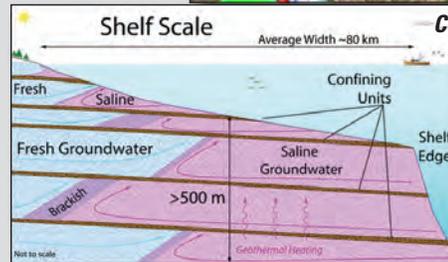
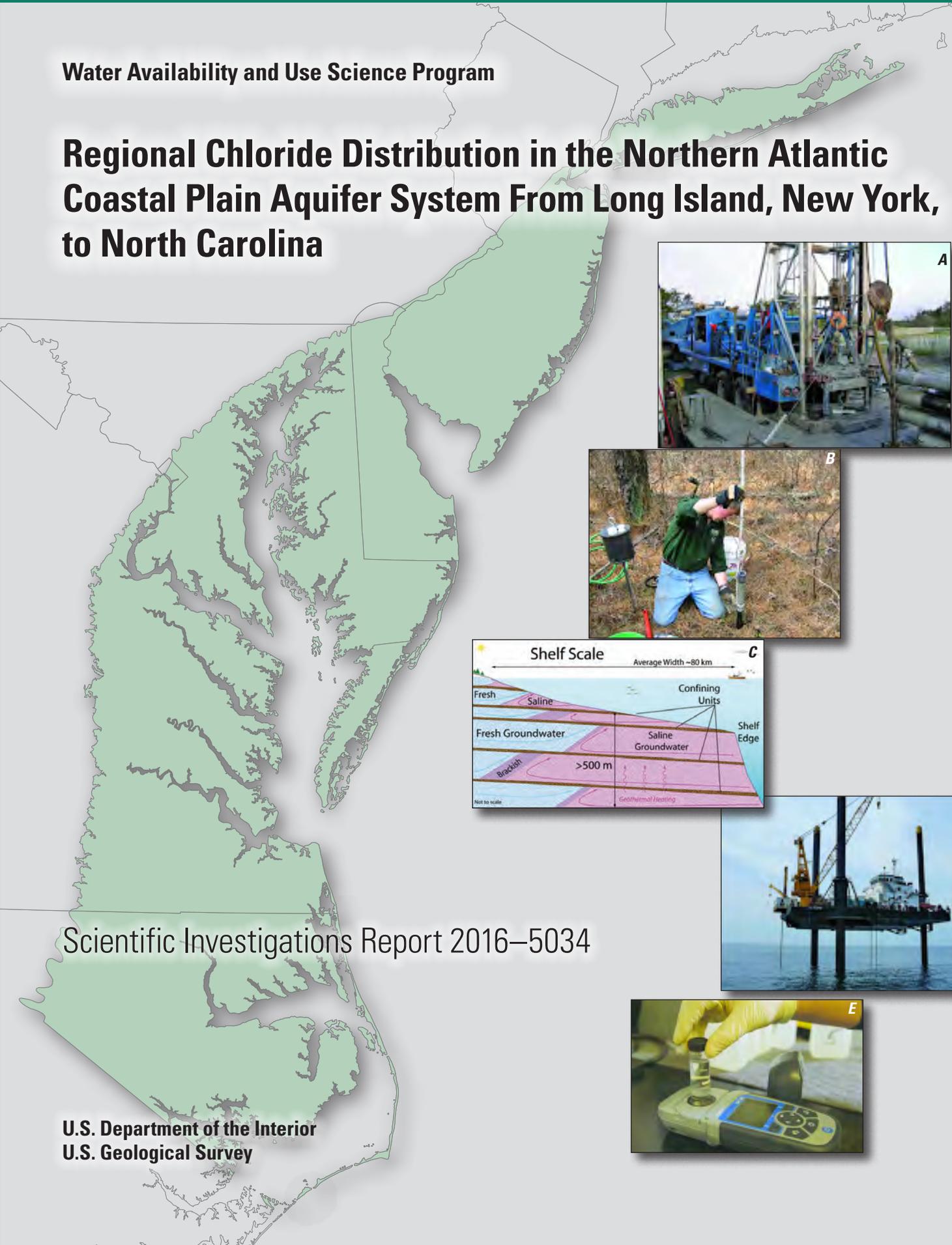


Water Availability and Use Science Program

Regional Chloride Distribution in the Northern Atlantic Coastal Plain Aquifer System From Long Island, New York, to North Carolina



Scientific Investigations Report 2016–5034

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

Cover photographs.

A, Geophysical logging on Long Island, New York (photograph by Anthony Chu, U.S. Geological Survey).

B, Sampling groundwater in New Jersey (photograph by U.S. Geological Survey personnel).

C, Schematic of U.S. Atlantic Continental Shelf-scale interfaces of fresh-saline groundwater (from Bratton, 2010).

D, Scientific drilling on eastern U.S. Continental Shelf (photograph by U.S. Geological Survey personnel).

E, Testing ground water, Dare County Water Department, North Carolina (frame from YouTube video).

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U.S. Geological Survey

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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2016

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Suggested citation:

Charles, E.G., 2016, Regional chloride distribution in the Northern Atlantic Coastal Plain aquifer system from Long Island, New York, to North Carolina: U.S. Geological Survey Scientific Investigations Report 2016–5034, 37 p., appendices, <http://dx.doi.org/10.3133/sir20165034>.

ISSN 2328-0328 (online)

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
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)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
 $^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as
 $^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8.$

Datum

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

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

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

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25 °C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

EPA	U.S. Environmental Protection Agency
NACP	Northern Atlantic Coastal Plain
ODP	Ocean Drilling Program
RASA	Regional Aquifer-System Analysis
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

Regional Chloride Distribution in the Northern Atlantic Coastal Plain Aquifer System From Long Island, New York, to North Carolina

By Emmanuel G. Charles

Abstract

The aquifers of the Northern Atlantic Coastal Plain are the principal source of water supply for the region's nearly 20 million residents. Water quality and water levels in the aquifers, and maintenance of streamflow, are of concern because of the use of this natural resource for water supply and because of the possible effects of climate change and changes in land use on groundwater. The long-term sustainability of this natural resource is a concern at the local community scale, as well as at a regional scale, across state boundaries. In 2010, the U.S. Geological Survey (USGS) began a regional assessment of the Northern Atlantic Coastal Plain aquifers. An important part of this assessment is a regional interpretation of the extent of saltwater and the proximity of saltwater to fresh-groundwater resources and includes samples and published interpretations of chloride concentrations newly available since the last regional chloride assessment in 1989. This updated assessment also includes consideration of chloride samples and refined interpretations that stem from the 1994 discovery of the buried 35 million year old Chesapeake Bay impact structure that has substantially altered the understanding of the hydrogeologic framework and saltwater distribution in eastern Virginia.

In this study, the regional area of concern for the chloride samples and interpretations extends from the Fall Line in the west to the outer edge of the Continental Shelf in the east and from the eastern tip of Long Island in the north to about halfway down the North Carolina coast in the south. Discussions of chloride distribution are presented for each of the 10 regional aquifer layers of the Northern Atlantic Coastal Plain, including the offshore extents. Maps of interpreted lines of equal concentration or isochlors were manually prepared for nine of the regional aquifers; a map was not prepared for the surficial regional aquifer. The isochlor interpretations include the offshore extent of the nine regional aquifers and are presented on a 1:2,000,000 scale base map. Vertically, the chloride samples and interpretations range from deepest (oldest) to shallowest (youngest)—Potomac-Patuxent, Potomac-Patapsco, Magothy, Matawan, Monmouth-Mount

Laurel, Aquia, Piney Point, Lower Chesapeake, and Upper Chesapeake regional aquifers.

The approach of this study maximizes the overall density of chloride information and data by assessing relevant published interpretations, all USGS chloride samples, and all relevant offshore samples in one comprehensive interpretation. Published isochlors, where they were interpreted by regional aquifer, were used as much as possible for this regional isochlor assessment. Publication dates for the isochlors used range from 1982 to 2015, and the scales for the isochlors range from local (county or municipality) to state (sub-regional) to regional. The USGS National Water Information System database provided well sample data for the parts of aquifers that are mainly beneath the land areas and yielded 37,517 water-quality records for 1903 through 2011. Published data reports from four phases of research-related offshore coring (1976, 1993, 1997, 2009) were the main source of water-quality data for the parts of aquifers from the shoreline to the outer edge of the Continental Shelf and yielded samples from multiple depths of each of 13 cores. This study also used interpretations and offshore core data from the last regional chloride assessment (1989) which, in addition to 7 offshore cores, included water-quality data from about 500 wells, and borehole geophysics interpretations from a subset of 11 wells. All published information and data that were used in this study were considered time independent and did not assess the published interpretations or data for temporal trends. The approach used here examined only published interpretations and available chloride data, and did not directly use supplemental techniques that can provide insight into the distribution of saltwater, such as geochemical characterization, borehole geophysical information, and geochronology.

Isochlor maps for this study are limited to manual interpretations of the 250-milligram per liter (mg/L) and 10,000-mg/L boundaries developed for 9 of the 10 regional aquifers that constitute the regional hydrogeologic framework of the Northern Atlantic Coastal Plain. For a given aquifer, the approach was to initially consider published isochlor interpretations, where available, then to modify the published interpretations, if necessary, to the extent indicated by the well and core samples. The final step was to interpolate isochlors

to the full extent of each aquifer layer in areas with sufficient samples or cited interpretations, or to extrapolate isochlors in areas with no samples or where samples were sparse.

The principal limitation of this study is that, because of its regional extent, data and information density can vary greatly, and thus confidence in interpretations can vary widely for onshore and offshore areas across the study area. In areas of sparse data, some samples of elevated chloride could be misinterpreted as being part of a regional elevated chloride trend, and in other cases, an elevated concentration could be misinterpreted as being of only local importance. The interpretive work of this study was applied to a 1:2,000,000 scale base map. Locations of isochlors, wells, cores, political boundaries, and shorelines are meant to be considered approximate.

The isochlors presented in this study were manually interpreted for each aquifer unit as a conceptual representation of an equal concentration line approximately in the middle of an aquifer's thickness. Differences in chloride concentration lines between the top and bottom of an aquifer could be substantial, especially for the thick parts of aquifers, but that information is not presented in this regional assessment.

Although additional offshore chloride data are available compared to 27 years ago (1989), the offshore information remains sparse, resulting in less confidence in the offshore interpretations than in the onshore interpretations. Regionally, the 250- and 10,000-mg/L isochlors tend to map progressively eastward from the deepest to the shallowest aquifers across the Northern Atlantic Coastal Plain aquifer system but with some exceptions. The additional data, conceptual understanding, and interpretations in the vicinity of the buried Chesapeake Bay impact structure in eastern Virginia resulted in substantial refinement of isochlors in that area. Overall, the interpretations in this study are updates of the previous regional study from 1989 but do not comprise major differences in interpretation and do not indicate regional movement of the freshwater-saltwater interface since then.

Introduction

The Northern Atlantic Coastal Plain (NACP) study area (fig. 1) includes parts of New York, New Jersey, Delaware, Maryland, Washington, D.C., Virginia, and North Carolina. The study area is underlain by a complex of aquifers, which are the principal source of water supply for the region's nearly 20 million residents (Masterson, 2013). Water quality and water levels within these aquifers are a concern, as well as maintenance of streamflow, which is dependent on these aquifers. In 2010, the U.S. Geological Survey (USGS) began a program (U.S. Geological Survey, 2015) to assess the groundwater resources of the NACP. Chloride concentration is a measure of water quality that is widely used to indicate the amount of mixing of saltwater with fresh groundwater or the proximity of saltwater to fresh groundwater. Chloride iso-concentration (isochlor) maps are often used in regional assessments to

define useful extents of the groundwater resource and areas of concern. In order to define the freshwater and saltwater extents of groundwater, isochlor maps are presented in this report for 9 of the 10 regional aquifers; a map was not prepared for the surficial regional aquifer.

Description of Study Area

The NACP study area is situated along the eastern seaboard of the United States and extends from the eastern tip of Long Island in the north to a line about halfway down the North Carolina coast in the south. The Fall Line is the western limit of the study area, and to the east-southeast, the study area extends as much as 120 miles offshore to the outer edge of the Continental Shelf (fig. 1).

The sediments of the Coastal Plain consist of a seaward-dipping wedge of unconsolidated sediments (fig. 2), ranging in age from Lower Cretaceous to Holocene. The fine-grained sediments (silts, clays) function as confining units, and the medium- to coarse-grained material (sands and gravels) function as aquifers. The study area encompasses 10 regional aquifer layers from the shallow surficial aquifer to the deepest regional Potomac-Patuxent aquifer (fig. 2).

The urban centers within the NACP consist primarily of, from north to south, all or parts of the areas surrounding New York City and western Long Island, N.Y.; northern New Jersey; Baltimore, Maryland; Washington, D.C.; Richmond, Virginia; and Norfolk, Virginia. Much of the population is dependent on aquifers to meet their water demand, and in general, the urban centers and surrounding areas have the highest withdrawals from the NACP aquifers (Masterson and others, 2013). Besides being about 13 percent developed, the overall land use in the NACP study area is about 57 percent undeveloped and about 30 percent agricultural (Masterson and others, 2013; Fry and others, 2011). Topography in the study area ranges from moderately flat to hilly and, because of the temperate, humid climate, is heavily vegetated. The highest land surfaces, which approach several hundred feet in altitude, are along the western edge of the study area (Masterson and others, 2013).

Purpose and Scope

In the NACP study area, chloride concentrations in groundwater are a useful indicator of the presence of or proximity to saltwater. The last regional-scale chloride assessment conducted by the USGS for the NACP study area was published by Meisler (1989). Water-quality samples gathered since that time have resulted in updated interpretations of the extent of chloride concentrations at both the local and sub-regional (state) scales.

This report provides an updated regional-scale-chloride assessment and interpretation for the entire NACP. The interpretations presented in this report take into consideration historical and recent published chloride and saltwater

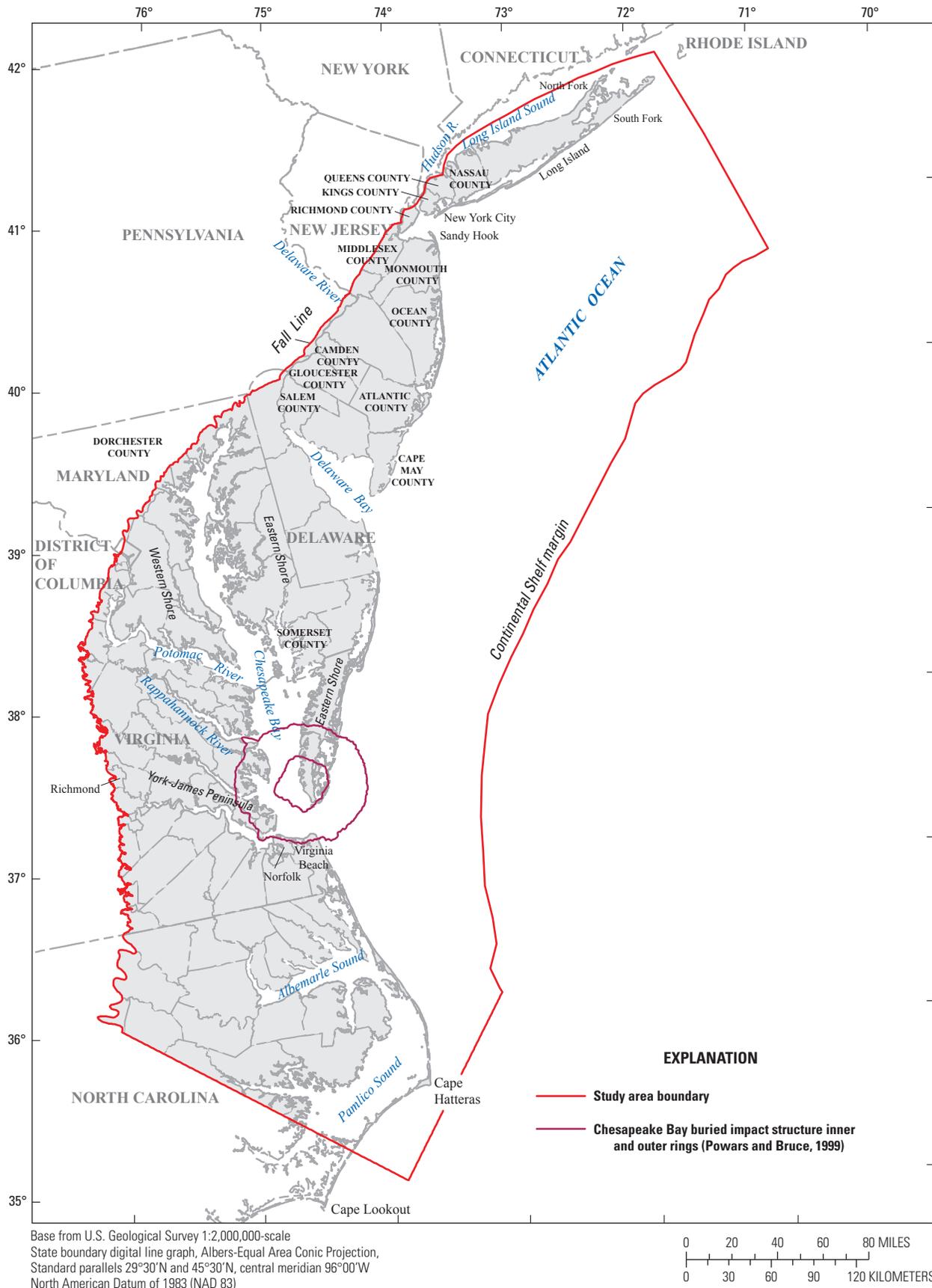


Figure 1. Location of the Northern Atlantic Coastal Plain study area.

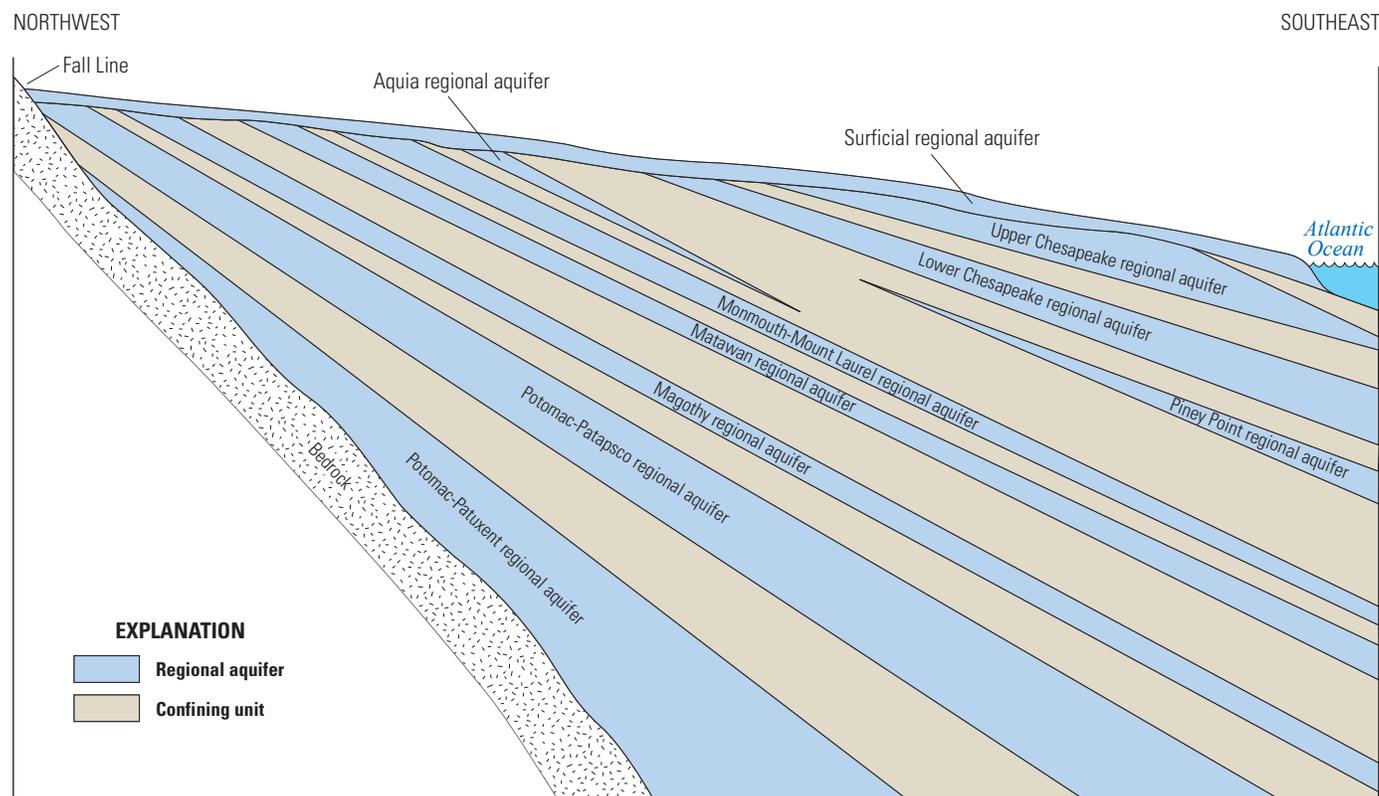


Figure 2. Generalized section showing Northern Atlantic Coastal Plain regional aquifer system.

interpretations at the regional, sub-regional (state), and local scales. The extent of the supporting water-quality records (samples) is far reaching and ranges from a large onshore sample set from 1903 through 2011 to a small but valuable dataset from offshore drilling in 1976, 1993, 1997, and 2009. The report and interpretations are intended as an updated accounting of regional freshwater-saltwater trends for use by the scientifically informed public, and Federal, state, and local officials when making water-supply decisions.

The main product of this chloride assessment is, for nine of the regional aquifers in the NACP, up-to-date interpreted lines of equal concentration or isochlors on a 1:2,000,000 scale. Two manually drawn isochlors (boundaries) are presented for a given aquifer—250-milligrams per liter (mg/L) isochlor and 10,000-mg/L isochlor. The hydrogeologic framework that is used for the chloride presentation was taken directly from recent regional-scale work (Pope and others, 2016) and is briefly described and referenced; it is followed by a summary of selected previous investigations. Selection of water-quality records (samples) is described, and the method is presented that was used to derive the regional isochlor interpretations from samples and published chloride interpretations. Isochlor interpretations are presented in map form and are discussed for the nine aquifer layers, from the oldest hydrogeologic units to the youngest hydrogeologic units.

Limitations and uncertainties of the interpretations are also discussed. Comparisons of isochlors are made between interpretations of this study and those of Meisler's (1989) regional chloride study. This was done for the Potomac-Patapsco, Monmouth-Mount Laurel, and Piney Point regional aquifers because the 1989 chloride study presented isochlors only for those aquifers.

Previous Investigations

The previous investigations discussed here are limited to those that were used for, or have background relevance to, this study. The publications discussed here contain fundamental concepts of chloride distribution, regional and state-scale hydrogeologic frameworks, isochlor interpretations drawn manually or from simulations, and for background purposes, simulations and hypotheses of regional chloride distribution and sources. The USGS National Water Information System database (NWIS) provides a comprehensive well sample set for aquifers in the study area, so the publications cited here consist mostly of interpretive studies; less emphasis was given to data reports. For the offshore areas, however, reports that include original data (not NWIS data) from the offshore-coring program are used.

A review of the basic principles of the interaction of freshwater and saltwater, as part of a summary of the basic concepts of groundwater hydrology, is provided by Heath (2004). A general review of the chemistry of chloride in natural waters is provided by Hem (1985) in a handbook on the chemistry of natural waters. Published data, interpretations, and hypotheses that were directly relevant to the interpretations in this report, range from the local scale (county or municipality) to the state scale and to the regional scale; the reports were published from 1913 to 2015. For a comprehensive bibliography of reports on the presence of chloride and saltwater in groundwater along the Atlantic Coast, organized by state, see Barlow and Wild (2002). Selected summaries of freshwater-saltwater issues along the Atlantic Coast that illustrate cases and concepts directly relevant to this study are presented in Barlow (2003).

The chloride data and interpretations presented in this study were reconciled with the regional NACP hydrogeologic framework described by Masterson and others (2013) and Pope and others (2016), which represents an updated version of the regional NACP framework described by Trapp (1992). The regional NACP hydrogeologic framework is derived from the current understanding of hydrogeologic frameworks at state scales reported in Smolensky and others (1989) for New York, Zapecza (1989) for New Jersey, Andreasen and others (2013) for Maryland and Delaware, McFarland and Bruce (2006) for Virginia, and Gellici and Lautier (2010) and McFarland (2013) for North Carolina.

Although describing the working hypotheses of the sources and movement of saltwater was not an objective of this study, concepts of the presence of saltwater and chloride were kept in mind when producing the isochlor maps. Back (1966) recognized that regional trends in geochemistry in the NACP are, in part, related to lithologic controls, which was fundamental to his concept of hydrochemical facies. Upson (1966) examined freshwater-saltwater boundaries and relations from New York to Maryland and related them, in part, to paleo-coastlines. Geochemistry and groundwater flow simulations were used by Meisler and others (1984) to support the concept that the freshwater-saltwater interface in the NACP is likely not in equilibrium with the current sea level.

In the NACP study area, chloride is a useful indicator of the degree of, or proximity and mixing of, nearby saltwater. Regional-scale interpretations of the presence of chloride in the NACP study area were published originally by Meisler (1989), who took a close look at water-quality data from about 500 wells, including data from 7 offshore cores, and at borehole-geophysics interpretations from a subset of 11 wells. His maps show the relation of chloride concentrations to depth and are presented at the 1:2,000,000 scale, and isochlor maps for the regional Potomac-Patapsco, Monmouth-Mount Laurel, and Piney Point aquifers are presented at the 1:4,000,000 scale. Meisler's (1989) study differs from this study in that, in addition to chloride, he examined geochemical indicators of freshwater-saltwater mixing, freshwater flow, brines as a possible source, and geologic evidence of sea-level rise; he

considered all these indicators for insight into the geometry and development of the saltwater transition zone. Although the study described in this report differs in approach and scope from Meisler's (1989), it relies on and can be considered an update of his original regional-scale chloride interpretations.

Leahy and Martin (1993) used Trapp's (1992) regional hydrogeologic framework for a NACP regional groundwater flow simulation, which accounted for saltwater and freshwater and the transition zone between the two. Isotope and supporting data examined by Sanford and others (2013) indicate that observations of high salinity in some of the sediments relate to the Chesapeake Bay impact structure, and high salinity in sediments at other locations along the Atlantic Coast might have their origin in hypersaline waters of the North Atlantic Ocean of the Early Cretaceous period.

Much of the published chloride or saltwater interpretations and hypotheses for the offshore areas are derived from data from four phases of offshore coring (Hathaway and others, 1976, 1979; Mountain and others, 1994; Austin and others, 1998; and Mountain and others, 2010). Manheim and Hall (1976) examined the changes in salinity with depth, using a core taken from the Continental Slope off New York and New Jersey and hypothesized that a likely source of salinity in certain offshore sediments is upward diffusion from deeply buried evaporite deposits of Jurassic age. Stable isotope geochemistry, based on offshore core data, was examined by van Geldern and others (2013), who categorized three types of pore water—fresh with stable isotopes similar to that of modern precipitation, salty with stable isotopes similar to that of modern marine water, and in the deeper parts of many of the cores, brine with isotopes that indicate a mixing with modern seawater. Lofi and others (2013) found that the alternating layers of saltwater and freshwater in offshore pore waters appear highly dependent on lithology, porosity, permeability, and in some cases, cemented layers. Salty water was largely contained within the coarse-sediment intervals, whereas freshwater was contained mostly within the fine-grained intervals. At greatest depths in the cores, pore water was progressively more salty, regardless of lithology. Post and others (2013) compare a world-wide dataset of freshwater and saltwater in offshore sediments and suggest that geologic-scale sea-level changes play a major role in the observed distributions; they note that freshwater reservoirs typically occur farther offshore than predicted by present hydrologic conditions.

Luscynski and Swarzenski (1966) produced an early chloride interpretation for southern Nassau County and southeastern Queens County in the northeasternmost extent of the study area in Long Island, N.Y. For Kings and Queens Counties, N.Y., Buxton and Shernoff (1999) provide a historical retrospective on salty groundwater. Results of a simulation of chloride concentrations in the aquifer system are presented by Kontis (1999), and results of a simulation and interpretation of the saltwater transition zone are presented by Misut and Voss (2007). Interpretations of the isochlor along the northern boundary of Nassau County next to Long Island Sound are presented by Stumm (2001), Stumm and others (2002), and

Stumm and others (2004), and simulations of chloride concentrations are presented by Monti and others (2009). Misut and others (2004) present simulations of chloride concentrations and interpretations of the data for the North Fork of Long Island. Nemickas and Koszalka (1982) report on a comprehensive hydrogeologic appraisal, which includes data on the saltwater interface for the South Fork of Long Island.

For the Coastal Plain aquifers in New Jersey, dePaul and Rosman (2015) provide statewide isochlor interpretations. Schaefer (1983) provides chloride concentrations and interpretations from data for 1977–81, and Pope and Gordon (1999) discuss the simulated freshwater-saltwater interface for 1896 through 1988 for the Coastal Plain aquifers. The following studies report on chloride concentrations elevated above background conditions and interpretations at the local or county scale: Farlekas and others (1976) for Camden County, Hasan and others (1969) for Middlesex County, Schaefer and Walker (1981) for Monmouth County, Anderson and Appel (1969) for Ocean County, Voronin and others (1996) for Atlantic County, Lacombe and Carleton (2002) for Cape May County, and Ervin and others (1994) for Gloucester and Salem Counties. In addition, Cohen and McCarthy (1962) report on a salinity survey that, for this current study, provided a qualitative context for the possible reach of salinity effects on aquifers in the upper reaches of Delaware Bay.

For the Delaware-Maryland-Washington, D.C., area, Andreasen and others (2013), as part of their Maryland hydrogeologic framework report, provide the most recent comprehensive interpretation of statewide isochlors. Andreasen and others (2013) adapted the interpretations from Meisler (1989) to show isochlor interpretations at the tops and bottoms of aquifers. Werkheiser (1990) provides simulations of an isochlor for the Manokin (Upper Chesapeake) aquifer in Somerset County, Maryland. Drummond (2001) provides groundwater flow simulations with an emphasis on brackish water concerns for the Aquia aquifer in Eastern Shore Maryland. In addition, Wells and others (1929) report on a salinity survey of Chesapeake Bay waters that, for this current study, provide a qualitative context for the possible reach of salinity effects on shallow aquifers that could be hydraulically connected to the bay.

For the Coastal Plain aquifers in Virginia, McFarland (2010) provides a recent comprehensive set of isochlor interpretations. Earlier studies with chloride information relevant to the extent of the Coastal Plain aquifers in Virginia include Sanford (1913), Cederstrom (1943), and Larson (1981). Richardson (1994) provides isochlors as part of groundwater-simulation studies for the Columbia (surficial) and Yorktown (Upper Chesapeake) aquifers in the Eastern Shore of Virginia, and Sanford and others (2009) provide isochlors for the Yorktown (Upper Chesapeake) aquifer. A study of the hydrologic conditions of the Potomac aquifer in Virginia and parts of Maryland and North Carolina (McFarland, 2013) included isochlors for the top and bottom of that aquifer. Smith (1999) provides contour lines for total dissolved solids in the York-James peninsula area (fig. 1) and

a useful overview of the historical saltwater interpretations in Virginia.

The southernmost extent of the study area is a line about halfway down the coast of North Carolina (fig. 1). Comprehensive interpreted isochlor maps for the aquifers of the North Carolina Coastal Plain from Winner and Coble (1996) were used in the current study. As part of support for a groundwater-availability study in North and South Carolina, Campbell and Coes (2010) present chloride interpretations in cross-section views. Investigations of elevated chloride concentrations in coastal areas include Winner (1975) for the Cape Hatteras area and Winner (1978) for the Cape Lookout area (fig. 1). Vinson and others (2011) evaluate the geochemistry observed in public-supply wells completed in the Yorktown (Upper Chesapeake) aquifer in North Carolina coastal areas and conclude that rising chloride concentrations are mainly the result of localized upconing from underlying hydrogeologic units.

Hydrogeology

The NACP aquifer system consists of a southeast-dipping wedge of mainly unconsolidated sediments (fig. 2) that range in age from Lower Cretaceous to Holocene. The alternating layers of gravel, sand, silt, and clay that constitute the NACP aquifer system are underlain by consolidated bedrock of Jurassic to Middle Proterozoic age (Maguire and others, 1999; Horton and others, 1991). The wedge of unconsolidated sediments thickens toward the Atlantic Ocean and continues offshore to the edge of the Continental Shelf; the greatest distance to the shelf edge is about 120 miles from the western end of Long Island, N.Y. (fig. 1). Over the land areas, the thickness of the unconsolidated sediments ranges from zero at the western edge of the Coastal Plain Physiographic Province to thousands of feet along the coastline; maximum thickness is about 10,000 feet in Cape Hatteras, N.C. (Trapp, 1992). Offshore, cores collected by the USGS record typical sediment thicknesses on the Continental Shelf of about 1.0 to 1.75 miles (Hathaway and others, 1976; Mountain and others, 1994; Austin and others, 1998; Mountain and others, 2010), although a maximum sediment thickness of greater than 7.5 miles has been estimated (Klitgord and Behrendt, 1979).

Interpretations of chloride concentrations presented in this report use the hydrogeologic framework, described by Masterson and others (2013) and Pope and others (2016), which was adapted from that used for the NACP regional groundwater model by Leahy and Martin (1993). The hydrogeologic framework is fully described by Trapp (1992). The framework used in this study consists of 10 regional aquifers (fig. 3); the main difference between the framework used in this study and that of Leahy and Martin (1993) is that, in most of Virginia and northeastern North Carolina, the Potomac aquifers are now considered a single heterogeneous aquifer. Additionally, some regional aquifer names have been updated to better reflect local names in the states that are the main

NACP aquifer (This study)	NACP aquifer (1993)	New York (Long Island)	New Jersey	Delaware	Maryland	Virginia	North Carolina
Surficial	Surficial	Upper Glacial	Surficial (Holly Beach)	Surficial	Surficial	Surficial	Surficial
Upper Chesapeake	Upper Chesapeake	Absent	Upper Kirkwood-Cohansey	Pocomoke, Manokin	Pocomoke, Ocean City, Manokin	Yorktown-Eastover	Yorktown
Lower Chesapeake	Lower Chesapeake		Lower Kirkwood-Cohansey and Confined Kirkwood	Milford, Frederica, Federalsburg, Cheswold	Choptank, Calvert	St. Marys	Pungo River
Piney Point	Castle Hayne-Piney Point		Piney Point	Piney Point	Piney Point	Piney Point	Castle Hayne
Aquia	Beaufort-Aquia		Vincentown	Rancocas	Aquia	Aquia*	Beaufort
Monmouth-Mount Laurel	Peedee-Severn		Wenonah-Mount Laurel	Mount Laurel	Monmouth	Peedee	Peedee
Matawan	Black Creek-Matawan		Englishtown	Englishtown	Matawan	Virginia Beach	Black Creek
Magothy	Upper Potomac and Magothy	Magothy	Upper Potomac-Raritan-Magothy	Magothy	Magothy		Upper Cape Fear, Lower Cape Fear
Potomac-Patapsco	Middle Potomac	Lloyd	Middle Potomac-Raritan-Magothy	Upper Patapsco-Lower Patapsco	Upper Patapsco-Lower Patapsco	Potomac (undivided)*	Lower Cretaceous (undivided)
Potomac-Patuxent	Lower Potomac	Absent	Lower Potomac-Raritan-Magothy	Patuxent, Waste Gate	Patuxent, Waste Gate		

*Aquifer and associated confining units are truncated in part of Virginia by sediments related to the Chesapeake Bay impact crater.

Figure 3. Regional aquifers and sub-regional aquifers in the Northern Atlantic Coastal Plain (NACP) aquifer system (Modified from Masterson and others, 2013).

focus of this study—New York, New Jersey, Delaware, Maryland, and Virginia (Masterson and others, 2013). From bottom to top (oldest to youngest), the 10 regional aquifers are the Potomac-Patuxent aquifer, the Potomac-Patapsco aquifer, the Magothy aquifer, the Matawan aquifer, the Monmouth-Mount Laurel aquifer, the Aquia aquifer, the Piney Point aquifer, the Lower Chesapeake aquifer, the Upper Chesapeake aquifer, and the surficial aquifer. Although the units of the hydrogeologic framework are extended offshore to the edge of the Continental Shelf, the long distances of extrapolation and the minimal number of framework control points present considerable uncertainty with the naming of aquifer layers and their associated chloride samples. The chart in figure 3 shows how aquifer layers and names from Masterson and others (2013), Leahy and Martin (1993), and the various state-level frameworks are related. Expanded descriptions of the hydrogeology and defining attributes of the NACP aquifers addressed in this report are provided in Masterson and others (2013).

Subsequent to the last USGS regional-scale chloride assessment of the NACP (Meisler, 1989), new groundbreaking information became available with the discovery of the 35 million year old Chesapeake Bay impact structure (Poag and others, 1994). Although research is ongoing, this structure, buried beneath Coastal Plain sediments in eastern

Virginia (fig. 1), has already proven to be essential to a better understanding of the hydrogeologic framework and saltwater distribution in eastern Virginia (Powars and Bruce, 1999; Powars, 2000). Until discovery of this structure, the high chloride and discontinuous stratigraphy observed in parts of eastern Virginia (Cederstrom, 1943, 1945) were a challenge to explain. The Chesapeake Bay impact structure is important hydrogeologically because it has truncated regional aquifer layers and is a center of elevated salinity (McFarland and Bruce, 2005; McFarland, 2010).

Within the limits of the impact structure (crater) site, all or part of the regional NACP aquifers below the Piney Point aquifer are replaced by very low permeability crater-fill sediments of the Exmore Clast and the Exmore Matrix confining units (McFarland and Bruce, 2006). These crater-fill sediments are overlain by post-impact low-permeability crater-cap sediments of the Chickahominy confining unit, which together with the crater-fill sediments form a plug of extremely low permeability. Groundwater salinity of as much as twice that (hypersaline) of modern seawater within the crater structure (Sanford and others, 2009) is explained by the extremely low permeability sediments that prevent the hypersaline groundwater from being flushed out by the surrounding fresh groundwater (McFarland, 2010). The

resulting situation is a high chloride mound centered at the crater structure, which has a substantial effect on the chloride interpretations for the adjacent regional NACP aquifer units that are the topic of this report.

Sanford and others (2013) provide further insight into the occurrence of hypersalinity in crater sediments by using chemical, isotopic, and physical evidence to determine that waters within the 35 million year old crater-fill sediments actually consist of 100 to 145 million year old seawater. They suggest that the 100 to 145 million year old water is a remnant of hypersaline seawater from the North Atlantic Ocean of the Early Cretaceous period, which was remobilized by the impact and has remained relatively locked into these extremely low-permeability sediments since the impact, in spite of being surrounded by freshwater. Sanford and others (2013) suggest that other locations of hypersalinity observed in sediments along the Atlantic Coast are likely explainable as remnants of the North Atlantic Ocean seawaters from the Early Cretaceous period.

Identification of Water-Quality Records and Sites

Individual water-quality records (samples) used in this study for the onshore areas were from the USGS NWIS database. Within the NWIS database, each water-quality record includes a unique sample number, site identifier, and other essential information. This extensive sample set is presented only in the figures of this report, and only as color-coded display elements that represent ranges of chloride concentration, in support of the isochlor interpretations.

Chloride samples collected from offshore cores are listed and identified in a supporting electronic geodatabase file (appendix 1) that was set up specifically for this study, and are also summarized in table 1. The offshore chloride samples and location information were gathered from published reports (Meisler, 1989; Hathaway and others, 1976, 1979; Mountain and others, 1994; Austin and others, 1998; and Mountain and others, 2010) and entered into the geodatabase for this study. The offshore samples are structured as 13 core-site records that correspond to the selected offshore core sites. Within each core-site record used for this study, the multiple-sample depths (hydrogeologic layers) are identified. The core-site identifiers and locational information used for this project are the same as that assigned by each of the offshore coring expeditions.

Sources and Method for Isochlor Interpretations

The interpretation of the regional isochlors was conducted in four steps. The first step was to retrieve the available chloride samples for the onshore and offshore extent of the study area. The second step was to review and use or modify

isochlor interpretations at the regional, state and local scale obtained from published or written communication sources. The third step was to manually interpolate isochlors where information was sufficient. The fourth and final step was to manually extrapolate isochlors where information was non-existent or too sparse to be considered interpolated. All data and interpretive results were re-projected from the Universal Transverse Mercator coordinate system (UTM) to the Albers equal-area conic projection. The horizontal datum of the dataset is the North American Datum of 1983, and the vertical datum is North American Vertical Datum of 1988.

The maps of isochlors represent interpretations of the 250-mg/L and 10,000-mg/L boundaries and were developed for nine regional aquifers of the Northern Atlantic Coastal Plain. The 250-mg/L isochlor is used because 250 mg/L is the Secondary Maximum Contaminant Level in Drinking Water (U.S. Environmental Protection Agency, 2012). The 10,000-mg/L isochlor is a commonly used indicator of the approximate halfway point between the chloride concentration in freshwater and that in modern seawater.

Sources of Data and Information

Records of water-quality samples in NWIS are maintained by the USGS Water Science Center in each state or group of small states, and these served as the onshore well sample set. The water-quality data in NWIS have gone through thorough quality-assurance assessments and quality-control standards (QA/QC). The initial data retrievals from NWIS consisted of gathering all water-quality records that included chloride analyses from wells from each USGS Water Science Center database (Jack Monti, U.S. Geological Survey, written commun., 2013). These data were filtered by eliminating records for wells outside the NACP study area and those that had too much missing information to be useful. Because many of the water-quality records represent multiple-sampling events from the same well, often over a period of years, the NWIS dataset used for the study area consists of 37,517 records from 6,160 wells with sample dates from 1903 through 2011.

Published reports (Hathaway and others, 1976, 1979; Mountain and others, 1994; Austin and others, 1998; and Mountain and others, 2010) from four phases of research-related coring (1976, 1993, 1997, 2009) were the primary source of data for the offshore parts of aquifers, which extend from the shoreline to the outer edge of the Continental Shelf. Thirteen offshore core sites had information that was relevant to this study, and nine of the cores had chloride information relevant to more than one NACP regional aquifer. Each of the 13 core-site records contained the altitude of the ocean floor and top altitude, thickness, and a chloride value for each sample interval. Aquifer names assigned from altitudes of the NACP framework (Pope and others, 2016) were related to each sample interval, and the average chloride value of the sample intervals was calculated for each aquifer at any given

site (table 1; appendix 1). Offshore sampling depths that reconciled to a regional confining unit layer and not to an aquifer layer of the hydrogeologic framework were not considered further. The offshore data did not yield chloride values for the Patuxent or Aquia regional aquifers. Isochlor interpretations were not provided for the surficial regional aquifer in this study so offshore chloride data were not presented. Note that offshore chloride concentrations from the Atlantic Margin Coring Project (Hathaway and others, 1976) were summarized and used in Meisler's (1989) regional chloride assessment, which served as the source for this current study. Meisler (1989) also reported that a side-by-side comparison between chloride concentrations from pore-squeezing compared to well samples from the same hydrogeologic horizon indicate that "pore-water analyses can reliably provide approximate chloride concentrations."

Method of Isochlor Interpretations

The primary purpose of this assessment is to provide observation-based, updated regional chloride concentration interpretations for the onshore and offshore extent of NACP regional aquifers. Maps of isochlors were manually constructed to estimate the extent of the fresh groundwater resource and areas where chloride concentrations are elevated, indicating proximity to saltwater. Isochlor interpretations prepared for this report are based on a combination of isochlor interpretations from published and written communication sources and historical sample data. New data and interpretations available since the last NACP regional chloride assessment (Meisler, 1989) were specifically considered.

Construction of regional isochlors can be highly interpretive. Despite the large set of published interpretations and samples that support this study, regional chloride interpretations can be complicated by many factors, including the lack of samples in some places and the overall variable density of the samples. In cases where there were few or no previous interpretations, chloride samples, or clear regional trends, the concept was applied that the overall geometry of the saltwater-transition zone across the entire thickness of the regional aquifer system is generally a broad landward-dipping wedge. When this concept is applied, the assumption is that the chloride concentrations in the overlying aquifers are lower than those in the underlying aquifers. Exceptions to the above assumption are noted in the discussion as "inversions" and occur where samples indicate that chloride concentrations in the overlying aquifer unit are higher than those in the underlying aquifer unit. An additional assumption made for much of the study area is that the strike of the saltwater-transition wedge in the aquifers is, in a broad sense, approximately parallel to sub-parallel to the regional trend of the shoreline and the aquifer units. Although sources and movement of saltwater are not the focus of this study, hypotheses regarding regional sources and (or) conclusions of regional simulation of

saltwater in the study area were kept in mind when manually interpolating or extrapolating the isochlors.

The first step in the assessment was to examine the onshore and offshore samples assigned to a particular NACP aquifer and categorize the samples with respect to those with chloride concentrations less than 250 mg/L, those from 250 to 9,999 mg/L, and those of 10,000 mg/L and higher. The samples used for the interpretations in this study were considered time independent, within the set of the supporting data for 1903–2011. For example, if a well has multiple samples through time but only a few of the concentrations exceeded a 250- or 10,000-mg/L chloride threshold, in many cases the sample(s) that exceeded the threshold was given the priority at that well, on the assumption that the chloride exceedance is representative of regional chloride concentrations. If this situation occurred in the vicinity of one or more groundwater withdrawal wells, a likely explanation is that induced upward hydraulic gradients (up-coning of salty water) caused the localized elevated chloride concentrations during periods of high withdrawal rates. Whatever the cause, a few chloride threshold exceedances among many samples at a well, through time, indicates proximity to an elevated chloride source—a fact that was considered when determining whether that well's elevated chloride is likely of regional importance or only local importance.

The second step was to review published and written communication isochlor interpretations at the regional, state, and local scale, compare them to the samples from step one, and either use these interpreted isochlors unmodified or modify them as the samples indicate. For this study of regional extent, the interpreted 250- and 10,000-mg/L chloride contours are each represented as a single isochlor per aquifer. A few of the published interpreted isochlors referenced in this study are presented as a pair of lines—one along the top of the aquifer and another along the bottom of the aquifer. Together, the two isochlors define an iso-concentration surface within an aquifer; the top line is referred to as the "tip" and the bottom line, the "toe." The surface that the tip and toe define within an aquifer typically is a wedge-shaped boundary with the more dense saltwater (higher chloride) lying underneath the less dense freshwater. In cases where published isochlor information includes the tips and toes of iso-concentration surfaces, that information was adapted to this regional assessment by interpolating a single medial line per aquifer, typically about mid-way by map view between the tip and toe lines. The interpolated medial line then represents the approximate map position of the iso-concentration surface at the mid-point of the aquifer thickness. Most of the interpretations used within the study area were not in the form of tip and toe lines, and for those areas, available cited isochlors and samples were used in combination to construct and present the interpretations as a medial isochlor.

The third step was to interpolate from sample values. Isochlors were drawn between sample data in areas where the sample density was adequate but no citable interpretations were available. For interpolated isochlors, judgment was

Table 1. Site information and selected pore water sample chloride concentrations, by regional aquifer, for the offshore (Continental Shelf) portion of the Northern Atlantic Coastal Plain study area.

[No offshore chloride samples for Patuxent or Aquia regional aquifers. NAVD 88, North American Vertical Datum of 1988; bls, below land surface; NA, not applicable]

Drilling program or ODP expedition ¹	Core site identifier	Latitude (decimal degrees)	Longitude (decimal degrees)	Approximate distance from shore (miles)	Reported water depth at site (feet bls)	Altitude of top of aquifer interval (feet, NAVD 88) ²	Altitude of bottom of aquifer interval (feet, NAVD 88)	Number of core samples collected from the aquifer interval, with chloride analyses ³	Average chloride concentration in sample from aquifer interval ⁴ (milligrams per liter) ⁴	Minimum chloride concentration in sample from aquifer interval (milligrams per liter)	Maximum chloride concentration in sample from aquifer interval (milligrams per liter)	Year of sample	Reference ^{5,6}
Upper Chesapeake regional aquifer													
AMCOR	6008	38.403613	74.896786	9	68	-190	-564	4	940	720	2,602	1976	Hathaway and others, 1976
ODP Leg 313	M0027A	39.634101	73.621691	27	110	-283	-557	14	13,400	5,169	18,780	2009	Mountain and others, 2010
ODP Leg 313	M0029A	39.519508	73.413208	42	118	-360	-747	11	8,300	3,635	16,589	2009	Mountain and others, 2010
AMCOR	6007	37.299975	74.652269	54	279	-418	-943	10	15,500	13,008	17,491	1976	Hathaway and others, 1976
AMCOR	6009	38.854622	73.590727	56	183	-491	-1,138	7	8,210	5,037	16,993	1976	Hathaway and others, 1976
AMCOR	6010	39.061790	73.097876	62	249	-540	-1,209	8	13,700	11,458	13,451	1976	Hathaway and others, 1976
AMCOR	6012	39.992953	71.334319	77	862	-671	-897	1	18,100	NA	NA	1976	Hathaway and others, 1976
ODP Leg 174A	1072	39.365508	72.694412	79	322	-497	-1,075	10	18,600	16,650	19,987	1997	Austin and others, 1998
ODP Leg 174A	1071	39.382462	72.727982	80	289	-489	-1,055	12	17,200	15,975	18,744	1997	Austin and others, 1998
AMCOR	6021	38.965459	72.819531	87	987	-787	-1,408	6	18,000	18,400	17,600	1976	Hathaway and others, 1976

Table 1. Site information and selected pore water sample chloride concentrations, by regional aquifer, for the offshore (Continental Shelf) portion of the Northern Atlantic Coastal Plain study area.—Continued

[No offshore chloride samples for Patuxent or Aquia regional aquifers. NAVD 88, North American Vertical Datum of 1988; bls, below land surface; NA, not applicable]

Drilling program or ODP expedition ¹	Core site identifier	Latitude (decimal degrees)	Longitude (decimal degrees)	Approximate distance from shore (miles)	Reported water depth at site (feet bls)	Altitude of top of aquifer interval (feet, NAVD 88) ²	Altitude of bottom of aquifer interval (feet, NAVD 88)	Number of core samples collected from the aquifer interval, with chloride analyses ³	Average chloride concentration in sample from aquifer interval (milligrams per liter) ⁴	Minimum chloride concentration in sample from aquifer interval (milligrams per liter)	Maximum chloride concentration in sample from aquifer interval (milligrams per liter)	Year of sample	Reference ^{5,6}
Lower Chesapeake regional aquifer													
AMCOR	6011	39.725120	73.976241	7	73	-396	-581	2	1,300	830	1,273	1976	Hathaway and others, 1976
ODP Leg 313	M0027A	39.634101	73.621691	27	110	-753	-1,009	10	2,880	1,743	3,855	2009	Mountain and others, 2010
ODP Leg 313	M0028A	39.565713	73.497247	35	115	-857	-1,195	15	8,040	3,401	16,834	2009	Mountain and others, 2010
ODP Leg 313	M0029A	39.519508	73.413208	42	118	-914	-1,244	8	14,400	9,670	18,077	2009	Mountain and others, 2010
AMCOR	6007	37.299975	74.652269	54	279	-1,022	-1,385	1	17,000	NA	NA	1976	Hathaway and others, 1976
AMCOR	6012	39.992953	71.334319	77	862	-972	-1,252	5	17,200	16,883	17,547	1976	Hathaway and others, 1976
ODP Leg 174A	1071	39.382462	72.727982	80	289	-1,156	-1,447	4	19,500	18,851	20,235	1997	Austin and others, 1998
AMCOR	6021	38.965459	72.819531	87	987	-1,500	-1,743	3	18,000	18,000	18,000	1976	Hathaway and others, 1976
ODP Leg 150	903	38.938383	72.817067	88	1,465	-1,682	-1,767	3	19,900	19,845	20,022	1993	Mountain and others, 1994

Table 1. Site information and selected pore water sample chloride concentrations, by regional aquifer, for the offshore (Continental Shelf) portion of the Northern Atlantic Coastal Plain study area.—Continued

[No offshore chloride samples for Patuxent or Aquia regional aquifers. NAVD 88, North American Vertical Datum of 1988; bls, below land surface; NA, not applicable]

Drilling program or ODP expedition ¹	Core site identifier	Latitude (decimal degrees)	Longitude (decimal degrees)	Approximate distance from shore (miles)	Reported water depth at site (feet bls)	Altitude of top of aquifer interval (feet, NAVD 88) ²	Altitude of bottom of aquifer interval (feet, NAVD 88)	Number of core samples collected from the aquifer interval, with chloride analyses ³	Average chloride concentration in sample for interval (milligrams per liter) ⁴	Minimum chloride concentration in sample from aquifer interval (milligrams per liter)	Maximum chloride concentration in sample from aquifer interval (milligrams per liter)	Year of sample	Reference ^{5,6}
Piney Point regional aquifer													
AMCOR	6011	39.725120	73.976241	7	73	-705	-847	2	5,100	2,159	8,690	1976	Hathaway and others, 1976
ODP Leg 313	M0027A	39.634101	73.621691	27	110	-1,104	-1,155	1	1,670	NA	NA	2009	Mountain and others, 2010
ODP Leg 313	M0028A	39.565713	73.497247	35	115	-1,247	-1,265	1	17,600	NA	NA	2009	Mountain and others, 2010
Monmouth-Mount Laurel regional aquifer													
ODP Leg 313	M0027A	39.634101	73.621691	27	110	-1,423	-1,591	6	7,380	2,233	15,393	2009	Mountain and others, 2010
ODP Leg 313	M0028A	39.565713	73.497247	35	115	-1,531	-1,695	6	12,100	11,161	13,156	2009	Mountain and others, 2010
ODP Leg 313	M0029A	39.519508	73.413208	42	118	-1,608	-1,776	6	27,900	26,714	29,092	2009	Mountain and others, 2010
Matawan regional aquifer													
ODP Leg 313	M0027A	39.634101	73.621691	27	110	-1,759	-1,822	2	10,800	10,125	11,442	2009	Mountain and others, 2010
ODP Leg 313	M0028A	39.565713	73.497247	35	115	-1,859	-1,942	3	13,300	7,608	18,219	2009	Mountain and others, 2010
ODP Leg 313	M0029A	39.519508	73.413208	42	118	-1,944	-2,001	6	31,300	30,679	31,978	2009	Mountain and others, 2010
ODP Leg 150	903	38.938383	72.817067	88	1,465	-2,595	-2,914	3	24,500	23,359	25,809	1993	Mountain and others, 1994

Table 1. Site information and selected pore water sample chloride concentrations, by regional aquifer, for the offshore (Continental Shelf) portion of the Northern Atlantic Coastal Plain study area.—Continued

[No offshore chloride samples for Patuxent or Aquia regional aquifers. NAVD 88, North American Vertical Datum of 1988; bis, below land surface; NA, not applicable]

Drilling program or ODP expedition ¹	Core site identifier	Latitude (decimal degrees)	Longitude (decimal degrees)	Approximate distance from shore (miles)	Reported water depth at site (feet bis)	Altitude of top of aquifer interval (feet, NAVD 88) ²	Altitude of bottom of aquifer interval (feet, NAVD 88)	Number of core samples collected from the aquifer interval, with chloride analyses ³	Average chloride concentration in sample from aquifer interval (milligrams per liter) ⁴	Minimum chloride concentration in sample from aquifer interval (milligrams per liter)	Maximum chloride concentration in sample from aquifer interval (milligrams per liter)	Year of sample	Reference ^{5,6}
Magothy regional aquifer													
ODP Leg 150	903	38.938383	72.817067	88	1,465	-3,729	-3,845	3	31,800	31,418	32,234	1993	Mountain and others, 1994
Potomac-Patapsco regional aquifer													
ODP Leg 150	903	38.938383	72.817067	88	1,465	-4,377	-4,813	3	34,200	33,938	34,613	1993	Mountain and others, 1994

¹AMCOR, Atlantic Margin Coring Project; ODP, Ocean Drilling Program.

²Altitudes of aquifer intervals from regional hydrogeologic framework (Pope and others, 2016).

³Core samples and chloride results assigned to an aquifer interval based on the reported depth of the core sample and depth of water at the core site.

⁴Average chloride values are rounded to three significant figures. AMCOR values (Meisler 1989, table 1, as summarized from Hathaway and others, 1976) are estimated from dissolved solids content or specific conductance, or from chemical analysis of core squeezing. ODP values converted from reported chloride measurements [chloride (millimolar) \times 35.5 = chloride (milligrams per liter)].

⁵Reference to original data source includes record of core sampling procedure and analyses.

⁶This report used Meisler's (1989) data summary of the data from Hathaway and others, 1976.

exercised in determining whether a well with elevated chloride concentrations is of only local importance or is interpreted as being part of a regional areal trend. Particularly in outlying areas, where chloride concentrations at only a sample or two or a scattering of samples exceeded a chloride threshold among many samples with concentrations less than the threshold, the exceedances were disregarded because they were considered to be of only local importance. In a few situations of isolated elevated chloride concentrations, knowledge of local conditions in the area was used to explain the isolated elevated chloride concentrations, which were the result of a broken well-casing or storm overwash, and thus the concentrations were considered to be only locally relevant. Caution needs to be exercised when using the groundwater chloride-concentration maps because, in some cases, what appears to be an isolated and localized elevated chloride concentration could actually be part of a regional areal trend.

The fourth and final step was to manually extrapolate the interpretations by drawing isochlors either where sample density was sparse or where there were no samples at all. The same concern applies for extrapolated isochlors, whether the concentration represents regional importance or only local importance, as it did for interpolated isochlors. Extrapolated isochlors are displayed in illustrations in this report as orange lines to represent the greater uncertainty of extrapolated isochlors compared to interpolated or cited isochlors. In offshore areas, orange lines representing chloride interpretations are typical because there are very few samples. The end result of the above four steps is an integration of the sample data and the published interpreted isochlors, resulting in interpreted isochlors for 9 of the 10 regional aquifers, presented in illustrations at the 1:2,000,000 scale. Each interpreted isochlor is shown by using one of five possible line colors, indicating the different ways in which the interpretations are supported.

Isochlor Interpretations by Regional Aquifer

Regional interpretive maps of chloride concentrations for this study are limited to the presentation of 250- and 10,000-mg/L isochlors. Each isochlor represents the estimated chloride concentration at the approximate mid-point of the aquifer thickness (medial line). Supporting information for the isochlor interpretations can vary considerably. In some cases, an isochlor segment is annotated as either unmodified or modified from a cited interpretation. In all other cases, the isochlor is annotated as either interpolated (estimated among or between adequate chloride samples or information) or extrapolated (estimated beyond adequate chloride samples or information). In general, the supporting information indicated by the annotation is provided for that specific isochlor segment only and is independent of the supporting information for adjoining isochlor segments. Feature classes, including the

annotation for all the isochlor interpretations are included as an electronic supplement to this report (appendix 2).

Chloride distribution information from this study are discussed below, by regional aquifer layer. To represent the specific type of supporting information, each isochlor segment presented in this study is shown as one of five possible line colors—(1) black for an isochlor that is unmodified from a cited isochlor interpretation, (2) gray for an isochlor that was directly interpolated from a published set of tip and toe isochlor interpretations, (3) green for an isochlor that was modified from a cited isochlor interpretation, (4) blue for an isochlor that was interpolated from a relatively adequate areal set of samples, and (5) orange for an isochlor that was extrapolated or speculated from regional trends, is estimated beyond an adequate set of supporting samples, and does not warrant citing of other interpretations.

Overall, the interpretations presented below are considered updates to the previous regional study (Meisler, 1989) and do not comprise fundamental differences in interpretation. Differences between interpretation of this study and those of Meisler (1989) mainly reflect the differing approaches and use of new data, and do not indicate regional movement of saltwater interfaces from 27 years ago (1989). As new water-quality data, hydrogeologic framework information, and various future studies are accumulated, there will be an opportunity to update and refine the interpretations discussed below.

Potomac-Patuxent Aquifer

The Potomac-Patuxent regional aquifer is the oldest and deepest hydrogeologic unit and extends (fig. 4) from southern New Jersey to northern Virginia (Pope and others, 2016). Offshore, the only section of the Potomac-Patuxent aquifer that extends to the southeast edge of the Continental Shelf is off New Jersey. The Potomac-Patuxent regional aquifer is not present onshore or offshore of Long Island, N.Y., North Carolina, and most of Virginia.

Chloride samples from NWIS for the Potomac-Patuxent aquifer consists of 1,426 chloride records from 354 wells. The areas of greatest sample density for the Potomac-Patuxent aquifer are in Burlington, Gloucester, and Salem Counties, N.J. (fig. 4). Substantial samples are available for Maryland and northern Virginia (fig. 4). NWIS data indicate an area with chloride concentrations from 250 mg/L to 9,999 mg/L in Gloucester and Salem Counties, N.J., and Baltimore City, Prince Georges County, and Charles County, Maryland. Chloride concentrations of 10,000 mg/L and greater occur in Cumberland County, N.J., and Dorchester and Somerset Counties, Md. (fig. 4). There are no offshore data for the Potomac-Patuxent aquifer (fig. 5).

The northeastern extent (from Camden County, N.J., to offshore New Jersey) of the 250-mg/L isochlor was extrapolated. From Camden County, N.J., to the Delaware Bay, the 250-mg/L interpreted isochlor is from dePaul and Rosman (2015). The 10,000-mg/L isochlor in northern New Jersey was

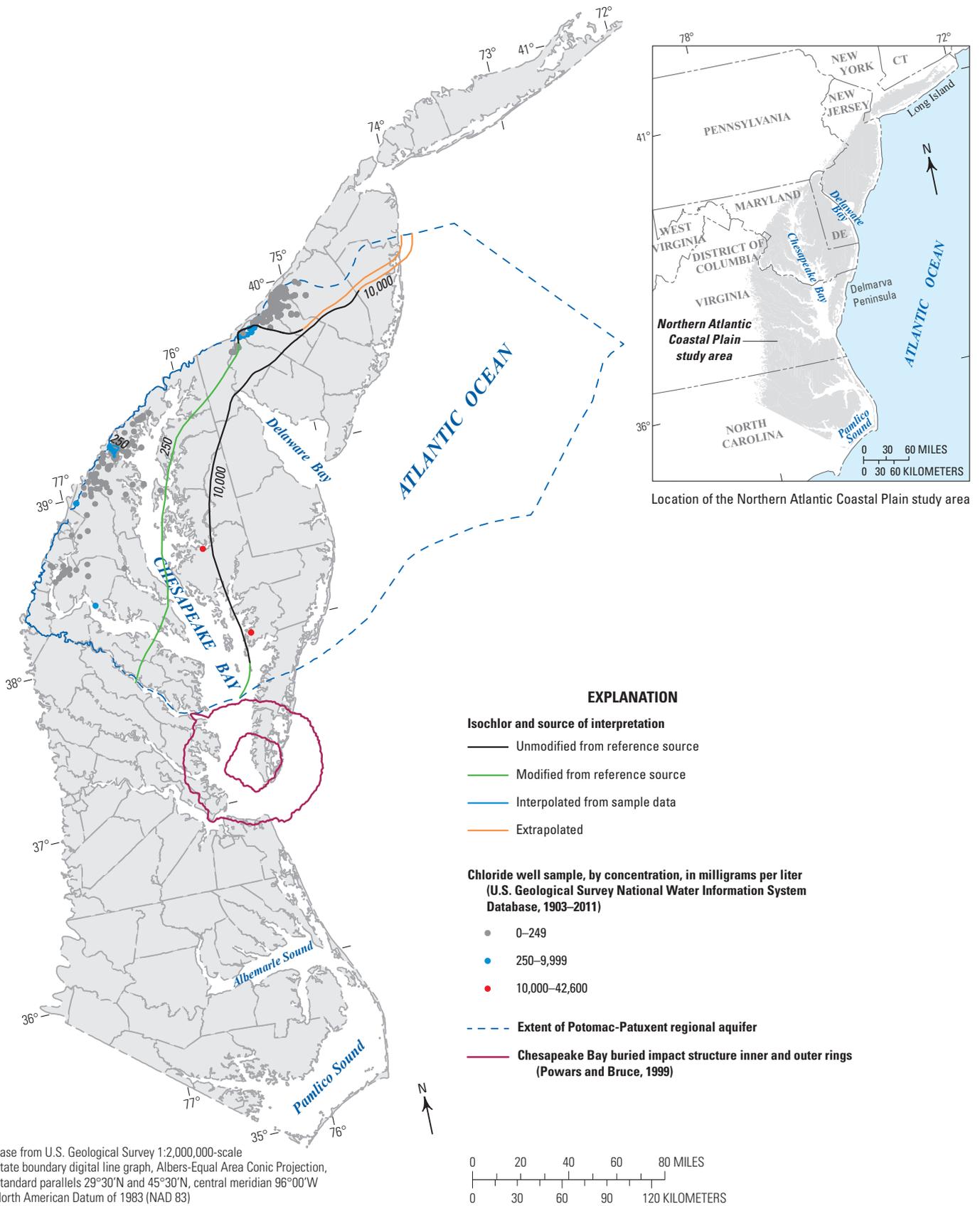
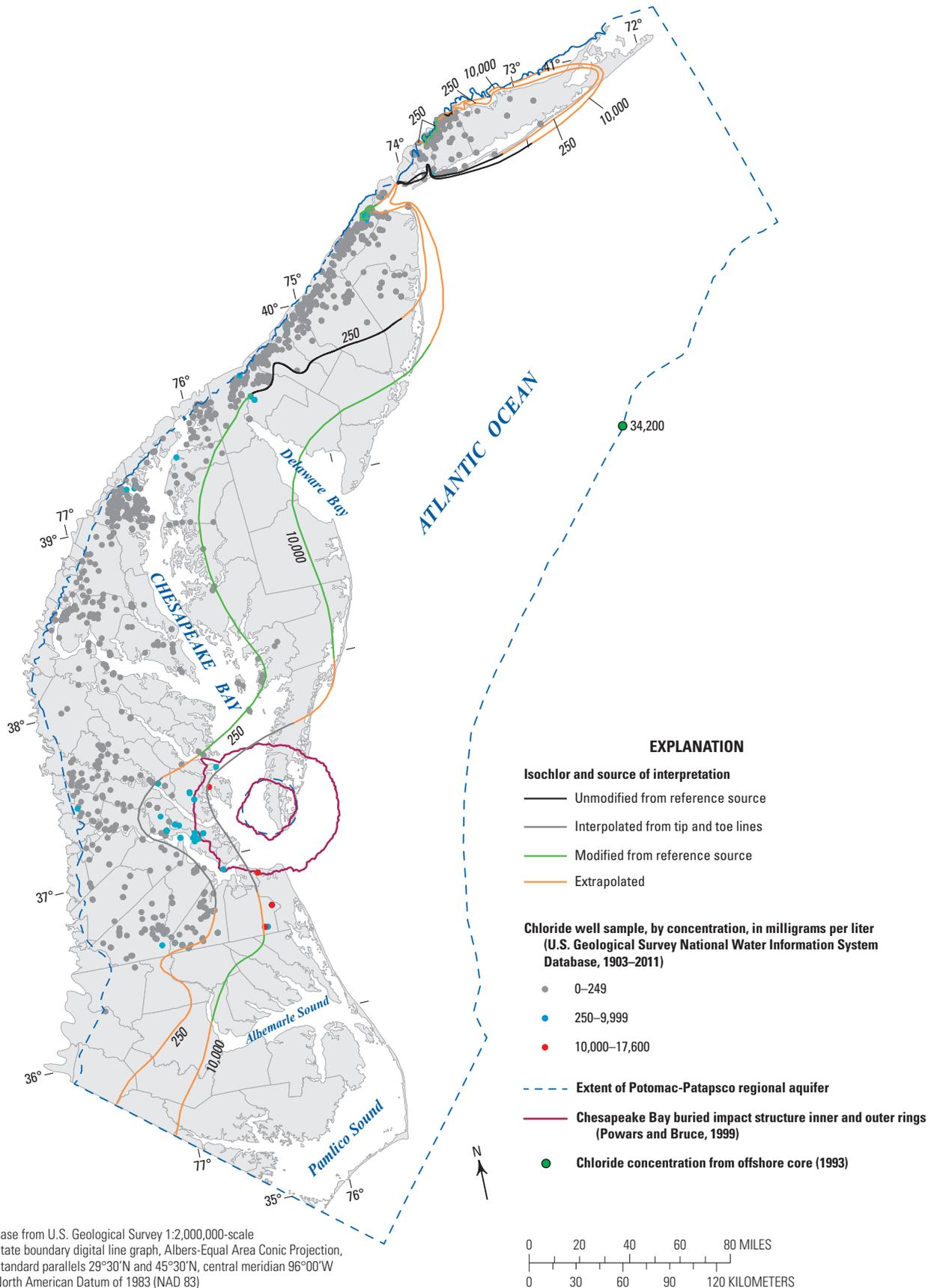


Figure 4. Groundwater chloride concentrations, in milligrams per liter, at well locations, and as interpreted 250 and 10,000 isochlors, Potomac-Patuxent regional aquifer, Northern Atlantic Coastal Plain study area.



Base from U.S. Geological Survey 1:2,000,000-scale State boundary digital line graph, Albers-Equal Area Conic Projection, Standard parallels 29°30'N and 45°30'N, central meridian 96°00'W North American Datum of 1983 (NAD 83)

Figure 5. Groundwater chloride concentrations, in milligrams per liter, at well and core locations, and as interpreted 250 and 10,000 isochlors, Potomac-Patapsco regional aquifer, Northern Atlantic Coastal Plain study area.

extrapolated, but the isochlor in southern New Jersey is from the simulations of Pope and Gordon (1999). The 250-mg/L isochlor from the Delaware Bay across the Chesapeake Bay into Virginia was modified from Andreasen and others (2013), and the outlying 250-mg/L isochlor in Baltimore City, Md., was interpolated from samples. McFarland (2013) indicates that the Potomac-Patuxent aquifer in northern Virginia is probably hydraulically connected to the Potomac-Patapsco and Potomac-Patuxent aquifers in southern Maryland, which cannot be entirely reconciled with the regional aquifer framework or isochlors presented here. From the Delaware Bay to northern Virginia, the interpreted 10,000-mg/L isochlor is from Vroblesky and Fleck (1991).

Overall, the most prominent features of the interpreted isochlor for the Potomac-Patuxent aquifer are the landward tongue of the 250-mg/L isochlor in New Jersey and the outlying 250-mg/L isochlor near Baltimore City, Md. The historical NACP regional isochlors (Meisler, 1989) did not present a separate isochlor interpretation for the Potomac-Patuxent aquifer, so no comparison is possible.

Potomac-Patapsco Aquifer

Except in the inner crater area of the Chesapeake Bay impact structure, the Potomac-Patapsco regional aquifer extends across the entire study area (fig. 5) from New York to North Carolina (Pope and others, 2016). Offshore, the Potomac-Patapsco aquifer extends to the southeast edge of the Continental Shelf.

Chloride samples from NWIS for the Potomac-Patapsco aquifer consist of 4,684 records from 1,216 wells. Samples in New Jersey and Delaware, the areas of greatest sample density for the Potomac-Patapsco aquifer, are typically within 10 miles of the updip extent of the aquifer, and in New York, the samples are mainly in Kings and Queens Counties. In Maryland and Virginia the samples are distributed within 60 miles of the updip extent of the aquifer (fig. 5). In North Carolina, only four samples (two wells) are present. NWIS samples indicate that the main areas of chloride concentrations of 250 to 9,999 mg/L in New York are along the north and south shores of Queens and Kings Counties, and along the south shore of Richmond County. In Camden, Gloucester, and Cumberland Counties, N.J., the main areas of chloride concentrations of 250 to 9,999 mg/L are within 10–20 miles of the updip extent of the aquifer. In Delaware, Maryland, Virginia, and North Carolina, chloride concentrations of 250 to 9,999 mg/L occurred within 10–80 miles of the updip extent of the aquifer. Chloride concentrations of 10,000 mg/L and greater occur only in eastern Virginia. The dataset of offshore cores yielded one chloride sample for the aquifer, which exceeds 9,999 mg/L at the outer boundary of the Continental Shelf (fig. 5).

Along the north shore of Long Island, N.Y., a segment of the 250-mg/L interpreted isochlor was used from Stumm and others (2004), whereas other segments are modifications from Monti and others (2009), Stumm (2001), and Stumm and

others (2002). The other segments of the 250-mg/L isochlor along the north shore were extrapolated. Along the south shore of Long Island, the eastern end of the 250-mg/L isochlor was extrapolated, whereas the western end was provided by Frederick Stumm (U.S. Geological Survey, written commun., 2015). For the 10,000-mg/L isochlor along the north shore of Long Island, the short segment at the western end is a modification from Stumm (2001), and the rest of the segments to the east were extrapolated. Along the south shore, the approximate western half of the 10,000-mg/L isochlor was used unmodified from Frederick Stumm (U.S. Geological Survey, written commun., 2015), and the approximately eastern half was extrapolated.

In Richmond County, N.Y. (Staten Island), the 250-mg/L isochlor was extrapolated, and the two wells that exceed 249 mg/L were considered to be due to local effects and not of regional importance. The short section of 250-mg/L isochlor shown in Middlesex County, N.J., was slightly modified from dePaul and Rosman (2015), and this isochlor was connected to the extrapolated isochlor that follows the Raritan Bay and Atlantic Coast shorelines. The 250-mg/L isochlor from Ocean County, N.J., to the Delaware Bay was modified from dePaul and Rosman (2015). The 10,000-mg/L isochlor was extrapolated from the mouth of the Hudson River to offshore of southern Ocean County, N.J. From southern Ocean County to the Delaware Bay, the 10,000-mg/L isochlor was modified from simulations of Pope and Gordon (1999) and from the interpretation of Meisler (1989).

Through Delaware and Eastern Shore Maryland, and into Virginia, the 250-mg/L isochlor was modified from Andreasen and others (2013); the three wells that exceed 249 mg/L in Baltimore City and Baltimore County, Md., are considered likely to be due to local effects and not of regional importance. From Delaware Bay through Delaware and into Eastern Shore Maryland, the 10,000-mg/L isochlor was modified from Meisler (1989) and Vroblesky and Fleck (1991).

In northern Virginia and along the southern border of Virginia to the limit of the study area in North Carolina, sections of the 250-mg/L isochlor were extrapolated and are joined by an interpolated isochlor that wraps around the western side of the Chesapeake Bay impact structure. This 250-mg/L isochlor is interpolated within the thick Potomac-Patapsco aquifer, estimated as the approximate medial line between the large east-to-west separation in tip and toe isochlors of McFarland's (2010) interpretation. Outlying chloride concentrations in Virginia that exceeded 249 mg/L were considered to be the result of local effects and are not of regional importance. The 10,000-mg/L isochlors that extend from offshore Maryland to the middle of the Eastern Shore, Va., from Norfolk, Va., to the Virginia border and from Albemarle Sound south to the edge of the study area in North Carolina, were all extrapolated. The 10,000-mg/L isochlor from Eastern Shore Virginia to Norfolk, Va., was interpolated from tip and toe lines of McFarland (2010) and the 10,000-mg/L isochlor in northern North Carolina is a modification from Meisler (1989).

Overall, the interpreted 250- and 10,000-mg/L isochlors for the Potomac-Patapsco aquifer in Long Island closely follow the shoreline. The isochlors form a broad landward tongue in southwest New Jersey, Delaware, and eastern Maryland and form a second tongue around the western boundary of the Chesapeake Bay impact structure. The 10,000-mg/L interpreted isochlor presented here is for the middle of the Potomac-Patapsco aquifer and so is slightly more landward in most areas than that presented for the top of the Potomac-Patapsco aquifer by Meisler (1989) for the historical NACP regional 10,000-mg/L isochlor. In a few areas, the 10,000-mg/L isochlor is at a location similar to the historical interpretation (Meisler, 1989) but is skewed westward along the boundary of the outer ring of the Chesapeake Bay impact crater.

Magothy Aquifer

The Magothy regional aquifer was mapped in two segments. The northern segment extends (fig. 6) from Long Island, N.Y., to an irregular east-west line just south of Delaware. The southern segment extends from near the Virginia-North Carolina border to the southernmost extent of the study area (Pope and others, 2016). In most of the study area, the offshore extent of the Magothy aquifer is present to the southeastern boundary of the Continental Shelf. The Magothy regional aquifer is not shown in southern Maryland and Virginia (Pope and others, 2016). McFarland (2013), however, indicates that across southern Maryland and into North Carolina, the locations of the hydrogeologic equivalents of the Matawan, Black Creek, and Cape Fear aquifers (fig. 3) within the Magothy regional aquifer are unclear.

Chloride samples from NWIS for the Magothy aquifer consist of 19,078 records from 1,710 wells (fig. 6). On Long Island, N.Y., and in New Jersey, much of the Magothy aquifer has substantial sample coverage, and the greatest density of the samples is in the highly developed areas in Queens and Nassau Counties, N.Y., and within 15 miles of the updip extent of the aquifer in New Jersey. Sample density is light in Delaware, Eastern Shore Maryland, and North Carolina but heavy in Western Shore Maryland. Chloride concentrations from 250 to 9,999 mg/L are present in a few scattered clusters along the southern barrier islands of Long Island, N.Y., in Middlesex and Monmouth Counties, N.J., in the vicinity of the Delaware River, in northern Delaware, and in Western Shore Maryland. At four scattered wells in the downdip areas of southern New Jersey, Delaware, and North Carolina, chloride concentrations range from 250 to 9,999 mg/L. Chloride concentrations greater than 9,999 mg/L are evident only in Kings and Nassau Counties, N.Y. The dataset of offshore cores contained one chloride concentration for the Magothy aquifer at the outer boundary of the Continental Shelf; the concentration exceeds 9,999 mg/L (fig. 6).

The 250- and 10,000-mg/L isochlors along the western half of the southern shoreline and the eastern end of Long Island were based on interpretations provided by Frederick Stumm (U.S. Geological Survey, written commun., 2015).

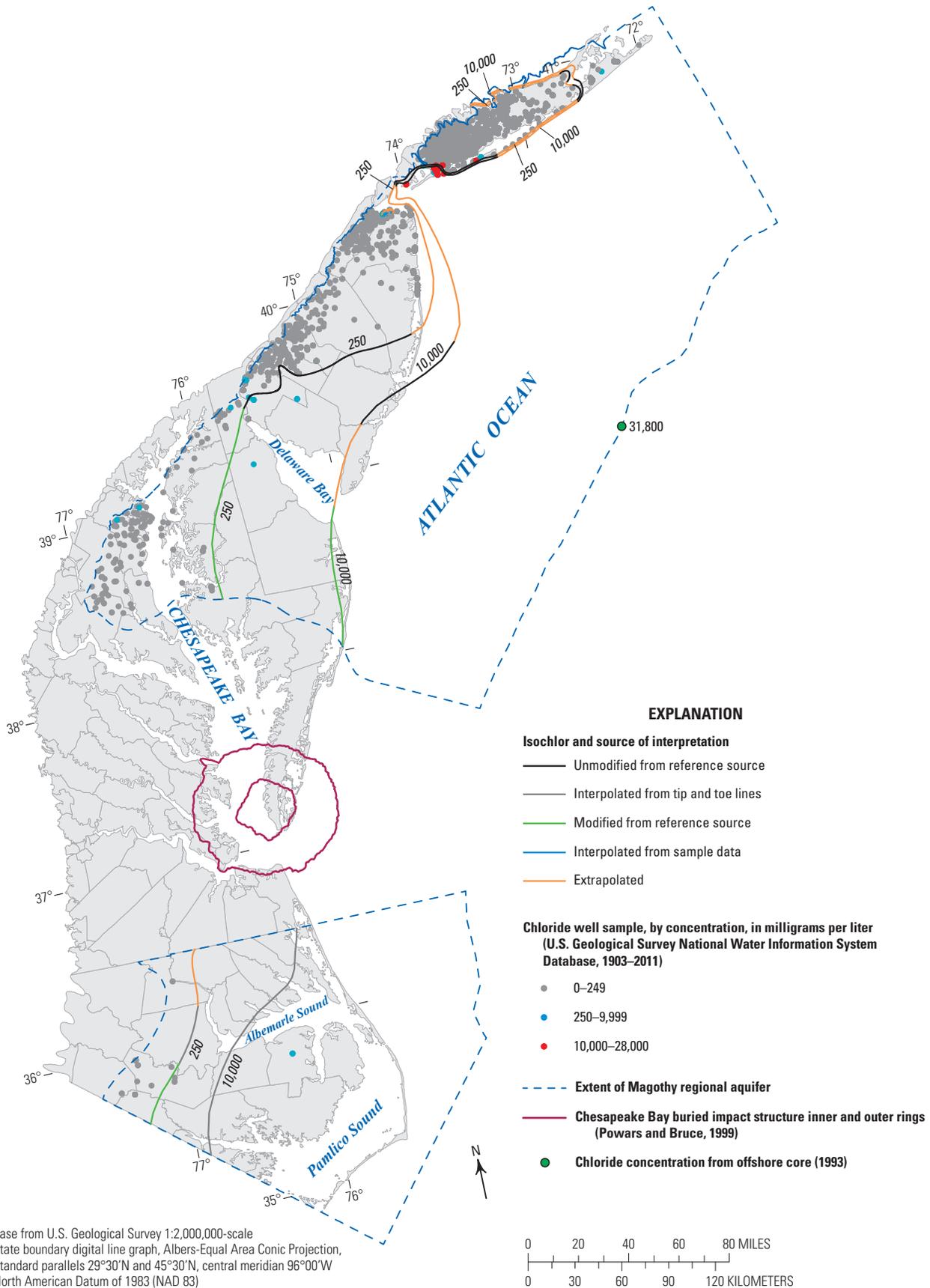
In the North Fork area of Long Island, a section of 250-mg/L isochlor is unmodified from the simulation of Misut and others (2004). The remainder of the 250- and 10,000-mg/L isochlors on Long Island were extrapolated. Along much of the southern boundary of Long Island, the Magothy aquifer contains higher chloride concentrations than those in the Potomac-Patapsco aquifer below it. This is an inversion, or an exception to the regional concept of an overall landward-dipping wedge-shaped geometry of the saltwater-freshwater interface. In the typical relation of chloride concentrations, the overlying aquifers have lower chloride concentrations than the underlying aquifers.

Along Richmond County, N.Y. (Staten Island), through Raritan Bay, and offshore of Ocean County, N.J., the 250- and 10,000-mg/L isochlors were extrapolated. A small outlying 250-mg/L isochlor in northern Monmouth County, N.J., is partly extrapolated and partly interpolated from samples. From Ocean County, N.J., to the Delaware River, the 250-mg/L isochlor is from dePaul and Rosman (2015); chloride concentrations of 250 to 9,999 mg/L at a few wells along the Delaware River were considered to be from local effects and not of regional importance. In Delaware and along the Delaware-Maryland border, the 250-mg/L isochlor in the Magothy aquifer was modified from Andreasen and others (2013); again, chloride concentrations of 250 to 9,999 mg/L at a few wells near the updip limit of the Magothy aquifer in Western Shore Maryland are not considered to be of regional importance. The 10,000-mg/L isochlor offshore of Ocean County, N.J., to the southern end of Cape May is from the simulation of Pope and Gordon (1999). From Cape May, N.J., to the southern limit of the aquifer off the coast of Maryland, the 10,000-mg/L isochlor is from Vroblesky and Fleck (1991). In North Carolina, the northern section of the 250-mg/L isochlor was extrapolated; the central and southern sections were interpolated and modified, respectively, from Winner and Coble (1996). The entire length of the 10,000-mg/L isochlor in North Carolina was interpolated from the tip and toes lines presented by Winner and Coble (1996).

Overall, both the 250- and 10,000-mg/L isochlors for the Magothy aquifer in Long Island, N.Y., closely follow the shoreline, then form a broad landward tongue in southwestern New Jersey and Delaware. The NACP regional isochlors by Meisler (1989) did not include a separate interpretation for the Magothy aquifer, so no comparison is possible.

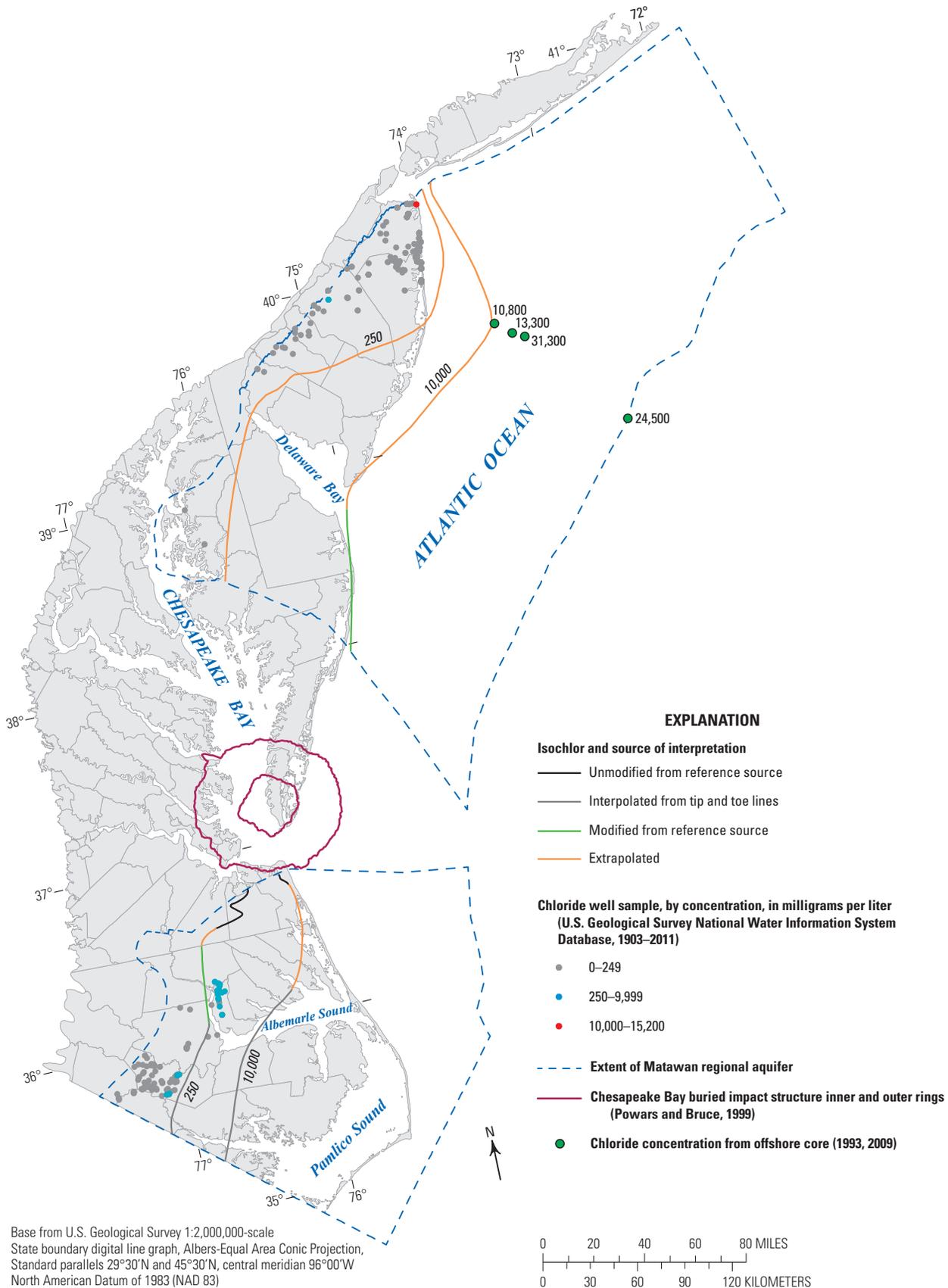
Matawan Aquifer

The Matawan regional aquifer is divided into two segments. The northern segment extends (fig. 7) from just south of Long Island, N.Y., to a slightly curved northwest-southeast line south of Delaware. The southern segment extends from Virginia Beach, Va., to the southernmost extent of the study area (Pope and others, 2016). Offshore, the Matawan aquifer extends to the southeastern edge of the Continental Shelf. The Matawan regional aquifer is not present on Long Island, N.Y., Western Shore Maryland, and most of Virginia.



Base from U.S. Geological Survey 1:2,000,000-scale State boundary digital line graph, Albers-Equal Area Conic Projection, Standard parallels 29°30'N and 45°30'N, central meridian 96°00'W North American Datum of 1983 (NAD 83)

Figure 6. Groundwater chloride concentrations, in milligrams per liter, at well and core locations, and as interpreted 250 and 10,000 isochlores, Magothy regional aquifer, Northern Atlantic Coastal Plain study area.



Base from U.S. Geological Survey 1:2,000,000-scale State boundary digital line graph, Albers-Equal Area Conic Projection, Standard parallels 29°30'N and 45°30'N, central meridian 96°00'W North American Datum of 1983 (NAD 83)

Figure 7. Groundwater chloride concentrations, in milligrams per liter, at well and core locations, and as interpreted 250 and 10,000 isochlors, Matawan regional aquifer, Northern Atlantic Coastal Plain study area.

Chloride samples from NWIS for the Matawan aquifer consist of 905 records from 197 wells (fig. 7). Most of the locations for the northern segments of the isochlors are in New Jersey and for the southern segments are in North Carolina; for both segments most of the wells are within 20 miles of the aquifer outcrop. Chloride concentrations ranging from 250 to 9,999 mg/L are documented for one well in New Jersey and for numerous wells across the middle of North Carolina. The only chloride concentration in excess of 9,999 mg/L is for a well in northern New Jersey (fig. 7) and is not believed to be of regional relevance. The four chloride concentrations along the transect offshore of New Jersey exceed 9,999 mg/L.

The interpretation of the 250-mg/L isochlor within and offshore of New Jersey and through Delaware was extrapolated. The 10,000-mg/L isochlor offshore of New Jersey to the mouth of Delaware Bay overall is extrapolated, although some control was provided by a single transect of offshore samples. The 10,000-mg/L isochlor from Delaware Bay to offshore Virginia was modified from Vroblesky and Fleck (1991). The northern segments of the 250-mg/L and 10,000-mg/L isochlors in southern Virginia are from McFarland (2010), and the rest of the isochlors in Virginia were extrapolated. The northern segment of the 250-mg/L isochlor in North Carolina was modified from Winner and Coble (1996), and the southern segment was interpolated from tip and toes lines from Winner and Coble (1996). The 10,000-mg/L isochlor from Albemarle Sound to the southern extent of the study area was interpolated from tip and toes lines from Winner and Coble (1996).

Overall, the northern segments of the interpreted 250- and 10,000-mg/L isochlors for the Matawan regional aquifer extend offshore of the New Jersey coast. The isochlors form a landward tongue in the Delaware Bay region similar to that of the deeper aquifer units. In North Carolina, the 250- and 10,000-mg/L isochlors are entirely onshore. The NACP regional chloride assessment by Meisler (1989) did not present a separate isochlor interpretation for the Matawan aquifer, so no comparison is possible.

Monmouth-Mount Laurel Aquifer

The Monmouth-Mount Laurel regional aquifer is divided into northern and southern segments. The northern segment extends (fig. 8) from southeast of Long Island, N.Y., to a slightly curved northwest-southeast line just south of Delaware. The southern segment extends from an irregular east-west line south of Virginia Beach, Va., to the southern extent of the study area (Pope and others, 2016). Offshore, the Monmouth-Mount Laurel regional aquifer extends to the southeastern edge of the Continental Shelf. The Monmouth-Mount Laurel regional aquifer is not present on Long Island, N.Y., Western Shore Maryland, and most of Virginia.

Chloride samples from NWIS for the Monmouth-Mount Laurel aquifer consist of 426 chloride records from 161 wells (fig. 8). In the northern segment, most of the wells are in New Jersey and within 20 miles of the outcrop area. A few additional wells are in Delaware and Eastern Shore Maryland.

In the southern segments of the isochlors, there are a few scattered wells near the southernmost extent of the study area boundary in North Carolina. Chloride concentrations ranged from 250 to 9,999 mg/L at 3 wells in New Jersey, 2 wells in eastern Maryland, and at 1 well in North Carolina. Offshore of the coast of New Jersey, chloride concentrations are in excess of 9,999 mg/L at two of the three core locations.

From Raritan Bay to halfway down the New Jersey coast, the 250-mg/L isochlor is offshore and is extrapolated. The 10,000-mg/L isochlor from Raritan Bay to halfway down the New Jersey coast is overall considered extrapolated, although some control was provided by a single transect of offshore samples. The 250-mg/L isochlor for the rest of New Jersey, Delaware, and Maryland was modified from Meisler (1989). Three wells within 5 miles of the outcrop in New Jersey had chloride concentrations ranging from 250 to 9,999 mg/L, but these were not considered to be of regional relevance. A section of 10,000-mg/L isochlor offshore from Atlantic City, N.J., was modified from the simulation of Pope and Gordon (1999). The section of the 10,000-mg/L isochlor east of Cape May County, N.J., was extrapolated. The 10,000-mg/L isochlor offshore from the Maryland-Virginia border is from Meisler (1989).

The segments of the 250-mg/L and 10,000-mg/L isochlors in southern Virginia were extrapolated, as was the extension of the 250-mg/L isochlor into North Carolina. The southern half of the 250-mg/L isochlor in North Carolina was interpolated from tip and toe isochlors provided by Winner and Coble (1996). The 10,000-mg/L isochlor in North Carolina is from Meisler (1989).

Overall, in the northern segment the 250-mg/L isochlor is partly onshore in New Jersey and entirely onshore across Delaware and Maryland. The northern segment of the 10,000-mg/L isochlor is entirely offshore, and the 250- and 10,000-mg/L isochlors form a seaward bulge off the coast of New Jersey. In Virginia, a short section of the 250-mg/L isochlor is onshore, and the 10,000-mg/L isochlor is partly offshore. In North Carolina, the 250-mg/L and 10,000-mg/L isochlors are entirely onshore. Where present, the NACP regional isochlors of Meisler (1989) for the Monmouth-Mount Laurel aquifer are consistent with those presented in this report.

Aquia Aquifer

The Aquia regional aquifer extends from south of Long Island, N.Y., (fig. 9) in a relatively narrow band across New Jersey and Delaware; it continues as a relatively wide band across Western Shores of Maryland and Virginia, and North Carolina (Pope and others, 2016). The only offshore extent of the Aquia aquifer is adjacent to Long Island, N.Y. The Aquia regional aquifer is not present on Long Island, N.Y., and in substantial portions of the Coastal Plain of New Jersey, Delaware, and Eastern Shores of Maryland and Virginia.

Chloride samples from NWIS for the Aquia aquifer consist of 2,609 chloride records from 876 wells (fig. 9). The greatest density of samples is in Maryland, but substantial

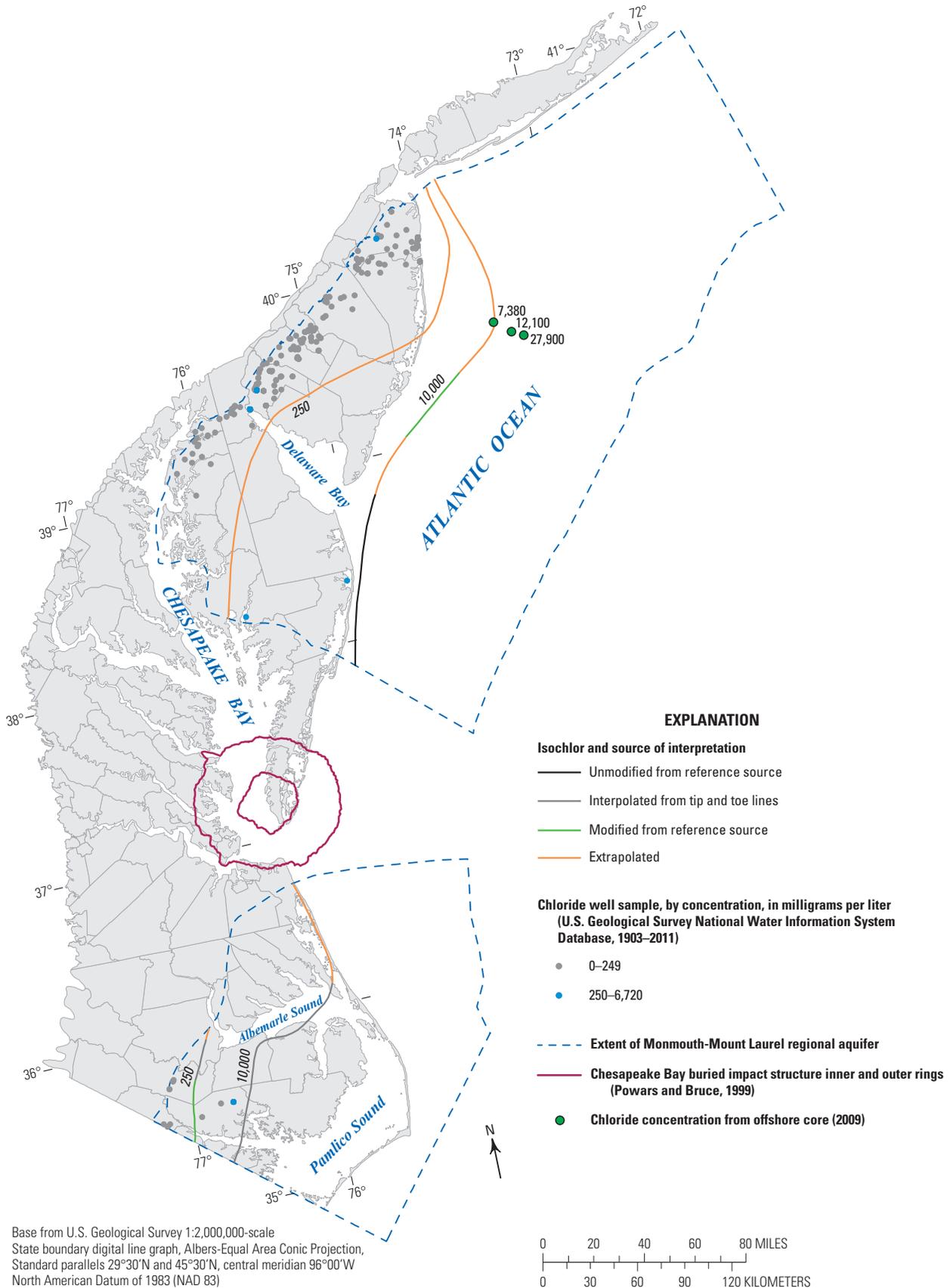


Figure 8. Groundwater chloride concentrations, in milligrams per liter, at well and core locations, and as interpreted 250 and 10,000 isochlors, Monmouth–Mount Laurel regional aquifer, Northern Atlantic Coastal Plain study area.

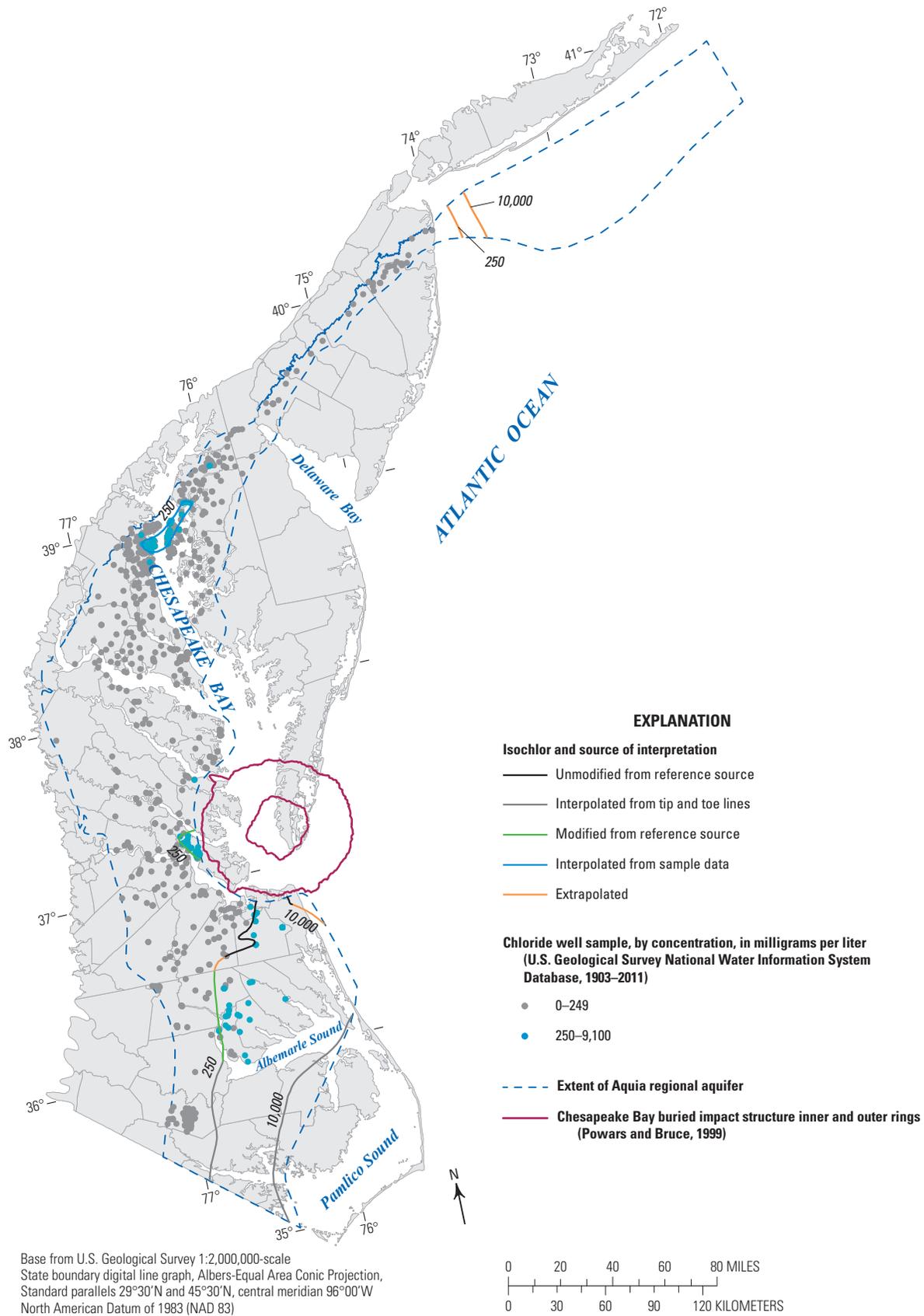


Figure 9. Groundwater chloride concentrations, in milligrams per liter, at well locations, and as interpreted 250 and 10,000 isochlors, Aquia regional aquifer, Northern Atlantic Coastal Plain study area.

data are available for the entire aquifer. Samples with chloride concentrations ranging from 250 to 9,999 mg/L are clustered within Eastern and Western Shores in Maryland, along the western and southern boundaries of the Chesapeake Bay impact structure, and in northern North Carolina. No chloride concentrations exceeding 9,999 mg/L were recorded in the NWIS dataset for this aquifer, and no offshore core samples were recorded.

The interpreted 250- and 10,000-mg/L isochlors offshore of western Long Island and the coast of New Jersey were extrapolated. The 250-mg/L isochlor in the Chesapeake Bay area of Maryland was interpolated from sample data. The segment of the 250-mg/L isochlor adjacent to the western boundary of the Chesapeake Bay impact structure was modified from McFarland (2010). In Virginia, south of the impact structure, two segments of the 250- and 10,000-mg/L isochlors are from McFarland (2010), and the extrapolated 250- and 10,000-mg/L segments extend to the North Carolina border and to the offshore extent of the Aquia regional aquifer, respectively. In North Carolina, the 250- and 10,000-mg/L isochlors were interpolated from the aquifer tip and toe isochlors published in Winner and Coble (1996).

The most prominent features of the interpreted isochlors for the Aquia regional aquifer are the offshore occurrence of salty water southeast of Long Island, N.Y., the outlying 250-mg/L isochlor in the northern Chesapeake Bay area, and the 250-mg/L isochlor along the western boundary of the Chesapeake Bay impact structure. Meisler (1989) did not present an isochlor interpretation for the Aquia regional aquifer, so no comparison is possible.

Piney Point Aquifer

The Piney Point regional aquifer extends (fig. 10) from offshore of Long Island, N.Y., to the study area boundary in North Carolina (Pope and others, 2016). Offshore, the Piney Point aquifer is only present part way across the Continental Shelf and off New York, New Jersey, and North Carolina.

Chloride samples from NWIS for the Piney Point aquifer consist of 1,200 chloride records from 540 wells (fig. 10). The greatest densities of well samples are in Maryland, Virginia, and central North Carolina. Wells are less dense in Delaware and New Jersey. There are three samples from cores off the coast of New Jersey. Chloride samples ranging from 250 to 9,999 mg/L were recorded from five wells across New Jersey, Delaware, and Eastern Shore Maryland. Clusters of chloride samples ranging from 250 to 9,999 mg/L were recorded for wells in the vicinity of the western boundary of the Chesapeake Bay impact structure, near the southern border of Virginia, and in central North Carolina. Only one of the three core samples off the New Jersey coast had a chloride concentration exceeding 9,999 mg/L.

The 250-mg/L isochlor offshore of New Jersey to the area where it crosses the Coastal Plain of New Jersey was extrapolated. The 250-mg/L isochlor in the Coastal Plain was

modified from dePaul and Rosman (2015). The chloride well sample along the Delaware Bay in Cumberland County, N.J., which exceeds 249 mg/L, is not considered to be of regional importance. The 10,000-mg/L isochlor offshore of New Jersey overall is considered extrapolated, although some control was provided by a single transect of offshore samples. The 250-mg/L isochlor across Delaware Bay, Delaware, and Eastern Shore Maryland was extrapolated. The 250- and 10,000-mg/L isochlors through most of Virginia are from McFarland (2010). The exceptions are the 10,000-mg/L segments extrapolated north and south of the impact structure and the short extrapolated segment of the 250-mg/L isochlor in North Carolina. In North Carolina, the northern segment of the 250-mg/L isochlor was modified from Winner and Coble (1996), and the southern segment was interpolated from the tip and toe isochlors of Winner and Coble (1996). In the northern part of North Carolina, the 10,000-mg/L isochlor is modified from Meisler (1989), and the southern segment was extrapolated.

Overall, the interpretation of chloride data for the Piney Point regional aquifer placed the 10,000-mg/L isochlor offshore of New Jersey and in the vicinity of the coastline in the rest of the study area, except around the Chesapeake Bay impact structure. The 250-mg/L isochlor is onshore in southern New Jersey, Delaware, Eastern Shore Maryland, Virginia, and North Carolina. In the historical NACP chloride interpretation by Meisler (1989) for the Piney Point aquifer, the 10,000-mg/L isochlor is shown only within North Carolina; the interpretation for this report resulted in a slightly modified version of the isochlor from Meisler (1989). The remaining segments of the 250- and 10,000-mg/L isochlors presented here for the Piney Point regional aquifer are consistent with the 1,000- and 5,000-mg/L isochlors presented by Meisler (1989).

Lower Chesapeake Aquifer

The Lower Chesapeake regional aquifer is divided into two segments. The northern segment extends from offshore New York (fig. 11) to the Chesapeake Bay. The southern segment is mostly in eastern North Carolina (Pope and others, 2016). Offshore, the Lower Chesapeake regional aquifer extends to the southeastern edge of the Continental Shelf. The Lower Chesapeake regional aquifer is not present on Long Island, N.Y., or in most of Virginia. In New Jersey, the Lower Chesapeake regional aquifer consists of the confined parts of the sub-regional undifferentiated Kirkwood-Cohansey aquifer, which includes the Atlantic City 800-foot sand and the Rio Grande water-bearing zone.

Chloride samples from NWIS for the Lower Chesapeake aquifer consist of 4,552 chloride records from 305 wells (fig. 11). Most of the wells are in New Jersey and are distributed throughout the aquifer extent. The samples for Delaware and eastern Maryland are sparse, and for Virginia and North Carolina, samples were available for only a few

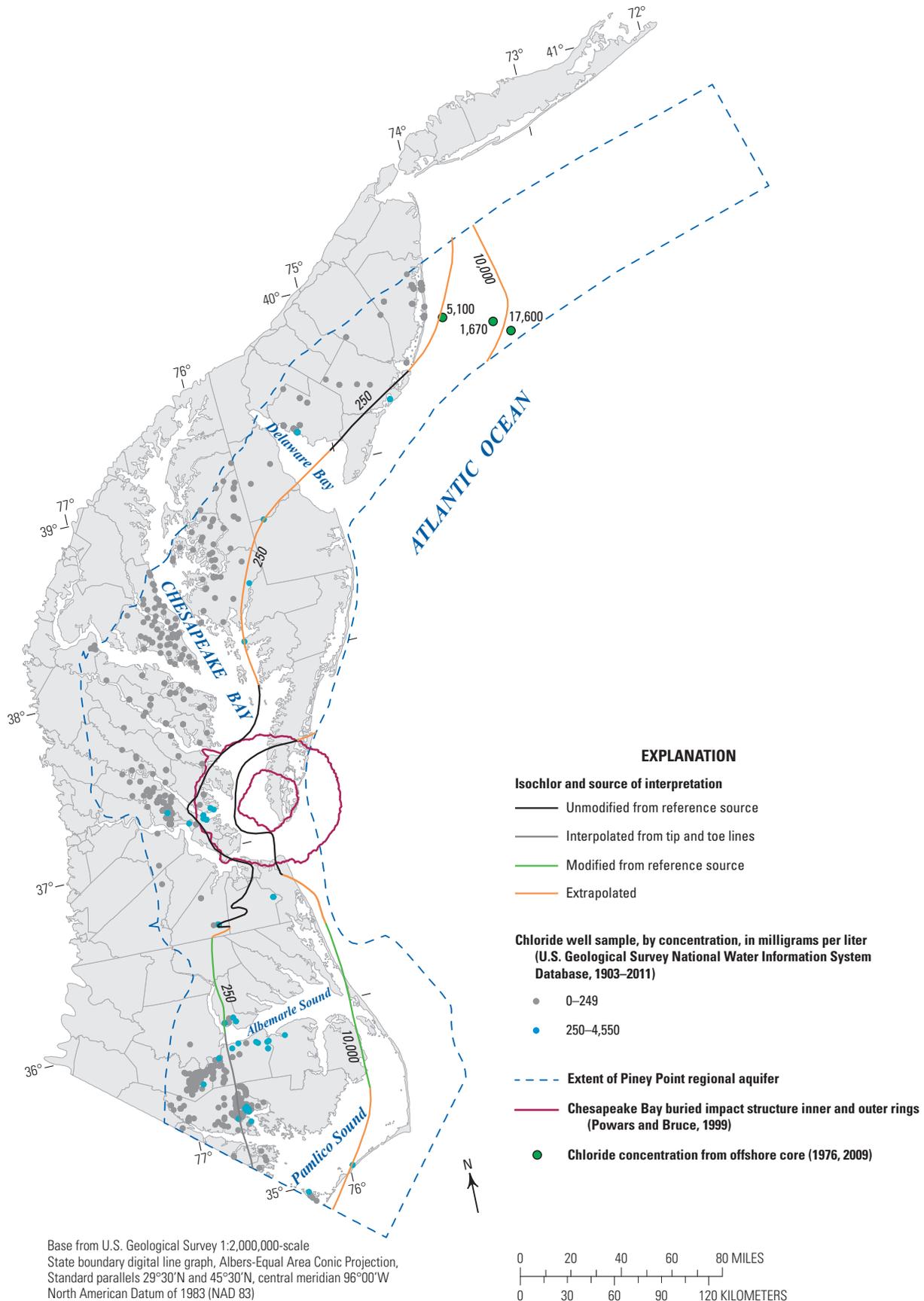


Figure 10. Groundwater chloride concentrations, in milligrams per liter, at well and core locations, and as interpreted 250 and 10,000 isochlors, Piney Point regional aquifer, Northern Atlantic Coastal Plain study area.

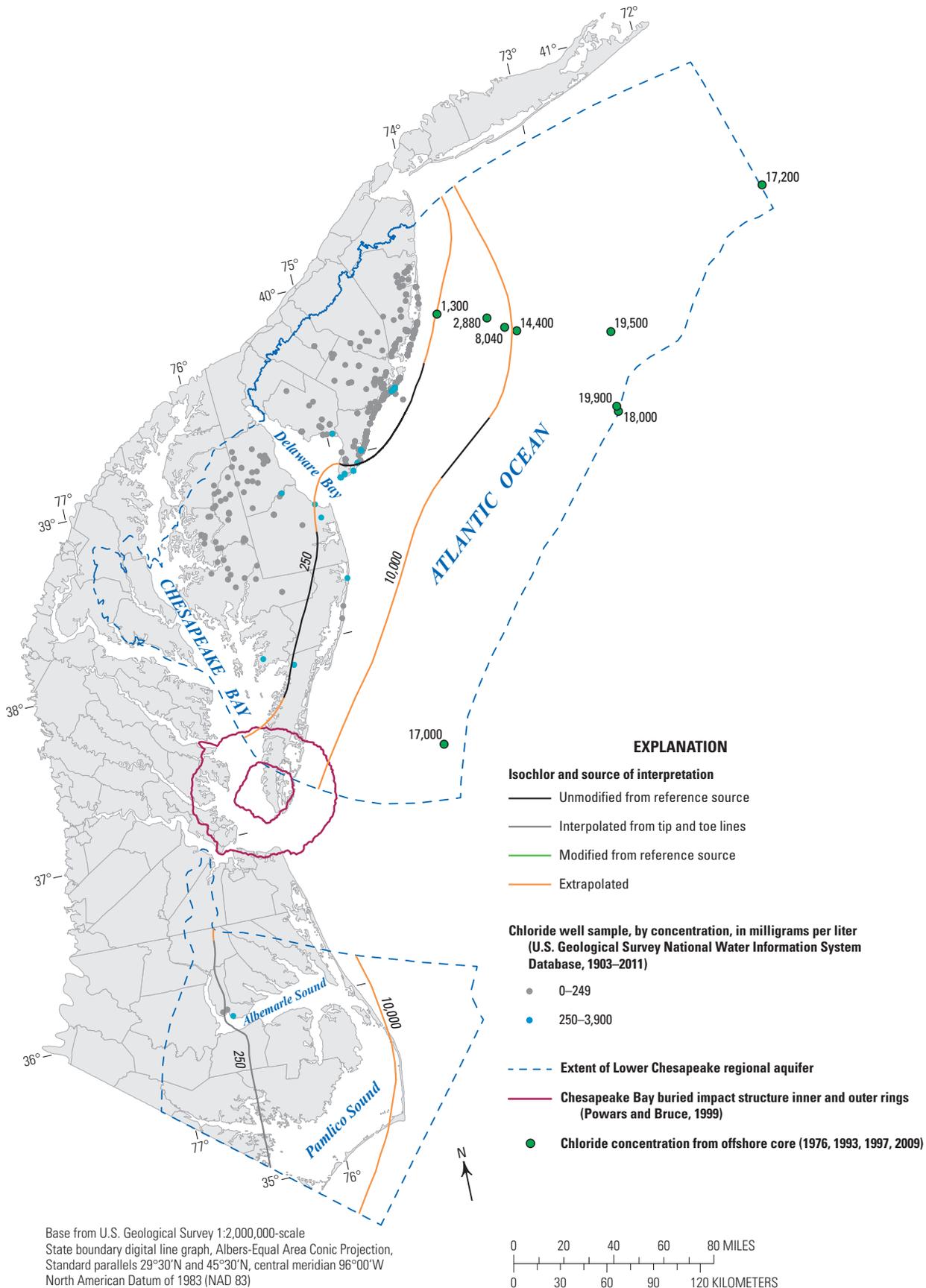


Figure 11. Groundwater chloride concentrations, in milligrams per liter, at well and core locations, and as interpreted 250 and 10,000 isochlors, Lower Chesapeake regional aquifer, Northern Atlantic Coastal Plain study area.

scattered wells. Chloride concentrations ranging from 250 to 9,999 mg/L were recorded for eight onshore wells in the study area. For the offshore area, samples from NWIS consist of two chloride concentrations of less than 250 mg/L for wells within 5 miles of Atlantic City, N.J. The nine remaining offshore concentrations are from cores, with six of the nine concentrations exceeding 9,999 mg/L of chloride.

The 250-mg/L isochlor offshore east of Atlantic County, N.J., and through Cape May County is from dePaul and Rosman (2015). The 250-mg/L isochlor was extrapolated through Delaware Bay into southern Delaware. From southern Delaware to part way down Eastern Shore Virginia, the 250-mg/L isochlor was modified from Andreasen and others (2013). The 250-mg/L isochlor segment from Eastern Shore Virginia to the aquifer extent about halfway across Chesapeake Bay was extrapolated. Chloride concentrations ranging between 250 and 9,999 mg/L in New Jersey, Delaware, Maryland, and Virginia that are outside of the 250-mg/L contour are considered not relevant to a regional or areal trend. In North Carolina, the 250-mg/L isochlor was interpolated from tip and toe lines mapped by Winner and Coble (1996), and the short segments to the north and south were extrapolated.

A segment of the 10,000-mg/L isochlor off the New Jersey coast was modified from simulations by Pope and Gordon (1999). The rest of the 10,000-mg/L isochlor is extrapolated, although a single transect of offshore samples provided some control. Two wells in Atlantic City had chloride concentrations greater than 9,999 mg/L; however, these are not believed to represent regional conditions.

The interpreted 10,000-mg/L isochlor for the Lower Chesapeake regional aquifer is offshore, except for a short portion interpreted as underlying the barrier islands of North Carolina. The 250-mg/L isochlor is offshore of New Jersey, except at the tip of Cape May County; otherwise, in the study area, the 250-mg/L isochlor is onshore. The historical NACP regional isochlor assessment by Meisler (1989) did not include a separate isochlor interpretation for the Lower Chesapeake aquifer, so no comparison is possible.

Upper Chesapeake Aquifer

The Upper Chesapeake regional aquifer (fig. 12) is offshore of New Jersey, except under the southern part of Cape May County, where it consists of the confined part of the sub-regional Cohansey Sand. South of Cape May County, the Upper Chesapeake aquifer extends through the lower part of Delaware, part of Eastern Shore Maryland, southeastern Virginia, and eastern North Carolina (Pope and others, 2016). The Upper Chesapeake aquifer extends offshore to the southeastern edge of the Continental Shelf. The Upper Chesapeake regional aquifer is not present on Long Island, N.Y., most of New Jersey, and Western Shore Maryland.

Chloride samples from NWIS for the Upper Chesapeake aquifer consist of 2,637 chloride records from 801 wells

(fig. 12). The samples are distributed throughout the land portion of the regional aquifer; the greatest sample densities are in Cape May County, N.J., Eastern Shores of Maryland and Virginia, southern Virginia, and North Carolina. Chloride concentrations ranging from 250 to 9,999 mg/L are scattered throughout the coastal and estuary areas. A well on the Atlantic Coast in Maryland had a chloride concentration exceeding 9,999 mg/L. Offshore, chloride concentrations for 7 of the 10 cores exceeded 9,999 mg/L.

The 250-mg/L chloride isochlor in Cape May County, N.J., is from dePaul and Rosman (2015). Along the Atlantic Coast of Delaware and Eastern Shore Maryland, the 250-mg/L isochlor was interpolated from well samples. The 250-mg/L isochlor segment on Eastern Shore Virginia was modified from Richardson (1994) and Sanford and others (2009). The 250-mg/L isochlor across Eastern Shore Maryland is from Werkheiser (1990); short segments on both ends of that isochlor were extrapolated. Except for a short extrapolated section in the area north of the Chesapeake Bay impact structure, the 250-mg/L isochlor in Virginia was interpolated from the tip and toe lines mapped by McFarland (2010). McFarland's (2010) interpretations included wells not used in this study, and his study indicates greater variability of chloride concentrations in the areas of eastern and southeastern Virginia than does the NWIS data. The 250-mg/L isochlor in North Carolina was interpolated from well samples, except for a short extrapolated segment near the Virginia border.

The 10,000-mg/L isochlor for the Upper Chesapeake regional aquifer in the study area is entirely offshore, and although some control was provided by a single transect of offshore samples, it is overall considered extrapolated. For one well in Maryland with a chloride concentration exceeding 9,999 mg/L, the concentration is attributed to a local effect and is not considered to be of regional importance. The offshore chloride concentrations of 8,300 and 8,210 mg/L are not consistent with the plot of the regional 10,000-mg/L isochlor. These samples might represent the observation from offshore core (van Geldern and others, 2013) that relatively lower chloride concentrations can be observed in localized fine-grained facies with respect to relatively higher chloride concentrations that typically are observed in the coarse-grained facies.

Overall, the interpretation of chloride concentrations for the Upper Chesapeake regional aquifer indicates that the 10,000-mg/L isochlor is entirely offshore. In southern Cape May County, and to a greater extent offshore of New Jersey, the data are compelling, and the 250- and 10,000-mg/L isochlors were interpreted to indicate that the Upper Chesapeake aquifer contains substantially higher chloride concentrations than the Lower Chesapeake aquifer below it. This case of inversion is most areally extensive for the offshore interpretations and is consistent with the conclusions of the offshore distribution of saltwater and freshwater made by Lofi and others (2013) and van Geldern and others (2013) using the same offshore data that were used in this study. A similar case of an inversion with respect to the underlying

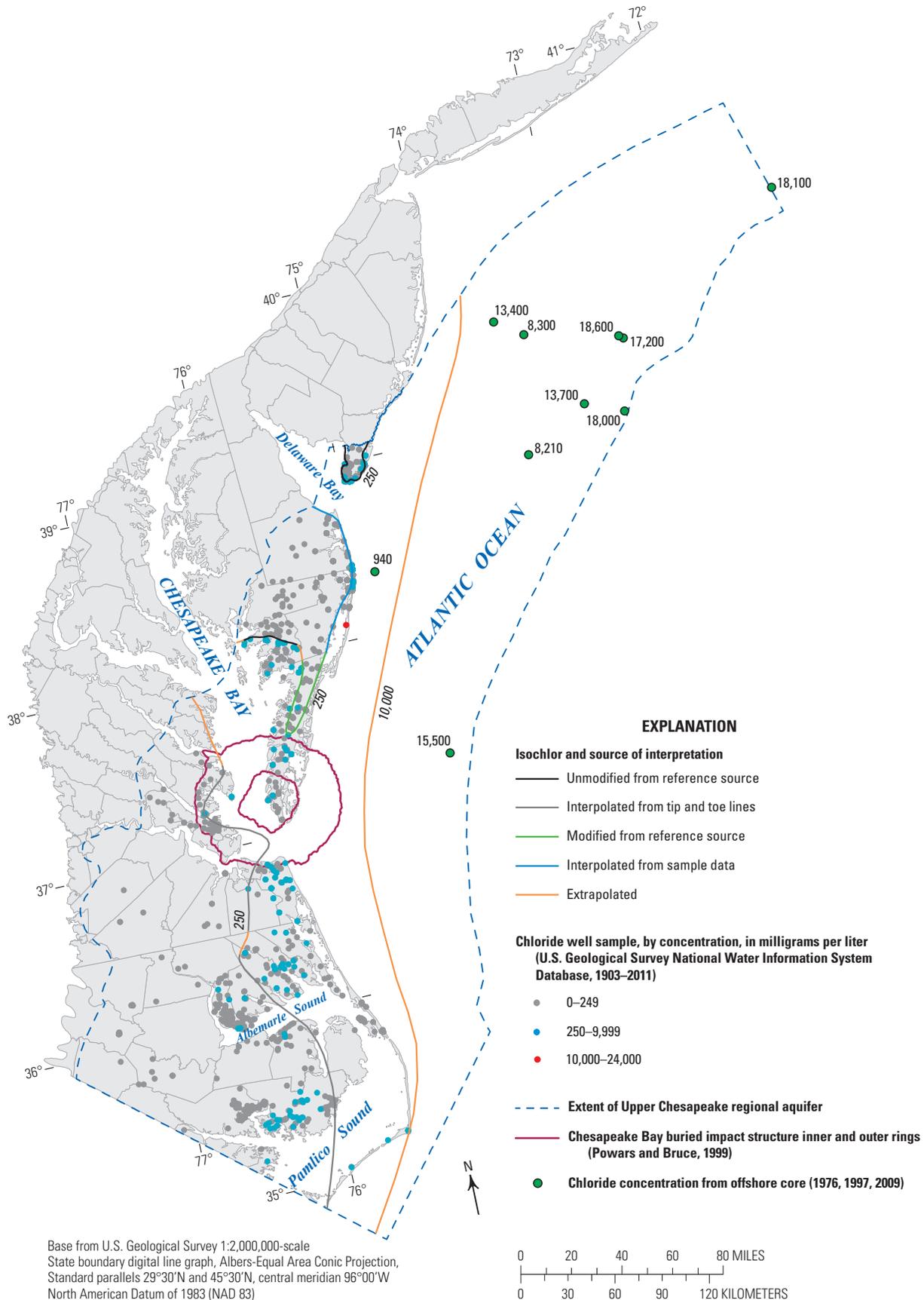


Figure 12. Groundwater chloride concentrations, in milligrams per liter, at well and core locations, and as interpreted 250 and 10,000 isochlors, Upper Chesapeake regional aquifer, Northern Atlantic Coastal Plain study area.

Lower Chesapeake regional aquifer is interpreted for an area in Eastern Shore Maryland and Virginia. The historical NACP regional isochlors of Meisler (1989) did not include a separate isochlor interpretation for the Upper Chesapeake aquifer, so no comparison is possible.

Surficial Aquifer

The surficial regional aquifer is the youngest and shallowest aquifer and is considered unconfined throughout the regional extent, except for some locally confined areas (Trapp, 1992). The surficial aquifer extends over the entire study area (fig. 1) from Long Island, N.Y., to North Carolina, to the southeastern edge of the Continental Shelf (Pope and others, 2016). Surficial aquifer isochlor interpretations have been published for localized areas of Long Island, N.Y., by Nemickas and Koszalka (1982), Stumm (2001), Stumm and others (2002, 2004), Misut and others (2004), Misut and Voss (2007), and Monti and others (2009). In New Jersey, surficial aquifer isochlors for Cape May County were published by Lacombe and Carleton (2002). For Eastern Shore Virginia, surficial aquifer isochlors have been published by Richardson (1994) and Sanford and others (2009).

Highly detailed investigations of the geochemistry and sediments of surficial aquifers beneath selected coastal bays and estuaries of Delaware, Maryland, and Virginia have been reported (Krantz and others, 2004; Manheim and others, 2004; Bratton and others, 2009). These studies used data from water samples, cores, and streaming horizontal resistivity and other geophysical techniques, demonstrating that the interaction of shallow fresh groundwater with marine or estuarine water can result in horizontally and vertically complex freshwater-saltwater interfaces in the groundwater system. Bratton (2010) provides a useful conceptual overview of the three main scales of freshwater-saltwater interface geometries that are observed on continental margins.

The conceptual guidance provided by Bratton (2010), combined with the localized studies cited above, indicate that the 250- and 10,000-mg/L isochlors in the surficial aquifer would, in most places, map close to each other and slightly offshore and in many cases within 350 feet of and parallel to the shoreline. Ideally, isochlor interpretations for the surficial aquifer would be supported by chloride samples from the area of critical data, slightly offshore. The overall NWIS chloride dataset for the surficial aquifer is substantial, but slightly offshore data are nearly non-existent in the dataset. In the absence of useful NWIS data, the alternative is to map isochlors in much of the study area by consistent offsets with respect to and within 350 feet of the shoreline. For this study however, isochlors mapped in this manner would be indistinguishable and not meaningful at the regional scale, beyond the concept of the consistent offset approach. For the reasons cited above, isochlor interpretations and chloride sample points for the surficial regional aquifer are not presented.

Limitations of the Study

Limitations of the regional isochlor maps stem mainly from the requirement to use data of highly variable density while meeting the requirement that chloride concentrations be interpreted for the full extent of each of the regional aquifers. Interpolation and extrapolation are inherent to manual isochlor interpretations. In this regional assessment, confidence in the isochlor (chloride boundary) interpretations varies substantially across the study area. Greater confidence is attributed to areas with relatively high sample density or published interpretations, and lower confidence is attributed to areas with sparse or no samples, or lack of published interpretations. Among the many assumptions inherent to the interpretations is that the regional default geometry of the saltwater-freshwater interface is that of an overall landward-dipping wedge, where the overlying aquifer units typically have lower chloride concentrations than the underlying units. Many of the publications cited in this report refer to areas of focused sub-regional or local studies and can provide additional interpretive information beyond that provided in this regional assessment.

A limitation and caution is that there will be wells with groundwater chloride concentrations greater than or less than an isochlor threshold that are truly only of localized and not of regional extent. Those samples could cause inaccurate interpretation if they are included as part of a regional areal trend. On the other hand, wells with chloride concentrations greater than or less than an isochlor threshold that are interpreted as isolated or localized, or perhaps presented as a scattering of wells, could actually be part of a regional areal trend. Areal differences in hydrogeologic materials, such as facies changes related to paleo-channels or other reasons, may not be apparent from subsurface information and represent a limitation or unknown that can have a substantial bearing on saltwater distribution and interpretation at any scale.

Samples used for the regional interpretations in this study were considered time independent, and a systematic examination for possible temporal trend was not included in the study. If a well had multiple samples collected through time, in many cases the sample(s) that exceeded the threshold was given the priority, in the absence of an interpretation or established explanation.

Use of a single isochlor to represent chloride concentrations in an aquifer represents a limitation. In this regional study, the isochlors (250 mg/L and 10,000 mg/L) were interpreted as being located conceptually in the middle of an aquifer's thickness. Especially in thick portions of an aquifer, the difference in chloride concentrations between the top and bottom of the aquifer can be substantial, so the generalization of using a single middle-aquifer isochlor will not show that difference.

Offshore areas have far less data than land areas with which to extrapolate or interpolate the hydrogeologic framework, and thus, confidence is low regarding the accuracy of the aquifer units to which chloride concentrations were assigned in offshore areas. To further complicate this concern,

analyses of the offshore data (Lofi and others, 2013; Post and others, 2013; van Geldern and others, 2013) indicate that chloride concentrations alternate sharply between many of the hydrogeologic layers, subjecting the offshore interpretations to even greater uncertainty.

The difference in scale between the base map (1:2,000,000) and NWIS data (1:24,000 or surveyed) will typically cause locational discrepancies to appear between wells, and shorelines and rivers, upon close examination (zooming in). In addition, many of the isochlor interpretations were developed at the 1:2,000,000 scale, so close examination of isochlor locations with respect to political boundaries is best avoided.

Summary and Conclusions

A regional assessment of chloride concentrations in groundwater was conducted to produce maps of the estimated locations of the 250- and 10,000-milligrams per liter (mg/L) isochlors for 9 of the 10 regional aquifers of the Northern Atlantic Coastal Plain (NACP). Previous isochlor interpretations, published from 1982 to 2015 at local, state, and regional scales, were used where feasible in the regional assessment. Chloride data used for the onshore parts of the regional aquifers were obtained from the U.S. Geological Survey National Water Information System (NWIS) database, which provided 37,517 water-quality records of chloride concentrations obtained from 6,160 wells from 1903 through 2011. For the offshore part of the aquifers, the assessment used multilevel chloride data from 13 cores collected during four phases of research-related coring (1976, 1993, 1997, 2009). This report also incorporates updated interpretations and chloride samples for eastern Virginia that are related to the 35 million year old Chesapeake Bay impact structure discovered in 1994. With some exceptions, the isochlors (250 and 10,000 mg/L) generally tend to map progressively eastward, from the deepest aquifer units to the shallowest aquifer units, which indicates an increasing seaward extent of fresh groundwater from the deep aquifers to the shallow aquifers within the NACP. Prominent features of the isochlor interpretations are summarized below.

- The most prominent features of the isochlors in the Potomac-Patuxent regional aquifer are the landward tongue of the 250-mg/L isochlor in southwestern New Jersey and the regional landward bulge of the 250- and 10,000-mg/L isochlors across southwestern New Jersey, Delaware, and Maryland.
- The main features of the 250- and 10,000-mg/L isochlors in the Potomac-Patapsco regional aquifer are that the isochlors trace the approximate perimeter of Long Island and form a broad landward bulge across southwestern New Jersey, Delaware, and eastern Maryland and a landward tongue in the vicinity of the Chesapeake Bay impact structure in Virginia. The 250- and 10,000-mg/L isochlors are entirely onshore in southern Virginia and North Carolina.
- The most prominent features of the 250- and 10,000-mg/L isochlors in the Magothy regional aquifer are that the isochlors trace the approximate perimeter of Long Island and form a landward bulge across southwestern New Jersey, Delaware, and eastern Maryland. The 250- and 10,000-mg/L isochlors are entirely onshore in southeastern Virginia and North Carolina.
- In the Matawan regional aquifer, the northern segment of the 250-mg/L isochlor forms a landward bulge across southwestern New Jersey, Delaware, and eastern Maryland. The northern segment of the 10,000-mg/L isochlor is offshore, except at the tip of Cape May County, N.J., and the Delaware-Maryland coast. The 250- and 10,000-mg/L isochlors are entirely onshore in southeastern Virginia and North Carolina.
- In the Monmouth-Mount Laurel regional aquifer, the northern segment of the 250-mg/L isochlor forms a landward bulge across southwestern New Jersey, Delaware, and eastern Maryland, whereas the northern segment of the 10,000-mg/L isochlor is entirely offshore. The 250- and 10,000-mg/L isochlors are entirely onshore where present in southeastern Virginia and North Carolina.
- In the Aquia regional aquifer, the 250- and 10,000-mg/L isochlors are offshore only to the northeast of New Jersey. There is an outlying 250-mg/L isochlor in the Chesapeake Bay area, and the 250- and 10,000-mg/L isochlors are onshore in southern Virginia and North Carolina.
- The 250-mg/L isochlor in the Piney Point regional aquifer is entirely onshore, except for the northernmost extent off the coast of New Jersey. The 250- and 10,000-mg/L isochlors bulge landward in the vicinity of the Chesapeake Bay impact structure. The 10,000-mg/L isochlor is onshore, except for a segment off the coast of New Jersey and two segments off the coast of southeastern Virginia and North Carolina.
- In the Lower Chesapeake regional aquifer, the 250-mg/L isochlor is onshore, except north of the tip of Cape May County in New Jersey. The 10,000-mg/L isochlor is offshore, except near the barrier islands of North Carolina.
- In the Upper Chesapeake regional aquifer, the 250-mg/L isochlor traces the coastline in Cape May County, N.J., extends a few miles landward from the coastline through Delaware, eastern Maryland and northern Virginia and reaches from 0 to 30 miles landward of the shoreline from southeastern Virginia through North Carolina. From New Jersey to North Carolina, the 10,000-mg/L isochlor is entirely offshore. The Upper Chesapeake regional aquifer encompasses

substantial areas off the coast of New Jersey, Eastern Shore Maryland, and Virginia, and smaller areas in North Carolina where the water is saltier than in the underlying Lower Chesapeake regional aquifer.

- Isochlor interpretations and supporting data are not presented for the surficial regional aquifer. The limited information available for the surficial aquifer indicates that in most places, the 250- and 10,000-mg/L isochlors typically would map close to each other and slightly offshore and, in many cases, within 350 feet of and parallel to the shoreline. Isochlors in the vicinity of bays and estuaries are typically complex vertically and horizontally and reflect the interaction of freshwater and saltwater within the surficial aquifer beneath those areas.

The isochlors in this study represent an update of the historical NACP chloride assessment (1989). The historical approach used water-quality data from about 500 wells, including 7 offshore cores, and borehole geophysics interpretations from a subset of 11 wells. In addition to a geochemical-based working hypothesis for the origin and geometry of the saltwater transition zone, the historical assessment presented isochlor maps for the tops of the Potomac-Patapsco, Monmouth-Mount Laurel, and Piney Point regional aquifers and a series of regional maps of depth-to-chloride iso-concentration surfaces. In contrast, the interpretations in this study used chloride samples from 6,160 wells, 13 offshore cores, and many published isochlor interpretations. The approach of this study maximizes the overall density of chloride information and data by gathering all NWIS data and published interpretations into one comprehensive interpretation. This approach does not directly make use of supplemental techniques to enhance the interpretation and distribution of saltwater, such as characterization of geochemistry, borehole geophysical information, and geochronology.

Differences between the regional interpretations of this study and those from 1989 reflect the differing approaches and the use of new data, and do not indicate regional movement of the saltwater interface from 27 years ago. As new water-quality data, hydrogeologic framework information, and various future studies are accumulated, there will be an opportunity to update and refine the interpretations in this report.

Acknowledgments

The author acknowledges the assistance of John Masterson and Jason Pope of the U.S. Geological Survey who provided technical advice that stemmed from their related studies in the Northern Atlantic Coastal Plain. Special thanks are extended to Jack Monti, Jr., of the U.S. Geological Survey, for essential guidance and technical assistance in compiling the database of chloride concentrations. Reviewers Anthony Chu, Fred Stumm, Vince dePaul, Betzy Reyes,

Randy McFarland, Bruce Campbell, and Pierre Lacombe of the U.S. Geological Survey provided invaluable comments and suggestions that improved this report. The author also acknowledges Kevin Dennehy of the U.S. Geological Survey for his support and guidance with stressing the importance of an up-to-date assessment of regional chloride distribution.

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Appendixes

[Available for download at <http://dx.doi.org/10.3133/sir20165034>]

Appendix 1. Chloride concentrations from select offshore core data

Appendix 2. Interpretive isochlors for 250 and 10,000 milligrams per liter, by aquifer layer

Manuscript approved March 22, 2016

Prepared by the USGS Science Publishing Network

Edited by Ruth Larkins
West Trenton Publishing Service Center

Illustrations by James E. Banton
Lafayette Publishing Service Center

Layout by Ann Marie Squillacci
Pembroke Publishing Service Center

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