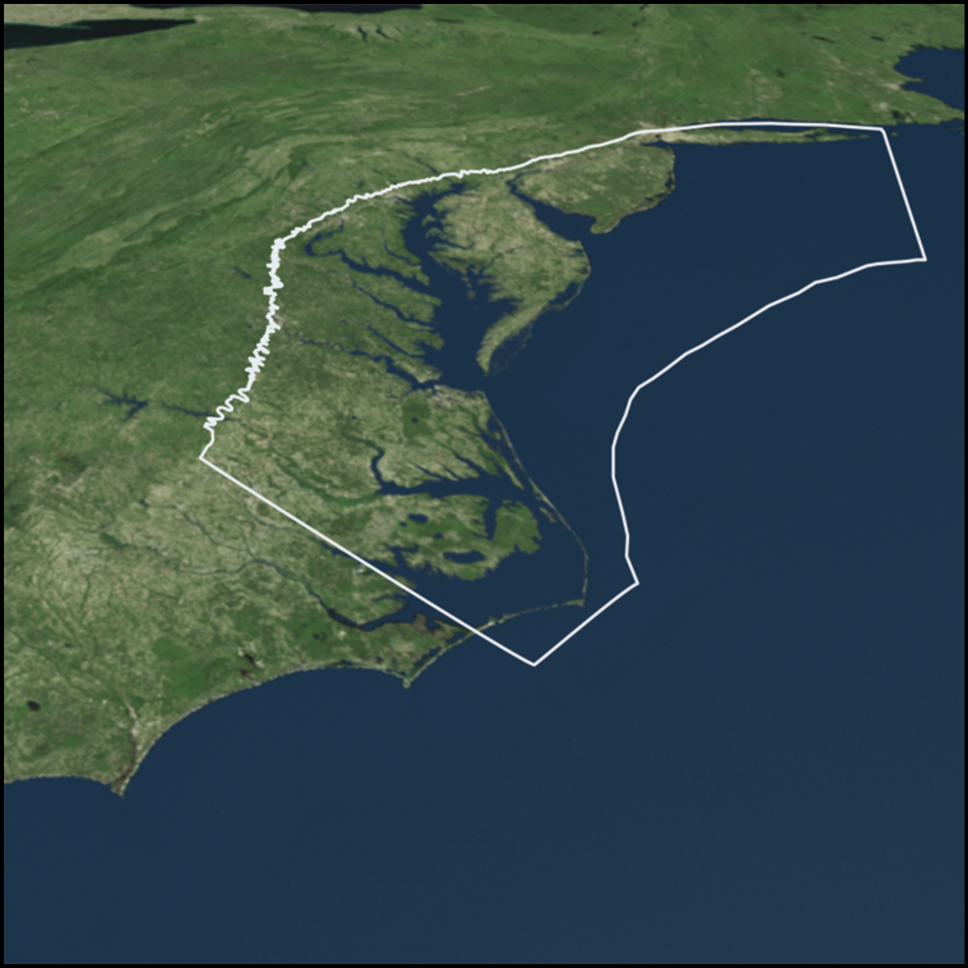
Groundwater Resources Program

Hydrogeology and Hydrologic Conditions of the Northern Atlantic Coastal Plain Aquifer System From Long Island, New York, to North Carolina



Scientific Investigations Report 2013–5133

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U.S. Department of the Interior
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Front cover art. Modified animation-frame from National Aeronautics and Space Administration (NASA) Goddard Space Flight Center, Scientific Visualization Studio, accessed July 24, 2013, at http://svs.gsfc.nasa.gov/vis/a000000/a003400/a003472/. White boundary outlines study area.
Back cover art. Lansat 7 mosaic of Chesapeake Bay region, from NASA Goddard Space Flight Center, Scientific Visualization Studio, accessed July 24, 2013, from http://svs.gsfc.nasa.gov/vis/a000000/a003400/a003473/.

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Conversion Factors and Datum

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

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) and the North American Vertical Datum of 1988 (NAVD 88).

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

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

Abbreviations

ASCII	American Standard Code for Information Interchange
NACP	Northern Atlantic Coastal Plain
NAD 83	North American Datum of 1983
NGVD 29	National Geodetic Vertical Datum of 1929
NAVD 88	North American Vertical Datum of 1988
NHDPlus	National Hydrography Dataset Plus
RASA	Regional Aquifer Systems Analysis
SWB	Soil-water balance
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

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Abstract

The seaward-dipping sedimentary wedge that underlies the Northern Atlantic Coastal Plain forms a complex groundwater system. This major source of water provides for public and domestic supply and serves as a vital source of freshwater for industrial and agricultural uses throughout the region. Population increases and land-use and climate changes, however, have led to competing demands for water. The regional response of the aquifer system to these stresses poses regional challenges for water-resources management at the State level because hydrologic effects often extend beyond State boundaries. In response to these challenges, the U.S. Geological Survey Groundwater Resources Program began a regional assessment of the groundwater availability of the Northern Atlantic Coastal Plain aquifer system in 2010.

The initial phase of this investigation included a refinement of the hydrogeologic framework and an updated hydrologic budget of this aquifer system from the last regional aquifer system assessment completed by the U.S. Geological Survey in the 1980s. Refinements to the hydrogeologic framework include revision of the regional aquifer names to be more consistent with local names in New York, New Jersey, Delaware, Maryland, and Virginia, the primary States included in the study area. Other revisions to the framework include characterization of the aquifers of the regional Potomac aquifer system. The regional Potomac aquifer system is subdivided for this report into two regional aquifers. These aquifers include the single Potomac aquifer in Virginia and two aquifers in Maryland, Delaware, and New Jersey, where the Potomac aquifer system thickens within the Salisbury Embayment. The two regional aquifers making up the Potomac aquifer system include the Potomac-Patapsco aquifer and the underlying Potomac-Patuxent aquifer.

The Potomac-Patuxent aquifer includes the Lower Potomac-Raritan-Magothy aquifer in southern New Jersey and the Patuxent aquifers in Delaware and Maryland. In northern New Jersey and on Long Island, New York, the Potomac-Patuxent aquifer is absent, but the Late Cretaceous fluvial-deltaic aquifer that is laterally equivalent with the upper part of the Potomac Formation now is considered part of the regional Potomac-Patapsco aquifer. This aquifer includes the Middle Potomac-Raritan-Magothy aquifer in New Jersey and the Lloyd aquifer on Long Island.

The name “Upper Potomac aquifer” has been removed as part of this regional framework revision. The local aquifer previously considered part of the Upper Potomac aquifer now are part of the regional Magothy aquifer. These units include the Upper Potomac-Raritan-Magothy aquifer in New Jersey, the Magothy aquifers on Long Island, Delaware, and Maryland, and the Virginia Beach aquifer in Virginia.

Updates to the regional hydrologic budget include revised estimates of aquifer recharge, water use and streamflow data. Inflow to the aquifer system of about 20,000 million gallons per day (Mgal/d) includes 19,600 Mgal/d from recharge from precipitation, 200 Mgal/d of recharge from wastewater via onsite domestic septic systems, and 200 Mgal/d from the release of water from aquifer storage. Outflow from the aquifer system includes groundwater discharge to streams (11,900 Mgal/d), groundwater withdrawals (1,500 Mgal/d), and groundwater discharge to coastal waters (6,600 Mgal/d). A numerical modeling analysis is required to improve this hydrologic budget calculation and to forecast future changes in water levels and aquifer storage caused by groundwater withdrawals, land-use changes, and the effects of climate variability and change.

Introduction

The Northern Atlantic Coastal Plain (NACP) aquifer system extends from Long Island, New York, to northeastern North Carolina (fig. 1), and includes aquifers primarily within New York, New Jersey, Delaware, Maryland, and Virginia. Although, the NACP aquifer system is one of the smallest of the 66 principal aquifer systems in the Nation recognized by the U.S. Geological Survey (USGS; Miller, 2000), it ranks 13th overall in terms of total groundwater withdrawals (Reilly and others, 2008). Despite abundant precipitation [about 45 inches per year (in/yr)], the supply of

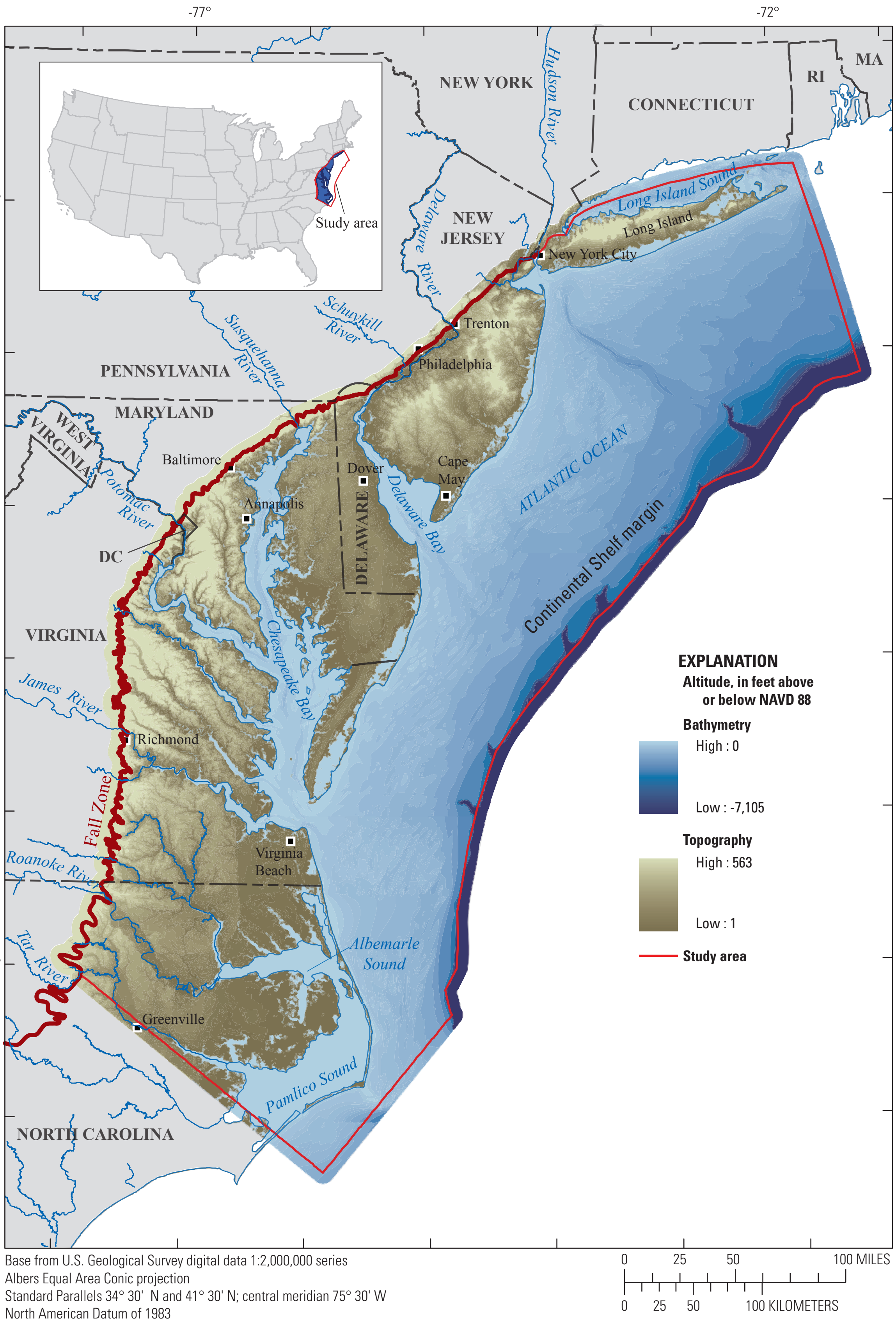


Figure 1. Location and extent of the Northern Atlantic Coastal Plain study area.

fresh surface water in this region is limited because many of the coastal surface waters in this area are brackish estuaries. As a result, many communities in the NACP rely heavily on groundwater to meet their water demand. Water supply, however, can be limited by the amount of available drawdown, drought, saltwater intrusion, and agricultural and industrial contamination. Some communities also rely on surface water imported from outside the NACP, which, after used, may be discharged into shallow aquifers, streams, or coastal waters.

Increases in population and changes in land use during the past 100 years have resulted in diverse increased demands for fresh water throughout the NACP. Substantial groundwater withdrawals had begun in the northern part of the study area by the late 1800s. By 1900, about 100 Mgal/d of water was pumped from the NACP aquifer system, about half of which was from western Long Island, to provide for the New York City water-supply system (Buxton and Shernoff, 1999).

Groundwater serves as a vital source of drinking water for the nearly 20 million people who live in the region. Densely populated areas within the NACP (fig. 2) are generally those with the largest groundwater withdrawals (fig. 3) and, therefore, are most susceptible to effects from withdrawal over time. Total groundwater withdrawal in 2005 was estimated to be about 1,500 Mgal/d and accounts for about 40 percent of the drinking water supply for the NACP (Kenny and others, 2009).

Water levels in many of the confined NACP aquifers are declining by up to 2 feet per year (ft/yr) in response to extensive development and subsequent increased withdrawals throughout the region. Total declines are more than a hundred feet in some aquifers from their predevelopment (1900) levels (fig. 4A–B; DePaul and others, 2008). In some areas, such as southeastern Virginia, declines greater than 200 feet (ft) result in water levels approximately 200 ft below the mean sea-level altitude relative to the National Geodetic Vertical Datum of 1929 (NGVD 29; Heywood and Pope, 2009).

Water-level declines also extend across State lines and under the Chesapeake and Delaware Bays, creating the potential for interstate aquifer management issues. Regional water-resources managers in the NACP face challenges beyond those imposed by the competing local domestic, industrial, agricultural, and environmental demands for water. Large changes in regional water use have made the State-level management of aquifer resources increasingly more difficult because of hydrologic effects that extend beyond State boundaries. Understanding how groundwater flow is affected regionally by natural and human stresses is vital to managing and protecting the water resources of the NACP. Therefore, a comprehensive assessment of water availability in the NACP groundwater system is needed.

In 2010, the USGS Groundwater Resources Program began a 4-year regional assessment of the groundwater availability of the NACP aquifer system as part of its ongoing regional assessments of groundwater availability of the principal aquifers of the Nation (U.S. Geological Survey, 2013). The primary goal of these regional assessments is to provide consistent and integrated information that is useful to those who use and manage the resource across political boundaries at the State and local levels (Reilly and others, 2008).

Location and Physical Setting

The portion of the NACP included in this investigation occupies a land area of more than 30,000 square miles (mi^2) along the eastern seaboard of the United States from Long Island, New York, southward to the northeastern part of North Carolina (fig. 1). A seaward-dipping wedge of mostly unconsolidated stratified sediments comprising clay, silt, sand, and gravel underlies this area. This sedimentary wedge forms a complex groundwater system in which strata of sand and gravel function predominantly as aquifers, and those of silt and clay, as confining units. The aquifers of the NACP are major sources of water for public and domestic supply and serve as a vital source of freshwater for industrial and agricultural uses throughout the region.

Land use and land cover compose primarily a mosaic of forest, wetlands, and agriculture (Loveland and others, 1999). Dominant land uses are farming and forestry, with locally dense urban development. More than half (57 percent) of the NACP area is undeveloped, nearly a third (30 percent) is agricultural, and 13 percent is developed. Land use varies from north to south with Long Island mostly (65 percent) developed, more than half (53 percent) of Delaware is agricultural, and Virginia is mostly (64 percent) undeveloped (fig. 5; Fry and others, 2011).

Land cover from the early 1900s has trended toward conversion of open space and agricultural land to residential, industrial, and commercial development (Brown and others, 1972). The amount of land conversion was greatest from 1973 to 2000 when forested lands and wetlands were converted for residential and urban uses throughout the NACP. Although total agricultural land cover has not changed appreciably, substantial changes in crop types have increased water-use demands (Loveland and others, 1999).

Purpose and Scope

Recent studies from the last USGS regional assessment conducted in the 1980s (Trapp and Meisler, 1992) have led to significant, but generally non-coordinated refinements of the hydrostratigraphic framework and hydrologic budgets throughout the NACP. These studies have provided local-scale improvements in the understanding of the groundwater-flow system, but do not provide a regional perspective of prevailing hydrogeologic conditions. This report synthesizes local-scale efforts as part of an updated regional characterization of the hydrogeologic conditions of the NACP aquifer system. This updated characterization includes (1) revisions to regional hydrogeologic units, (2) an updated hydrologic budget for conditions in 2005, and (3) use of local-scale

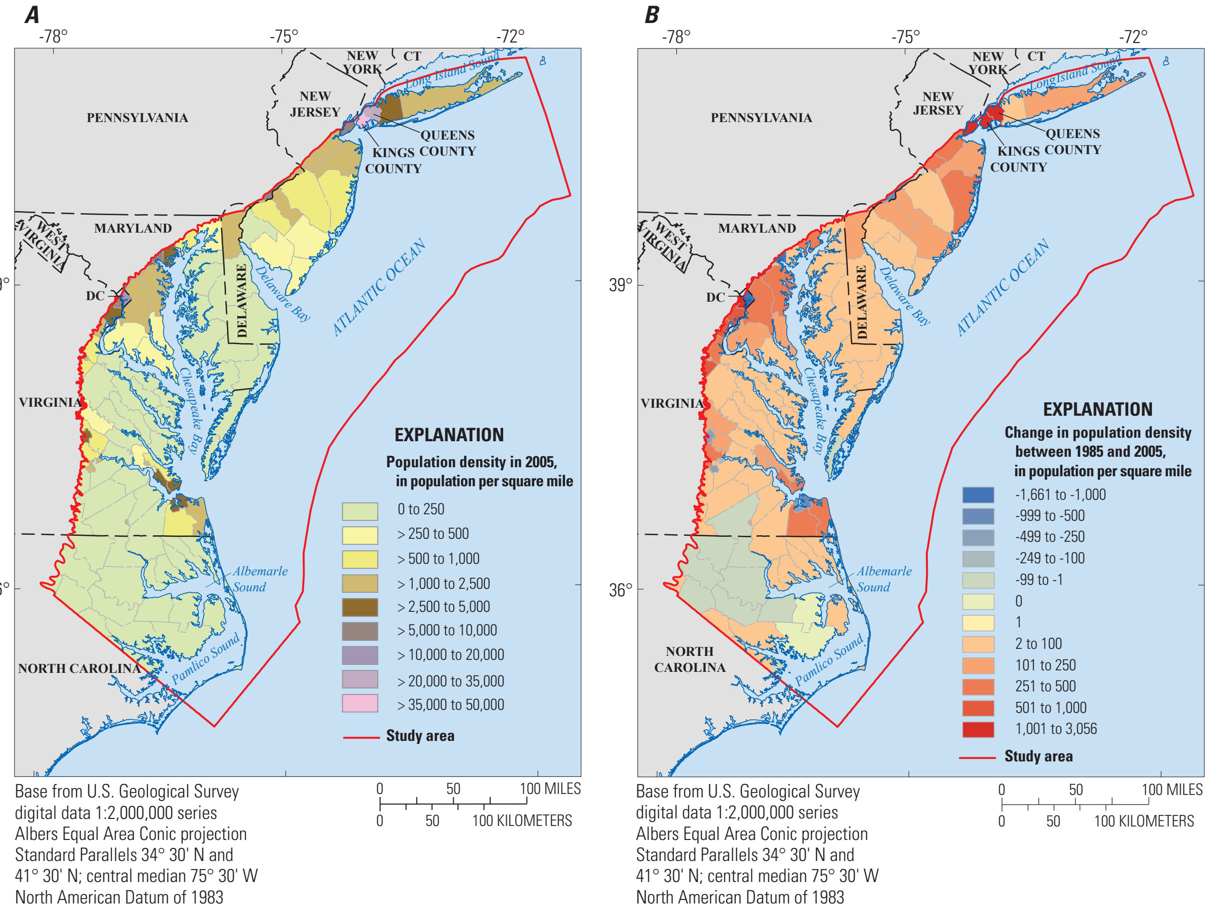


Figure 2. Population density by county in the area of the Northern Atlantic Coastal Plain aquifer system for *A,* 2005 and *B,* changes in population density from 1985 to 2005.

studies to highlight issues related to changes in groundwater withdrawals, wastewater return flow, and the potential effects of climate change on groundwater flow in the NACP.

Refinements to the hydrogeologic framework include reclassification of the local aquifers of the regional Potomac aquifer system to reflect the more recent understanding of the extent and geometry of these aquifers across State lines and throughout the region. This refinement also includes a revision of the regional aquifer names more consistent with local names in New York, New Jersey, Delaware, Maryland, and Virginia. The study area for this investigation includes only the northeasternmost part of North Carolina because the main scope of this analysis is from Virginia to Long Island. A detailed investigation of the hydrogeologic framework and groundwater availability of the coastal plain of North Carolina was completed recently as part of the regional groundwater availability study for the Atlantic Coastal Plain of North and South Carolina (Campbell and Coes, 2010).

The regional hydrologic budget presented in this report includes a new estimate of aquifer recharge rates across the NACP from 2005 through 2009, updated estimates of streamflow, and a synthesis of water use for conditions in 2005. The new methodology used to calculate recharge is documented in appendix 1 of this report. Streamflows were totaled by hydrologic basin using the USGS National Hydrography Dataset Plus (NHDPlus) attribute data in order to characterize the amount of surface water entering the NACP and the amount of groundwater discharging to streams leaving the NACP. Groundwater withdrawals and wastewater return flow estimates were compiled for conditions based on a detailed analysis of data from the USGS National Water-Use Information Program for 2005 (Kenny and others, 2009) and the U.S. census.

Examples of previous local-scale studies are presented in this report to help describe the hydrogeologic conditions throughout the NACP and to highlight local-scale or statewide issues that have the potential to affect the regional groundwater system in the future. These examples include the response of the groundwater system to large-scale pumping stresses in western Long Island, New Jersey, and Virginia from changes in public-supply and industrial uses throughout these areas. An example of changes in wastewater returnflow on Long Island also is presented to show how this change has affected water levels and streamflows and to illustrate how issues facing more urbanized areas may arise in less developed parts of the NACP with increased development.

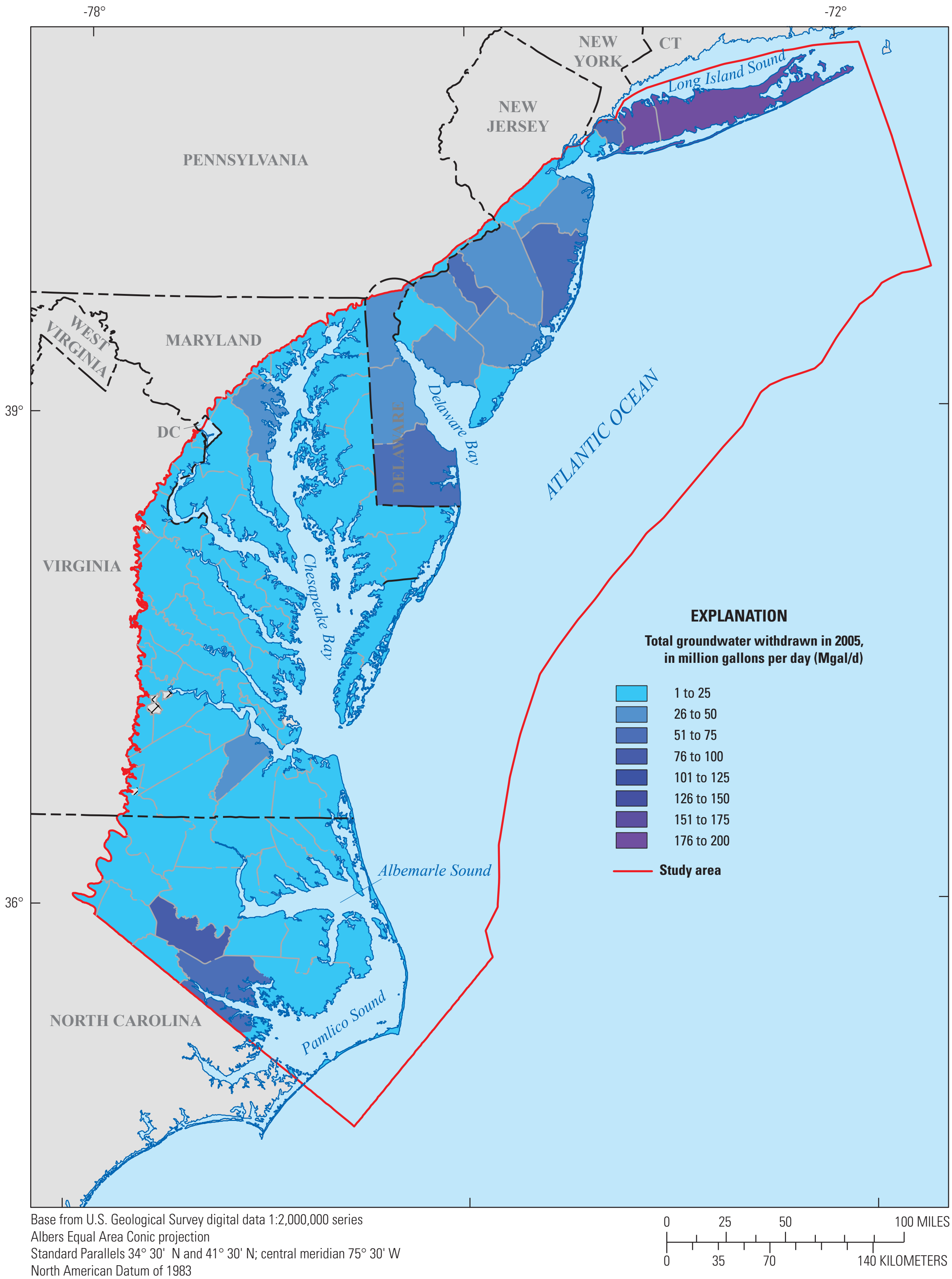


Figure 3. Groundwater withdrawals by county in the Northern Atlantic Coastal Plain for 2005.

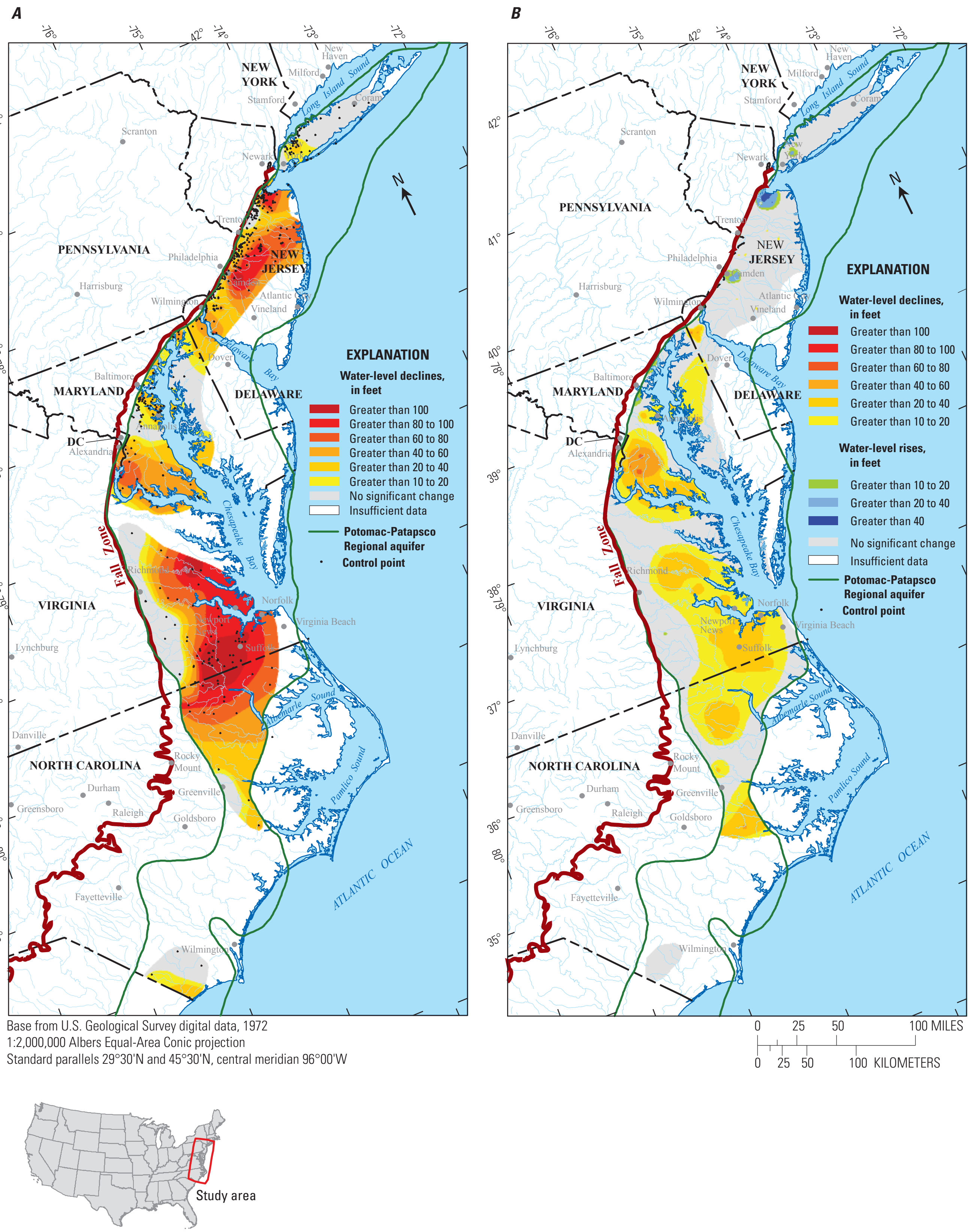


Figure 4. Change in water levels in response to groundwater withdrawals in the Potomac-Patapsco regional aquifer of the Northern Atlantic Coastal Plain aquifer system for *A,* 1900 to 1980 and *B,* 1980 to 2000. Modified from DePaul and others (2008).

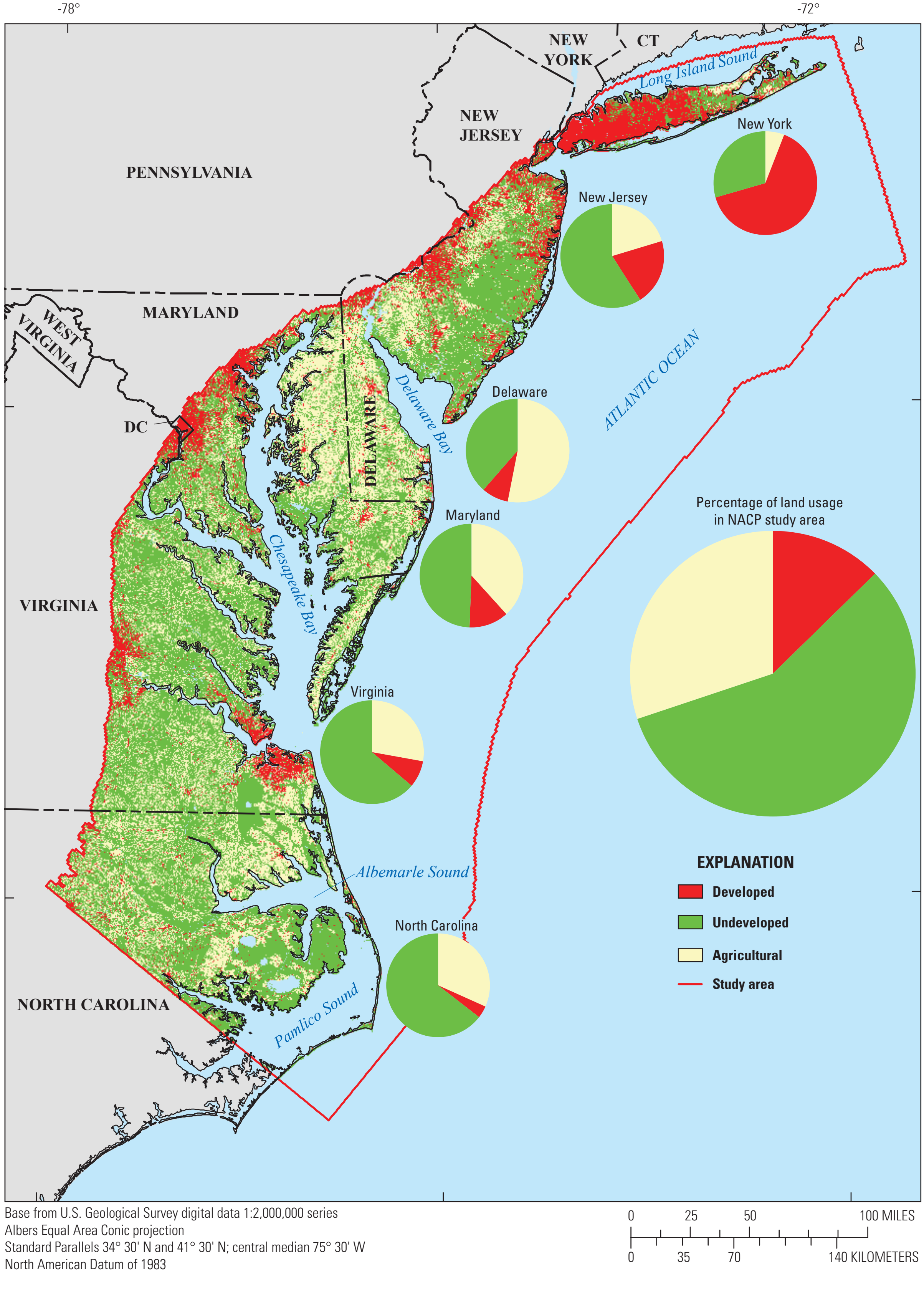


Figure 5. Land use and land cover for the Northern Atlantic Coastal Plain for conditions in 2006. Modified from Fry and others (2011).

Hydrogeology

The NACP is underlain by a wedge of unconsolidated to partially consolidated sediments that range in age from Early Cretaceous to Holocene (fig. 6). These sediments unconformably overlie a basement of Precambrian to Paleozoic-age consolidated bedrock. The western limit of the Coastal Plain is the Fall Zone, the transition between the igneous and metamorphic rocks of the Piedmont Province and the sedimentary environment of the Coastal Plain (fig. 1). The coastal plain sedimentary wedge is aligned approximately parallel to the Fall Zone and dips and thickens to the east and south (fig. 7).

Sediments in the NACP are typically thousands of feet thick along the coastline with a maximum thickness of about 10,000 ft beneath Cape Hatteras, North Carolina, at the southern edge of the study area (fig. 1). These sediments are several miles thick where they terminate to the east along the edge of the Continental Shelf. Coastal Plain sediments are continuous approximately from Newfoundland in the north to Honduras in the south, covering the Continental Shelf, but they are entirely submerged north of Cape Cod (Trapp, 1992). The eastern end of Long Island is considered the northern limit of their continuous exposure (fig. 1).

Previous Investigations

The USGS Regional Aquifer Systems Analysis (RASA) investigation of the NACP aquifer system, which was conducted from 1978 through 1987, provided a detailed review and summary of the literature describing the hydrogeologic setting of this region (Trapp, 1992). The RASA investigation (1) provided a summary of the regional geologic history, (2) described stratigraphic correlations across the States of this region, and (3) outlined the regional stratigraphic nomenclature.

The report by Trapp (1992) also presented a regional hydrogeologic framework for the NACP, which composed 10 aquifers and 9 confining units, synthesized from State-level investigations for Long Island (Smolensky and others, 1989), Virginia (Meng and Harsh, 1988), New Jersey (Zapecza, 1989), North Carolina (Winner and Coble, 1989), and Delaware and Maryland (Vroblesky and Fleck, 1991). The detailed summary and analysis of the hydrogeologic framework presented by Trapp is outlined only briefly in this report, with further emphasis on revisions to that framework from more recent studies.

During the past two decades, continued geologic and hydrogeologic investigations in the NACP by the USGS and cooperating agencies have built upon the information contained in the previous RASA reports. New information and interpretations have resulted in refinement and revision of the geology and the related hydrogeologic framework of the region. Many of these framework revisions concern relatively minor adjustments in altitudes of hydrogeologic units based

ERA/EON	PERIOD	EPOCH	
Cenozoic	Quaternary	Holocene	
		Pleistocene	
	Tertiary	Pliocene	Late
			Early
		Miocene	Late
			Middle
			Early
		Oligocene	Late
			Early
		Eocene	Late
			Middle
			Early
		Paleocene	Late
			Early
Mesozoic	Cretaceous	Late	
		Early	
	Jurassic		
	Triassic		
Paleozoic			
Proterozoic			

Figure 6. Geologic time scale for the Northern Atlantic Coastal Plain aquifer system.

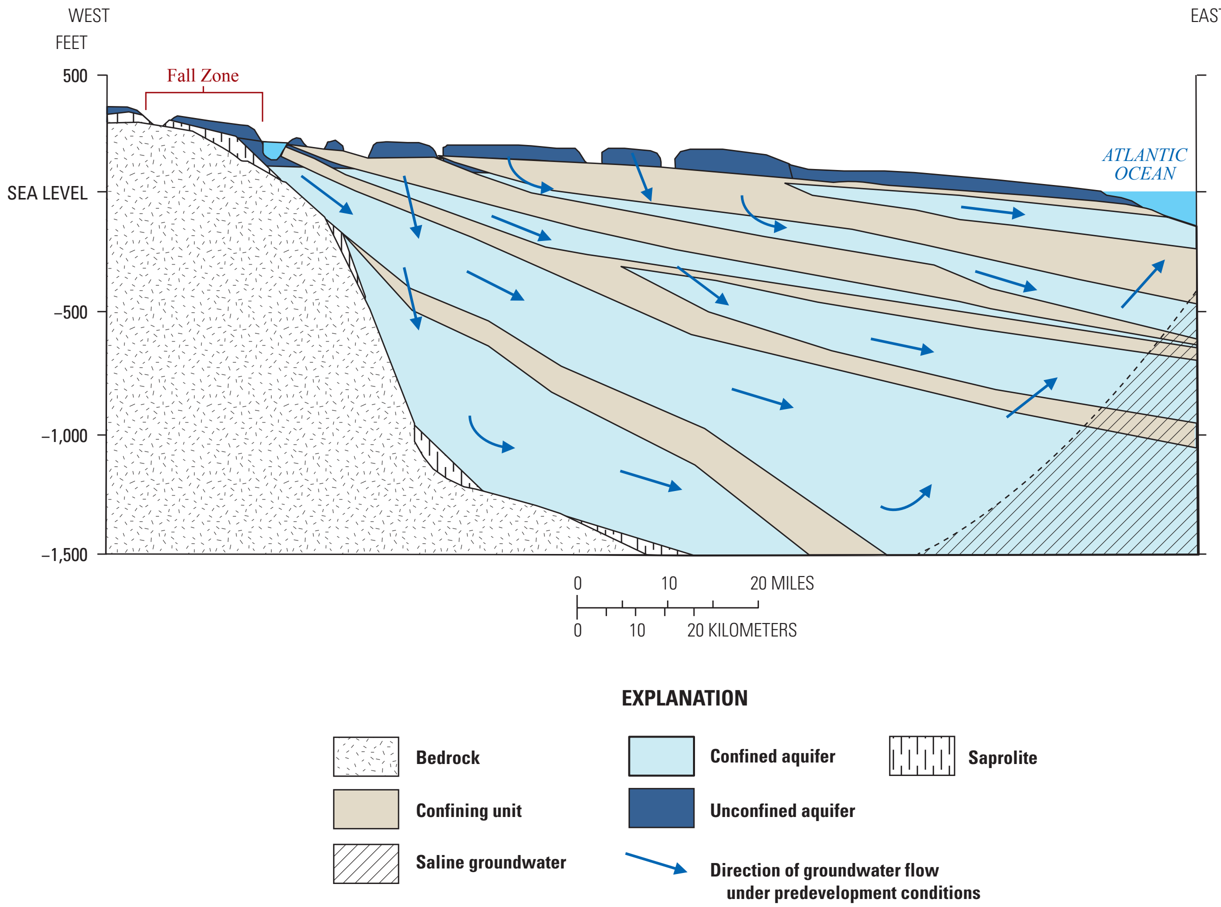


Figure 7. Generalized section showing Northern Atlantic Coastal Plain aquifer system from the Fall Zone to the coast. From Leahy and Martin (1993).

on acquisition of additional data. However, groundwater investigations at the local, State, and subregional scale have increasingly recognized that understanding groundwater conditions at many locations in an interconnected system like the NACP often requires a regional approach that transcends jurisdictional boundaries. Consequently, recent State-level groundwater investigations in Virginia (McFarland and Bruce, 2006; Heywood and Pope, 2009; McFarland, 2013), Maryland (Andreasen and others, 2013), and New Jersey (Martha Watt, U.S. Geological Survey, written commun., 2011) have involved substantial efforts to incorporate hydrogeologic data and interpretations from neighboring States. The refined interpretations from these studies have been immensely valuable in the creation of an updated regional hydrogeologic framework for the NACP.

In addition to the minor framework revisions mentioned above, recent investigations since the previous regional assessment have provided substantial advancements in the general understanding of geology and hydrogeology in the NACP. The most substantial revisions have resulted from the discovery of the buried Chesapeake Bay impact crater near the mouth of the Chesapeake Bay in southeastern Virginia (Powars and Bruce, 1999; Powars, 2000; McFarland and Bruce, 2006). Recent and ongoing work in the Virginia Coastal Plain also has resulted in a revised understanding of the Potomac aquifer system, the largest and most productive aquifer system in the NACP. This aquifer system is now considered a single heterogeneous aquifer (Potomac aquifer) in most of Virginia, except for an area along the Maryland border where confining units subdivide the system (McFarland, 2013). This new work has altered the previous understanding of the regional correlations between the Potomac and overlying Cretaceous-age aquifers across southern Maryland, Virginia, and northeastern North Carolina in the southern half of the NACP study area. These major revisions to the regional hydrogeology are incorporated now into the updated understanding of the regional hydrogeologic conditions.

Depositional History

Deposition of the sedimentary wedge forming the Continental Shelf and the Atlantic Coastal Plain began during the Triassic and Jurassic Periods with the opening of the Atlantic Ocean in the rift zone separating the North American continent from the previous supercontinent (Trapp and Meisler, 1992). Since that time, sedimentary development of the NACP has continued along the edge of the North American continent with periods of deposition and erosion driven by global sea-level fluctuations across a tectonically dynamic region.

The basement surface, upon which NACP sediments have been deposited, generally dips eastward and southward from the Piedmont Province toward the coast and the edge of the Continental Shelf. However, a series of broad regional inflections in this sloping surface have contributed to substantial regional variability in the depositional environment across the NACP and have partially controlled the distribution and thickness of sedimentary units (McFarland and Bruce, 2006). These inflections typically are described as a series of basins separated by intervening bedrock highs, also called arches or platforms (fig. 8; Owens and Gohn, 1985).

From north to south within the study area, the highs in the basement surface include the Long Island Platform, the South New Jersey Arch, the Norfolk Arch, and the Cape Fear Arch, whereas the lows in the basement surface include the Raritan, Salisbury, and Albemarle Embayments (fig. 8). The most substantial inflections in the basement surface that control the large-scale geologic structure of the NACP are associated with the Long Island Platform, a composite Salisbury-Raritan Embayment, and a composite Cape Fear-Norfolk Arch (Owens and Gohn, 1985).

Aside from these large regional features, the continental margin has been tectonically and structurally dynamic since its formation, as indicated by varied and shifting patterns of deposition among sedimentary units of different ages and spatial extents (McFarland and Bruce, 2006). This additional complexity is reflected in subregional variability in some geologic units that is not fully explained by the combination of seaward subsidence of the continental margin or by the pattern of topographic highs and lows in the bedrock surface. Nonetheless, the primary controls on the structure and characteristics of sedimentary deposits in the NACP appear to be (1) sea-level fluctuations driven by changes in climate and (2) geographic variability in the geometry of the depositional basin from the Early Cretaceous to present.

In Virginia, NACP sediments were altered dramatically during the late Eocene by the impact of an asteroid or comet near the mouth of the Chesapeake Bay (fig. 8; Powars and Bruce, 1999). The Virginia Coastal Plain was inundated at the time by a marine transgression, and the impact occurred in a shallow-shelf environment (Powars and Bruce, 1999). The resulting Chesapeake Bay impact crater is more than 50 miles (mi) in diameter and penetrates the sequence of preexisting NACP sediments to basement (fig. 8).

The crater contains a mixture of material deposited immediately after the impact. The crater fill contains slumped blocks of pre-impact sediments at the crater margin and a chaotic mix of impact-related sediments with a thickness reaching several thousands of feet within the crater, including variously sized clasts of displaced pre-impact sediments within a variable textured matrix of disaggregated and poorly sorted sands, silts, and clays (McFarland and Bruce, 2006). As marine sedimentation continued in the late Eocene, deposition into the submerged basin on the Continental Shelf left atop the previous crater-fill materials a layer of up to about 200 ft of low permeability, gray-brown silts and clays composing the Chickahominy Formation (McFarland and Bruce, 2006). Subsequent sediment deposition on the coastal plain of Virginia from the Eocene to the present has buried the crater and the crater-fill sediments about 1,000 ft below the present-day land surface.

Recognition of the recently discovered impact crater has led to a revised understanding of structural and stratigraphic relations among sediments deposited after the impact, including features anomalous to surrounding coastal plain depositional patterns (Powars, 2000; McFarland and Bruce, 2006). The effects of the impact crater on the regional geology are an area of active research. The interior of the buried impact crater is known now to contain brines, and horizontal and vertical chloride concentration patterns in and around the crater impact area reflect complex structure and extremely varied hydraulic properties associated with impact-affected sediments (McFarland, 2010).

In areas outside the Chesapeake Bay impact crater zone, widespread sedimentary deposition on the NACP in the late Eocene through the early Miocene continued in a cyclical pattern controlled by marine transgressions and regressions (Trapp, 1992). Marine deposition later in the Miocene was more episodic and spatially variable, probably as the result of tectonic movement and evolving and shifting depositional environments.

During the Pleistocene Epoch of the Quaternary Period (fig. 6), NACP sediments on Long Island were affected substantially by several episodes of glaciation. Tertiary sediments of marine origin are absent onshore, and thick glacial deposits directly overlie severely eroded Cretaceous sediments (Smolensky and others, 1989). The glacial deposits crop out at land surface over most of Long Island, and two east-west moraine ridges and a gradually southward-sloping outwash plain dominate the topography of Long Island (Smolensky and others, 1989).

Much of the modern landscape of the NACP south of Long Island also was formed during the Pleistocene from repeated depositional and erosional events as coastal areas were alternately submerged and exposed during closely spaced sea-level fluctuations associated with continental glaciation. Three broad physiographic bands have been identified, each with a characteristic geomorphology related to its formation (Ator and others, 2005).

A band of relatively high relief along the Fall Zone from New Jersey to North Carolina contains some of the oldest and most deeply weathered landscapes of the Atlantic Coastal Plain (Ator and others, 2005). This area is underlain primarily by subcrops and outcrops of Cretaceous sediments near the western edge of their extent. The landscape exhibits a deeply

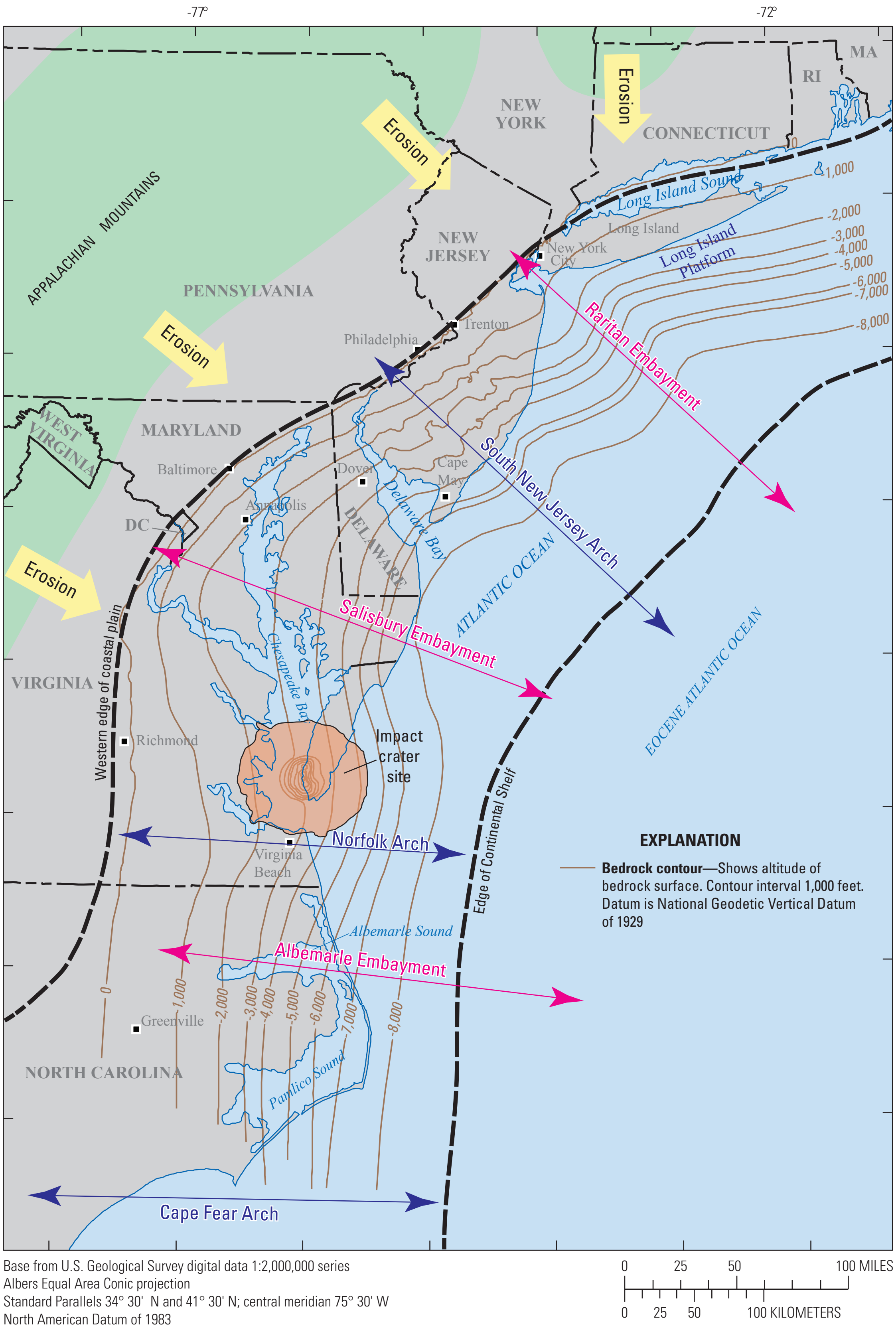


Figure 8. Schematic diagram showing the structural setting and inferred sediment sources for the Northern Atlantic continental margin (modified from Poag, 1998).

incised drainage network, often with underfit streams in wide valleys. Land-surface altitudes in this band of high relief approach several hundred feet, the highest altitudes in the study area.

East of the Fall Zone is a broad, seaward-sloping plain bounded to the northwest by several scarps along the Inner Coastal Plain and to the southeast by the Suffolk Scarp (Ator and others, 2005). This plain is subdivided by several less prominent scarps into a series of stair-step terraces with progressively lower altitudes toward the coast. These terraces were formed by repeated transgressions and regressions of sea level from the Pliocene through the Pleistocene.

Lowland areas closest to the modern coastline include modern barrier islands and lagoons along the Atlantic Ocean, extensive tidal marshes along the coastal bays, and estuarine terraces that parallel the lower reaches of major rivers (Ator and others, 2005). This is an area of extremely low relief, with a poorly developed stream network, and the topographic boundary with the terraces to the west is very prominent. This lowland constitutes only a narrow fringe along the coast and major bays in the northern part of the study area but is more extensive east of the Suffolk Scarp in North Carolina and southeastern Virginia where it ranges from about 30 to 50 mi in width.

The sediments comprising the terraces and floodplains of major rivers throughout the NACP were deposited during the Holocene by fluvial and estuarine processes (Ator and others 2005). These landscapes are characterized as being of low relief and consisting of poorly drained soils. Marine transgression has dominated in the Holocene, drowning the lower reaches of the alluvial valleys (Trapp, 1992). Throughout most of the study area, the river valleys—including the Hudson, Delaware, and Susquehanna—are tidal and estuarine to the Fall Zone (Ator and others, 2005). The rivers in the far southern part of the study area, south of the James River in Virginia, are wider and less deeply incised than the northern rivers and are nontidal about halfway across the NACP.

Northern Atlantic Coastal Plain Hydrologic Units

The sediments of the NACP have been divided for this study into 10 regional aquifers (fig. 9) and 9 regional confining units. These divisions are based on similarities and differences in hydrologic characteristics resulting from geologic origins of the units. The regional hydrogeologic units defined here are typically groupings of aquifers or confining units previously recognized at the State or local scale, with correlations across State boundaries based primarily on the continuity of hydraulic permeability. These regional delineations are based on previous work summarized in the RASA report on the NACP hydrogeologic framework (Trapp, 1992), with substantial updates interpreted from the numerous reports published during the two decades since the publication of the RASA report (Smolensky and others, 1989; Zapecza, 1989; McFarland and Bruce, 2006; Gellici and Lautier, 2010; Andreasen and others, 2013; McFarland, 2013).

The revised regional aquifers are summarized in figure 9, and the units are described briefly below. The names of some of the regional aquifer units from the RASA report have been revised to reflect a decreased emphasis on the hydrogeology of the NACP in North Carolina given the change in the areal extent of the study area compared with the previous regional assessment in this area, as described in the Introduction (Trapp and Meisler, 1992). Consequently, several regional names have been changed to remove references to units in North Carolina and to emphasize nomenclature from the primary States of the study area: New York, New Jersey, Delaware, Maryland, and Virginia. The hydrogeologic units of North Carolina are included in this report to enable a description and analysis of hydrogeologic conditions across the Virginia-North Carolina border.

Revised names and delineations for other units reflect substantial revisions in the understanding of hydrogeologic correlations across the study area. A primary example is the reclassification of the aquifers that were considered part of the regional Potomac aquifer system, which are now considered a single aquifer unit in most of Virginia, four local aquifers in Maryland and Delaware, two local aquifers in New Jersey, and a single local aquifer in New York. These local aquifers have been classified into two regional aquifers, the Potomac-Patapsco and Potomac-Patuxent aquifers. These new designations approximately correspond to the Middle Potomac and Lower Potomac regional aquifers of Trapp (1992). Permeable sediments previously classified as the Upper Potomac aquifer have been regrouped with either the Potomac-Patapsco or the Magothy regional aquifers in this report. In another example, the revised nomenclature of the Monmouth-Mount Laurel aquifer reflects improved understanding of the local units composing this regional aquifer, as well as the elimination of the North Carolina reference from the regional name.

The other substantial changes from the previous regional study reflect recently improved understanding of the transition in geology and hydrogeology in southeastern Virginia and across the border with North Carolina. Whereas these revisions include alterations in geometry of hydrogeologic units and revisions to regional correlations with units in North Carolina, including the Lower Cretaceous, Cape Fear, and Black Creek aquifers, no changes were made in aquifer nomenclature.

The final substantive revision to the hydrogeologic framework of the NACP discussed in this report is the recognition of the Chesapeake Bay impact crater, which includes three hydrogeologic units described by McFarland and Bruce (2006)—the Chickahominy confining unit, the Exmore matrix confining unit, and the Exmore clast confining unit—that comprise the crater-fill and crater-cap sediments. These units do not affect regional hydrogeologic delineations beyond the vicinity of the crater, but it should be recognized that these units truncate and replace all units

NACP aquifer	New York (Long Island)	New Jersey	Delaware	Maryland	Virginia	North Carolina
Surficial	Upper Glacial	Surficial (Holly Beach)	Surficial	Surficial	Surficial	Surficial
Upper Chesapeake	*absent*	Upper Kirkwood-Cohansey	Pocomoke, Manokin	Pocomoke, Ocean City, Manokin	Yorktown-Eastover	Yorktown
Lower Chesapeake		Lower Kirkwood-Cohansey and Confined Kirkwood	Milford, Frederica, Federalsburg, Cheswold	Choptank, Calvert	Saint Marys	Pungo River
Piney Point		Piney Point	Piney Point	Piney Point	Piney Point	Castle Hayne
Aquia		Vincentown	Rancocas	Aquia	Aquia*	Beaufort
Monmouth-Mount Laurel		Wenonah-Mount Laurel	Mount Laurel	Monmouth	Peedee	Peedee
Matawan		Englishtown	Englishtown	Matawan	Virginia Beach	Black Creek
Magothy	Magothy	Upper Potomac-Raritan-Magothy	Magothy	Magothy		Upper Cape Fear, Lower Cape Fear
Potomac-Patapsco	Lloyd	Middle Potomac-Raritan-Magothy	Upper Patapsco, Lower Patapsco	Upper Patapsco, Lower Patapsco	Potomac (undivided)*	Lower Cretaceous (undivided)
Potomac-Patuxent	*absent*	Lower Potomac-Raritan-Magothy	Patuxent, Waste Gate	Patuxent, Waste Gate		

Figure 9. Correlation chart showing regional aquifer names and subregional aquifer names for the Northern Atlantic Coastal Plain (NACP) aquifer system. Data for New York are from Smolensky and others (1989); data for New Jersey are from Zapecza (1989); data for Delaware and Maryland are from Andreasen and others (2013); data for Virginia are from McFarland and Bruce (2006); and data for North Carolina are from Gellici and Lautier (2010) and McFarland (2013); *, aquifer and associated confining units are truncated in part of Virginia by sediments related to the Chesapeake Bay impact crater.

older than the regional Piney Point aquifer within the impact area (fig. 10D). These crater-fill materials are extremely impermeable, represent a substantial discontinuity to the units they have replaced, and have been shown to influence regional groundwater flow in several important ways (McFarland and Bruce, 2006; Heywood and Pope, 2009).

Fluvial Deltaic Cretaceous Units in the Potomac Aquifer System

Unconsolidated Cretaceous-age sediments of fluvial-deltaic origin comprise an aquifer system that is the thickest, deepest, and most important source of groundwater throughout the NACP. This Potomac aquifer system (Potomac-Patuxent and Potomac-Patapsco aquifers, fig. 9) overlies basement bedrock throughout the NACP and ranges in thickness from a thin edge in the Fall Zone to thousands of feet offshore along the Atlantic Continental Shelf (fig. 10). The Potomac aquifer system takes its name from the Potomac Formation or Potomac Group ranging in age from Early Cretaceous to early Late Cretaceous Period. Consequently, the regional aquifers given the Potomac designation in this report include only fluvial-deltaic sediments of the Potomac Formation or the Potomac Group. These include sediments previously delineated as the Middle Potomac and Lower Potomac aquifers in the last regional study of this system (Trapp, 1992). For the purpose of this investigation, the Lloyd aquifer of Long Island, as the Lloyd Sand Member of the Raritan Formation, is considered part of the regional Potomac-Patapsco aquifer.

The highly heterogeneous sediments comprising the Potomac aquifer system have been subdivided in different parts of the NACP, depending on the presence and recognition of confining units or zones that are interpreted to define regionally continuous aquifers (fig. 9). In the previous RASA of the NACP aquifer system, three regional subdivisions of the Potomac aquifer system were recognized in Maryland, Virginia, and North Carolina: the Upper Potomac aquifer, the Middle Potomac aquifer, and the Lower Potomac aquifer (Trapp and Meisler, 1992; Leahy and Martin, 1993).

Two decades of subsequent investigation in Virginia and adjacent States have revealed that these three subdivisions are no longer valid in this area because of the absence of regionally extensive confining units or zones. Instead, a single, undivided Potomac aquifer is now recognized for the Virginia Coastal Plain, except for the area along the border with Maryland (fig. 11; McFarland and Bruce, 2006), and correlations with the Potomac aquifer system in adjacent States are better understood (McFarland, 2013). The Upper Potomac aquifer as previously defined by Meng and Harsh (1988) in Virginia and by Trapp and Meisler (1992) for the NACP no longer is recognized in Virginia or elsewhere (McFarland and Bruce, 2006). The top of the Potomac aquifer in Virginia correlates with the top of the Lower Cretaceous aquifer in North Carolina, and both units are overlain in southeastern Virginia and northeastern North Carolina by the distinct and regionally continuous upper Cenomanian confining unit (fig. 11; McFarland and Bruce, 2006; McFarland, 2013).

The top of the Potomac aquifer in Virginia now correlates with the top of the Upper Patapsco aquifer in Maryland, where the Potomac aquifer system includes the Upper Patapsco, Lower Patapsco, Patuxent, and Waste Gate aquifers (figs. 9, 11). This subdivision of the Potomac aquifer system into separate aquifers begins in northern Virginia south of the Potomac River with the occurrence of confining units as the system thickens into the Salisbury Embayment (McFarland, 2013). However, the extent and geometry of these confining units have not yet been delineated in Virginia and remain uncertain. In Delaware, the Potomac aquifer system is considered to be a single aquifer with multiple zones (Benson, 2006); however, in a regional refinement of the hydrogeologic framework in Maryland and Delaware, the division (Upper Patapsco, Lower Patapsco, Patuxent, and Waste Gate aquifers) of the Potomac aquifer system was extended north and east across Delaware (Andreasen and others, 2013). For this report, the local aquifers recognized in Delaware, Maryland, and northern Virginia are grouped regionally into the Potomac-Patapsco and the Potomac-Patuxent aquifers, with the local Upper and Lower Patapsco aquifers grouped into a single regional Potomac-Patapsco aquifer (fig. 9).

In New Jersey, the Potomac aquifer system is subdivided into the Middle Potomac-Raritan-Magothy and Lower Potomac-Raritan-Magothy aquifers (figs. 9, 10B). These subdivisions of the Potomac aquifer system in Maryland and New Jersey are herein referred to as the regional Potomac-Patapsco and Potomac-Patuxent aquifers. Farther north, the Potomac-Patapsco aquifer correlates with the Lloyd aquifer, which is the lowermost aquifer in Long Island (figs. 9, 10A). Possibly, because of the local upward slope in the bedrock surface (fig. 8), the Potomac-Patuxent aquifer was not deposited and therefore is not present in Long Island.

Potomac-Patuxent Aquifer

The Potomac-Patuxent aquifer is the lowermost (depth) regional aquifer of the NACP. This regional aquifer includes the Lower Cretaceous aquifer of North Carolina, the undifferentiated Potomac aquifer of Virginia, the Patuxent and Waste Gate aquifers of Maryland and Delaware, and the lower aquifer of the Potomac-Raritan-Magothy aquifer system of New Jersey (fig. 9). The Potomac-Patuxent aquifer is absent beneath Long Island (fig. 10B).

The Potomac-Patuxent aquifer is primarily of Early Cretaceous age and of fluvial-deltaic origin. It consists primarily of lenses of medium- to coarse-grained quartz sand with some gravel interbedded with lenses of clay and silt. It is highly heterogeneous, and the distribution of less permeable interbeds is highly variable, apparently controlled by regional

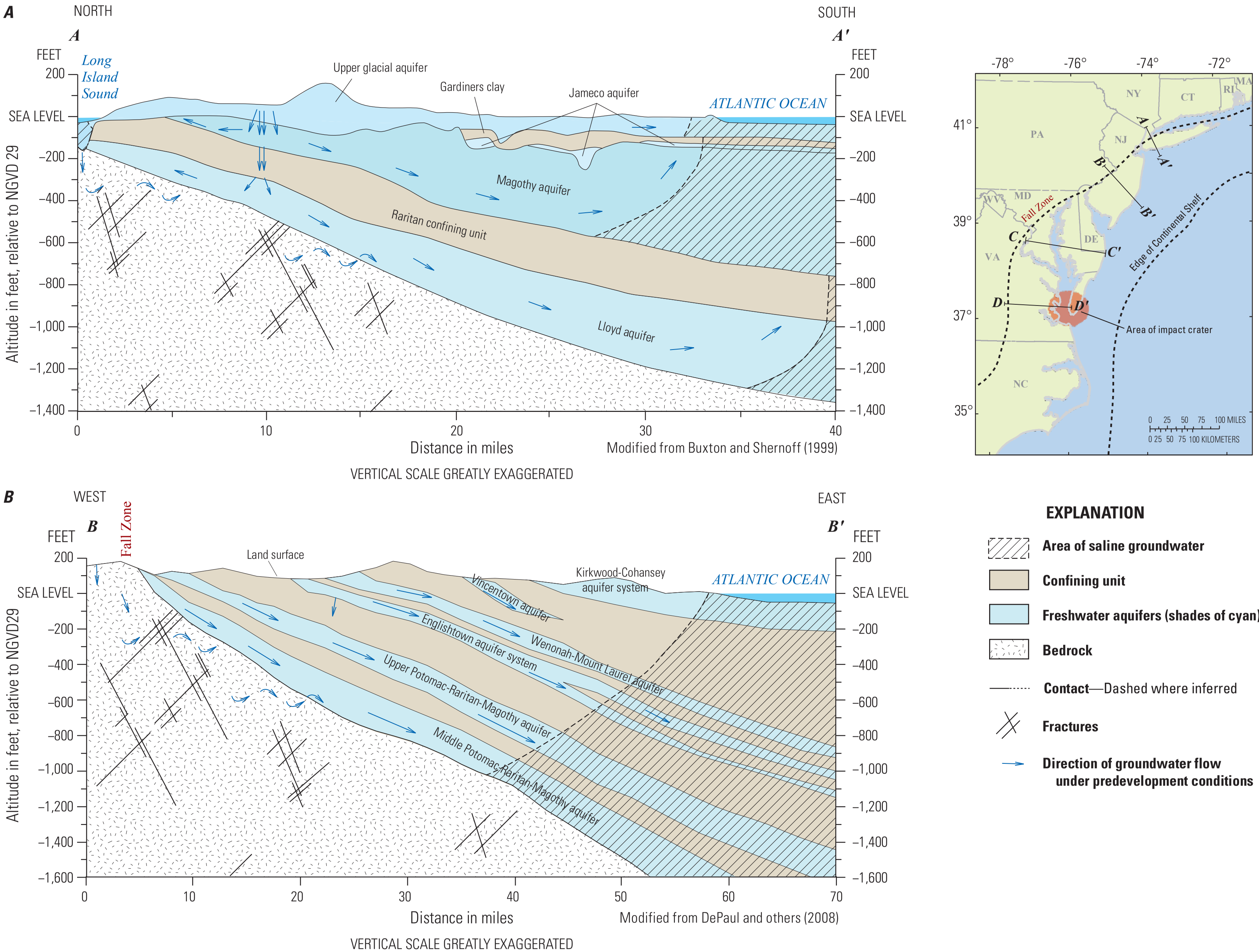


Figure 10. Cross-sections *A, A–A′* on Long Island, New York, *B, B–B′* in New Jersey, *C, C–C′* in Delaware and Maryland, and *D, D–D′* in Virginia, showing the regional variations in the hydrogeologic framework of the Northern Atlantic Coastal Plain aquifer system. Cross-section *D–D′* includes the impact crater in the Chesapeake Bay.

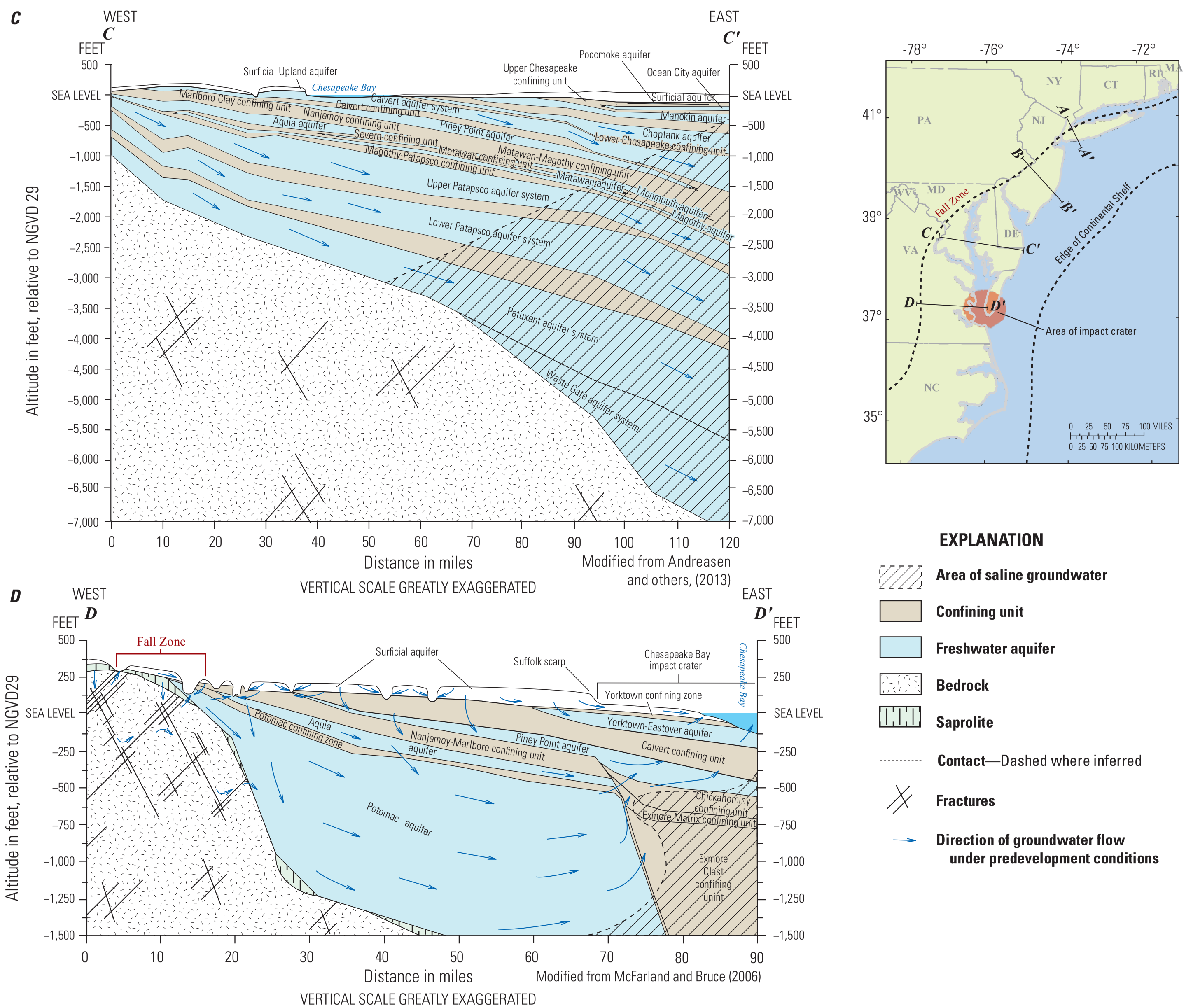


Figure 10. Cross-sections *A, A–A′* on Long Island, New York, *B, B–B′* in New Jersey, *C, C–C′* in Delaware and Maryland, and *D, D–D′* in Virginia, showing the regional variations in the hydrogeologic framework of the Northern Atlantic Coastal Plain aquifer system. Cross-section *D–D′* includes the impact crater in the Chesapeake Bay.

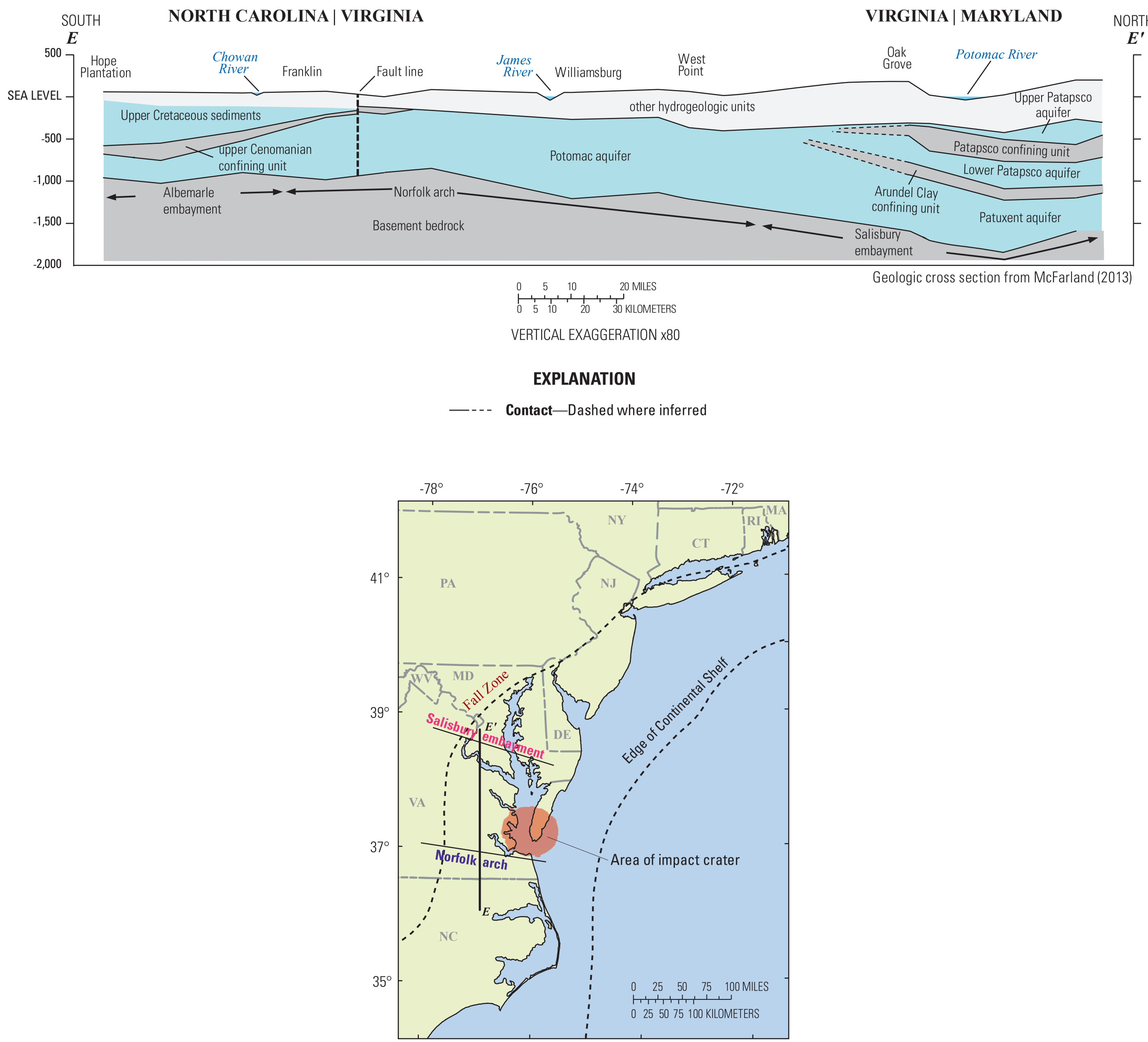


Figure 11. Cross-section showing distribution of the variable geometry and sediment composition of the Potomac aquifer system across the southern half of the Northern Atlantic Coastal Plain.

variations in the depositional environments under which the sediments were deposited (McFarland, 2013). The proportion of fine-grained sediments increases downdip toward the coast as well as laterally toward the Salisbury Embayment. The Potomac-Patuxent aquifer is a thick, productive aquifer and an important source of groundwater throughout most of its extent, except where it contains salty groundwater in downdip areas near the Atlantic coastline. The wedge shape of the aquifer is thinnest in the Fall Zone where it pinches out against bedrock of the Piedmont Province and thickest at and beyond the Atlantic coastline. The Potomac-Patuxent aquifer reaches a thickness of more than 1,000 ft in Maryland and Delaware (Trapp and Meisler, 1992). The aquifer thins northward in New Jersey where the average thickness penetrated by wells, mostly in the thinner updip section, is about 300 ft.

The Potomac-Patuxent aquifer (where present) is overlain by a confining unit separating this aquifer from the overlying Potomac-Patapsco aquifer. This regional confining unit, called the Potomac confining unit in the RASA study and known as the Arundel Clay confining unit in Maryland, composes hard clays and silts within the fluvial-deltaic Potomac and Raritan formations in New Jersey, Delaware, Maryland, and northern Virginia (Trapp, 1992). The confining unit ranges in thickness from a thin western edge in the Fall Zone to more than 1,000 ft along the Atlantic coast in Delaware and pinches out along the flank of the Norfolk Arch in northern Virginia, though this southern boundary of the unit is not yet well defined (McFarland, 2013). South of the southern edge of the confining unit, the Potomac-Patuxent regional aquifer is no longer differentiated from the overlying Potomac-Patapsco regional aquifer, and the Potomac aquifer system is considered to be a single heterogeneous aquifer.

Potomac-Patapsco Aquifer

The Potomac-Patapsco regional aquifer includes the Lloyd aquifer in New York (Long Island), the middle aquifer of the Potomac-Raritan-Magothy aquifer system in New Jersey, the Upper and Lower Patapsco aquifers of Delaware and Maryland, the undifferentiated Potomac aquifer of Virginia, and the Lower Cretaceous aquifer in North Carolina (fig. 9). In Maryland and in northern Virginia, the Potomac-Patapsco regional aquifer consists of two local aquifers, the Upper Patapsco and Lower Patapsco, separated by an intervening confining unit (fig. 9; Andreasen and others, 2013). In most of Virginia and North Carolina, the Potomac aquifer system is considered to be a single heterogeneous aquifer, and the Potomac-Patapsco regional aquifer is not differentiated from the underlying Potomac-Patuxent regional aquifer.

The Potomac-Patapsco aquifer is similar to the underlying Potomac-Patuxent aquifer in that it consists primarily of lenses of medium- to coarse-grained quartz sand with some gravel, interbedded with lenses of clay and silt. This aquifer is highly heterogeneous, and the hydraulic properties vary considerably with the proportion of fine-grained sediments. It is composed of fluvial-deltaic sediments of primarily Early Cretaceous age in Maryland and Delaware, and Late Cretaceous age in New Jersey and New York.

The Potomac-Patapsco regional aquifer is a thick, productive aquifer and an important source of groundwater throughout most of its extent. Similar to the underlying Potomac-Patuxent aquifer, the wedge shape of the aquifer is thinnest near the Fall Zone where it pinches out against bedrock of the Piedmont Province and thickest at and beyond the Atlantic coastline. In a north-south direction, the regional Potomac-Patapsco aquifer is thickest in southern Maryland (referred to locally as the Upper and Lower Patapsco aquifer system) where it is more than 500-ft thick (fig. 11). The aquifer thins northward into New Jersey and is thinnest in New York where the average onshore thickness of the Lloyd aquifer is less than 300 ft (fig. 10A; Smolensky and others, 1989).

In Virginia, the fluvial-deltaic sediments of Early Cretaceous age have been delineated as a single Potomac aquifer except in northern Virginia (McFarland, 2013). The Potomac aquifer is entirely truncated within the area of the Chesapeake Bay impact crater by crater-fill sediments (fig. 10D) and contains tilted and faulted layers of fluvial-deltaic sediments at the edges of the impact zone (McFarland and Bruce, 2006). The crater-fill sediments are hydrogeologically quite distinct and are considered separately from the other regional hydrogeologic units discussed in this report.

The thickness of the undifferentiated Potomac and Lower Cretaceous aquifers in Virginia and North Carolina reaches about 1,500 ft, although the depth of production wells penetrating the aquifer is much less (Trapp and Meisler, 1992). The average depth of production wells in this aquifer ranges from about 225 ft on Long Island to as much as 900 ft in Maryland. The Potomac-Patapsco aquifer appears to be a somewhat more transmissive and productive aquifer than the underlying Potomac-Patuxent aquifer (Trapp and Meisler, 1992).

The Potomac-Patapsco aquifer is overlain by a regionally identified, but locally highly variable confining unit separating the primarily fluvial-deltaic Cretaceous units from units that are primarily marine in origin. This unit is referred to as the Raritan Clay confining unit in New York and New Jersey, the Magothy-Patapsco confining unit in Delaware and Maryland, the Potomac confining zone in northern and central Virginia, and the upper Cenomanian confining unit in southeastern Virginia and northeastern North Carolina. The transition from the fluvial-deltaic sediments of the Potomac aquifer system to the various overlying hydrogeologic units throughout the study area has resulted in a confining unit that is extremely variable in its properties and thickness (Trapp, 1992). The sediments comprising this regional unit in northern and central Virginia are referred to as a confining zone rather than a confining unit to reflect a high degree of heterogeneity and discontinuity, but in southeastern Virginia, the overlying upper Cenomanian confining unit is included in the regional unit and provides much greater hydrologic separation (McFarland and Bruce, 2006). In other parts of the study area, the local sediments comprising this unit also may provide substantial hydrologic separation between the regional Potomac-Patapsco aquifer and overlying units (Trapp, 1992; Andreasen and others, 2013).

Marine Cretaceous Units

After the fluvial-deltaic deposition that formed the Potomac aquifer system, a transition to a predominantly marine environment resulted in the deposition of sediments with substantially greater spatial homogeneity. These sediments form three primary aquifers—the Magothy, Matawan, and Monmouth-Mount Laurel aquifers—in the northern part of the study area (fig. 9), all pinching out in southern Maryland on the flank of the Salisbury Embayment (figs. 8, 10A, C). These aquifers are absent across almost all the Virginia Coastal Plain, likely because of structural control provided by the Norfolk Arch. However, other laterally discontinuous sediments of similar age are now recognized in far southeastern Virginia and form hydrogeologic units that appear to dip and thicken southward into the Albemarle Embayment and out of the study area to the south.

Magothy Aquifer

The Magothy regional aquifer composes the Magothy aquifer of New York, New Jersey, Delaware, and Maryland (fig. 9). On Long Island, this regional aquifer also may include sediments of the Matawan and Monmouth Groups (not included on fig. 9) as well as the Pleistocene-age Jameco Gravel and is only partially confined, primarily along the southern shore (fig. 10A). The southern boundary of the Magothy aquifer is north of the Potomac River in southern Maryland. Sediments of similar age and composition are identified as the Cape Fear aquifer in northeastern North Carolina, but this unit is entirely separate from the Magothy aquifer to the north, it is fluvial in deposition, and its importance as a groundwater resource is only in areas outside of the focus area of this investigation. The Cape Fear aquifer of North Carolina may be continuous with other permeable units in Virginia, such as the Virginia Beach aquifer, but the exact correlation has not been established definitively (McFarland, 2013).

The Magothy aquifer composes primarily sandy parts of the Magothy Formation, which were deposited in a transitional fluvial-marine environment during the Late Cretaceous (Andreasen and others, 2013). The Magothy aquifer consists of very fine to medium quartz sand, with discontinuous layers of carbonaceous clayey silt; it also contains coarse to very coarse sand and gravel, particularly in the thicker parts (Trapp, 1992). The coarsest materials typically are found at the base of the aquifer, which fines upward into the clays of the overlying confining unit (Andreasen and others, 2013). The aquifer is confined except on Long Island and in subcrop areas near the western limit of the aquifer in the Fall Zone. Throughout much of Long Island, the Magothy aquifer is only partially confined or unconfined where it is in contact with surficial glacial deposits and may act as a continuation of the surficial aquifer. This aquifer is a very important water resource throughout most of its areal extent and particularly on Long Island.

The Magothy aquifer is typically less than 200 ft thick in New Jersey, Delaware, and Maryland, and intervals penetrated by production wells are less than 100 ft thick on average (Trapp, 1992). This aquifer is thickest on Long Island, however, where it reaches a thickness of more than 1,000 ft onshore, with an average of at least 500 ft (Smolensky and others, 1989). The average interval penetrated by production wells in this aquifer on Long Island is 460 ft (Trapp, 1992).

Except on Long Island, the Magothy regional aquifer is overlain by a confining unit that separates it from the overlying Matawan aquifer. This regional confining unit includes the Merchantville-Woodbury confining unit in New Jersey, consisting of glauconitic and micaceous clay and silt, and the Matawan-Magothy confining unit in Delaware and Maryland, consisting of silt and clay of the Magothy Formation and part of the overlying Matawan Group or Matawan Formation (Trapp, 1992; Andreasen and others, 2013).

Matawan Aquifer

The Matawan aquifer primarily consists of sands deposited by a marine transgression during the Late Cretaceous, including fine to medium quartz sand in New Jersey and fine silty to clayey sand in Delaware and Maryland. It may contain glauconite and mica, which distinguishes it from the underlying Magothy aquifer (Andreasen and others, 2013). The Matawan aquifer is confined throughout most of its extent, except where it crops out or subcrops in the Fall Zone at the western edge of the aquifer. It is a locally important water resource in New Jersey and parts of Maryland. The regional Matawan aquifer as defined in this report includes a northern section in New Jersey, Delaware, and Maryland and a laterally discontinuous southern section in southeastern Virginia and northeastern North Carolina. The Virginia Beach aquifer may also be continuous with the underlying Upper and Lower Cape Fear aquifers in North Carolina (Magothy regional aquifer), but the nature of this relation has not been definitively established (McFarland, 2013).

The northern section of the Matawan aquifer includes the Englishtown aquifer in New Jersey, the Englishtown aquifer in Delaware, and the Matawan aquifer in Maryland. On Long Island, equivalent sediments of the Matawan Group are included with the underlying Magothy aquifer (fig. 9) (Trapp and Meisler, 1992). As defined, the extent of the Matawan aquifer is much larger to the east and south than previously indicated by Trapp (1992). The southern limit of the Matawan aquifer is north of the Maryland-Virginia State line and east of the Chesapeake Bay where it thins along the southern edge of the Salisbury Embayment (Andreasen and others, 2013).

In the northern section, the Matawan aquifer is overlain by a confining unit that separates it from the

Monmouth-Mount Laurel aquifer. This section of the regional confining unit includes the Marshalltown-Wenonah confining unit in New Jersey, composing glauconitic silt and fine sand, and the Matawan confining in Delaware and Maryland, composing clay and silt (Trapp, 1992).

In the southern part of the study area, sediments of similar age and composition to the northern section of the Matawan aquifer form a local unit known as the Virginia Beach aquifer in southeastern Virginia that may be the thin northern edge of the Black Creek aquifer of North Carolina (fig. 9) (McFarland and Bruce, 2006). The Virginia Beach and Black Creek aquifers are entirely separate, but equivalent to the Matawan aquifer of Maryland, Delaware, and New Jersey. The southern flank of the Norfolk Arch (fig. 8) controls the northern extent of these aquifers. The Virginia Beach aquifer is of limited local significance as a water resource, but the Black Creek aquifer becomes more important as it thickens southward into east-central North Carolina, beyond the focus area of this investigation. The Virginia Beach aquifer may also be continuous with the underlying Upper and Lower Cape Fear aquifers in North Carolina, but the nature of this relation has not been established (McFarland, 2013).

The southern section of the Matawan regional aquifer in Virginia and North Carolina is overlain by a confining unit that separates this aquifer from the Peedee aquifer above. This part of the regional confining unit includes the Virginia Beach confining zone in Virginia and the Black Creek confining unit in North Carolina. This confining unit in Virginia composes red beds consisting of sequences of interbedded oxidized clay, silty clay, and silty fine sand (McFarland and Bruce, 2006). The unit's designation as a confining zone reflects the considerable variability in the composition and configuration of this unit, as well as the sometimes indistinguishable relations between the underlying Virginia Beach aquifer and overlying aquifer units. This unit is reported to be as much as several tens of feet thick in Virginia and thickens into North Carolina.

Monmouth-Mount Laurel Aquifer

The Monmouth-Mount Laurel regional aquifer (previously referred to by Trapp and Meisler (1992) as the Peedee-Severn aquifer) includes the Wenonah-Mount Laurel aquifer in New Jersey, the Mount Laurel aquifer in Delaware, and the Monmouth aquifer in Maryland (fig. 9). On Long Island, laterally equivalent sediments are included as part of the regional Magothy aquifer.

The southern limit of the continuous Monmouth-Mount Laurel regional aquifer is north of the Maryland-Virginia State line and east of the Chesapeake Bay (Andreasen and others, 2013). In the southern part of the study area, sediments of similar age form a unit known as the Peedee aquifer, which is not continuous with rest of the Monmouth-Mount Laurel aquifer but is considered part of the same regional aquifer. The Peedee aquifer has been identified in southeastern Virginia (McFarland and Bruce, 2006) where it is poorly constrained. From there, it extends southward into northeastern North Carolina, thickening into the Albemarle Embayment (Trapp and Meisler, 1992).

The Monmouth-Mount Laurel aquifer is the uppermost regional aquifer of Late Cretaceous age in the study area. It includes permeable parts of the marine Mount Laurel Formation, which is the lower part of the Monmouth Group (Andreasen and others, 2013). This aquifer consists of very fine to coarse, slightly glauconitic sand in New Jersey and fine glauconitic sand in Delaware and Maryland and ranges in thickness from about 10 to 120 ft in Delaware and Maryland and in southern New Jersey (Zapecza, 1989; Andreasen and others, 2013).

The Monmouth-Mount Laurel aquifer is confined throughout most of its extent, except where it crops out or subcrops near the Fall Zone at its westernmost extent. It is a locally developed and moderately productive aquifer in New Jersey, Delaware, and eastern Maryland. In the southern section of the Monmouth-Mount Laurel regional aquifer, the Peedee aquifer is unused as a groundwater resource in Virginia (McFarland and Bruce, 2006), but it is a more important groundwater resource in North Carolina outside of the focus area of this investigation.

The northern section of the Monmouth-Mount Laurel regional aquifer is separated from the Aquia regional aquifer above by an overlying confining unit that includes the Navesink-Hornerstown confining unit in New Jersey and the Severn confining unit in Delaware and Maryland. The confining unit consists of marine silt, clay, and silty and clayey glauconitic sand of primarily Cretaceous age (Trapp, 1992). Its thickness is generally less than 100 ft.

The southern section of this regional confining unit includes the Peedee confining zone in Virginia and the Peedee confining unit in North Carolina. The section's designation as a confining zone in Virginia reflects the variable configuration and composition of the sediments above the Peedee aquifer and the transition to the overlying Aquia aquifer (McFarland and Bruce, 2006). The thickness of this section may be as great as several tens of feet in Virginia and up to 50 ft in North Carolina (McFarland and Bruce, 2006; Gellici and Lautier, 2010).

Marine Tertiary Units

Sediments deposited by continuing cyclical marine deposition in the Tertiary comprise aquifers and intervening confining units that are relatively homogeneous in composition and extend across most of the study area. The Aquia and Piney Point aquifers are thickest and most transmissive in the Salisbury Embayment, where they are most important to groundwater resources.

Aquia Aquifer

The Aquia regional aquifer (previously referred to by Trapp and Meisler (1992) as the Beaufort-Aquia aquifer) includes the Vincentown aquifer in New Jersey, the Rancocas aquifer in Delaware, the Aquia aquifer in Maryland and Virginia, and the Beaufort aquifer in North Carolina (fig. 9). The Aquia aquifer is not present on Long Island; it is uncertain if Tertiary-age marine sediments were deposited and subsequently eroded or never deposited here (Smolensky and others, 1989).

The sediments comprising the Aquia aquifer were deposited in a relatively uniform marine shallow-shelf environment, and therefore, this aquifer is widespread and relatively homogeneous throughout the study area. These sediments are reported to exist off the southeastern shore of Long Island in continuation with their extent in eastern New Jersey (Trapp, 1992). The Aquia aquifer forms only a narrow band in eastern New Jersey but is much more laterally extensive elsewhere, particularly in Maryland, near the Salisbury Embayment (fig. 8).

The Aquia aquifer composes permeable marine sediments of Paleocene age and consists primarily of medium- to coarse-grained glauconitic and fossiliferous quartz sands (Trapp, 1992). In Virginia, the sediments that fill the Chesapeake Bay impact crater truncate the Aquia aquifer (McFarland and Bruce, 2006). In North Carolina and southern Virginia, the aquifer also includes thin shell and limestone beds. It is confined throughout most of its extent, except where it crops out or subcrops near the Fall Zone in a very narrow band at the western edge of the aquifer. The Aquia aquifer is most important as a groundwater resource in Maryland where it is as much as 250 ft thick (Andreasen and others, 2013).

The Aquia aquifer is overlain over most of its extent by a confining unit that separates it from the Piney Point aquifer above. The regional confining unit includes the Vincentown-Manasquan confining unit in New Jersey; the Nanjemoy-Marlboro Clay confining unit in Delaware, Maryland, and Virginia; and the Beaufort confining unit in North Carolina. The confining unit overlaying the Aquia aquifer is made of marine silt, clay, and sandy clay ranging from a thickness of 50 ft in North Carolina to more than 900 ft in New Jersey (Trapp, 1992). In contrast to the highly variable composition and configuration of several of the Cretaceous-age confining units, this regional confining unit extends over almost all the study area and substantially impedes regional groundwater flow (Trapp, 1992; McFarland and Bruce, 2006).

Piney Point Aquifer

The Piney Point regional aquifer (previously referred to by Trapp and Meisler (1992) as the Castle Hayne-Piney Point aquifer) includes the Piney Point aquifer of New Jersey, Delaware, Maryland, and Virginia, as well as the Castle Hayne aquifer of North Carolina (fig. 9). Composing geologic formations deposited in relatively uniform shallow-shelf and marginal marine conditions along the Continental Shelf, the Piney Point aquifer is somewhat consistent and homogeneous across the study area, though it is absent (truncated by younger units) along the western margin of the NACP and across Long Island (Trapp and Meisler, 1992).

The Piney Point aquifer consists of marine sediments of mostly Eocene to Oligocene age, though it also may include sediments of Miocene age in some locations (Trapp and Meisler, 1992). This aquifer generally consists of mostly glauconitic sand with shells from New Jersey to Virginia and limestone, sandy marl, and limey sand in North Carolina. However, a productive section of the Piney Point aquifer north of the James River and south of the Potomac River in Virginia composes calcite-cemented sands and moldic limestone (McFarland and Bruce, 2006). The Piney Point aquifer consists of sediments deposited both before and after the Chesapeake Bay impact, so its geometry and composition are altered by the presence of the impact crater; the Piney Point aquifer extends across the impact zone.

The part of the aquifer penetrated by production wells is thinnest in Virginia where it averages about 45 ft and thickest in Maryland and Delaware where it averages about 120 ft (Trapp and Meisler, 1992). The aquifer is confined over its extent except for very limited subcrop areas along its western edge in the Fall Zone or where truncated by major river valleys. It is an important groundwater resource in New Jersey, Delaware, and Maryland. It is a moderately used resource in Virginia, but only over the consolidated part. The part of North Carolina where it is an important water resource is located mostly south of Albemarle Sound and outside the study area of this report.

The confining unit overlying the Piney Point regional aquifer and separating it from the Lower Chesapeake aquifer above includes the Basal Kirkwood confining unit in New Jersey, the Calvert confining unit in Delaware, Maryland, and Virginia, and the Castle Hayne confining unit in North Carolina. It consists primarily of marine clay and sandy clay of Miocene age, and its thickness increases northward from less than 50 ft in North Carolina to a range of 100 to 250 ft over the northern half of the study area (Trapp, 1992). As with the aquifers it separates, this confining unit is absent in New York. Otherwise, this unit extends across almost the entire study area and impedes groundwater flow regionally.

Chesapeake Bay Impact Crater and Associated Units

The Chesapeake Bay impact crater has had a profound effect on the hydrogeology of the NACP in southeastern Virginia (fig. 8). Consequently, an entirely separate description of the hydrogeologic units associated with the impact crater is warranted here, and special consideration of the crater area is required in the regional analysis of groundwater flow. Aquifer and confining unit sediments deposited before the impact were entirely truncated by the sediments filling the crater and altered around the crater edges (McFarland and Bruce, 2006). The crater-fill sediments now are buried under about 1,000 ft of sediments deposited in the 35 million years since the impact. They extend from a depth of about 1,000 ft to a maximum depth of about 6,000 ft where they directly overlie the basement bedrock in the inner part of the crater.

The previously described Potomac aquifer system (Potomac-Patuxent and Potomac-Patapsco regional aquifers) and the overlying confining unit are present within the outer part of the crater, but these units are disrupted at least partially by the crater (Powars and Bruce, 1999). Previously deposited sedimentary units within the inner part of the crater were removed entirely by the impact, which also substantially altered the regional bedrock basement. Most of the buried crater is filled by a chaotic mass referred to as tsunami-breccia that ranges in thickness from hundreds of feet around the outer part of the crater to almost 5,000 ft near the center. The sediments associated with the crater, aside from remnants of the regional aquifer and confining unit, are unique to the impact area and are limited to Virginia (McFarland and Bruce, 2006).

The Exmore clast confining unit is the lowermost unit of crater-fill material and extends across the entire impact crater area depicted in figure 8. The confining unit consists primarily of boulder-sized clasts of formations older than the impact; voids between the clasts are filled with poorly sorted sands, silts, and clays of various ages (McFarland and Bruce, 2006). In the inner part of the crater, the Exmore clast confining unit directly overlies the altered bedrock basement and reaches its maximum thickness of more than 4,500 ft. The Exmore clast confining unit overlies the local Potomac confining zone across most of the crater area, which in turn, overlies the Potomac aquifer. The portion of the Exmore clast confining unit that is outside the inner crater is several hundred feet thick on average and reaches a maximum thickness of almost 2,000 ft. The Exmore matrix confining unit directly overlies the Exmore clast confining unit over its entire areal extent within the impact crater area (fig. 1). It consists of pebble- to cobble-sized clasts of older sediments within a matrix of poorly sorted sands, silts, and clays. It reaches a maximum thickness of about 200 ft (McFarland and Bruce, 2006). This unit is differentiated from the underlying Exmore clast confining unit by the relative abundance of matrix material. The Exmore clast and Exmore matrix confining units, composing primarily tsunami-breccia deposited during and after the impact are overlain by the Chickahominy confining unit, which composes primarily dense and very fine-grained silts and clays deposited in an abyssal basin on the Continental Shelf following the impact event. The Chickahominy confining unit is up to 200 ft thick and overlies the Exmore matrix confining unit throughout its extent, but also extends well beyond the impact area to the north and east, to approximately the Virginia-Maryland State line on the Eastern Shore (fig. 1).

The impact-related sediments described and identified as confining units by McFarland and Bruce (2006) individually and collectively impede horizontal and groundwater flow throughout the impact crater area. Information on the hydraulic properties of these units is limited because these units have only recently been identified, but hydraulic conductivity is known to vary widely with the highly variable composition and configuration of these units. The crater-fill sediments have been shown to substantially affect patterns of groundwater flow in the coastal plain of southeastern Virginia, especially under 2003 withdrawal conditions (Heywood and Pope, 2009). Nonetheless, the physical configuration of the impact crater and the hydraulic effects of the crater sediments continue to be the subject of active research.

Transitional Tertiary and Quaternary Units

The Lower Chesapeake and Upper Chesapeake regional aquifers described in this section compose sediments of Miocene and Pliocene (Tertiary) age. These aquifers are described here with the Quaternary units because they represent a transition from shallow marine to mixed estuarine and fluvial deposition; this transition is reflected in the increasingly heterogeneous character of the aquifer units they comprise. In addition, these units may, in some locations, form the surficial aquifer or be included with undifferentiated sediments forming the surficial aquifer.

On Long Island, the oldest unit in this group is the Gardiners Clay confining unit, which locally separates the surficial Upper Glacial aquifer from the underlying Magothy aquifer. The Tertiary units are not present on Long Island, suggesting that they were never deposited here or deposited and subsequently removed by erosion (Smolensky and others, 1989).

Lower Chesapeake Aquifer

The Lower Chesapeake regional aquifer includes the Lower Kirkwood-Cohansey aquifer system in New Jersey, the Milford, Frederica, Federalsburg, and Cheswold local aquifers in Delaware, the Choptank and Calvert local aquifers in Maryland, the Saint Marys aquifer in Virginia, and the Pungo River aquifer in North Carolina (fig. 9). The Lower Chesapeake aquifer is absent on Long Island (Smolensky and others, 1989). In Maryland, it is limited to the Delmarva Peninsula and a small section west of the Chesapeake Bay (Andreasen and others, 2013). In Virginia, it is mostly absent west of the Chesapeake Bay except for a small portion south of the James River (McFarland and Bruce, 2006). The southern part of the Lower Chesapeake aquifer, which is in North Carolina and south of the James River in Virginia, is entirely separate and discontinuous from the northern part of the aquifer.

The Lower Chesapeake aquifer consists primarily of marine sands ranging in age from Oligocene to Pliocene. In New Jersey, the aquifer includes interbedded sand and gravel (Trapp, 1992). In Maryland and Delaware, permeable zones of shelly sand are separated by less permeable silt and clay zones. The Lower Chesapeake aquifer includes fine, shelly sands in Virginia and phosphatic sands and limestone beds in North Carolina.

The Lower Chesapeake aquifer is confined over most of its extent, but it includes up-dip unconfined sections in New Jersey, Delaware, and Maryland where overlying confining units are absent and the aquifer is in direct hydraulic connection with the surficial aquifer (Andreasen and others, 2013). The Lower Chesapeake aquifer is thickest in the Salisbury Embayment in Maryland and Delaware where its average thickness is about 300 ft. In New Jersey, the average thickness of the Lower Chesapeake aquifer is about 200 ft (Trapp, 1992). The Lower Chesapeake aquifer thins to the north and west. The southern section in Virginia and North Carolina is typically less than 50 ft thick (McFarland and Bruce, 2006; Trapp, 1992). This aquifer is an important groundwater supply in New Jersey, Delaware, and Maryland east of the Chesapeake Bay, but is sparsely used elsewhere (Martin, 1998; Andreasen and others, 2013).

The regional confining unit overlying the Lower Chesapeake aquifer includes an unnamed confining unit in New Jersey, the Saint Marys confining unit in Delaware, Maryland, and Virginia, and the Pungo River confining unit in North Carolina. This Miocene unit primarily composes silt and clay but is diatomaceous in New Jersey and silty and shelly in Delaware, Maryland, and Virginia (Trapp, 1992). The thickness of the unnamed confining unit is about 100 ft across much of its extent but may be as great as several hundred feet (Trapp, 1992; McFarland and Bruce, 2006). Despite some spatial variability in its configuration, this confining unit serves as a regional impediment to groundwater flow over a large part of its extent.

Upper Chesapeake Aquifer

The Upper Chesapeake aquifer includes the Upper Kirkwood-Cohansey aquifer in New Jersey, the Pocomoke and Manokin aquifers in Delaware, the Pocomoke, Ocean City, and Manokin aquifers in Maryland, the Yorktown-Eastover aquifer in Virginia, and the Yorktown aquifer in North Carolina (fig. 9). The Upper Chesapeake aquifer is not present on Long Island.

This aquifer consists of permeable sediments of the upper part of the Miocene to Pliocene-age Chesapeake Group. The aquifer composes primarily sands of marine origin in North Carolina and Virginia but transitions northward to New Jersey into coarser sands and gravels of fluvial origin (Trapp, 1992). The permeable sands of the Upper Chesapeake aquifer contain substantial interbeds of less permeable silt and clay, particularly in Delaware, Maryland, and Virginia.

This regional aquifer is confined over most of its extent by an overlying clay layer and forms the uppermost confined aquifer in the NACP aquifer system (Trapp and Meisler, 1992). The Upper Chesapeake aquifer subcrops beneath the surficial aquifer along the thin western margin of the surficial aquifer and where the overlying confining unit has been incised by major river valleys. The average thickness of the Upper Chesapeake aquifer ranges from less than 100 ft in North Carolina to about 400 ft in Maryland and Delaware and is between 100 and 200 ft in New Jersey and Virginia (Trapp, 1992). It is a moderately important water resource over much of its extent.

Surficial fluvial-deltaic sediments, possibly of the Lower Chesapeake and Upper Chesapeake aquifers, were included in previous studies (Meng and Harsh, 1988; Trapp, 1992) in an unconfined part of the Yorktown-Eastover aquifer in the northwestern coastal plain of Virginia. These sediments are now considered part of the surficial aquifer in Virginia (McFarland and Bruce, 2006) and are included in the regional Surficial aquifer based on their hydraulic connection with other parts of the unconfined Surficial aquifer system. In contrast, unconfined Surficial sediments in the northwestern part of the Upper Kirkwood-Cohansey aquifer in New Jersey have previously been included in the Upper Chesapeake regional aquifer where a distinct Surficial aquifer was not identified separately, despite the presence of undifferentiated Quaternary sediments (Trapp, 1992).

The regional confining unit that overlies the Upper Chesapeake aquifer over most of its extent and underlies the unconfined Surficial aquifer includes the Holly Beach aquifer in New Jersey (only on the Cape May peninsula), the Upper Chesapeake confining unit in Delaware and Maryland, the Yorktown confining zone in Virginia, and the Yorktown confining unit in North Carolina. This regional unit consists of Pleistocene estuarine clays in New Jersey and clay, silty and sand clay, and shells of Miocene to Pliocene age in Delaware, Maryland, Virginia, and North Carolina (Trapp, 1992). Over much of its area, this confining unit is less than 20 ft thick, but it may be up to tens of feet thick in some locations (Trapp, 1992; McFarland and Bruce, 2006). The spatially variable composition and configuration of this unit is responsible for highly variable interactions between the Upper Chesapeake regional aquifer and the overlying Surficial aquifer. In general, this confining unit impedes groundwater flow to a greater extent with increasing distance from the Fall Zone.

Surficial Aquifer

The Surficial aquifer is the uppermost aquifer in the NACP aquifer system, with its top altitude at land surface (fig. 9). It is unconfined, mostly shallow, and usually hydraulically continuous throughout the NACP but may exhibit lateral discontinuities and contain locally confined zones (Trapp, 1992).

Across most of the New Jersey Coastal Plain, permeable surficial sediments of Pleistocene to Holocene age that are hydraulically continuous with older, underlying sediments have been grouped with these older sediments into the unconfined upper part of the undifferentiated Kirkwood-Cohansey aquifer system (Upper Chesapeake regional aquifer) and have not been separately identified as the Surficial aquifer (Trapp, 1992). However, at least part of the unconfined Kirkwood-Cohansey aquifer is hydrologically equivalent to the Surficial aquifer as described in other States, and therefore could be grouped with the regional Surficial regional aquifer.

In New Jersey, the Surficial aquifer also includes the Holly Beach local aquifer of Holocene age near Cape May; the Holly Beach aquifer is separated from the underlying Upper Kirkwood-Cohansey aquifer by the Cape May confining unit (Martin, 1998).

On Long Island, the Surficial aquifer is composed of mostly glacial deposits and is referred to as the Upper Glacial aquifer. Across much of its extent, the unconfined Upper Glacial aquifer is hydraulically continuous with the underlying Magothy aquifer (Smolensky and others, 1989).

The Surficial aquifer is of extremely heterogeneous composition due to the variable depositional origin of its sediments, which consist of unconsolidated sand and gravel in valley, terrace, dune, beach, marine, and glacial deposits ranging in age from Miocene to Holocene (Trapp, 1992). The thickness of the Surficial aquifer is highly variable but averages about 50 ft over most of its extent. The Upper Glacial portion of the Surficial aquifer on Long Island is much thicker, with an average of about 250 ft. The Surficial aquifer also may be as thick at 250 ft in buried channels on the Delmarva Peninsula in Delaware, Maryland, and Virginia where older marine sediments were eroded and replaced by Quaternary sediments of fluvial origin.

In most locations, the Surficial aquifer is a moderately important groundwater resource, providing the most accessible water supply for individual domestic users and small community systems. On the Delmarva Peninsula in Delaware and Maryland, the Surficial aquifer is an important supply of groundwater for agricultural irrigation and municipal supply. On Long Island, the Upper Glacial aquifer is a major water resource for many uses and, in combination with the Magothy aquifer, is part of an unconfined system that supplies most of the groundwater withdrawn.

Hydraulic Properties

A substantial amount of data exists on the hydrologic properties of the aquifers and confining units within the NACP. Hundreds of measurements of transmissivity, hydraulic conductivity (most commonly horizontal for aquifers and vertical for confining units), and specific storage from aquifer tests and laboratory permeameter samples are available throughout the study area. Even so, data are relatively sparse for the apparent heterogeneity of the hydrogeologic units, and the spatial distribution of measurements is extremely uneven and focused primarily around major pumping centers. Consequently, measurements of hydraulic properties are more readily available in areas of higher groundwater use and for those particular aquifer units receiving the most use.

Similarly, many more data are available of the hydraulic properties for aquifers than for confining units. For example, hundreds of measurements of hydraulic conductivity or transmissivity are available for the Potomac aquifer system, but data on other, less commonly used aquifers are much more limited, and for a few of the confining units, only a handful of measurements may be available throughout the entire study area.

Sources of published measurements of aquifer and confining unit properties summarized in this report include the NACP RASA hydrogeologic framework report (Trapp, 1992) and several State-level hydrogeologic framework reports and analyses (McClymonds and Franke (1972) for Long Island, Martin (1998) for New Jersey, Andreasen and others (2013) for Delaware and Maryland, and McFarland and Bruce (2006) for Virginia). In addition to hydraulic properties from published reports, unpublished data from more recent analyses were obtained for Delaware (John Callahan, Delaware Geological Survey, written commun., 2012), Maryland (Andreasen and others, 2013), and Virginia (McFarland, 2013). However, these data have not been analyzed extensively for spatial trends or patterns and are discussed in this report only in terms of summary statistics.

As a result, data on hydraulic properties available for aquifers generally are not sufficient to determine consistent patterns of variation at either the local or the regional scale, and only a few studies have attempted to describe systematically these spatial variations. Notable examples include an analysis of hydraulic properties of all the aquifers on Long Island (McClymonds and Franke, 1972), the analysis of transmissivity values in the Maryland Coastal Plain (Hansen, 1971), and a very recent analysis of the hydrogeologic characteristics of the Potomac aquifer in Virginia (McFarland, 2013). More commonly, available measurements of hydraulic properties serve only as starting points for groundwater modeling studies, and hydraulic properties for individual units then are determined through the model-calibration process. These estimates are somewhat dependent on the spatial and temporal discretization of the groundwater-flow models but probably are more representative of the regional hydraulic properties than estimates obtained from short-term pump tests or laboratory permeameter tests.

Published values of transmissivity and hydraulic conductivity from aquifer tests and laboratory studies for NACP aquifers and confining units reveal some general similarities and differences among various hydrogeologic units, though transmissivity variations generally appear to be more of a function of aquifer thickness than of large measured differences in the hydraulic conductivity of aquifer materials.

Published values of horizontal hydraulic conductivity for aquifers of the fluvial-deltaic Potomac aquifer system range from less than 1 foot per day (ft/d) to more than 500 ft/d within the individual States, whereas regionally the averages range from about 30 to about 200 ft/d. The large thickness of the Potomac aquifer system in Virginia has resulted in published transmissivity values as large as 58,000 square feet per day (ft^2/d; McFarland, 2013).

Published values of hydraulic conductivity for the Magothy aquifer in New York, New Jersey, Delaware, and Maryland are very similar to those in the Potomac aquifer system. A horizontal hydraulic conductivity value of 642 ft/d for the Magothy aquifer on Long Island (McClymonds and

Franke, 1972) may be the highest value reported for any aquifer in the NACP. Transmissivity values of 56,000 ft^2/d reported on Long Island are similar to the values reported for the Potomac aquifer in Virginia despite the much thinner Magothy aquifer on Long Island.

The Tertiary and Cretaceous aquifers formed from marine transgressions and regressions tend to exhibit similar hydraulic properties to each other, based on a limited number of published values. These aquifers include the regional Piney Point, Aquia, Monmouth-Mount Laurel, and Matawan aquifers, all of which are considerably thinner than most of the other NACP aquifers. Horizontal hydraulic conductivity values of as much as several hundred feet per day have been reported in these aquifers, but average values range from about 10 to about 40 ft/d across the NACP. Transmissivity values typically are less than 5,000 ft^2/d and reflect both the lower hydraulic conductivities and thinner aquifer units.

Published values of horizontal hydraulic conductivity for the relatively clean and coarse marine sands of the surficial aquifer reveal a similar range to the Cretaceous fluvial-deltaic sands, with a minimum of less than 1 ft/d and a maximum of about 500 ft/d. The upper end of this range, however, is most typical of the thick Upper Glacial aquifer on Long Island, where transmissivity values as high as 27,000 ft^2/d have been reported (McClymonds and Franke, 1972). Buried fluvial channels on the Delmarva Peninsula exhibit values approaching those observed on Long Island. The confining and Lower Chesapeake aquifers of Pliocene and Miocene age have a range of measured hydraulic conductivities typically lower than that of the Surficial aquifer, particularly in Maryland (Andreasen and others, 2013).

Hydraulic properties of the confining units separating these regional aquifers are known primarily from a very limited number of laboratory permeameter measurements and from estimates based on groundwater-flow model calibration. Consequently, the large range of values for vertical hydraulic conductivity may reflect the scales of those estimates and measurements in addition to the range of vertical hydraulic conductivity values in the confining units. Published values of vertical hydraulic conductivity for confining units range from about 3.0×10^{-9} to 0.1 ft/d in the NACP. The high value of 0.1 ft/d was reported for the confining unit above the Monmouth-Mount Laurel aquifer in New Jersey, and the low value of 3.0×10-9 ft/d was reported for the confining unit above the Middle Potomac aquifer in Maryland. The observed range of values within each hydrogeologic unit, however, is almost as large as the observed range reported here for all hydrogeologic units together, indicating substantial spatial variations in the properties of these confining units that are not yet fully understood at the regional scale.

Storage properties in the confined aquifers and confining units of the NACP aquifer system have been determined from aquifer tests conducted primarily for water-supply development throughout the study area. Measured values of elastic specific storage (S_s) in the confining units typically are in the range of 1.8×10^{-6} to 4.0×10^{-6} per foot (ft^{-1}). However, values of one to two orders of magnitude greater have been reported throughout the study area, and these larger values appear to be more common in the shallow units (Martin, 1998; Heywood and Pope, 2009; Andreasen and others, 2013).

The large reported values of S_s are higher than expected for these types of materials and may reflect specific issues with the aquifer tests, such as short screens in thick aquifers, as well as interpretive problems arising from borehole storage effects, partial well penetration, or aquitard leakage (Heywood and Pope, 2009). Given the uncertainty in the measured values, model-calibrated values for S_s may reflect more realistically ambient aquifer conditions and behavior at the regional scale.

In previous regional and subregional simulations of the NACP aquifer system, a dimensionless storage coefficient value of 1.0×10^{-4} was used for all aquifers (Harsh and Laczniak, 1990; Leahy and Martin, 1993). This storage coefficient would translate to a range of S_s between 2.0×10^{-7} and 1.0×10^{-5} ft^{-1} for NACP aquifers over a thickness ranging from 10 to 500 ft. Most previous groundwater models of the NACP have not explicitly simulated storage in confining units, but a recent model of the Virginia Coastal Plain estimated values of specific storage ranging from about 5.0×10^{-4} to 1.0×10^{-6} ft^{-1} (Heywood and Pope, 2009).

Actual measurements of S_s in confining units are limited to a few laboratory consolidation tests of clayey sediments. One such study conducted in Maryland reported S_s values ranging from 3.6×10^{-5} to 9.0×10^{-5} ft^{-1} for the marine Marlboro Clay confining unit and from 4.6×10^{-5} to 7.6×10^{-5} ft^{-1} for the Upper Potomac confining unit (Hansen, 1977). A study estimating aquifer depletion for the Virginia Coastal Plain assumed a range of values between 1.0×10^{-5} and 1.0×10^{-4} ft^{-1} for specific storage of confining layers (Konikow and Neuzil, 2007).

Another study applied analysis and modeling of extensometer data from the coastal plain of Virginia to estimate inelastic specific storage values ranging from 4.6×10^{-6} to 1.6×10^{-5} ft^{-1} for fine-grained interbeds within the Potomac aquifer system and from 3.0×10^{-5} to 4.6×10^{-5} ft^{-1} for post-Cretaceous fine-grained sediments (Pope and Burbey, 2004). This study also determined elastic specific storage values between 1.4×10^{-6} and 1.8×10^{-6} ft^{-1}.

A comprehensive analysis of the updated information on hydrogeologic framework geometries since the previous regional assessment of the NACP aquifer system (Trapp and Meisler, 1992) may reveal spatial patterns in aquifer and confining unit hydraulic properties that have yet to be determined. In addition to descriptions of variations in hydraulic conductivity and transmissivity described in this report, a more comprehensive understanding of the storage properties of the confining units and aquifers is needed to properly characterize groundwater flow through each of these units; such an analysis was beyond the scope of the data synthesis presented in this report.

Hydrologic Conditions

Continued land development and population growth in the NACP have created concerns regarding the supply of potable groundwater and the quality and quantity of water discharging to ponds, streams, and coastal waters. An important component of assessing groundwater availability is an understanding of the processes that govern how water enters, flows through, and exits aquifer systems.

Previous Investigations

Numerous studies have been conducted to characterize the hydrogeology of the NACP, some dating back to the early 20th century (Crosby, 1900; Freeman, 1900; Sanford, 1911). These early studies were synthesized for the region-wide study of hydrologic and geologic constraints on groundwater flow and water availability conducted from 1978 through 1987 (RASA program; Trapp and Meisler, 1992). Hydrogeologic data collected as part of the RASA effort served as the basis for the subsequent numerical models developed for the NACP aquifer system throughout the study area.

Numerical models provide a means to synthesize existing hydrogeologic information into an internally consistent mathematical representation of a real system and, during the past 30 years, have been instrumental in understanding the processes that affect groundwater flow and availability in the NACP aquifer system. A regional model (Leahy and Martin, 1993) that extended from Long Island to South Carolina and subregional models of New Jersey (Martin, 1998), Maryland and Delaware (Fleck and Vroblesky, 1996), Virginia (Harsh and Laczniak, 1990), and North Carolina (Giese and others, 1997) were used to assess water budgets from pumping conditions from predevelopment (pre-1900) through 1980. The regional and subregional models incorporated the hydrogeologic framework derived from the statewide RASA programs for New Jersey (Zapecza, 1989), Virginia (Meng and Harsh, 1988), Maryland and Delaware (Vroblesky and Fleck, 1991), and North Carolina (Winner and Coble, 1989). In addition to these statewide RASA studies, a separate analysis of groundwater availability was conducted for Long Island based on the regional model of the island (Reilly and Harbaugh, 1980).

Since the RASA study, more recent analyses have built upon the statewide NACP models, including updates to the hydrogeologic framework, finer grid discretization, and improved numerical codes. More recent modeling efforts in New Jersey include the use of the USGS numerical code SHARP (Essaid, 1990) to simulate the position and movement of the interface between freshwater and saltwater (Pope and Gordon, 1999) and later, a conversion of the model datasets (Voronin, 2005) to be compatible with the modular three-dimensional (3-D) finite-difference groundwater flow model MODFLOW–96 (Harbaugh and McDonald, 1996). The updated model by Voronin (2005) also included a finer grid discretization, spatially variable recharge, and a more recent pumping period (1968–1998).

The first model for the Virginia Coastal Plain (Harsh and Laczniak, 1990) originally used a numerical finite-difference code developed by Trescott (1975) and was updated in the late 1990s to MODFLOW–96 (McFarland, 1998). The most recent model for the Virginia Coastal Plain (Heywood and Pope, 2009) was developed to include the latest interpretation of the hydrostratigraphy (McFarland and Bruce, 2006), most notably the presence of the large impact crater discovered in the Chesapeake Bay in the early 1990s (Powars and Bruce, 1999). This model was based on the numerical code SEAWAT (a computer program for simulation of 3-D variable-density groundwater flow and transport; Guo and Langevin, 2002) to simulate position and movement of the interface between freshwater and saltwater for the simulation period (1891–2003). The model for the Long Island region (Reilly and Harbaugh, 1980) also was updated, for use with MODFLOW–88 (McDonald and Harbaugh, 1988) for the averaged period between 1968 and 1983. The updated model for Long Island (Buxton and Smolensky, 1999) included an updated interpretation of the hydrostratigraphy of the island (Smolensky and others, 1989).

In addition to regional and statewide assessments, several small-scale studies have been done in the area that focus on the surficial unconfined and shallow, confined aquifers. These studies include areas such as in the Eastern Shore of Virginia where there has been concern about the effects of pumping on the position and movement of the interface between freshwater and saltwater (Richardson, 1994; Sanford and others, 2009). Ongoing work by the Chesapeake Bay Program in the Delmarva Peninsula is focused on understanding the transport of nutrients to the bay through the shallow groundwater flow system (Sanford and Pope, 2007; Sanford and others, 2012).

These recent studies have improved the understanding of the hydrogeologic and water-use conditions in the NACP, but the information obtained from these studies has not been synthesized into a regional hydrogeologic perspective similar to what had been done as part of the original RASA study for the NACP (Trapp and Meisler, 1992). A region-wide assessment of water-level changes (DePaul and others, 2008) based on long-term and synoptic water-level data from predevelopment (1900) to 2000 shows significant changes in water levels since the RASA study and highlights the need for an updated regional assessment of hydrologic impacts resulting from changing stresses since 1980.

Sources of Water to the Northern Atlantic Coastal Plain Aquifer System

About 81,000 Mgal/d or about 29 trillion gallons per year (Tgal/yr) of freshwater enters the NACP area. The sources of water to the NACP aquifer system include recharge from precipitation, wastewater, leaky sewer and water-supply lines, and the eastward flow of groundwater and surface water across the Fall Zone (fig. 12). Estimates of freshwater input from wastewater and leaky water-supply and sewer lines are described in the "Wastewater Return Flow" section.

Aquifer Recharge

The primary source of water into the NACP aquifer system is recharge from precipitation. The average annual rate of precipitation (2005–2009) was about 45 in/yr in the NACP study area (see appendix 1). Over the study area (30,000 mi^2), this rate of precipitation is equal to about 62,000 Mgal/d or 23 Tgal/yr of freshwater input. Although there is as much 23 Tgal/yr of precipitation in the NACP study area, only about 31 percent (19,600 Mgal/d) or about 7 Tgal/yr of it enters the underlying aquifer system as recharge. The majority of the precipitation in the NACP (69 percent) is lost to evaporation, transpiration, or surface runoff and, therefore, never reaches the underlying groundwater system. A detailed description of the SWB method used to calculate aquifer recharge for the NACP is included in appendix 1.

Nearly all the recharge that enters the NACP aquifer system does so in the shallow unconfined aquifers. Previous analyses (Leahy and Martin, 1993; McFarland, 1999) have determined that only a small percentage (less than 2 percent) of the available aquifer recharge enters the deeper, confined aquifer system under predevelopment conditions, where the deeper confined units crop out near the Fall Zone in the western part of the study area (fig. 7).

Recharge also can enter the underlying confined aquifers indirectly as induced infiltration of water from overlying aquifers and confining units in response to pumping in the deeper aquifers (fig. 13). Leahy and Martin (1993) calculated that the area contributing recharge to the underlying confined aquifer system increased from 25 percent to 45 percent of the land area in response to 1980 pumping conditions as compared to predevelopment.

The amount of recharge entering the NACP aquifer system in 2005 was determined for this investigation by the SWB method described in Westenbroek and others (2010) and presented in appendix 1 of this report. The results of this analysis indicate that aquifer recharge is about 13.9 in/yr, which results in about 19,600 Mgal/d of water entering the NACP aquifer system (fig. 14). The average recharge value of 13.9 in/yr is consistent with the range of reported recharge values (11.8 to 21.7 in/yr) throughout the study area. A more detailed description of the methodology used to calculate aquifer recharge from 2005 through 2009 and a listing the recharge rates reported throughout the NACP are included in appendix 1 of this report.

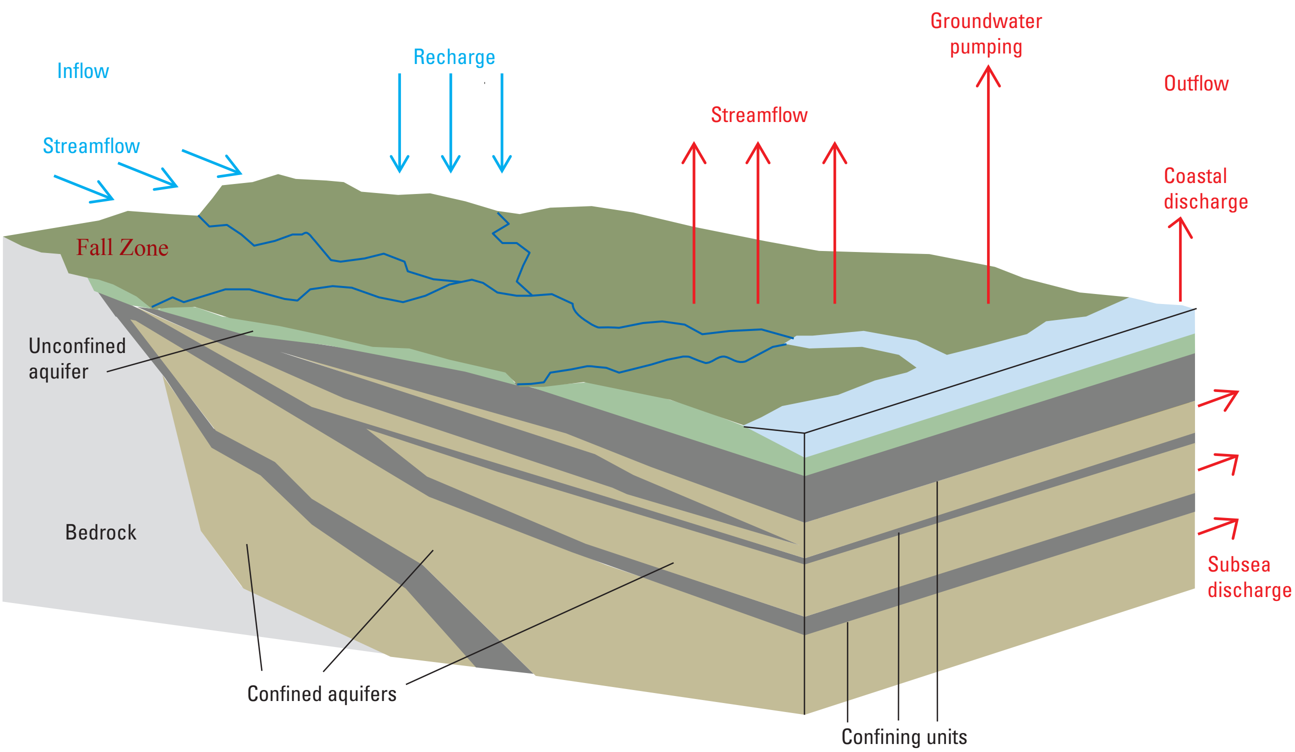


Figure 12. Schematic diagram showing the conceptual hydrogeologic model of the Northern Atlantic Coastal Plain aquifer system; modified from Edwin McFarland (U.S. Geological Survey, written commun., 2010).

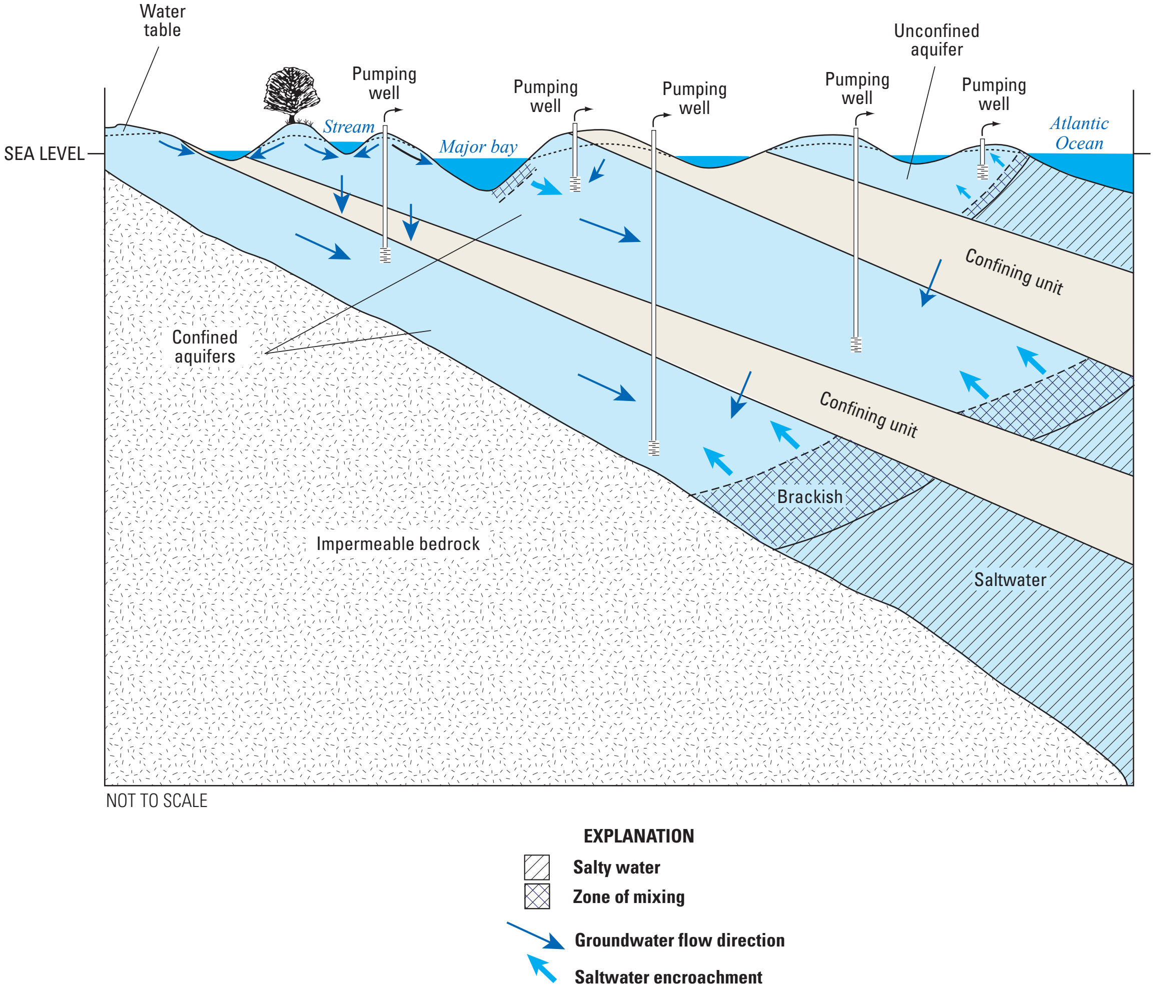


Figure 13. Schematic diagram showing the effects of pumping on groundwater flow in the Northern Atlantic Coastal Plain aquifer system. From Barlow (2003).

Wastewater Return Flow

Recharge of wastewater from centralized sewage treatment facilities or from onsite domestic septic systems also can be an important source of water to the NACP aquifer system. This wastewater can originate as (1) fresh groundwater withdrawn from the underlying aquifer system, (2) treated saline groundwater withdrawn from the aquifer system, (3) surface-water sources within the NACP area, or from (4) surface waters imported into the NACP for drinking water. Regardless of the origin of this wastewater, eventually it all discharges to the NACP groundwater system or nearby surface waters. Nearly all the centralized wastewater treatment facilities in the NACP are located in close proximity to surface waters, and therefore, wastewater released from these facilities most likely discharges directly to these water bodies and reaches the coast without interacting with the groundwater system (fig. 15). However, in areas with aging public-supply distribution and sewer systems, such as the New York City area, leakage from these aging infrastructures can contribute as much as 70 Mgal/d of water to the shallow aquifer system from leaking lines throughout the area (Misut and Monti, 1999).

The importance of inflow of water from leaking sewer systems to the underlying aquifer system may not be as great, however, because sewer lines in low-lying coastal areas have the potential to be below the water table. If sewer lines are below the water table, then the potential exists for groundwater also to flow into the leaky sewer lines, thus offsetting the contribution of water to the aquifer system from leaks along sewer lines (Buxton and Smolensky, 1999). A more comprehensive analysis than was possible for this investigation would be needed to assess fully the interaction of sewer systems with the shallow, unconfined aquifer system of the NACP and its relative importance to the hydrologic budget.

A potentially more substantial source of water to the aquifer system from wastewater comes from the about 3.3 million residents who use onsite domestic septic systems in non-sewered areas. Assuming that as much as 85 percent of the 70 gallons per day (gal/d) of the estimated

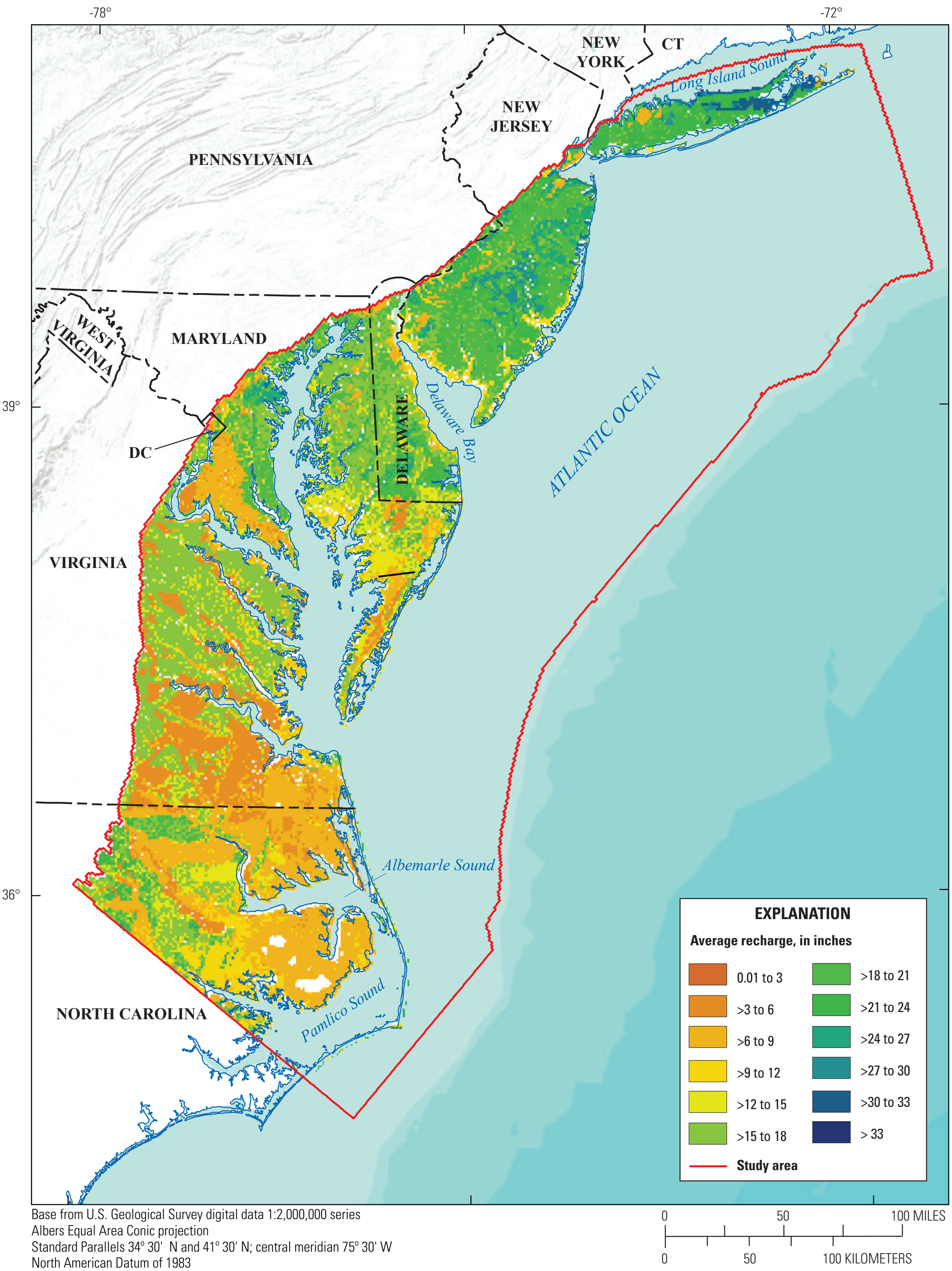


Figure 14. Distribution of aquifer recharge for the Northern Atlantic Coastal Plain aquifer system.

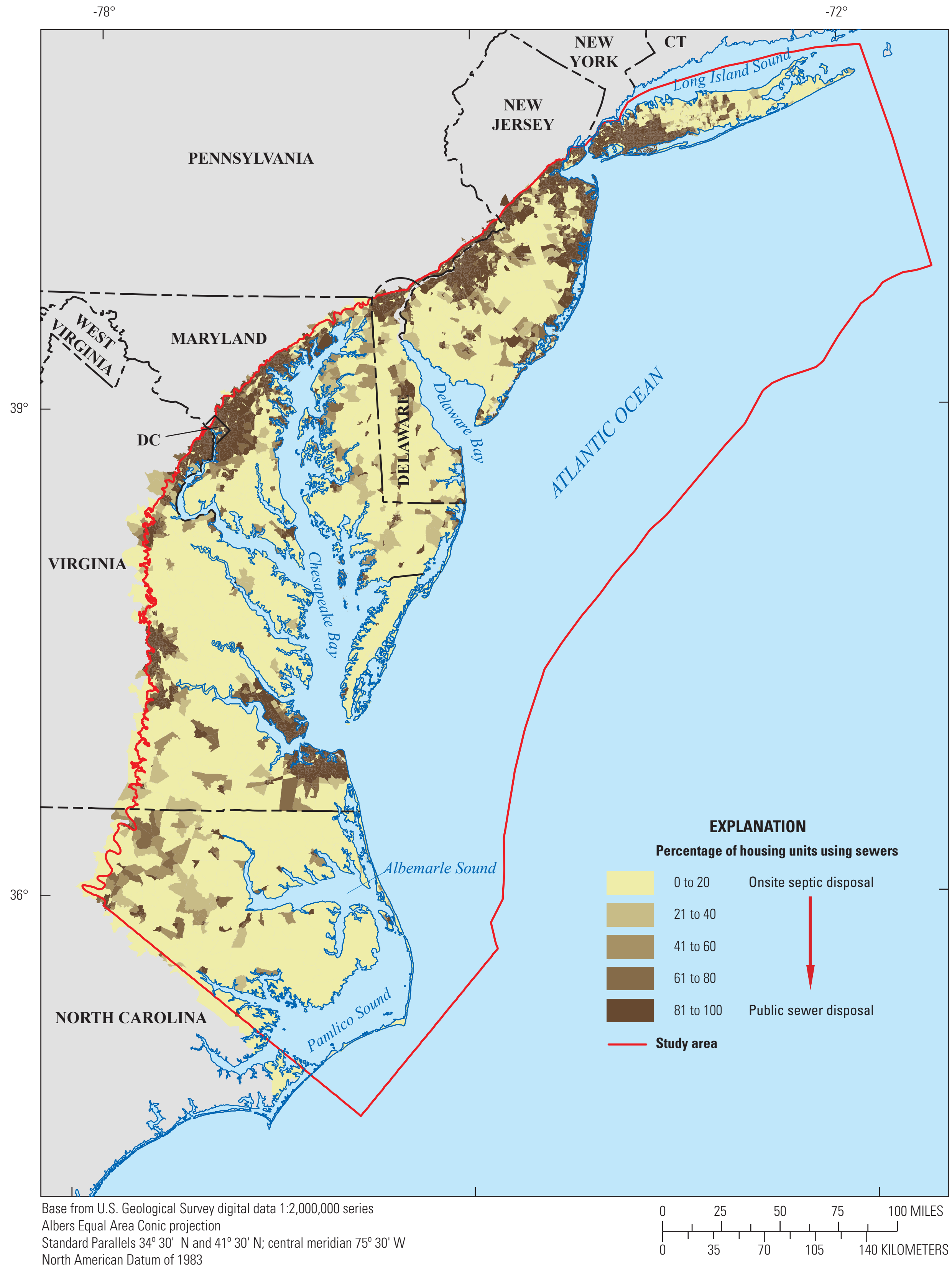


Figure 15. Distribution of sewer and wastewater systems in 2005 in the Northern Atlantic Coastal Plain.

per capita consumption of water (Shaffer and Runkle, 2007) is discharged to domestic septic systems, a total of about 200 Mgal/d of wastewater would be estimated to be discharged to the shallow, unconfined aquifers throughout the NACP.

Wastewater returned to the aquifer system through domestic septic systems can mitigate the potentially adverse effects of pumping on the flow system depending where the water originated and ultimately where it is discharged. Groundwater withdrawn from deep confined aquifers that returns as wastewater to the shallow, unconfined aquifer system may represent only a 15 percent loss to the overall hydrologic budget; however, this redistribution of pumped water may actually represent a complete loss of water from the deep confined aquifer from which the water was withdrawn. This loss of water from the deeper system then may result in decreased deep subsea coastal discharge and increase the potential for saltwater intrusion (fig. 13).

Lateral Inflow

Another source of freshwater to the NACP is streamflow across the Fall Zone (fig. 1). Streamflow in the NACP can be grouped into three categories: (1) rivers that flow directly from upland areas to coastal water bodies along the Fall Zone, (2) rivers that flow eastward across the Fall Zone and through a portion of the NACP before discharging at the coast, and (3) rivers that originate entirely within the NACP. Regardless of origin, all the major rivers that flow through the NACP discharge to the coastal waters of the Atlantic Ocean (fig. 16).

Selected larger streams (Strahler stream order 3 or higher; Pierson and others, 2008) were evaluated spatially to determine their contributions to surface-water flow in the study area. Streamflows were totaled by period of record by hydrologic basin using the NHDPlus attribute data (table 1; U.S. Environmental Protection Agency, 2006). Stream segments crossing the Fall Zone, which defines the western boundary of the NACP, are considered surface-water inflows to the NACP, whereas segments intersecting the tidal zone downstream as delineated by Titus and Wang (2008) are considered part of the coastal discharge areas.

NHDPlus attribute data include computation of mean annual flow (unit runoff method; Research Triangle Institute, 2001) and Strahler stream order (Pierson and others, 2008) for every segment in the stream network. These attributes were extremely useful in evaluating the surface-water network because they allowed for estimation of flow at any location in the stream network. Initial analysis determined that the large rivers account for the majority of the surface-water flow through the NACP, and therefore, a simple network of the large rivers and streams could be used to represent the flow network for the purposes of a hydrologic budget analysis. NHDPlus streams of order 3 and larger comprise a network of streams totaling about 4,000 mi in length (fig. 16) and account for about 98 percent of the mean annual flow into the NACP at the Fall Zone (table 1).

For some of the large rivers in the study area, tidal zones in the primary channels extend westward of the Fall Zone, and water flows directly from the Piedmont Province to coastal waters entirely bypassing the fresh surface-water and groundwater flow systems of the NACP. Flow from these rivers, including the Hudson, Delaware, Susquehanna, Potomac, and Roanoke (fig. 16), was not considered as either inflow or outflow to the NACP, despite the large total flow (about 47,000 Mgal/d).

For streams that originate in the Blue Ridge or Piedmont Provinces and flow into the NACP at the western boundary of the study area, the surface-water inflow to the NACP totals about 18,600 Mgal/d (table 1). Of this total amount of flow, most if not all flows through the NACP and discharges directly to the coast without contributing water to the underlying aquifer system.

Previous analyses in Virginia and New Jersey have examined the potential contribution of streamflow to the underlying groundwater system along the Fall Zone in the NACP. McFarland (1999) determined that rivers entering the Virginia Coastal Plain away from the influence of groundwater pumping stresses act as drains to the local groundwater system and, therefore, do not contribute water to the underlying groundwater system (fig. 17).

Navoy and Carleton (1995) determined that under certain pumping conditions, groundwater withdrawals in the western portion of the NACP in New Jersey resulted in induced infiltration of surface water from the Delaware River into the aquifer system and served as a source of water to pumping wells in Camden, N.J. Therefore, the amount of freshwater contribution from streamflow entering the NACP across the Fall Zone to the deep, confined aquifer system is difficult to quantify and may vary across the study area depending on local hydrogeologic conditions and on the amount and distribution of groundwater withdrawals.

Additional sources of freshwater into the NACP that are not readily quantifiable and are assumed to be of less importance are the subsurface flow across fractured rock in the upland Piedmont Province and the lateral flow across the southern boundary of the study area in North Carolina. In Virginia, the subsurface fractured rock flow from the upland Piedmont Province to the NACP deposits was about 13 Mgal/d (Heywood and Pope, 2009). Previous regional modeling efforts of the NACP aquifer system (Leahy and Martin, 1993) assumed that subsurface fractured rock flow was negligible.

The southern boundary of the study area for this investigation coincides with the east-west regional groundwater flow direction. Large changes in groundwater withdrawals can alter flow patterns near this boundary and locally affect the water budget to the NACP aquifer system (Heywood and Pope, 2009; Campbell and Coes, 2010); however, for the purpose of this analysis, it was assumed that any flow that either enters or exits across this southern boundary represents only a small portion of the total flow in this aquifer system.

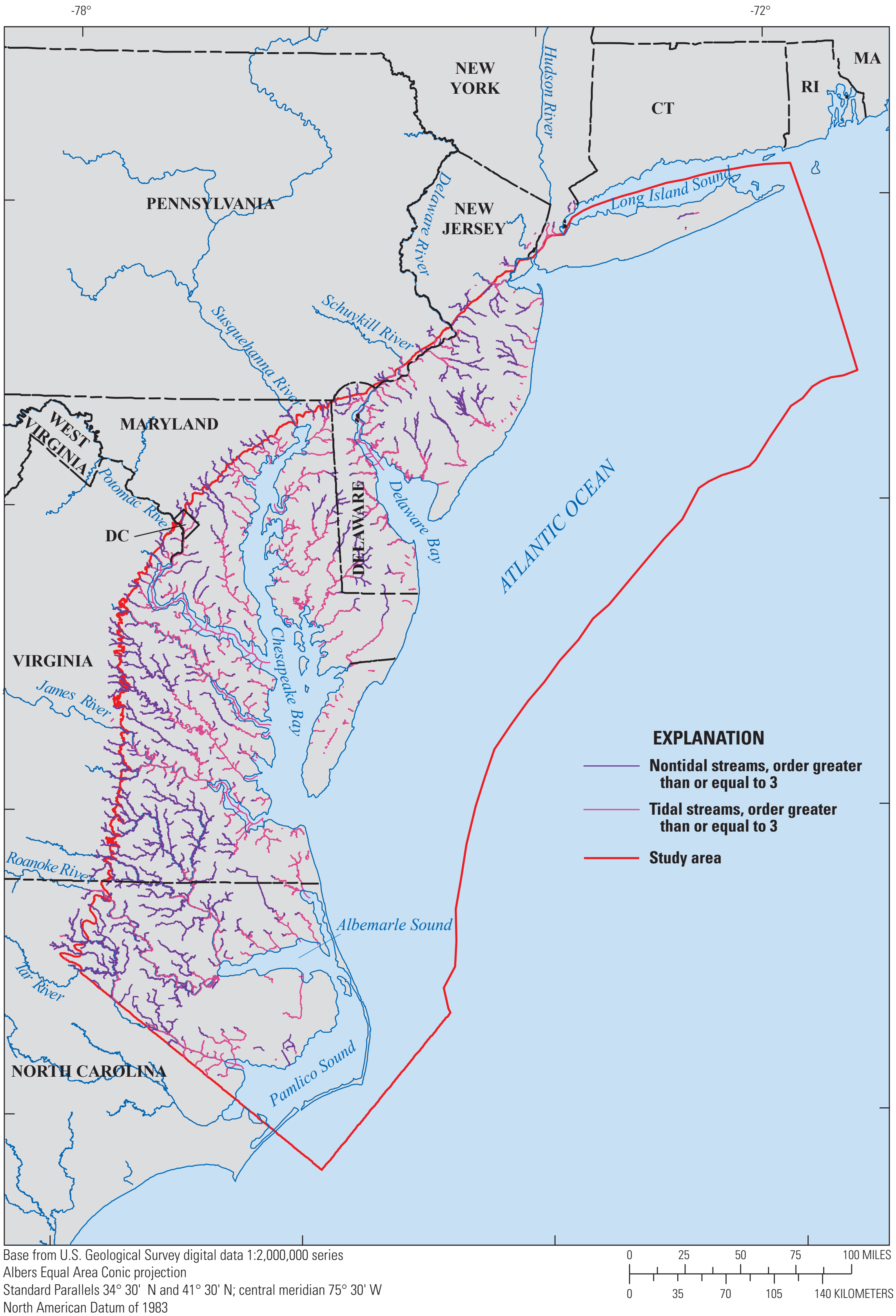


Figure 16. Distribution of major streams and rivers that flow across the Northern Atlantic Coastal Plain.

Table 1. Mean annual inflows and outflows for major river systems in the Northern Atlantic Coastal Plain (NACP) for conditions in 2005.

[All values are in billion gallons per day. NACP, North Atlantic Coastal Plain; —, no data reported]

River system	Surface-water inflow across Fall Zone	Groundwater discharge		Total outflow to tidal waters
		To rivers originating outside NACP	To rivers originating in NACP	
Hudson River tributaries	—	—	0.2	0.2
Delaware River tributaries	8.4	0.1	1.2	9.7
Atlantic Ocean (New Jersey)	—	—	1.1	1.1
Upper Chesapeake Bay:				
Upper Delmarva Peninsula	0.1	0	0.9	1
Patapsco River	0.4	0.4	—	0.8
Patuxent River	0.2	0.1	0.1	0.4
Middle Chesapeake Bay, Potomac River tributaries	0.2	0.5	0.5	1.2
Lower Chesapeake Bay:				
Middle and lower James River	5.7	0.3	0.2	6.2
Piankatank River	—	—	0.1	0.1
Rappahannock River	1.2	0	0.2	1.4
York River	0.8	0.4	0.2	1.4
Roanoke River tributaries	—	—	0.5	0.5
Chowan River	0.9	0.8	1.5	3.2
Tar and Pamlico Rivers	0.7	1.2	1.4	3.3
Total	18.6	3.8	8.1	30.5

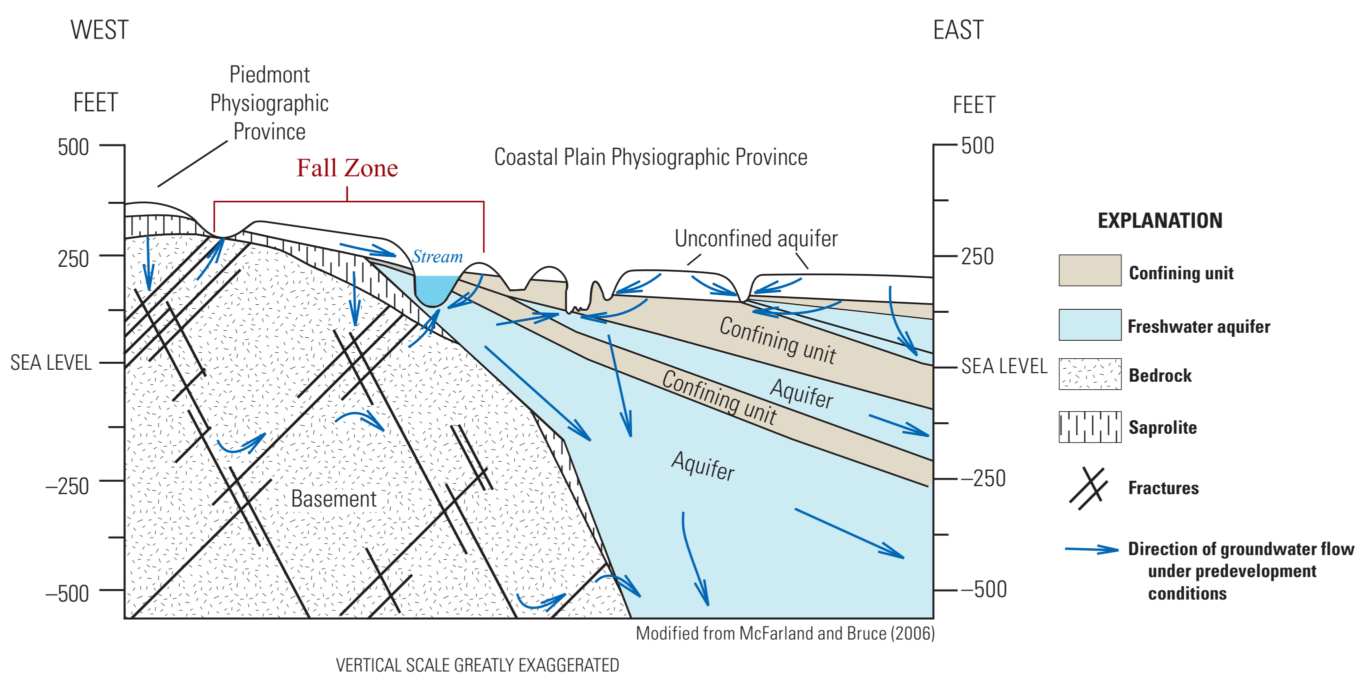


Figure 17. Schematic cross-section showing groundwater flow near the Fall Zone of the Northern Atlantic Coastal Plain.

Loss of Water from the Northern Atlantic Coastal Plain Aquifer System

For predevelopment conditions, all the water entering the aquifer system is balanced by water leaving the aquifer system. Water leaves the aquifer system as discharge to streams, discharge to shallow coastal waters, and deep subsea discharge farther offshore in the Atlantic Ocean. For post-development conditions, an additional loss of water from the aquifer system is water removed by groundwater withdrawals. Depending on type of water use and whether pumped water is removed through sewers, a substantial amount of the water withdrawn from the aquifer system may be returned in the form of wastewater return flow.

Groundwater Discharge to Streams

About 30,500 Mgal/d of total streamflow leaves the NACP as surface-water discharge to coastal waters (table 1). Of the 30,500 Mgal/d of water that flows through the NACP, about 18,600 Mgal/d originated as streamflow west of the NACP and entered the study area across the Fall Zone (table 1). The difference between the total flow leaving the NACP at the coast (30,500 Mgal/d) and the amount streamflow entering the NACP area across the Fall Zone (18,600 Mgal/d) is the amount of groundwater that discharges to streams in the NACP (about 11,900 Mgal/d), of which about 8,100 Mgal/d is to streams that originate within the NACP, and 3,800 Mgal/d is discharge to streams that originate outside of the NACP. Consequently, there is a net loss of freshwater from the NACP aquifer of about 11,900 Mgal/d from groundwater discharge to streams.

Groundwater Withdrawals

Groundwater is withdrawn from the NACP aquifer system for multiple uses, including drinking water and for commercial, industrial, and agricultural purposes. In 2005, the total amount of groundwater withdrawn was about 1,500 Mgal/d (Kenny and others, 2009). The distribution of water-use type varied spatially across the NACP, with drinking water being the primary use type in the northern part of the study area, agricultural use dominant in the middle part of the study area, and commercial and industrial uses dominant in the southern part of the study area.

The total drinking water use for the 20 million people living in the NACP in 2005 was about 2,500 Mgal/d, about 39 percent of which (or about 1,000 Mgal/d) was derived from public and domestic groundwater sources in the underlying aquifer system (fig. 18, table 2; Kenny and others, 2009). The groundwater withdrawn for drinking water accounted for 65 percent of all groundwater withdrawals in the study area (fig. 18). Most (70 percent) of these groundwater withdrawals occurred on Long Island and in New Jersey. Of the about 1,000 Mgal/d of groundwater withdrawn for drinking water, 85 percent was used for public supply, and 15 percent was from self-supplied domestic sources (table 2).

In the northern part of the study area (New York, Pennsylvania, New Jersey, and Delaware), nearly all (91 percent) the groundwater pumped for drinking water was derived from public-supply sources. In the southern part of the study area (Maryland, Virginia, and North Carolina), as much as 35 percent of the total groundwater pumped for drinking water was derived from self-supplied domestic sources (fig. 18). This change in the source of drinking water from north to south is reflected in the land use and land cover throughout the NACP (fig. 5); water demand is met by public-supply systems in the more highly developed areas to the north and by domestic self-supplied sources in the less developed areas to the south.

Treated saline groundwater provides an additional source of drinking water in several coastal communities in which saltwater intrusion issues are of concern. Desalinization of saline groundwater is a significant source of drinking water in southeastern Virginia west of the Chesapeake Bay (fig. 1) where about 11 Mgal/d of treated saline groundwater is used for drinking water (Kenny and others, 2009). Cape May, N.J.

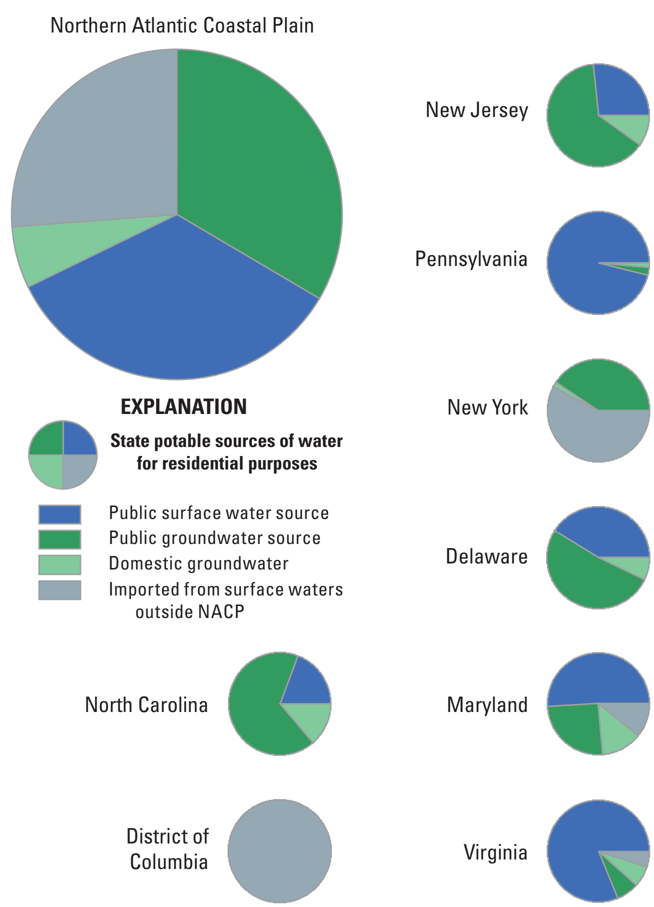


Figure 18. Distribution of drinking water sources by State across the Northern Atlantic Coast Plain.

Table 2. Distribution of drinking water sources by State across the Northern Atlantic Coastal Plain.

[Values are in million gallons per day. Water use data are from Kenny and others (2009). Grey shaded box indicates that value is zero or rounded to zero. NACP, Northern Atlantic Coastal Plain]

State	Public groundwater source	Public surface-water source	Domestic groundwater	Imported from surface waters outside NACP	Total
Distrtict of Columbia	0	0	0	70	70
Delaware	47	37	6	0	90
Maryland	83	165	42	35	325
North Carolina	32	9	7	0	48
New Jersey	260	109	41	0	410
New York	361	0	15	513	889
Pennsylvania	2	93	1	0	96
Virginia	38	430	36	26	530
Total	823	843	148	644	2,458

(fig. 1) is another location of where desalinization is used to augment drinking water supplies during the high-demand summer months.

The total agricultural water use in the NACP in 2005 was estimated to be about 300 Mgal/d with about 60 percent (179 Mgal/d) derived from groundwater sources (table 3) (Kenny and others, 2009). Most (89 percent, or 160 Mgal/d) of the 179 Mgal/d of groundwater withdrawals was for crop irrigation, with the remaining 11 percent (20 Mgal/d) for livestock (15 Mgal/d) and aquaculture (5 Mgal/d) uses. More than half (56 percent) of the 2005 agricultural groundwater withdrawals from the NACP occurred in the Delmarva Peninsula. Agricultural groundwater withdrawals were the highest in Delaware (57 Mgal/d) and accounted for about 47 percent of the total groundwater withdrawals in the State (fig. 19, table 3).

Commercial and industrial freshwater use in the NACP in 2005 was about 800 Mgal/d, of which 43 percent (338 Mgal/d) was derived from groundwater sources (table 3; Kenny and others, 2009). Groundwater withdrawals in Virginia and North Carolina accounted for about 62 percent of the total commercial and industrial groundwater uses in the NACP. The primary use of this water was for the pulp and paper industry in southern Virginia and northern North Carolina. Groundwater withdrawals for this industrial purpose resulted in the large water-level declines throughout the southern portion of the NACP (fig. 4).

Thermoelectric power plants also use a substantial amount of water in the NACP. About 20,000 Mgal/d of water is used for cooling power plants; however, nearly all this water is derived from fresh and saline surface waters, with only a small amount coming from fresh groundwater sources. The total fresh groundwater use for thermoelectric power plants throughout the NACP is about 6 Mgal/d (Kenny and others, 2009).

Total rates of groundwater withdrawals for the NACP were apportioned by aquifer for the 10 principal (regional) aquifers shown in figure 9. This analysis was based on screen interval information and local aquifer designations associated with reported withdrawals across the study area (table 4, fig. 20). The largest withdrawals occur in the Magothy regional aquifer, which accounts for about 38 percent of the total withdrawals in the NACP aquifer system. The Surficial and the Upper and Lower Chesapeake regional aquifers combined account for about 33 percent of the total use (table 4). The Surficial aquifer provides almost half (49 percent) the groundwater pumped in Delaware and almost a third of the water pumped in Maryland (30 percent). Withdrawals from the Lower Chesapeake aquifer account for only 15 percent of the total withdrawals in the NACP yet make

Table 3. Distribution of groundwater use by State across the Northern Atlantic Coastal Plain.

[Values are in million gallons per day. May not add to totals shown because of independent rounding. Water use data are from Kenny and others (2009). Grey shaded box indicates that value are is zero or rounded to zero]

State	Public and domestic supply	Agricultural	Commercial and industrial	Total
Delaware	53	57	12	122
Maryland	124	36	16	177
North Carolina	39	29	140	207
New Jersey	300	40	31	372
New York	376	9	68	454
Pennsylvania	4	0	1	4
Virginia	74	8	70	151
Total	971	179	338	1,488

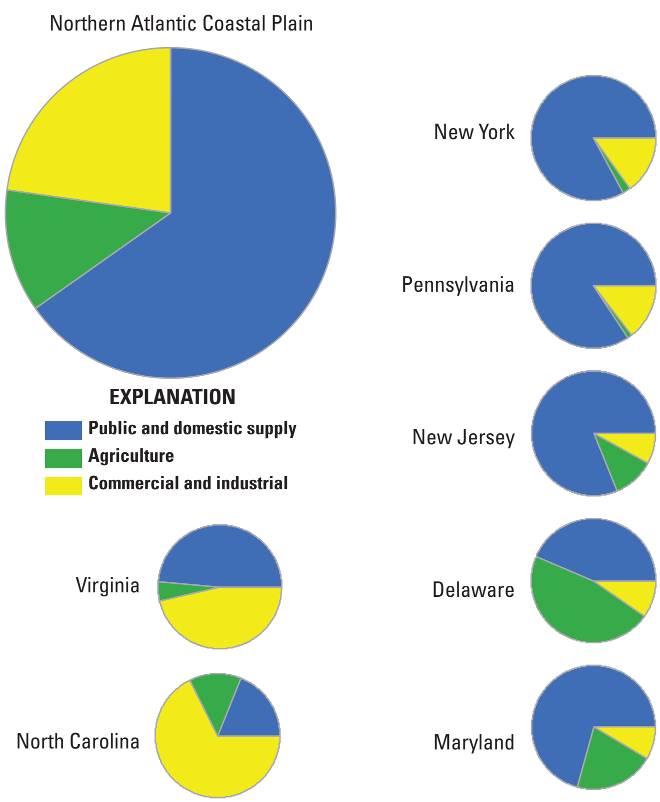


Figure 19. Distribution of groundwater use by State across the Northern Atlantic Coast Plain.

up about half (44 percent) of the total withdrawals in New Jersey where this aquifer is the primary source of drinking water in southeastern coastal areas of the State. About only 25 percent of the total NACP groundwater is withdrawn from the Potomac aquifer system, but it accounts for more than 90 percent of the total withdrawals in Virginia. The remaining 4 percent of the total withdrawals in the NACP was pumped from the Aquia, Matawan, Monmouth-Mount Laurel, and Piney Point regional aquifers (table 4).

Groundwater Discharge to Coastal Areas

Coastal waters that border the NACP are the ultimate freshwater discharge areas from the groundwater-flow system. Freshwater enters these coastal waters as either streamflow or as direct groundwater discharge through the shallow coastal seabed in the nearshore environment or farther offshore as deep subsea discharge from the deeper confined aquifers (fig. 13). Although it is not possible to make direct measurements to quantify coastal groundwater discharge, an estimate of this outflow from the aquifer system can be determined if all the other inflows and outflows to the aquifer systems can be quantified.

Groundwater in Storage

Aquifer storage can be considered both a source and sink of water for the aquifer system as water moves into and out of storage in response to changing stresses to the

Table 4. Percentage of groundwater withdrawals in 2005 by aquifer and by State in the Northern Atlantic Coastal Plain.

[Water use data are from Kenny and others (2009). Grey shaded boxes indicate that aquifer does not exist in this geographic location. NACP, Northern Atlantic Coastal Plain]

Regional Aquifer	Percentage withdraw from regional aquifer					
	New York	New Jersey	Delaware	Maryland	Virginia	NACP
Surficial	21	0	49	30	0	15
Upper Chesapeake	0	2	7	8	6	3
Lower Chesapeake	0	44	7	1	0	15
Piney Point	0	2	5	2	4	1
Aquia	0	0	0	10	0	1
Monmouth Mt-Laurel	0	2	0	1	0	1
Matawan	0	2	0	0	0	1
Magothy	77	24	5	6	0	38
Potomac[1]	2	24	27	42	90	25

[1]The Potomac aquifer includes the Potomac-Patuxent and Potomac-Patapsco regional aquifers.

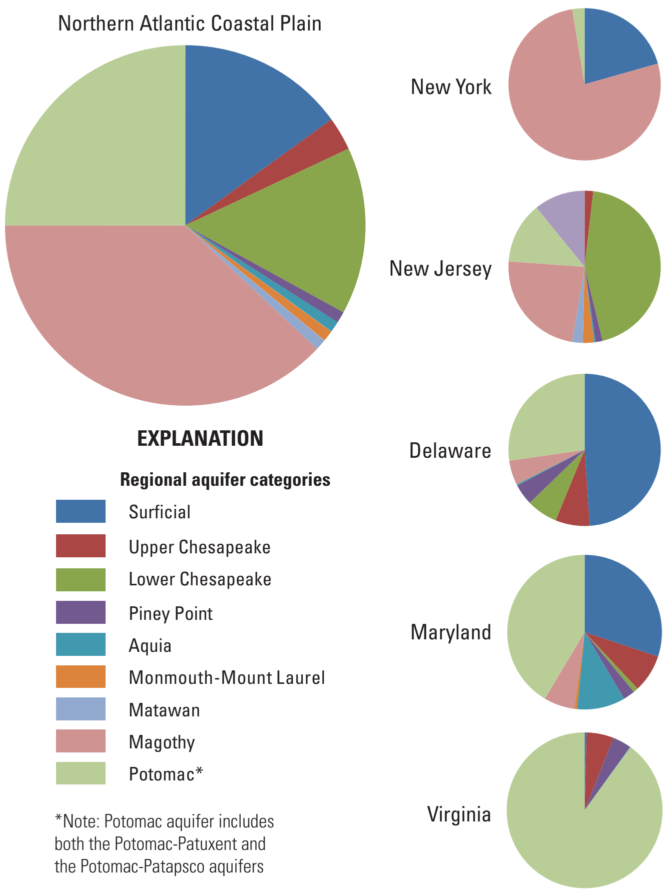


Figure 20. Distribution of groundwater withdrawals in 2005 by aquifer and by State in the Northern Atlantic Coastal Plain.

groundwater flow system. Increased population over time throughout the NACP has resulted in increased groundwater withdrawals from the aquifer system as well as increased return of wastewater to the aquifer system. Changes in these aquifer stresses can affect water levels and, therefore, the amount of water going into and out of storage. As groundwater withdrawals increase, water is removed from the aquifer system, resulting in water-level declines. One source of this pumped water is the release of water from aquifer storage. As groundwater withdrawals increase, so does the potential for the return of wastewater to the aquifer system. Enhanced recharge from the return of wastewater can result in increases in water levels as water goes into aquifer storage; in this case, storage serves as a sink for increased water added to the aquifer system.

The advent of the large-scale use of groundwater resources in the early 1900s has resulted in the depletion of aquifer storage from increased pumping, which in turn has resulted in decreases in water levels, streamflows, and discharge to coastal receiving waters, leading to saltwater intrusion along the coast (Konikow, 2013). Decreases in aquifer storage have imposed limitations on groundwater availability and resulted in shifts from groundwater resources to the importation of surface waters to meet the growing demand for water resources. Shifts in the use of groundwater throughout the NACP have resulted in changes in water moving both into and out of aquifer storage over time. Understanding the timing and magnitude of changes in aquifer storage is critically important in assessing groundwater availability in the NACP aquifer system.

Hydrologic Budget for the Northern Atlantic Coastal Plain Aquifer System

The sources and sinks of water to the NACP aquifer system can be depicted in terms of a hydrologic budget to illustrate how water enters, flows through, and exits this aquifer system (fig. 21). Under steady-state conditions, it is assumed that inflows are balanced by outflows; however, in thick, multilayered, aquifer systems such as the NACP, the response to hydrologic stresses can be slow (on the order of decades), and therefore, changes in the amount of water stored and released in the aquifer system may continue to occur until a steady-state condition is achieved.

From this analysis, it was determined that, for conditions in 2005, about 20,000 Mgal/d of freshwater enters the NACP aquifer system with nearly all this inflow from natural recharge (about 98 percent), with minor amounts from wastewater return flow, water released from confined aquifer storage, and subsurface fractured rock flow across the Fall Zone (fig. 21B). A substantial amount of freshwater does enter the NACP as streamflow across the Fall Zone (18,600 Mgal/d); however, it is assumed that, at a regional scale, this freshwater inflow discharges directly to the coast without interacting with the underlying groundwater flow system.

The largest component of outflow or loss of freshwater to the NACP aquifer system is from evapotranspiration (derived from evaporation and plant transpiration) and surface runoff. About 69 percent of the precipitation that enters the NACP is lost to evapotranspiration or runoff, and therefore, of the 61,800 Mgal/d of precipitation in the NACP area, only 19,600 Mgal/d enters the groundwater flow system as aquifer recharge (see appendix 1).

Most of the 19,600 Mgal/d of aquifer recharge enters the shallow unconfined aquifer and discharges to streams that either originate within or flow through the NACP or discharges directly to the coastal receiving waters and never reaches the deeper confined aquifer system. The previous regional assessment (Trapp and Meisler, 1992) estimated that only 2 percent of the recharge that enters the aquifer system reaches the deeper confined system under unstressed conditions. For this analysis, 2 percent of the total aquifer recharge would result in about 400 Mgal/d of recharge to the confined aquifer system.

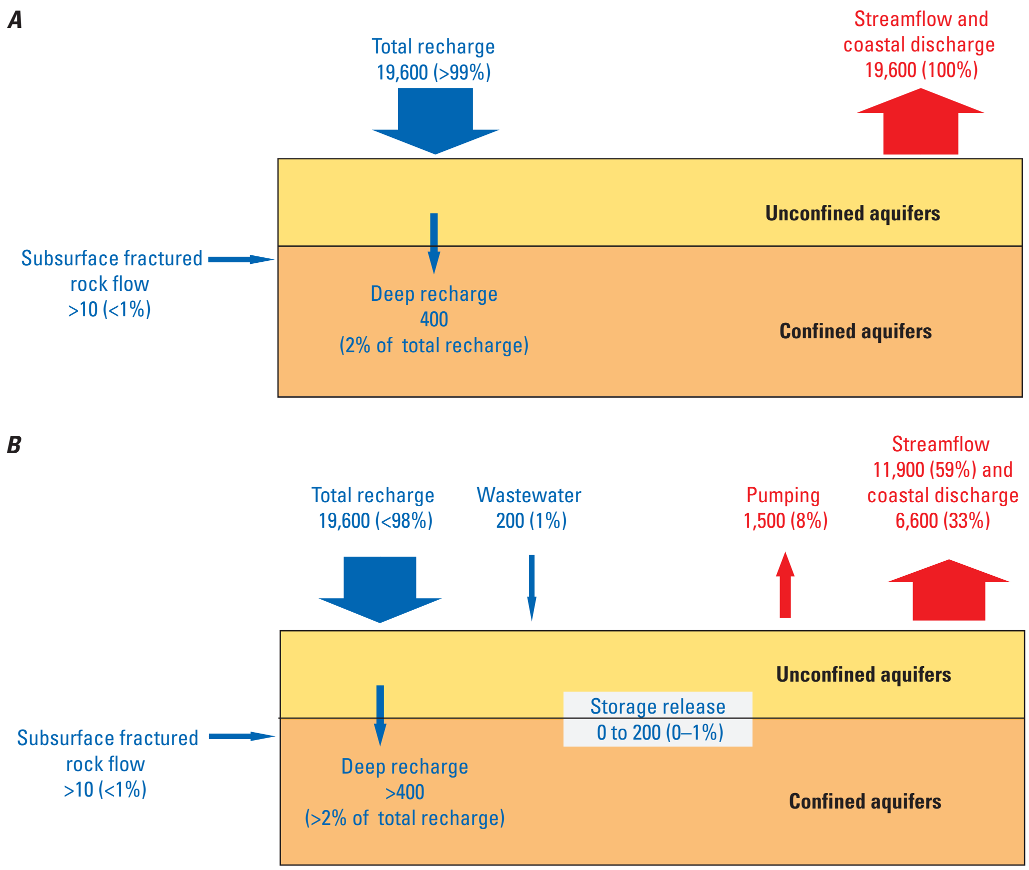


Figure 21. Schematic showing hydrologic budget in millions of gallons per day (Mgal/d) for *A,* predevelopment (1900) and *B,* conditions in 2005 for the Northern Atlantic Coastal Plain aquifer system.

The primary loss of freshwater from the NACP aquifer system is from groundwater discharge to streams. About 18,600 Mgal/d of freshwater enters the NACP across the Fall Zone as streamflow. Streamflow increases by about 3,800 Mgal/d from additional groundwater discharge to streams as the streams flow toward the coast. Another loss of freshwater from the aquifer system is from groundwater discharge to streams that originate entirely within the NACP. About 8,100 Mgal/d of groundwater discharges to the streams that originate in the NACP area and discharge to the coastal receiving waters. In total, about 11,900 Mgal/d of groundwater discharges to streams and transported to coastal receiving waters and, therefore, is removed from the aquifer system. Groundwater discharge to streams accounts for about 59 percent of the 20,000 Mgal/d of total outflow of freshwater from the groundwater flow system for conditions in 2005 (fig. 21B).

In 2005, groundwater withdrawals totaled about 1,500 Mgal/d and represented about 8 percent of the total outflow from the groundwater flow system. Most of this water (about 1,000 Mgal/d) was withdrawn from the deep confined aquifer system, suggesting that the amount of water entering the deep system as recharge under predevelopment conditions (about 400 Mgal/d) accounted for less than half of the total water pumped from the confined system. For the hydrologic budget to be in balance, this pumping rate must be offset by decreases in outflows from predevelopment conditions (as defined by total inflow from recharge) and (or) from the release of water from aquifer storage. Decreases in outflows from predevelopment conditions may include a reduction in deep subsea discharge from the confined system or decreases in streamflow and shallow coastal discharge resulting from an increase in downward leakage (deep recharge) from the shallow, unconfined system (fig. 21).

The previous regional assessment (Trapp and Meisler, 1992) determined that the source of most of the water pumped from the deep confined aquifer system was derived from induced infiltration from the overlying shallow, unconfined aquifer system. For predevelopment conditions, the area that contributed recharge to the deep confined aquifer system was estimated to be about 26 percent of the total land area of the NACP. For 1980 pumping conditions, this area was estimated to increase to about 45 percent of the total NACP land area. The previous analysis also determined that this increase in downward percolation (and resulting reduction in streamflow and shallow coastal discharge) would account for 61 percent of the total loss of water from pumping. An additional 37 percent of the loss of water from the aquifer system from pumping was derived from a decrease in deep subsea discharge to coastal areas, which creates concerns for saltwater intrusion into the freshwater system (fig. 13).

The source of the remaining 2 percent of the water lost to the aquifer system from pumping was determined to be from the release of water from storage. This estimate from the previous analysis (Trapp and Meisler, 1992) was based on a quasi-3D modeling approach, in which confining units were not explicitly simulated but were represented instead by equivalent vertical conductance between model layers representing aquifers. Therefore, this approach did not consider potential storage release from the confining units.

More recent studies have determined that the release of water from confining unit storage potentially could be a substantial source of water to pumped wells in the confined aquifer system (Heywood and Pope, 2009; Konikow, 2013). Konikow (2013) determined that release of water from storage (that is, groundwater depletion) was about 200 Mgal/d for 2001–2008, about 13 percent of 2005 pumping rate (1,500 Mgal/d). Pope and Burbey (2004) determined that storage release from the confining units in response to large groundwater withdrawals in southern Virginia resulted in dewatering and compaction of these fine-grained sediments, explaining in part the increased rates of land subsidence and anomalously higher rates of sea-level rise observed in the lower Chesapeake Bay area.

The remaining loss of groundwater from the NACP aquifer system is from shallow and deep subsea coastal discharge. Unlike the rate of groundwater withdrawals and streamflow, the rate of groundwater discharge to the coast is impossible to measure directly for this regional system. Therefore, absent of a groundwater flow model, the rates of groundwater discharge to the coast can be estimated only by a process of elimination in order to balance out the known inflows to the flow system, assuming that the water released from storage can be quantified.

Assuming that about 13 percent (200 Mgal/d) of the groundwater pumping (1,500 Mgal/d) was derived from a release of water from storage, the amount of water estimated to discharge to the coast would be about 6,600 Mgal/d, or 33 percent of the total outflow, from the groundwater system as shown in figure 21B. A numerical model that explicitly represents confining unit storage would be required to refine the estimates of the amount of water released from storage and the amount of shallow coastal and deep subsea discharge and would be instrumental in assessing the potential for decreases in groundwater discharge to the coastand the resulting effects.

Changes in Hydrologic Conditions from 1900 to Present

The NACP aquifer system has undergone significant changes in the past 100 years in response to the large changes in population and the advent of large-scale public supply systems for the delivery of drinking water and the removal of wastewater. In additional to changes in groundwater withdrawals, changes also occurred in precipitation rates and temperature thereby affecting aquifer recharge and discharge to fresh and coastal receiving waters.

Aquifer Recharge

Aquifer recharge is a function of temperature, precipitation, and land use; therefore changes in any of these factors can affect the rate and distribution of recharge across the study area. An analysis presented in the report appendix of the historical changes in temperature and precipitation suggests that area the average-annual temperature has increased by 3 degrees Fahrenheit from 1895 to 2010 in the NACP while precipitation changes during the same period are much more variable (fig. 22). A limited analysis of recharge rates were calculated for the 5-year periods of 1895 to 1900 and 2005 through 2009. This analysis determined that the average recharge rates for these two periods decreased from about 16.6 in/yr to 13.9 in/yr; however, a more complete analysis during the entire 115-year period of record would be needed to assess fully any possible trend in recharge over time.

Furthermore, land use and land cover has changed with increased population, resulting in more runoff and evaporation from impervious surfaces that can reduce aquifer recharge over time. In attempt to mitigate these effects, densely populated areas, such as on Long Island and in New Jersey, have installed recharge/catchment basins to recharge the surficial aquifer system from captured storm-water runoff on impervious surfaces. The effects of these infiltration basins on the water-levels in the shallow, unconfined groundwater systems is such that locally these basins may even increase recharge above predevelopment rates (Ku and others, 1992; Carleton, 2010).

Groundwater Withdrawals

Groundwater withdrawals in the NACP began in earnest in the late 1890s and account for about 1,500 Mgal/d of water removed from this aquifer system for conditions in 2005 (table 3). Although pumping rates have generally increased for more than a century, notable large-scale decreases in groundwater withdrawals have occurred at different points in time in response to contamination concerns, changes in industrial water-use practices, or improved water conservation measures. In the northern part of the study area, there were large reductions in groundwater withdrawals in the late 1930s in western Long Island and in the late 1980s

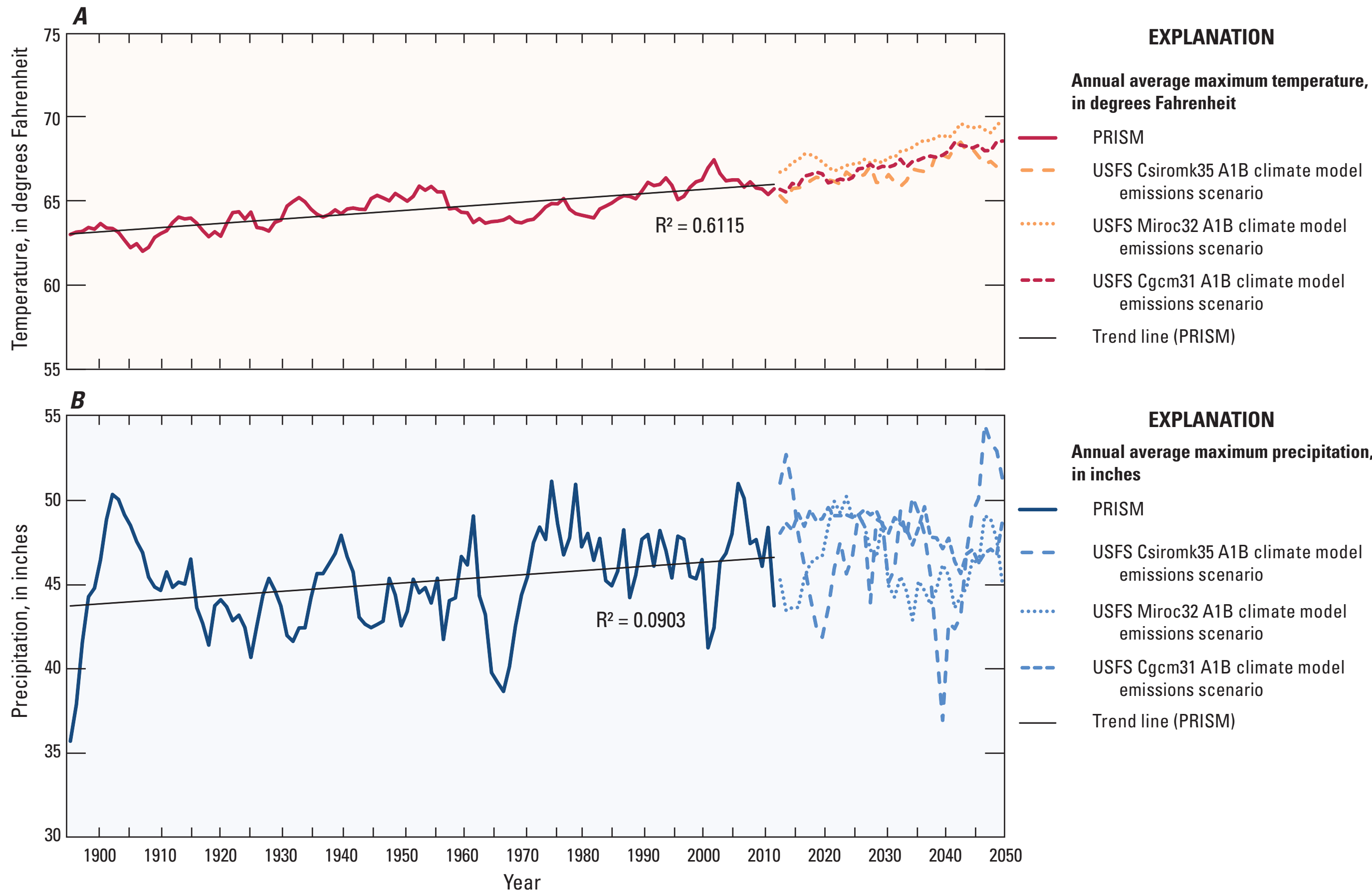


Figure 22. Observed and predicted changes in temperature and precipitation over time for the Northern Atlantic Coastal Plain aquifer system. Data are for 5-year moving average values for 1895 through 2050 for the area near 74°39′39″ W 39°54′40″ N in Southampton Township, New Jersey. °F, degrees Fahrenheit; PRISM, Prism Climate Group (2007) data; R2, coefficient of determination; USFS, U.S. Forest Service.

in east-central New Jersey in response to effects from overpumping on surface receiving waters and the threat of saltwater contamination to drinking water supplies. A more recent reduction in groundwater withdrawals also occurred in southern Virginia because of changes in water use by the pulp and paper industry.

Shift in Groundwater Use: Western Long Island and East-Central New Jersey

Before the mid-1930s, groundwater was the sole source of freshwater for the densely populated areas of Kings and Queens Counties in western Long Island (fig. 2). High rates of withdrawals resulted in large drawdowns of the water table and large declines in potentiometric heads of underlying aquifers in these areas. The development and completion of sanitary sewer systems during this period compounded the effect of withdrawals on the groundwater system by diverting wastewater directly to coastal water bodies instead of returning it as recharge to the underlying aquifer system. By 1936, water levels in northern Kings County had declined by as much as 45 ft from 1903 levels (fig. 23A, B), and by 1951, water levels in southern Queens County had declined by as much as 35 ft from 1903 levels (fig. 23C; Buxton and Shernoff, 1999).

The decline in water levels caused the natural seaward groundwater flow gradient to reverse in some areas, inducing saltwater intrusion, which in turn necessitated the shutdown of all public-supply wells in Kings County and some in Queens County by the 1940s. From that point forward, water-supply needs in this area were met by water imported from a reservoir system in upstate New York. Once pumping in this area had stopped, the water table began to recover to predevelopment conditions (fig. 23D), and the rising water levels in some areas ultimately began to flood subterranean structures, such as basements and subway tunnels, that had been built during the period when the water table was much lower (Buxton and Shernoff, 1999).

Because of this water-level recovery from the cessation of pumping, many basements and subway tunnels in Kings County today require nearly continuous dewatering. The pumped water is directed to the combined sanitary and storm-water sewer system, which ultimately discharges to nearby coastal waters and thereby is removed from the groundwater system. Dewatering accounts for at least 30 percent of the estimated 40 Mgal/d pumped for industrial use in Kings and western Queens Counties with the New York City Metropolitan Transit Authority alone, withdrawing as much as 10 Mgal/d from subway tunnels in Kings County (Misut and Monti, 1999).

By the late 1980s, parts of east-central New Jersey experienced a similar response to overpumping as that observed in western Long Island, raising concerns of saltwater intrusion and reductions of groundwater flow to ecologically sensitive surface waters in what is referred to as Water Supply Critical Area 1 (Spitz and others, 2008). In this area, groundwater withdrawals generally were reduced by 25 to 30 Mgal/d by the late 1980s because the nearby Manasquan Reservoir was used to meet water-supply needs. By 2003, reductions in pumping resulted in water-level increases in the local Middle Potomac-Raritan-Magothy aquifer (referred to regionally as the Potomac-Patapsco aquifer; fig. 9) by more than 80 ft near large pumping centers in northern Monmouth County and as much as 10 ft on Sandy Hook, N.J. (fig. 24).

Across the Raritan and Lower New York Bays, water levels in the local Lloyd aquifer also rose by as much as 5 ft on Coney Island, N.Y. (fig. 25A). The water-level changes in the local Lloyd aquifer occurred during a similar time in which water levels were recovering in the local Middle Potomac-Raritan-Magothy aquifer at Fort Hancock near Sandy Hook (fig. 25B), the lateral equivalent to the local Lloyd aquifer. A comparison of changes in pumping on Long Island and in northern New Jersey indicate that pumping decreased in both areas from 1988 to 1996. Changes in water levels in the local Lloyd aquifer on Long Island appear to be affected less by changes in pumping in the local Lloyd aquifer than by changes in pumping in the overlying local Magothy aquifer on Long Island or possibly by decreases in pumping in New Jersey (fig. 25A–D). Further investigation would be needed to assess fully the potential hydrologic connection between the local Lloyd and Magothy aquifers on western Long Island or the possibility of a hydrologic connection between New Jersey and Long Island in the local Middle Potomac-Raritan-Magothy and Lloyd aquifers (referred to as the Potomac-Patapsco regional aquifer; fig. 9).

Shift in Groundwater Use: Southern Virginia

The pulp and paper industry in southeastern Virginia and northeastern North Carolina has been the largest user of groundwater in this region since the 1960s. The large amounts of water used by this industry have resulted in large-scale declines in water levels in this region (fig. 4). The recent (2009) economic downturn resulted in dramatically curtailed operations for this industry, which led to substantial reductions in groundwater withdrawals. As an example, a single pulp mill and paper manufacturing facility in southeastern Virginia pumped more than 30 Mgal/d until a reduction in operations in 2009 followed by a complete shutdown in early 2010 (Katchmark, 2012). Since the shutdown, this cessation of withdrawals has resulted in a rapid recovery of water levels in the surrounding area (fig. 26). By April 2012, water levels in the Potomac aquifer near the well field recovered more than 100 ft, and water levels as much as 40 mi away from the facility recovered by about 4 ft. Since the recovery, the facility has resumed limited operations and water levels near the well field have begun to decline again.

Regional Effects of Recent Pumping

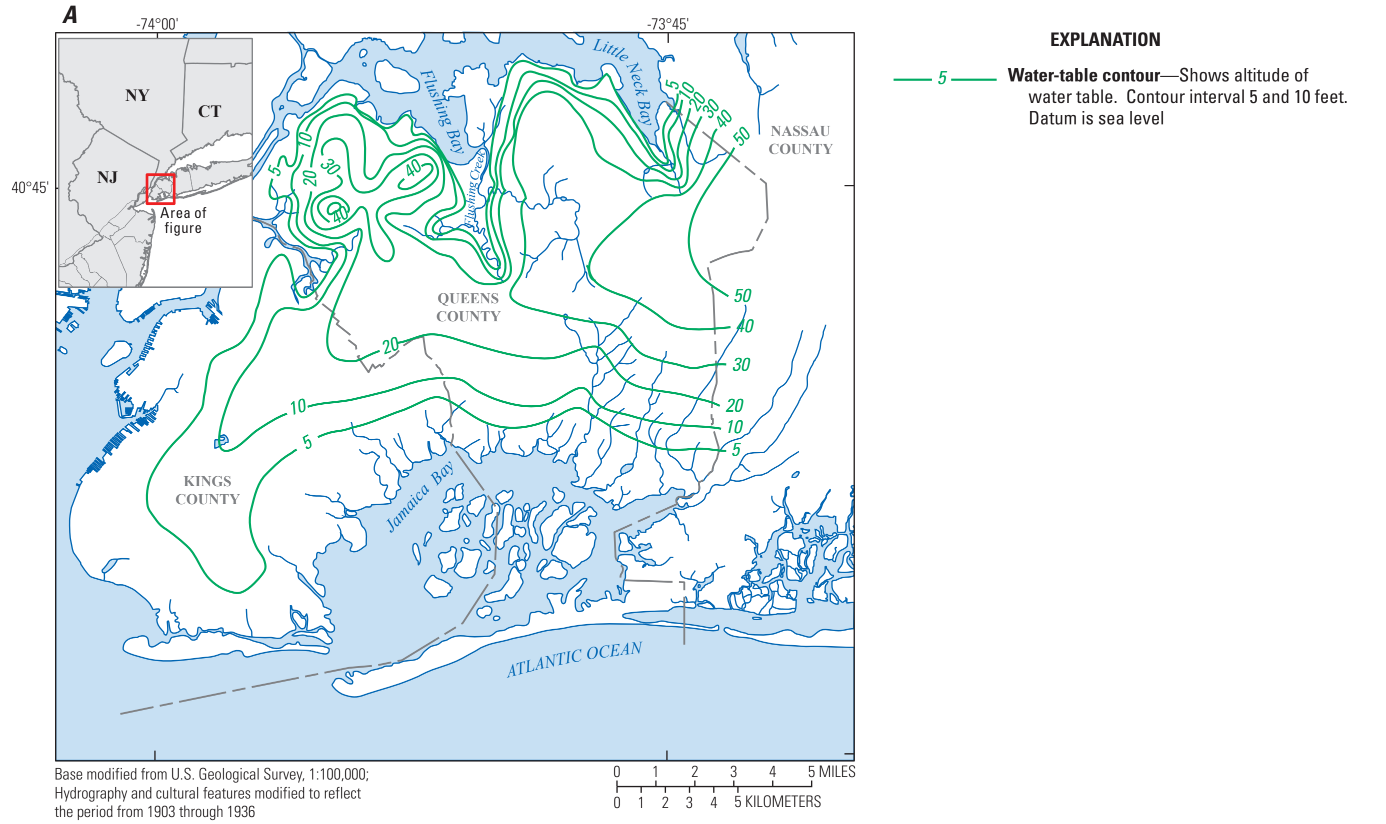
Since large-scale groundwater withdrawals began in the NACP at the turn of 20th century, about 110 cubic kilometers (km^3) of freshwater have been withdrawn from the groundwater flow system. Half (about 55 km^3) of this total volume of water was removed from the flow system during the 80-year period from 1900 to 1980; the remaining half of the total withdrawals occurred only in the past 30 years (fig. 27). Konikow (2013) estimates that these groundwater withdrawals have resulted in about 10 km^3 of groundwater depletion from 1900–2008 with about 25 percent of this depletion (2.5 km^3) occurring from 2000– 2008. Therefore, the long-term hydrologic effects of the large removal of groundwater from the NACP aquifer system during a relatively short period of time (30 years) may yet to have occurred, particularly with respect to decreases in groundwater discharge to streams and coastal receiving waters and in areas of suspected compaction of confining units and the accompanying land subsidence.

During the 20-year period from 1985 to 2005, public-supply withdrawals have increased in the NACP on average by about 25 percent (fig. 28). During this same period, summer season (May-September) usage increased by about 50 percent, nearly three times the rate of winter season (October–April) increase (20 percent), suggesting that increased population and development throughout the NACP (fig. 2B) that requires greater water use during the summer season may account for most of the total increases during this 20-year period. Such increases in development in coastal areas create additional concerns for potential increases in saltwater intrusion at public-supply sources.

Increased pumping from the confined aquifer system in coastal areas can result in a decrease in the deep subsea discharge needed to balance the interface between freshwater and saltwater (figs. 13, 21B). Assuming that storage release from confining units can be a significant source of water pumped from the confined system (Konikow and Nuezil, 2007), the response of the flow system to increased pumping could be delayed as water is released from storage and effects such as saltwater intrusion may yet to be fully realized for recent pumping conditions (fig. 13).

Wastewater Return Flow

In addition to concerns about changes in groundwater withdrawals, concerns also exist regarding the return of wastewater to the groundwater flow system from onsite domestic systems as well as from centralized treatment



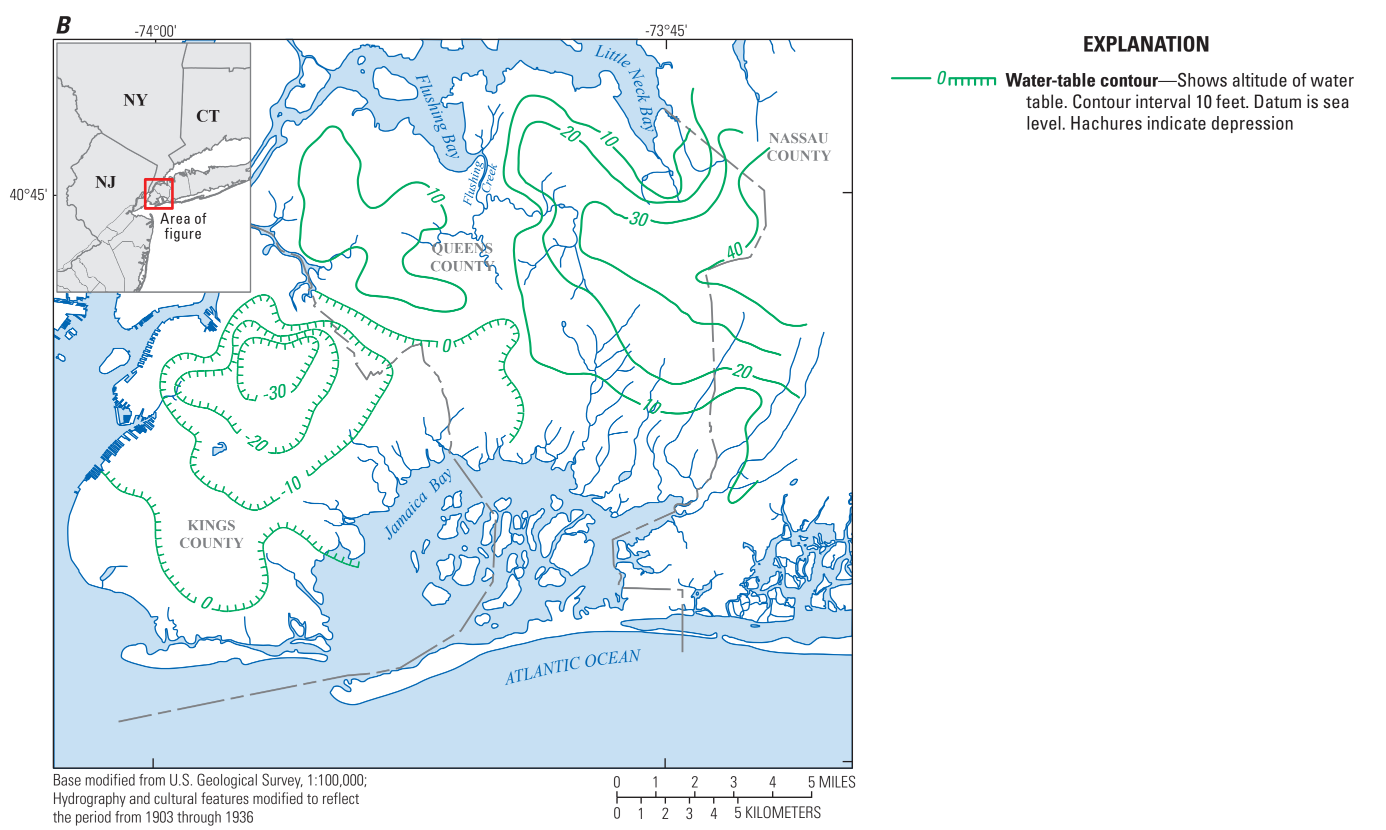
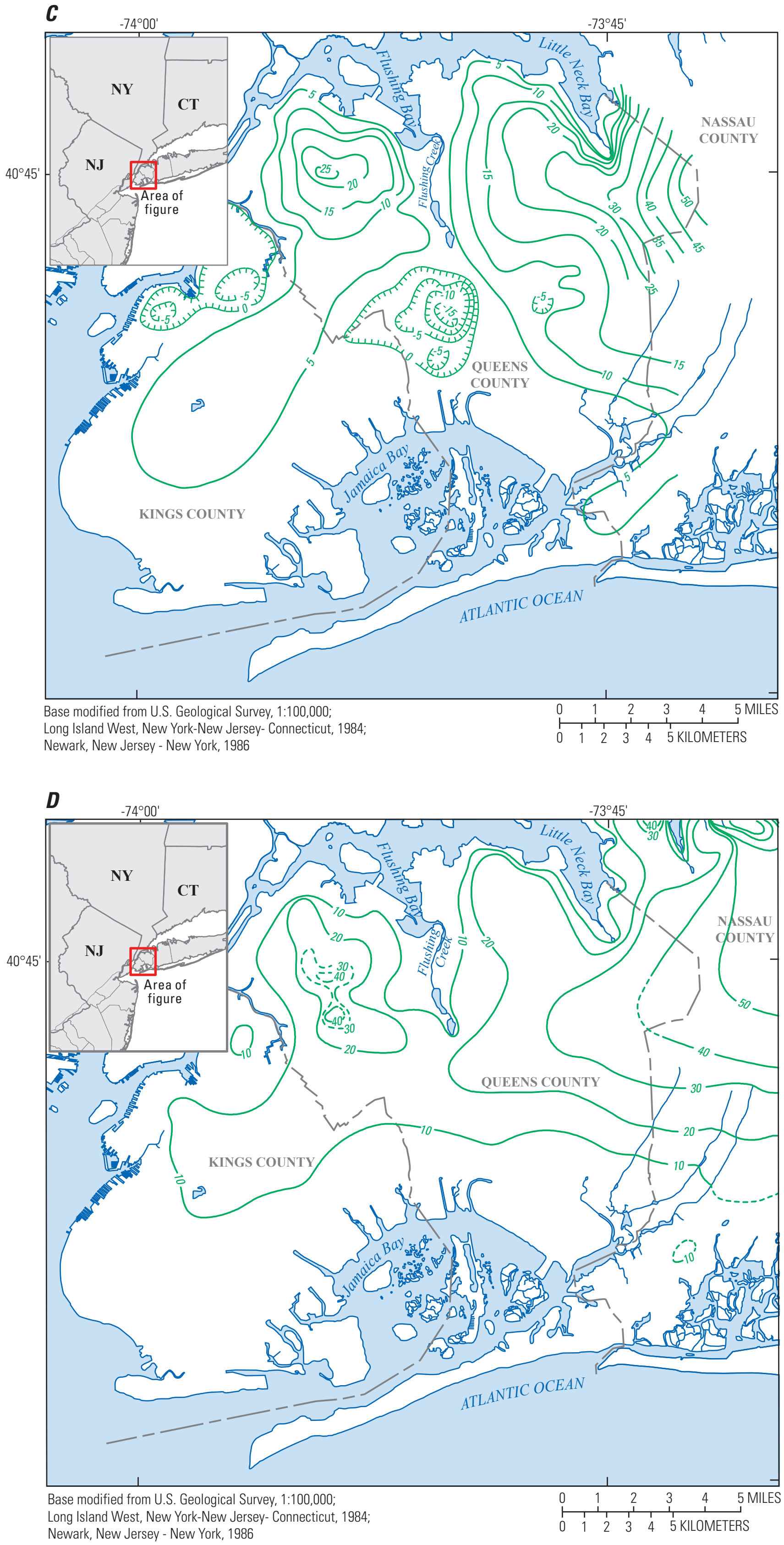


Figure 23. Water levels in Kings and Queens Counties, New York, in *A,* 1903, *B,* 1936, *C,* 1961, and *D,* 2006.



EXPLANATION

0 — **Water-table contour**—Shows altitude of water table. Contour interval 5 feet. Datum is sea level. Hachures indicate depression

EXPLANATION

0 - - - **Water-table contour**—Shows altitude of water table in 2006. Contour interval 10 feet. Datum is sea level. Dashed where inferred

Figure 23. Water levels in Kings and Queens Counties, New York, in A, 1903, B, 1936, C, 1961, and D, 2006.

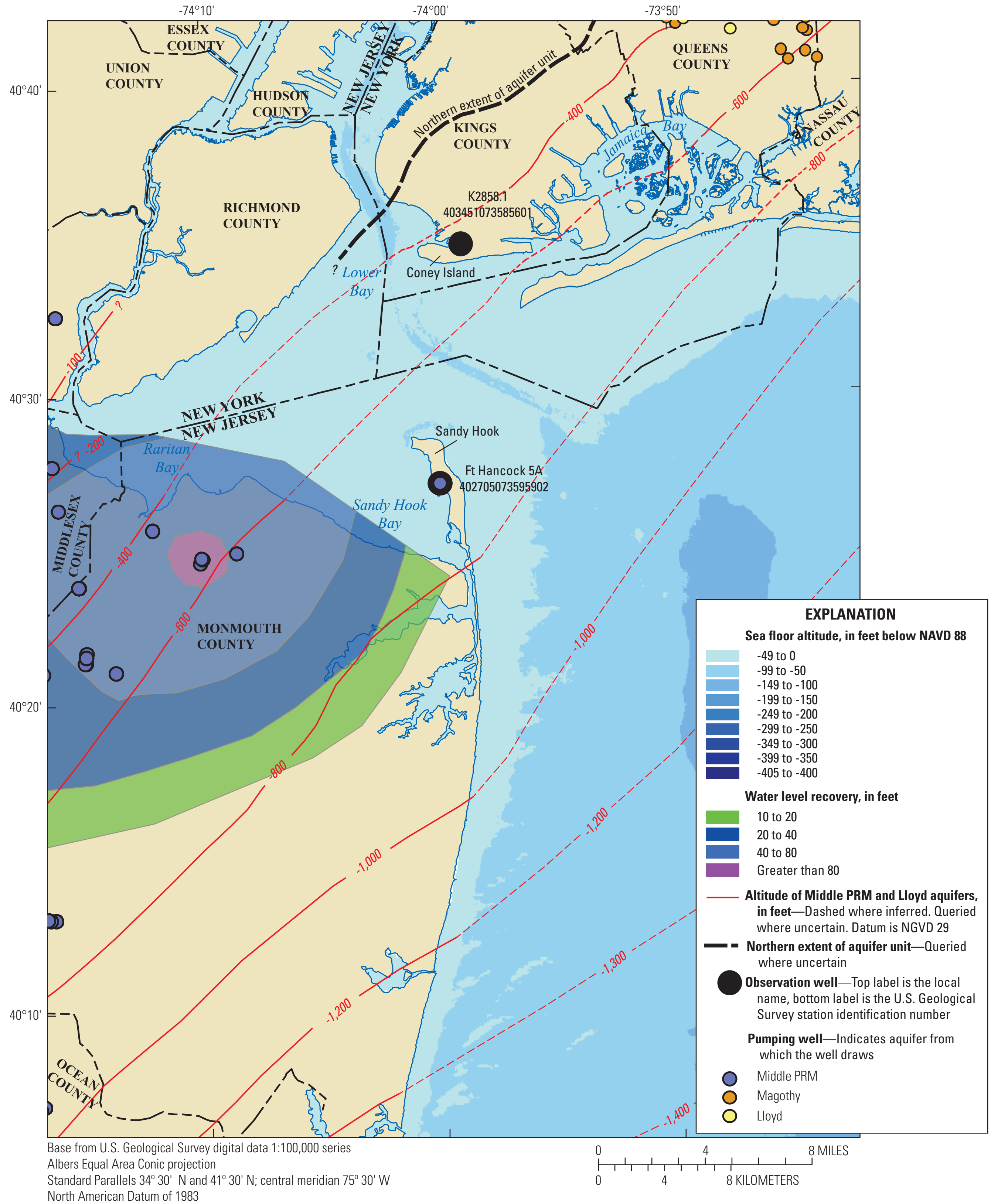


Figure 24. Water-level recovery in east-central New Jersey in late 1980s (from Spitz and others, 2008) and the surface contours of the top of the Middle Potomac-Raritan-Magothy (PRM) and Lloyd aquifers, Sandy Hook, New Jersey, and Coney Island, New York. The observation wells are U.S. Geological Survey identification number (ID) 403451073585601 (local site designation K2858.1) on Coney Island, and 402705073595902 (local site designation Ft Hancock 5A) at Sandy Hook. NAVD 88, North American Vertical Datum of 1988 ; NGVD 29, National Geodetic Vertical Datum of 1929.

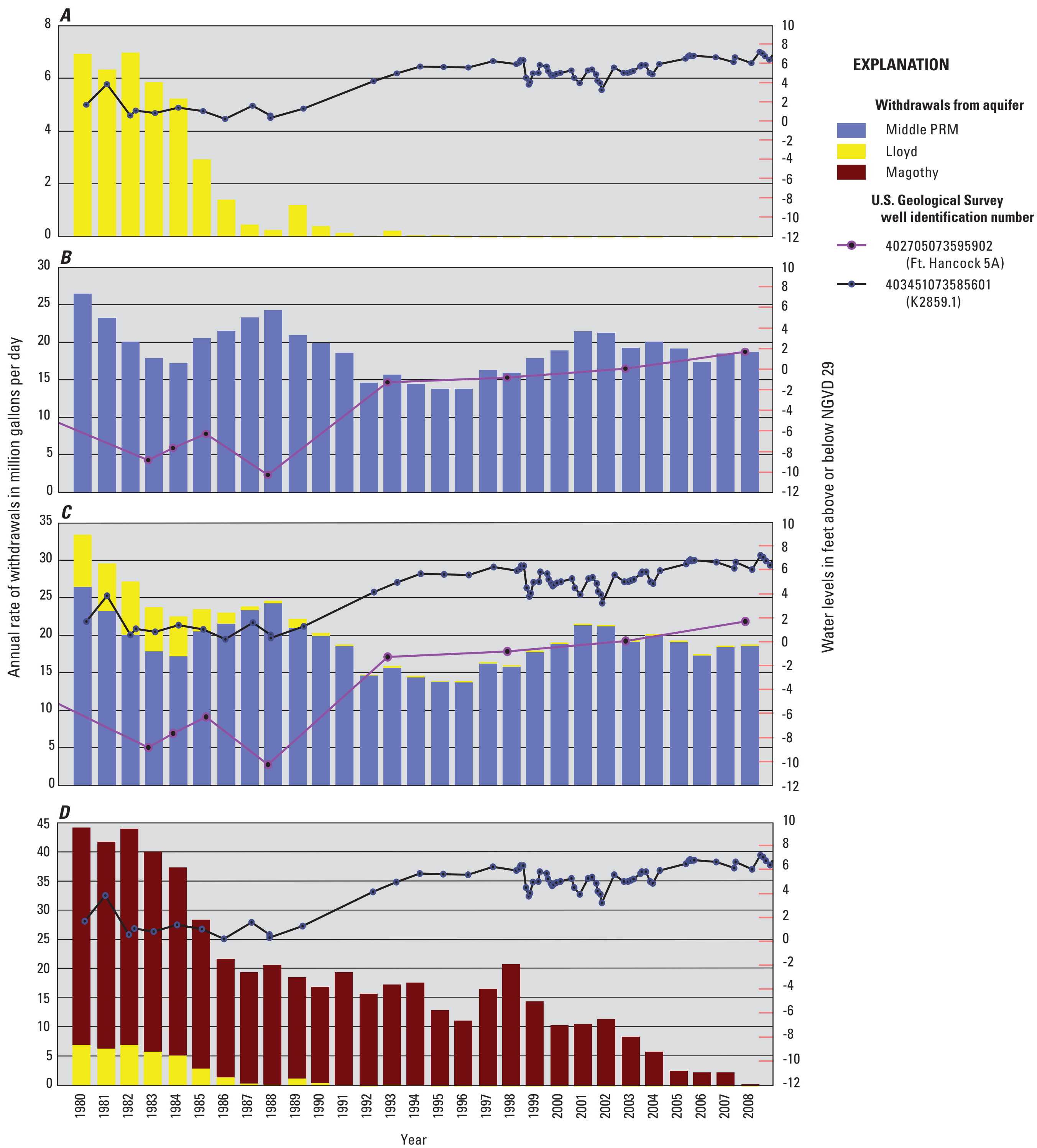


Figure 25. Changes in water levels in the local Lloyd and Middle Potomac-Raritan-Magothy (PRM) aquifers and changes in pumping in the *A,* Lloyd aquifer, *B,* Middle PRM aquifer, *C,* Lloyd and Middle PRM aquifers combined, and *D,* the Lloyd and Magothy aquifers combined.

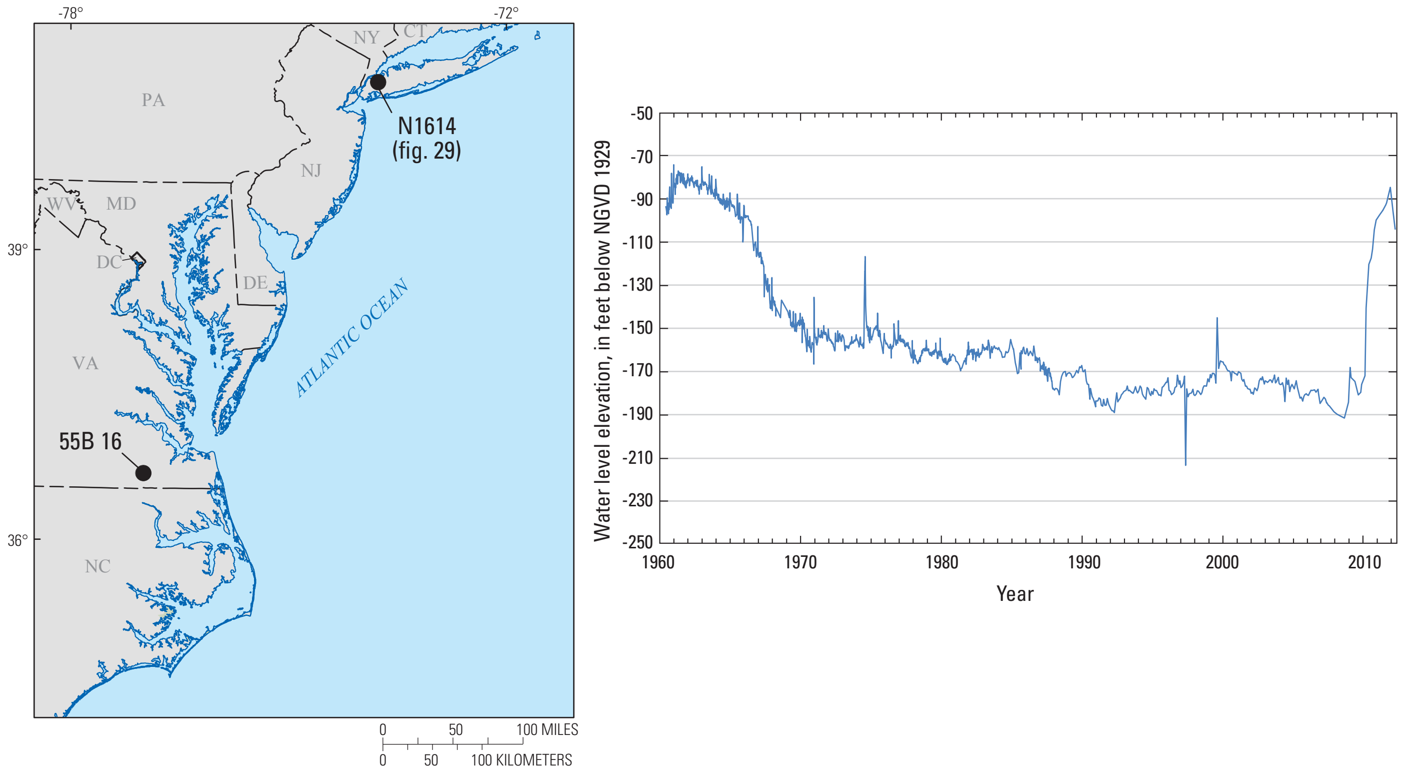


Figure 26. Hydrograph showing effects of pumping on groundwater levels in southeastern Virginia from 1960 through 2012. Data are from U.S. Geological Survey well 364059077654901 (local site designation 55B 16) east of Franklin, Isle of White County. NGVD 29, National Geodetic Vertical Datum of 1929.

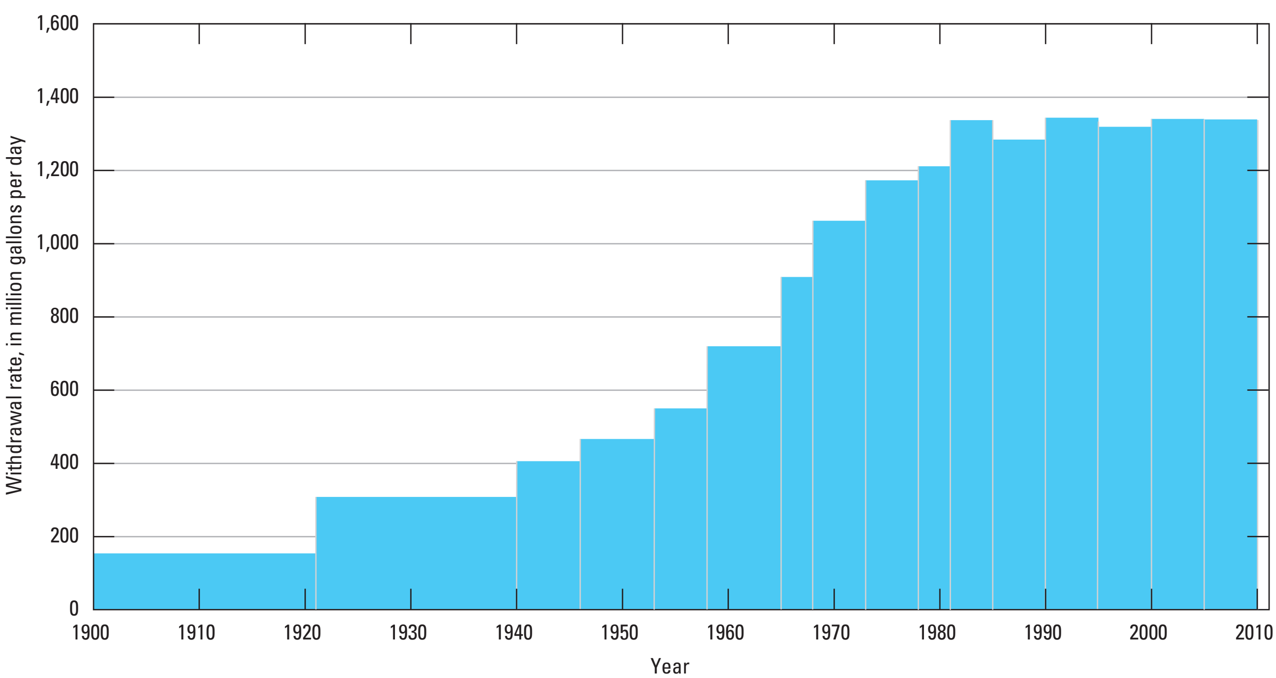


Figure 27. Groundwater withdrawal rates from the Northern Atlantic Coastal Plain aquifer system from 1900 to 2010.

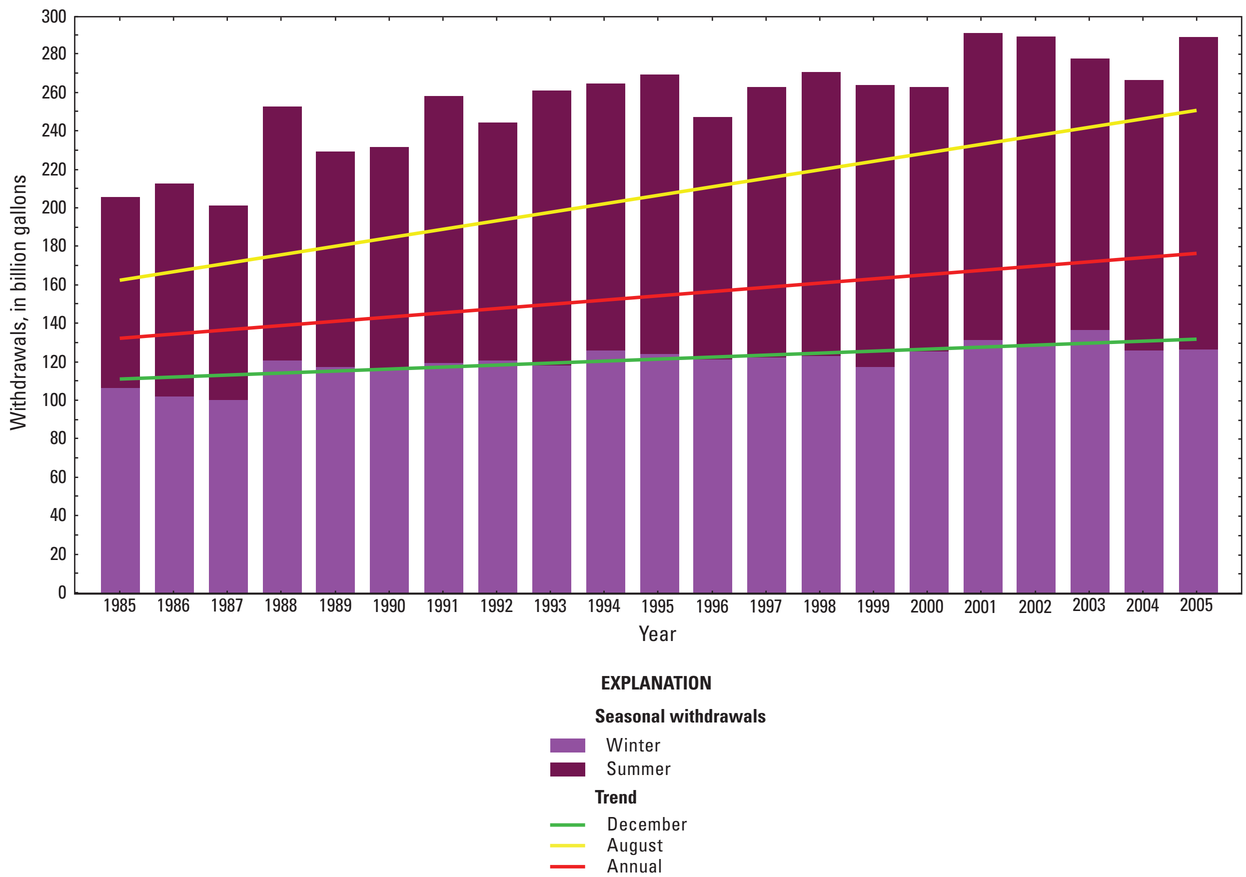


Figure 28. Seasonal changes in groundwater withdrawals from 1985 through 2005 in the Northern Atlantic Coastal Plain aquifer system.

facilities. In 2005, more than 20 million people in the NACP use about 2,500 Mgal/d of drinking water from groundwater and surface water sources (Kenny and others, 2009). Depending on where this water is returned to the hydrologic system and the extent to which it is treated can affect the quantity and quality of the groundwater that discharges to ponds, streams, and coastal waters.

The Mid-Atlantic area includes many important coastal ecosystems, such as the New York-New Jersey Harbor Estuary, New Jersey Barnegat Bay, New Jersey Meadowlands, Delaware Inland Bays, Delaware Seashore, Delaware Estuary, and Chesapeake Bay (the largest estuary in the United States and the first in the Nation to be selected for restoration as an integrated watershed ecosystem; Chesapeake Bay Program, (2010)). Increased discharge of wastewater to the shallow flow system can increase nutrient loading and concerns about eutrophication in the near-shore ecosystems of these coastal receiving waters.

In response to increased concerns about nonpoint source contamination of the local groundwater system, Nassau County on Long Island began to transition in the mid-1950s from onsite domestic septic systems to more centralized wastewater treatment facilities (Buxton and Smolensky, 1999). By 1983, nearly 66 percent of the 183 Mgal/d of groundwater pumped in Nassau County was discharged to coastal waters from sanitary sewers. The removal of this water from the groundwater system resulted in decreased water levels (fig. 29; Busciolano, 2005). Numerical modeling analyses by Buxton and Smolensky (1999) determined that water levels in this area are about 8 ft lower than they would have been had the practice of discharging wastewater to onsite domestic septic systems continued. The transition from onsite domestic systems to centralized wastewater treatment facilities also resulted in decreased flow to groundwater-fed streams. The most notable example of this hydrologic response is East Meadow Brook in southwest Nassau County, where flows have decreased by as much as 70 percent from predevelopment conditions (Scorca, 1997).

Although sanitary sewer systems were designed to reduce nonpoint contamination from septic systems, these systems are not 100 percent efficient. In 1983, recharge to the shallow aquifer system from leaky sewer and water-supply lines, as calculated from the number of miles of lines and the number of connections and multiplied by a leakage factor, is estimated

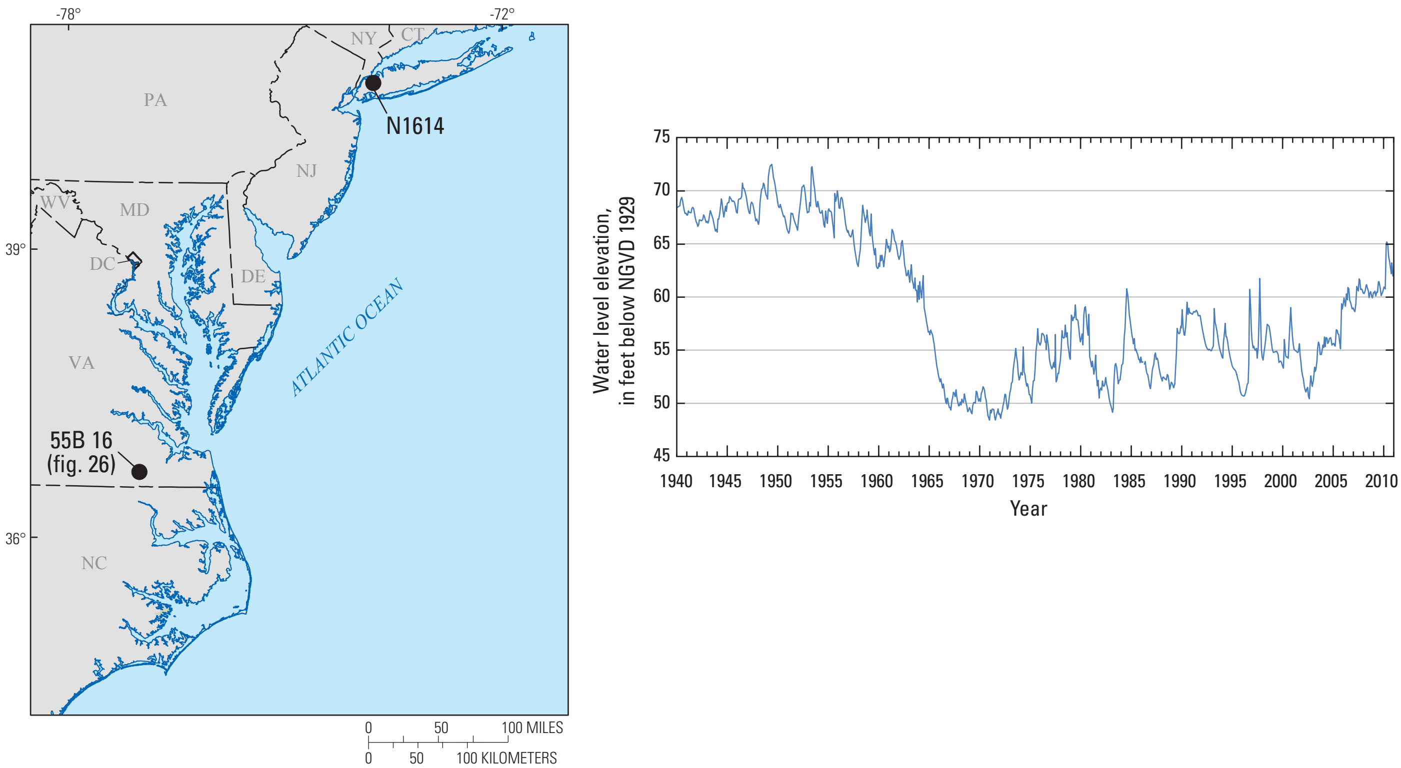


Figure 29. Water-level response to increased sewering in Nassau County, New York, from 1940 through 2010. Data are from U.S. Geological Survey station identification 404446073392901 (local site designation N1614.1) for 1940 through 1950; 404446073392902 (N1614.2) for 1951 through 1962; 404446073392903 (N1614.3) for 1963 through 1995; 404446073392904 (N1614.4) for 1966 through 2000; and 404454073393001 (N1614.5) for 2001 through 2010.

to have been as much as 70 Mgal/d in Kings and Queens Counties on western Long Island (Buxton and Shernoff, 1999). Additional leakage from combined sanitary and storm sewers has probably increased, because the lines have aged, and therefore leakage from sewer and supply lines has become an increasingly large component of the hydrologic budget in the urbanized areas of the NACP.

Saltwater Intrusion

The interface between fresh and saline groundwater generally appears to coincide with the coastline throughout most of the NACP in the Potomac aquifer (fig. 30) but potentially can be shifted inland locally in response to groundwater withdrawals (fig. 13). The previous regional analysis (Trapp and Meisler, 1992) indicated that a decrease in groundwater discharge to streams and coastal receiving waters in response to increased pumping from 1900 to 1980 created the potential for saltwater intrusion into this coastal aquifer system. It was in response to saltwater intrusion concerns in the mid-1930s and later in the late 1980s that initiated the reduction of pumping and increase in imported surface water in western Long Island and east-central New Jersey (see Shift in Groundwater Use: Western Long Island and East-Central New Jersey section).

More recent saltwater intrusion concerns in coastal areas such as Cape May, N.J. (fig. 1) have prompted the need for the desalinization of saline groundwater to help meet drinking water demand in these coastal communities. The effects of increased pumping on the position of the interface between freshwater and saltwater are expected to be exacerbated further by rising sea levels and land subsidence from the compaction of confining units, particularly in the lower Chesapeake Bay area.

Climate Change and Groundwater Resources

The potential effects of long-term climate change and variability on the hydrologic system and availability of water resources continue to be of serious societal concern

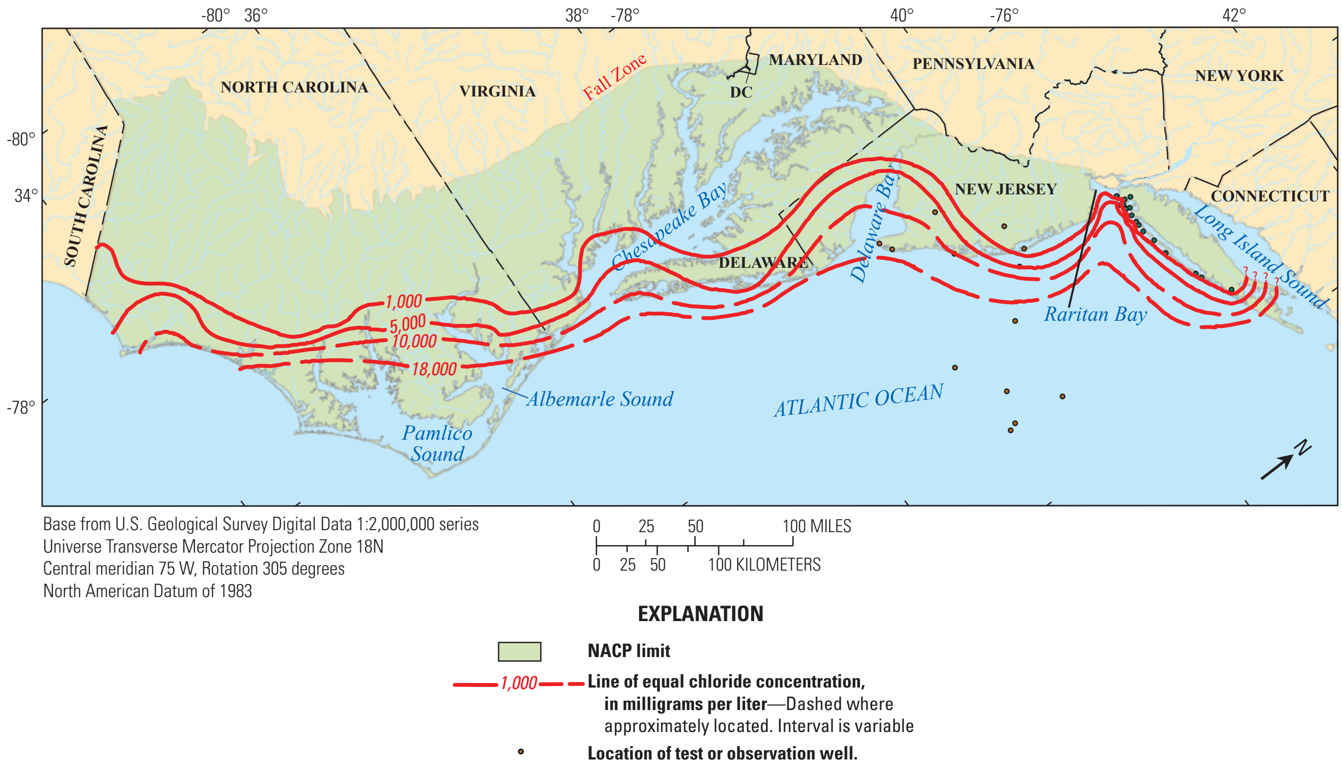


Figure 30. Chloride distribution in the regional Potomac-Patapsco aquifer of the Northern Atlantic Coastal Plain aquifer system. Modified from Meisler (1989) by Frederick Stumm (U.S. Geological Survey, written commun., 2012).

in the NACP. Most climate models (Coulson and others, 2010) predict warmer temperatures with more variable and unreliable precipitation patterns (fig. 22).

Warmer temperatures potentially may have any number of effects that could act as drivers to increase summertime water demand. Increased evapotranspiration coupled with more highly variable precipitation patterns will likely prompt agricultural producers to rely more heavily on irrigation from groundwater sources to minimize drought risk. Livestock producers will likely demand more water for consumption and stock cooling. Increased demand for domestic and commercial cooling is likely to require increased electricity production and commensurate water use by thermoelectric power plants (Legesse and others, 2003).

Another concern facing coastal communities in the NACP is the potential effects of sea-level rise on coastal aquifer systems. Trends in relative sea-level rise from 1902 to 2006 vary across the region from about 2.4 millimeters per year (mm/yr) on the northern shore of Long Island to more than 6.0 mm/yr at the Chesapeake Bay Bridge Tunnel (fig. 31; National Oceanic and Atmospheric Administration, 2012). Sea-level rise throughout the region averages about 3.5 mm/yr, or about 1 ft total for the past 100 years, a rate higher than the apparent average for the Atlantic Coast.

Recent analyses of the relative rates of sea-level rise along the Atlantic coast indicate that the Mid-Atlantic region represents a hot spot with anomalously higher rates of sea-level rise than observed elsewhere in the U.S. (Sallenger and others, 2012). In the lower Chesapeake Bay area, it is believed that the anomalous rates of observed sea-level rise are the result of eustatic sea-level rise coupled with land subsidence from the compaction of confining units caused by groundwater pumping (Pope and Burbey, 2004). These concerns are heightened because projected rates of sea-level rise could result in increases in mean sea level of 3 to 5 ft during the next 100 years in parts of the NACP (Intergovernmental Panel on Climate Change, 2008) resulting in changes in groundwater levels, surface-water discharge, and increased potential for saltwater intrusion (Masterson and Garabedian, 2007).

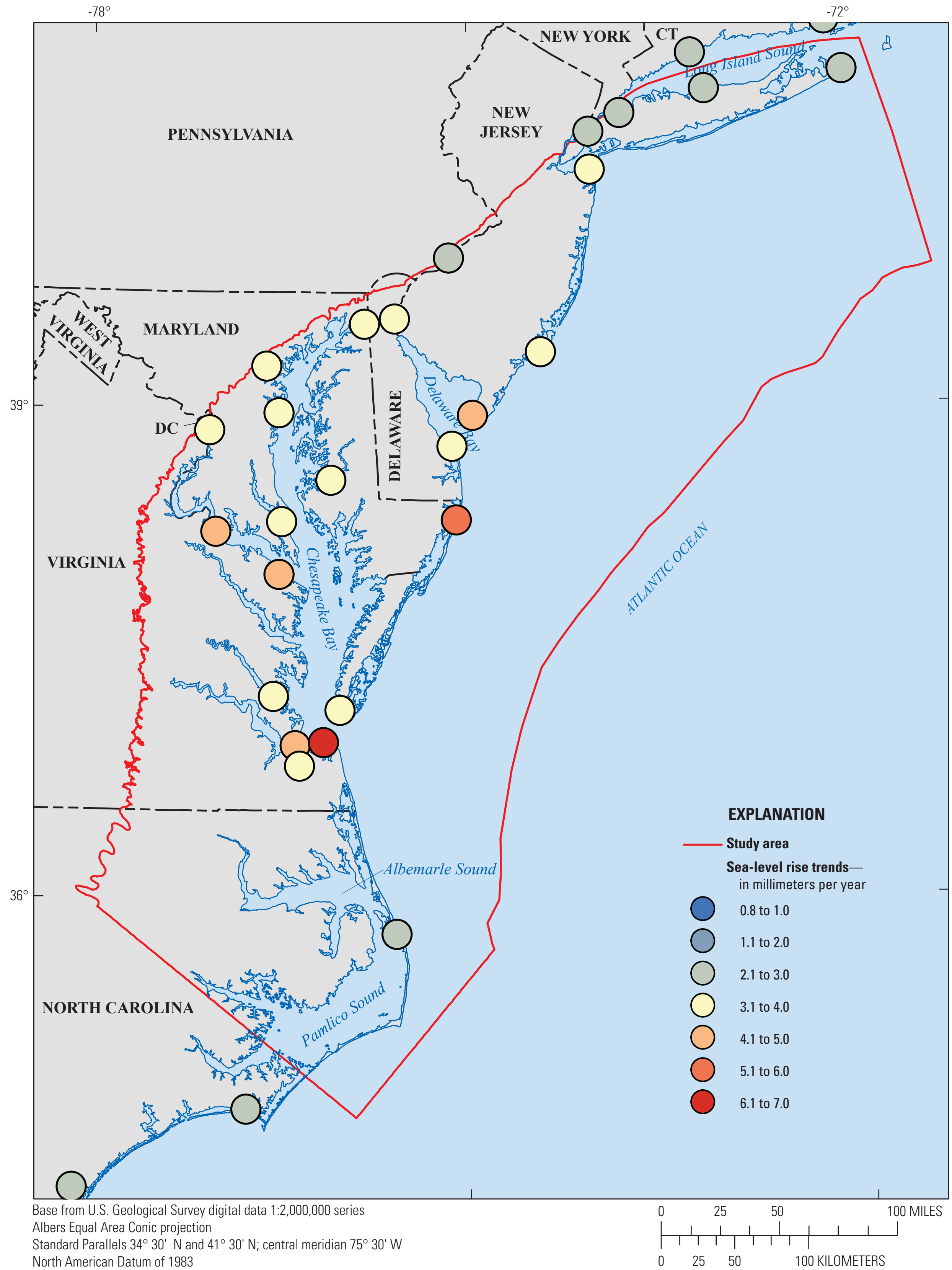


Figure 31. Trends in sea-level rise across the Northern Atlantic Coastal Plain from 1902 to 2006. From National Oceanic and Atmospheric Administration (2012).

Summary and Conclusions

The Northern Atlantic Coastal Plain (NACP) occupies a land area of about 30,000 square miles along the eastern seaboard of the United States from Long Island, New York, southward to the northern part of North Carolina. A seaward-dipping wedge of sediments comprising clay, silt, and sand and gravel underlies this area. This sedimentary wedge forms a complex groundwater system and constitutes a major source of public and domestic water supply as well as a vital source of freshwater for industrial and agricultural uses throughout the region.

Continued land development and population growth in the NACP during the past 100 years have resulted in increased and diverse demands for fresh water and have created concerns regarding the supply of potable groundwater and the quality and quantity of water discharging to ponds, streams, and coastal waters. Substantial withdrawals of groundwater from the underlying aquifer system had begun by the late 1800s. Groundwater withdrawals have increased steadily throughout the NACP since then, and as of 2005, groundwater withdrawals have increased to about 1,500 million gallons per day (Mgal/d), serving as a vital source of drinking water for the region.

The need for water-resources management in this area creates hydrologic challenges beyond those imposed by the competing local domestic, industrial, agricultural, and environmental demands for water. Large changes in regional water use have made single-state management of aquifer resources increasingly more difficult because of hydrologic effects that extend beyond State boundaries. In response to this need, the U.S. Geological Survey (USGS) Groundwater Resources Program began a second regional assessment of the groundwater availability of the NACP aquifer system in 2010. As part of the USGS ongoing regional assessments of groundwater availability of the principal aquifers of the Nation, the goal of this analysis is to provide an updated regional characterization of the hydrogeologic framework and conditions of the NACP aquifer system.

The areal extent of what was defined previously as the NACP aquifer system has been reduced from the area defined in the first analysis of the aquifer system to focus primarily from Long Island to Virginia to complement a recently completed regional assessment on the Atlantic Coastal Plain aquifer system of North and South Carolina (Campbell and Coes, 2010). Consequently, several regional aquifer names have been edited in this investigation to remove references to units in North Carolina and emphasize nomenclature from the primary States of the study area, which are New York, New Jersey, Delaware, Maryland, and Virginia.

Other revisions to the hydrogeologic framework reflect substantial revisions in the understanding of hydrogeologic correlations across the study area since the previous analysis. A primary example is the treatment of the aquifers of the regional Potomac aquifer system, which now is considered to be a single aquifer in Virginia. In Maryland, Delaware, and New Jersey, the Potomac aquifer system is subdivided into two aquifers as it thickens within the Salisbury Embayment. Regionally, the two parts of the Potomac aquifer system in these States are referred to as the Potomac-Patapsco and Potomac-Patuxent aquifers. Farther to the north in New York, the Potomac-Patapsco aquifer consists locally of the Lloyd aquifer, and the Potomac-Patuxent aquifer is absent.

The final substantial revision to the hydrogeologic framework of the NACP is the recognition of the Chesapeake Bay impact crater, which includes three hydrogeologic units—the Chickahominy confining unit, the Exmore matrix confining unit, and the Exmore clast confining unit—that comprise the crater-fill materials.

The hydrologic budget also has been updated since the previous regional assessment to reflect the change in the study area extent and hydrologic data collection since the 1980s. The average annual rate of precipitation of about 45 inches per year (in/yr) resulted in about 62,000 Mgal/d or 23 trillion gallons per year (Tgal/yr) of freshwater input. Although there is as much 23 Tgal/yr of precipitation in the NACP study area, only 31 percent (19,600 Mgal/d or about 7 Tgal/yr) of it enters the underlying aquifer system as recharge, but accounts for more than 99 percent of the total inflow of freshwater to the NACP aquifer system.

Remaining inflows to aquifer system include wastewater from onsite domestic septic systems in nonsewered areas and leaking water-supply lines from water imported from outside the NACP. In 2005, about 3.3 million residents discharged as much as 200 Mgal/d of wastewater from onsite septic systems to the shallow, unconfined aquifers throughout the NACP.

Most (62 percent) of the 30,500 Mgal/d of streamflow enters the NACP across the Fall Zone on the western border of the NACP and discharges to the coast without interacting with the underlying aquifer system. The remaining 38 percent of the total streamflow that does interact with the groundwater system is groundwater discharge to streams that is lost from the aquifer system. This discharge (11,900 Mgal/d) accounts for about 59 percent of the total groundwater outflow from the system.

Groundwater withdrawals account for about 8 percent of the total outflow from the NACP aquifer system. In 2005, the total amount of groundwater withdrawn was about 1,500 Mgal/d. The groundwater withdrawn for drinking water accounted for 65 percent of all groundwater withdrawals in the study area. Most (70 percent) of these groundwater withdrawals occurred on Long Island and in New Jersey. The total agricultural water use in the NACP in 2005 was estimated to be about 300 Mgal/d, with about 60 percent (179 Mgal/d) derived from groundwater sources Commercial and industrial freshwater use in the NACP in 2005 was about 800 Mgal/d, of which, 43 percent (338 Mgal/d) was derived from groundwater sources. Groundwater withdrawals in Virginia and North Carolina, accounted for about 62 percent of the total commercial and industrial groundwater uses in the NACP.

Although the NACP aquifer system consists of ten principal aquifers, the largest withdrawals occur in the Magothy regional aquifer system. Withdrawals from the Magothy regional aquifer system account for about 38 percent of the total withdrawals in the NACP aquifer system. The Surficial and the Upper and Lower Chesapeake regional aquifers combined account for about 33 percent of the total use. The Surficial regional aquifer provides almost half (49 percent) the groundwater pumped in Delaware and almost a third of the water pumped in Maryland (30 percent). Withdrawals from the Lower Chesapeake regional aquifer account for 15 percent of the total withdrawals in the NACP and make up about half (44 percent) of the total withdrawals in New Jersey; the Lower Chesapeake regional aquifer is the primary source of drinking water in southeastern and coastal areas of the State. About only 25 percent of the total groundwater in the NACP aquifer system is withdrawn from the Potomac aquifer system and accounts for more than 90 percent of total withdrawals in Virginia. The remaining 4 percent of the total withdrawals in the NACP aquifer system were derived from the Piney Point, Aquia, Monmouth Mount-Laurel, and Matawan regional aquifers.

The remaining outflow component of the revised hydrologic budget for the NACP aquifer system is coastal discharge. Coastal discharge cannot be measured directly so it is determined indirectly by the process of balancing inflows and outflows to and from the NACP aquifer system. Assuming that the release of water from aquifer storage is about 200 Mgal/d for pumping conditions in 2005, then the amount of groundwater discharge to the coast would be 6,600 Mgal/d, or 33 percent of the total outflow from the groundwater system.

Effects of climate variability and change on the aquifer system were not considered as part of the previous RASA analysis. An analysis of changes in temperature and precipitation conducted as part of this investigation suggest that, in the NACP area, the average annual temperature has increased by 3 degrees Fahrenheit from 1895 to 2010, whereas precipitation changes during the same period are much more variable. A limited analysis of recharge rates calculated for the 5-year periods of 1895 to 1900 and 2005 through 2009 indicate that the average recharge rates for these two periods decreased from about 16.6 in/yr to 13.9 in/yr.

Another set of climate-change effects not previously considered in the earlier analysis of the NACP aquifer system are the potential effects of sea-level rise on coastal aquifer systems. Regional trends in relative sea-level rise vary across the region from about 2.4 millimeter per year (mm/yr) on the northern shore of Long Island to more than 6.0 mm/yr at the Chesapeake Bay Bridge Tunnel. Sea-level rise throughout the region averages about 3.5 mm/yr, or about 1 foot (ft) in the past 100 years, a rate higher than the apparent average for the Atlantic Coast. These concerns are heightened because projected rates of sea-level rise could result in increases in mean sea level of 3 to 5 ft during the next 100 years in parts of the NACP, which would result in changes in groundwater levels, surface-water discharge, and increased potential for saltwater intrusion.

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Appendix 1. Soil-Water Balance Methodology and Analysis

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Contents

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Tables

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Appendix 1. Soil-Water Balance Methodology and Analysis

Introduction

Precipitation is the largest source of freshwater to the Northern Atlantic Coastal Plain (NACP). A proper accounting of the hydrologic budget for the NACP aquifer system requires an understanding of how much precipitation reaches the underlying aquifer system as groundwater recharge. Soil-water balance (SWB) models estimate shallow groundwater recharge by simulating the physical processes of the movement of water as it enters and moves through the soil column downward to the water table. Conditions such as the amount of precipitation and evapotranspiration and the capacity of soils to absorb and store water are important components used by the model when calculating recharge. The SWB model used for this investigation is based on a modified Thornthwaite-Mather (Thornthwaite and Mather, 1957) approach that incorporates spatially distributed landscape, soils properties, and daily metrological data and produces model output of detailed spatial and temporal variability of recharge and evapotranspiration across the study area (Westenbroek and others, 2010). The aquifer recharge calculation described in this appendix section was critical for the development of the hydrologic budget analysis presented in the main section of the report.

Data Requirements for the SWB Model

The SWB model structure consists of tabular and gridded datasets of (1) precipitation and temperature, (2) land-use classification, (3) hydrologic soil group, and (4) available soil-water capacity, all of which are required to calculate recharge on a cell-by-cell basis as described in detail in the SWB model documentation (fig. 1–1, Westenbroek and others, 2010). The SWB model grid for the NACP (fig. 1–2) extends along a north-south axis from southern Massachusetts to North Carolina and along a west-east axis from western Maryland to the end of Cape Cod. This area is much larger than the NACP study area (fig. 1–2, grey-shaded area) to minimize the potential that boundary effects could influence the model results in the area of interest. This grid consists of a uniform 1-square mile (mi^2) grid spacing of 518 rows and 554 columns for a total of 286,972 cells. Results reported for this analysis are limited to the NACP study area, an irregularly shaped area with about 74,000 model cells.

Precipitation and Temperature

The SWB model calculates recharge from weather data on a daily time step over a user-specified period (usually annually or monthly). Daily weather data can be input as either tabular time series or gridded datasets. Gridded data were developed for this analysis because of the large geographic size and latitudinal extent of the study area. Daily minimum and maximum temperature grids were created from tabular data of National Oceanic and Atmospheric Administration (NOAA) daily surface observations (National Oceanic and Atmospheric Administration, 2011). The tabular surface data were somewhat spatially and temporally discontinuous. The number of surface stations used in the temperature grid development varied depending on data availability for the period of interest (fig. 1–3; table 1–1). Statistical Analysis Systems routines (SAS version 4.2; 2008) were used to quality check the data and reformat and combine the data into files with daily data for each station, which then were verified and, along with station latitude and longitude, were combined into single files of daily data, one for each day of the processing period. The temperature files were processed into 1-mi^2 gridded surfaces using Surfer, a semi-automated thin-plate spline method (Golden Software Inc., 2010). Data grids of precipitation were obtained from the NOAA National Climate Data Center (NCDC; National Oceanic and Atmospheric Administration, 2011) and were found to be spatially and temporally continuous. Esri ArcInfo grid functionality then was used to process all of the gridded precipitation and temperature data into SWB-compatible American Standard Code for Information Interchange (ASCII) data grids.

Precipitation grids for 2005 through 2009 were downloaded at a grid resolution of 0.25 degrees (approximately 13 miles at the latitude of the NACP study area) from the National Oceanic and Atmospheric Administration (2012) and were converted to a raster image for use in the SWB model using the Environmental Data Connector (EDC) (Applied Science Associates, undated). These precipitation grids were resampled to a grid resolution of 1 mi^2 for input into the SWB model. Mean annual precipitation data from 2005 through 2009 for the NACP area is shown in figure 1–4 (Prism Climate Group, 2012). The highest rainfall trends toward the northeastern and southeastern coastal parts of the study area.

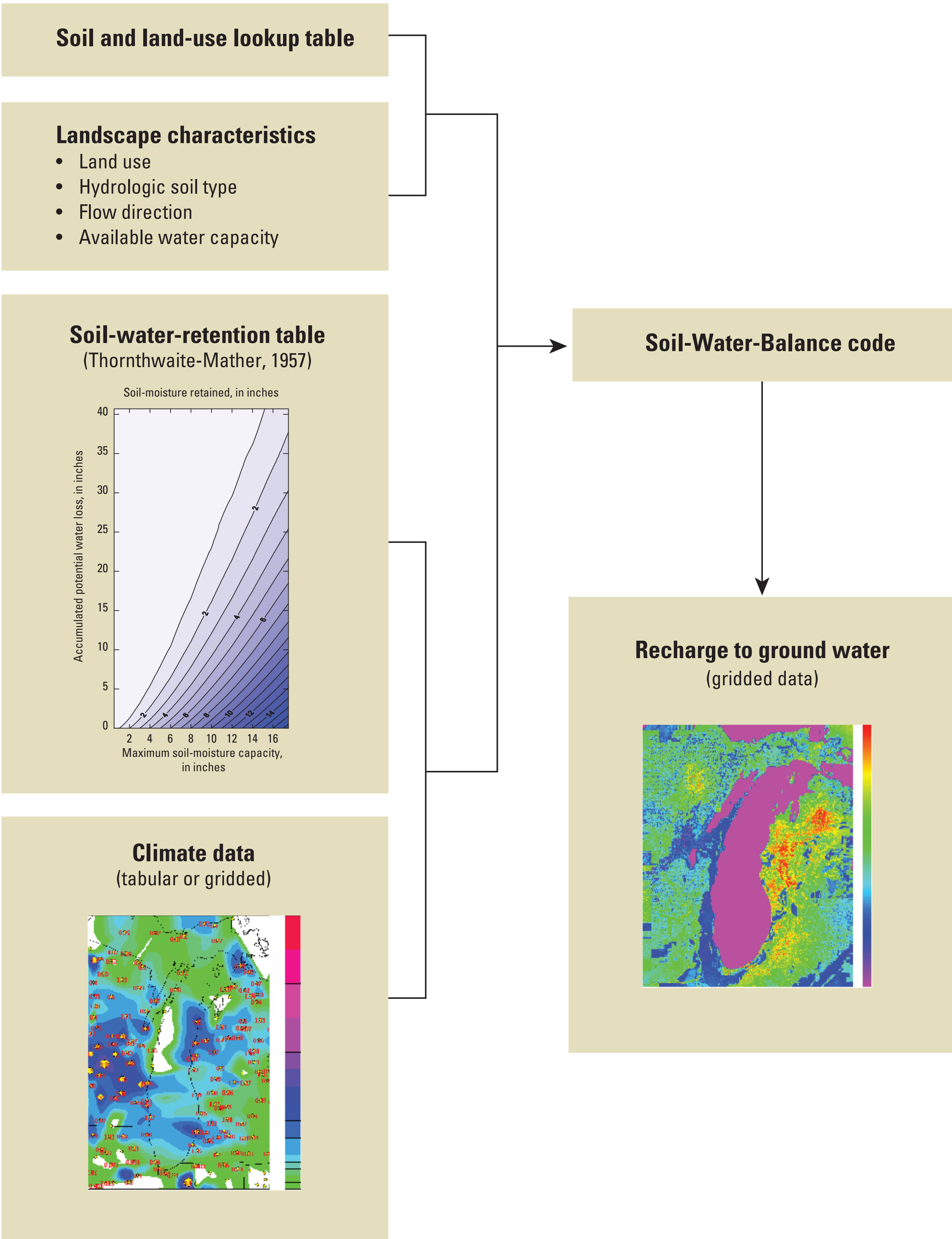

Figure 1–1. Diagram of the interaction between the soil-water balance code and input data. From Westenbroek and others (2010).

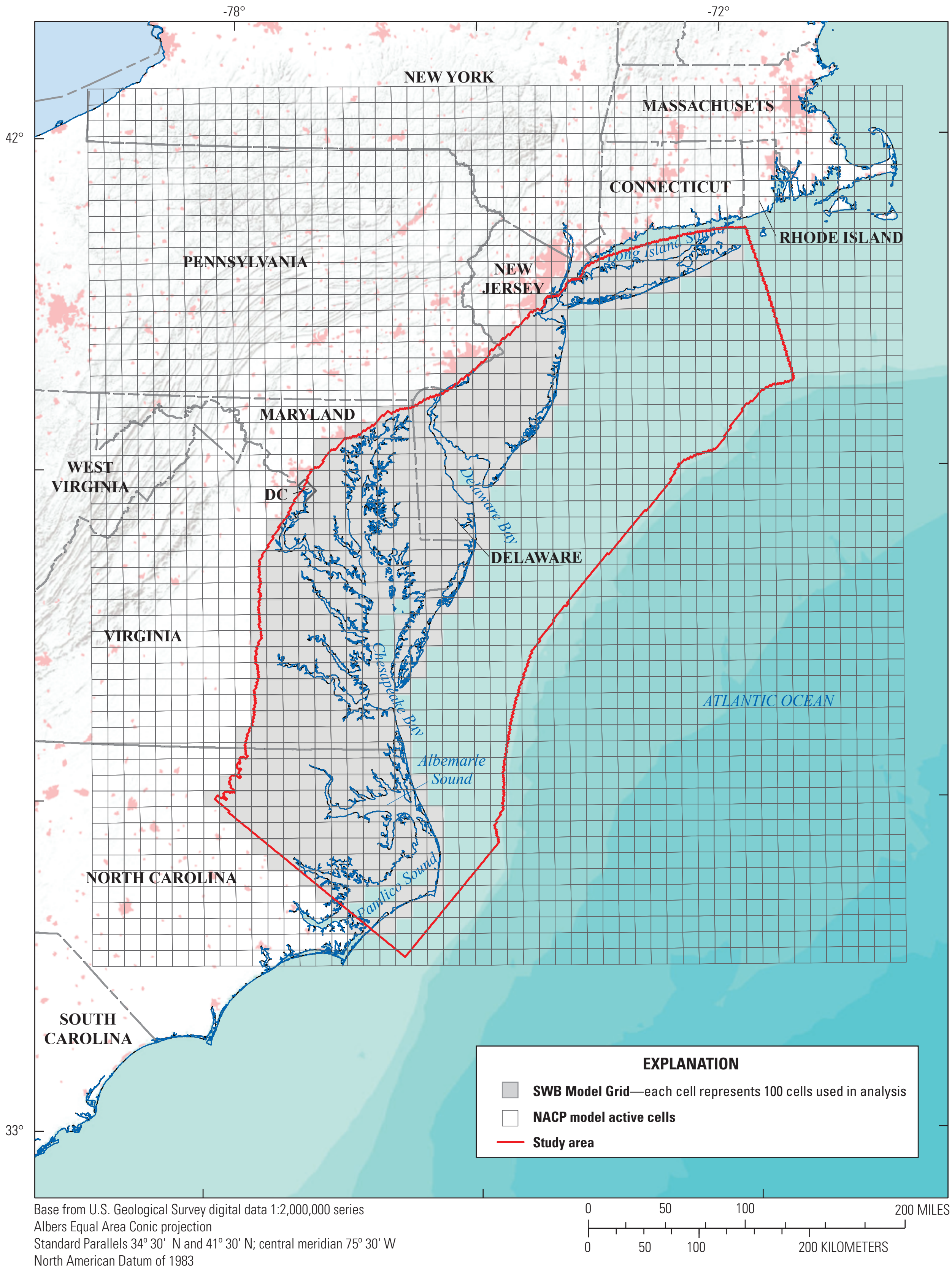

Figure 1–2. The soil-water balance (SWB) model grid for the Northern Atlantic Coastal Plain study area.

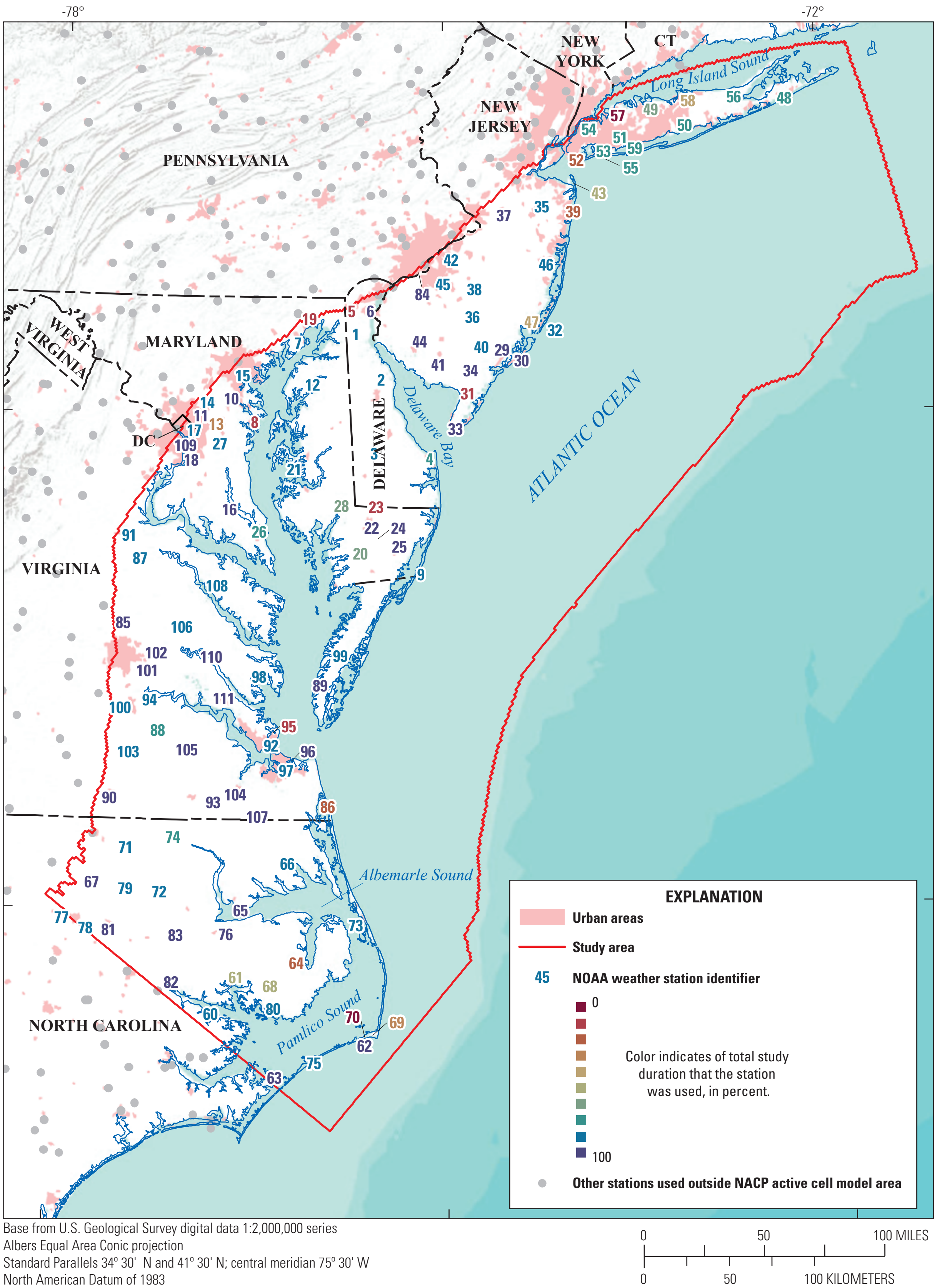

Figure 1–3. Surface observation data for the Northern Atlantic Coastal Plain (NACP). National Oceanic and Atmospheric Administration (NOAA) weather stations are listed in table 1–1.

Table 1–1. National Oceanic and Atmospheric Administration (NOAA) surface stations used for precipitation and average temperatures in the Northern Atlantic Coastal Plain from 2005 through 2009.

[Data are from National Oceanic and Atmospheric Administration (2011). NCDC, National Climatic Data Center]

Map identifier (fig. 1–1)	NOAA station identification number	NCDC station name
1	71200	BEAR 2 SW
2	72730	DOVER
3	73595	GREENWOOD 2NE
4	75320	LEWES
5	76410	NEWARK UNIV FARM
6	79595	WILMINGTON NEW CASTLE CO AP
7	180015	ABERDEEN PHILLIPS FLD
8	180193	ANNAPOLIS POLICE BRKS
9	180335	ASSATEAGUE
10	180465	BALTIMORE WASH INTL AP
11	180700	BELTSVILLE
12	181750	CHESTERTOWN
13	183675	GLENN DALE BELL STN
14	185111	LAUREL 3 W
15	185718	MD SCI CTR BALTIMORE
16	185865	MECHANICSVILLE 5 NE
17	186350	NATL ARBORETUM DC
18	186800	OXON HILL
19	187230	PORT DEPOSIT 2 NE
20	187330	PRINCESS ANNE
21	187806	ROYAL OAK 2 SSW
22	188000	SALISBURY
23	188003	SALISBURY POLICE BRKS
24	188005	SALISBURY WICOMICO RGNL AP
25	188380	SNOW HILL 4 N
26	188405	SOLOMONS
27	189070	UPPER MARLBORO 3 NNW
28	189140	VIENNA
29	280311	ATLANTIC CITY INTL AP
30	280325	ATLANTIC CITY
31	280690	BELLEPLAIN STN FOREST
32	280990	BRANT BEACH BECH HAVEN
33	281351	CAPE MAY 2 NW
34	282805	ESTELL MANOR
35	283181	FREEHOLD-MARLBORO
36	283662	HAMMONTON 1 NE
37	283951	HIGHTSTOWN 2 W
38	284229	INDIAN MILLS 2 W
39	284987	LONG BRANCH OAKHURST
40	285346	MAYS LANDING 1 W
41	285581	MILLVILLE MUNI AP

Table 1–1. National Oceanic and Atmospheric Administration (NOAA) surface stations used for precipitation and average temperatures in the Northern Atlantic Coastal Plain from 2005 through 2009.—Continued

[Data are from National Oceanic and Atmospheric Administration (2011). NCDC, National Climatic Data Center]

Map identifier (fig. 1–1)	NOAA station identification number	NCDC station name
42	285728	MOORESTOWN
43	287865	SANDY HOOK
44	287936	SEABROOK FARMS
45	288173	SOMERDALE 4 SW
46	288816	TOMS RIVER
47	288899	TUCKERTON 2 NE
48	300889	BRIDGEHAMPTON
49	301309	CENTERPORT
50	304130	ISLIP LI MACARTHUR AP
51	305377	MINEOLA
52	305796	NY AVE V BROOKLYN
53	305803	NEW YORK JFK INTL AP
54	305811	NEW YORK LAGUARDIA AP
55	306138	OCEANSIDE
56	307134	RIVERHEAD RSCH FM
57	307587	SEA CLIFF
58	307633	SETAUKET STRONG
59	308946	WANTAGH CEDAR CREEK
60	310375	AURORA 6 N
61	310674	BELHAVEN 3 NE
62	311458	CAPE HATTERAS AP
63	311606	CEDAR ISLAND
64	311949	COLUMBIA AG GUM NECK
65	312635	EDENTON
66	312719	ELIZABETH CITY
67	312827	ENFIELD
68	312940	FAIRFIELD
69	313333	FRISCO
70	313336	FRISCO 2NNE
71	314456	JACKSON
72	314962	LEWISTON
73	315303	MANTEO 2 WNW
74	315996	MURFREESBORO
75	316349	OCRACOKE
76	316853	PLYMOUTH 5 E
77	317395	ROCKY MOUNT
78	317400	ROCKY MT 8 ESE
79	317725	SCOTLAND NECK #2
80	318450	SWANQUARTER FERRY
81	318500	TARBORO 1 S
82	319100	WASHINGTON WWTP 4W

Table 1–1. National Oceanic and Atmospheric Administration (NOAA) surface stations used for precipitation and average temperatures in the Northern Atlantic Coastal Plain from 2005 through 2009.—Continued

[Data are from National Oceanic and Atmospheric Administration (2011). NCDC, National Climatic Data Center]

Map identifier (fig. 1–1)	NOAA station identification number	NCDC station name
83	319440	WILLIAMSTON 1 E
84	366889	PHILADELPHIA INTL AP
85	440327	ASHLAND
86	440385	BACK BAY WR
87	442009	CORBIN
88	442400	DISPUTANTA
89	442635	EASTVILLE
90	442790	EMPORIA 1 WNW
91	443204	FREDERICKSBURG SEWAGE
92	443713	HAMPTON UNIV
93	444044	HOLLAND 1 E
94	444101	HOPEWELL
95	444720	LANGLEY AFB
96	446139	NORFOLK INTL AP
97	446147	NORFOLK SOUTH
98	446161	NORTH
99	446475	PAINTER 2W
100	446656	PETERSBURG
101	447201	RICHMOND INTL AP
102	447541	SANDSTON
103	448129	STONY CREEK 2 N
104	448192	SUFFOLK LAKE KILBY
105	448800	WAKEFIELD 1NW
106	448829	WALKERTON 2 NW
107	448837	WALLACETON LK DRUMMOND
108	448894	WARSAW 2 NW
109	448906	WASHINGTON REAGAN AP
110	449025	WEST POINT 2 NW
111	449151	WILLIAMSBURG 2 N

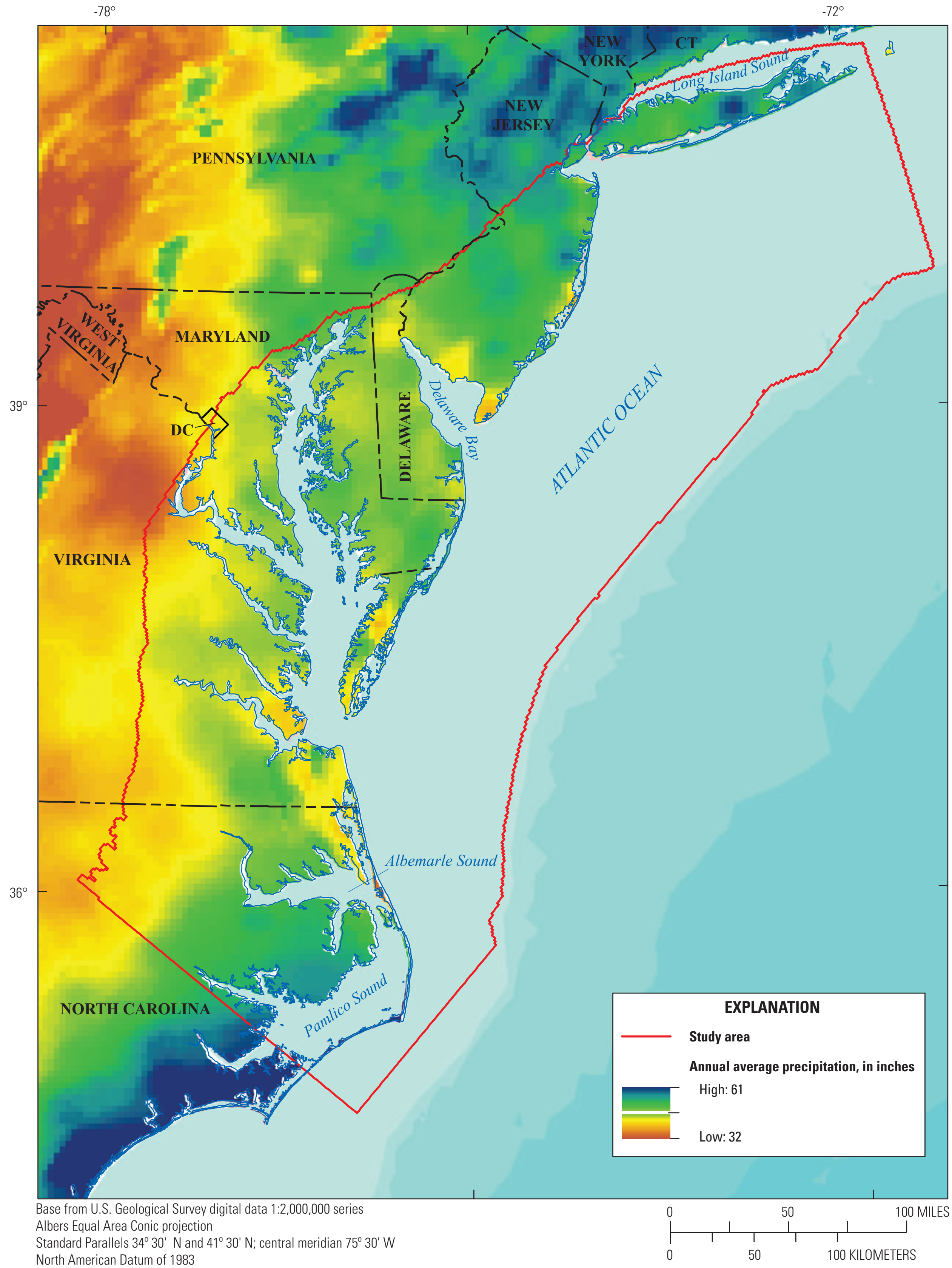

Figure 1–4. Mean annual precipitation from 2005 through 2009 in the Northern Atlantic Coastal Plain (NACP).

Land Use Classification

Land-use cover data are required in the SWB model for the calculation of net recharge to the groundwater flow system. Land use and land cover in the NACP is primarily a mosaic of forest, wetlands, and agriculture (Loveland and others, 1999). Dominant land uses are farming and forestry, with locally dense urban development. More than half (57 percent) of the NACP area is undeveloped, nearly a third (30 percent) is agricultural, and 13 percent is developed (fig. 5). Grids of land-use classifications were developed from the Multi-Resolution Land Characteristics Consortium's (MRLC) 2001 National Land Cover Database (NLCD; LaMotte, 2008a,b). The NLCD dataset includes 16 different land-cover classifications for 2001.

Hydrologic Soil Groups

The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS; undated) has classified more than 14,000 series of soils within the United States into one of four major hydrologic soils groups, which are assigned a letter designation (A–D) that describes soils with similar physical and runoff characteristics. This designation is focused specifically on water transmissivity, or infiltration capacity, through the soil. Soils designated as group A have a high capacity for infiltration (greater than 0.30 inch per hour (in/hr)) and low runoff potential, whereas those with a designation of group D have low infiltration capacity (less than 0.05 in/hr) and high runoff potential (Cronshey and others, 1986). The soils in almost half (about 43 percent) of the NACP, areas primarily in the southern Delmarva Peninsula in Delaware, Maryland, and Virginia and in northeastern North Carolina, are classified in group D (fig. 1–5; table 1–2). Areas with soils that have a high capacity for infiltration (groups A and B) are located in the northern portion of the study area (fig. 1–5). The data on the groups of hydrologic soils provided in the NRCS U.S. General Soil Map (STATSGO2) dataset (Natural Resources Conservation Service, undated a) were used to define gridded datasets of hydrologic soils and associated lookup tables to be used as input for hydrologic capacity in the SWB model.

Available Soil-Water Capacity

The SWB model uses land-use and land-cover information, in conjunction with available soil-water capacity and water interception coefficients of plants to calculate surface runoff and assign a maximum soil-moisture holding capacity for each grid cell in the model. Each soil type or soil series within the model area must be assigned an available water capacity. Available soil-water capacity is the water held in soil between its field capacity and the permanent wilting point (U.S. Department of Agriculture, 1998); it is often reported as inches of water per foot of soil thickness. Field capacity is the amount of water remaining in a soil 2 to 3 days after the soil has been saturated and allowed to drain freely. Permanent wilting point is the moisture content of a soil at which plants wilt and fail to recover when supplied with sufficient moisture (Tolk, 2003).

Available soil-water capacity is determined primarily by soil texture. Coarse soils have a lower field capacity than fine-textured soils because the large pore spaces between these coarse soils allow water to drain more freely than in the fine-textured soils. For this analysis, available soil-water capacity was assigned for the top 59 inches (or approximately 150 centimeters (cm)) of the soil column from the STATSGO2 database.

STATSGO2 reports available soil-water capacity for four depth classes:

- A, 0 to 25 cm
- B, 0 to 50 cm
- C, 0 to 100 cm
- D, 0 to 150 cm

The total soil-water capacity for each of the four classes was calculated and used as input for the SWB model. The SWB calculates the maximum soil-water capacity as the product of available soil water capacity and rooting depth, the depth of soil from which plant roots take up water. Within the NACP study area, soils with the highest available soil-water capacity tend to be located in low-lying areas along rivers and near the coast in the southern portion of the study area (fig. 1–6; table 1–3).

Lookup Tables

The SWB model uses a lookup-table scheme, consisting of two tables that contain text fields, to assign model cell properties related to soils and land use. The land-use table holds information on soil characteristics, such as rooting depth, runoff curve numbers, and maximum daily recharge based on land-use classifications.

Rooting depth is an important component of the recharge calculation because of the effect of rooting depth on water flow and transpiration. For example, Seyfried and Wilcox (2006) showed that recharge rates increase in areas where shallow rooted plants (crops) have replaced deep-rooted woody vegetation (forests). Rooting depths used for the calculation of recharge for the NACP area are derived from the Thornthwaite and Mather (1957) water-balance analysis that was conducted in central New Jersey.

The runoff curve value is an empirical parameter developed by the USDA Soil Conservation Service (SCS) that is used to estimate rainfall runoff or infiltration (Hjelmfelt, 1991). The SWB model applies runoff curve values to soil types defined in the land-use lookup table; for this analysis, the values of land use were derived from Westenbroek and others (2010).

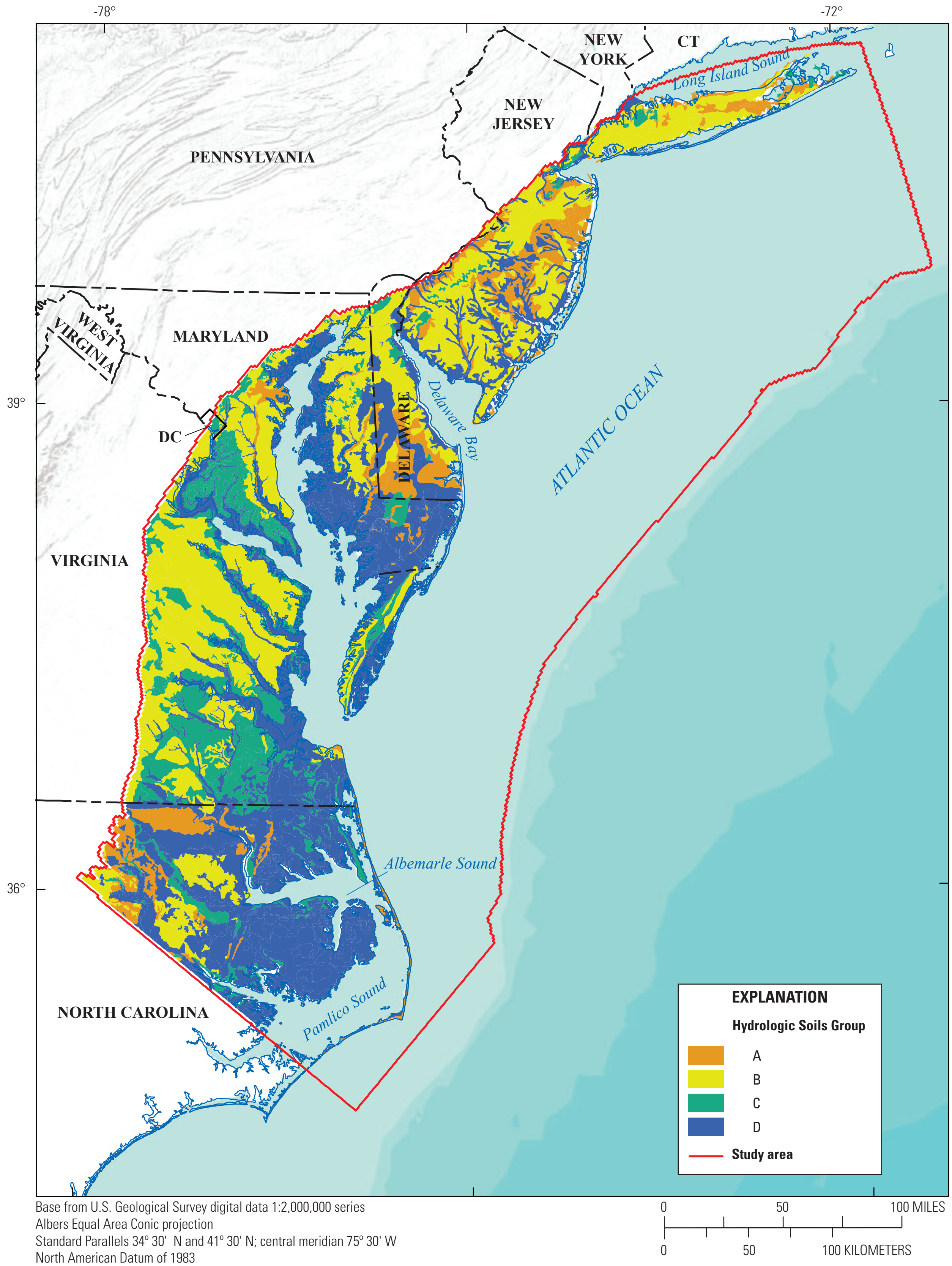

Figure 1–5. Hydrologic soil groups in the Northern Atlantic Coastal Plain; from U.S. Department of Agriculture (2006).

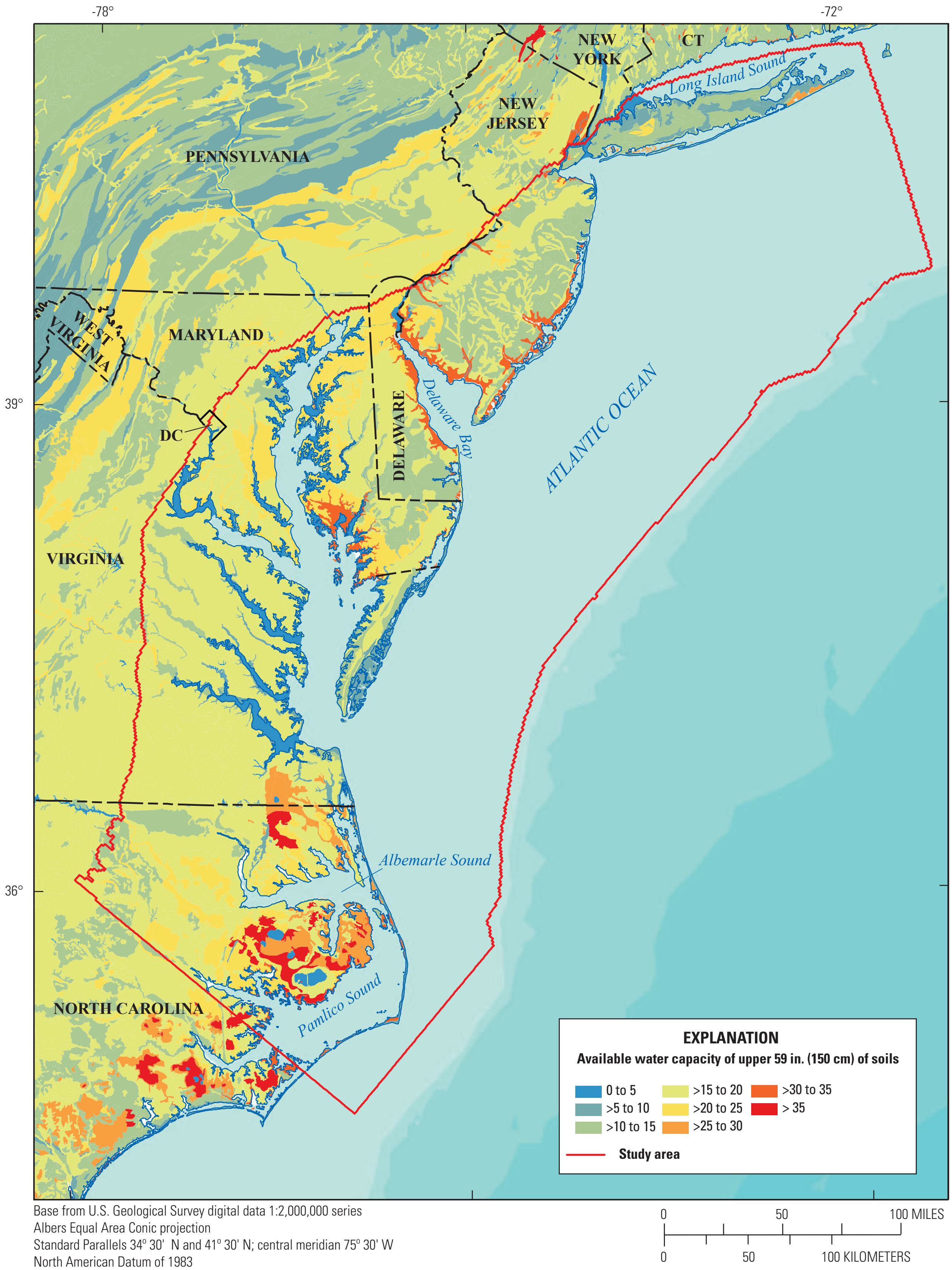

Figure 1–6. Available water capacity for soils in the Northern Atlantic Coastal Plain. From U.S. Department of Agriculture (2006).

Table 1–2. Distribution of soils in the Northern Atlantic Coastal Plain study area.

[Designations of groups of hydrologic soils are from U.S. Department of Agriculture (2006). NACP, Northern Atlantic Coastal Plain]

Hydrologic soil group	Percentage of total NACP area
A	9.6
B	33.8
C	14.2
D	42.4

Table 1–3. Estimated available water capacities for various soil-drainage classifications.

[Soil drainage is expressed in terms of hydrologic soil groups, as defined in Natural Resources Conservation Service (undated a,b). Values are rounded to the nearest tenth. NACP, North Atlantic Coastal Plain]

Soil drainage classification	Average available water capacity, in inches[1]	Soil type area, percentage of total NACP area
Excessively drained	8.6	5.7
Somewhat excessively drained	12.1	0.9
Well drained	16.8	39.9
Moderately well drained	18.0	11.8
Somewhat poorly drained	20.8	0.9
Poorly drained	19.0	23.6
Very poorly drained	23.6	17.3

[1]Average available water capacity in top 59 inches (or approximately 150 centimeters (cm)) of soil..

The maximum daily recharge rate is the measure of the maximum quantity at which soil is able to absorb water from rainfall or irrigation. This recharge value is influenced by soil characteristics, such as texture, organic matter, and compaction as well as land-cover conditions. The SWB model applies maximum daily recharge values to soil types defined in the land-use lookup table; for this analysis, the values of land use were derived from Westenbroek and others (2010).

The second lookup table is an extended version of the Thornthwaite-Mather soil-water retention tables that describe the ability of different soils to hold water (Thornthwaite and Mather, 1957). The ability of soil to hold water is strongly related to particle size, and water molecules hold more tightly to clay than they do coarse materials, such as sand grains. Generally, sandy soils will hold water through capillary binding whereas clay soils retain water through other physical binding processes. The soil-water retention tables are provided with the SWB model and require no user modification.

Simulation Results

The SWB model was run for conditions between 2005 and 2009. Results of the simulation indicate that the average recharge rate for the study area is about 13.9 in/yr and varies from a minimum of 4.2 in/yr in the low lands of North Carolina and Virginia to a maximum of 37.6 in/yr on eastern Long Island (fig. 1–7). Simulation results compared favorably to previously published recharge rates within the NACP study area (table 1–4).

The SWB model used in this analysis calculates recharge as follows:

$$Rc = Pr - Inf - Ro - ETa, \qquad (1\text{–}1)$$

where

- Pr is gross precipitation (including snowfall and snowmelt)
- Inf is interception
- Ro is runoff
- ETa is actual evapotranspiration

Interception by plant foliage, runoff, and actual evapotranspiration (evaporation and plant transpiration) components are calculated by the SWB model from input datasets such as daily meteorological data, soils, and land use. In this analysis, the highest recharge rates occurred in areas with porous sandy soils where model results showed recharge rates of up to 50 percent of gross precipitation. Conversely, thick, clayey coastal soils and marshy areas showed recharge rates as low as 12 percent of gross precipitation. Differences attributable to soil properties drove model results especially with regard to evapotranspiration and runoff, both of which were seen to be high in the low-permeability soils typically found in flat low-lying coastal areas. If taken as a whole of the total gross precipitation that fell across the entire model area, the SWB model indicates the two largest components of water loss before recharge are evapotranspiration at 35 percent and runoff at 9 percent. The results presented here compare favorably with previous studies in the NACP in terms of both recharge rates and spatial distribution (Sanford and others, 2012).

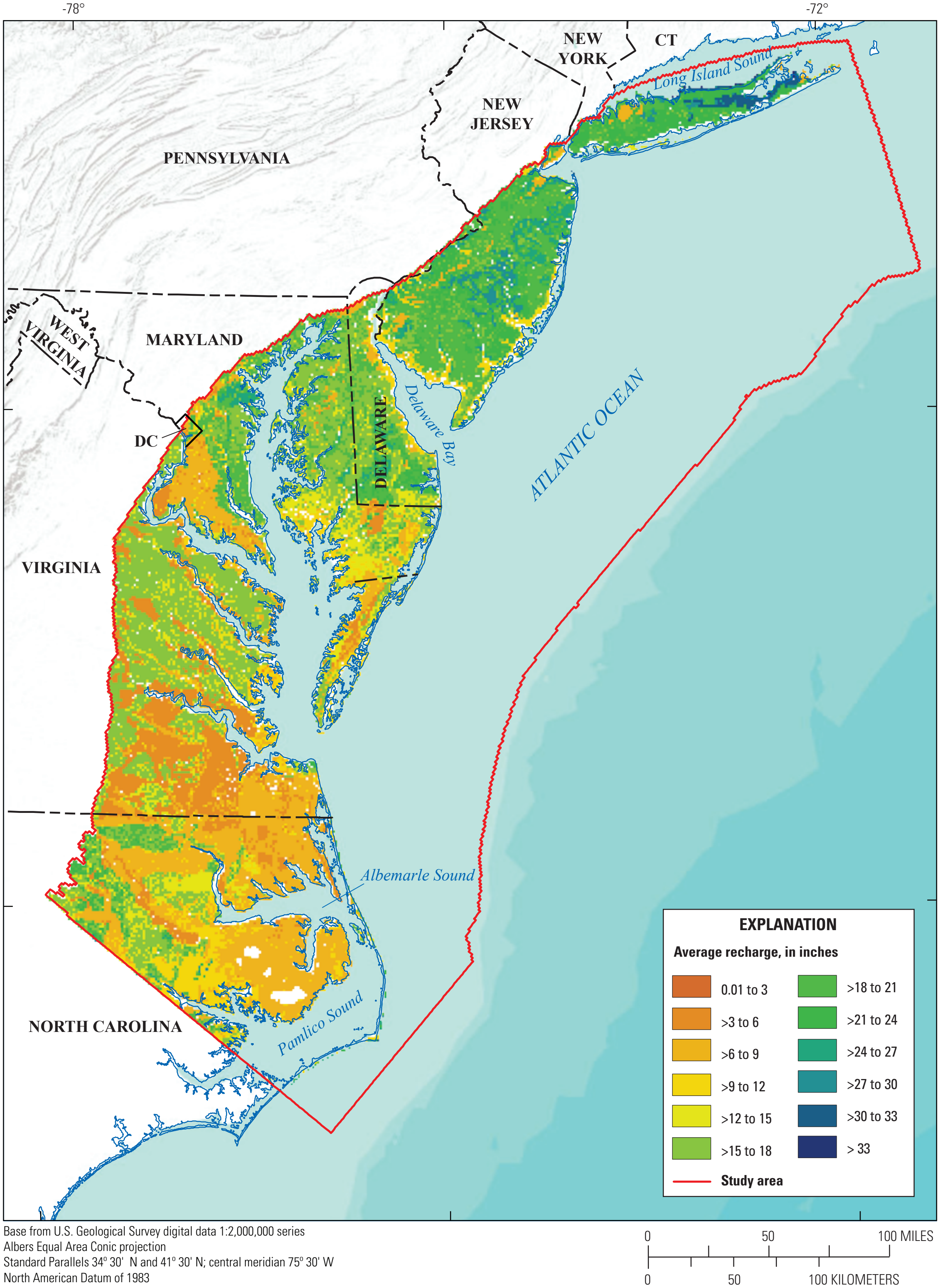

Figure 1–7. Average annual recharge from 2005 through 2009 in the Northern Atlantic Coastal Plain.

Table 1–4. Recharge rates from previous investigations in the Northern Atlantic Coastal Plain.

Geographic area	Rate, in inches per year	Method	Reference
Delaware, Coastal Plain	14–26	Base flow separation	Johnston (1976)
Maryland:			
Anne Arundel County Coastal Plain	14.4–21.2	Specific yield (Meinzer 1929)	Achmad (1991)
Anne Arundel County Coastal Plain	20.1	Base flow separation	Achmad (1991)
Wicomico County Coastal Plain	15–27	Physical methods (precipitation and well hydrograph analysis)	Rasmussen and Andreasen (1959)
North Carolina:			
Coastal Plain	5–21	Unknown	Heath (1994)
Southern Coastal Plain	5–40	Unknown	North Carolina Department of Environment and Natural Resources (2003)
New Jersey:			
Kirkwood-Cohansey aquifer system	15–20	Average precipitation and variances in evapotranspiration and runoff	Modica (1996)
Kirkwood-Cohansey aquifer system and Vincentown aquifer	19.4	Water-budget analyses (Watt and others, 1994)	Nicholson and Watt (1997)
Kirkwood-Cohansey Coastal Plain	16.2	Water-budget analyses (Charles and others, 2001)	Cauller and Carleton (2006)
Kirkwood-Cohansey Coastal Plain	13.03	Water-budget analyses (Charles and others, 1997)	Cauller and Carleton (2006)
Northern Atlantic Coastal Plain	2.5–15.7	Age dating	McMahon and others (2011)
New York:			
Coastal Plain	22	Unknown	Wood (2006)
Long Island Brookhaven National Lab	23	Unknown	Brookhaven National Laboratory (2001)
Long Island Coastal Plain	22 to 23	Unknown	Wen (undated)
Virginia:			
Coastal Plain	22.95	Zonebudget	Heywood and Pope (2009)
Eastern Shore Coastal Plain	7.4–24	Inverse simulation and SF6	Sanford and others (2009)
Western Massachusetts, eastern New York, and northwestern Connecticut	17.5–22	Base flow separation	Bent (1999)
Average	11.8–21.7		

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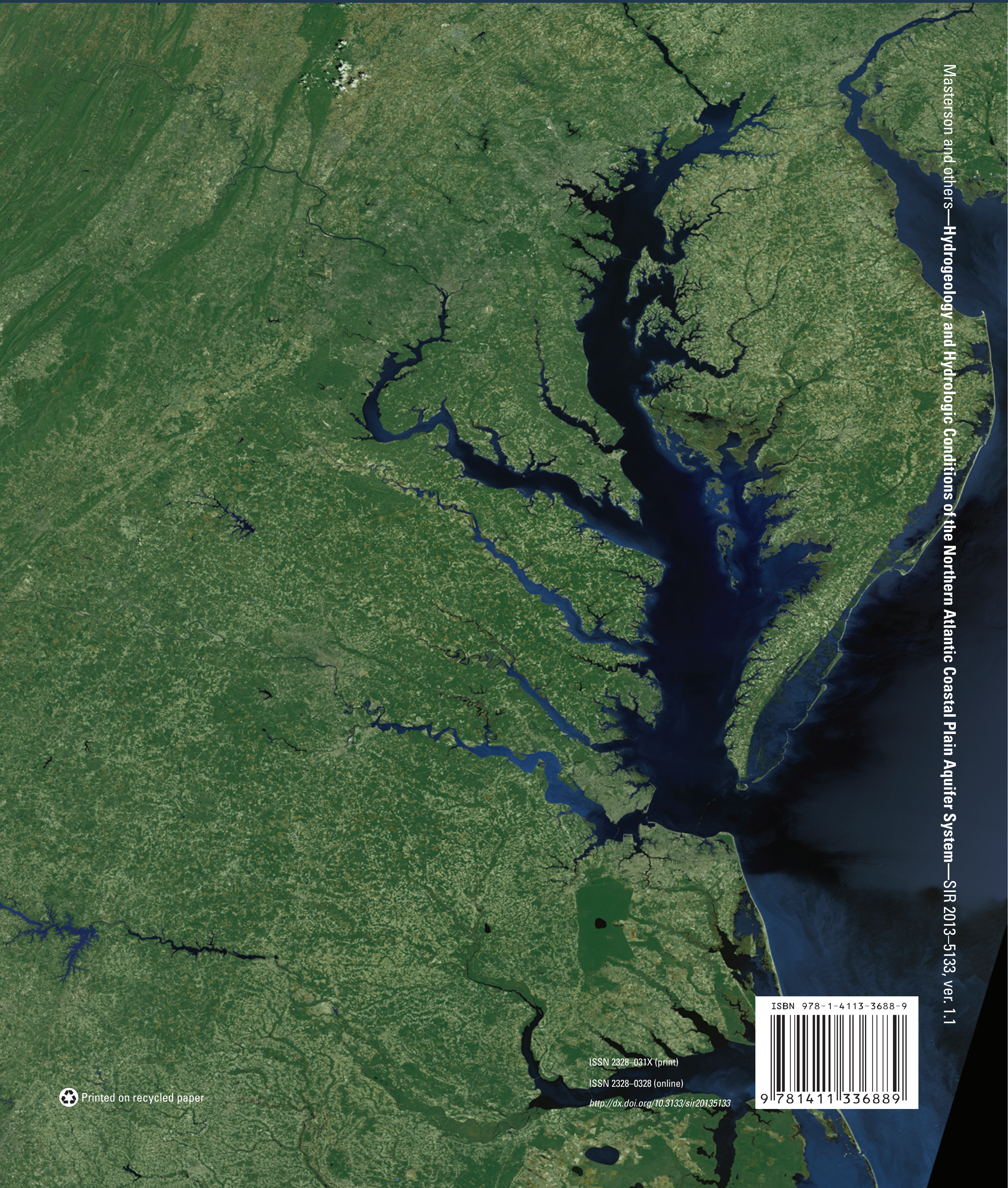

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