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Hydrologic Assessment of the Edwin B. Forsythe National Wildlife Refuge, New Jersey



Scientific Investigations Report 2017–5088

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

Front cover. Location of the Edwin B. Forsythe National Wildlife Refuge (green), New Jersey. Photograph shows salt marsh area of the Edwin B. Forsythe National Wildlife Refuge, New Jersey. Photo by Christine Wieben, U.S. Geological Survey.

Back cover. Photographs showing land and water surfaces of the Edwin B. Forsythe National Wildlife Refuge, New Jersey. Photos by Christine Wieben, U.S. Geological Survey.

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By Christine M. Wieben and Mary M. Chepiga

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U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Deputy Director
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U.S. Geological Survey, Reston, Virginia: 2018

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Suggested citation:
Wieben, C.M., and Chepiga, M.M., 2018, Hydrologic assessment of the Edwin B. Forsythe National Wildlife Refuge, New Jersey: U.S. Geological Survey Scientific Investigations Report 2017–5088, 38 p., https://doi.org/10.3133/sir20175088.

ISSN 2328-0328 (online)

Acknowledgments

The authors gratefully acknowledge the cooperation of the well owners and operators who granted access to their wells for water-level measurements. Additionally, the authors gratefully acknowledge U.S. Geological Survey (USGS) colleagues Jerilyn Collenburg, Alex Fiore, Eric Jacobsen, Amy McHugh, Pamela Reilly, Robert Reiser, Robert Rosman, Lois Voronin, and Timothy Wilson for providing technical advice and assistance with a variety of field activities, including well installation, establishing surface-water reference points, surveying, and collecting water-level data. Gratitude is also expressed to a number of current and former USGS colleagues who contributed their time and knowledge to help complete this study, including Emmanuel Charles, Pierre Lacombe, Jon Janowicz, Robert Nicholson, and Martha Watt.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

Datum

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

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

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

Abbreviations

DEM	Digital elevation model
ET	Evapotranspiration
ETo	Reference evapotranspiration
NWIS	National Water Information System
PET	Potential evapotranspiration
USGS	U.S. Geological Survey

Hydrologic Assessment of the Edwin B. Forsythe National Wildlife Refuge, New Jersey

By Christine M. Wieben and Mary M. Chepiga

Abstract

The Edwin B. Forsythe National Wildlife Refuge (hereafter Forsythe refuge or the refuge) is situated along the central New Jersey coast and provides a mixture of freshwater and saltwater habitats for numerous bird, wildlife, and plant species. Little data and information were previously available regarding the freshwater dynamics that support the refuge's ecosystems. In cooperation with the U.S. Fish and Wildlife Service, the U.S. Geological Survey conducted an assessment of the hydrologic resources and processes in the refuge and surrounding areas to provide baseline information for evaluating restoration projects and future changes in the hydrologic system associated with climate change and other anthropogenic stressors.

During spring 2015, water levels were measured at groundwater and surface-water sites in and near the Forsythe refuge. These water-level measurements, along with surface-water elevations obtained from digital elevation models, were used to construct water-table-elevation and depth-to-water maps of the refuge and surrounding areas. Water-table elevations in the refuge ranged from sea level to approximately 65 feet above sea level; in most of the refuge, the water-table elevation was within 3 feet of sea level. The water-table-elevation map indicates that the direction of shallow groundwater flow at the regional scale is generally from west to east (much of it from the northwest to the southeast), and groundwater moves downgradient from the uplands toward major groundwater discharge areas consisting of coastal streams and wetlands. The depth to water is estimated to be less than 2 feet for approximately 86 percent of the refuge, which coincides closely with the percentage of wetland area in the refuge. Depth to water in excess of 20 feet below land surface is limited to higher elevation areas of the refuge.

Streamflow data collected at continuous-record streamgages and partial-record stations within the Mullica-Toms Basin were summarized. Hydrograph separation of streamflow data for eight streamgages (2004–13) reveals that base flow accounts for 68–94 percent of streamflow in basins upstream from the refuge. The high base-flow inputs underscore the importance of groundwater as a source of freshwater that supports both the streams that flow into the refuge and the hydroecology of the contributing basins. Mean annual flow typically ranged from 1.7 to 2.1 cubic feet per second per square mile at the streamgages (2004–13) and between 1.2 and 2.3 cubic feet per second per square mile at the partial-record stations (1965–2015) but was notably greater or lower than these ranges at several stations.

Mean annual water budgets were estimated for multiple regions of the refuge for 2004–13 using data compiled from nearby meteorological stations and groundwater flows derived from previously calibrated groundwater-flow models. Precipitation, groundwater recharge, and evapotranspiration were estimated from available data; direct runoff was calculated as the residual component of the water balance. Groundwater recharge rates were greatest in the upland-dominated areas of the refuge with estimates of 14.4 to 18.9 inches per year, which are equivalent to 30 to 40 percent of precipitation. Groundwater recharge rates were nearly zero in the central coastal areas because these areas are major groundwater discharge zones, the water table is near land surface, the subsurface is close to saturation and cannot accept much recharge, and much of the area is underlain by thick marsh deposits likely with low permeability. Estimates of evapotranspiration varied from about 26 inches per year in the upland-dominated areas to more than 35 inches per year in the coastal wetlands, equivalent to 55–79 percent of mean annual precipitation, indicating that it is a major component of the hydrodynamics of the Forsythe refuge.

On the basis of output from previously calibrated groundwater-flow models, nearly all of the groundwater exiting the surficial aquifer system in the central coastal areas of the refuge is discharged to wetlands, which highlights the importance of groundwater discharge in supporting the ecosystems of the Forsythe refuge. In the central coastal areas, horizontal flow contributes more than 90 percent of the groundwater flow to the surficial system, indicating that the upbasin areas are a substantial source of water that ultimately discharges to streams and wetlands in the refuge.

Introduction

The Edwin B. Forsythe National Wildlife Refuge (hereafter Forsythe refuge or the refuge) encompasses more than 47,000 acres of coastal habitats in southern New Jersey. More than 75 percent of the refuge is tidal salt marsh. The refuge also features freshwater wetlands, wooded uplands, beaches, and open water habitat. The refuge's ecosystems, which are an integral part of the coastal habitats, are dynamic environments shaped by complex interactions among freshwater resources, saltwater resources, sediment processes, and vegetation communities. Coastal wetlands provide many ecosystem services, including shoreline stabilization, storm surge attenuation, flood water storage, filtering of pollutants, and critical habitat for fish and wildlife (Tiner, 2013; Barbier and others, 2011).

On October 29, 2012, Hurricane Sandy, the largest hurricane (in diameter) in recorded history, made landfall near Brigantine, N.J. (Blake and others, 2013). The storm devastated coastal communities and habitats along much of the eastern seaboard. The eye of the storm passed directly over the Forsythe refuge. The storm brought high winds and an immense storm surge accompanied by coastal erosion and flooding. The Forsythe refuge acted as a buffer, protecting inland communities from the worst of the storm's effects. In the aftermath of Hurricane Sandy, numerous Federal agencies, including the U.S. Geological Survey (USGS) and the U.S. Fish and Wildlife Service, received supplemental funding to support recovery and restoration projects for areas affected by Hurricane Sandy. This study was funded by the U.S Fish and Wildlife Service with Sandy Supplemental funds.

On the seaward side, sea-level rise and coastal storm events present major challenges for the sustainability of the refuge's ecosystems. Sea level is projected to rise between 1.1 and 2.3 feet (ft) along the New Jersey coast by 2050 (Miller and others, 2013), stressing habitats. On a global scale, the ability of coastal wetlands to keep pace with rising sea level through vertical accretion of terrestrial-sourced sediment and organic matter or through horizontal landward migration of shoreline sediments (marine transgression) varies and is dependent on a number of factors, including topography, changes in land elevation, rate of sea-level rise, and erosion and sediment deposition rates (Cahoon, 2009; U.S. Climate Change Science Program, 2009; Tiner, 2013). The presence of anthropogenic barriers to landward migration (for example, dikes, retaining walls, and housing developments) diminishes the ability of coastal habitats to adapt to sea-level rise (Cahoon, 2009; Tiner, 2013). A panel of experts on accretionary processes—convened to assess wetland response to sea-level rise for the mid-Atlantic region—identified the saline fringe wetlands of New Jersey as among the most vulnerable to loss associated with sea-level rise (Cahoon, 2009; Tiner, 2013).

On the landward side, pressures from increased population growth and associated development upstream from the refuge may affect freshwater resources within the refuge. For example, increased water withdrawals upstream can lead to reductions in water availability downstream, marked by reductions in groundwater discharge to streams and wetlands and changes in surface-water flow patterns. Also, depending on groundwater-flow patterns, contaminants introduced upstream can be transported to downstream environments.

Little has been studied about the freshwater resources that shape the freshwater and saltwater ecosystems of the Forsythe refuge, particularly in terms of wetland groundwater and surface-water interactions. Baseline scientific data and analyses are needed to improve understanding of the freshwater resources and hydrologic processes that affect the refuge to inform decisions regarding management of the refuge as it relates to habitat restoration and climate change. It is necessary to quantify freshwater inflows to the refuge and outflows from the refuge as part of a water balance to better understand the dominant hydrologic resources, how they vary throughout the refuge, and how they may be affected in the future by climate change and other anthropogenic stressors.

The purpose of this study was to improve the understanding of the hydrologic system and processes that support the ecological resources of the Edwin B. Forsythe National Wildlife Refuge. Although the analytical assessment was conducted on the freshwater resources (for example, precipitation and groundwater inflows and outflows), the effects of these resources apply to the entire refuge area, including freshwater and saltwater habitats. The hydrologic assessment was conducted using available hydrologic information and newly collected data.

Purpose and Scope

This report includes discussion of data collection and analysis, construction of depth-to-water and water-table elevation maps, and the development of mean annual water budgets for multiple areas of the refuge. This report documents the methods used to conduct a water-level synoptic study at groundwater and surface-water sites during spring 2015 and provides a hydrologic context for the period of synoptic measurements. Depth-to-water and water-table-elevation maps created using the water-level data are presented. Water-level data are used to illustrate potential groundwater-flow directions and describe horizontal hydraulic gradients in the aquifer system.

Mean annual water budgets are presented for different areas of the refuge using precipitation, groundwater recharge, evapotranspiration, and direct runoff estimates. The water budgets provide baseline information useful for habitat restoration and evaluation of future changes in the hydrologic system associated with climate change. Water-level and hydrologic data collected for this study provided information needed to construct and calibrate a groundwater-flow and salinity model that was developed to simulate effects of sea-level rise on the Forsythe refuge. Details of this model are documented in Fiore and others (2018).

Description of Study Area

The Forsythe refuge is one of more than 550 national wildlife refuges managed by the U.S. Fish and Wildlife Service. The refuge, which encompasses more than 47,000 acres, extends for more than 50 miles along the New Jersey coast and encompasses parts of Ocean, Burlington, and Atlantic Counties (fig. 1). The refuge is made up of discontinuous parcels of land that extend from West Mantoloking in the north to Oceanville in the south. Several shallow bays that separate the mainland from the barrier islands, including Grassy Bay, Little Bay, Great Bay, Little Egg Harbor, Manahawkin Bay, and Barnegat Bay, extend along the eastern boundary of the mainland part of the refuge. Some refuge parcels are located on the barrier islands. Only parcels of refuge land that are located on the mainland of New Jersey were considered for the water-table mapping and water-budget estimates.

Two separate refuge management divisions—the Brigantine Division to the south and the Barnegat Division to the north—were established in 1939 and 1967, respectively, to protect tidal wetland and shallow bay habitat for migratory waterfowl (U.S. Fish and Wildlife Service, 2009). In 1984, the two divisions were combined under the Edwin B. Forsythe name. In 1986, the wetlands of the Forsythe refuge were designated as Wetlands of International Importance under the Ramsar Convention (Ramsar, 2017; U.S. Fish and Wildlife Service, 2015).

The Forsythe refuge is located along a major migratory flight path within the Atlantic Flyway and provides important feeding, resting, and nesting grounds for migratory and wintering birds, wading birds, and shorebirds. The refuge is of particular importance to rails, *Branta bernicla* (Brant goose, or Atlantic brant) and *Anas rubripes* (American black duck) (U.S. Fish and Wildlife Service, 2009). Additionally, the refuge supports a number of Federally listed and State-listed endangered and threatened species, including *Charadrius melodus* (piping plover), *Falco peregrinus* (peregrine falcon), *Pandion haliaetus* (osprey), *Sterna antillarum* (least tern) and *Rhynchops niger* (black skimmer) (U.S. Fish and Wildlife Service, 1997).

For much of the refuge, the landscape shifts from a narrow band of uplands along the Route 9 corridor to wide swaths of relatively flat, low-lying salt marsh. About 84 percent of the refuge has an elevation less than 5 ft above sea level, and about 98 percent has an elevation less than 40 ft above sea level. Several parcels of refuge land farther inland along the Garden State Parkway have elevations as much as 95 ft above sea level (fig. 1).

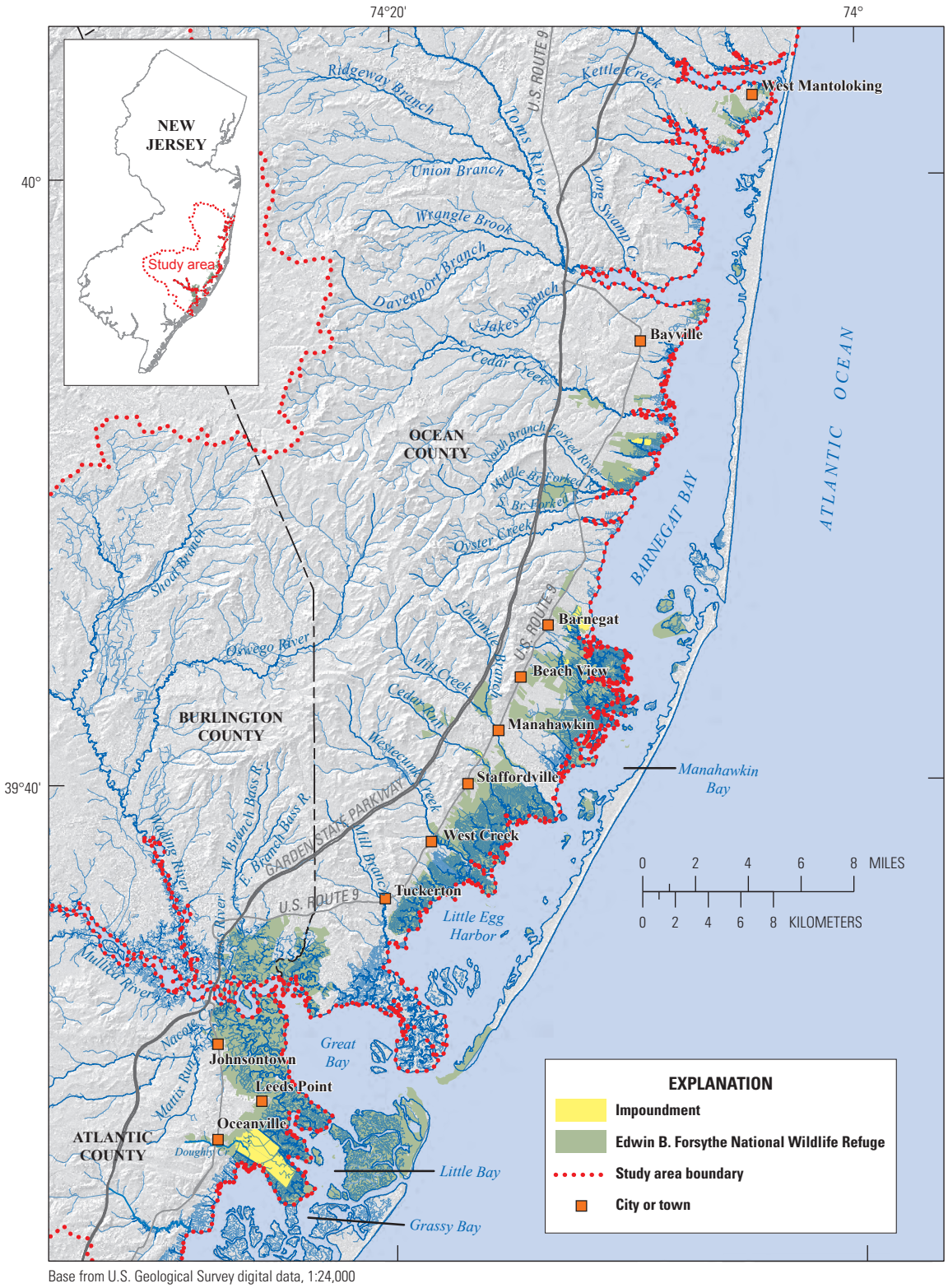
Portions of the refuge are present in areas of low topographic relief and are subject to inundation by tides. Tidal wetlands, including salt marsh, broadly fall into two zones—those that are regularly flooded and those that are irregularly flooded—with the frequency of flooding dependent on elevation (Tiner, 2013). Low marsh generally lies between mean low tide and mean high tide, and is inundated daily. High marsh generally lies above mean high tide and is inundated during extreme high tides (spring tides) and storms (storm tides).

Salt marsh wetlands make up 78 percent of the Forsythe refuge. High marsh vegetation is dominated by *Spartina patens* (saltmeadow cordgrass), and low marsh vegetation is dominated by *Spartina alterniflora* (smooth cordgrass). Like many coastal marshes in the United States, much of the salt marsh of the Forsythe refuge was ditched for mosquito control (U.S. Fish and Wildlife Service, 2004). Ditching can have long-lasting effects on the hydrology and geomorphology of salt marsh systems.

Freshwater wetlands make up approximately 4 percent of the refuge and are characterized by *Acer rubrum* (red maple), *Nyssa sylvatica* (black gum), *Quercus* spp. (oaks) and *Chamaecyyparis thyoides* (Atlantic white cedar) (U.S. Fish and Wildlife Service, 1997, 2004). The remainder of the refuge consists of wooded uplands, grasslands, beaches, dunes, and open water habitat. Open water habitat includes ponds, reservoirs, and several impoundments that were constructed to provide freshwater or brackish water habitat in an otherwise salt marsh environment.

The refuge falls within the drainage basins of numerous streams that discharge to estuaries and bays along the Atlantic coast. These streams include Doughty Creek, Mullica River and its tributaries Nacote Creek and Bass River, Westecunk Creek, Cedar Run, Mill Creek, Middle Branch Forked River, Cedar Creek, and other small streams and channels. Headwaters for many of the larger streams are located within the mostly undeveloped Pinelands area. Although there is little to no urban development within the boundaries of the Forsythe refuge, areas along the western boundary of the refuge in the northern and central parts of the study area are heavily developed.

The refuge is situated entirely within the Atlantic Coastal Plain Physiographic Province, specifically the Outer Coastal Plain. The shallow, unconfined Kirkwood-Cohansey aquifer system, also referred to in this report as the surficial aquifer system, underlies most of the Coastal Plain, including the refuge. The unconfined Kirkwood-Cohansey aquifer system includes the Cohansey Formation, which is characterized primarily by medium- to coarse-grained sand, with local lenses of silt and clay, and some gravel; the Kirkwood Formation, which is characterized by fine-to-medium-grained sand with clay beds; the Cape May Formation, which consists mostly of fine-to-medium sand with a clay and silt unit at its base; the Bridgeton Formation which is primarily sand and gravel; and localized areas of other recently deposited sands (Canace and Sugarman, 2009, Martin, 1998; Newell and others, 2000; Fiore and others, 2018). The layers of sands and gravels are highly permeable, whereas the clay layers act as local confining units. These local and basin-wide variations in hydrogeology can affect water resources, including groundwater-flow patterns and the occurrence of groundwater discharge areas. Because it is shallow and unconfined, the aquifer system generally is well-connected hydraulically to surface-water bodies, and groundwater is the primary source of freshwater



Base from U.S. Geological Survey digital data, 1:24,000
Universal Transverse Mercator projection, Zone 18, NAD83

Figure 1. Location of the Edwin B. Forsythe National Wildlife Refuge, New Jersey.

to streams and wetlands within the Coastal Plain (Watt, 2000). Much of the marsh area of the refuge is underlain by heterogeneous deposits that can consist of relatively high fractions of fine-grained sediment, which indicates that the deposits may be areas of low permeability (Stanford, 2013, 2014). Fiore and others (2018) provide a more quantitative assessment of the hydrogeologic framework of the Forsythe refuge.

Previous Investigations

A series of surficial aquifer studies was conducted to assess the hydrologic resources of the unconfined aquifer system of the New Jersey Coastal Plain to provide a basis for regional water-supply planning and other water-resource management decisions. These studies were completed for several basins in and adjacent to the refuge study area, specifically the Toms River, Metedeconk River, and Kettle Creek Basins for 1987–90 (Watt and others, 1994), the Forked River Basin and nearby basins for 1998–99 (Gordon, 2004), and the Mullica River Basin for 1991–92 (Johnson and Watt, 1996). Water-level contours and water budgets are presented at the regional scale for each surficial aquifer study; given the regional nature of these studies, contours presented generally lie inland of the Forsythe refuge boundary.

Several groundwater-flow models have been developed for the Coastal Plain aquifers of New Jersey. Pope and others (2012) evaluated the effects of water withdrawals on aquifers in the Great Egg Harbor and Mullica River Basins and developed groundwater-flow budgets for their model area. Cauller and others (2016) developed a groundwater-flow model to simulate the effects of groundwater withdrawals on water levels and base flow for multiple aquifers in Ocean County and vicinity.

Site-Numbering System

Information for all groundwater sites included in this study is stored in the USGS National Water Information System (NWIS) database (http://waterdata.usgs.gov/nj/nwis). Groundwater sites are identified by a unique identifier consisting of a county code followed by a sequential number. The county codes used in this report are 1 for Atlantic County, 5 for Burlington County, and 29 for Ocean County. For example, well 29-100 is the 100th well inventoried in Ocean County.

Information on surface-water sites used in this study also is stored in NWIS. Surface-water sites are identified by a site code assigned according to one of two naming conventions. Sites located on streams are identified by a site code, which consists of an 8-digit number beginning with 01. One surface-water site at an impoundment has a 15-digit site code that represents the site's latitude and longitude in degrees, minutes, and seconds.

Methods of Investigation

This section documents the methods used to establish a data-collection network and to obtain and analyze data to describe the hydrologic characteristics of the Forsythe refuge and surrounding areas. This section also documents the approaches used to create water-table elevation and depth-to-water maps of the refuge, as well as the methods used to estimate a mean annual water budget for nine areas of the refuge for the period 2004–13.

Data-Collection Network

The data-collection network includes groundwater and surface-water sites at which manual synoptic water-level measurements were made to provide a snapshot of the water table throughout the refuge during May 2015.

Wells and Well-Installation Methods

Forty-four temporary water-table wells (piezometers) were installed in and near the refuge using one of two methods. Most piezometers were installed using a hand auger. Several piezometers were installed using the Geoprobe® direct push method. Piezometers were constructed of either 0.5- or 1-inch-diameter polyvinyl chloride (PVC) casing and were screened at the water table. Post-installation, these wells were pumped and water-quality field characteristics—water clarity, specific conductance, and water temperature—were monitored to ensure good hydraulic connection with the aquifer.

Piezometers were distributed throughout the refuge in upland, transition, and marsh areas to provide adequate spatial coverage for the water-table mapping effort. In some cases, piezometers were installed along transects from the upland to the marsh as a means to evaluate groundwater-flow gradients. Site selection was limited to locations that were reasonably accessible by vehicle.

To supplement information from the newly installed piezometers, the USGS NWIS database (http://waterdata.usgs.gov/nj/nwis) was mined to identify wells useful to the hydrologic assessment and to the groundwater-flow model developed by Fiore and others (2018). Thirty-three previously installed wells in the contributing Mullica-Toms Basin and screened in the Kirkwood Cohansey aquifer system were identified and included in the water-level synoptic study.

Land-surface elevations for all groundwater sites were obtained from a statewide 10-ft digital elevation model (DEM) derived from high-resolution lidar (Light Detection and Ranging) land-surface elevation data (New Jersey Department of Environmental Protection, 2012). This statewide DEM was developed using lidar data collected for multiple projects; the original lidar data were collected at 1-meter (3.28-ft)

resolution for Atlantic and Ocean Counties and 2-meter (6.56-ft) resolution for Burlington County. Analysis of vertical accuracy by the New Jersey Department of Environmental Protection using different approaches resulted in estimates of root mean square error in Z direction (RMSEz) of 0.562–0.292 ft with a calculated accuracy at the 95-percent confidence level of 1.102–0.571 ft. Elevations for 13 piezometers were determined using Global Navigation Satellite System (GNSS) technology in accordance with protocols and quality assurance procedures outlined in Rydlund and Densmore (2012). A Real-Time Network (RTN) approach was used. These surveyed elevations were compared to elevations derived from the DEM and were found to agree within 1.2 ft.

Surface-Water Sites

Measurement reference points (RPs) were established for selected streams and impoundments in and near the refuge. Lag bolts and PK nails were secured to bridges, cement culverts, and other stable structures to establish RPs. For most RPs, elevation was determined using GNSS technology in accordance with protocols and quality-assurance procedures outlined in Rydlund and Densmore (2012). An RTN approach was used. For several RPs, tree canopy cover required the use of differential leveling in conjunction with the GNSS RTN approach.

Collection of Synoptic Water-Level Measurements

Synoptic measurements of groundwater and surface-water levels were made during spring 2015 to provide a snapshot of the water table throughout the refuge prior to the onset of summer water withdrawals. The water-level synoptic study was conducted during the last 2 weeks of May 2015; most sites were measured during May 20–22. Synoptic measurements were initiated following an extended period of little to no precipitation to depict the water table under stream base-flow conditions (Walker and others, 2011). Light rain fell on the study area beginning on the afternoon of May 21, 2015; approximately 0.2 inch of rain fell in the northern part of the study area while measurements were still being made. Several surface-water sites were measured at a later date in July 2015 but under similar base-flow conditions. During the synoptic study, water levels were measured at 77 groundwater sites and (fig. 2, table 1) and at 20 surface-water sites (fig. 2, table 2).

Groundwater-level measurements were made manually using a steel tape or electrical tape following protocols and quality-assurance methods outlined in Cunningham and Schalk (2011). For surface-water sites, water levels were measured relative to RPs using a weighted steel tape.

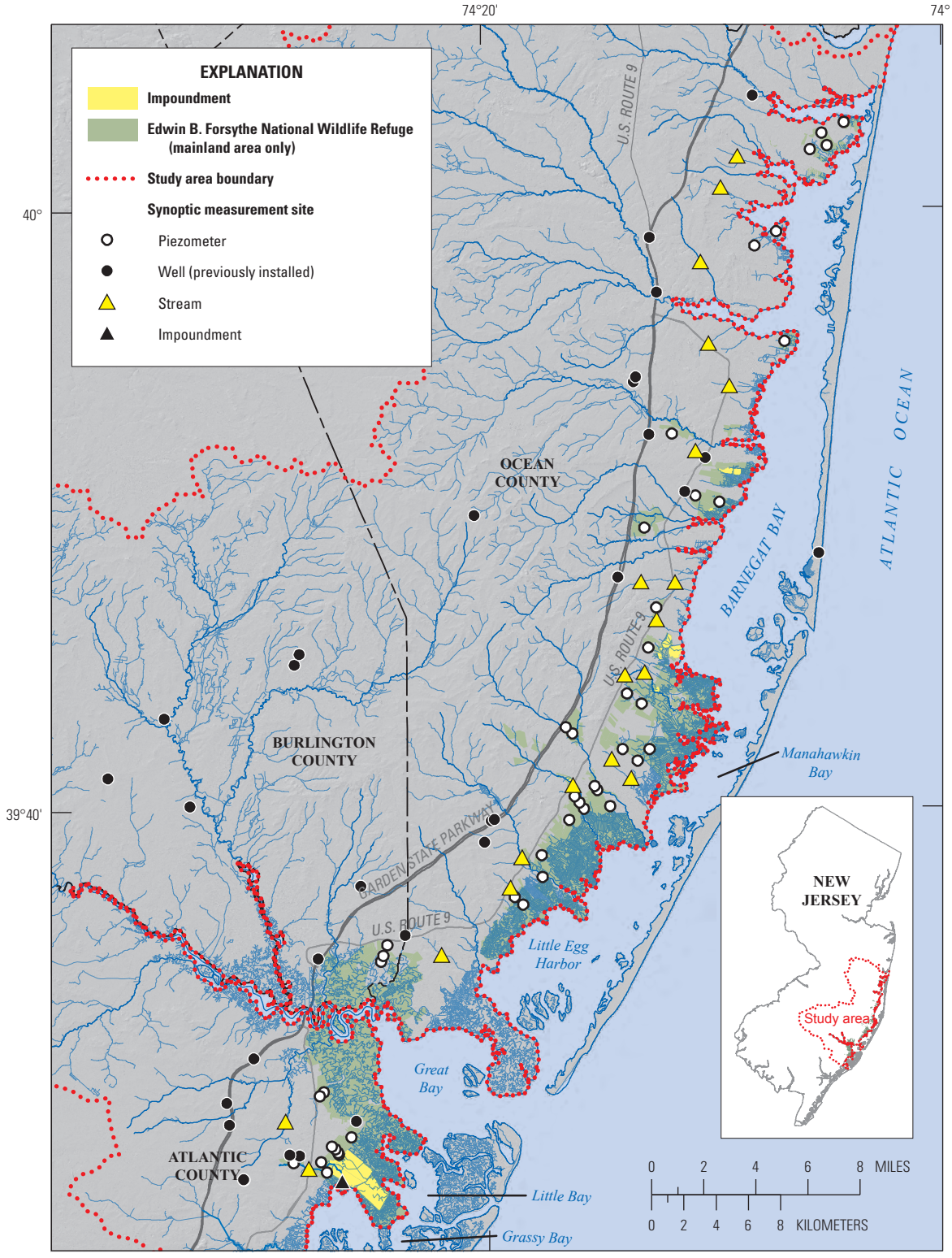
Several groundwater and surface-water sites measured during the water-level synoptic study are affected by tides such that water levels vary over short periods of time in response to tidal fluctuations. Although a thorough assessment of tidal effects was beyond the scope of this study, water-level measurements were made at two random times in the tidal cycle at sites close to the marsh whenever possible to determine the general extent of tidal effects.

Water-Table Mapping

Water-table elevation and depth-to-water maps were produced for spring 2015 using a combination of manual and analytical methods. The water-table-elevation contours and depth-to-water grid produced as a result of this analysis are available as a data release (Wieben and Chepiga, 2018). Water levels from 66 of the 77 measured groundwater sites, as established by the screening criteria described below, were used during the water-table mapping analysis. Measurements from the other 11 wells were incorporated into the model developed by Fiore and others (2018) because the model boundaries extend beyond the boundaries of this hydrologic assessment and because the model includes water-level measurements for several deep wells that were excluded from the mapping analysis (table 1).

The water-table elevation map for spring 2015 was prepared using synoptic water-level measurements for selected groundwater and surface-water sites, and water-surface and land-surface elevations obtained from the DEM. Negative values are present in the DEM near the coast and are likely an artifact of collection of the lidar data under low-tide conditions. Negative values for land surface and surface-water features are inconsistent with a sea level of 0 ft above National Vertical Datum of 1988 (NAVD 88), which was used for the rest of the analysis; therefore, negative values in the DEM were set to zero prior to the rest of the analysis. Synoptic groundwater levels from shallow wells and piezometers located in the refuge or in close proximity to the refuge were used to create the map because they are most representative of the water table underlying the refuge. Groundwater sites less than or equal to 40 ft deep and screened in the Kirkwood-Cohansey aquifer system were included in the analysis. Water-level elevations for these sites were obtained by subtracting the measured depth-to-water value (below land surface) from the DEM-derived land-surface elevation for the site location. Surface-water levels measured during the synoptic study were referenced to their respective surveyed RPs to obtain water-surface elevations. If multiple measurements were made at groundwater and surface-water sites to determine tidal effects, the first of the recorded measurements was used to produce the water-table maps.

Additional surface-water features including streams, ponds, lakes, and impoundments were used to indicate the position of the water table; the point where these surface-water features intersect land surface represents the elevation of the water table at that location. These surface-water features were derived from the geographical representation of their extent in the USGS 1:24,000-scale National Hydrography Dataset (NHD); features listed as canals and ditches were excluded



Base from U.S. Geological Survey digital data, 1:24,000
Universal Transverse Mercator projection, Zone 18, NAD83

Figure 2. Location of groundwater and surface-water sites included in the spring 2015 water-level synoptic study of the Edwin B. Forsythe National Wildlife Refuge and vicinity, New Jersey.

Table 1. Description of groundwater sites included in the spring 2015 water-level synoptic study of the Edwin B. Forsythe National Wildlife Refuge, New Jersey.

[--, not applicable or data unavailable. All sites are screened in the Kirkwood-Cohansey aquifer system. Wells were previously installed. NWIS, National Water Information System; NAVD 88, North American Vertical Datum of 1988; NGVD 29, National Geodetic Vertical Datum of 1929; M, map; N, Digital Elevation Model (DEM) of various accuracy; L, Leveled]

Site identifier	U.S. Geological Survey site number	Site name	Site type	Land-surface elevation from DEM, in feet above NAVD 88[1]	Land-surface elevation in NWIS, in feet above NAVD 88[2]	Elevation method, in NWIS	Elevation accuracy in NWIS, in feet	Date of construction	Well depth, in feet below land surface	Top of screen, in feet below land surface	Bottom of screen, in feet below land surface	Site used to create water-table maps[3]
1-721	393144074301001	Ac 11 Obs	Well	32.5	[4]29.74	M	5	11/7/1985	25.9	22.9	25.9	Yes
1-726	392938074254301	Ac 12 Obs	Well	24.8	[4]23.73	M	2.5	11/7/1985	30.95	27.95	30.95	Yes
1-756	392830074281201	Slf MW-1-1980	Well	27.4	[4]28.53	L	0.1	3/6/1980	34.0	24	34	Yes
1-757	392834074282602	Slf MW-2-1980	Well	33.2	[4]40.93	L	0.1	3/--/1980	32.0	22	32	Yes
1-761	392740074303702	Slf MW-2-1983	Well	56.4	56	L	0.1	1/12/1983	38	28	38	Yes
1-1501	392933074310901	Mm OW-2S	Well	40.5	39.88	N	5	8/25/2004	40	30	40	Yes
1-1566	393016074311701	Mm Up-5	Well	36.5	39.7	N	5	3/7/2005	25	20	25	Yes
1-1622	392744074303401	MW-2	Well	59.7	58.66	L	0.01	10/2/1986	30	10	30	Yes
1-2250	392757074265801	EBF-PZ-01	Piezometer	6.8	7	N	1.6	2/11/2015	11.13	10.28	11.13	Yes
1-2251	393038074270501	EBF-PZ-03	Piezometer	5.8	6	N	1.6	4/15/2015	8.35	6.1	8.1	Yes
1-2252	392907074255501	EBF-PZ-02	Piezometer	13.6	13	N	1.6	4/15/2015	7.67	5.42	7.42	Yes
1-2253	393030074271501	EBF-PZ-04	Piezometer	13.9	14	N	1.6	4/15/2015	8.72	6.47	8.47	Yes
1-2254	392817074282501	EBF-PZ-32	Piezometer	21.5	22	N	1.6	5/6/2015	7.95	5.7	7.7	Yes
1-2255	392818074271301	EBF-PZ-28	Piezometer	24.3	23	N	1.6	4/30/2015	21.1	18.85	20.85	Yes
1-2256	392833074262701	EBF-PZ-26	Piezometer	5.1	5	N	1.6	4/30/2015	5.52	4.27	5.27	Yes
1-2257	392837074262901	EBF-PZ-27	Piezometer	14.1	14	N	1.6	4/30/2015	11.03	9.78	10.78	Yes
1-2258	392843074263601	EBF-PZ-24	Piezometer	22.9	23	N	1.6	4/30/2015	17.7	16.7	17.7	Yes
1-2259	392849074264501	EBF-PZ-25	Piezometer	40.7	41	N	1.6	4/30/2015	35.35	34.35	35.35	Yes
5-511	394009074325101	Mullica 6D	Well	37.9	[4]41.1	L	0.01	5/28/1975	250	245	250	No
5-570	394106074362501	Mount Obs	Well	62.7	[4]62	L	0.01	1955	25.0	0	25	No
5-613	394305074335702	Mullica 45S	Well	41.2	[4]39.82	L	0.01	7/28/1975	35.0	25	35	No
5-628	394452074281901	Penn Sf Shallow Obs	Well	78.6	[4]77.53	L	0.01	1936	12.0	12	--	No
5-630	394513074280601	Penn Sf Deep Obs	Well	106.1	[4]103.05	L	0.1	1936	41.0	41	--	No
5-1102	393729074252901	Bass R Sf-Pz-2	Well	23.0	[4]21.74	M	5	6/12/1991	18	3	18	Yes
5-1103	393729074252902	Bass R Sf-MW-1[5]	Well	23.0	[4]21.74	M	5	6/13/1991	60	5	30	No
5-1138	393550074233601	Cedar Ave-MW1	Well	20.8	[4]21.73	M	5	12/13/1988	20	5	20	Yes
5-1156	393504074272101	MW 1	Well	3.2	[4]6.33	L	0.1	1986	13.41	--	--	Yes
5-1926	393458074243501	EBF-PZ-29	Piezometer	4.3	5	N	1.6	5/6/2015	3.82	2.57	3.57	Yes

Table 1. Description of groundwater sites included in the spring 2015 water-level synoptic study of the Edwin B. Forsythe National Wildlife Refuge, New Jersey.—Continued

[--, not applicable or data unavailable. All sites are screened in the Kirkwood-Cohansey aquifer system. Wells were previously installed. NWIS, National Water Information System; NAVD 88, North American Vertical Datum of 1988; NGVD 29, National Geodetic Vertical Datum of 1929; M, map; N, Digital Elevation Model (DEM) of various accuracy; L, Leveled]

Site identifier	U.S. Geological Survey site number	Site name	Site type	Land-surface elevation from DEM, in feet above NAVD 88[1]	Land-surface elevation in NWIS, in feet above NAVD 88[2]	Elevation method, in NWIS	Elevation accuracy in NWIS, in feet	Date of construction	Well depth, in feet below land surface	Top of screen, in feet below land surface	Bottom of screen, in feet below land surface	Site used to create water-table maps[3]
5-1927	393510074242901	EBF-PZ-30	Piezometer	8.5	9	N	1.6	5/6/2015	6.45	5.2	6.2	Yes
5-1928	393532074241901	EBF-PZ-31	Piezometer	13.2	13	N	1.6	5/6/2015	7.28	5.03	7.03	Yes
29-0017	394829074053501	Island Beach 1 Obs	Well	4.8	[4]7.26	L	0.1	1962	397	377	397	No
29-0020	394829074053504	Island Beach 4 Obs	Well	4.8	[4]6.95	L	0.01	1962	12.0	9	12	No
29-0058	395715074123101	PW 21	Well	6.1	[4]8.77	M	2.5	5/10/1968	56.0	46	56	No
29-0513	394742074142001	Garden St Pky 1 Obs	Well	49.5	[4]43.01	L	0.01	5/2/1962	21.0	18	21	Yes
29-0514	394742074142002	Garden St Pky 2 Obs	Well	49.5	[4]42.58	L	0.01	1962	316	306	316	No
29-0773	393855074200801	Bass R Sf 1	Well	45.2	[4]43.74	M	5	8/10/1983	37.0	27	37	Yes
29-0789	394949074202901	Cedar Brg Twr1	Well	199.1	[4]198.74	M	5	4/22/1983	69.0	59	69	No
29-1249	395414074133301	Lf MW-4A	Well	49.9	[4]52.74	M	2.5	5/11/1982	34	14	34	Yes
29-1251	395424074132701	Lf MW-2A	Well	51.5	[4]52.74	M	2.5	5/11/1982	34.5	14.5	34.5	Yes
29-1257	393938074195001	Slf MW-2	Well	52.0	[4]48.75	M	5	6/15/1983	31	16	31	Yes
29-1258	393941074194301	Slf MW-3	Well	50.1	[4]48.75	M	5	6/15/1983	35	20	35	Yes
29-1417	400346074081701	MW64	Well	9.1	[4]11.9	M	2.5	6/14/2001	18.5	13.5	18.5	Yes
29-1419	395034074112101	MW61	Well	17.2	[4]17.76	M	2.5	6/25/2001	20	15	20	Yes
29-1431	395229074125401	Service MW-118S	Well	38.6	[4]38.75	M	2.5	1991	15	--	--	Yes
29-2248	400158074054401	EBF-PZ-39	Piezometer	7.3	8	N	1.6	4/17/2015	6.56	5.56	6.41	Yes
29-2249	400205074050001	EBF-PZ-38	Piezometer	4.2	4	N	1.6	4/17/2015	4.57	2.32	4.32	Yes
29-2250	400230074051401	EBF-PZ-37	Piezometer	8.2	8	N	1.6	4/17/2015	5.85	3.6	5.6	Yes
29-2251	400251074041501	EBF-PZ-40	Piezometer	1.9	2	N	1.6	4/17/2015	5.05	2.8	4.8	Yes
29-2252	393829074173701	EBF-PZ-08	Piezometer	5.1	5	N	1.6	4/16/2015	5.53	4.53	5.38	Yes
29-2253	393940074162501	EBF-PZ-09	Piezometer	6.4	6	N	1.6	4/21/2015	5.22	2.97	4.97	Yes
29-2254	394001074154601	EBF-PZ-07	Piezometer	3.8	4	N	1.6	4/16/2015	5.08	2.83	4.83	Yes
29-2255	394014074155801	EBF-PZ-05	Piezometer	6.8	7	N	1.6	4/16/2015	3.1	0.85	2.85	Yes
29-2256	394026074161101	EBF-PZ-06	Piezometer	13.5	13	N	1.6	4/16/2015	3.37	2.37	3.22	Yes
29-2257	394137074132701	EBF-PZ-11	Piezometer	7.8	8	N	1.6	2/12/2015	4.95	4.1	4.95	Yes
29-2258	394331074131501	EBF-PZ-14	Piezometer	5.3	5	N	1.6	4/21/2015	4.94	3.69	4.69	Yes
29-2259	394351074135301	EBF-PZ-13	Piezometer	22.0	22	N	1.6	4/21/2015	6.48	5.48	6.33	Yes

Table 1. Description of groundwater sites included in the spring 2015 water-level synoptic study of the Edwin B. Forsythe National Wildlife Refuge, New Jersey.—Continued

[--, not applicable or data unavailable. All sites are screened in the Kirkwood-Cohansey aquifer system. Wells were previously installed. NWIS, National Water Information System; NAVD 88, North American Vertical Datum of 1988; NGVD 29, National Geodetic Vertical Datum of 1929; M, map; N, Digital Elevation Model (DEM) of various accuracy; L, Leveled]

Site identifier	U.S. Geological Survey site number	Site name	Site type	Land-surface elevation from DEM, in feet above NAVD 88[1]	Land-surface elevation in NWIS, in feet above NAVD 88[2]	Elevation method, in NWIS	Elevation accuracy in NWIS, in feet	Date of construction	Well depth, in feet below land surface	Top of screen, in feet below land surface	Bottom of screen, in feet below land surface	Site used to create water-table maps[3]
29-2260	394523074125601	EBF-PZ-15	Piezometer	16.1	16	N	1.6	4/23/2015	3.87	2.62	3.62	Yes
29-2261	394923074130401	EBF-PZ-20	Piezometer	18.7	19	N	1.6	4/23/2015	5.62	3.37	5.37	Yes
29-2262	395026074105101	EBF-PZ-18	Piezometer	13.1	13	N	1.6	4/23/2015	8.31	6.06	8.06	Yes
29-2263	395014074094801	EBF-PZ-17	Piezometer	3.4	3	N	1.6	2/18/2015	4.68	3.83	4.68	Yes
29-2264	395231074115101	EBF-PZ-19	Piezometer	16.1	16	N	1.6	4/23/2015	4.43	3.43	4.28	Yes
29-2265	394643074123501	EBF-PZ-16	Piezometer	28.9	29	N	1.6	4/23/2015	9.99	7.74	9.74	Yes
29-2266	394039074151101	EBF-PZ-10	Piezometer	9.1	9	N	1.6	4/21/2015	4.74	2.49	4.49	Yes
29-2267	394232074161501	EBF-PZ-12	Piezometer	38.1	38	N	1.6	4/21/2015	13.2	12.2	13.05	Yes
29-2268	393650074182601	EBF-PZ-34	Piezometer	3.7	4	N	1.6	5/6/2015	6.58	5.33	6.33	Yes
29-2269	393706074184801	EBF-PZ-33	Piezometer	5.4	5	N	1.6	5/6/2015	5.60	3.85	4.85	Yes
29-2270	394200074125501	EBF-PZ-22	Piezometer	1.2	1	N	1.6	4/29/2015	4.91	2.66	4.66	Yes
29-2271	394201074140601	EBF-PZ-21	Piezometer	13.6	13	N	1.6	4/29/2015	5.29	3.04	5.04	Yes
29-2272	394245074163201	EBF-PZ-23	Piezometer	38.8	39	N	1.6	4/29/2015	10.39	8.14	10.14	Yes
29-2273	395142074102401	WLT-1	Well	26.4	26	N	1.6	11/20/1996	28.7	--	--	Yes
29-2274	395904074124501	MW8	Well	44.2	44	N	1.6	1/3/1994	35	15	35	Yes
29-2275	395534074065501	EBF-PZ-41	Piezometer	1.6	2	N	1.6	5/8/2015	3.63	2.63	3.63	Yes
29-2276	393746074173501	EBF-PZ-35	Piezometer	3.2	3	N	1.6	5/8/2015	8.83	7.83	8.83	Yes
29-2277	394006074143901	EBF-PZ-42	Piezometer	2.9	3	N	1.6	5/20/2015	5.24	4.24	5.24	Yes
29-2278	394047074151801	EBF-PZ-36	Piezometer	11.1	11	N	1.6	5/8/2015	4.78	3.78	4.78	Yes
29-2279	395846074081201	EBF-PZ-44	Piezometer	11.0	11	N	1.6	5/22/2015	7.27	6.27	7.27	Yes
29-2280	395913074071401	EBF-PZ-43	Piezometer	4.2	4	N	1.6	5/22/2015	5.25	4.25	5.25	Yes

[1]Land-surface elevations interpolated from the statewide 10-foot digital elevation model (DEM) (New Jersey Department of Environmental Protection, 2012). These elevations are estimated to have an accuracy within 1.2 feet and were used during the water-table mapping process.

[2]Land-surface elevations available in the U.S. Geological Survey NWIS database. Elevations are reported, although they were not used during the water-table mapping process.

[3]No indicates site was not used for the hydrologic assessment because it was outside of the mapped area or too deep, but was used in the groundwater-flow model developed by Fiore and others (2018).

[4]Elevation converted from NGVD 29.

[5]Site has multiple screens. The second screen is 35–45 feet below land surface, and the third screen is 50–60 feet below land surface.

Table 2. Description of surface-water sites included in the spring 2015 water-level synoptic study of the Edwin B. Forsythe National Wildlife Refuge, New Jersey.

[For surface-water sites, the site identifier is the same as the U.S. Geological Survey site number. All reference points were surveyed to determine elevation. Survey levels shown in the table are in accordance with those described in Rydlund and Densmore (2012). NAVD 88, North American Vertical Datum of 1988]

Site identifier	Site name	Site type	Elevation of reference point, in feet above NAVD 88	Survey level
01408181	Long Causeway Branch near Silverton NJ	Stream	15.61	Level II
01408190	Silver Bay tributary near Silverton NJ	Stream	17.76	Level II
01408726	Long Swamp Creek at Lester Rd near Toms River NJ	Stream	27.88	Level II
01408736	Mill Creek near Pine Beach NJ	Stream	22.59	Level II
01408760	Potter Creek at Holly Park NJ	Stream	10.44	Level II
01408940	Cedar Creek tributary near Lanoka Harbor NJ	Stream	18.36	Level II
01409107	Waretown Creek at Webbs Mill Road near Waretown NJ	Stream	32.27	Level II
01409108	Waretown Creek at US Route 9 at Waretown NJ	Stream	14.17	Level II
01409126	Lochiel Creek at Pebble Beach NJ	Stream	19.25	Level I
01409136	Gunning River at Route 9 near Barnegat NJ	Stream	40.37	Level II
01409137	Gunning River at Lower Shore Road near Barnegat NJ	Stream	16.62	Level II
01409143	Manahawkin Creek at Stafford Rd near Manahawkin NJ	Stream	14.96	Level IV
01409144	Cedar Ck trib at Hilliard Blvd near Manahawkin NJ	Stream	2.16	Level II
01409254	Cedar Run at Route 9 near Mayetta NJ	Stream	19.20	Level II
01409281	Westecunk Creek at Railroad Ave at West Creek NJ	Stream	7.17	Level II
01409284	Parker Run at Parkertown NJ	Stream	6.99	Level III
01409314	Willis Creek at Center Street near Tuckerton NJ	Stream	20.13	Level II
01410230	Mattix Run near Smithville NJ	Stream	15.45	Level II
01410380	Doughty Creek at Oceanville NJ	Stream	16.26	Level III
392739074261901	EBFNWR Southwest pool near Oceanville NJ	Impoundment	3.95	Level III

from the analysis. The DEM used for this analysis was not hydroenforced; therefore, elevations obtained at road crossings may not be representative of actual surface-water elevations. For this reason, stream points within a 175-ft radius of road crossings were excluded from the analysis, except for the Garden State Parkway for which a 250-ft radius was used. Stream-surface elevations obtained from the DEM, and a coastline layer for which the elevation was set uniformly to 0 ft above sea level, were included in the analysis. Additionally, DEM-derived, average surface elevations for lakes, ponds, and impoundments were included.

Water-table-elevation contours were initially produced through interpolation of the aforementioned synoptic water-level measurements and surface-water features using geographic information system (GIS) methods. Contours were then manually adjusted to conform to topographic gradients and expected directions of groundwater flow. Aerial photography was consulted to confirm the presence or absence and potential effects of water features, as necessary. In some cases, ponds and lake features were excluded from the analysis because they were assumed to have a poor hydraulic connection with the groundwater system (for example, artificial ponds on golf courses) and therefore unrealistically affected the contours. For the purpose of the water-table elevation map display, independent, closed-loop contours of variable water-table elevations (typically 1–4 ft above sea level) located between the continuous 1-ft water-table-elevation contour and the coastline were eliminated. These small variations are numerous and are attributed to the low topographic relief of much of the coastal area combined with limitations in the accuracy of the DEM and complicated by the hummocky nature of the salt marsh. Contours in coastal areas affected by human-induced alterations such as filling and ditching may be less accurate than in other areas because addressing these landscape elements was beyond the scope of this project. Water-table elevation contours were extended beyond the refuge boundary to determine groundwater-flow patterns. Variable contour intervals were used. At water-table elevations

between 10 and 65 feet above sea level, contours are displayed at 5-ft intervals; between 6 and 10 feet above sea level, contours are displayed at 2-ft intervals; and from 1–5 ft, contours are displayed at 1-ft intervals to offer finer resolution within the refuge.

Depth to water, in feet below land surface, for spring 2015 was mapped as the difference between the DEM-derived land surface and the gridded output of the water-table elevation map. The areas of variable water-table elevations located between the continuous 1-ft water-table-elevation contour and the coastline were incorporated into this process to demonstrate minor differences in depth to water within the marsh. Depth to water was set to zero feet below land surface for streamlines mapped in the NHD, with the exception of canals and ditches which were not included in the analysis.

Streamflow

Available streamflow data collected at eight continuous-record streamgages were analyzed to assess hydrologic conditions in watersheds predominantly upstream from the Forsythe refuge to further describe the hydrologic dynamics affecting the refuge. Records of daily mean streamflow for continuous-record streamgages within the Mullica-Toms Basin were retrieved from the USGS NWIS database (http://waterdata.usgs.gov/nj/nwis). Streamgages with the most complete records (including 7 years or more of data available for 2004–13) were evaluated (fig. 3, table 3). Streamgage 01408900 is within one of the more inland parcels of refuge land; the other streamgages are in basins upstream from the refuge and adjoining coastal areas. For continuous-record streamgages, data typically collected at 15-minute intervals are used to calculate daily mean flows. Mean annual flow was calculated for each of these streamgages for 2004–13.

Hydrograph separation was conducted to estimate the relative contribution of base flow and direct runoff at each of the streamgages. Specifically, the program PART (Rutledge, 1998), as available in the USGS Groundwater Toolbox (Barlow and others, 2014, 2016), was used to partition streamflow into base flow and direct runoff components. Base flow represents groundwater that discharges to a stream, and direct runoff represents overland runoff to a stream following a precipitation event.

Records of instantaneous, or discrete, low-flow measurements for 13 partial-record stations near the refuge also were retrieved from the USGS NWIS database (fig. 3, table 8 [farther on]). For these stations, streamflow is periodically measured during low-flow conditions. MOVE1 (Maintenance of Variance Extension, Type1), a record-extension technique that relies on regression to correlate instantaneous low-flow measurements at partial-record stations to daily streamflow measurements at continuous-record streamgages in nearby hydrologically similar basins, was used to estimate mean annual flow at the partial-record stations. A detailed explanation of MOVE1 is given in Helsel and Hirsch (2002). Partial-record stations within 5 miles of the refuge that had measurements available for the 2004–13 period were analyzed. Partial-record stations 01409210 and 01409281 are along the western fringe of the coastal refuge parcels; the other partial-record stations are in basins upstream from the refuge and adjoining coastal areas. All low-flow measurements for the period of record for each partial-record station were included in the analysis to best define the relation between flow at the partial-record stations and each of the six continuous-record streamgages, or index stations, (01408120, 01408500, 01408900, 01409280, 01410000, 01410150) that were used in the analysis.

Water Budget

A water budget is a tool that can be used to represent and quantify the relation among the components of the hydrologic cycle. A land-surface-based equation was used to quantify gains and losses of water to and from the land and water surfaces of the refuge. Water reaches the surface of the refuge through precipitation, and water is lost through groundwater recharge, evapotranspiration, and direct runoff. Precipitation occurs mostly in the form of rain or snow. Groundwater recharge refers to water that infiltrates from the land surface to the underlying surficial aquifer. Evapotranspiration refers to the process by which water enters the atmosphere through vaporization from soil and surface-water bodies, and through transpiration from plants. Direct runoff (or overland flow) refers to runoff that is caused by, and directly follows, a precipitation event; direct runoff excludes the base-flow (groundwater discharge) portion of a hydrograph. The equation used to compute the water budget for the refuge surface is

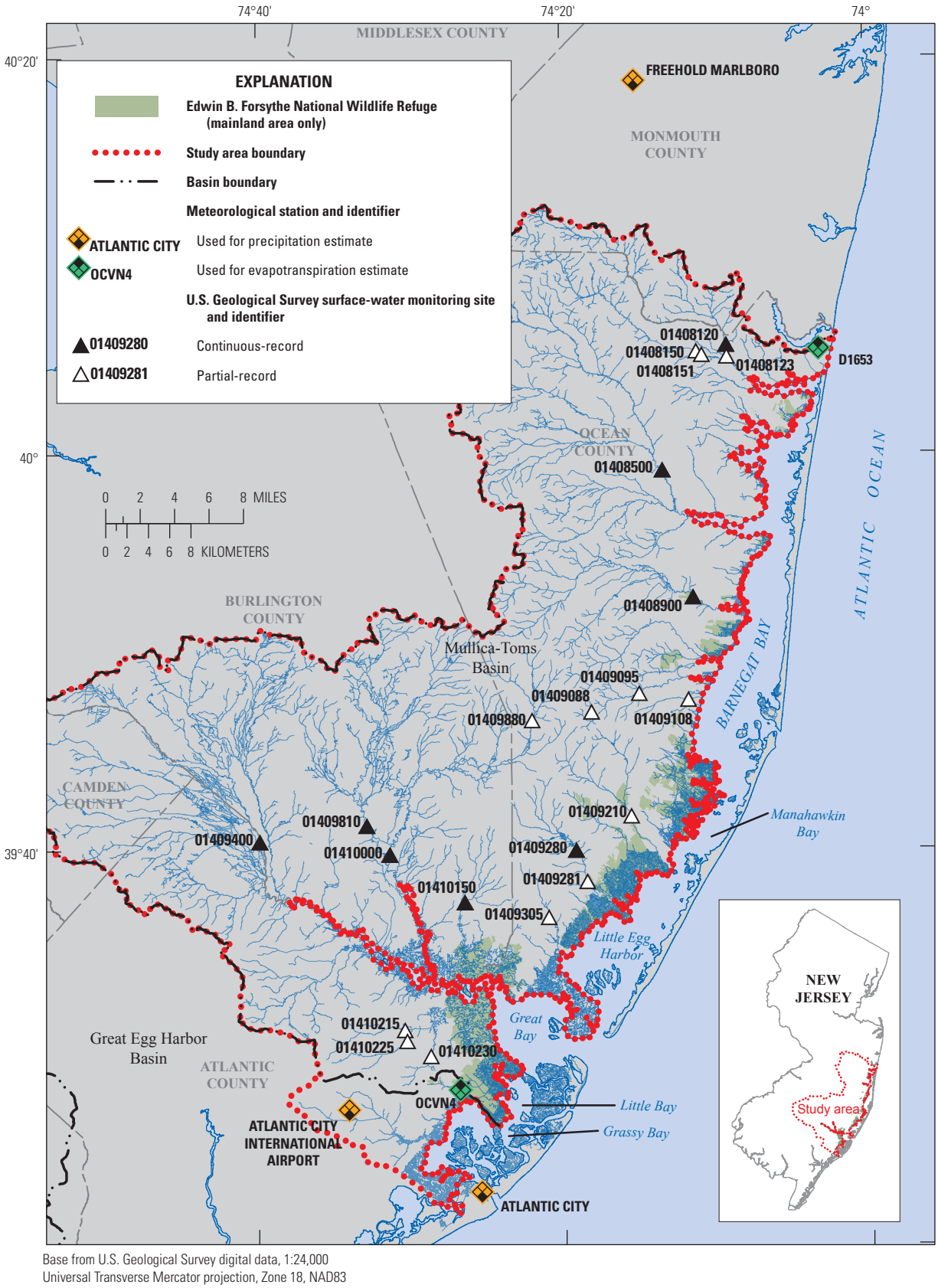
$$P = R_g + ET + Q_{dr} \quad (1)$$

where

P = precipitation,
R_g = groundwater recharge,
ET = evapotranspiration, and
Q_{dr} = direct runoff .

The relative importance of the water-budget components varies among hydrologic systems depending on climate, geology, and other factors. By evaluating the relative magnitude and variability of individual hydrologic components, a water budget serves as a valuable tool in understanding the hydrologic processes that take place in a system and provides insight into the potential effects of human activities and climate change on the hydrologic characteristics of a system, thereby serving as a foundation for effective water-resource management (Healy and others, 2007; Carter, 1996).

For this study, mean annual water budgets were estimated for multiple areas of the Forsythe refuge using data for 2004–13, except for the groundwater recharge component, which was estimated using 2000–03 groundwater-flow model results. As a result of substantial spatial variation in the surface



Base from U.S. Geological Survey digital data, 1:24,000
Universal Transverse Mercator projection, Zone 18, NAD83

Figure 3. Location of precipitation, evapotranspiration, and streamflow data-collection stations used in the hydrologic assessment of the Edwin B. Forsythe National Wildlife Refuge, New Jersey.

Table 3. Mean annual streamflow estimated for selected continuous-record streamgages in the Mullica-Toms Basin, New Jersey.

[ft^3/s, cubic feet per second; $ft^3/s/mi^2$, cubic feet per second per square mile]

Site identifier	Site name	Drainage area, in square miles	Period of record through 2013	Number of years with data, 2004–13	Mean annual streamflow			Percent of period-of-record mean annual streamflow
					Period of record, in ft^3/s	2004–13, in ft^3/s	2004–13, in $ft^3/s/mi^2$	
01408120	North Branch Metedeconk River near Lakewood NJ	34.9	1973–2013	10	61.3	66.2	1.9	108
01408500	Toms River near Toms River NJ	123	1929–2013	10	211.6	219.6	1.8	104
01408900	Cedar Creek at Western Blvd near Lanoka Harbor NJ	49.9	1933–1957, 2004–2013	10	96.4	93.9	1.9	97
01409280	Westecunk Creek at Stafford Forge NJ	15.8	1974–1987, 2004–2013	10	32.6	33.3	2.1	102
01409400	Mullica River near Batsto NJ	46.7	1958–2012	9	105.9	111.2	2.4	105
01409810	West Branch Wading River near Jenkins NJ	84.1	1975–1995, 2007–2013	7	139.9	141.9	1.7	101
01410000	Oswego River at Harrisville NJ	72.5	1931–2013	10	85.8	84.9	1.2	99
01410150	East Branch Bass River near New Gretna NJ	8.11	1978–2012	9	16.6	17.0	2.1	102

and groundwater hydrologic systems across the extent of the refuge, the relative importance of the hydrologic components was expected to vary among different geographic areas of the refuge. To account for this variability, the refuge was divided into nine "water-budget areas" (fig. 4) on the basis of geography, nearby land use, data availability, and output from available groundwater-flow models. The water-budget areas consist of nine unique subsets of the refuge that together are inclusive of nearly the entire mainland refuge extent. These water-budget areas generally do not conform to drainage basin boundaries because they are limited in extent to the boundaries of the refuge. A small portion of the mainland refuge area was excluded from the water-budget analysis because the area is too small to be accurately represented by the groundwater-flow models which provide regional representations of the flow system. A mean annual water budget was computed for each of the nine areas, balancing freshwater inputs to and outputs from the surface of the refuge. Values of water-budget inputs and outputs were assumed to be uniform across each water-budget area, given the small extent of the areas.

Precipitation

Precipitation data were compiled from the National Oceanic and Atmospheric Administration (2015) National Climatic Data Center for 2004–13. Daily precipitation records were retrieved for meteorological stations with the most complete records (2004–13) and closest to the refuge. Precipitation is typically higher in the northern part of Ocean County than in the southern part (Cauller and others, 2016). To account for this spatial variation, daily records were retrieved for three meteorological stations: Atlantic City and Atlantic City International Airport in the south, and Freehold Marlboro in the north (fig. 3). Mean annual precipitation was computed for each of the selected stations for 2004–13. Mean annual precipitation values for Atlantic City and Atlantic City International Airport were averaged because of their close proximity to each other. Linear interpolation was then used to estimate mean annual precipitation for each of the water-budget areas.

Groundwater Recharge

Groundwater flows into and out of the refuge, including infiltration from the land surface to the surficial aquifer system (groundwater recharge), were determined using calibrated groundwater-flow models completed as parts of previous studies conducted by the USGS. Groundwater flows for refuge areas in Tuckerton, N.J., (fig. 1) and northward were computed using a model developed for Ocean County and vicinity (Cauller and others, 2016). Groundwater flows for refuge areas west and south of Tuckerton, N.J., were computed using a model developed for the Great Egg Harbor and Mullica River Basins (Pope and others, 2012).

The groundwater-flow models were used to compute groundwater flows under average 2000–03 conditions; the 2000–03 period is the most recent period common to the two models. Groundwater flows were computed for model grid cells for the shallow Kirkwood-Cohansey aquifer system for 14 distinct refuge areas (polygons in fig. 4) to characterize and account for the variability in groundwater flows among different geographic regions of the refuge. Each water-budget area is associated with one or more corresponding groundwater-flow polygons for which groundwater flows were computed (fig. 4). Groundwater-flow polygons were oriented in line with the model grids, and the extent of the refuge within the representative polygons was maximized. Using the model output, groundwater flow values were then applied to the corresponding water-budget areas. When more than one groundwater-flow polygon corresponded to a single water-budget area, an area-weighted average was applied.

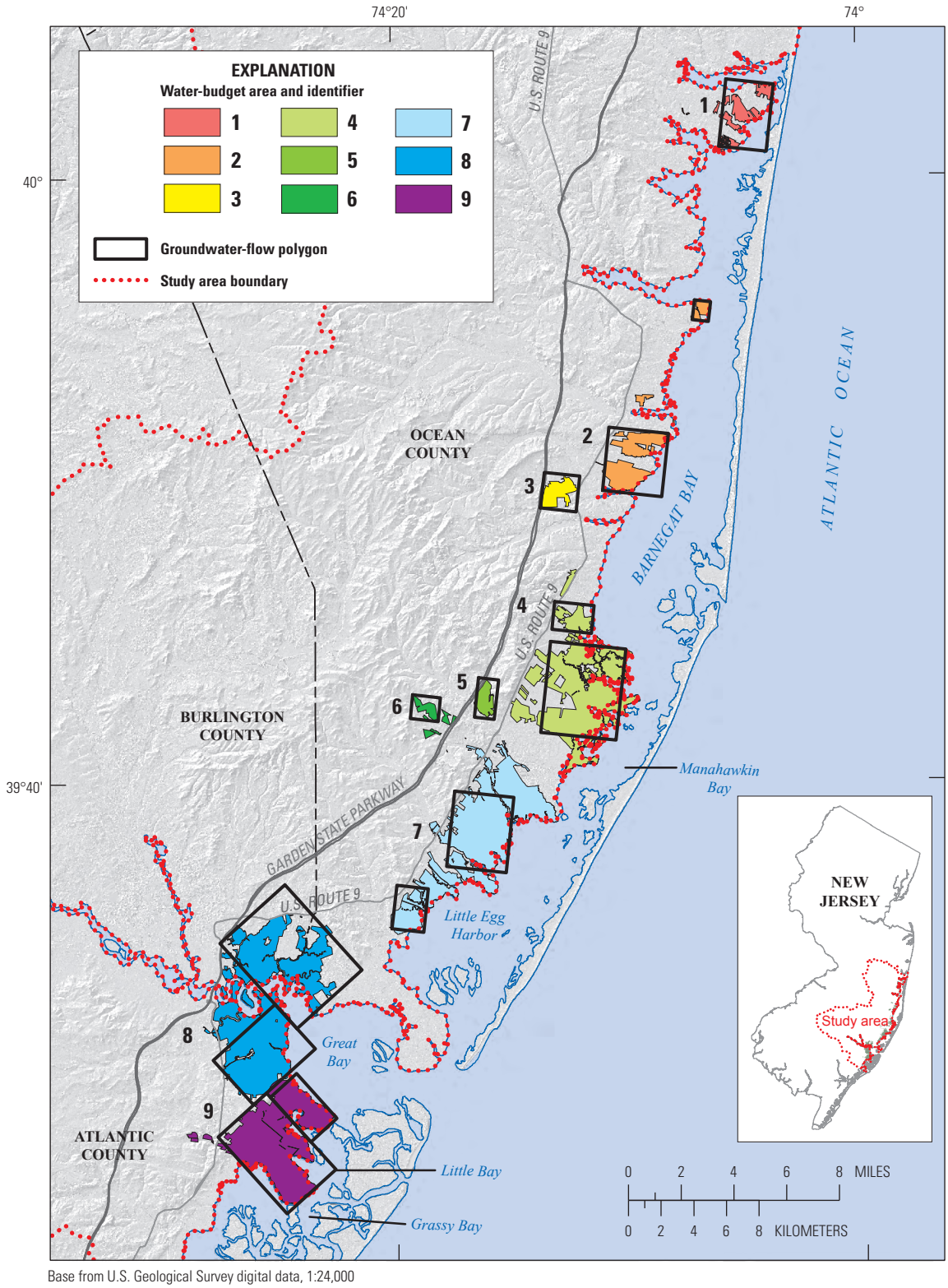
Of the groundwater flows that were computed from the model output, only groundwater recharge was evaluated as part of the land-surface-based water-budget equation. Discussion of other vertical and horizontal flows computed from the model output is presented in the "Groundwater-Flow Components" section of this report.

Evapotranspiration

The rate of evapotranspiration (ET) is dependent on a number of meteorological, physical, and biological factors, including surface temperature, wind speed, solar radiation, relative humidity, land use, soil moisture, and vegetation (Carter, 1996). The rate of ET varies widely, both spatially and temporally, and it is one of the most challenging components of a water budget to quantify. Information about ET rates within the Forsythe refuge is scarce. ET rates for this study were calculated by using a combination of empirical methods that rely on meteorological data and field-based estimates from previous studies.

Empirical equations were used to estimate mean annual ET rates at meteorological stations near the coast. Air temperature, wind speed, relative humidity, and solar radiation records were retrieved using the MesoWest (2016) web interface (accessed August 30, 2016, at http://mesowest.utah.edu/) for two stations: OCVN4 (EB Forsythe) in the south and D1653 (Point Pleasant) in the north (fig. 3). These data were available in 10-minute time steps, from which minimum and maximum air temperature, average wind speed, average relative humidity, and average solar radiation were computed at daily time steps. Using each of these variables, along with latitude, reference ET (ET_o) was calculated for each station using the Penman-Monteith equation, as described in Allen and others (1998). Solely for comparison, potential ET (PET) also was calculated for each station using the Thornthwaite equation (Dunne and Leopold, 1978), which is widely used but less comprehensive, taking into account only mean monthly air temperature and latitude.

Station OCVN4 is within the boundary of the southern part of the refuge, in close proximity to the main impoundment (fig. 3). This station borders the salt marsh and is surrounded primarily by wetlands and to a lesser extent forested



Base from U.S. Geological Survey digital data, 1:24,000
Universal Transverse Mercator projection, Zone 18, NAD83

Figure 4. Location of water-budget areas and groundwater-flow polygons for the Edwin B. Forsythe National Wildlife Refuge, New Jersey.

land, rendering its setting similar to much of the lowland areas of the refuge. Given the close proximity to wetlands and water, the mean annual ET rate (ET_o, determined by using the Penman-Monteith equation) calculated for station OCVN4 for 2005–13 was used to represent a uniform ET rate for lowland areas of the refuge ("lowland ET rate"). Because it is an incomplete year, 2004 was excluded from the estimate. In the Penman-Monteith equation, evaporation of freshwater is assumed to occur from a reference vegetation of open field grasses of uniform height (Allen and others, 1998). Coefficients to adjust the output for salt marsh grasses are not available; it was assumed for this study that the output from the Penman-Monteith equation represents the maximum ET rate occurring on the refuge.

During a study conducted in the New Jersey Pinelands from 2005 to 2006, ET rates monitored in the field in areas composed primarily of forest and freshwater wetlands were used to estimate total ET rates in three separate drainage basins (Walker and others, 2011). A comparison of ET measurements made concurrently at a forested site and a wetland site indicated that the ET rate at the forested upland site was, on average, equivalent to about 66 percent of the ET rate at the wetland site. Given the relative proximity of the Pinelands and Forsythe study areas, and the similarity in upland vegetation in the two areas, the lowland ET rate determined for the Forsythe refuge was multiplied by a factor of 0.66 to estimate a uniform ET rate for the upland areas of the refuge ("upland ET rate").

Using the 2007 land-use/land-cover digital dataset produced by the New Jersey Department of Environmental Protection (2010), the percentage of land in each land-use category was quantified for the nine water-budget areas. For the purpose of the ET calculation, lowland areas of the refuge were defined as areas with land use designated as wetland or water; upland areas of the refuge were defined as areas with all other land-use designations. The uniform upland and wetland ET rates estimated for the Forsythe refuge were multiplied by the fraction of corresponding land within each water-budget area and then summed to estimate total ET for each water-budget area.

The Penman-Monteith and Thornthwaite equations were used to estimate ET at meteorological station D1653 near the northern part of the refuge. This station is in close proximity to the coast but is surrounded predominantly by urban land. For station D1653, the variables necessary to complete the Penman-Monteith equation were available for 2012–15. ET estimates from this station are presented strictly for comparison with estimates for station OCVN4 for the same period and were not integrated into the water budget because the landscape setting at station D1653 is less representative of the refuge than the landscape setting at station OCVN4.

Direct runoff

Surface water is transported into the refuge through major stream channels that cross the refuge; this surface water ultimately discharges to the coastal bays. Additionally, precipitation that falls on the land surface but does not infiltrate to the underlying aquifer system as groundwater recharge or is not lost to evapotranspiration, flows to streams and to the coastal bays as direct runoff. Hydrograph separation of the continuous streamgage data was used to assess base-flow and direct runoff conditions in basins upstream from the refuge. However, these data are not considered to be representative of the widely dispersed base flow and direct runoff that occurs across the predominantly coastal wetland landscape of the Forsythe refuge. Additionally, direct runoff measurements were not available for the refuge because this component of the water budget is distributed among a complex network of natural and artificial stream channels and ditches that weave through the coastal wetlands and discharge to the neighboring bays. Therefore, direct runoff was estimated as the residual term for each of the refuge's water-budget areas.

Groundwater-Flow Components

Interactions among freshwater resources at the refuge occur in a three-dimensional space. It is important to consider not only what is happening on the surface of the refuge, but also what is happening in the subsurface. The land-surface-based water budget describes gains and losses of water to and from the land and water surfaces of the refuge, but it does not account for the interactions between the surficial aquifer system and wetlands and streams of the refuge. Also, the land-surface-based water budget does not account for horizontal flow of groundwater through the shallow subsurface from the uplands toward the coast.

As mentioned previously, subsurface groundwater inflows to and outflows from the refuge were computed from calibrated groundwater-flow models developed for Ocean County and vicinity (Cauller and others, 2016) and the Great Egg Harbor and Mullica River Basins (Pope and others, 2012). In addition to being used to compute the groundwater recharge component of the land-surface-based water budget, output from the groundwater-flow models was used to evaluate upward vertical flows into the refuge (groundwater discharge into streams and wetlands), downward vertical flows out of the refuge (infiltration from streams and wetlands to the underlying surficial aquifer), and horizontal flow into and out of the underlying surficial aquifer. These additional groundwater-flow components provide information to further describe the entire hydrologic system supporting the ecosystems of the refuge by highlighting the interaction between the surficial aquifer system and the wetlands and streams of the refuge. The components of the mean annual water budget for the refuge and the additional groundwater-flow components are illustrated in figure 5.

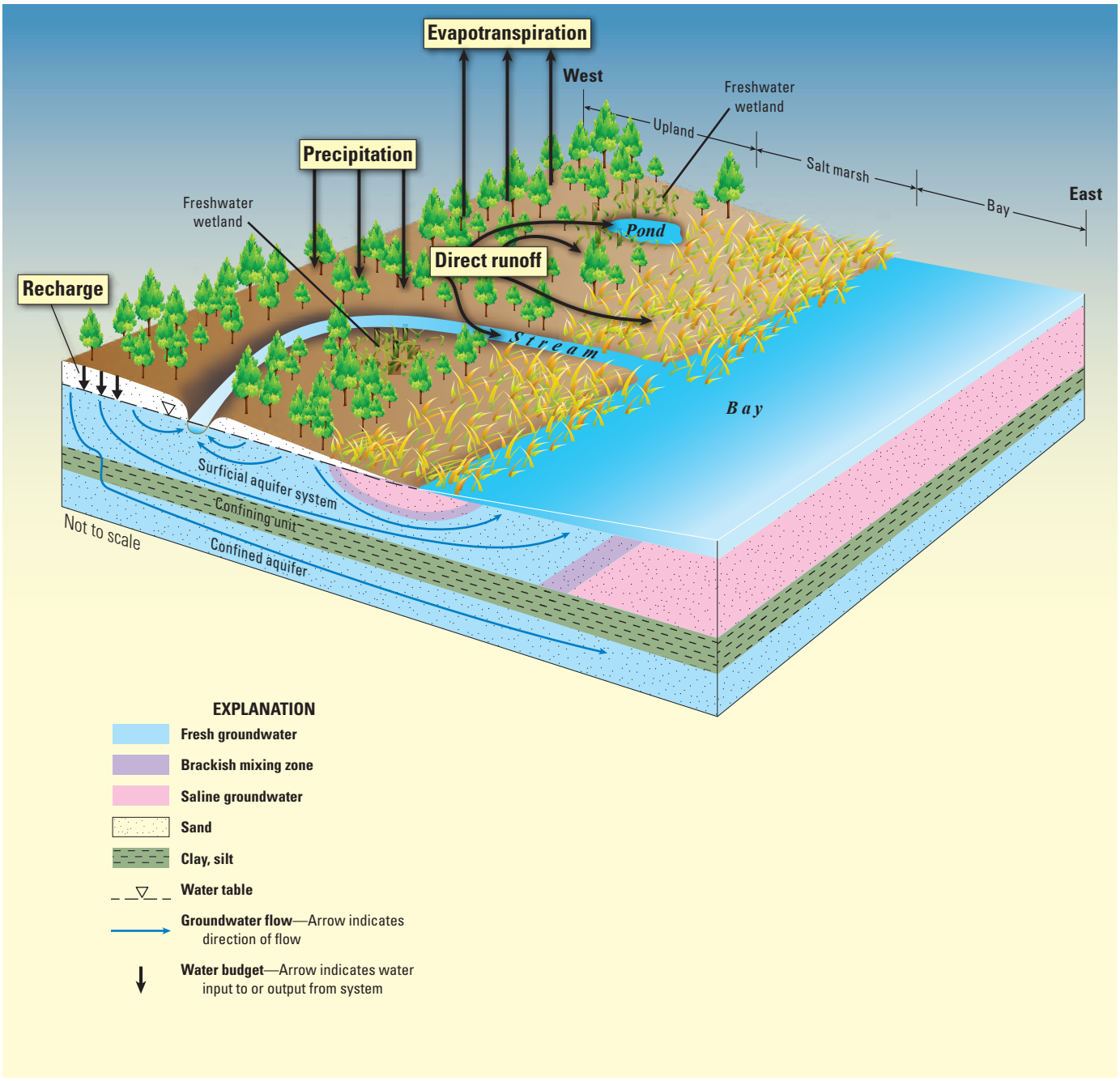


Figure 5. Major components of the mean annual water budget and groundwater flow for the Edwin B. Forsythe National Wildlife Refuge, New Jersey.

Hydrologic Assessment

The hydrologic characteristics of the Forsythe refuge and surrounding areas have been interpreted from an analysis of synoptic water-level measurements, available streamflow data, meteorological data, and previously simulated groundwater flows. Maps of the water-table elevation and depth to the water table are presented for the refuge, along with an analysis of groundwater-flow direction and hydraulic gradient in the shallow subsurface. Mean annual water budgets are presented for different areas of the refuge for 2004–13. The hydrologic contexts for the period of synoptic water-level measurements and for the mean annual water budget are provided. For the hydrologic assessment discussion, the term "wetlands" refers to all wetland types, including freshwater wetlands and salt marsh.

Water-Table Analysis

Water levels and streamflow measured at long-term monitoring stations during May 2015 were compared to summary statistics calculated for the period of record at the same stations to evaluate the hydrologic conditions in the refuge during the May 2015 synoptic study relative to historical records. Continuous-record streamgages located in the Mullica-Toms Basin that were active in May 2015 were considered. The period of record for these streamgages ranges from 24 to 85 years. Daily mean streamflow records for the North Branch Metedeconk River (01408120), Toms River (01408500), Cedar Creek (01408900), Westecunk Creek (01409280), Mullica River (01409400), West Branch Wading River (01409810), Oswego River (01410000), and East Branch Bass River (01410150) indicate that streamflow during the May 2015 synoptic study was lower than the period-of-record daily mean flow for the month of May at each of the streamgages (U.S. Geological Survey, 2016). Streamflow during the May 2015 synoptic study also was compared to mean monthly flow for a more recent time period, 2000–15, and was determined to be lower at all streamgages for May 2015, except for 01410150 where it was similar.

Groundwater levels in shallow wells within the study area that are part of the USGS Groundwater Watch Active Groundwater Level Network (accessed April 8, 2017, at https://groundwaterwatch.usgs.gov/) also were analyzed. Records were examined for wells that are screened in the Kirkwood-Cohansey aquifer system, continuously monitored, and located relatively close to the refuge. During the synoptic study, water levels for well 29-1419 (on the edge of the refuge boundary in the Forked River area) and well 5-628 (approximately 11.5 miles from the Manahawkin area of the refuge) were lower than the daily mean water level for the month of May calculated from 11 years and 42 years of record, respectively. However, groundwater levels at well 5-570 (about 11 miles from where the Bass River flows into the refuge) and well 1-776 (about 5 miles southwest of the southernmost part of the refuge) were higher than the monthly mean water levels for May on the basis of 37 years and 12 years of record, respectively. In general, comparison with historical hydrologic records indicates that during the synoptic study measured water levels were lower in some wells and higher in other wells than the long-term average water levels for the month of May.

Continuous water-level records for these wells also were evaluated for seasonal fluctuations from 2000 to 2015. In aquifers across the United States, water levels typically rise during winter and spring months as a result of increased precipitation and groundwater recharge, and decline during summer and fall months as a result of decreased groundwater recharge and increased evapotranspiration (Taylor and Alley, 2001). Shallow wells near the Forsythe refuge exhibit a similar pattern with the highest mean monthly water levels occurring between January and April, and the lowest mean monthly water levels occurring between August and October (table 4). The variation between the highest and lowest mean monthly water levels was about 1.5–1.9 ft during 2000–15 (no measurements were made in 2000) for the two wells closest to the refuge (1-776 and 29-1419), whereas the variation was about 2.3–2.7 ft at the more distant wells (5-570 and 5-628).

Water-table elevation maps (plates 1 and 2) provide information about the potential direction of groundwater flow, as well as information about water-table gradients. Groundwater

Table 4. Mean monthly water levels in selected continuously monitored wells near the Edwin B. Forsythe National Wildlife Refuge, New Jersey, using data available for 2000–15.

[All values are in feet below land surface. USGS, U.S. Geological Suvey; H, highest mean monthly water level; L, lowest mean monthly water level]

Site identifier	USGS site number	Site name	Period of measurement[1]	Water level											
				Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1-776	393232074263903	FAA Shallow Obs	7/1/2003–5/31/2015	19.43	19.24	19.09	18.80H	19.11	19.75	20.38	20.66	20.69L	20.54	20.07	19.48
5-570	394106074362501	Mount Obs	5/1/2001–5/31/2015	12.36	11.77	11.48H	11.51	11.56	12.24	12.63	13.20	13.52	14.17L	13.94	13.22
5-628	394452074281901	Penn Sf Shallow Obs	5/1/2001–12/31/2015	1.79	1.65	1.50	1.43H	1.94	2.44	3.06	3.69	3.62	3.77L	2.99	2.20
29-1419	395034074112101	MW61	7/1/2003–5/31/2015	8.15H	8.24	8.40	8.39	8.61	8.98	9.34	9.71L	9.60	9.44	8.92	8.45

[1]No measurements were made in 2000.

flows from areas of high water-table elevation (high hydraulic head) to areas of low water-table elevation (low hydraulic head) in a direction that is perpendicular to the water-table elevation contours. Groundwater flow typically has both horizontal and vertical components, given that hydraulic head can vary laterally and with depth (Conlon and others, 2005). Contour maps are useful for illustrating directions of flow for the horizontal component; the maps produced for this project depict horizontal flow in the shallow subsurface. The groundwater-flow model developed by Fiore and others (2018) addresses the vertical component of groundwater flow in the refuge and surrounding areas in more detail than is presented in this report.

The water-table elevation in the refuge ranged from sea level in low-lying areas near the coast to approximately 65 feet above sea level (plates 1 and 2, tables 5 and 6). For most of the refuge, the water-table elevation is within 3 feet of sea level. The highest water-table elevations occur in refuge parcels west of the Garden State Parkway.

Water-level measurements potentially affected by tides are noted in tables 5 and 6. Further study is needed for a comprehensive analysis of tidal effects on water levels across the refuge; however, measurements made during this study indicate that water levels at sites near the coast are variably affected by tides (for example, sites 29-2269 and 29-2254).

The water-table elevation maps (plates 1 and 2) indicate that the direction of shallow groundwater flow at the regional scale is generally from west to east (much of it from the northwest to the southeast) with groundwater moving downgradient from the uplands toward major groundwater discharge areas consisting of coastal streams and wetlands (plates 1 and 2). At the local scale, the direction of groundwater flow generally is toward adjacent streams. Groundwater divides are evident in several locations within the limits of the mapped area. One such location is on the ridge northwest of the main impoundment and southeast of Mattix Run (plate 2) where groundwater flows toward the marsh in northerly, northeasterly, and southeasterly directions. Another example occurs along a ridge between Fourmile Branch and Oyster Creek (plate 1) where groundwater flows in multiple directions: to the northeast toward Waretown Creek, and to the east and southeast toward different parts of the marsh.

Spacing of water-table-elevation contours indicates the magnitude of horizontal head gradients. For areas where water levels are mapped with the same contour intervals, closely spaced contours indicate a higher (or steeper) horizontal gradient than in areas where contours are spaced farther apart. Hydraulic gradient is one of the parameters used to estimate discharge, or flow rate. On the basis of Darcy's Law (Fetter, 2001), the rate of flow is directly proportional to the difference in hydraulic head between two points and inversely proportional to the length of the flow path between those two points, such that

$$Q = KA\,(\Delta h/L) \qquad (2)$$

where

Q = volumetric discharge or flow rate;
K = proportionality constant, called the hydraulic conductivity;
A = cross-sectional area;
Δh = difference in hydraulic head; and
L = flow length.

Using Darcy's Law, horizontal gradients indicate the amount and rate of horizontal flow moving from the upland areas to the coast. If the other variables remain constant, as the gradient ($\Delta h/L$) increases, discharge increases. In areas of steeper gradient, greater discharge is expected.

Within the boundaries of the refuge property, the steepest horizontal gradient occurs in the southern part of the refuge, northwest of the main impoundment and adjacent marshlands, stretching from Leeds Point to Oceanville (plate 2). In portions of this area, the water-table elevation declines from 10 ft above sea level to 1 ft above sea level over a distance of approximately 0.25 mile. Beyond the refuge proper, the steepest horizontal gradient occurs in the area leading into the central part of the refuge near Barnegat Township (east of the ridge between Fourmile Branch and Oyster Creek, plate 1), where the water-table elevation declines from 65 ft above sea level to 1 ft above sea level over the course of 1.5–2 miles. These areas of steeper horizontal gradients are located in areas with greater topographic relief, with elevations near the impoundment reaching close to 60 ft above sea level and elevations along the ridge between Fourmile Branch and Oyster Creek reaching more than 140 ft above sea level.

The lowest horizontal gradients occur in the marshlands in the central and southern parts of the refuge, which are areas of low topographic relief and are underlain by thick marsh deposits. In the marsh east of Beach View, Staffordville, West Creek, and Johnsontown, the water-table elevation generally declines from 1 ft above sea level to sea level over a distance of more than 2 miles (plates 1 and 2), with the exception of small localized variations in water-table elevation between the continuous 1-ft contour and the coastline. The northern part of the refuge lacks the extensive swaths of marsh that are characteristic of the rest of the refuge. In the northern part of the study area, the continuous 1-ft contour lies much closer to the coast.

Comparison of water-table elevation contours with those produced for the regional surficial aquifer studies (Watt and others, 1994; Johnson and Watt, 1996; Gordon, 2004) shows generally favorable agreement. In some places, stream-surface elevations are notably higher than previously mapped, particularly along Long Swamp Creek near the northern part of the study area (plate 1) and to a lesser degree at lower elevations of Uriah Branch, Parker Run, and tributaries to Tuckerton Creek in the southern part of the study area (plate 2). Differences in stream-surface elevations may be attributed to differences in time of measurement or to resolution differences among the data sources because the surficial studies relied on

Table 5. Water levels measured at groundwater sites in and near the Edwin B. Forsythe National Wildlife Refuge, New Jersey, spring 2015.

[NAVD 88, North American Vertical Datum of 1988; hh, hours; mm, minutes; time is eastern daylight time]

Site identifier	Site name	Land surface elevation, in feet above NAVD 88[1]	Date of water-level measurement	Time of water-level measurement, in hh:mm	Depth to water, in feet below land surface	Elevation of water level, in feet above NAVD 88	Measurement used to produce water-table maps
1-721	Ac 11 Obs	32.5	5/21/2015	14:25	11.19	21.31	Yes
1-726	Ac 12 Obs	24.8	5/20/2015	10:48	11.60	13.20	Yes
1-726	Ac 12 Obs	24.8	5/21/2015	15:45	11.60	13.20	No
1-756	Slf MW-1-1980	27.4	5/21/2015	08:45	6.86	20.54	Yes
1-757	Slf MW-2-1980	33.2	5/21/2015	08:35	11.44	21.76	Yes
1-761	Slf MW-2-1983	56.4	5/21/2015	09:10	16.79	39.61	Yes
1-1501	Mm OW-2S	40.5	5/21/2015	12:10	10.35	30.15	Yes
1-1566	Mm Up-5	36.5	5/21/2015	13:25	8.00	28.50	Yes
1-1622	MW-2	59.7	5/21/2015	09:36	23.96	35.74	Yes
1-2250	EBF-PZ-01	6.8	5/20/2015	13:09	4.20	2.60	Yes
1-2251	EBF-PZ-03	5.8	5/20/2015	14:07	2.92	2.88	Yes
1-2251	EBF-PZ-03	5.8	5/21/2015	12:12	2.95	2.85	No
1-2252	EBF-PZ-02	13.6	5/20/2015	11:27	5.84	7.76	Yes
1-2253	EBF-PZ-04	13.9	5/20/2015	14:18	8.05	5.85	Yes
1-2253	EBF-PZ-04	13.9	5/21/2015	12:38	8.07	5.83	No
1-2254	EBF-PZ-32	21.5	5/20/2015	10:12	4.81	16.69	Yes
1-2255	EBF-PZ-28	24.3	5/20/2015	13:07	16.06	8.24	Yes
1-2256	EBF-PZ-26	5.1	5/20/2015	12:33	1.18	3.92	Yes
1-2256	EBF-PZ-26	5.1	5/21/2015	14:20	1.18	3.92	No
1-2257	EBF-PZ-27	14.1	5/20/2015	12:28	9.21	4.89	Yes
1-2257	EBF-PZ-27	14.1	5/21/2015	14:00	9.21	4.89	No
1-2258	EBF-PZ-24	22.9	5/20/2015	12:19	15.02	7.88	Yes
1-2259	EBF-PZ-25	40.7	5/20/2015	12:03	30.68	10.02	Yes
5-511	Mullica 6D	37.9	5/20/2015	12:30	8.00	29.90	No
5-570	Mount Obs	62.7	6/12/2015	16:52	9.45	53.25	No
5-613	Mullica 45S	41.2	5/28/2015	13:08	4.50	36.70	No
5-628	Penn Sf Shallow Obs	78.6	5/21/2015	10:24	2.44	76.16	No
5-630	Penn Sf Deep Obs	106.1	5/21/2015	10:44	25.92	80.18	No
5-1102	Bass R Sf-Pz-2	23.0	5/20/2015	14:30	5.31	17.69	Yes
5-1103	Bass R Sf-MW-1	23.0	5/20/2015	14:10	5.29	17.71	No
5-1138	Cedar Ave-MW1	20.8	5/21/2015	13:03	7.64	13.16	Yes
5-1156	MW 1	3.2	5/21/2015	12:01	3.19	0.01	Yes
5-1926	EBF-PZ-29	4.3	5/20/2015	15:07	1.12	3.18	Yes
5-1926	EBF-PZ-29	4.3	5/20/2015	15:37	1.13	3.17	No
5-1927	EBF-PZ-30	8.5	5/20/2015	15:20	3.38	5.12	Yes
5-1927	EBF-PZ-30	8.5	5/20/2015	15:53	3.38	5.12	No
5-1928	EBF-PZ-31	13.2	5/20/2015	16:15	5.48	7.72	Yes
29-017	Island Beach 1 Obs	4.8	5/20/2015	15:36	4.36	0.44	No
29-020	Island Beach 4 Obs	4.8	5/20/2015	15:45	3.52	1.28	No
29-058	PW 21	6.1	5/22/2015	10:50	8.09	-1.99	No
29-513	Garden St Pky 1 Obs	49.5	5/20/2015	12:22	6.26	43.24	Yes
29-514	Garden St Pky 2 Obs	49.5	5/20/2015	12:15	8.71	40.79	No
29-773	Bass R Sf 1	45.2	5/28/2015	10:43	18.22	26.98	Yes
29-789	Cedar Brg Twr1	199.1	5/20/2015	10:35	54.96	144.14	No
29-1249	Lf MW-4A	49.9	5/20/2015	10:41	22.34	27.56	Yes
29-1251	Lf MW-2A	51.5	5/20/2015	10:26	20.00	31.50	Yes
29-1257	Slf MW-2	52.0	5/21/2015	08:02	19.35	32.65	Yes
29-1258	Slf MW-3	50.1	5/21/2015	08:27	15.60	34.50	Yes
29-1417	MW64	9.1	4/30/2015	09:33	7.98	1.12	Yes
29-1419	MW61	17.2	5/20/2015	12:54	9.14	8.06	Yes

Table 5. Water levels measured at groundwater sites in and near the Edwin B. Forsythe National Wildlife Refuge, New Jersey, spring 2015.—Continued

[NAVD 88, North American Vertical Datum of 1988; hh, hours; mm, minutes; time is eastern daylight time]

Site identifier	Site name	Land surface elevation, in feet above NAVD 88[1]	Date of water-level measurement	Time of water-level measurement, in hh:mm	Depth to water, in feet below land surface	Elevation of water level, in feet above NAVD 88	Measurement used to produce water-table maps
29-1431	Service MW-118S	38.6	5/20/2015	13:41	9.78	28.82	Yes
29-2248	EBF-PZ-39	7.3	5/21/2015	16:09	5.31	1.99	Yes
29-2249	EBF-PZ-38	4.2	5/21/2015	15:38	1.75	2.45	Yes
29-2250	EBF-PZ-37	8.2	5/21/2015	15:15	3.91	4.29	Yes
29-2251	EBF-PZ-40	1.9	5/21/2015	15:00	1.50	0.40	Yes
29-2252	EBF-PZ-08	5.1	5/20/2015	10:58	1.96	3.14	Yes
29-2253	EBF-PZ-09	6.4	5/20/2015	12:05	1.23	5.17	Yes
29-2254	EBF-PZ-07	3.8	5/20/2015	11:20	1.67	[2]2.13	Yes
29-2254	EBF-PZ-07	3.8	5/20/2015	14:50	1.72	[2]2.08	No
29-2255	EBF-PZ-05	6.8	5/20/2015	11:32	1.29	5.51	Yes
29-2256	EBF-PZ-06	13.5	5/20/2015	11:40	2.20	11.30	Yes
29-2257	EBF-PZ-11	7.8	5/20/2015	13:42	3.04	4.76	Yes
29-2258	EBF-PZ-14	5.3	5/20/2015	15:10	1.72	3.58	Yes
29-2259	EBF-PZ-13	22.0	5/20/2015	15:00	2.82	19.18	Yes
29-2260	EBF-PZ-15	16.1	5/21/2015	09:28	2.19	13.91	Yes
29-2260	EBF-PZ-15	16.1	5/21/2015	16:45	2.20	13.90	No
29-2261	EBF-PZ-20	18.7	5/21/2015	11:00	2.86	15.84	Yes
29-2262	EBF-PZ-18	13.1	5/21/2015	11:55	7.40	5.70	Yes
29-2263	EBF-PZ-17	3.4	5/21/2015	11:39	2.48	0.92	Yes
29-2263	EBF-PZ-17	3.4	5/21/2015	18:02	2.39	[3]1.01	No
29-2264	EBF-PZ-19	16.1	5/21/2015	12:57	0.60	15.50	Yes
29-2265	EBF-PZ-16	28.9	5/21/2015	09:40	8.74	20.16	Yes
29-2266	EBF-PZ-10	9.1	5/20/2015	12:53	2.72	6.38	Yes
29-2267	EBF-PZ-12	38.1	5/20/2015	17:35	11.77	26.33	Yes
29-2268	EBF-PZ-34	3.7	5/20/2015	10:06	2.83	[2]0.87	Yes
29-2269	EBF-PZ-33	5.4	5/20/2015	10:24	3.15	[2]2.25	Yes
29-2269	EBF-PZ-33	5.4	5/20/2015	16:06	3.67	[2]1.73	No
29-2270	EBF-PZ-22	1.2	5/20/2015	14:16	0.27	0.93	Yes
29-2271	EBF-PZ-21	13.6	5/20/2015	14:00	3.25	10.35	Yes
29-2272	EBF-PZ-23	38.8	5/20/2015	19:28	8.58	30.22	Yes
29-2273	WLT-1	26.4	5/20/2015	09:28	18.5	7.90	Yes
29-2274	MW8	44.2	5/28/2015	09:39	18.9	25.30	Yes
29-2275	EBF-PZ-41	1.6	5/21/2015	14:04	1.42	0.18	Yes
29-2276	EBF-PZ-35	3.2	5/20/2015	10:45	1.64	[2]1.56	Yes
29-2276	EBF-PZ-35	3.2	5/20/2015	14:25	1.75	[2]1.45	No
29-2277	EBF-PZ-42	2.9	5/20/2015	18:02	2.17	[2]0.73	Yes
29-2277	EBF-PZ-42	2.9	5/21/2015	15:55	1.93	[4]0.97	No
29-2278	EBF-PZ-36	11.1	5/20/2015	12:23	2.69	8.41	Yes
29-2279	EBF-PZ-44	11.0	5/22/2015	12:45	4.77	6.23	Yes
29-2280	EBF-PZ-43	4.2	5/22/2015	11:45	3.60	0.60	Yes

[1]Land-surface elevations for all groundwater sites were interpolated from the statewide 10-foot digital elevation model (DEM) (New Jersey Department of Environmental Protection, 2012).

[2]Water level may have been affected by tide.

[3]Water level may have been affected by recent rainfall.

[4]Water level may have been affected by tide or recent rainfall.

Table 6. Water levels measured at surface-water sites in and near the Edwin B. Forsythe National Wildlife Refuge, New Jersey, spring 2015.

[NAVD 88, North American Vertical Datum of 1988; hh, hours; mm, minutes; time is eastern daylight time]

Site identifier	Site name	Reference point elevation, in feet above NAVD 88[1]	Date of water-level measurement	Time of water-level measurement, hh:mm	Depth to water below reference point, in feet	Elevation of water level, in feet above NAVD 88	Measurement used to produce water-table maps
01408181	Long Causeway Branch near Silverton NJ	15.61	7/8/2015	12:40	6.84	8.77	Yes
01408181	Long Causeway Branch near Silverton NJ	15.61	7/8/2015	12:50	6.84	8.77	No
01408190	Silver Bay tributary near Silverton NJ	17.76	7/8/2015	12:20	7.95	[2]9.81	Yes
01408726	Long Swamp Creek at Lester Rd near Toms River NJ	27.88	7/8/2015	12:00	5.49	22.39	Yes
01408726	Long Swamp Creek at Lester Rd near Toms River NJ	27.88	7/8/2015	13:15	5.50	22.38	No
01408736	Mill Creek near Pine Beach NJ	22.59	5/21/2015	13:35	9.88	12.71	Yes
01408760	Potter Creek at Holly Park NJ	10.44	5/21/2015	13:10	2.75	7.69	Yes
01408760	Potter Creek at Holly Park NJ	10.44	5/21/2015	13:15	2.76	7.68	No
01408940	Cedar Creek tributary near Lanoka Harbor NJ	18.36	5/21/2015	12:39	8.22	10.14	Yes
01408940	Cedar Creek tributary near Lanoka Harbor NJ	18.36	5/21/2015	12:43	8.22	10.14	No
01409107	Waretown Creek at Webbs Mill Road near Waretown NJ	32.27	5/21/2015	10:11	4.55	[3]27.72	Yes
01409107	Waretown Creek at Webbs Mill Road near Waretown NJ	32.27	5/21/2015	17:21	4.59	[3]27.68	No
01409108	Waretown Creek at US Route 9 at Waretown NJ	14.17	5/21/2015	10:19	9.67	[3]4.50	Yes
01409108	Waretown Creek at US Route 9 at Waretown NJ	14.17	5/21/2015	17:10	9.56	[3]4.61	No
01409126	Lochiel Creek at Pebble Beach NJ	19.25	5/20/2015	09:30	9.18	10.07	Yes
01409126	Lochiel Creek at Pebble Beach NJ	19.25	5/21/2015	16:57	9.18	10.07	No
01409136	Gunning River at Route 9 near Barnegat NJ	40.37	5/20/2015	14:56	4.35	36.02	Yes
01409136	Gunning River at Route 9 near Barnegat NJ	40.37	5/20/2015	15:04	4.35	36.02	No
01409137	Gunning River at Lower Shore Road near Barnegat NJ	16.62	5/20/2015	15:13	4.86	11.76	Yes
01409137	Gunning River at Lower Shore Road near Barnegat NJ	16.62	5/20/2015	15:18	4.86	11.76	No
01409143	Manahawkin Creek at Stafford Rd near Manahawkin NJ	14.96	5/20/2015	12:02	0.72	14.24	Yes
01409143	Manahawkin Creek at Stafford Rd near Manahawkin NJ	14.96	5/20/2015	13:02	0.72	14.24	No
01409144	Cedar Ck trib at Hilliard Blvd near Manahawkin NJ	2.16	5/20/2015	13:37	1.41	[2]0.75	Yes
01409144	Cedar Ck trib at Hilliard Blvd near Manahawkin NJ	2.16	5/20/2015	14:10	1.45	[2]0.71	No
01409254	Cedar Run at Route 9 near Mayetta NJ	19.20	5/20/2015	11:11	4.96	14.24	Yes
01409254	Cedar Run at Route 9 near Mayetta NJ	19.20	5/20/2015	14:56	4.96	14.24	No
01409281	Westecunk Creek at Railroad Ave at West Creek NJ	7.17	5/20/2015	10:40	6.58	[2]0.59	Yes
01409281	Westecunk Creek at Railroad Ave at West Creek NJ	7.17	5/20/2015	14:32	6.65	[2]0.52	No
01409284	Parker Run at Parkertown NJ	6.99	5/20/2015	09:35	4.26	2.73	Yes
01409284	Parker Run at Parkertown NJ	6.99	5/20/2015	14:14	4.25	2.74	No
01409314	Willis Creek at Center Street near Tuckerton NJ	20.13	5/20/2015	15:31	7.37	12.76	Yes
01409314	Willis Creek at Center Street near Tuckerton NJ	20.13	5/21/2015	10:46	7.37	12.76	No
01410230	Mattix Run near Smithville NJ	15.45	5/20/2015	14:13	2.50	12.95	Yes
01410230	Mattix Run near Smithville NJ	15.45	5/21/2015	12:53	2.50	12.95	No
01410380	Doughty Creek at Oceanville NJ	16.26	5/20/2015	10:12	9.98	6.28	Yes
01410380	Doughty Creek at Oceanville NJ	16.26	5/20/2015	16:17	9.99	6.27	No
392739074261901	EBFNWR Southwest pool near Oceanville NJ	3.95	5/20/2015	11:26	3.72	0.23	Yes
392739074261901	EBFNWR Southwest pool near Oceanville NJ	3.95	5/21/2015	13:16	3.73	0.22	No

[1]All reference points were surveyed to determine elevation.

[2]Water level may have been affected by tide.

[3]Water level may have been affected by tide or recent rainfall.

elevations available from topographic maps. A comparison of water-table elevations less than 10 feet above sea level was not possible because of a lack of historical data.

In May 2015, depth to water in the Forsythe refuge varied spatially from 0 ft to approximately 58.5 ft below land surface (fig. 6, table 5). Depth to water was 0 ft below land surface at points of groundwater discharge, such as streams, ponds, and wetlands. The depth to water was less than 2 feet below land surface for approximately 86 percent of the refuge, coinciding closely with the percentage of wetland area in the refuge. A histogram showing the distribution of depth to water offers a refuge-wide picture of water-table conditions that support present-day vegetation communities (fig. 7).

Less than 2 percent of the refuge had depth to water in excess of 20 feet. The depth to water generally was greater in areas of higher elevation. Depth to water greater than 40 feet below land surface was limited to two upland areas: one in the upland area adjoining the northwestern corner of the main impoundment (in the southern part of the refuge; fig. 6*B*) and the other in the Mill Creek Basin along the eastern edge of the Garden State Parkway (in the central part of the refuge; fig. 6*A* and 6*B*).

Streamflow

Analyses of streamflow data collected at continuous-record streamgages and partial-record stations provide information on hydrologic processes that are happening in basins predominantly upstream from the refuge. Streamflow measurements at the continuous-record streamgages and partial-record stations take into account hydrologic processes for the entire contributing basin. The percentage of streamflow that is contributed by base flow (groundwater discharge) ranged from 68 to 94 percent at eight streamgages, all within the Mullica-Toms Basin, during 2004–13 (table 7, fig. 3). Base flow accounts for the lowest percentage of streamflow in the North Branch Metedeconk Basin; this is attributed to the high percentage of urban development within the basin (Baker and others, 2014). Impervious surfaces resulting from the presence of structures and pavement, soil compaction, and other urban characteristics increase flashiness and decrease groundwater recharge and base flow in streams (Aichele, 2005). For Toms, Mullica, West Branch Wading, and Oswego Rivers, base flow accounts for between 80 and 90 percent of streamflow. For Cedar Creek, Westecunk Creek, and East Branch Bass River, base flow accounts for more than 90 percent of streamflow, reflecting the low levels of urban development within these basins. The variation in the percentage of base flow as it relates to land use underscores the sensitivity of this resource to urban development.

The sustainability of aquatic ecosystems in this region is dependent on the input of fresh groundwater discharge to streams and wetlands because this input affects water availability and water quality. The high base-flow inputs underscore the importance of groundwater as a source of freshwater that supports the streams that flow into the refuge and the hydroecology of the contributing basins.

Mean annual flow normalized by drainage area is a metric that facilitates comparison of streamflow among basins of different sizes. Mean annual flow at the continuous-record streamgages ranged from 1.2 cubic feet per second per square mile ($(ft^3/s)/mi^2$) to 2.4 $(ft^3/s)/mi^2$ for 2004–13 (table 3). Streamflow values at the Mullica River near Batsto (01409400) were high likely as a result of the input of diverted flows from a nearby tributary, and streamflow values at Oswego River at Harrisville (01410000) were low possibly as a result of groundwater discharging out of the basin (Johnson and Watt, 1996) and into the Oyster Creek Basin (Gordon, 2004). Mean annual flow for the remaining six streamgages ranged from 1.7 $(ft^3/s)/mi^2$ to 2.1 $(ft^3/s)/mi^2$. These values show the variability of streamflow among basins in the study area.

Mean annual flow also was calculated for selected partial-record stations in the Mullica-Toms Basin using MOVE1 (table 8, fig. 3) for the period of record for each station. Mean annual flow at the partial-record stations ranged from 0.2 $(ft^3/s)/mi^2$ to 3.8 $(ft^3/s)/mi^2$. Mean annual flow is notably higher at Oyster Creek near Brookville (01409095) than the other partial-record stations, and mean annual flow is notably lower on the Oswego River near Brookville (01409880) likely because Oyster Creek receives base-flow contributions from the Oswego River Basin (Gordon, 2004; Baker and others, 2014). Mean annual flow is also notably low at Mattix Run near Smithville (01410230). Mean annual flow values for the rest of the partial-record stations analyzed ranged from 1.2 to 2.3 $(ft^3/s)/mi^2$.

Land-Surface-Based Water Budget

Mean annual land-surface-based water budgets, which account for gains and losses of water to and from land and water surfaces, were estimated for nine areas of the Forsythe refuge using data for 2004–13, except for the groundwater recharge component which was estimated using 2000–03 groundwater-flow model results. Values presented in table 9 correspond to the land-surface-based water-budget components, as described for equation 1. To put streamflow during 2004–13 into a long-term hydrologic context, mean annual streamflow for continuous-record streamgages within the Mullica-Toms Basin for 2004–13 was compared to mean annual streamflow for the period of record at each of the streamgages. Streamgages with 7 or more years of data for 2004–13 were evaluated (table 3). Mean annual flow values for 2004–13 ranged from 97 to 108 percent of the mean annual flows for the entire period of record at each of the streamgages, indicating that the period used for this water-budget analysis is representative of long-term average conditions.

For 2004–13, the annual precipitation at Freehold Marlboro meteorological station ranged from a minimum of 40.3 inches per year in 2012 to a maximum of 63.9 inches per year in 2011 with a mean of 48.9 inches per year. The

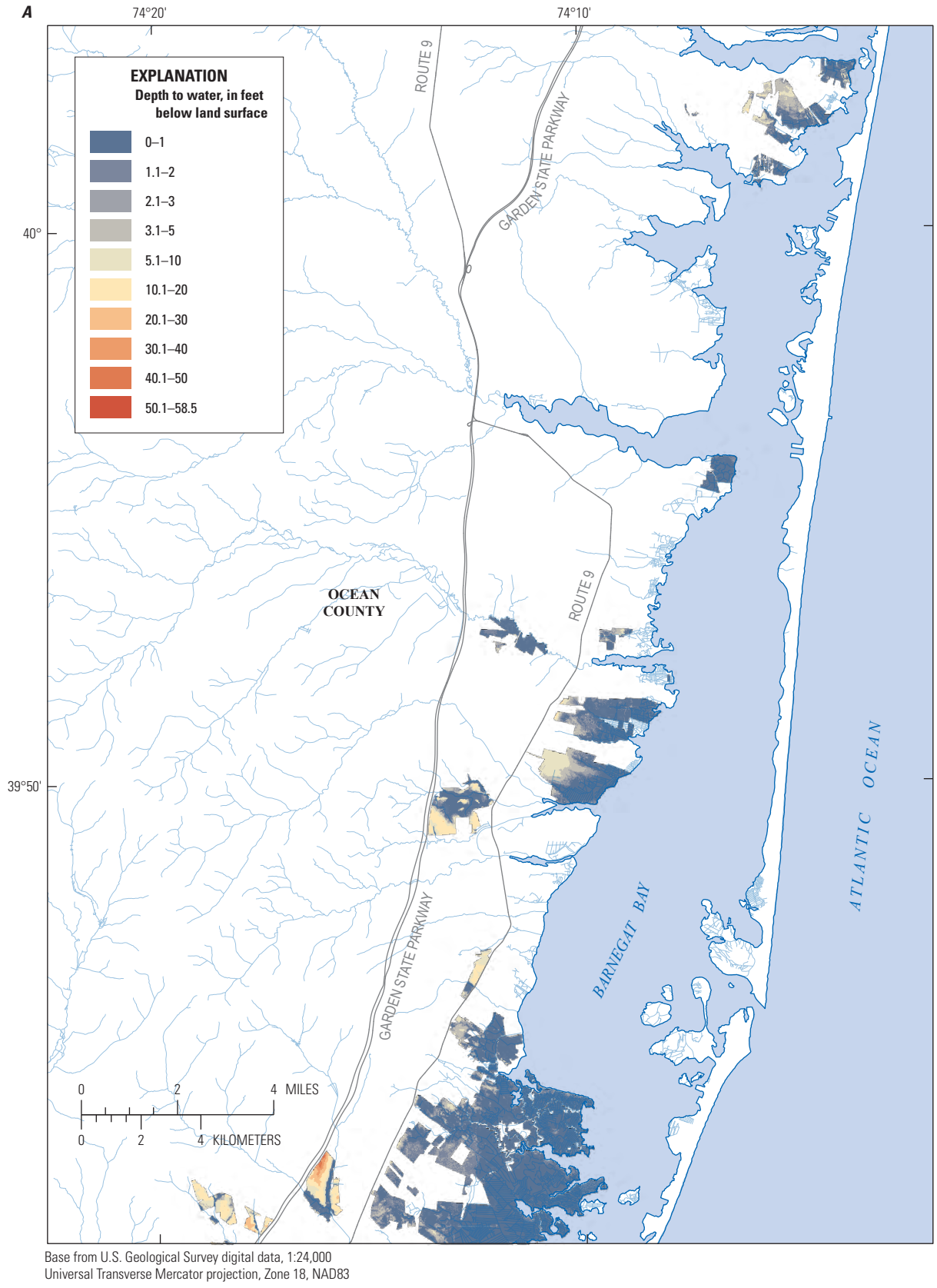
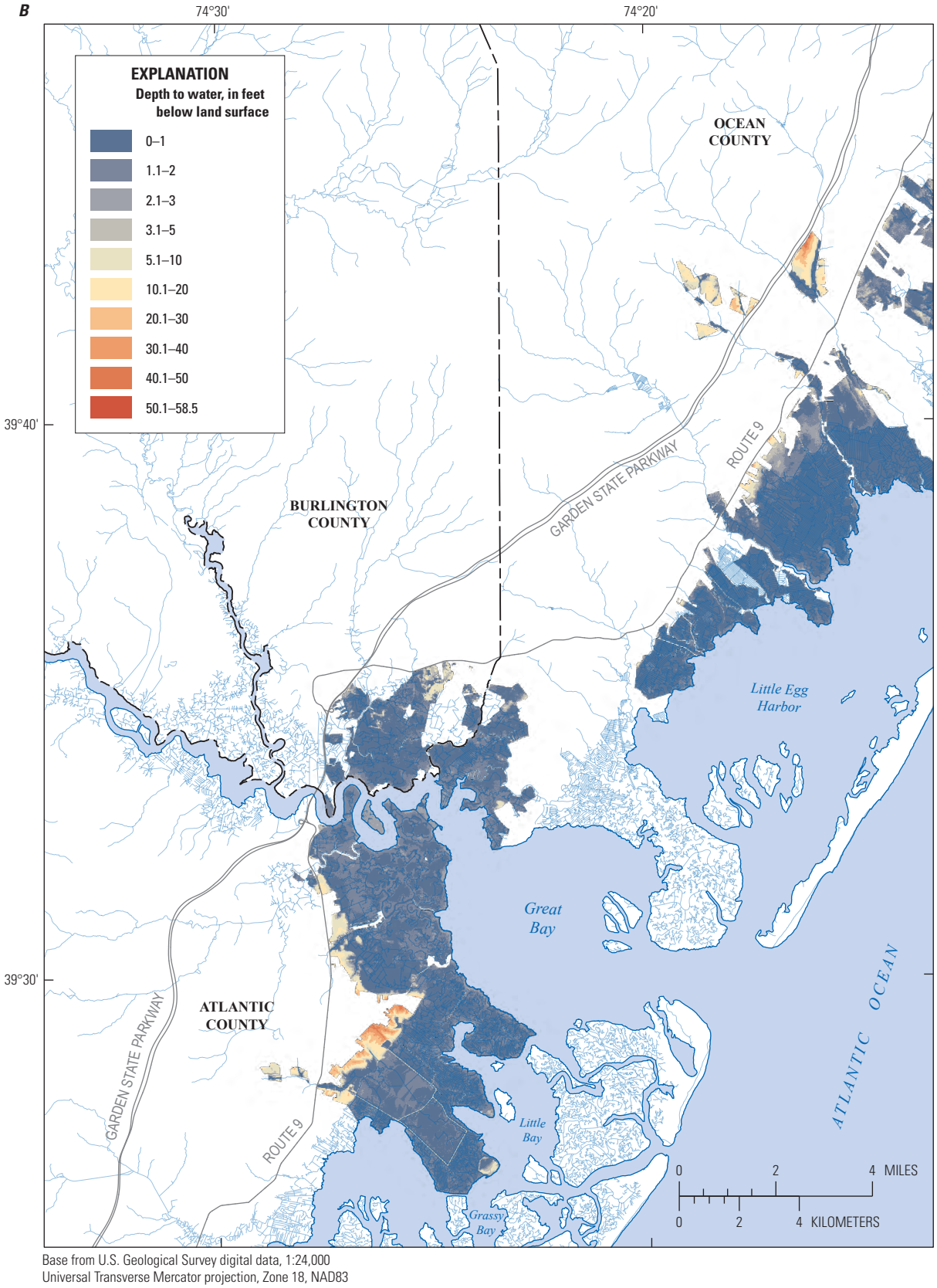


Figure 6. Depth to water in the *A*, northern part and *B*, southern part of the Edwin B. Forsythe National Wildlife Refuge, New Jersey, spring 2015.



Base from U.S. Geological Survey digital data, 1:24,000
Universal Transverse Mercator projection, Zone 18, NAD83

Figure 6. Depth to water in the *A*, northern part and *B*, southern part of the Edwin B. Forsythe National Wildlife Refuge, New Jersey, spring 2015.—Continued

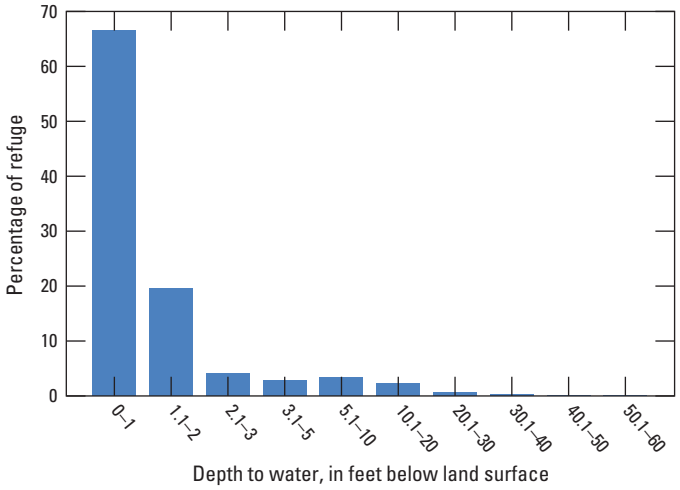


Figure 7. Histogram showing depth to water in relation to percentage of the Edwin B. Forsythe National Wildlife Refuge, New Jersey, spring 2015.

Table 7. Mean annual streamflow, base flow, and runoff for selected continuous-record streamgages in the Mullica-Toms Basin, New Jersey, for 2004–13.

Site identifier	Site name	Streamflow, in inches	Base flow[1], in inches	Runoff[1], in inches	Percent[1] base flow
01408120	North Branch Metedeconk River near Lakewood NJ	25.4	17.3	8.1	68.1
01408500	Toms River near Toms River NJ	24.2	20.3	4.0	83.8
01408900	Cedar Creek at Western Blvd near Lanoka Harbor NJ	25.6	23.3	2.3	91.0
01409280	Westecunk Creek at Stafford Forge NJ	28.6	26.8	1.8	93.6
01409400	Mullica River near Batsto NJ	32.2	28.1	4.1	87.5
01409810	West Branch Wading River near Jenkins NJ	22.9	18.7	4.2	82.0
01410000	Oswego River at Harrisville NJ	15.9	13.3	2.6	84.1
01410150	East Branch Bass River near New Gretna NJ	28.6	26.5	2.1	92.8

[1]Determined by means of hydrograph separation using PART, A Computer Program for Calculating Groundwater Discharge from Streamflow Records (Rutledge, 1998).

Table 8. Mean annual streamflow at selected partial-record stations in the Mullica-Toms Basin, New Jersey, 1965–2015.

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

Site identifier	Site name	Drainage area, in square miles	Period of measurement	Mean annual streamflow[1]		Average number of [2] measurements used in MOVE1 analysis
				ft^3/s	ft^3/s per square mile	
01408123	North Branch Metedeconk River near Laurelton NJ	38.6	10/28/2002–10/11/2007	65.2	1.7	8.7
01408150	South Branch Metedeconk River near Lakewood NJ	27.5	11/29/1965–7/21/2015	57.7	2.1	55
01408151	SB Metedeconk R at New Hampshire Av nr Lakewood NJ	29.5	6/24/2011–9/10/2014	67.4	2.3	15.9
01409088	Brookville Creek at Brookville NJ	0.5	6/25/1998–4/7/2010	0.7	1.4	15.4
01409095	Oyster Creek near Brookville NJ	7.43	8/10/1960–9/8/2014	27.9	3.8	42.9
01409108	Waretown Creek at US Route 9 at Waretown NJ	2.98	11/18/2002–7/12/2012	3.7	1.3	26.6
01409210	Mill Ck at Manahawkin NJ	20.4	6/6/2011–9/9/2014	40.4	2.0	26.9
01409281	Westecunk Creek at Railroad Ave at West Creek NJ	20.4	3/11/2010–6/26/2013	43.1	2.1	46.2
01409305	Mill Branch at Nugentown Road at Tuckerton NJ	9.86	11/7/2002–7/12/2012	12.8	1.3	27.7
01409880	Oswego River near Brookville NJ	16.4	6/16/2005–7/12/2012	3.3	0.2	19
01410215	Clarks Mill Stream at Port Republic NJ	8.61	9/17/1986–9/12/2006	12.4	1.4	14.7
01410225	Morses Mill Stream at Port Republic NJ	8.25	9/17/1986–10/2/2007	9.8	1.2	42.8
01410230	Mattix Run near Smithville NJ	5.33	11/21/2002–12/16/2010	2.7	0.5	26.3

[1]Determined using Maintenance of Variance Extension, Type 1 (MOVE1) (Helsel and Hirsch, 2002).

[2]Average number of measurements used to develop the MOVE1 correlations with each of the six index stations (01408120, 01408500, 01408900, 01409280, 01410000, 01410150).

Table 9. Summary of mean annual land-surface-based water budgets for areas of the Edwin B. Forsythe National Wildlife Refuge, New Jersey, 2004–13.

[Water-budget areas shown in figure 4. Flow data are in inches per year. --, not applicable or data unavailable]

Water-budget area identifier	Water-budget area, in square miles	Precipitation (P)	Groundwater recharge (R_g)	Evapotranspiration (ET)	Direct runoff (Q_{dr})	Associated salt marsh management units
1	1.38	48.2	2.8	35.6	9.8	Reedy Creek, Kettle Creek, Metedeconk River
2	3.20	47.7	5.3	35.0	7.4	Forked River, Good Luck Point, Ocean Gate, Stouts Creek
3	0.93	47.6	12.4	31.6	3.6	--
4	11.42	47.3	0.3	37.0	10.0	ATT[1], Barnegat
5	0.67	47.3	14.4	28.7	4.2	--
6	0.61	47.2	18.9	25.8	2.5	--
7	13.35	47.1	0.9	36.9	9.3	Little Egg South, Cedar Run, West Creek
8	14.89	46.9	2.9	36.9	7.1	Oyster Creek, Nacote Creek Motts Creek, Motts Mullica Wilderness, Bass River-Ballanger, Nacote Creek West
9	9.72	46.7	1.8	35.7	9.2	Reeds Bay Hammock Cove

[1]AT&T Corporation.

annual precipitation at Atlantic City and Atlantic City International Airport stations ranged from a minimum of 39.5 and 39.1 inches per year, respectively, in 2004 to a maximum of 64.6 and 61.6 inches per year, respectively, in 2009. The average of the mean annual precipitation at the two Atlantic City stations is 46.5 inches per year. This north–south variation in precipitation is consistent with that reported for Ocean County by Cauller and others (2016) and that reported for the State by Watson and others (2005).

Using linear interpolation between the value for the station in the north, and the average of the values for the two stations in the south, mean annual precipitation varied from approximately 48.2 inches per year in the northern part of the refuge to approximately 46.7 inches per year in the southern part of the refuge during 2004–13 (table 9, fig. 8).

Groundwater recharge from the land surface to the surficial aquifer system as estimated from previously developed groundwater-flow models, ranged from 0.3 to 18.9 inches per year (table 9). Groundwater recharge rates of 14.4 and 18.9 inches per year were greatest in the upland-dominated areas (water-budget areas 5 and 6, respectively) (fig. 4), equivalent to 30 and 40 percent of precipitation, respectively. Groundwater recharge rates for the upland areas are fairly consistent with rates determined for the regional surficial aquifer studies, which ranged from 15 to 19.4 inches (Watt and others, 1994; Johnson and Watt, 1996; Gordon, 2004). The higher recharge rates of the upland-dominated areas result from a combination of factors, including highly permeable sandy soils that allow for greater infiltration, a greater depth to water, and less water lost to evapotranspiration.

Groundwater recharge rates were nearly zero in the central coastal wetland-dominated water-budget areas 4 and 7. Groundwater recharge rates were lowest in these areas because they are primarily groundwater discharge zones, the water table is near land surface, and the subsurface is close to saturation and cannot accept much recharge. In addition, much of the coastal wetlands are underlain by thick marsh deposits, which likely have low permeability. In other coastal areas, groundwater recharge rates computed from model output ranged from 1.8 to 5.3 inches per year, equivalent to

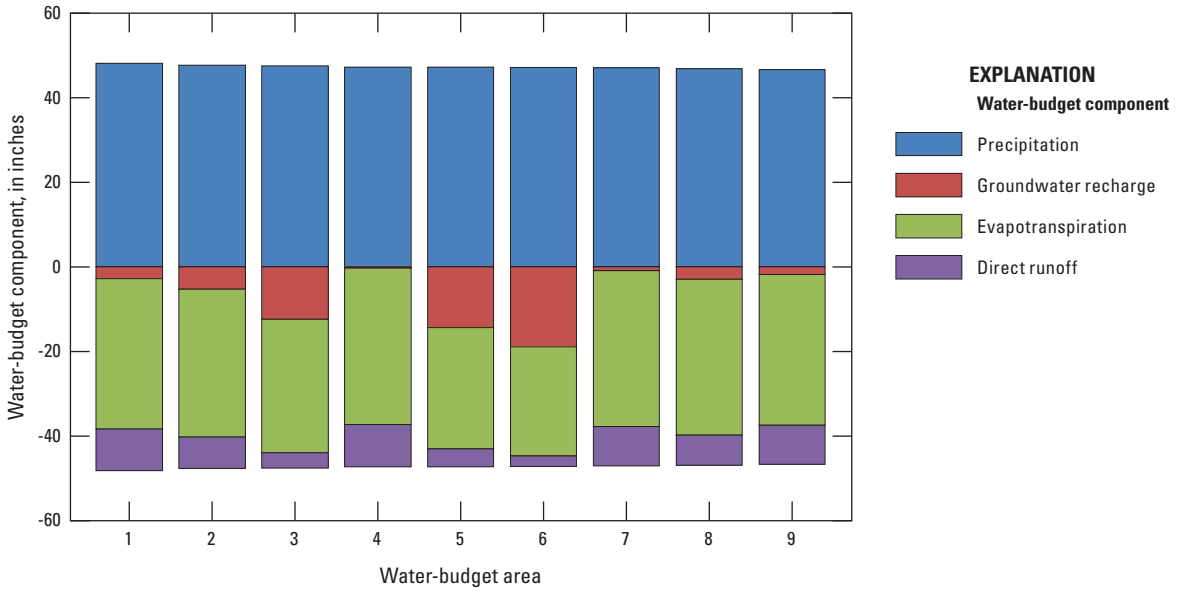


Figure 8. Components of the mean annual water budget for selected areas of the Edwin B. Forsythe National Wildlife Refuge, New Jersey, 2004–13.

4 to 11 percent of precipitation with variations attributed to differences in the percentage of wetlands and differences in assumptions made as part of the models.

Mean annual ET (ET_o, determined by using the Penman-Monteith equation) was estimated to be 37.3 inches per year at meteorological station OCVN4 for 2005–13 (table 10; fig. 3); this value is the estimated lowland ET rate. The high ET rate at this station may be explained by the shallow water table, primarily wetland surroundings, and generally greater exposure to wind along the coast. In comparison, mean annual PET at the same station was estimated to be 29.5 inches per year for 2005–13 using the Thornthwaite equation. The Penman-Monteith equation is likely more representative of actual ET conditions on the refuge than the Thornthwaite equation, given that the former can account for the refuge-unique variables of wind speed, relative humidity, and solar radiation, in addition to temperature. For this study, the ratio between upland and lowland ET rates is assumed to be the same as that measured during the Pinelands study (Walker and others, 2011). The estimated upland ET rate (24.6 inches per year) is 0.66 of the estimated lowland ET rate. As discussed in the "Methods of Investigation" section, these rates were then prorated for the corresponding land uses to estimate the mean annual ET rate for each water-budget area.

Mean annual ET rates varied from approximately 25.8 to 37.0 inches per year, depending on location (table 9). The lowest ET rates (25.8–28.7 in.) occurred in the upland-dominated water budget areas 5 and 6. ET rates were consistently greater along the coast, particularly in the central and southern parts of the refuge, owing to the high percentage of wetlands in these areas. Overall, ET was equivalent to 55–79 percent of mean annual precipitation, indicating that it is a major factor affecting freshwater availability for the Forsythe refuge.

Table 10. Mean annual evapotranspiration estimated using two methods for selected meteorological stations in and near the Edwin B. Forsythe National Wildlife Refuge, New Jersey, 2005–13 and 2012–15.

[All values are in inches per year. --, no data; ET_o, reference evapotranspiration; PET, potential evapotranspiration]

Method	2005–2013	2012–2015
Meteorological station: OCVN4		
Penman-Monteith, ET_o	37.3	36.4
Thornthwaite, PET	29.5	29.3
Meteorological station: D1653		
Penman-Monteith, ET_o	--	30.8
Thornthwaite, PET	--	29.6

For further comparison, mean annual ET (ET_o, determined by using the Penman-Monteith equation) for 2012–15 was estimated to be 36.4 and 30.8 inches per year at the OCVN4 and D1653 meteorological stations, respectively, whereas PET (Thornthwaite equation) was estimated to be 29.3 and 29.6 inches per year (table 10; fig. 3). These results indicate that the Penman-Monteith equation shows differences in ET rates among geographic regions that would otherwise be masked by the Thornthwaite method. Further study is needed

to determine the cause of the difference between the Penman-Monteith ET estimates in the north and the south of the study area, but possibilities include differences in the effects of surrounding land use (there is more urban development near the northern station, D1653) and depth to water.

Direct runoff ranged from 2.5 to 4.2 inches per year in the primarily upland areas of the refuge (water-budget areas 5 and 6), and from 7.1 to 10 inches per year in the primarily coastal wetland areas (table 9; fig. 4). Direct runoff rates in the uplands are comparable to direct runoff rates estimated using hydrograph separation of the continuous streamgage data. Direct runoff estimates for most streamgages within the Mullica-Toms Basin range from 1.8 to 4.2 inches per year (table 7), with the exception of the North Branch Metedeconk River which receives a higher contribution from direct runoff (8.1 inches per year) because that basin is highly urbanized.

Estimated direct runoff rates in the coastal wetlands are higher than in the uplands because the coastal wetlands are primarily groundwater discharge areas and the water table is near land surface. Infiltrating water quickly saturates the subsurface. Water that is not lost through evapotranspiration or infiltration flows into streams and neighboring bays as direct runoff. For this study, direct runoff was calculated as the residual of the water-budget equation, and therefore, it includes the net error of the other water-budget terms.

Groundwater-Flow Components

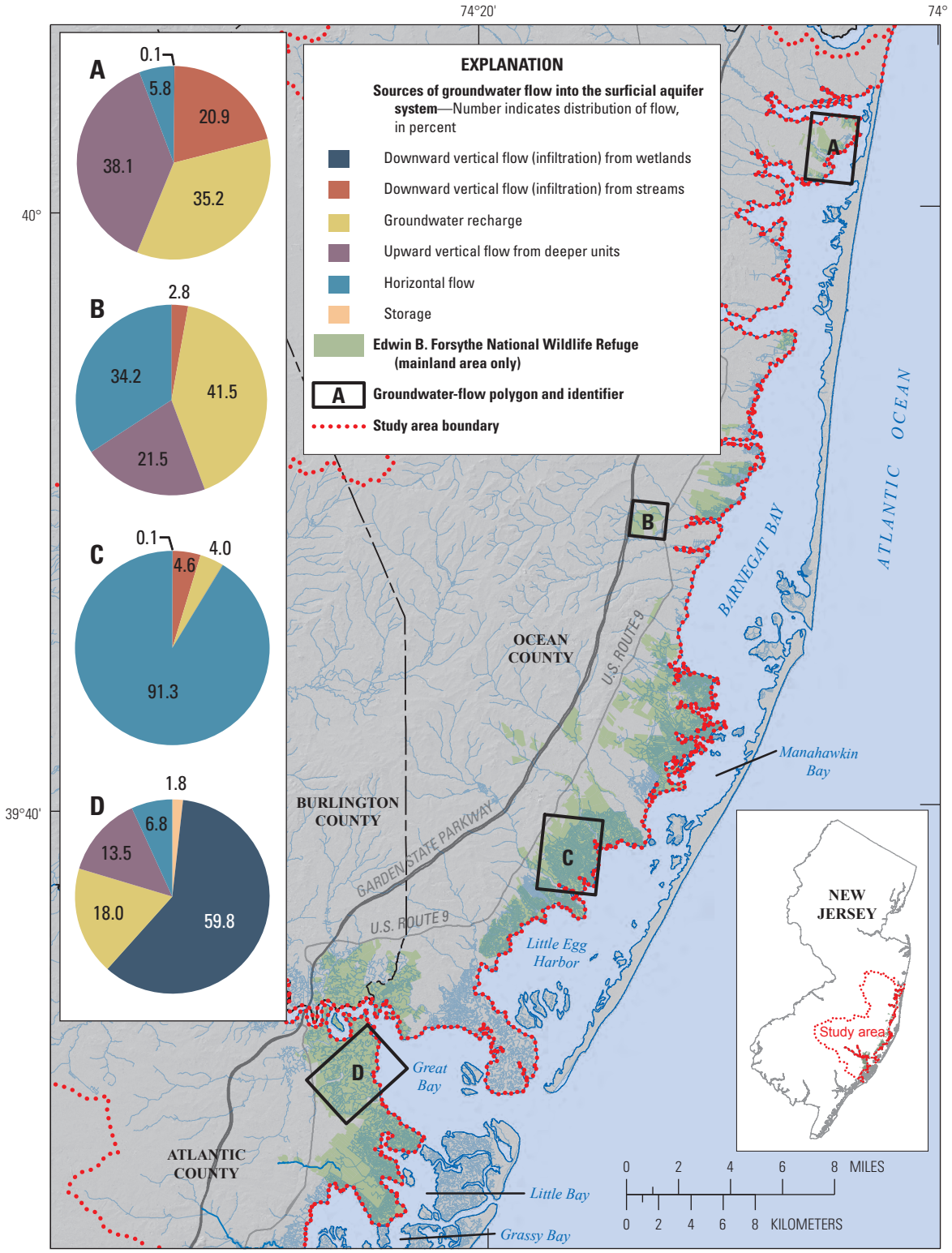
In addition to hydrologic processes described by the land-surface-based water-budget equation, an analysis of some of the major components of the groundwater-flow system offers additional information to further describe the hydrologic system supporting the ecosystems of the refuge. Output from the Ocean County and Great Egg Harbor–Mullica groundwater-flow models (Cauller and others, 2016; Pope and others, 2012) illustrates the relative contributions of groundwater flows to and from the unconfined Kirkwood-Cohansey aquifer system (the surficial aquifer system). As mentioned previously, groundwater flows were computed for model cells for 14 distinct refuge areas. Examples of the distribution of all vertical and horizontal groundwater flows entering and exiting the surficial aquifer system underlying the Forsythe refuge are presented for four representative regions of the refuge in figures 9 and 10. Estimates of the groundwater contributions to, and losses from, wetlands and streams within each of the nine water-budget areas of the refuge are presented in table 11.

The main source of groundwater flow entering the surficial aquifer system varies depending on location (fig. 9). For example, in the upland-dominated area B of the refuge (fig. 9) 42 percent of water infiltrates the unconfined Kirkwood-Cohansey aquifer system from the land surface as groundwater recharge. In general, groundwater moves along flow paths of varying lengths from areas of groundwater recharge to areas of discharge (Winter and others, 1998). For the refuge, groundwater recharge in area B and other upland areas moves downgradient through the shallow subsurface toward the coast primarily as near-horizontal flow along the flow paths illustrated in plates 1 and 2.

In the central coastal area C of the refuge, horizontal flow contributes more than 90 percent of the groundwater flow to the surficial aquifer system (fig. 9). Some of the horizontal flow to area C and other areas is transported along local flow paths (short, shallow flow paths that originate from groundwater recharge in nearby upland areas), whereas some of it is transported along regional flow paths (longer, deeper flow paths that originate farther inland and near major basin divides to the northwest of the refuge).

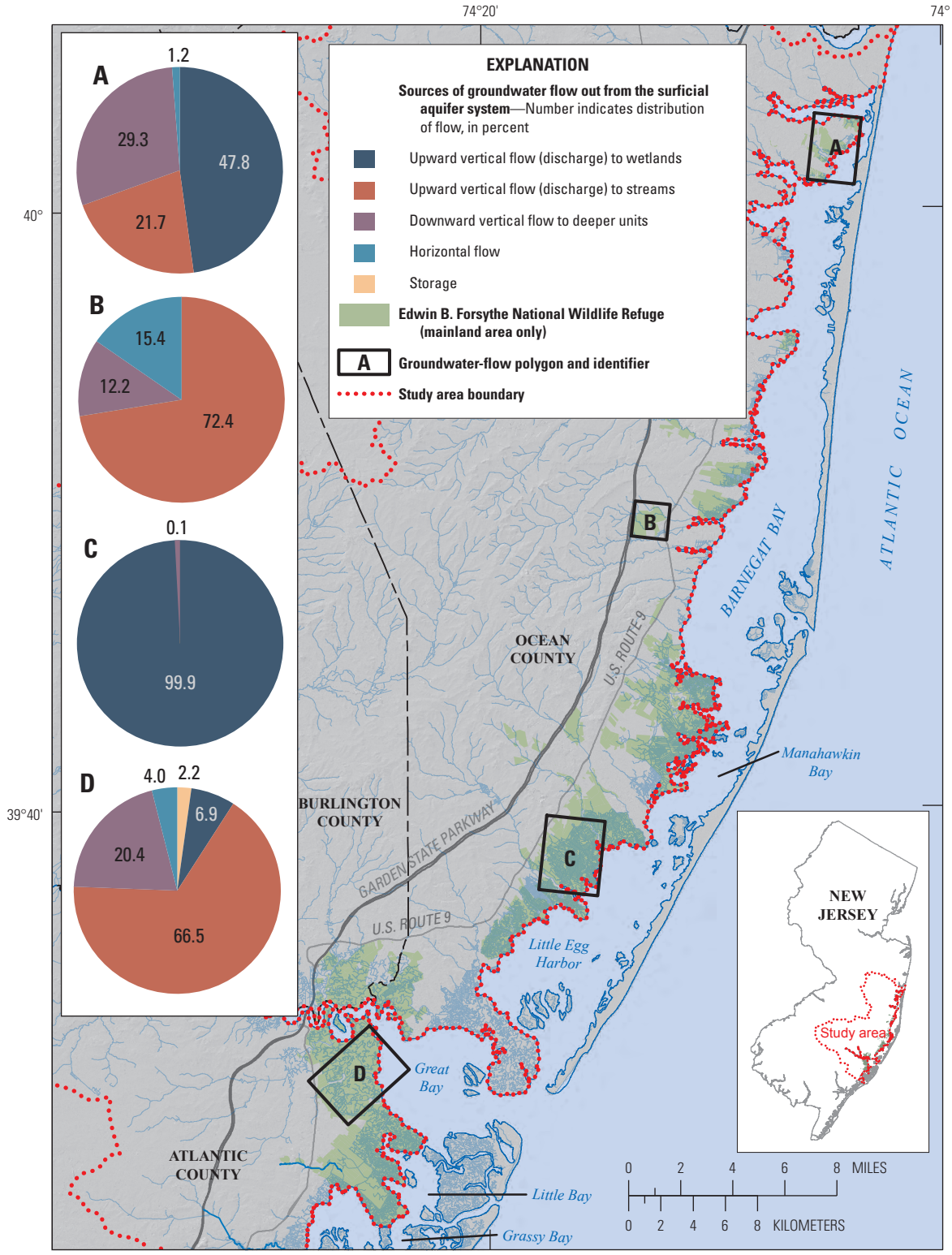
In northern and southern coastal areas A and D (fig. 9), downward flow, or infiltration, from streams or wetlands to the surficial aquifer system is a larger percentage of flow (21–60 percent) than for other areas of the refuge. This may be attributed to downward flow to regional cones of depression brought on by water withdrawals in the underlying confined aquifers—the Atlantic City 800-foot sand and the Piney Point aquifer (Cauller and others, 2016; Pope and others, 2012). A cone of depression (a region of lower hydraulic head shaped like an inverted cone) forms in the aquifer around a pumped well as drawdown of the hydraulic head occurs. Lower hydraulic head surrounding the cone of depression results in more flow to deeper confined aquifers and, consequently, less upward flow and discharge to streams and wetlands. The regional cones of depression in the Atlantic City 800-foot sand (mostly in the south) and the Piney Point aquifer (mostly in the north) extend throughout much of the confined aquifers underlying the Forsythe study area. Groundwater withdrawals will be further discussed at the end of this section.

Nearly all of the groundwater exiting the surficial aquifer system from central coastal area C of the refuge is discharged to wetlands (fig. 10), which highlights the importance of fresh groundwater discharge in supporting the ecosystems of the Forsythe refuge. Groundwater that was transported downgradient toward the coast primarily as horizontal flow exits the surficial aquifer system primarily as discharge to coastal streams and wetlands. In the northern and central coastal areas A and C (fig. 10), groundwater flow out of the surficial aquifer system is dominated (48–100 percent) by upward vertical flow (or discharge) to wetlands. In the upland and southern coastal areas B and D (fig. 10), groundwater flow is dominated (67–73 percent) by upward vertical flow (or discharge) to streams. The reason that groundwater discharges to wetlands in the central and northern coastal areas but to streams in the southern coastal areas may be differences in local and basin-wide hydrogeologic characteristics (such as the presence or absence of clay layers) and differences in model design for the two regions. Some groundwater exits the surficial aquifer system as vertical flow downward to deeper units of the aquifer system. This downward flow is evident to a greater degree in the northern and southern coastal areas of the refuge (fig. 10 areas, A and D), likely a result of downward flow to regional cones of depression in the underlying confined aquifers.



Base from U.S. Geological Survey digital data, 1:24,000
Universal Transverse Mercator projection, Zone 18, NAD83

Figure 9. Percentage of flows into the surficial aquifer system for selected areas of the Edwin B. Forsythe National Wildlife Refuge, New Jersey, 2000–03.



Base from U.S. Geological Survey digital data, 1:24,000
Universal Transverse Mercator projection, Zone 18, NAD83

Figure 10. Percentage of flows out of the surficial aquifer system for selected areas of the Edwin B. Forsythe National Wildlife Refuge, New Jersey, 2000–03.

Estimates for the rates of selected groundwater-flow components, as computed from calibrated groundwater-flow models (Cauller and others, 2016; Pope and others, 2012), are provided in table 11 for the nine water-budget areas shown in figure 4. Groundwater discharge to streams and wetlands ranged from 0 to more than 30 inches per year, depending on water-budget area. The greatest rates of groundwater discharge occurred in the central water-budget areas 4 and 7, which are predominantly coastal wetlands, indicating that these are major groundwater discharge zones. Water-budget area 3 also exhibits high groundwater discharge, even though it is inland. In contrast, groundwater discharge was smallest in the primarily upland water-budget areas 5 and 6.

Downward flow, or infiltration, from streams and wetlands to the underlying surficial aquifer ranged from 0.3 to 11.0 inches per year (table 11). Rates of groundwater infiltration from streams and wetlands were greatest in the upland-dominated water-budget areas 5 and 6. Rates of groundwater infiltration from streams and wetlands were greater in the southern coastal water-budget areas 8 and 9 than in the central coastal water-budget areas 4 and 7, possibly because of differences in model design or the effects of a nearby cone of depression.

Groundwater withdrawals could affect the flow of fresh groundwater to the Forsythe refuge. Groundwater withdrawals were accounted for in the output from the groundwater-flow models. Groundwater withdrawals for the Ocean County and vicinity model area for 2000–03 were used primarily for public drinking-water supply and industrial uses; most public-supply withdrawals occurred in the northern part of Ocean County (Cauller and others, 2016). Withdrawals in the Great Egg Harbor and Mullica River basins for 1998–2005 were used primarily for public supply and seasonal irrigation; most public-supply withdrawals in the vicinity of the refuge occurred near Pleasantville (Pope and others, 2012). Distribution of withdrawal wells by water-use category and aquifer are detailed in the two groundwater-flow model reports (Cauller and others, 2016; Pope and others, 2012).

Groundwater withdrawals in the Piney Point and Atlantic City 800-foot sand aquifers produce large regional cones of depression that induce flow downward from the overlying Kirkwood-Cohansey aquifer system which could decrease flow to streams and wetlands or induce infiltration from streams and wetlands into the aquifer. Additionally, withdrawals from the Kirkwood-Cohansey aquifer system could affect freshwater flow to the refuge. The effect of these withdrawals could be important to vegetation within the refuge that relies on fresh groundwater discharge.

Table 11. Summary of selected groundwater-flow components for water-budget areas of the Edwin B. Forsythe National Wildlife Refuge, New Jersey, 2004–13.

[Water-budget areas shown in figure 4. Flow data are in inches per year]

Water-budget area identifier	Groundwater discharge to wetlands and streams	Groundwater infiltration from wetlands and streams	Groundwater recharge (R_g)
1	5.6	1.7	2.8
2	7.0	0.3	5.3
3	21.6	0.8	12.4
4	31.8	2.8	0.3
5	4.5	10.5	14.4
6	0.0	11.0	18.9
7	22.6	1.3	0.9
8	9.3	5.3	2.9
9	8.6	6.6	1.8

Summary and Conclusions

The Edwin B. Forsythe National Wildlife Refuge (hereafter Forsythe refuge or the refuge) is one of more than 550 national wildlife refuges managed by the U.S. Fish and Wildlife Service. The refuge encompasses more than 47,000 acres, extends for more than 50 miles along the New Jersey coast, and provides critical tidal wetland and shallow bay habitat for numerous bird and wildlife species. Sustainability of the refuge's ecosystems is threatened by pressures from sea-level rise, coastal storms, and development.

On October 29, 2012, Hurricane Sandy made landfall near Brigantine, N.J., with the eye of the storm passing directly over the refuge. This study was conducted by the U.S. Geological Survey in cooperation with the U.S. Fish and Wildlife Service; it was funded with supplemental funds in support of recovery and restoration projects for areas affected by Hurricane Sandy. The purpose of this study was to improve the understanding of the hydrologic system and processes that support the ecological resources of the Edwin B. Forsythe National Wildlife Refuge to inform decisions regarding management of the refuge as it relates to habitat restoration and climate change.

This report documents the methods used to conduct a water-level synoptic study at groundwater and surface-water sites throughout the Forsythe refuge during spring 2015 and the methods used to construct water-table maps based on water-level data collected in the field and digital elevation data. In May 2015, the water-table elevation in the refuge ranged from sea level in low-lying areas near the coast to approximately 65 feet above sea level. For most of the refuge, the water-table elevation was within 3 feet of sea level. The direction of shallow groundwater flow at the regional scale is generally from west to east (much of it from the northwest to the southeast), and groundwater moves downgradient from the uplands toward major groundwater discharge areas consisting of coastal streams and wetlands.

The steepest horizontal gradient within refuge boundaries occurs in the southern part of the refuge, leading into the main impoundment and adjacent marshlands, where the water-table elevation declines 9 feet (ft) over a distance of approximately 0.25 mile. Beyond the refuge proper, the steepest horizontal gradient occurs in the area leading into the central part of the refuge near Barnegat Township, where the water-table elevation declines from 65 ft above sea level to 1 ft above sea level over the course of 1.5–2 miles. Areas of steep horizontal gradients indicate areas where the flow of groundwater through the shallow subsurface from the upland areas toward the coastal wetlands is likely greater. The lowest horizontal gradients occur in the marshlands in the central and southern parts of the refuge, which are areas of low topographic relief and are underlain by thick marsh deposits. In May 2015, depth to water in the Forsythe refuge varied spatially from 0 ft to approximately 58.5 ft below land surface. Depth to water was less than 2 feet below land surface for approximately 86 percent of the refuge, coinciding closely with the percentage of wetland area in the refuge.

Hydrograph separation of streamflow was performed to estimate the relative contribution of base flow and direct runoff at each of the continuous-record streamgages in the Mullica-Toms Basin. For most streams, base flow (groundwater discharge) accounted for more than 80 percent of the annual streamflow during 2004–13, underscoring the importance of groundwater as a source of freshwater that supports the streams that flow into the refuge and the hydroecology of the contributing basins. Base flow accounted for a substantially lower fraction of flow at the North Branch Metedeconk River streamgage than at the other streamgages, which is attributed to a high degree of urban development within the basin.

Mean annual water budgets were developed for 2004–13 for nine areas of the refuge by using a land-surface-based water-budget equation that incorporated estimates for precipitation, evapotranspiration, groundwater recharge, and direct runoff. Mean annual precipitation varied from approximately 48.2 inches per year in the northern part of the refuge to approximately 46.7 inches per year in the southern part of the refuge. In the upland areas, estimated groundwater recharge ranged from 14.4 to 18.9 inches per year, equivalent to 30–40 percent of precipitation. Groundwater recharge ranged from 0.3 to 5.3 inches per year along the coast (equivalent to as much as 11 percent of precipitation) with minimal recharge occurring in the central coastal areas of the refuge. Mean annual evapotranspiration (ET) rates varied from approximately 25.8 to 37.0 inches per year with the higher rates occurring in coastal areas in the central and southern parts of the refuge, owing to the high percentage of wetlands in these areas. ET was equivalent to 55–79 percent of mean annual precipitation, indicating that it is a major component of the hydrodynamics of the Forsythe refuge. Because of a lack of measured streamflow data in the coastal regions, direct runoff was calculated as the residual term of the water-budget equation. Direct runoff ranged from 2.5 to 4.2 inches per year in the upland areas of the refuge and from 7.1 to 10 inches per year in the coastal wetland areas. Estimated direct runoff rates for the coastal wetlands are higher than those for the uplands because the coastal wetlands are primarily groundwater discharge areas and the water table is near land surface. Infiltrating water quickly saturates the subsurface. Water that is not lost through evapotranspiration or infiltration flows into streams and neighboring bays as direct runoff.

This study identifies groundwater as a major contributor to the freshwater dynamics of the refuge, as evidenced by hydrograph separation analyses, groundwater-flow model output interpretation, and interpreted flow direction. The analyses presented in this report point to the need to protect the aquifer system from potential anthropogenic stressors, such as unsustainable water use and water-quality contamination upstream because either of these may affect groundwater discharge and surface-water flows into the refuge.

This study serves as a baseline assessment of the freshwater resources and processes at play in the Forsythe refuge.

Future hydrologic conditions have known variability related to factors including sea-level rise, precipitation, air temperature, and water use. Evaluating scenarios of sea-level rise could provide information about the effects of sea-level rise on the groundwater-flow system underlying the refuge. Evaluating scenarios of future changes in climatic variables and water use to predict changes in water availability for the refuge could be used to support habitat management plans.

Results presented in this report offer a reference for studies of other aspects of the refuge; for example, depth-to-water information may be related to vegetation in the refuge and therefore may be useful in habitat restoration efforts. Results of the water-level synoptic measurements and interpreted contours are useful for constructing and calibrating a groundwater-flow and salinity model to simulate effects of sea-level rise on the Forsythe refuge. Results of the water-budget analysis provide information about the dominant water resources and how they vary throughout the refuge, which also can be used as a reference for future restoration efforts.

A limitation of the study design in terms of the water-level synoptic study is that it was based on a one-time measurement of water levels within the refuge. The inclusion of continuous water-level data in future monitoring efforts within the refuge would improve understanding of seasonal and interannual water-level fluctuations, provide details about the magnitude and extent of tidal effects, and be useful in monitoring the success of restoration projects. Additionally, collection of evapotranspiration data specifically in the salt marsh could be useful in reducing uncertainty and further refining the water-budget estimates for the refuge.

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Publishing support provided by the West Trenton Publishing Service Center



ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20175088