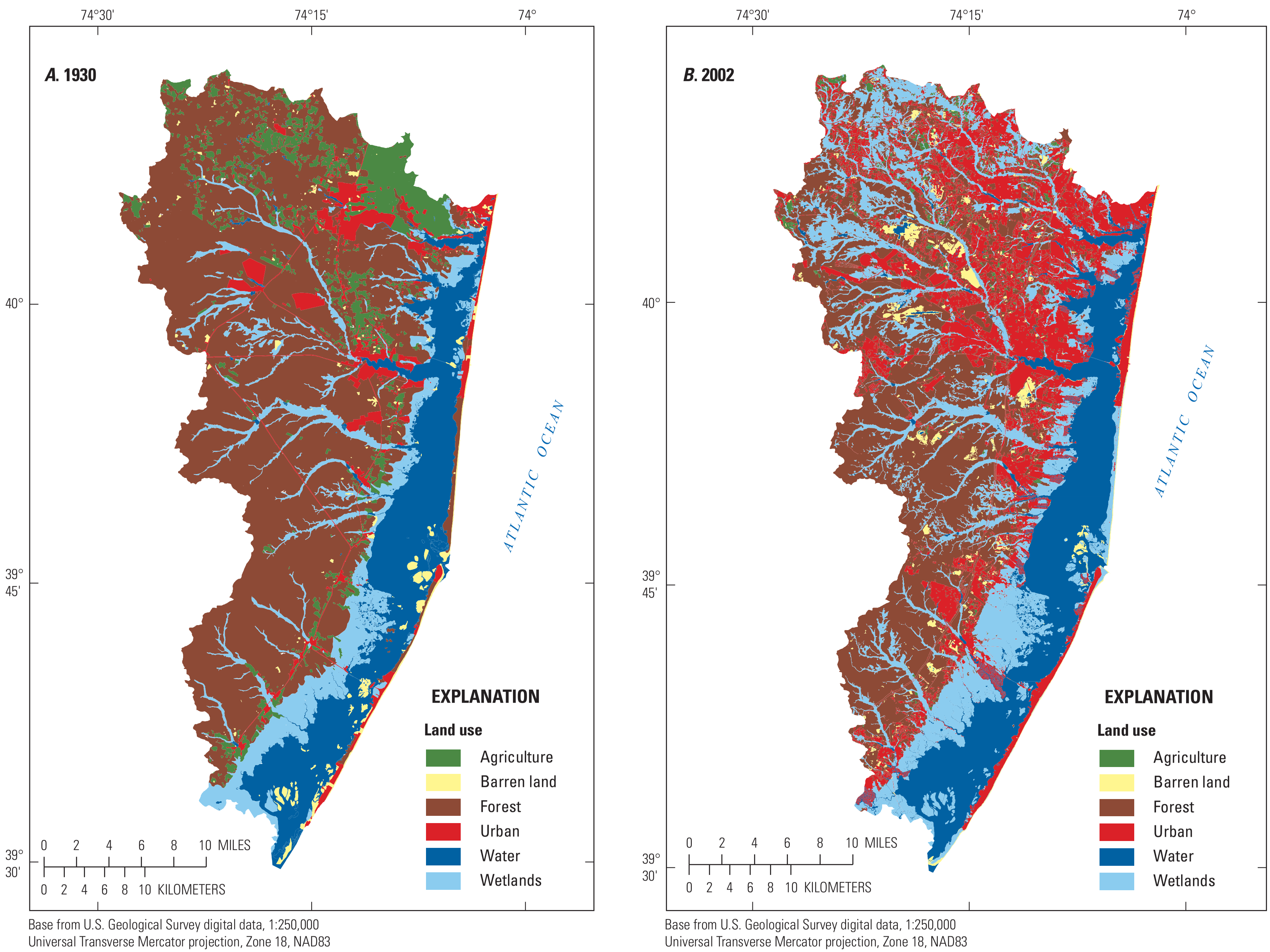

Figure 2. Land use in the Barnegat Bay–Little Egg Harbor watershed, N.J., during *A*, 1930 and *B*, 2002.

Methods of Study

A three-dimensional steady-state groundwater-flow model of 2000 to 2003 average yearly withdrawal conditions of the unconfined Kirkwood-Cohansey aquifer system and deeper confined aquifers of the Ocean County area, New Jersey, (Cauller, Voronin and Chepiga, 2016) was used in this study. For this study, the model will be referred to as the Southern Ocean County model. Output from the flow model was post-processed using the particle-tracking computer program MODPATH (Pollock, 1994) to characterize groundwater flow paths for this study. Starting locations and travel times of water that infiltrates the land surface through various land uses to recharge the groundwater-flow system, and end points where groundwater particles discharge from the groundwater-flow system, were determined using MODPATH. The original model was used to conservatively track particles of water through the system. No additional stresses were modeled with the original model.

Nitrogen concentrations at the points of recharge were estimated and assigned to the starting point of each flow path on the basis of the land-use class for years with land-use delineations—1930, 1973, 1986, 1995, and 2002. Nitrogen concentrations for years prior to 1930 were set to those for undeveloped (forest and barren land) land use. Nitrogen concentrations were estimated using linear interpolation for intervening years. The predominant form of nitrogen observed in groundwater is nitrate, and concentrations act conservatively in the groundwater-flow system (Kauffman and others, 2001). Particles were simulated on the basis of conservative behavior using the same nitrate concentration at the point of recharge and at the associated discharge (end) point. It was assumed that most of the ammonia present in groundwater would convert to nitrite, then to nitrate under oxygenated conditions (the process of nitrification) in the shallow aquifer system. The implications of the conservative transport of nitrogen are that there are no chemical zones in the aquifer system that will convert nitrate to other species, such as in the unsaturated zone or hyporheic zone.

The recharge-weighted average nitrogen concentration for all particles discharging to Toms River upstream from streamflow-gaging station, Toms River near Toms River, NJ, 01408500, were derived using a GIS. To calculate the weighted average, the concentration of each particle was multiplied by the scaled recharge rate of each model cell at the point of recharge. The recharge-weighted average concentration of nitrogen was compared to the measured median concentration in surface-water samples collected from the same location as reported in Wieben and Baker (2009). Wieben and Baker calculated median concentrations based upon multiple samples collected from 1987 through 2008. The same methodology was applied to all particles that discharge directly to the BB-LEH estuary and adjoining coastal wetlands to attain the recharge-weighted average nitrogen concentration in groundwater discharge to the estuary.

Groundwater-Flow Model

The mathematical representation of the hydrologic system simulated in the Southern Ocean County model was developed using MODFLOW-2005, a finite-difference groundwater-flow-model code written by Harbaugh (2005). The model was developed to evaluate groundwater flow, distribution of heads, and water budgets under various withdrawal strategies; to provide a framework for flow-path analysis; and to aid in the understanding of advective transport of contaminants to streams and the estuary.

The Ocean County study area, which includes the BB-LEH watershed, was discretized using a uniform grid spacing of 800 feet (ft) along each row and column over the land mass and the BB-LEH estuary. Variable spacing in the column direction was used over the open ocean to a maximum of 2,400 ft. The model consists of 196 columns and 344 rows. The areal extent of the active model grid is 1,185 square miles. The vertical dimension of the hydrogeologic framework extends from land surface through the subsurface to the lower boundary defined by the base of the Vincentown aquifer and the Piney Point aquifer with underlying confining units (fig. 3). The groundwater-flow system was represented by 11 model layers (fig. 3).

The steady-state model represents average annual 2000–03 withdrawals and recharge and model results represent average 2000–03 hydrologic conditions. Annual 2000–03 groundwater withdrawals in the Ocean County study area ranged from approximately 12.5 to 14 billion gallons per year for the aquifers studied. Annual 2000–03 recharge ranged from 16 to 21 inches.

Particle-Tracking Approach

Output from the flow model described above was used with MODPATH to estimate particle starting locations, groundwater flow paths, travel time of particles, and discharge (end) points. A porosity of 0.30 was specified for the unconfined Kirkwood-Cohansey aquifer system and 0.35–0.40 for confined aquifers and confining units. These values are typical for the type of sediments that compose the aquifers and confining units in the Ocean County area (Freeze and Cherry, 1979) and are similar to the values used by Kauffman and others (2001) and Voronin and others (1996).

A forward-tracking approach was used to analyze flow paths, travel times, starting locations, and discharge points. Nine particles were started on the top of each model cell representing the water-table aquifer and tracked forward to produce flow paths that discharge from the aquifer system to a well, a stream, the BB–LEH estuary, or the Atlantic Ocean.

Land use at the point of recharge was determined using a GIS. Starting locations of flow paths were overlain on the land-use maps for 1930, 1973, 1986, 1997, and 2002. Land-use classification at the time and location of recharge, time of travel to the discharge location, and location of the discharge

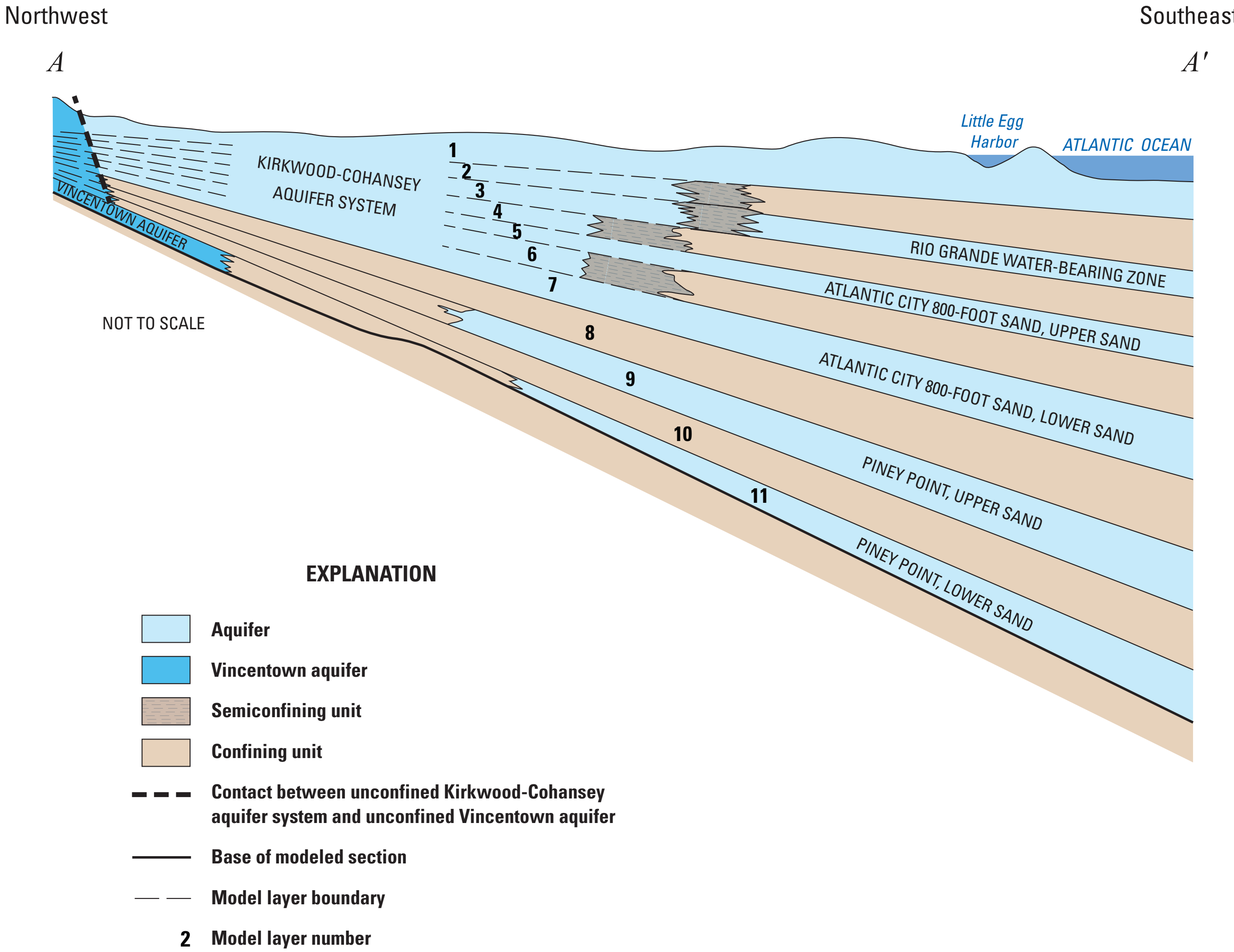

Figure 3. Diagrammatic section through the subsurface illustrating hydrogeologic units and model layers of the groundwater flow model, Ocean County area, N.J.

point were assigned to each simulated flow path. This information was stored in a geodatabase as attribute information associated with each flow path.

Simulation of Advective Transport of Nitrogen

The Ambient Groundwater Quality Monitoring Network (AGWQMN) is a long-term monitoring network of 150 wells distributed throughout New Jersey. Wells are located within three primary land-use categories—agricultural, urban, and undeveloped. The network was designed to assess the status of groundwater quality by examining the concentration of specific constituents, assess long-term water-quality trends, and determine the effects of land-use on shallow groundwater quality (DeLuca and others, 2006). Wells in the network are screened in different aquifers. Fifty AGWQMN wells screened exclusively within the Kirkwood-Cohansey aquifer system were selected for this study (table 1). The top of the screened interval is less than 25 feet below land surface in 41 of the wells and less than 50 feet below land surface in the remaining 9 wells.

Samples were collected periodically at all wells over a 5-year cycle and analyzed for a variety of constituents, including nutrients. Dates of sample collection vary by well and range from July 2002 to July 2009. Results of chemical analyses are stored in the USGS National Water Information System (NWIS) database (table 1). Concentrations of nitrogen species were determined from chemical analysis of 83 groundwater samples collected from the 50 wells. The nitrogen concentration in each sample was estimated as the sum of nitrate plus nitrite as nitrogen and ammonia as nitrogen.

The land use surrounding each well at the land surface, derived from digital 2002 land-use maps, was classified into five different classes—agricultural cropland or pasture, agricultural orchard or vineyard, urban non-residential, urban

Table 1. U.S. Geological Survey site number and land-use class for wells in the AGWQMN and screened in the Kirkwood-Cohansey aquifer system that were used to calculate median nitrogen concentration, N.J.

[USGS, U.S. Geological survey; Water-quality data are available from the USGS National Water Information System (U.S. Geological Survey, 2010) by searching on site number]

USGS site number	Land-use class
391145074520401	Undeveloped
391357074575501	Agricultural cropland or pasture
391611074383801	Undeveloped
391844074451501	Undeveloped
391854075065501	Undeveloped
392123074534801	Undeveloped
392328074315401	Urban non-residential
392435075072801	Agricultural orchard or vineyard
392558075051901	Undeveloped
392715075173101	Agricultural orchard or vineyard
392753075204701	Undeveloped
392820075122601	Agricultural cropland or pasture
392920075011901	Urban residential
393104075122201	Agricultural cropland or pasture
393129074383201	Urban residential
393301074591601	Agricultural cropland or pasture
393313075254101	Agricultural cropland or pasture
393413075141901	Agricultural orchard or vineyard
393415074563601	Agricultural cropland or pasture
393531074523901	Urban residential
393532075101201	Urban non-residential
393712075121201	Agricultural orchard or vineyard
393738075221401	Agricultural cropland or pasture
393744074244101	Undeveloped
393818075132401	Agricultural cropland or pasture
393940074534201	Undeveloped
393947074464501	Agricultural cropland or pasture
394014075060001	Urban non-residential
394018074324701	Undeveloped
394117074214001	Undeveloped
394123074435101	Undeveloped
394245075151001	Agricultural cropland or pasture
394256075101001	Agricultural orchard or vineyard
394342075040301	Urban non-residential
394446075031001	Urban non-residential
394640074323201	Undeveloped
394642074375401	Undeveloped
394647074592701	Urban residential
395034074112101	Urban non-residential
395341074345101	Undeveloped
395417074143401	Undeveloped
395448074370701	Undeveloped
395643074295201	Undeveloped
395900074242801	Undeveloped
400052074191201	Urban residential
400204074145401	Undeveloped
400346074081701	Urban non-residential
400529074260601	Undeveloped
401021074030601	Urban non-residential
401335074042701	Urban non-residential

residential, and undeveloped (forest and barren land). Nonparametric summary statistics of constituent concentrations in 83 samples determined the median concentration of nitrogen for each land-use class. The relation between median nitrogen concentration in samples and land-use class at the sample collection site (well) provided estimates of the nitrogen concentration for each recharge particle (table 2).

Nitrogen concentration at the point of recharge was assigned to each flow path for each year in which land use in the watershed was delineated—1930, 1973, 1986, 1995, and 2002—on the basis of the values in table 1. Concentrations were set to the undeveloped or background value [0.03 milligram per liter (mg/L)] for years prior to 1930 and linearly interpolated for intervening years. Particle-tracking

Table 2. Nitrogen concentrations in samples of shallow groundwater collected from AGWQMN wells screened in the Kirkwood-Cohansey aquifer system, N.J.

[Median concentration in 50 wells determined from 83 samples collected from July 2002 to July 2009; mg/L, milligram per liter]

Land-use class	Median nitrogen concentration, in mg/L	Number of samples	Number of censored observations
Agricultural cropland or pasture	6.38	18	0
Agricultural orchard or vineyard	7.74	11	0
Undeveloped	0.03	30	16
Urban non-residential	3.2	18	0

analysis provided the link from discharge points to the estimated points of recharge, particle flow paths, and total travel times. Travel time of each flow path was extrapolated to determine the year of recharge for the associated particle. The land use at the time of recharge determined the nitrogen concentration associated with each flow path. Recharge rates applied to layer 1 of the groundwater flow model vary per model cell so the initial nitrogen concentration of each flow path was multiplied by a scaled recharge rate to obtain a recharge-weighted concentration. One or multiple particles can discharge to individual model cells in layer 1; therefore, a recharge-weighted average nitrogen concentration was calculated for (a) each model cell with one or more particles that discharge to the water table, (b) all particles that discharge to the water table upstream of streamflow-gaging station 01408500, and (c) all particles that discharge to the water table in the BB-LEH estuary and adjoining coastal wetlands.

Simulated Groundwater Flow Paths, Travel Times, and Transport of Nitrogen

Prior to extensive land development and groundwater withdrawals in Ocean County, prepumping water levels in the Atlantic City 800-foot sand and the Piney Point aquifer (aquifers are shown in fig. 3) were at an altitude of 20 to 25 feet (Zapecza and others, 1987) along the western shoreline of the BB–LEH estuary, indicative of upward groundwater flow to the Kirkwood-Cohansey aquifer system. A regional cone of depression centered in Atlantic City (not shown in figures but located approximately 12 miles south of the study area) developed in response to large groundwater withdrawals from the Atlantic City 800-foot sand along the shore in Atlantic County. Local cones of depression in the Piney Point aquifer, centered in Seaside Heights and Barnegat Light Boroughs, have developed in response to large groundwater withdrawals from that aquifer (Lacombe and Rosman, 2001). Groundwater-flow directions in the confined aquifers below the BB–LEH estuary have reversed, due to groundwater withdrawals, and discharge from the groundwater flow system to the estuary has decreased.

Relation of Simulated Groundwater Discharge to Simulated Flow Paths, Travel Time, and Land Use

Results of the simulation of average 2000 to 2003 groundwater-withdrawal conditions indicate that approximately 13 percent (64 million gallons per day) of the total groundwater discharge in the study area flows directly to the BB-LEH estuary (fig. 4*A*). Model simulations indicate that 19 percent of groundwater that discharges directly to the BB-LEH estuary does so in less than 7 years (fig. 4*B*). Ten percent of this discharge (1 percent of the total groundwater flow through the study area) originates in urban areas, and travel time is less than 7 years. Approximately 29 percent of discharge to the estuary has travel times that range from 36 to less than 200 years.

Particle-tracking results indicate that 56 percent of simulated groundwater flow reaches a stream in less than 7 years (fig. 4*C*). Fourteen percent of the groundwater discharges to the streams in less than 7 years and originates in urban land. Thirty-three percent of the groundwater discharges to the streams in less than 7 years and originates in forest land. Groundwater discharge to the streams in the watershed, in general, is younger than groundwater discharge to the BB-LEH estuary, and a higher percentage of the discharge originates in urban areas. A schematic representating of general groundwater flow paths and travel times illustrates the correlation between land use, the concentration of nitrogen in recharge, and time of travel from recharge to discharge locations (fig. 5).

Nitrogen in Groundwater Discharge

Previous studies (Hunchak-Kariouk and Nicholson, 2001; Baker and Hunchak-Kariouk, 2006; and Wieben and Baker, 2009) indicate that groundwater discharge to streams within the BB-LEH watershed can be a substantial source of nitrogen in streamflow. Simulated average groundwater discharge to streams in the BB-LEH watershed is approximately 400 million gallons per day. The streams eventually flow into, and are a source of nitrogen to, the BB–LEH estuary. Stream base flow is composed of groundwater that originates in various locations in the watershed, and the age of the groundwater can range from months to hundreds of years (fig. 4 and 5).

The particle-tracking methodology used in this study to compute nitrogen concentrations in groundwater discharge was evaluated by comparing simulated and measured nitrogen concentrations in base flow at streamflow-gaging station 01408500 in the Toms River Basin (fig. 1). As of 2012, the chemical composition of groundwater that discharges directly to the BB-LEH estuary was not known. Analytical data describing nitrogen concentrations in groundwater beneath, and potentially discharging to, the BB-LEH estuary do not exist as a result of the complexities of collecting representative groundwater samples from beneath the estuary where groundwater is flowing upward. To provide an estimate of this data gap, the same methodology used to compute nitrogen concentrations in groundwater discharging into the Toms River, was applied to estimate the average nitrogen concentration entering the estuary from groundwater flow.

Advective transport results demonstrate that the recharge-weighted average nitrogen concentration per model cell ranges from near detection limits to 6.38 mg/L throughout the watershed and estuary. Detections limits vary over time and between inorganic forms of nitrogen and range from 0.01 to 0.06 mg/L. The spatial distribution of nitrogen in groundwater discharge indicates that concentrations tend to be greater in downstream areas close to the shoreline (fig. 6)

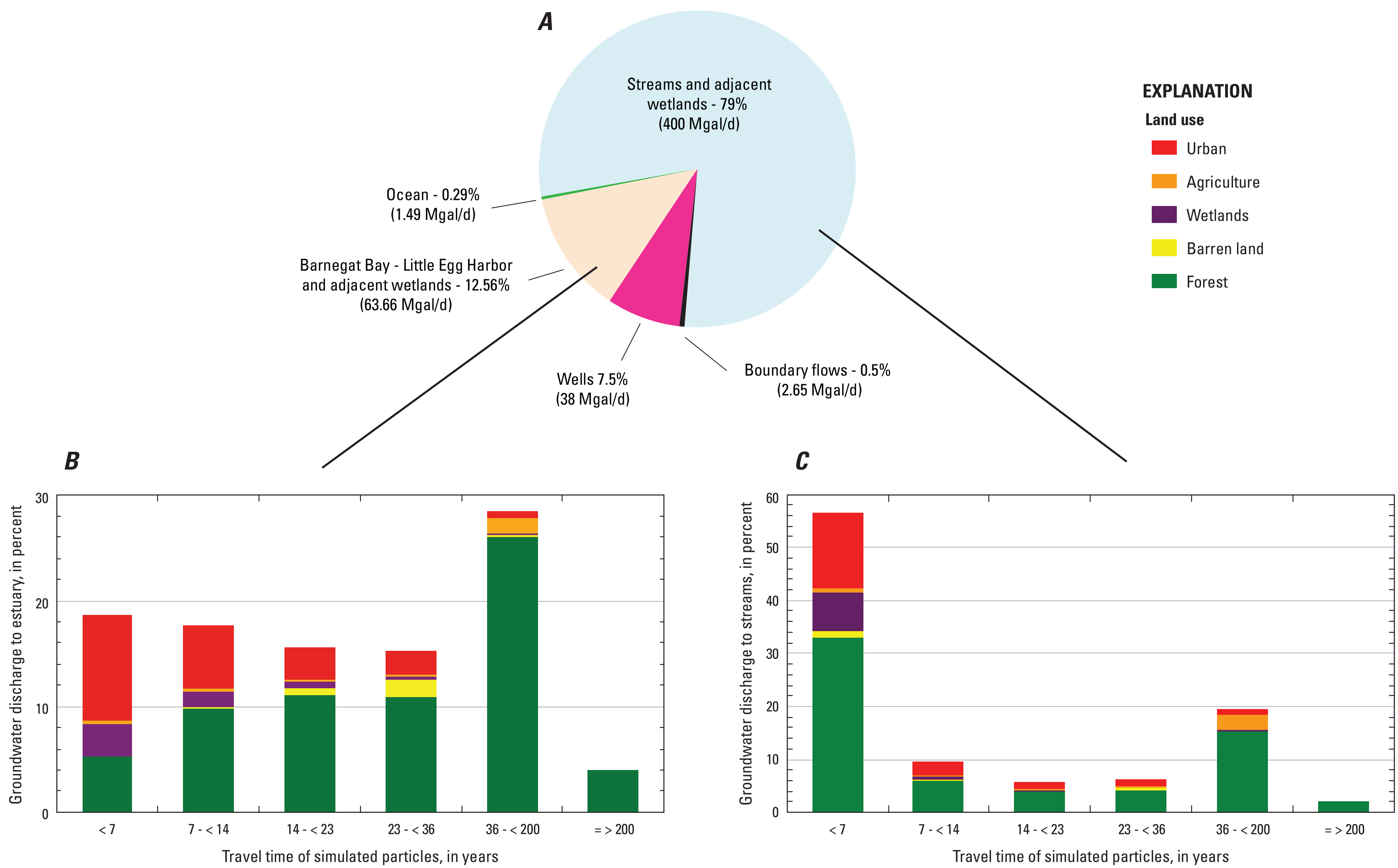

Figure 4. *A*, Percentage of simulated groundwater discharge from the Kirkwood-Cohansey aquifer system to surface-water bodies, wells, and boundary flows; *B*, land use at time and point of recharge, and travel time through the groundwater flow system, of particles that discharge to the Barnegat Bay–Little Egg Harbor estuary; and *C*, land use at time and point of recharge, and travel time through the groundwater flow system, of particles that discharge to streams in the Barnegat Bay–Little Egg Harbor watershed, N.J. (Mgal/d, million gallons per day)

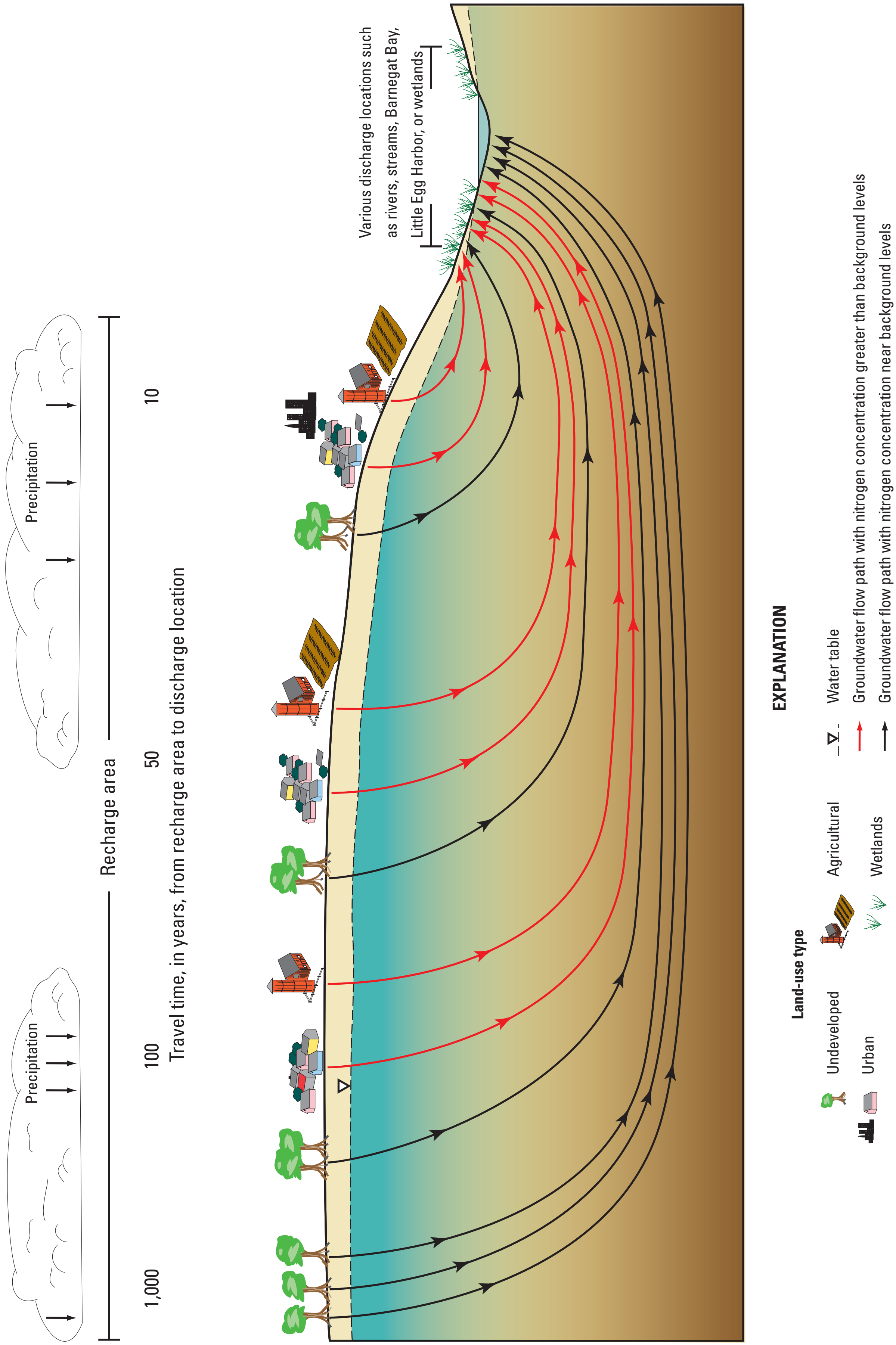

Figure 5. Schematic representation of groundwater flow paths, travel times, and nitrogen transport from various land uses to a discharge location.

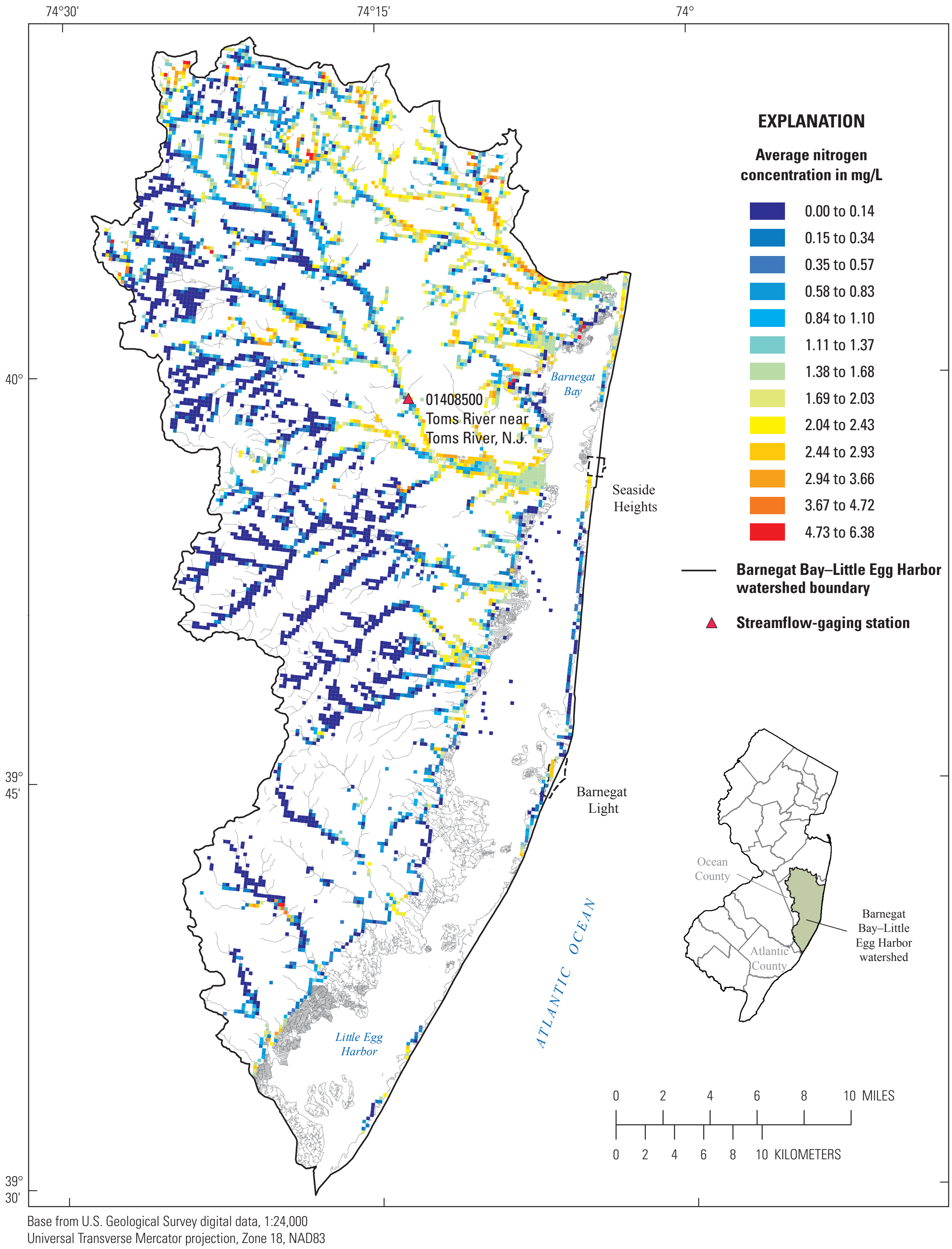

Figure 6. Average nitrogen concentrations in groundwater discharge, per model cell, Barnegat Bay–Little Egg Harbor watershed, N.J. (mg/L, milligrams per liter)

Nitrogen Transport to the Toms River

Approximately one-third of the streamflow to the BB-LEH estuary originates within the Toms River Basin. Average 1929–2009 streamflow in the Toms River, measured at streamflow-gaging station 01408500, is 211 cubic feet per second or 136 million gallons per day (U.S. Geological Survey, 2009). Approximately 20 percent of the land in the Toms River Basin during 2002 was classified as urban. Urban areas in the basin are concentrated near the lower reach of the Toms River and along the banks of the river (fig. 2). Travel times and land use at the time of recharge for simulated particles that discharge to the Toms River, upstream from streamflow-gaging station 01408500, are shown in figure 7. Seventeen percent of the groundwater that discharges to the Toms River above this location originates in urban areas and travels through the groundwater flow system in less than 14 years.

Streamflow-gaging station, 01408500, Toms River near Toms River, N.J., (fig. 6) is an active gage on the Toms River that has been operational since the 1920s. Long-term monitoring of streamflow and the periodic collection of surface water samples for chemical analysis, including nutrients, has occurred at this site for several decades. Trench and others (2011) conducted an analysis of the trend of the total nitrogen and nitrite-plus-nitrate nitrogen loads for streamflow-gaging station 01408500. Trench and others concluded there was no upward or downward trend in the concentration of the total nitrogen and nitrite-plus-nitrate nitrogen loads for streamflow-gaging station 01408500 from 1993 to 2003. Surface-water samples collected during 1987–2008 at streamflow-gaging station 01408500 were analyzed for nutrients during low, high, and all flow conditions; constituent concentrations are summarized by Wieben and Baker (2009). The median concentrations of total nitrogen in all samples are 1.20 mg/L during low flow, 0.83 mg/L during high flow, and 1.00 mg/L during all flows. The median concentrations of nitrate plus nitrite and ammonia, which are the predominant nitrogen species present in groundwater, are 0.63 and 0.20 mg/L, respectively (0.83 mg/L combined), during low flows; 0.34 and 0.13 mg/L (0.47 mg/L combined) during high flows; and 0.51 and 0.17 mg/L (0.68 mg/L combined) during all flows (Wieben and Baker, 2009). The sample concentration used for comparison is the combined median (nitrate plus nitrite and ammonia) concentration of 0.83 mg/L from samples collected during low-flow or base-flow conditions. The simulated recharge-weighted average concentration of nitrogen associated with groundwater flow paths that discharge upstream from streamflow-gaging station 01408500 (Toms River near Toms River, NJ) is 0.68 mg/L, which agrees closely with 0.83 mg/L derived from analytical data. Location of simulated discharge points, including discharge to the Toms River upstream from streamflow-gaging station 01408500 are shown in figure 8.

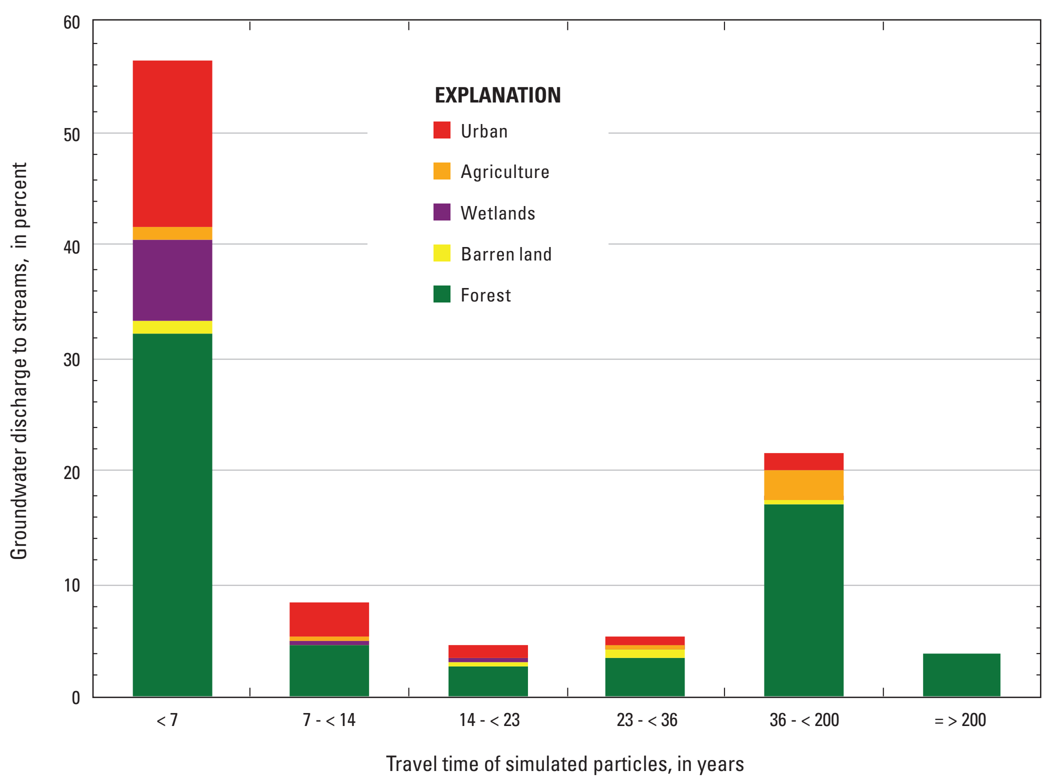

Figure 7. Land use at time and point of recharge, and travel time through the groundwater flow system, of particles that discharge to the Toms River upstream from streamflow-gaging station, Toms River near Toms River, N.J., 01408500.

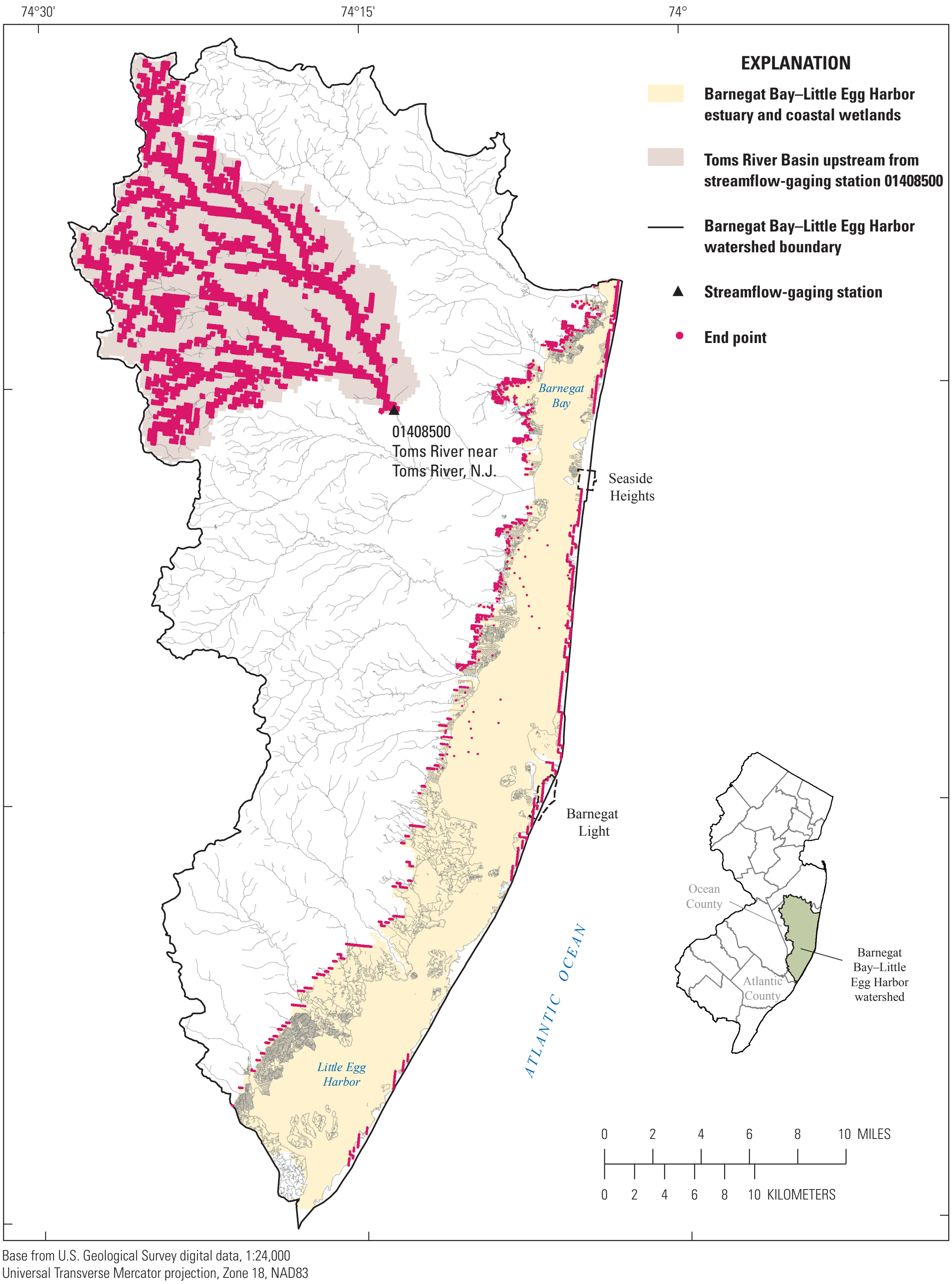

Figure 8. Location of simulated groundwater particles that discharge to the Toms River upstream from streamflow-gaging station 01408500, Toms River near Toms River, N.J., or to the Barnegat Bay–Little Egg Harbor estuary and adjoining coastal wetlands, N.J.

Nitrogen Transport to the Barnegat Bay–Little Egg Harbor

The particle tracking methodology was used to estimate the contribution of groundwater discharge to the nitrogen load in the BB–LEH estuary and adjoining coastal wetlands. Advective transport simulation estimated the recharge-weighted average nitrogen concentration equivalent to 0.93 mg/L in groundwater flow that discharges directly to the estuary and adjoining coastal wetlands (locations shown in fig. 8). At the time of this study (2009), the chemical composition of groundwater that discharges directly to the BB-LEH estuary has not been determined and is a data gap.

Summary and Conclusions

Groundwater is essential to the water supply for residents of, and the health of surface-water and estuarine ecosystems in, the Atlantic coastal watersheds of south-central New Jersey. Communities in this area rely heavily on groundwater from the unconfined Kirkwood-Cohansey aquifer system for water supply. Groundwater discharge to streams accounts for a substantial portion of the streamflow in the area. Streamflow also provides a large portion of the freshwater input to the Barnegat Bay–Little Egg Harbor (BB–LEH) estuary. Groundwater discharge to surface water is an important contaminant transport pathway that can result in degraded surface-water quality and habitats in the New Jersey Coastal Plain. Elevated concentrations of nutrients have been identified in shallow groundwater in the area; groundwater discharge to streams and direct groundwater discharge to the BB–LEH estuary may contribute substantial nutrient loads.

An analysis of groundwater flow in the Kirkwood-Cohansey aquifer system and deeper confined aquifers that underlie the BB–LEH watershed and estuary was undertaken by the U. S. Geological Survey in cooperation with the Barnegat Bay Partnership. Simulation results from a regional three-dimensional groundwater-flow model of the Ocean County area, in conjunction with the particle-tracking computer program MODPATH, provided estimates of groundwater flow paths, travel times, and the subsurface transport of nitrogen to streams and the BB-LEH estuary. The land use at the time of recharge, location of recharge, time of travel to the discharge location, and the location of discharge were assigned to each simulated flow path. Particle-tracking analysis provided the link from the point of recharge, along the particle flow path, to the point of discharge, and the total travel time.

Results of the simulation of average year 2000 to 2003 groundwater withdrawal conditions indicate that groundwater discharge to streams in the BB-LEH watershed totals approximately 19 percent of the total groundwater discharge in the study area or 400 million gallons per day. These streams eventually flow into the BB-LEH estuary and are a source of nitrogen to the estuary. Streamflow is composed mostly of groundwater that originates in various locations in the watershed, and the travel time of the groundwater can range from months to hundreds of years. Approximately 13 percent of the total groundwater discharge in the study area or 64 million gallons per day flows directly to the BB-LEH estuary. The subsurface residence time for 18 percent of this discharge is less than 7 years; 10 percent (1 percent of the total groundwater flow through the study area) has a travel time of less than 7 years and originates in urban areas.

Results of particle tracking indicate that 56 percent of simulated flow reaches a stream in less than 7 years. Travel time for the 14 percent of the groundwater originating in urban land and discharging to the streams is less than 7 years. For the 33 percent of the groundwater originating in forested land and discharging to the streams, travel time is less than 7 years. Groundwater discharge to the streams in the watershed is generally younger, and a higher percentage originates in urban areas, than groundwater discharging directly to the BB-LEH estuary.

Water-quality data from the Ambient Groundwater Quality Monitoring Network were used to establish the initial nitrogen concentration in recharge for five different land-use classes—agricultural cropland or pasture, agricultural orchard or vineyard, urban non-residential, urban residential, and undeveloped. Nonparametric summary statistics of constituent concentrations in 83 samples indicated the median concentration of nitrogen for each land-use class. The relation between the median nitrogen concentration in samples and land-use class at the sample-collection site (well) provided estimates of the nitrogen concentration of each simulated recharge particle. The land use at the time of recharge determined the nitrogen concentration associated with each flow path, based on an analysis of groundwater-quality data from the study area. The recharge-weighted average nitrogen concentration of all flow paths that discharge to the Toms River upstream from streamflow-gaging station 01408500 or to the BB-LEH estuary was calculated. Particles were simulated on the basis of conservative behavior using the same nitrate concentration at the point of recharge and at the associated discharge (end) point. It was assumed that most of the ammonia present in groundwater would convert to nitrite, then to nitrate under oxygenated conditions (the process of nitrification) in the shallow aquifer system. The implications of the conservative transport of nitrogen are that there are no chemical zones in the aquifer system that will convert nitrate to other species, such as in the unsaturated zone or hyporheic zone.

Approximately one-third of the streamflow to the BB-LEH estuary originates within the Toms River Basin. Average 1929–2009 streamflow in the Toms River at streamflow-gaging station 01408500 is 211 cubic feet per second or 136 million gallons per day. Approximately 20 percent of the land in the Toms River Basin is urban land. Urban areas in the basin are concentrated near the lower reach of the Toms River and along the banks of the river. Seventeen percent of the groundwater that discharges to the Toms River upstream from streamflow-gaging station 01408500 originates in urban areas and travels through the groundwater flow system in less than 14 years.

Nutrient analyses of surface-water samples collected in low flow conditions during 1987–2008 at streamflow-gaging station Toms River near Toms River, NJ, (01408500) provide the basis of comparison within the Toms River Basin. The median concentrations of nitrate plus nitrite and ammonia, the predominant nitrogen species present in groundwater, are 0.63 and 0.20 mg/L, respectively (0.83 mg/L combined), during low flows. The simulated recharge-weighted average concentration of nitrogen associated with groundwater flow paths that discharge to the Toms River near Toms River, NJ, streamflow-gaging station is 0.68 mg/L, which agrees closely with 0.83 mg/L derived from samples collected during low flow or base-flow conditions.

At the time of this study (2009), the chemical composition of groundwater that discharges directly to the BB-LEH estuary has not been determined and is a data gap. Advective transport simulation provides an estimate of nitrogen concentrations entering the BB-LEH estuary from groundwater flow. Summary calculations indicate a recharge-weighted average nitrogen concentration of 0.93 mg/L in groundwater that discharges directly to the Barnegat Bay–Little Egg Harbor estuary and adjoining coastal wetlands.

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