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Simulation of Groundwater-Level and Salinity Changes in the Eastern Shore, Virginia



Scientific Investigations Report 2009–5066

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

Cover. Eastern Shore Wildlife Refuge, Cape Charles, Virginia, February 2007. Photo courtesy of F. Ray Gefken, Eagle Eyes' Aerial Photography.

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By Ward E. Sanford, Jason P. Pope, and David L. Nelms

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U.S. Department of the Interior
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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Datums and Base Map Credits

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

Base map modified from

City locations: U.S. Census Bureau, "Census 2000-Incorporated places/census designated places cartographic boundary files," accessed January 2004 at *http://www.census.gov/geo/www/cob/pl2000.html*

Shorelines: Elevation data from U.S. Geological Survey 30-meter National Elevation Dataset accessed January 2004 at *http://seamless.usgs.gov*

Streets: ESRI "StreetMap USA," developed by Tele-Atlas, accessed January 2004 at *http://webhelp.esri.com/arcgisdesktop/9.1/index.cfm?TopicName=About%20StreetMap%20USA%20data*

Conversion Factors

Multiply	By	To obtain
	Length	
inch	2.54	centimeter (cm)
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

$$°F = (1.8 \times °C) + 32$$

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

$$°C = (°F - 32) / 1.8$$

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in grams per liter (g/L), milligrams per liter (mg/L), or micrograms per liter (µg/L).

Simulation of Groundwater-Level and Salinity Changes in the Eastern Shore, Virginia

By Ward E. Sanford, Jason P. Pope, and David L. Nelms

Abstract

Groundwater-level and salinity changes have been simulated with a groundwater model developed and calibrated for the Eastern Shore of Virginia. The Eastern Shore is the southern part of the Delmarva Peninsula that is occupied by Accomack and Northampton Counties in Virginia. Groundwater is the sole source of freshwater to the Eastern Shore, and demands for water have been increasing from domestic, industrial, agricultural, and public-supply sectors of the economy. Thus, it is important that the groundwater supply be protected from overextraction and seawater intrusion. The best way for water managers to use all of the information available is usually to compile this information into a numerical model that can simulate the response of the system to current and future stresses.

A detailed description of the geology, hydrogeology, and historical groundwater extractions was compiled and entered into the numerical model. The hydrogeologic framework is composed of a surficial aquifer under unconfined conditions, a set of three aquifers and associated overlying confining units under confined conditions (the upper, middle, and lower Yorktown-Eastover Formation), and an underlying confining unit (the St. Marys Formation). An estimate of the location and depths of two major paleochannels was also included in the framework of the model. Total withdrawals from industrial, commercial, public-supply, and some agricultural wells were compiled from the period 1900 through 2003. Reported pumpage from these sources increased dramatically during the 1960s and 70s, up to currently about 4 million gallons per day. Domestic withdrawals were estimated on the basis of population census districts and were assigned spatially to the model on the assumption that domestic users are located close to roads.

A numerical model was created using the U.S. Geological Survey (USGS) code SEAWAT to simulate both water levels and concentrations of chloride (representing salinity). The model was calibrated using 605 predevelopment and transient water-level observations that are associated predominantly with 20 observation nests of wells sited across the study area. Sampling for groundwater chemistry at these sites revealed that chloride has not increased significantly in the last 20 years. Environmental tracers in the samples also indicated that the water in the surficial aquifer is typically years to decades old, whereas water in the confined aquifers is typically centuries to millennia old. The calibration procedure yielded distributions of hydraulic conductivity and storage coefficients of the aquifers and confining units that are based on 21 pilot points, but vary smoothly across the study area. The estimated values are consistent with other measurements of these properties measured previously on cores and during hydraulic tests at various well fields.

Simulations performed with the model demonstrated that the calibrated model can reproduce the observed historical water levels fairly well ($R^2 = 0.93$). The chloride concentrations were also simulated, but a match with chloride concentrations was more difficult to achieve ($R^2 = 0.16$) because of the lack of sufficient data and the unknown exact behavior of the entire transition zone in the millennia leading up to the present day. Future pumping scenarios were simulated through 2050, with pumping set to either 2003 rates or total permitted withdrawal rates. Water levels in 2050 are predicted to be lower than current levels by a few feet where stresses are currently heaviest but potentially by tens of feet if total permitted withdrawals are extracted at current low-stressed sites. Simulations of chloride concentrations through 2050 revealed some potential for seawater intrusion in the areas of Cape Charles, Chincoteague, east of the town of Exmore, and east of the town of Accomac, but precise estimates of concentration increases are highly uncertain. Simulation results were also used to estimate that the downward transit time of potential dissolved contaminants (such as nitrate) across the uppermost confining unit is on the order of 100–300 years.

An automated parameter estimation software package (UCODE) was used to help calibrate the model. This allowed for an analysis of errors, parameter sensitivities, and 95 percent confidence intervals. Overall, errors between observed and simulated water levels were typically small, and a comparison of weighted simulated observations and weighted residuals suggested no bias in the model. Calculations of the composite sensitivities of parameters indicated which parameters were well-constrained and which were not. The more well-constrained parameters typically lie in regions where

long-term stresses have produced long-term drawdowns, such as in central Accomack County. The confining unit parameters generally were better constrained than the aquifer parameters. The confidence-interval results were consistent with the sensitivity results, indicating which parameters were more or less well-constrained. These results should help guide future work by indicating where additional data may yield the biggest improvements for a future model calibration.

Introduction

The Eastern Shore of Virginia is the land situated between the Chesapeake Bay and the Atlantic Ocean at the southern end of the Delmarva Peninsula and includes Accomack and Northampton Counties. The peninsula is surrounded on three sides by saltwater and has no streams of any substantial size. The two counties, therefore, have no source of surface water and must depend on groundwater as their sole water supply. Fresh groundwater is present at depths shallower than approximately 300 feet (ft), whereas salty groundwater (>250 milligrams per liter [mg/L] chloride) is present at depths greater than 300 ft and along the coastlines at shallower depths. The freshwater is present in a series of four layered aquifers comprised of sediment that is composed predominantly of sand, gravel, and shell material. The aquifers generally are separated and underlain by four confining layers comprised of sediment that is composed predominantly of very fine sand, silt, and clay.

Beginning in the late 1960s, withdrawals for industrial, commercial, and agricultural uses increased, causing water-level declines and creating deeper depressions in the water-level surface around the major pumping centers. In 1976, the Eastern Shore was declared by the Virginia Water Control Board (VWCB) to be a Ground water Management Area. This designation required all groundwater users that withdraw more than 300,000 gallons per month to apply for a permit. In 1982, the Commonwealth began keeping records of permitted withdrawals within the Eastern Shore.

The Virginia Department of Environmental Quality (DEQ) and the Accomack-Northampton Planning District Commission (ANPDC) have recognized that increased water needs in response to intensifying commercial, urban, industrial, and agricultural development could adversely affect the supply of freshwater on the Eastern Shore. The potential problems include (1) declining water levels, (2) decreased freshwater discharge to near-shore estuaries, (3) intrusion of salty water into freshwater parts of the aquifers, and (4) contamination of potable water by the accumulation and migration of nitrate, herbicides, and pesticides. A computer-simulation model of the aquifer system was developed in the early 1990s (Richardson, 1994). In 2002, the USGS, in cooperation with the Virginia DEQ and the ANPDC, began a study to develop a state-of-the-art computer simulation model that could be used to help the Commonwealth and local water managers better plan water use and estimate future changes in water and salinity levels in response to changes in water use.

Purpose and Scope

The purpose of this report is to describe the development and calibration of a groundwater model for the Eastern Shore of Virginia. The report includes discussions of (1) the hydrogeologic framework of the Eastern Shore, (2) the nature of the digital model used to simulate the aquifers, (3) the water-level and chemical conditions used to calibrate the model, (4) hydraulic characteristics of the calibrated model, (5) current and future water levels and chloride concentrations simulated with the model, and (6) potential errors and limitations of the model.

This study was conducted primarily to create a new and improved groundwater model of the Eastern Shore of Virginia. The new model allows for the simulation of changes in salinity (represented by changes in chloride concentrations), allows for a more refined description of the spatial hydraulic conductivity fields, and includes estimates of domestic water use. The geologic framework from a previous study (Richardson, 1994) was used, but more recent water-level and salinity observations were used to calibrate a more refined spatial distribution of the values of hydraulic conductivity. Water samples were collected and analyzed to determine the distribution of chloride and other environmental tracers that might help improve the understanding of the flow system. A number of individual and time-series of water-level observation data were used to calibrate the model with the aide of automated calibration software. Simulations of historical water-level changes and also of future potential changes in water levels and salinity were made on the basis of differing future withdrawal limitations. Simulations were made of travel times through the upper confining layer and travel paths to public-supply wells. Sensitivities of the observations to model parameter values and 95 percent linear confidence intervals for the models were calculated.

Location and Setting of the Study Area

The study area is situated along the Atlantic Ocean to the east of the Chesapeake Bay in the Coastal Plain Physiographic Province (fig. 1). Two counties, Accomack and Northampton, make up the area known as the Eastern Shore of Virginia. The Eastern Shore is a peninsula that is about 70 miles long and 10–20 miles wide, and covers approximately 700 square miles of land area. It is bounded on the east by the Atlantic Ocean, the south and west by the Chesapeake Bay, and the north by the State of Maryland. The model area extends into the state of Maryland and includes offshore areas in the Chesapeake Bay and the Atlantic Ocean. The offshore areas are included to allow the model to simulate interaction between the fresh and salty groundwaters. The Eastern Shore is dominated by a 30–40 ft ridge that runs down the center of the peninsula and is covered by marshes along the coasts and a combination of agriculture and forest in the center (fig. 2). Rainfall in the study area averages about 43 inches per year, and winters are milder than in western areas of Virginia because of the proximity of the Eastern Shore to the Chesapeake Bay and Atlantic Ocean.

Previous Investigations

Previous studies have provided general information about the groundwater resources of the Eastern Shore. Sanford (1913) was the first to describe the geology and groundwater throughout the Coastal Plain of Virginia. Cederstrom (1945) was the first to describe the distribution of salinity in the Virginia Coastal Plain. Sinnot and Tibbitts (1954, 1957, 1968) described the groundwater resources of the Eastern Shore before substantial industrial and commercial withdrawals began. Bal (1977) developed the first digital groundwater-flow model of the Eastern Shore. Larson (1981) provided a description of the distribution of chloride throughout the Virginia Coastal Plain. Fennema and Newton (1982) presented a summary of groundwater information for the Eastern Shore based on a series of test holes that were drilled and nests of observation wells that were installed across the region in the late 1970s and early 1980s. These observation wells have become the primary source from which water levels and quality have been monitored across the Eastern Shore (fig. 3). Mixon (1985) described the geomorphic framework and stratigraphy of the uppermost deposits of Cenozoic

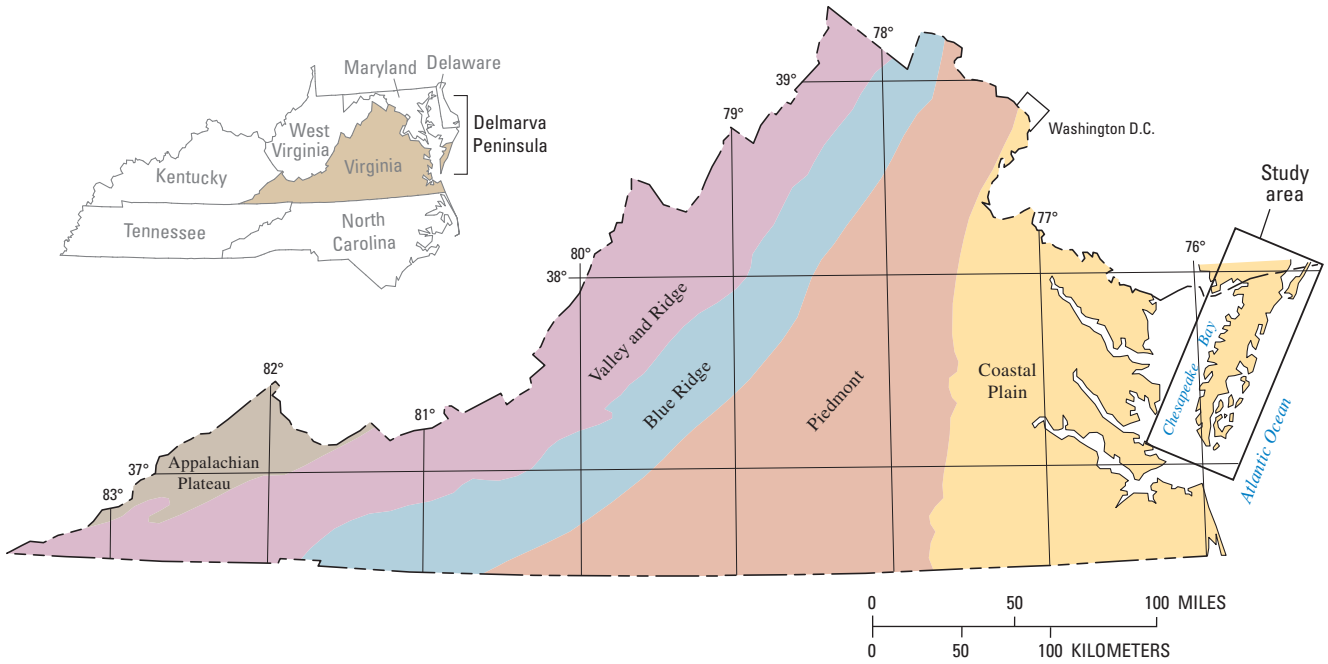


Figure 1. Physiographic provinces of Virginia and the location of the study area.
[Physiographic province data modified from Fenneman, 1938, pl. ii]

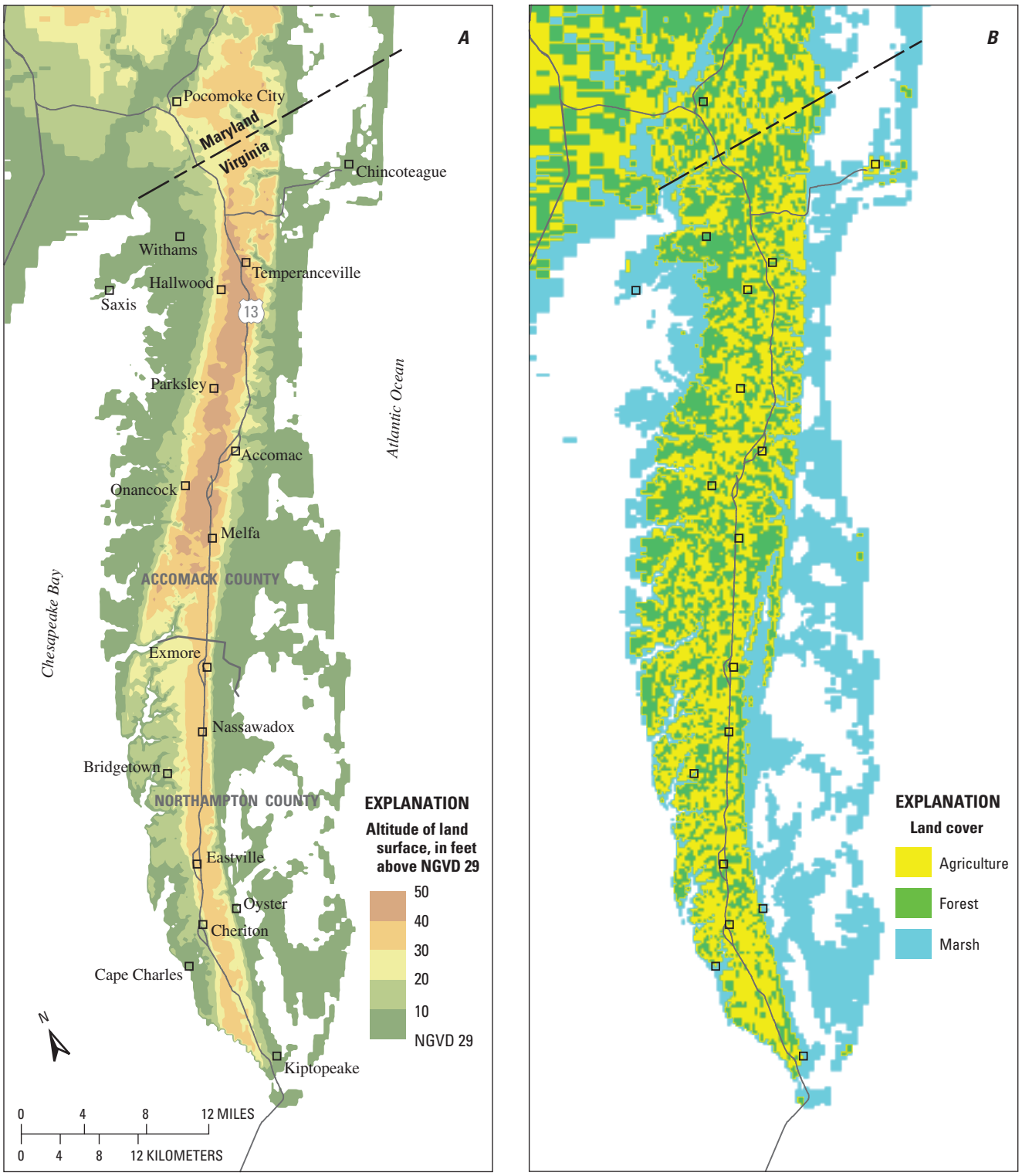


Figure 2. *(A)* Land-surface topography and *(B)* generalized land-cover categories of the Eastern Shore of Virginia. [Land-surface data from U.S. Geological Survey (USGS) 30-meter National Elevation Dataset, accessed January 2004 at *http://seamless.usgs.gov*, land-cover data from USGS National Land Cover Database 2001, accessed September 2003 at *http://gisdata.usgs.net/website/MRLC/viewer.htm*]

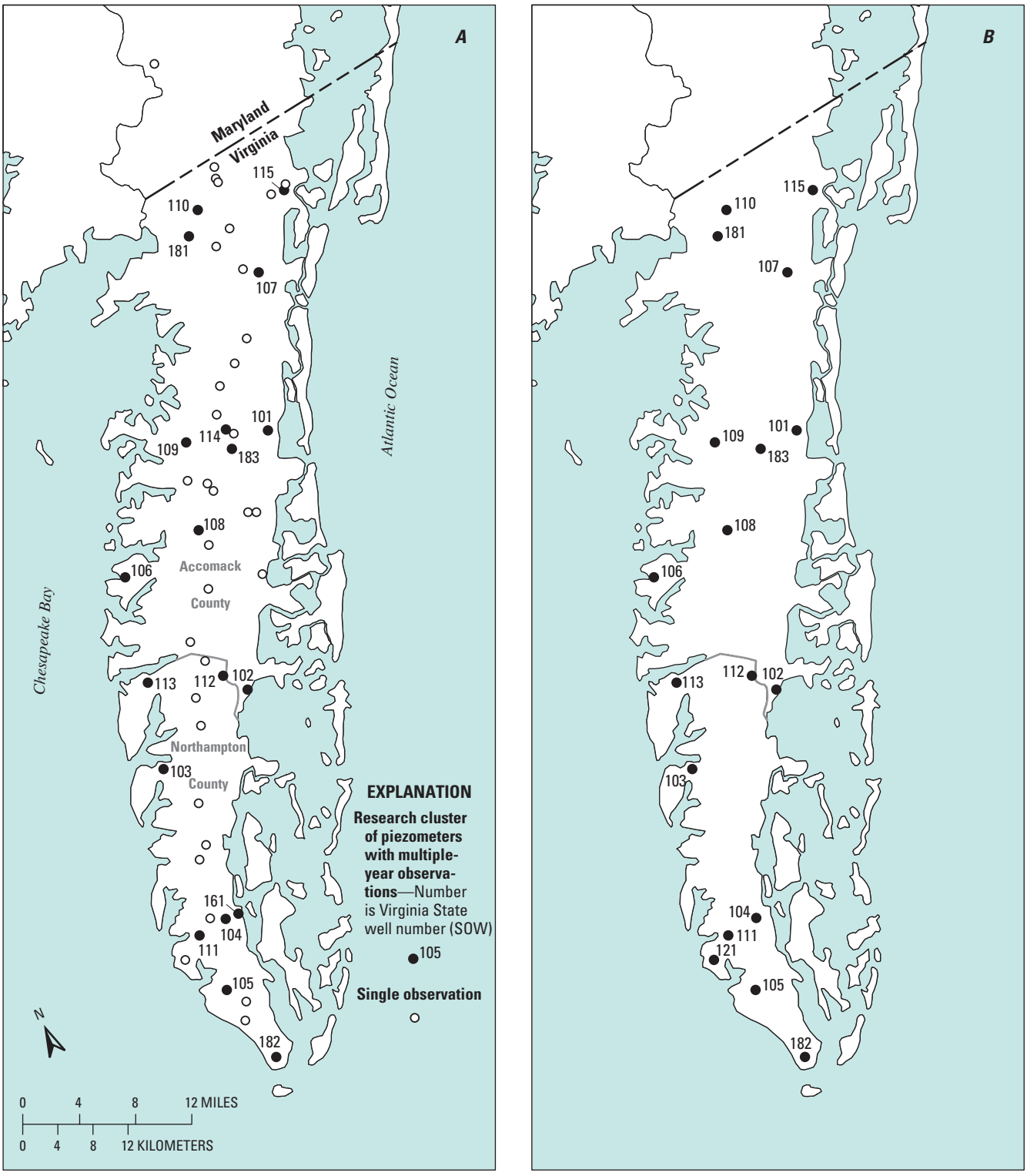


Figure 3. Locations of wells in the Yorktown-Eastover aquifer that were sampled for groundwater *(A)* levels and *(B)* chemistry of the Eastern Shore of Virginia.

age in the southern Delmarva Peninsula. Meisler and others (1985) document the distribution of salty groundwater within the northern Atlantic Coastal Plain system. Harsh and Laczniak (1986) and Meng and Harsh (1988) described the hydrogeologic framework and a conceptualization of groundwater flow in the Virginia Coastal Plain, including the Eastern Shore.

A digital groundwater model of the Eastern Shore was developed in the early 1990s using the USGS code SHARP (Essaid, 1990). The SHARP model treats the transition zone between fresh and salty water as a sharp interface. The model was developed by Richardson (1994) to simulate water-level declines caused by pumping and the relative position of the saltwater interface. The model has the limitation that it does not simulate changes in salinity (or chloride concentrations). The 1994 study compiled geologic and hydrogeologic information about the Eastern Shore and summarized this information in the conceptual framework of a surficial aquifer, three confined aquifers, and three confining layers. Another limitation was that the water levels in the surficial aquifer were considered to be constant in time, and only the levels in the three confined aquifers were allowed to vary as a result of hydrologic stresses imposed on the system. This model has been used by both the Virginia DEQ and the ANPDC over the last decade or so to assess the affect of future groundwater withdrawals. Advances in computer hardware and groundwater simulation software since the early 1990s now make it possible to overcome some of the inherent limitations of the 1994 SHARP model.

Geologic Setting

The sedimentary deposits that make up the Eastern Shore generally thicken and dip northeastward, and range in thickness from about 2,000 ft west of the peninsula to about 7,000 ft east of the peninsula (Meng and Harsh, 1988). These sediments generally overlie a hard-rock surface, commonly referred to as the "basement," that also dips northeastward. In Northampton County, the sediments also overly the sedimentary breccia deposits created by the Chesapeake Bay bolide impact that occurred in the late Eocene Epoch (Powars and Bruce, 1999; Powars, 2000). Post-impact sediments in the area range from late Eocene to Quaternary in age and were deposited in mostly marine environments. In Accomack County, the lower 70 percent of the sediments are of Early to Late Cretaceous age and were deposited in fluvial environments (Robbins and others, 1975). The remaining 30 percent of the sediments are mostly Tertiary in age and were deposited in marine environments (Cushing and others, 1973). The sediments of Tertiary age in both counties were deposited in marine environments and were overlain by a thin veneer of sediments of Quaternary age that were deposited in various environments (Mixon, 1985). The bolide impact and deposits of Cretaceous age and deposits are much deeper than the local freshwater flow system of the Eastern Shore, and so additional discussion of the sediments will be limited to the Tertiary and Quaternary units that make up the freshwater aquifers. The saltwater in the Chesapeake Bay impact crater does not impinge on the freshwater in the aquifers of the Eastern Shore, nor is it likely to in the near future.

Miocene Sediments

The deposits of Miocene age on the Eastern Shore include the Calvert Formation (lower to middle Miocene), the St. Marys Formation (upper Miocene), and the Eastover Formation (upper Miocene) (fig. 4). The Calvert Formation is predominantly a light- to dark-olive-gray, very fine, sandy clay silt and is approximately 700 ft thick on average in the Eastern Shore. The St. Marys Formation is predominantly a massive, mostly dense, well-sorted, dark-greenish-gray clayey silt that is approximately 300 ft thick on average in the Eastern Shore. Both the Calvert and the St. Marys Formations contain scattered shells, pyrite, and disseminated organic matter. The Eastover Formation consists of massive to laminated, dark-gray to greenish-gray, muddy, fine sand interbedded with finer and coarser-grained beds. It is sparsely to abundantly shelly and burrowed, and contains some shell hashes and indurated beds (Powars and Bruce, 1999).

Pliocene Sediments

The only Pliocene deposit on the Eastern Shore is the Yorktown Formation (lower and upper Pliocene), which ranges in thickness from approximately 100 to 300 ft in the study area, with increasing thickness toward the east. The Yorktown formation consists of bluish-gray to greenish-gray, commonly shelly, very-fine to coarse quartz sand interbedded with sandy and silty clay to clay silt. The Yorktown Formation is stratigraphically equivalent to the Pocomoke aquifer (fig. 4) in southern Maryland and the Pensauken Formation in the northern Delmarva Peninsula.

Pleistocene Sediments

During the ice ages of the Pleistocene Epoch, sea levels fluctuated and the drainage patterns of the major river systems in the Chesapeake Bay were altered, eroding channels across the Eastern Shore into previously deposited sediments. These channels were eroded during sea level low stands (in some spots more than 200 ft below sea level into the Yorktown formation) and were filled during high stands. Such paleo-channels are known to exist near Cape Charles, Eastville, and Exmore (Mixon, 1985), although the Cape Charles channel is partially off the southwestern shore of the peninsula. The remaining sediments of Quaternary age were deposited in marginal-marine and estuarine environments; the Nassawadox and Omar Formations were deposited in the central uplands, and the Kent Island Formation and the Joynes Neck Sand and Wachapreague Formations were deposited in the flanking bayside and oceanised terraces, respectively (Mixon, 1985). Holocene-age deposits make up the salt-marsh, back-bay, and barrier-island sediments around the edges of the peninsula. The sediments of Quaternary age range in thickness from approximately 40 to 150 ft.

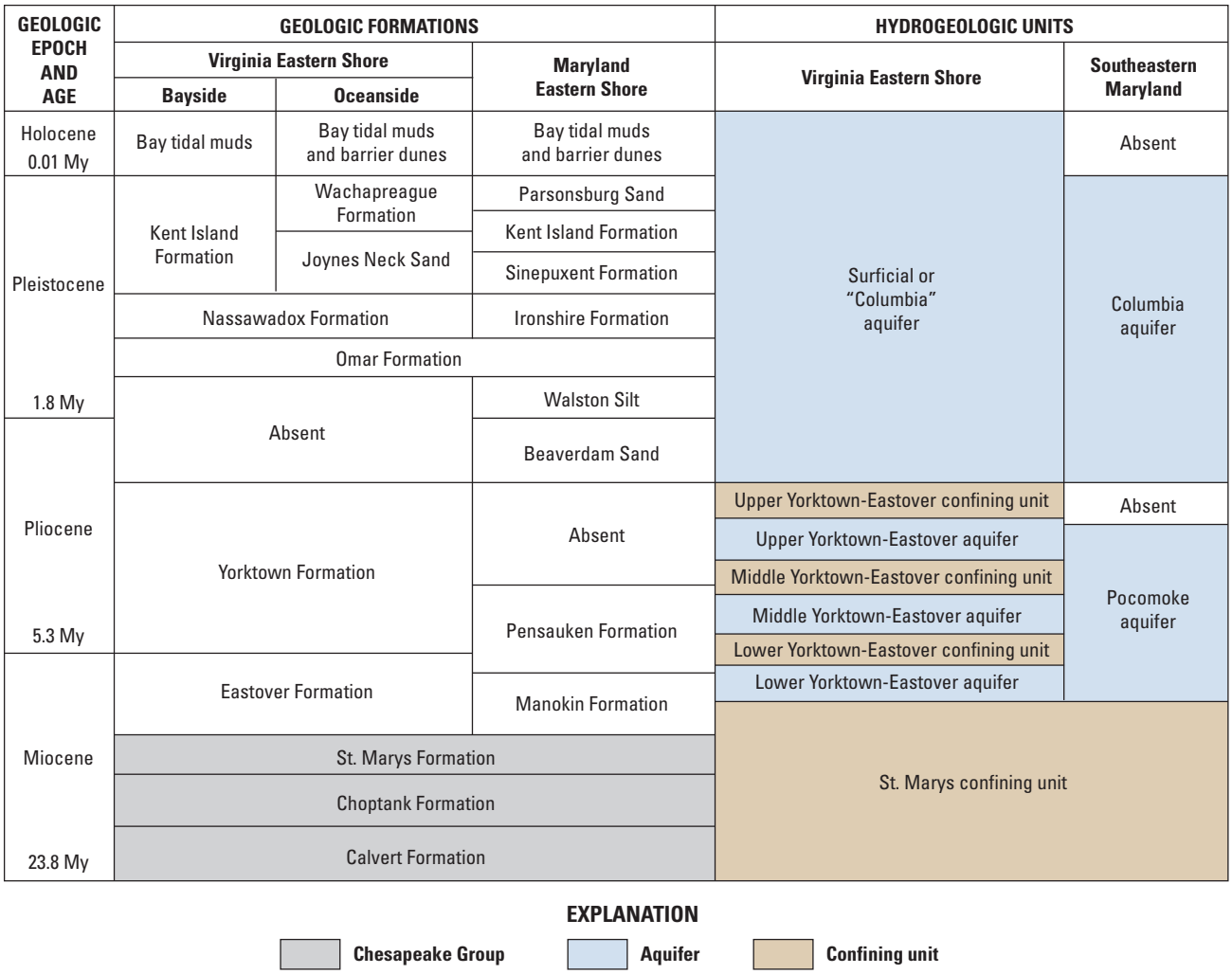


Figure 4. Hydrostratigraphy of the Cenozoic sediments of the Eastern Shore of Virginia and Maryland.
[Information compiled from Owens and Denny, 1979; Mixon, 1985; and Richardson, 1994; My, millions of years]

Hydrogeologic Setting

The Eastern Shore is part of the Atlantic Coastal Plain that contains a regional groundwater flow system in Virginia (McFarland and others, 2006; Heywood and Pope, 2009), within which the Eastern Shore makes up a more local flow system. Sediments beneath the Eastern Shore have been divided on the basis of hydrologic properties into a layered sequence of aquifers and confining units in a nearly identical form to that of Richardson (1994). The aquifers consist of predominantly sand- and gravel-size material of sufficient saturated thickness to yield substantial quantities of water. The confining units consist of predominantly very fine sand, silt, and clay; are generally continuous across the Shore (except where eroded by paleochannels); and yield little water and retard its movement. The aquifers often contain some interbedded clay and silt, and the confining units often contain some interbedded sand or gravel. The hydrogeologic framework used here has been delineated by correlating lithologic and geophysical logs and by analyzing water-quality and water-level data. Additional descriptions of the data sources used to create this framework are described in Richardson (1994). The framework from Richardson (1994) was adopted for this study because few additional data have become available since that time and because resources were not available to collect additional hydrogeologic data.

The hydrogeologic framework for this study includes a surficial (unconfined) aquifer, a series of three confined aquifers and confining layers, and a basal confining unit. The surficial aquifer was referred to as the Columbia aquifer in Richardson (1994), but because correlations with Maryland stratigraphy suggest the surficial aquifer on the Eastern Shore does not exactly correlate with the Columbia aquifer of southern Maryland (Owens and Denny, 1979; Bachman and Wilson, 1984), the unconfined aquifer in this study is referred to as the "surficial" aquifer. The confined aquifers are shallower than approximately 300 ft and are called the upper, middle, and lower Yorktown-Eastover aquifers and confining units. The basal confining unit in this study is called the St. Marys confining unit. Hydraulic conductivity values for aquifers discussed in this section refer predominantly to values of horizontal conductivity, unless otherwise noted.

Surficial Aquifer

The surficial aquifer is unconfined throughout the Eastern Shore and overlies the upper Yorktown-Eastover confining unit. The surficial aquifer is present throughout the study area (fig. 5), and the base is found between depths of 0 to 100 ft below sea level. The thickness ranges from approximately 1 to 80 ft. The surficial aquifer consists primarily of sediment from the Pleistocene formations, which lithologically have a wide range in composition. The aquifer sediments have been characterized by Sinnott and Tibbitts (1968) as mainly yellow sand and sandy clay, with minor lenses and beds of gravel. The water table makes a surficial expression in this aquifer as the small ponds and streams throughout the Eastern Shore. The aquifer historically has provided sufficient quantities of water for domestic and agricultural needs. Based on this general information, it is expected that hydraulic conductivity values in the surficial aquifer vary between approximately 1 and 100 feet per day (ft/d). The water quality in the aquifer can be poor in low-lying areas because of the local proximity of saltwater bodies. In recent decades, the water quality in the upland areas has been degraded by the increasing levels of nitrate from agricultural sources.

Paleochannel Aquifers

Evidence has continued to accumulate for the presence of subsurface erosional channels where all or part of the Yorktown Formation sediments have been removed and replaced by marginal-marine deposits of Pleistocene age. The sediments within these paleochannels are of a different type than those of the Yorktown Formation that they replace. The major paleochannels have been described by Mixon (1985) and D.S. Powars (U.S. Geological Survey, written communication, 2003). Two major channels are present onshore and affect this study—the Exmore channel to the north and the Eastville channel to the south (fig. 6). Although the Cape Charles channel is present in the area, the majority of it lies just offshore at the southern end of the peninsula. The Exmore channel is estimated to be more than 160 ft deep, and the Eastville channel is more than 120 ft deep. Their thicknesses in the central Eastern Shore are approximately 100 ft and 60 ft, respectively. The exact spatial configuration of these channels is not known in detail. Figure 12 shows approximate locations of the edges of the channels and approximate thicknesses of the deposits within them.

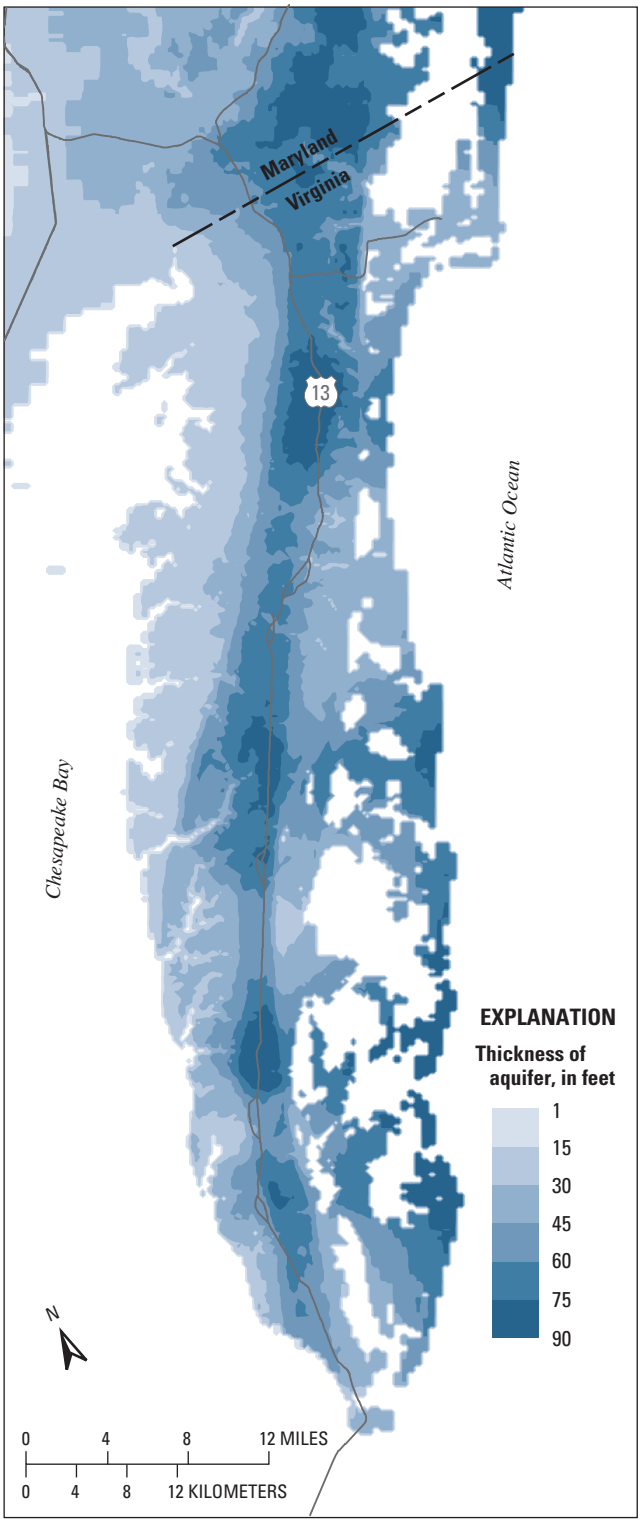


Figure 5. Thickness of the surficial aquifer of the Eastern Shore of Virginia. [Data from Richardson, 1994]

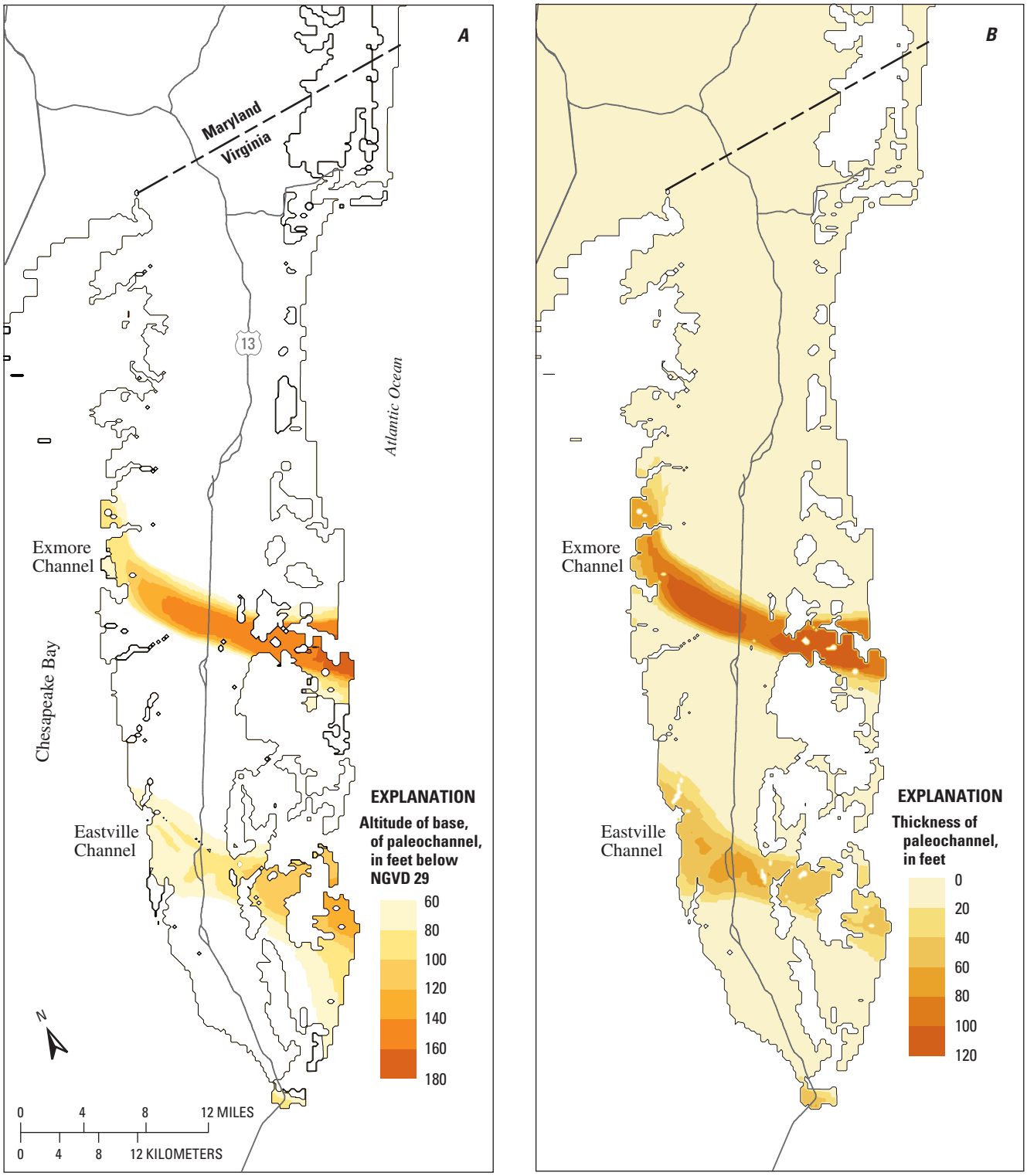


Figure 6. *(A)* Altitude of the base of and *(B)* thickness of the paleochannels of the Eastern Shore of Virginia. [Data from Richardson, 1994]

Upper Yorktown-Eastover Confining Unit and Aquifer

The upper Yorktown-Eastover confining unit underlies the surficial aquifer. The upper Yorktown-Eastover confining unit is present throughout the study area (fig. 7), and the base is found between depths of approximately 0 and 200 ft below sea level. The upper confining unit is typically somewhat thicker than the middle or lower unit, with thicknesses that range from approximately 1 to 120 ft. The hydraulic conductivity of the lower Yorktown-Eastover confining unit has not been measured in the field because typically wells are not completed within this unit, although one value of 1×10^{-5} ft/d has been reported from a core (Richardson, 1994). The characteristics and extent of these units in the offshore areas are unknown.

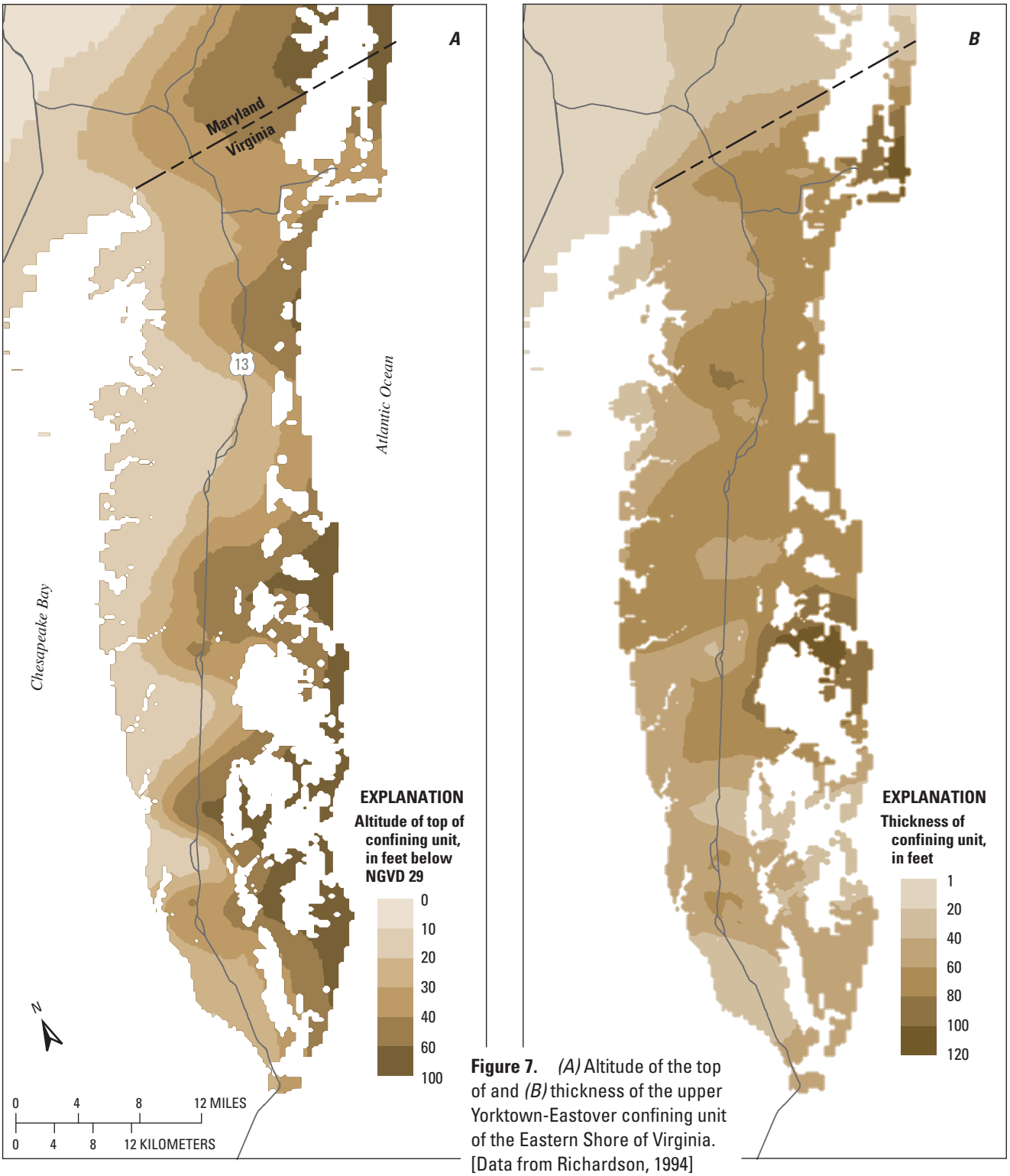


Figure 7. *(A)* Altitude of the top of and *(B)* thickness of the upper Yorktown-Eastover confining unit of the Eastern Shore of Virginia. [Data from Richardson, 1994]

The upper Yorktown-Eastover aquifer underlies the upper Yorktown-Eastover confining unit. The upper Yorktown-Eastover aquifer is present throughout the study area (fig. 8), and the base is found between depths of 0 to 300 ft below sea level. The thickness ranges from approximately 1 to 120 ft. Hydraulic conductivities of the lower aquifer have been reported from between 3.3 and 60.4 ft/d (Richardson, 1994). The upper Yorktown-Eastover aquifer, like the middle Yorktown-Eastover aquifer, primarily consists of sediment from the Yorktown Formation; therefore, the upper and middle Yorktown-Eastover aquifers have similar reported values of hydraulic conductivity.

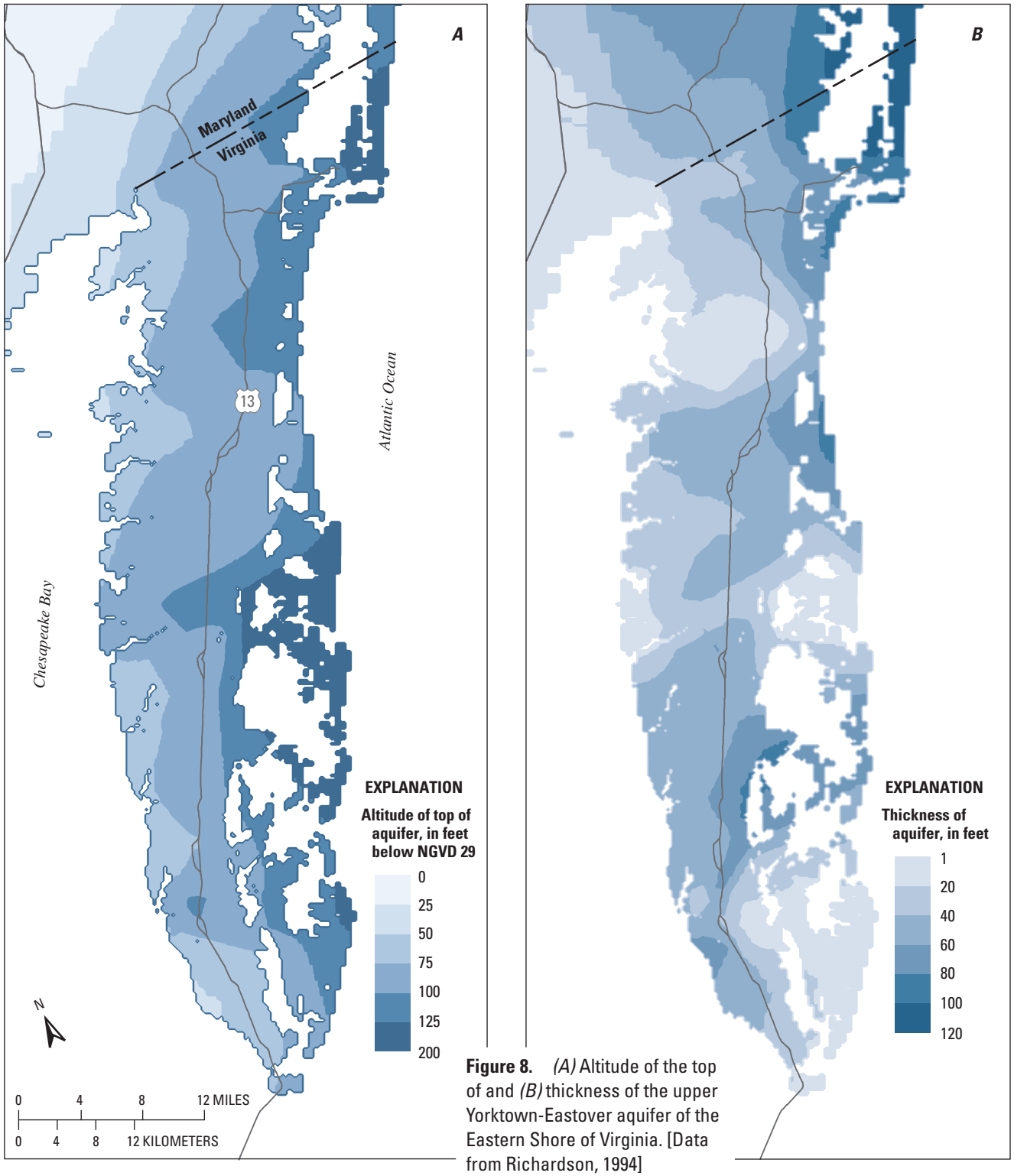


Figure 8. *(A)* Altitude of the top of and *(B)* thickness of the upper Yorktown-Eastover aquifer of the Eastern Shore of Virginia. [Data from Richardson, 1994]

Middle Yorktown-Eastover Confining Unit and Aquifer

The middle Yorktown-Eastover confining unit underlies the upper Yorktown-Eastover aquifer. The middle Yorktown-Eastover confining unit is present throughout the study area (fig. 9), and the base is found between depths of 80 and 350 ft below sea level. The thickness ranges from approximately 1 to 80 ft. The hydraulic conductivity of the middle Yorktown-Eastover confining unit has not been measured in the field because typically wells are not completed within this unit. The characteristics and extent of these middle Yorktown-Eastover units in the offshore areas are unknown.

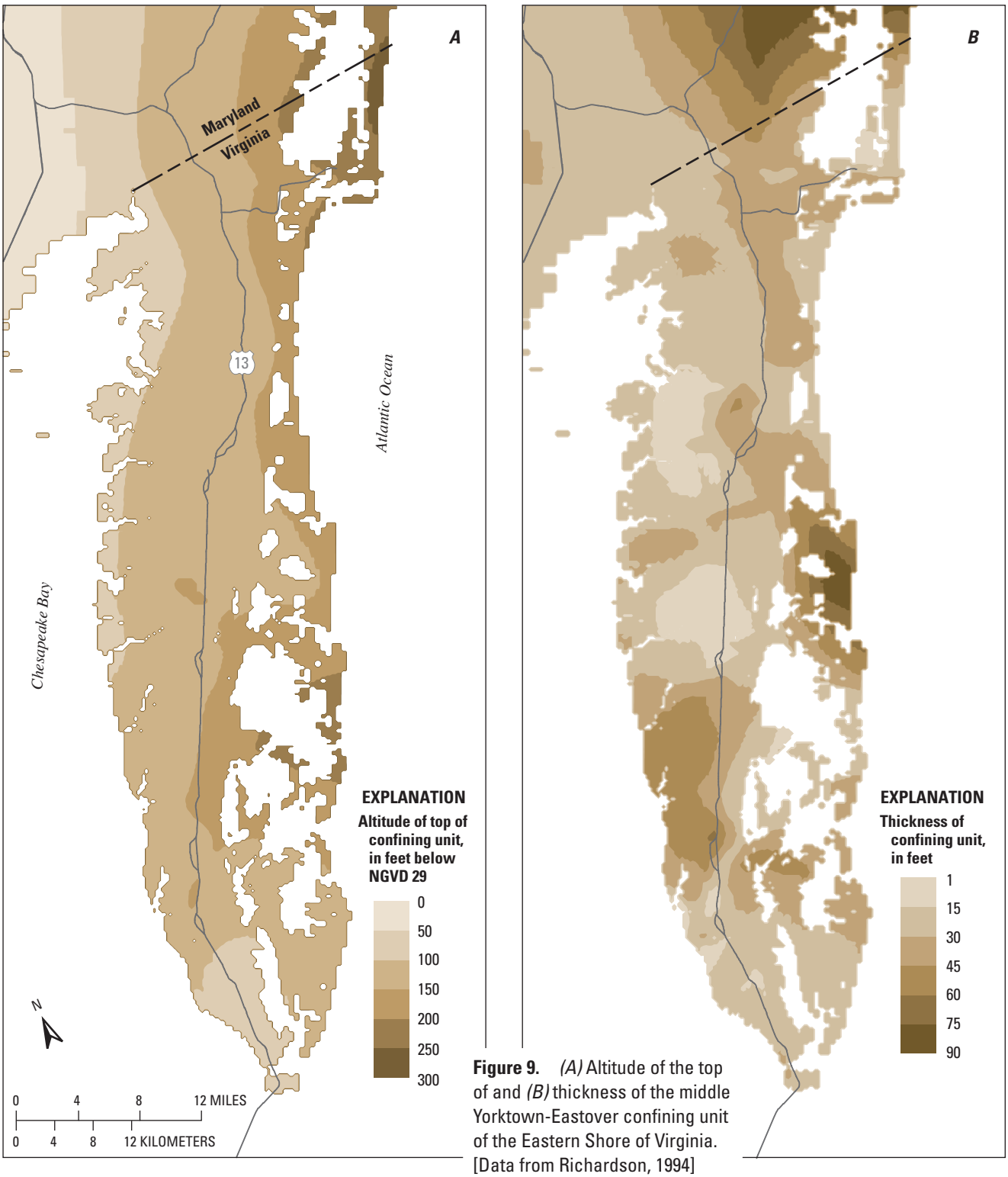


Figure 9. *(A)* Altitude of the top of and *(B)* thickness of the middle Yorktown-Eastover confining unit of the Eastern Shore of Virginia. [Data from Richardson, 1994]

The middle Yorktown-Eastover aquifer underlies the middle Yorktown-Eastover confining unit. The middle Yorktown-Eastover aquifer is present throughout the study area (fig. 10), and the base is found between depths of 100 to 400 ft below sea level. The thickness ranges from approximately 10 to 80 ft. Hydraulic conductivities of the middle aquifer have been reported from between 4.2 and 44.3 ft/d (Richardson, 1994).

The middle Yorktown-Eastover aquifer primarily consists of sediment from the Yorktown formation. Because the Yorktown Formation can have a wide range of sediment sizes between silt and gravels, the middle Yorktown-Eastover aquifer can have hydraulic conductivity values that vary by an order of magnitude or more across the Eastern Shore.

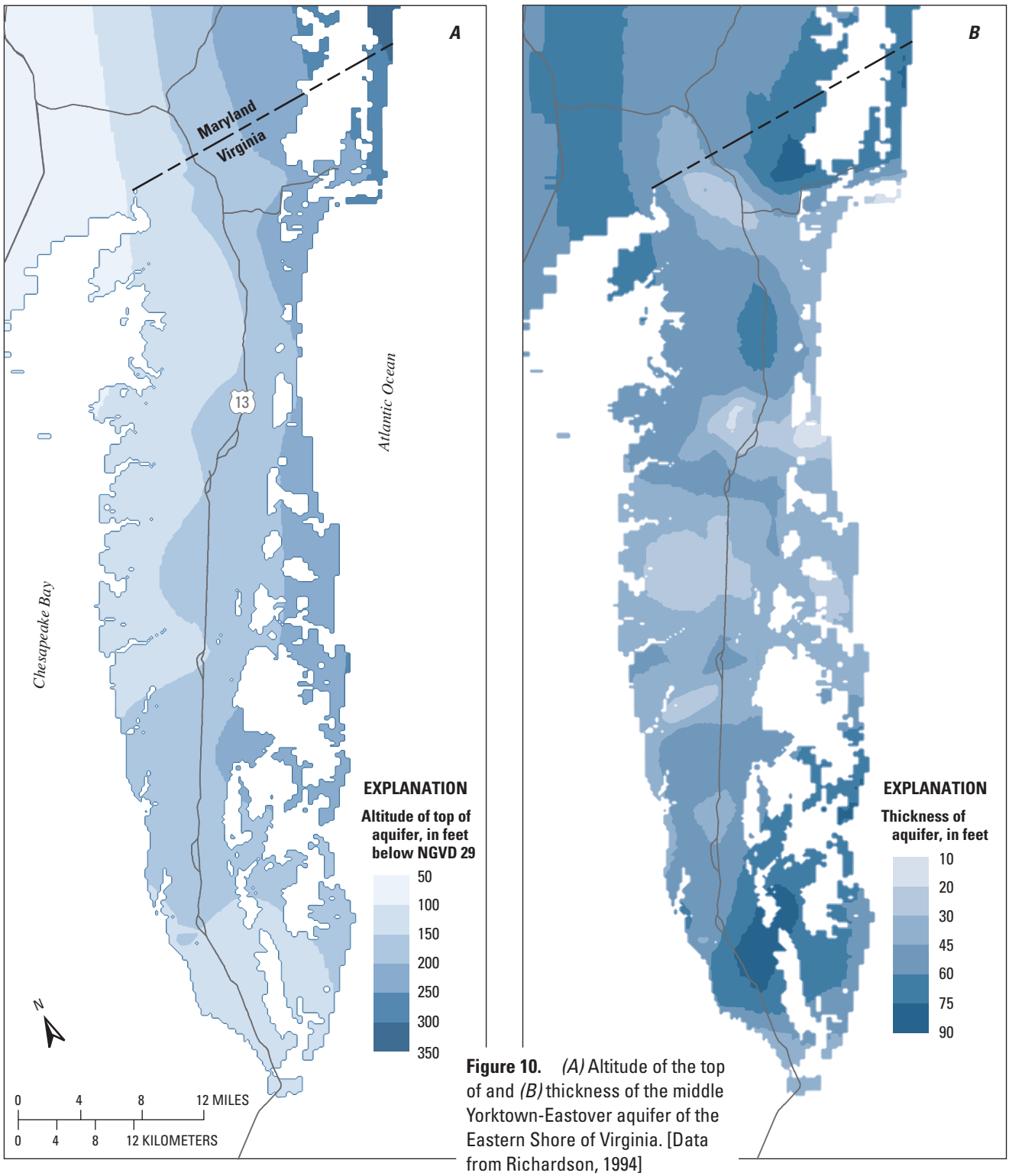


Figure 10. *(A)* Altitude of the top of and *(B)* thickness of the middle Yorktown-Eastover aquifer of the Eastern Shore of Virginia. [Data from Richardson, 1994]

Lower Yorktown-Eastover Confining Unit and Aquifer

The lower Yorktown-Eastover confining unit underlies the middle Yorktown-Eastover aquifer. The lower Yorktown-Eastover confining unit is present throughout the study area (fig. 11) and the base is found between depths of 100 and 450 feet below sea level. The thickness ranges from approximately 5 to 80 ft. The hydraulic conductivity for the lower Yorktown-Eastover confining unit has not been measured in the field because typically wells are not completed within this unit. The characteristics and extent of the lower Yorktown-Eastover units in the offshore areas are unknown.

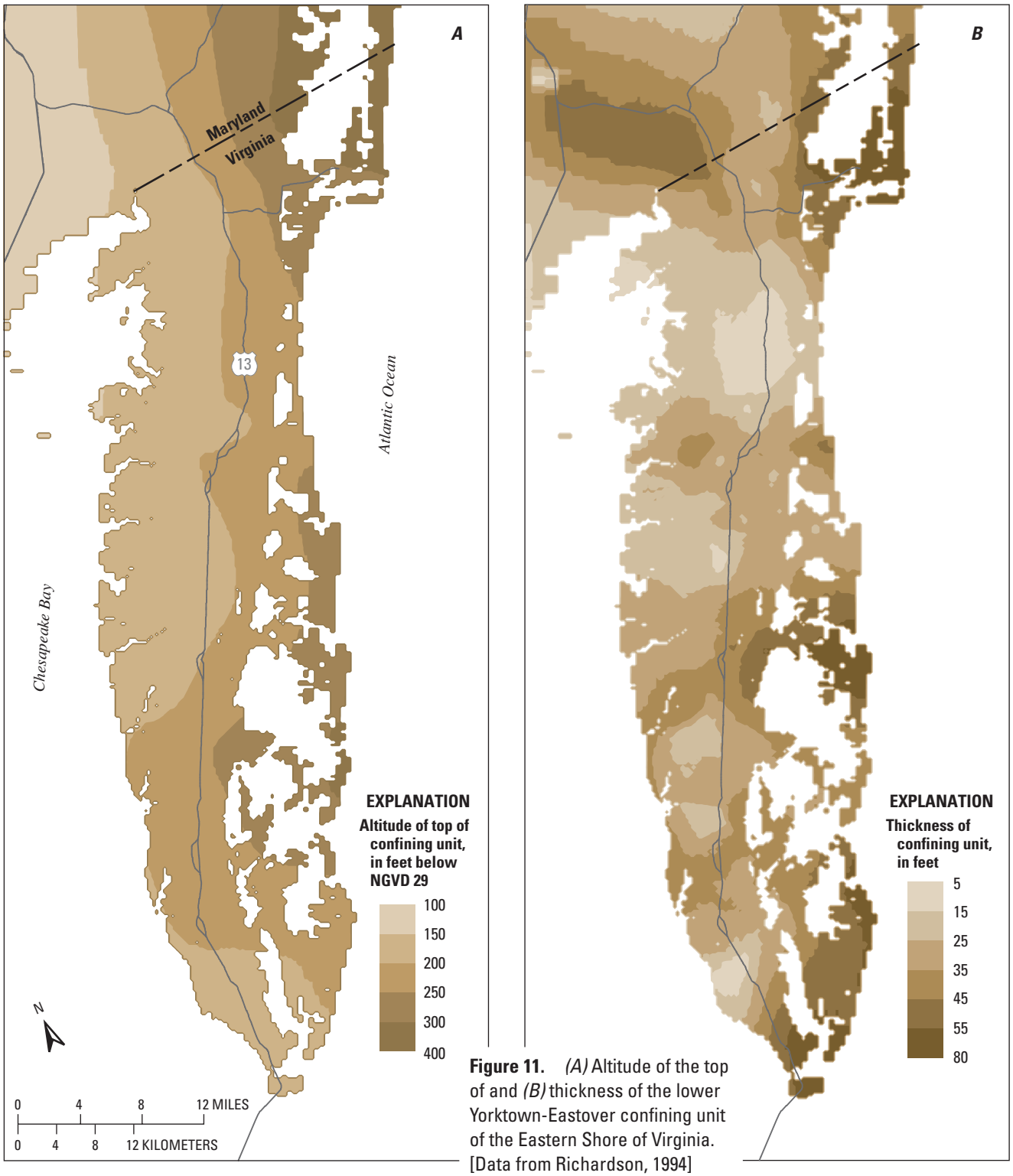


Figure 11. *(A)* Altitude of the top of and *(B)* thickness of the lower Yorktown-Eastover confining unit of the Eastern Shore of Virginia. [Data from Richardson, 1994]

The lower Yorktown-Eastover aquifer underlies the lower Yorktown-Eastover confining unit. The lower Yorktown-Eastover aquifer is present throughout the study area (fig. 12), and the base is found between depths of 150 to 500 ft below sea level. The thickness ranges from approximately 20 to 225 ft. Hydraulic conductivities of the lower aquifer have been reported from between 1.6 and 24.2 ft/d (Richardson, 1994).

The lower Yorktown-Eastover aquifer primarily consists of sediment from the Eastover formation. Because the Eastover Formation typically has finer-grained sediments than the Yorktown Formation, the lower Yorktown-Eastover aquifer typically has lower hydraulic conductivity values than the middle and upper Yorktown-Eastover aquifers.

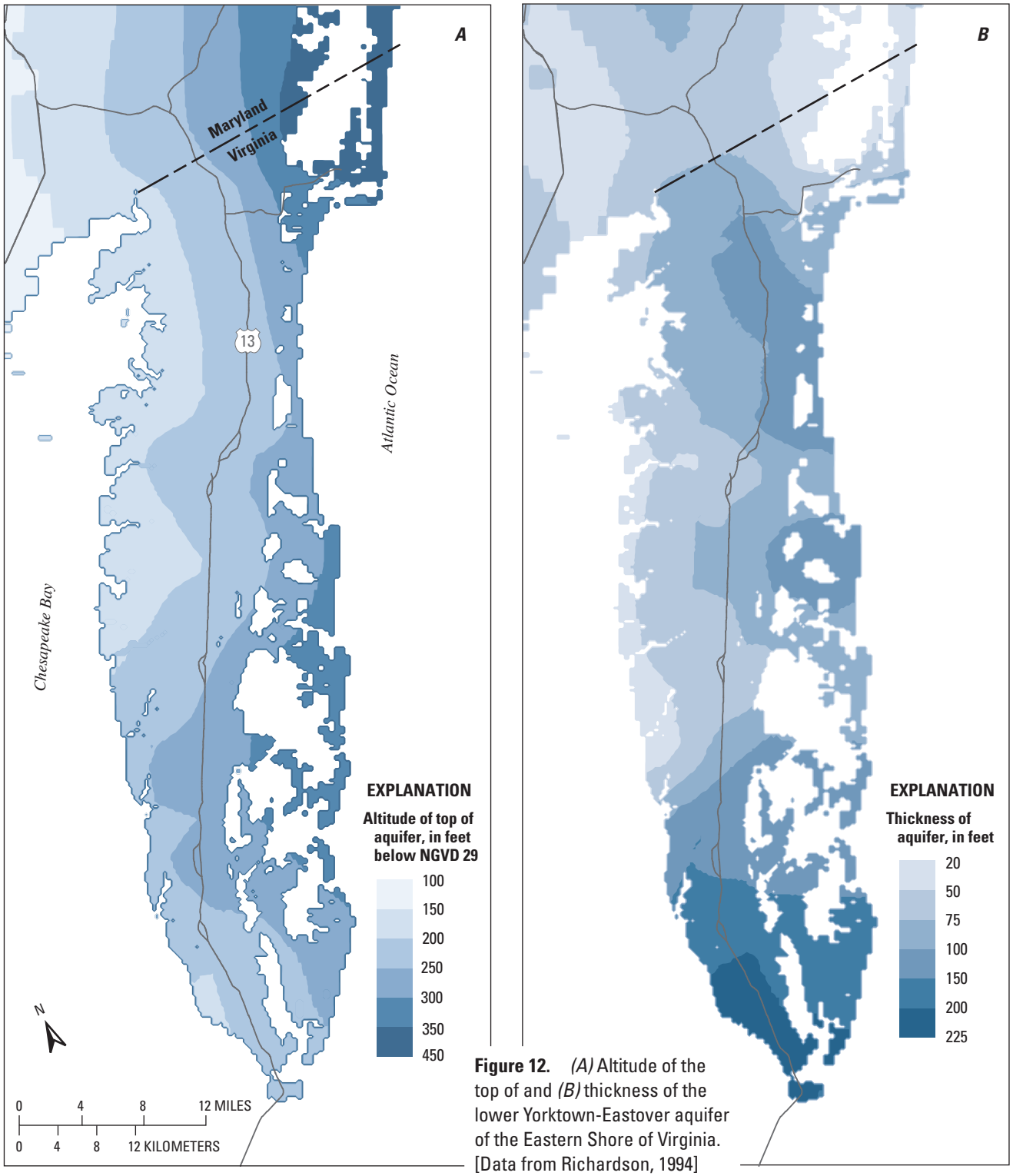


Figure 12. *(A)* Altitude of the top of and *(B)* thickness of the lower Yorktown-Eastover aquifer of the Eastern Shore of Virginia. [Data from Richardson, 1994]

St. Marys Confining Unit

The St. Marys confining unit in this study area consists of the clayey facies of the St. Marys Formation and the lower sandy, silty, and clayey facies of the Eastover Formation. The sediments are all Miocene in age and are conformably overlain throughout the study area by the lower Yorktown-Eastover aquifer. Laboratory analyses of sediment cores from the St. Marys Formation indicate vertical hydraulic conductivities of approximately 1×10^{-5} ft/d (Richardson, 1994). The St. Marys confining unit thickness across the study area ranges from approximately 50 to 400 ft. This massive clay-rich unit is effectively the lower boundary of the fresh groundwater-flow system of the Eastern Shore (fig. 13).

Hydrologic Setting

The hydrologic cycle of the Eastern Shore is similar to that of most humid climatic coastal environments. Rainfall on the Eastern Shore is approximately 43 inches per year (in/yr). Part of this rainfall runs off to streams and the rest infiltrates into the soil zone. Runoff on the Eastern Shore is low, as evidenced by the small number and size of streams on the peninsula. Typically in humid climates, about two-thirds of the water is lost to evapotranspiration (either direct evaporation to the atmosphere or transpiration by the plants), and the remaining one-third either runs off or percolates down to the water table as groundwater recharge. On the Eastern Shore there is very little runoff, so about one-third of precipitation (12–15 in/yr) likely is recharge. This recharged groundwater slowly migrates toward the lowlands where it discharges into streams or coastal bays. This migration typically takes years to decades in an unconfined groundwater system, but centuries to millennia in a deeper, confined system. At the end of the flow path, some of the water will be intercepted by plant roots in marshes or riparian zones and transpired and, thus, never reach the streams or bays.

As the groundwater approaches the coastal bays, it comes into contact with the brackish water that is present beneath the coastal saltwater bodies. The fresh groundwater entrains some of this salty water with it, and the discharging groundwater will have a dissolved solids content that is elevated above the freshwater content. This constant removal of saltwater by the freshwater circulation causes a slow migration of saltwater landward to replace the saltwater that is being entrained.

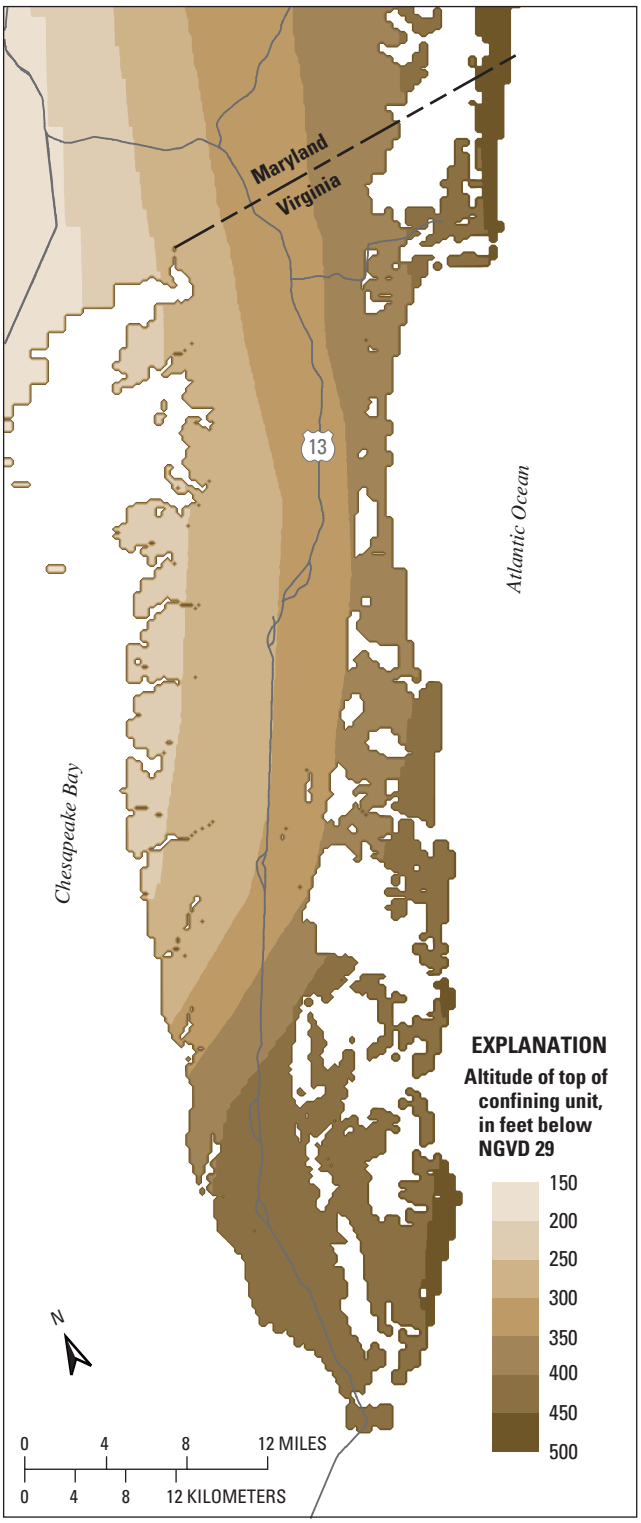


Figure 13. Altitude of the top of the St. Marys confining unit of the Eastern Shore of Virginia. [Data from Richardson, 1994]

Groundwater Hydrology

On the Eastern Shore, the groundwater-flow system can be illustrated in a schematic diagram such as the one shown in figure 14. Much of the freshwater recharge occurs in the central upland of the peninsula, moving into the surficial aquifer system. Using an average value of recharge of 12 in/yr over the area of the Eastern Shore of 450 square miles will yield an estimated natural recharge to the system of about 250 millions of gallons per day (Mgal/d) (Richardson, 1994). Groundwater flows mostly laterally from the central upland and discharges along the coastal bays (Speiran, 1996), but a small percentage will move vertically downward through the upper Yorktown-Eastover confining unit into the upper Yorktown-Eastover aquifer. Much of this water will flow laterally and then either discharge directly to the Chesapeake Bay or ocean, or migrate vertically back upward across the confining unit along the coast and discharge into the coastal bays. A small percentage of the water in the upper Yorktown-Eastover aquifer will move vertically downward into the middle aquifer, and similarly from the middle aquifer down to the lower aquifer. The fraction of any water that migrates to a lower aquifer is dependent on the vertical permeability or leakance of the intervening confining unit. Water in the middle and lower aquifers eventually migrates vertically back upward across the confining layers to ultimately discharge to the coastal bays along with the shallower circulating water.

Natural water levels in the wells across the Eastern Shore reflect the flow system described above. Water levels in the central upland area are higher than those at the coast. Also, in the central upland, water levels in the upper aquifers are higher than those in the lower aquifers. In contrast, along the coast, water levels in the lower aquifers are slightly higher than those in the upper aquifers. Some of the water in the aquifers does discharge to the coastal bays but is intercepted by withdrawal wells. Water levels in the aquifers decline around pumping wells in what are known as "cones of depression." These declining water levels are observed in wells, as it is the pressure in the aquifer that is declining, not the water table. Areas with large pumping can create water levels in wells that drop below sea level by tens of feet. This can, over long periods of time, lead to incursion of salty groundwater from the offshore areas. Examples of this magnitude of water-level decline can be seen in observation wells on the Eastern Shore (fig. 15). If pumping is stopped or greatly curtailed, however, water levels can recover to near prepumping levels as illustrated by the cessation of pumping near well SOW 161 in the early 1990s (fig. 15*C*).

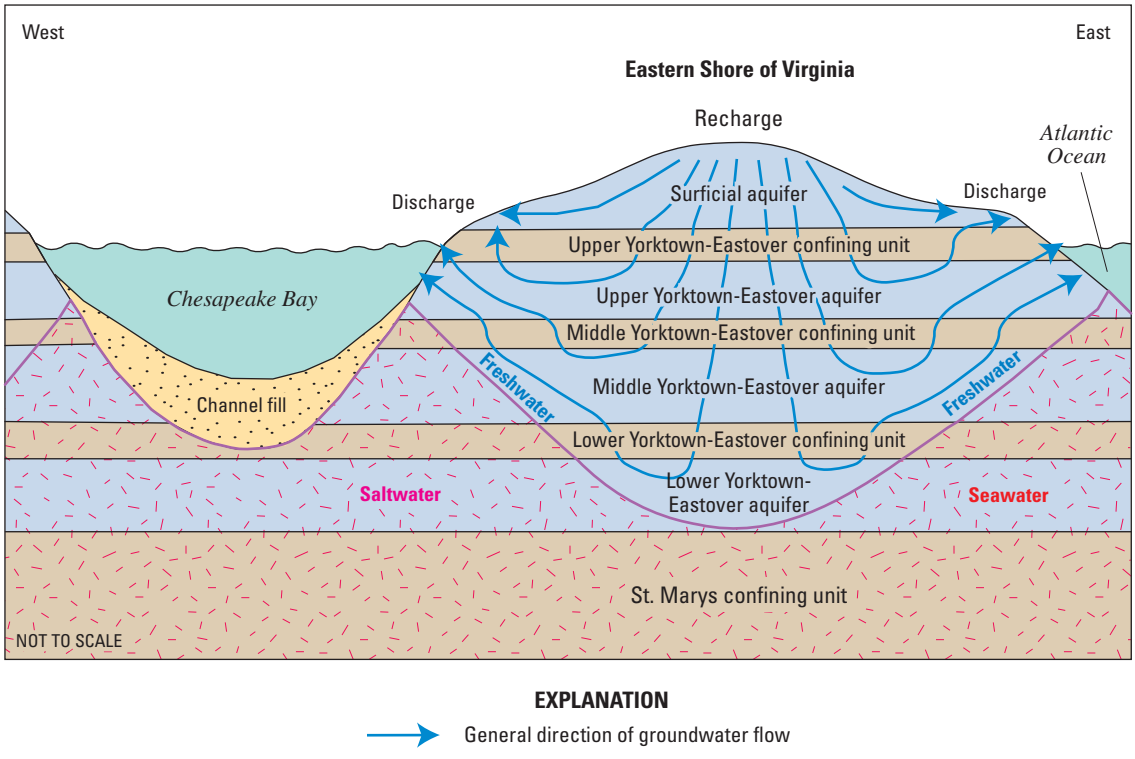


Figure 14. Schematic diagram of groundwater flow of the Eastern Shore of Virginia.

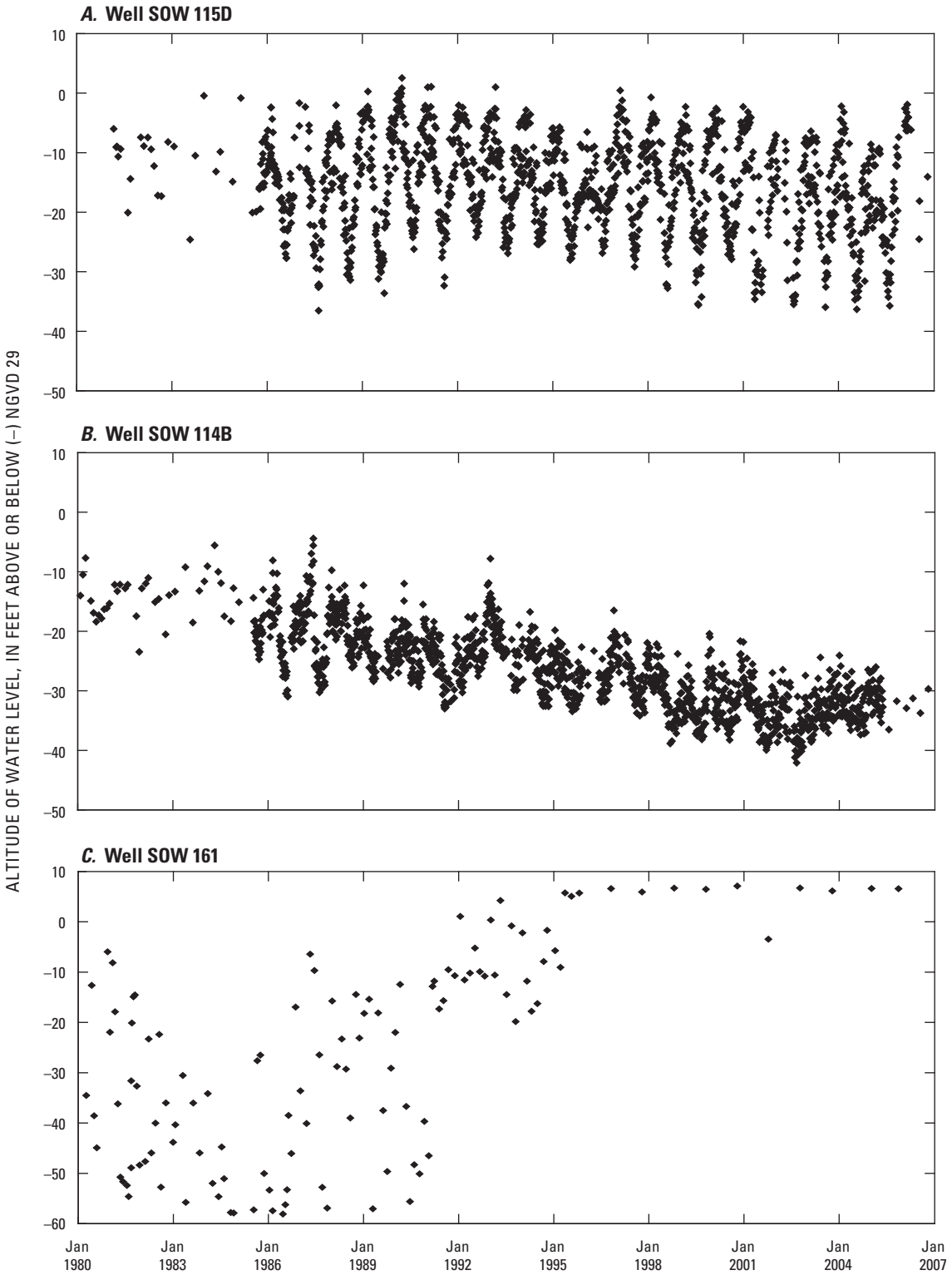


Figure 15. Groundwater levels in the Middle Yorktown-Eastover aquifer near *(A)* Chincoteague, *(B)* Accomac, and *(C)* Oyster, Virginia. See figure 3 for well locations.

Groundwater Chemistry

Dissolved chemical constituents in the groundwater can act as natural environmental tracers and provide valuable information on the source and movement of water. In September and October 2003, 51 wells across the Eastern Shore were sampled for groundwater chemistry. A summary of the results from this sampling is given by aquifer in table 1 and by individual well in table 2. In order to determine if saltwater intrusion was occurring, chloride was measured in these wells and compared to wells that were sampled in the early 1980s (Richardson, 1994). Chloride is used as an indicator of saltwater intrusion because it tends to be the most conservative (nonreactive) of the dissolved ions. The current U.S. Environmental Protection Agency (USEPA) guideline for the upper limit for chloride in drinking water is 250 mg/L. Some wells have had a slight increase in chloride, but others a slight decrease from the early 1980s to 2003. On average the upper and middle Yorktown-Eastover aquifer show a slight increase, but the lower aquifer shows a slight decrease. Overall, the lack of a significant increase in average chloride concentrations since the early 1980s suggests saltwater intrusion is not currently a widespread problem on the Eastern Shore, although there still may be local problems.

Table 1. Average values of chemical consituents in the groundwater of the Eastern Shore of Virginia by aquifer, 2003, calculated from data collected during this study.

[ft, feet; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; nmol/L, nanomoles per liter; Ca, calcium; Mg, magnesium; Sr, strontium; Na, sodium; K, potassium; Cl, chlorine; SO_4, sulfate; HCO_3, bicarbonate; NO_3, nitrate; TU, tritium units; $\delta^{18}O$, oxygen-18; per mil, parts per thousand; $\delta^{2}H$, deuterium; $\delta^{13}C$, carbon-13; ^{14}C, carbon-14; pmC, percent modern carbon; yrs, years; N/A, not available]

Preperty/constituent measured from well	Surficial aquifer	Upper Yorktown-Eastover aquifer	Middle Yorktown-Eastover aquifer	Lower Yorktown-Eastover aquifer
Well depth (ft)	33	142	227	301
Temperature (°C)	17.2	16.2	16.5	16.8
Specific conductance (µS/cm)	289	412	709	2,952
Dissolved oxygen (mg/L)	.8	.14	.22	.24
pH	5.9	7.8	8	7.8
Helium (nmol/L)	3	33	41	108
Ca (mg/L)	28	36	21	32
Mg (mg/L)	5	9	12	32
Sr (mg/L)	.19	.28	.27	1.03
Na (mg/L)	15	31	109	526
K (mg/L)	3	8	13	26
Cl (early 1980s)	47	20	89	637
Cl (2003)	47	33	110	575
SO_4 (mg/L)	35	26	11	26
HCO_3 (mg/L)	51	156	249	331
NO_3 (mg/L)	23	1	3	2
Tritium (TU)	3.6	.2	.6	.3
$\delta^{18}O$ (per mil)	–5.9	–5.9	–5.6	–5.3
$\delta^{2}H$ (per mil)	–33.2	–33.3	–31.1	–29.2
Recharge temperature (°C)	13.5	8.3	7.3	5.9
$\delta^{13}C$ (per mil)	–17.0	–12.0	–11.3	–11.2
^{14}C, in pmC	81.2	28.3	15.5	5.3
Raw ^{14}C age (yrs)	N/A	11,400	20,900	26,100
Adjusted ^{14}C age (yrs)	N/A	4,500	9,700	13,900

Table 2. Major ion chemistry, dissolved gases, and isotopes collected from wells across the Eastern Shore of Virginia. Samples collected by USGS personnel and analyzed at USGS laboratory, Reston, Virginia.

[USGS, U.S. Geological Survey; °, degrees; ', minutes; ", seconds; —, not available; <, less than]

Virginia State well number	USGS well number	Well name	Date collected	Time collected	Latitude (NAD 83)	Longitude (NAD 83)	Well depth (feet below land surface)
SOW 101A	66K 4	Bayly's Neck	9/16/2003	1545	37°43'19"	75°36'55"	152
SOW 101B	66K 3	Bayly's Neck	9/16/2003	1730	37°43'19"	75°36'55"	220
SOW 101C	66K 2	Bayly's Neck	9/16/2003	1700	37°43'19"	75°36'55"	292
SOW 102A	64H 6	Oceanside	9/11/2003	0920	37°29'25"	75°47'03"	154
SOW 102B	64H 7	Oceanside	9/11/2003	1050	37°29'21"	75°47'04"	220
SOW 102C	64H 5	Oceanside	9/11/2003	0930	37°29'21"	75°47'04"	306
SOW 103A	63H 6	PC Kellam	9/11/2003	1445	37°27'05"	75°55'58"	37
SOW 103B	63H 5	PC Kellam	9/11/2003	1655	37°27'05"	75°55'58"	132
SOW 103C	63H 4	PC Kellam	9/11/2003	1515	37°27'06"	75°55'58"	235
SOW 104A	63G 17	Doughty's Grocery	9/17/2003	1045	37°17'09"	75°56'07"	140
SOW 104B	63G 16	Doughty's Grocery	9/17/2003	1110	37°17'09"	75°56'07"	240
SOW 104C	63G 15	Doughty's Grocery	9/17/2003	0945	37°17'09"	75°56'06"	310
SOW 104S	63G 21	Doughty's Grocery	9/17/2003	0900	37°17'09"	75°56'07"	36
SOW 105A	63F 15	Cape Center	9/15/2003	1510	37°13'08"	75°58'34"	130
SOW 105B	63F 17	Cape Center	9/15/2003	1700	37°13'08"	75°58'34"	196
SOW 105C	63F 16	Cape Center	9/15/2003	1445	37°13'08"	75°58'34"	285
SOW 105S	—	Cape Center	9/15/2003	1630	—	—	20
SOW 106A	64K 9	Hack's Neck	9/9/2003	1425	37°38'45"	75°52'24"	37
SOW 106B	64K 8	Hack's Neck	9/9/2003	1620	37°38'45"	75°52'24"	95
SOW 106C	64K 7	Hack's Neck	9/9/2003	1520	37°38'45"	75°52'24"	176
SOW 107A	66L 2	Chessir Brothers	9/10/2003	1515	37°52'25"	75°32'16"	140
SOW 107B	66L 3	Chessir Brothers	9/10/2003	1730	37°52'25"	75°32'16"	206
SOW 107C	66L 1	Chessir Brothers	9/10/2003	1700	37°52'25"	75°32'16"	305
SOW 108A	64K 10	Melfa	9/9/2003	0920	37°39'32"	75°45'26"	50
SOW 108B	64K 11	Melfa	9/9/2003	1100	37°39'32"	75°45'26"	180
SOW 108C	64K 12	Melfa	9/9/2003	1015	37°39'32"	75°45'26"	284
SOW 109B	65K 25	Bayside	10/20/2003	1645	37°44'42"	75°43'24"	228
SOW 109S	65K 26	Bayside	10/20/2003	1615	37°44'42"	75°43'24"	25
SOW 110A	66M 16	Withams	9/8/2003	1430	37°57'23"	75°34'43"	130
SOW 110B	66M 17	Withams	9/8/2003	1400	37°57'23"	75°34'43"	178
SOW 110C	66M 18	Withams	9/8/2003	1155	37°57'23"	75°34'44"	240
SOW 110S	66M 19	Withams	9/8/2003	1015	37°57'23"	75°34'43"	36
SOW 111A	63G 22	Cheriton	9/12/2003	0930	37°16'53"	75°58'47"	150
SOW 111B	63G 23	Cheriton	10/20/2003	1200	37°16'53"	75°58'47"	280
SOW 111C	63G 24	Cheriton	9/12/2003	1000	37°16'53"	75°58'47"	330
SOW 112A	64J 9	Willis' Wharf	10/20/2003	0900	37°30'59"	75°48'44"	135
SOW 112B	64J 10	Willis' Wharf	10/21/2003	1105	37°30'59"	75°48'44"	210
SOW 112C	64J 11	Willis' Wharf	10/21/2003	1000	37°30'59"	75°48'44"	313
SOW 113A	63J 1	Concords Wharf	9/11/2003	1900	37°32'16"	75°54'06"	120
SOW 115E	67M 14	Chincoteague	9/10/2003	1135	37°56'17"	75°27'36"	280
SOW 121	62G15	Brown & Root	10/21/2003	1450	37°15'43"	76°00'33"	190
SOW 181C	66M 25	Jenkin's Bridge	9/8/2003	2030	37°56'10"	75°36'17"	340
SOW 181D	66M 26	Jenkin's Bridge	9/8/2003	1930	37°56'10"	75°36'17"	230
SOW 181E	66M 27	Jenkin's Bridge	9/8/2003	1730	37°56'10"	75°36'17"	30
SOW 182C	63F 53	Kiptopeke	9/15/2003	1130	37°08'08"	75°57'07"	220
SOW 182D	63F 54	Kiptopeke	9/15/2003	1050	37°08'08"	75°57'07"	60
SOW 182E	63F 55	Kiptopeke	9/15/2003	0935	37°08'08"	75°57'07"	20
SOW 183A	65K 59	Accomac	9/16/2003	1015	37°43'14"	75°40'13"	285
SOW 183B	65K 60	Accomac	9/16/2003	1150	37°43'14"	75°40'13"	235
SOW 183C	65K 61	Accomac	9/16/2003	1130	37°43'14"	75°40'13"	135
SOW 183D	65K 62	Accomac	9/16/2003	0930	37°43'14"	75°40'13"	20

Table 2. Major ion chemistry, dissolved gases, and isotopes collected from wells across the Eastern Shore of Virginia. Samples collected by USGS personnel and analyzed at USGS laboratory, Reston, Virginia.—Continued

[USGS, U.S. Geological Survey; °, degrees; ', minutes; ", seconds; —, not available; <, less than]

Virginia State well number	Screen interval (feet below land surface)	Temperature (degrees Celsius)	Specific conductance (microsiemens)	Dissolved oxygen (milligram per liter)	pH	Helium (nanomol per liter)
SOW 101A	144–154	16.6	237	0.1	8.0	4.7
SOW 101B	212–222	16.8	240	0.1	8.0	3.8
SOW 101C	284–294	16.2	605	0.2	7.6	32.1
SOW 102A	144–154	16.7	519	0.1	7.8	26.6
SOW 102B	210–220	16.8	1,671	0.2	8.0	74.8
SOW 102C	296–306	17.4	7,070	0.3	7.5	228.1
SOW 103A	27–37	16.2	417	0.6	5.6	3.4
SOW 103B	122–132	15.9	435	0.2	7.4	3.1
SOW 103C	225–235	17.4	1,136	0.2	8.1	50.1
SOW 104A	130–140	15.8	277	0.2	7.6	3.2
SOW 104B	230–240	16.3	249	0.1	8.1	3.8
SOW 104C	300–310	16.7	631	0.3	8.2	38.4
SOW 104S	26–36	17.1	228	5.1	5.4	2.4
SOW 105A	120–130	16.7	416	0.2	8.0	2.8
SOW 105B	186–196	16.5	310	0.1	8.3	29.1
SOW 105C	275–285	16.2	887	0.2	8.7	177.6
SOW 105S	—	18.8	243	0.1	6.0	2.7
SOW 106A	17–37	16.0	837	0.2	6.0	5.5
SOW 106B	85–95	16.4	1,072	0.1	7.5	19.3
SOW 106C	166–176	16.3	1,709	0.3	7.5	51.1
SOW 107A	130–140	15.3	246	0.1	7.5	2.3
SOW 107B	196–206	15.9	227	0.1	8.0	3.5
SOW 107C	300–310	17.2	333	0.5	7.8	9.1
SOW 108A	40–50	14.9	386	0.1	5.4	2.2
SOW 108B	170–180	16.4	213	0.1	8.0	3
SOW 108C	274–284	16.6	274	0.4	7.8	4.4
SOW 109B	218–228	15.7	418	0.2	8.4	25.6
SOW 109S	15–25	17.8	247	0.3	6.4	3
SOW 110A	120–130	15.8	410	0.4	7.7	9.2
SOW 110B	168–178	16.1	839	0.2	8.2	17.3
SOW 110C	230–240	16.1	3,429	0.3	7.8	58.3
SOW 110S	26–36	14.8	104	0.4	4.9	3.2
SOW 111A	140–150	17.2	290	0.1	8.0	2.7
SOW 111B	270–280	16.2	301	0.4	8.0	9.1
SOW 111C	320–330	17.5	2,339	0.2	7.5	146.1
SOW 112A	125–135	15.6	403	0.1	7.8	3.7
SOW 112B	200–210	16.0	446	0.2	8.2	27.2
SOW 112C	303–313	17.5	5,830	0.2	7.5	199.4
SOW 113A	110–120	15.7	220	0.2	7.1	7.8
SOW 115E	260–280	17.1	828	0.6	7.9	27.9
SOW 121	80–130	15.9	835	0.1	8.1	372
SOW 181C	330–340	17.4	7,906	0.1	7.6	133.7
SOW 181D	220–230	16.5	1,487	0.3	7.9	37.4
SOW 181E	20–30	15.9	155	0.4	5.4	3.7
SOW 182C	210–220	16.6	673	0.1	8.8	278.1
SOW 182D	45–55	16.9	336	0.1	8.1	3.4
SOW 182E	10–20	19.4	390	0.2	6.0	2.7
SOW 183A	275–285	16.1	489	0.1	8.0	61.9
SOW 183B	225–235	15.9	248	0.1	7.6	4.2
SOW 183C	124–134	17.4	204	0.1	8.2	3.4
SOW 183D	15–20	20.1	380	0.7	6.1	3.1

Table 2. Major ion chemistry, dissolved gases, and isotopes collected from wells across the Eastern Shore of Virginia. Samples collected by USGS personnel and analyzed at USGS laboratory, Reston, Virginia.—Continued

[USGS, U.S. Geological Survey; °, degrees; ', minutes; ", seconds; —, not available; <, less than]

Virginia State well number	Calcium	Magnesium	Strontium	Silica	Sodium	Potassium	Ferris iron	Silicon
	Milligrams per liter							
SOW 101A	26.4	7.81	0.230	22.0	6.40	5.1	0.11	10.3
SOW 101B	23.9	9.96	0.207	23.5	7.17	8.6	0.10	11.0
SOW 101C	30.6	14.7	0.334	24.0	62.4	13.1	0.07	11.2
SOW 102A	13.8	12.3	0.183	38.5	61.4	19.1	0.36	18.0
SOW 102B	11.7	18.4	0.370	15.6	306	23.8	0.07	7.27
SOW 102C	36.1	65.1	2.00	14.5	1,390	53.2	0.22	6.79
SOW 103A	41.6	8.01	0.394	13.0	15.1	8.0	<0.02	6.08
SOW 103B	69.4	6.56	0.467	15.9	15.8	1.6	<0.02	7.42
SOW 103C	10.4	7.13	0.166	25.5	272	14.5	<0.05	11.9
SOW 104A	37.5	1.99	0.249	25.5	14.9	1.4	0.19	11.9
SOW 104B	23.0	9.26	0.247	19.0	10.2	7.2	0.12	8.86
SOW 104C	24.5	13.8	0.284	17.3	65.9	12.3	0.08	8.10
SOW 104S	23.3	4.68	0.165	8.58	7.85	1.8	<0.02	4.01
SOW 105A	64.1	2.15	0.325	9.82	13.7	1.1	0.14	4.59
SOW 105B	13.6	1.56	0.086	15.3	55.0	3.4	0.09	7.14
SOW 105C	4.2	2.68	0.043	12.2	194	9.0	0.04	5.71
SOW 105S	16.5	7.08	0.111	6.70	12.7	4.9	1.52	3.13
SOW 106A	21.1	14.5	0.260	33.2	101	2.4	18.5	15.5
SOW 106B	79.7	16.7	0.577	28.9	101	8.0	2.07	13.5
SOW 106C	30.7	26.0	0.411	17.8	276	18.3	0.12	8.34
SOW 107A	17.8	8.69	0.129	30.0	11.1	10.4	2.04	14.0
SOW 107B	28.2	6.14	0.194	27.6	8.82	3.9	0.18	12.9
SOW 107C	29.1	14.5	0.281	19.5	13.7	14.3	0.16	9.13
SOW 108A	42.2	10.0	0.288	11.9	12.7	1.6	4.38	5.55
SOW 108B	32.1	2.90	0.196	30.4	8.48	1.4	0.29	14.2
SOW 108C	24.5	11.8	0.206	18.1	11.5	7.4	0.06	8.44
SOW 109B	8.7	4.84	0.141	17.5	76.9	8.0	0.04	8.16
SOW 109S	36.2	1.82	0.213	19.3	13.4	1.4	0.57	9.03
SOW 110A	17.0	8.42	0.145	43.2	66.8	9.4	0.31	20.2
SOW 110B	6.6	3.67	0.096	17.3	194	7.2	<0.05	8.11
SOW 110C	21.7	26.9	0.871	15.4	609	21.7	0.17	7.20
SOW 110S	3.4	1.83	0.054	20.5	10.5	1.1	1.97	9.57
SOW 111A	24.4	11.7	0.275	23.7	9.88	14.8	0.21	11.1
SOW 111B	23.1	12.0	0.343	19.5	7.32	19.6	0.09	9.12
SOW 111C	36.7	38.9	0.879	14.2	381	33.9	0.18	6.63
SOW 112A	37.9	15.1	0.385	25.7	12.3	14.8	0.46	12.0
SOW 112B	21.7	16.1	0.353	23.1	37.4	15.2	0.08	10.8
SOW 112C	36.5	54.2	1.99	14.7	1,050	38.3	0.40	6.89
SOW 113A	23.5	6.16	0.169	23.7	10.6	4.4	0.81	11.1
SOW 115E	34.8	33.2	0.630	10.2	58.1	30.8	0.22	4.79
SOW 121	38.0	15.4	0.394	17.4	98.2	19.5	0.10	8.14
SOW 181C	88.0	81.9	3.44	15.0	1,400	52.1	10.4	7.02
SOW 181D	36.3	11.0	0.417	12.7	244	13.8	7.63	5.95
SOW 181E	7.3	2.77	0.073	24.0	14.1	1.9	7.42	11.2
SOW 182C	4.3	3.68	0.095	12.0	137	11.4	0.03	5.61
SOW 182D	39.8	2.15	0.224	34.9	21.6	1.1	0.49	16.3
SOW 182E	35.5	5.68	0.176	7.44	25.6	2.2	3.66	3.48
SOW 183A	10.3	4.44	0.157	18.6	89.1	8.3	0.05	8.71
SOW 183B	23.1	9.13	0.224	36.8	7.00	11.3	0.11	17.2
SOW 183C	26.9	3.73	0.167	20.9	7.81	2.2	0.09	9.78
SOW 183D	36.7	5.44	0.183	14.1	20.0	6.7	0.07	6.61

Table 2. Major ion chemistry, dissolved gases, and isotopes collected from wells across the Eastern Shore of Virginia. Samples collected by USGS personnel and analyzed at USGS laboratory, Reston, Virginia.—Continued

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Virginia State well number	Bicarbonate	Chloride	Sulfate	Nitrate	As nitrogen	Bromide	Chloride/bromide mass ratio
	Milligrams per liter						
SOW 101A	132	9.06	0.8	0.98	0.22	<0.05	—
SOW 101B	140	8.02	<0.10	1.16	0.26	<0.05	—
SOW 101C	182	96.4	0.2	2.19	0.49	0.32	301.25
SOW 102A	239	45.7	<0.10	1.03	0.23	0.18	253.89
SOW 102B	332	377	0.24	11.2	2.54	1.87	201.60
SOW 102C	484	2,100	2.3	<0.2	<0.05	7.5	280.00
SOW 103A	19	31.0	70.4	56.5	12.76	0.22	140.91
SOW 103B	94	32.1	108.4	0.94	0.21	0.14	229.29
SOW 103C	401	238	24.8	5.51	1.24	0.87	273.56
SOW 104A	130	21.3	<0.10	0.10	<0.05	0.08	266.25
SOW 104B	123	17.5	0.1	1.21	0.27	0.06	291.67
SOW 104C	131	128	3.1	2.15	0.49	0.44	290.91
SOW 104S	14	20.3	24.6	36.1	8.15	<0.05	—
SOW 105A	89	26.1	90.1	0.10	<0.05	0.10	261.00
SOW 105B	165	13.0	7.2	1.77	0.40	<0.05	—
SOW 105C	400	79.2	5.0	2.43	0.55	0.29	273.10
SOW 105S	54	39.6	7.3	<0.1	<0.05	0.07	565.71
SOW 106A	66	220	4.72	1.11	0.25	<0.05	—
SOW 106B	243	197	22.8	1.39	0.31	0.65	303.08
SOW 106C	300	393	24.5	0.93	0.21	1.24	316.94
SOW 107A	117	9.34	14.8	0.77	0.17	<0.05	—
SOW 107B	130	8.30	1.11	0.69	0.16	<0.05	—
SOW 107C	208	12.9	<0.10	1.18	0.27	<0.05	—
SOW 108A	11	23.9	125	<0.2	<0.05	0.13	183.85
SOW 108B	120	8.08	1.06	0.73	0.16	<0.05	—
SOW 108C	163	9.7	<0.10	1.23	0.28	<0.05	—
SOW 109B	253	12.3	<0.1	<0.2	<0.05	0.06	205.00
SOW 109S	112	15.8	13.7	0.4	0.10	<0.05	—
SOW 110A	252	12.9	<0.1	1.6	0.36	<0.05	—
SOW 110B	476	62.8	3.63	1.9	0.42	0.21	299.05
SOW 110C	508	741	75.5	2.9	0.66	2.20	336.82
SOW 110S	9.0	14.2	15.5	<0.1	<0.05	<0.05	—
SOW 111A	170	6.26	<0.1	1.2	0.27	<0.05	—
SOW 111B	175	6.80	<0.1	<0.2	<0.05	<0.05	—
SOW 111C	266	625	16.8	0.14	0.03	2.25	277.78
SOW 112A	205	18.0	11.3	5.14	1.16	<0.05	—
SOW 112B	212	36.0	<0.1	6.29	1.42	0.13	276.92
SOW 112C	488	1550	0.51	<0.2	<0.05	5.9	262.71
SOW 113A	111	14.3	0.16	<0.1	<0.05	0.05	286.00
SOW 115E	237	144	<0.10	2.76	0.62	0.49	293.88
SOW 121	182	165	3.68	<0.2	<0.05	0.55	300.00
SOW 181C	470	2,370	134	<1	<0.05	6.8	348.53
SOW 181D	328	270	44.0	3.44	0.78	1.50	180.00
SOW 181E	63	17.5	3.70	0.37	0.08	<0.05	—
SOW 182C	299	62.5	1.37	<0.1	<0.05	0.25	250.00
SOW 182D	111	45.5	1.88	1.11	0.25	0.16	284.38
SOW 182E	55	45.8	60.3	5.74	1.30	0.10	458.00
SOW 183A	252	49.0	0.27	2.57	0.58	0.17	288.24
SOW 183B	136	6.70	2.11	1.48	0.33	<0.05	—
SOW 183C	103	8.78	6.85	0.36	0.08	<0.05	—
SOW 183D	69	32.0	24.0	59.2	13.4	<0.05	—

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[USGS, U.S. Geological Survey; °, degrees; ', minutes; ", seconds; —, not available; <, less than]

Virginia State well number	Tritium (tritium units)	Oxygen-18 (parts per thousand)	Deuterium (parts per thousand)	Carbon-14 (percent modern carbon)	Carbon-13 (parts per thousand)	Recharge temperature (degrees Celsius)	Recharge year	Sulfur hexafluoride age (years)
SOW 101A	<0.3	–5.72	–31.9	11.38	–11.72	7.6	—	—
SOW 101B	<0.3	–5.73	–31.9	11.29	–11.55	8.1	—	—
SOW 101C	<0.3	–5.56	–30.7	7.75	–11.82	7.2	—	—
SOW 102A	<0.3	–5.56	–29.9	6.12	–8.89	7.2	—	—
SOW 102B	<0.3	–5.15	–27.9	3.76	–8.26	8.2	—	—
SOW 102C	<0.3	–4.64	–25.1	0.49	–11.45	3.5	—	—
SOW 103A	3.6	–6.02	–33.7	—	—	10.2	1997	7
SOW 103B	7.0	–6.22	–34.3	42.39	–10.79	10.3	—	—
SOW 103C	1.4	–5.48	–29.2	2.89	–8.37	4.1	—	—
SOW 104A	<0.3	–6.04	–33.7	34.78	–13.87	8.0	—	—
SOW 104B	<0.3	–5.96	–32.8	12.59	–12.19	9.5	—	—
SOW 104C	<0.3	–5.86	–32.1	10.65	–11.96	8.4	—	—
SOW 104S	4.0	–6.02	–33.4	106.27	–20.14	14.2	1995	9
SOW 105A	3.0	–6.24	–35.0	27.77	–9.77	12.1	—	—
SOW 105B	<0.3	–5.99	–32.9	12.59	–9.93	10.1	—	—
SOW 105C	<0.3	–5.79	–31.0	2.81	–8.42	5.9	—	—
SOW 105S	5.0	–4.72	–27.6	—	—	23.4	1996	8
SOW 106A	<0.3	–5.72	–32.1	57.22	–15.23	9.8	1980	24
SOW 106B	<0.3	–5.40	–30.5	32.22	–12.76	8.1	—	—
SOW 106C	<0.3	–5.47	–30.4	5.23	–10.85	6.7	—	—
SOW 107A	0.8	–5.86	–34.1	41.07	–14.82	7.3	—	—
SOW 107B	<0.3	–5.86	–34.1	34.48	–13.59	7.8	—	—
SOW 107C	<0.3	–5.39	–31.6	21.47	–13.66	6.4	—	—
SOW 108A	8.5	–6.29	–35.4	—	—	24.4	1987	17
SOW 108B	<0.3	–6.10	–36.2	52.75	–15.66	8.1	—	—
SOW 108C	<0.3	–5.34	–32.4	34.09	–13.51	6.4	—	—
SOW 109B	<0.3	–5.43	–30.7	5.3	–12.64	6.8	—	—
SOW 109S	5.5	–6.14	–35.7	76.24	–17.55	7.9	1981	23
SOW 110A	<0.3	–5.61	–31.9	17.18	–12.44	6.4	—	—
SOW 110B	<0.3	–5.51	–30.2	3.41	–10.24	4.6	—	—
SOW 110C	<0.3	–5.35	–29.3	0.82	–9.77	3.6	—	—
SOW 110S	5.4	–6.13	–35.2	—	—	8.3	1979	25
SOW 111A	<0.3	–5.67	–30.4	11.66	–11.74	9.1	—	—
SOW 111B	<0.3	–5.87	–32.6	6.44	–11.49	8.2	—	—
SOW 111C	<0.3	–5.45	–29.5	3.53	–12.4	7.5	—	—
SOW 112A	2.4	–5.76	–34.6	46.85	–12.11	7.9	—	—
SOW 112B	<0.3	–5.63	–30.8	12.37	–10.42	7.3	—	—
SOW 112C	0.9	–5.00	–26.3	1.11	–11.17	4.2	—	—
SOW 113A	<0.3	–6.16	–36.6	43.5	–13.63	8.3	—	—
SOW 115E	<0.3	–5.39	–28.7	7.89	–12.45	6.6	—	—
SOW 121	<0.3	–5.72	–30.1	7.73	–11.56	8.5	—	—
SOW 181C	<0.3	–4.62	–26.6	1.56	–11.08	5.2	—	—
SOW 181D	1.9	–5.76	–31.1	24.76	–11.03	6.1	—	—
SOW 181E	<0.3	–5.90	–33.3	—	—	8.3	1976	28
SOW 182C	<0.3	–5.41	–27.9	39.78	–13.36	7.9	—	—
SOW 182D	<0.3	–6.12	–34.8	35.71	–13.66	11.1	—	—
SOW 182E	4.6	–5.64	–31.2	—	—	12.0	—	—
SOW 183A	0.5	–5.43	–29.7	3.04	–10.65	6.7	—	—
SOW 183B	<0.3	–6.05	–33.6	20.63	–12.07	7.2	—	—
SOW 183C	<0.3	–6.31	–36.8	20.63	–8.77	7.1	—	—
SOW 183D	5.0	–5.64	–31.7	106.44	–16.81	14.8	1998	6

Other constituent trends with aquifer depth are worth noting. Specific conductance has a strong positive correlation with chloride concentration. As there are no evaporate (halite) beds in the region that might be dissolving, this suggests that saltwater encroachment is the main source of elevated chloride concentrations, where present. The results from the 2003 sampling indicate the chloride in groundwater can be approximated from the following linear regression equation ($r^2 = 0.99$): Cl = 0.3 × (spec. cond.) – 84.83. This relation is valid for specific conductance values above approximately 300. Helium is close to equilibrium with atmospheric concentrations at shallow depth, but quite elevated at greater depth (fig. 16). This is best explained by very slow upward leakage of deep water from the St. Marys confining unit that is being entrained in the lower aquifers as the groundwater circulates through the Eastern Shore and by the long residence times in the deeper Yorktown-Eastover aquifers. Bicarbonate increases with depth as calcium carbonate shells are dissolved in the water. The average nitrate concentration exceeds the USEPA recommended drinking allowance (10 mg/L as N) in the surficial aquifer but is well below that concentration in the confined aquifers. The presence of substantial tritium in the surficial aquifer indicates the water has been recharged after nuclear testing began in the late 1950s and early 1960s.

The stable isotopes of water (^{18}O and ^{2}H) indicate the water in the lower aquifers may have recharged during different climatic conditions. This is further supported by the recharge temperatures that were calculated using total dissolved nitrogen and argon gas measurements (not shown). The recharge temperatures suggest waters in the deeper aquifer were recharged during much cooler climatic conditions, probably during the most recent ice age. The timing of this recharge is further supported by ^{14}C measurements on the dissolved inorganic carbon (DIC) in the water. The raw ages based on a 5,730-year half life suggest the deeper waters are tens of thousands of years old. Adjustments need to be made to ^{14}C ages, however, to account for other chemical reactions that occur with the carbon, including dissolution of shells in the aquifers that are composed of calcium carbonate (Kalin, 1999). Such adjustments were made using a mass-balance approach and the USGS geochemical model NETPATH (Plummer and others, 1994). The adjusted ages based on the Libby half-life of 5,568 years further suggest that many of the deep waters were recharged during the middle of the last ice age approximately 15,000–20,000 years ago (fig. 16).

Salinity Distribution

The presence of saltwater around the peninsula affects how groundwater circulates within the flow system of the Eastern Shore. The exact distribution of the salinity within the surface saltwater bodies and the depths of those water bodies affect the system by exerting additional fluid pressures caused by the excess salt mass present in the saltwater. Average seawater has a density that is 2.5 percent greater than that of freshwater. The bathymetry and salinity distribution surrounding the Eastern Shore are shown in figure 17. The Chesapeake Bay is relatively shallow, but a paleo-river channel exists in the southern part of the bay close to land where water depths exceed 100 ft. In this section of the bay, the upper confined

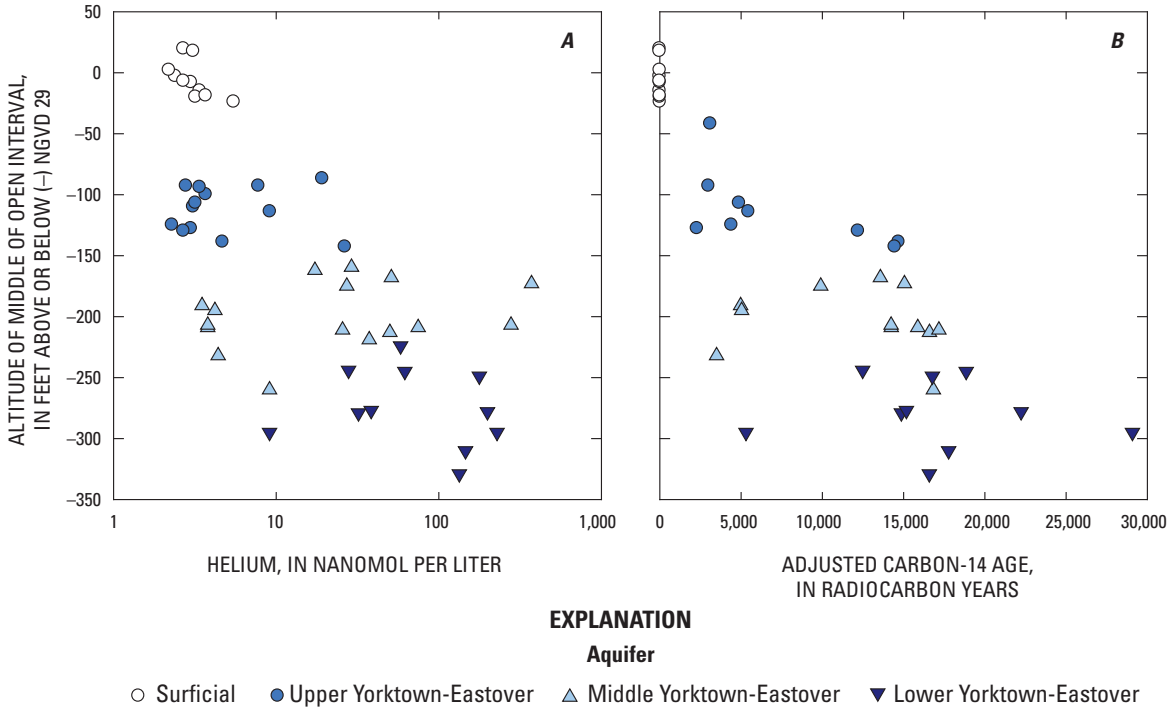


Figure 16. Relation between *(A)* helium concentration and *(B)* adjusted carbon-14 age, and altitude of middle of open-screened interval in wells sampled on the Eastern Shore of Virginia.

aquifer may have a direct connection to the saltwater in the bay. Salinity of seawater is approximately 35 parts per thousand (ppt), and salinities in the coastal bays on the ocean side do not fall much below this as the amount of freshwater runoff from the land is relatively small there. In the Chesapeake Bay, the salinity values decrease from near ocean values at the mouth of the bay to about half the value of seawater at the northwest coastline of the Eastern Shore. Salinity within the bay also varies with water depth and season, but average values (fig. 17*B*) are used for the calculations in this study.

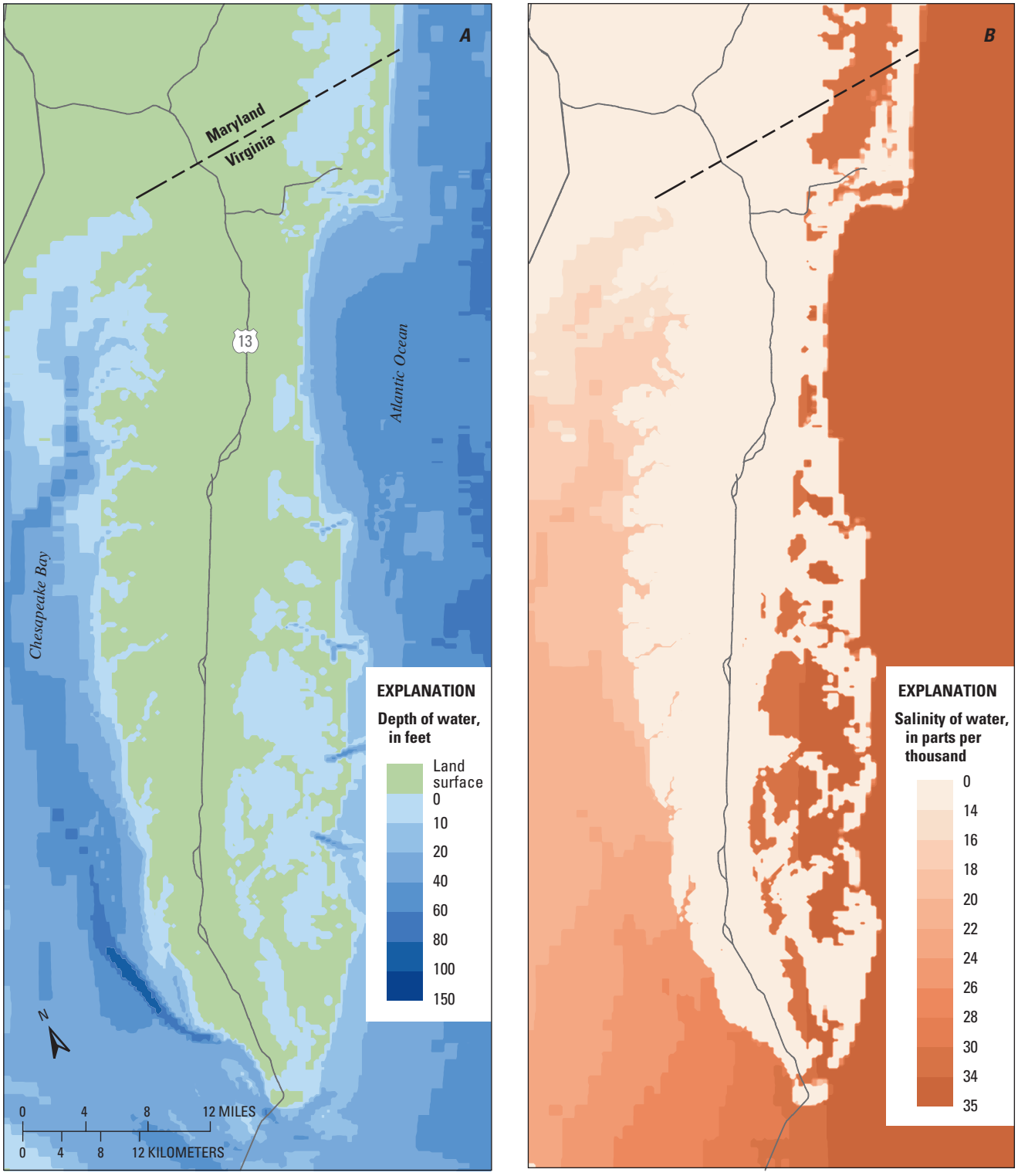


Figure 17. *(A)* Depth and *(B)* salinity of water bodies surrounding the Eastern Shore of Virginia. [Bathymetry data from Divins and Metzger, 2000; salinity data from National Oceanic and Atmospheric Administration, accessed September 2003 at *http://noaa.chesapeakebay.net/interpolatorimages/wqbrowsersearch.aspx*]

Groundwater Use

Groundwater is the main source of freshwater on the Eastern Shore, and categories of use include domestic, agricultural, industrial, and public supply. Before the mid 1960s, groundwater withdrawals were less than 1 Mgal/d and were predominantly for domestic and agricultural use. Beginning in the late 1960s, industrial and public-supply withdrawals increased to about 3 Mgal/d for Accomack County and 1.5 Mgal/d for Northampton County (fig. 18). Since the 1970s, the withdrawals in Accomack County have increased to about 4 Mgal/d, whereas the withdrawals in Northampton County are currently below 1 Mgal/d, primarily because saltwater intrusion became a problem that forced users to curtail pumping. The proportion of water uses has not changed dramatically since the 1980s (fig. 19). Industrial use is consistently the largest category in Accomack County (with the poultry processing industry being the largest user). Irrigation use can also be high but varies dramatically from year to year depending on the amount of rainfall received during the growing season. The proportion of water drawn from each confined aquifer has been approximately equal to about 30 percent from the lower aquifer and 35 percent each from the middle and upper aquifers.

Groundwater Model Development

In order to better assess the effect of future withdrawals on water levels and salinity in the aquifer system, a computer model was constructed to simulate water level and chloride concentration changes. The USGS code SEAWAT2000 (Guo and Langevin, 2002; Langevin and others, 2003) was used to create this model. SEAWAT2000 is a code that combines the USGS groundwater model MODFLOW2000 (Harbaugh and others, 2000) with the solute transport capabilities of the code MTD3D (Zheng and Wang, 1999) but, in addition, allows for the fluid density to vary according to solute concentration. The hydraulic properties of the model were varied in space until a best fit was obtained with historical water-level data, given the known magnitude and distribution of pumpage that has occurred on the Eastern Shore. The automated parameter estimation code UCODE (Poeter and Hill, 1998) was used to facilitate finding the optimal parameter values, to evaluate the sensitivity of the parameters to the observations, and to calculate confidence intervals for the parameters. The USGS particle tracking code MODPATH (Pollock, 1994) was also used to simulate groundwater age, and delineate areas contributing recharge to public supply wells on the Eastern Shore.

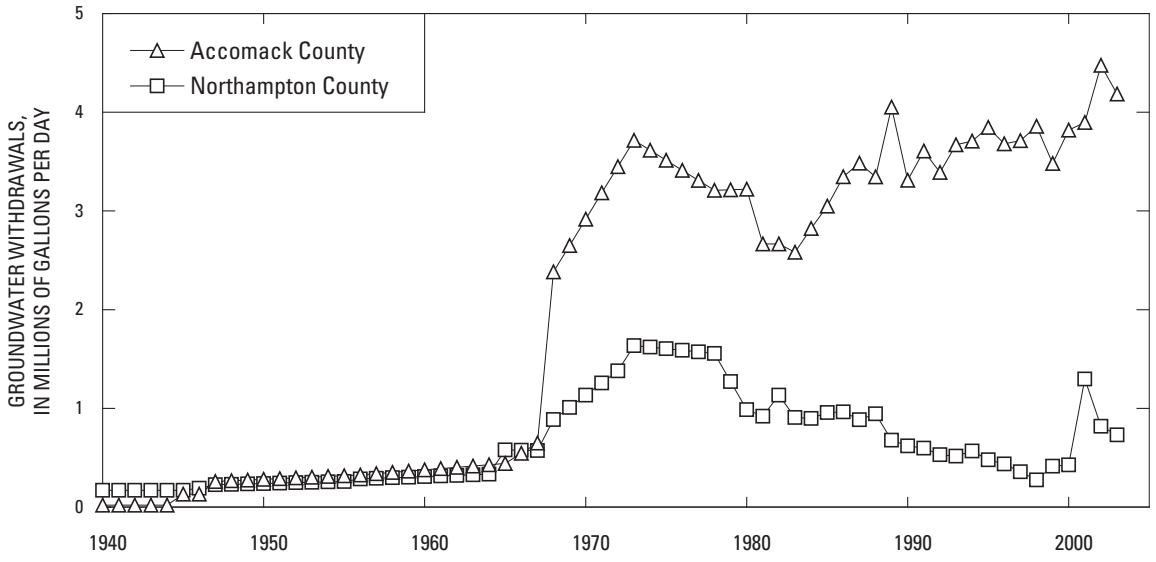


Figure 18. Reported confined groundwater withdrawals from Accomack and Northampton Counties, Virginia.

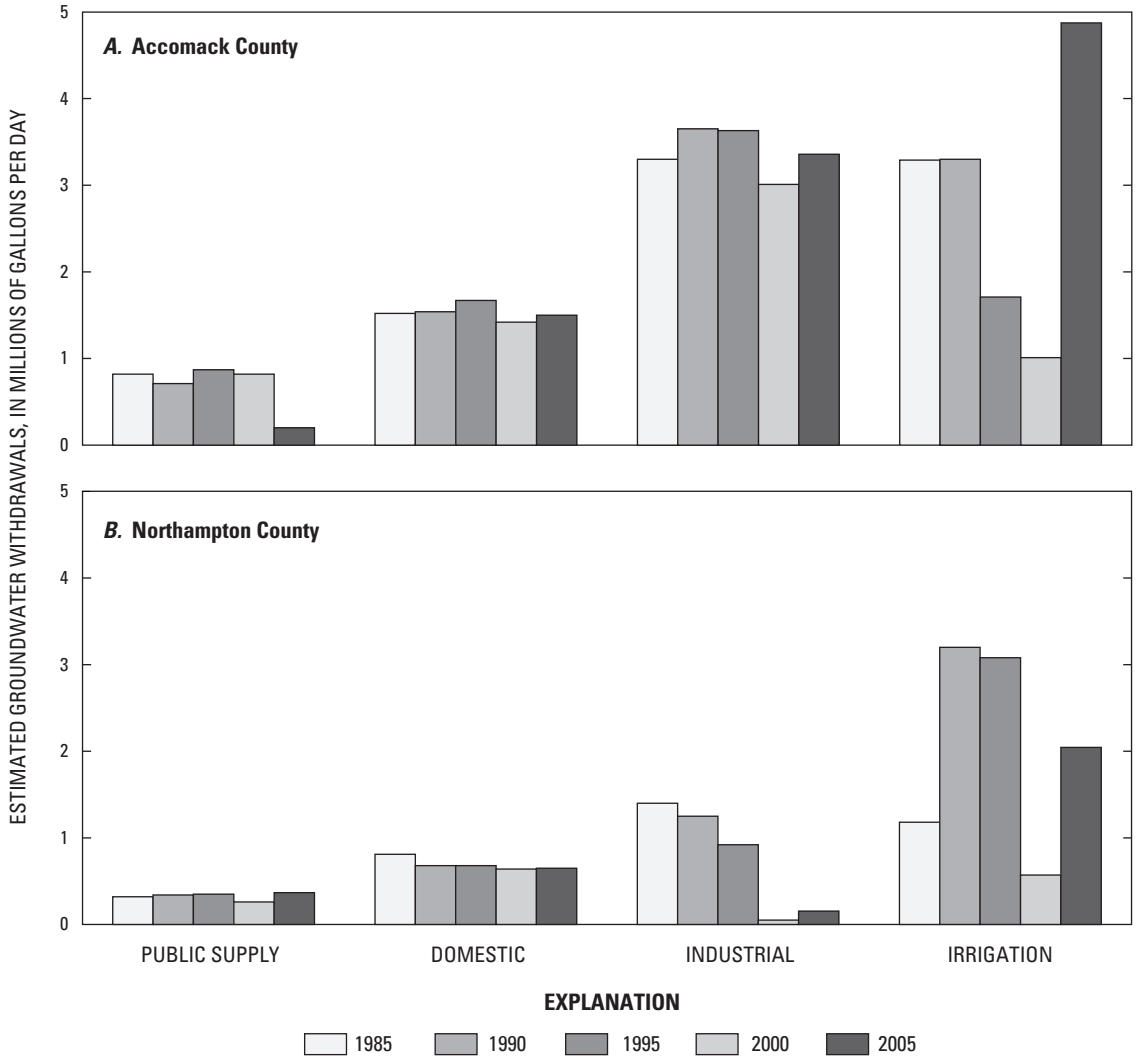


Figure 19. Estimated groundwater withdrawals by category of use in *(A)* Accomack and *(B)* Northampton Counties, Virginia. Irrigation values reflect estimates based on irrigated acreage rather than reported values.

Model Grid

The model developed of the Eastern Shore requires a numerical grid with a resolution that can represent topographic variations in the horizontal dimension and the transition zone between freshwater and saltwater in the vertical dimension. The grid contains 370 rows, 102 columns, and 46 layers (fig. 20) for a total of 1,736,040 cells. The cells are 1,000 ft on a side in the central part of the grid and up to 2,000 ft by 5,000 ft in the corners of the model area. The hydrogeologic units generally follow the model layers (fig. 21) and are composed of between 2 and 8 model layers each. The number of model layers is greater than the hydrogeologic layers in order to provide a better finite-difference simulation of the saltwater transition zone. The solute-transport equation was solved using standard finite differences with upstream weighting. Although upstream weighting creates more numerical dispersion than the more computationally intensive alternatives, there are few field data that define the average width of the transition zone beneath the Eastern Shore, and the alternative of making the grid finer or employing a solution algorithm with less numerical dispersion was beyond the capability of current computing power.

Boundary Conditions

Boundary conditions for the model include specified flux to simulate recharge at the land surface; head-dependent flux to simulate evapotranspiration from the water table; and leakage across the floor of the Atlantic Ocean, the Chesapeake Bay, the other coastal saltwater bodies, and the northern land boundary with Maryland. The remaining sides and bottom of the model are specified as no-flow boundaries.

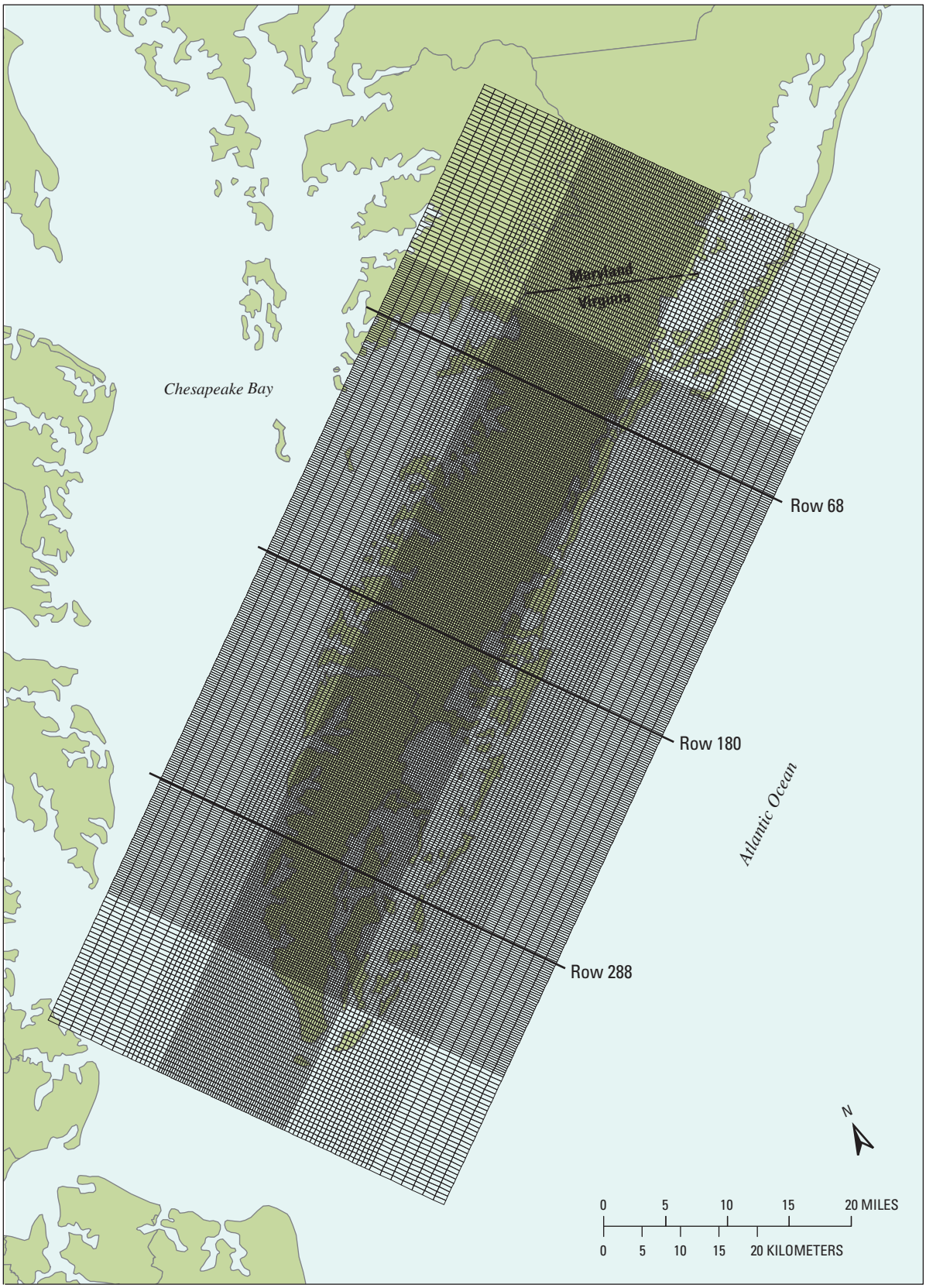


Figure 20. Areal view of the model grid, with row numbers of section lines of the Eastern Shore of Virginia.

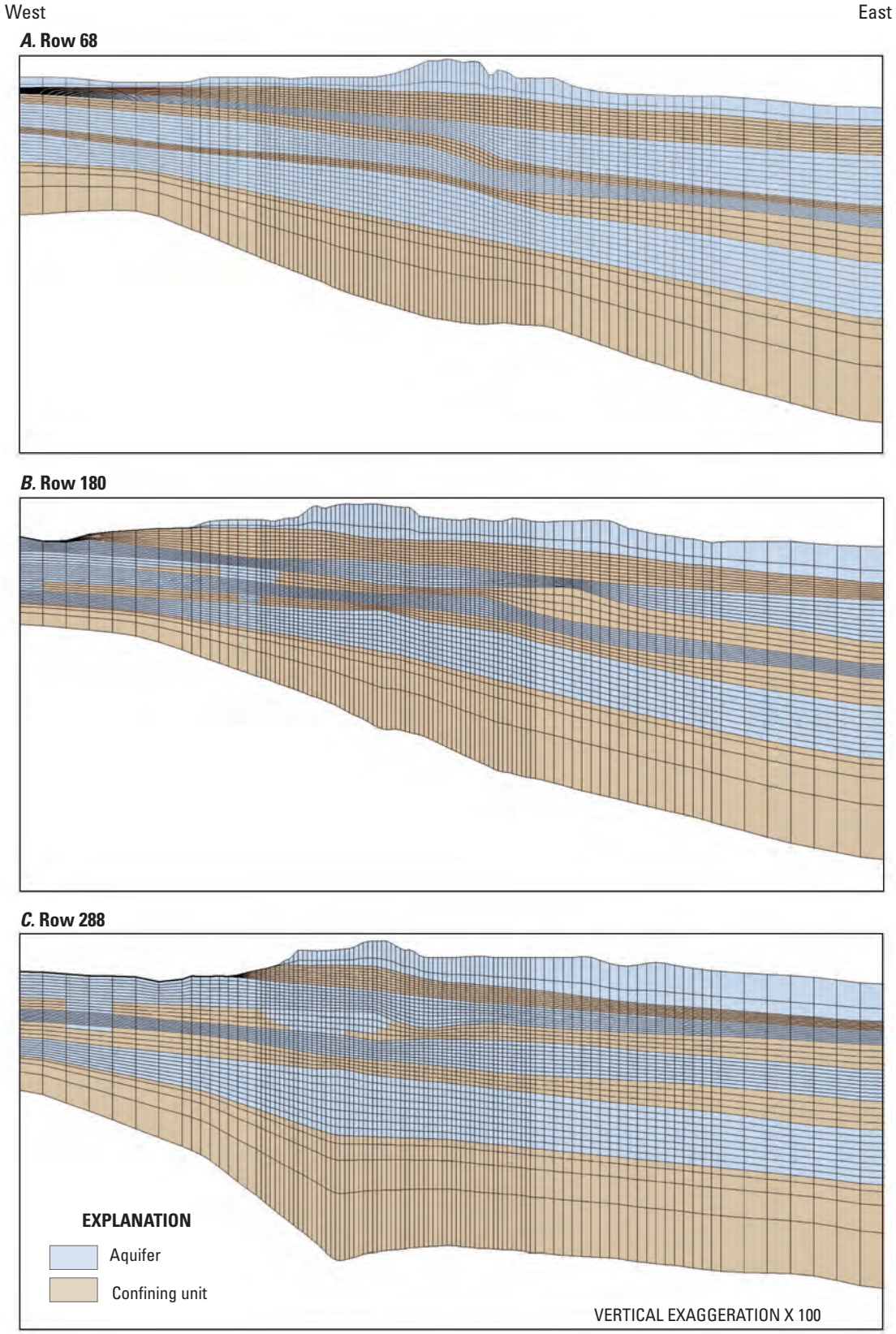


Figure 21. Cross-sectional views of the model grid at rows *(A)* 68, *(B)* 180, and *(C)* 288 of the Eastern Shore of Virginia. See figure 20 for locations.

Recharge

Recharge was specified to the land-surface areas of the model by zone (fig. 22). The zones were delineated on the basis of soil type and slope. Soils with high, moderate, and low permeabilities were mapped into the three recharge zones used in the model. Cells with a high topographic slope were shifted into a recharge zone with the next lower permeability class to represent the lower recharge caused by increased runoff. The magnitude of recharge assigned to these zones was estimated by an inverse simulation procedure that produced the best fit of water-level observations in the surficial aquifer and ages calculated from the SF6 measurements (table 2). The final estimated recharge values were 24, 13, and 7.4 in/yr for the high, moderate, and low recharge zones, respectively.

Evapotranspiration

Evapotranspiration (ET) from the water table is widespread across the Eastern Shore because of the relatively shallow depth to the water table, especially in the low-lying coastal areas. ET is simulated in the model by assigning a maximum ET flux when the water table is at the land surface and an extinction depth below which the ET flux becomes zero. The ET flux decreases linearly with water-table altitude between the specified land surface and ET extinction depths. The extinction depth often is approximated by the average depth of the root zone, which for this study was based on the land cover type (fig. 2*B*). The extinction depth for the forests, agricultural, and marsh regions was set to 6, 3, and 2 ft, respectively. The maximum ET rate was estimated during calibration with UCODE by obtaining a best fit of simulated to observed water levels. If no ET were simulated in the model, the water table would take on a concave downward appearance and be above land surface in much of the model area. With increasingly higher simulated ET fluxes, the water table more closely mimics the land surface. The maximum ET flux for the model was estimated to be 67.9 in/yr. This value is higher than what might be expected from local potential ET estimates (Milly, 1994; Nuttle and Harvey, 1995). The higher value may attributed to many low-lying areas where there are seepage-face outflows (Speiran, 1996) that, because they are not represented directly in the model, are simulated as part of the ET discharge in order to create a fit with water-table observations. Recharge and the maximum ET flux are specified for every land cell in the top layer, and the water-table elevation is calculated by the model. This approach can create numerical instabilities because of the nonlinear ET function (Sanford, 2002), especially for steady-state calculations; however, by taking small time steps at the beginning of the simulation, numerical stability can be achieved. The calculated net recharge (or discharge) at the land surface and the sub-marine discharge observed at water cells are depicted in figure 23. The time discretization of the model will allow for the calculation of a seasonal fluctuation in the water table (for example, from droughts) if the recharge is varied on a sub-year time scale. This option was not available in the previous model of the Eastern Shore (Richardson, 1994).

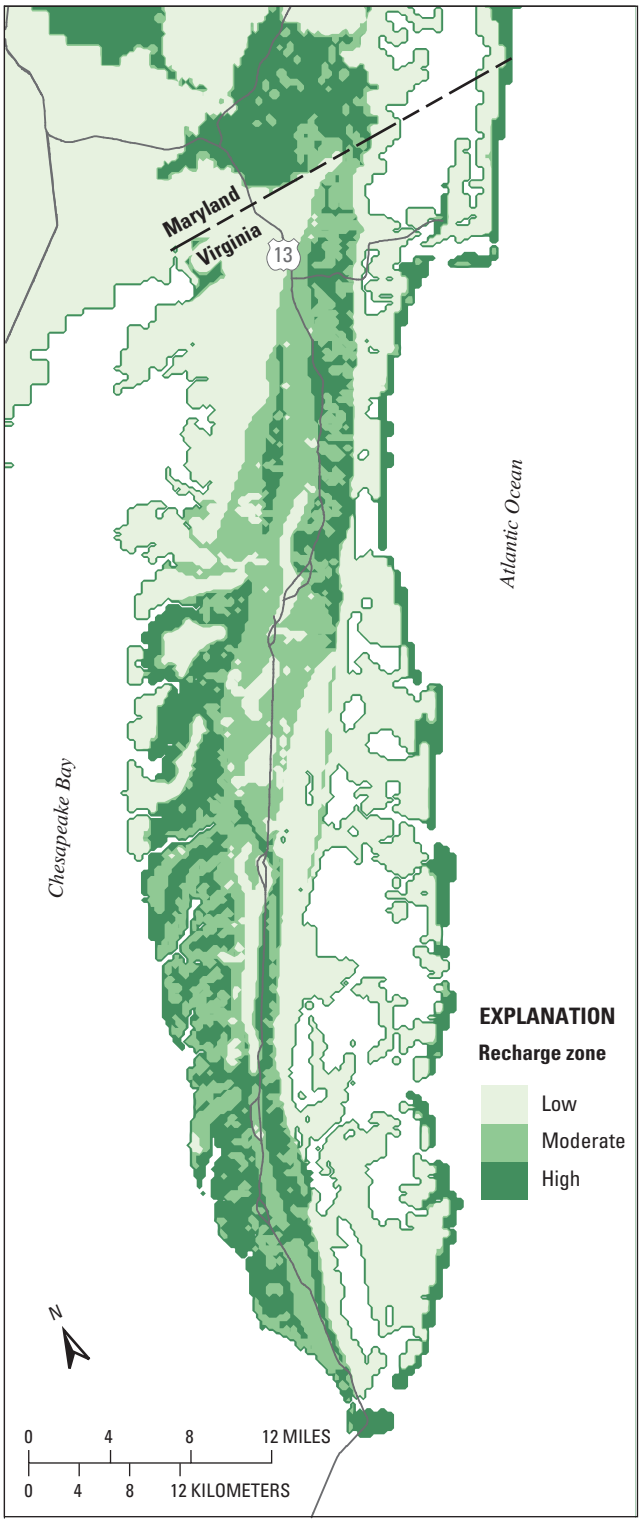


Figure 22. Recharge zonation based on soil types and slope of the Eastern Shore of Virginia. [Data from U.S. Department of Agriculture, Natural Resources Conservation Service, accessed February 2004 at *http://soildatamart.nrcs.usda.gov*; and U.S. Geological Survey 30-meter National Elevation Dataset, accessed January 2004 at *http://seamless.usgs.gov*]

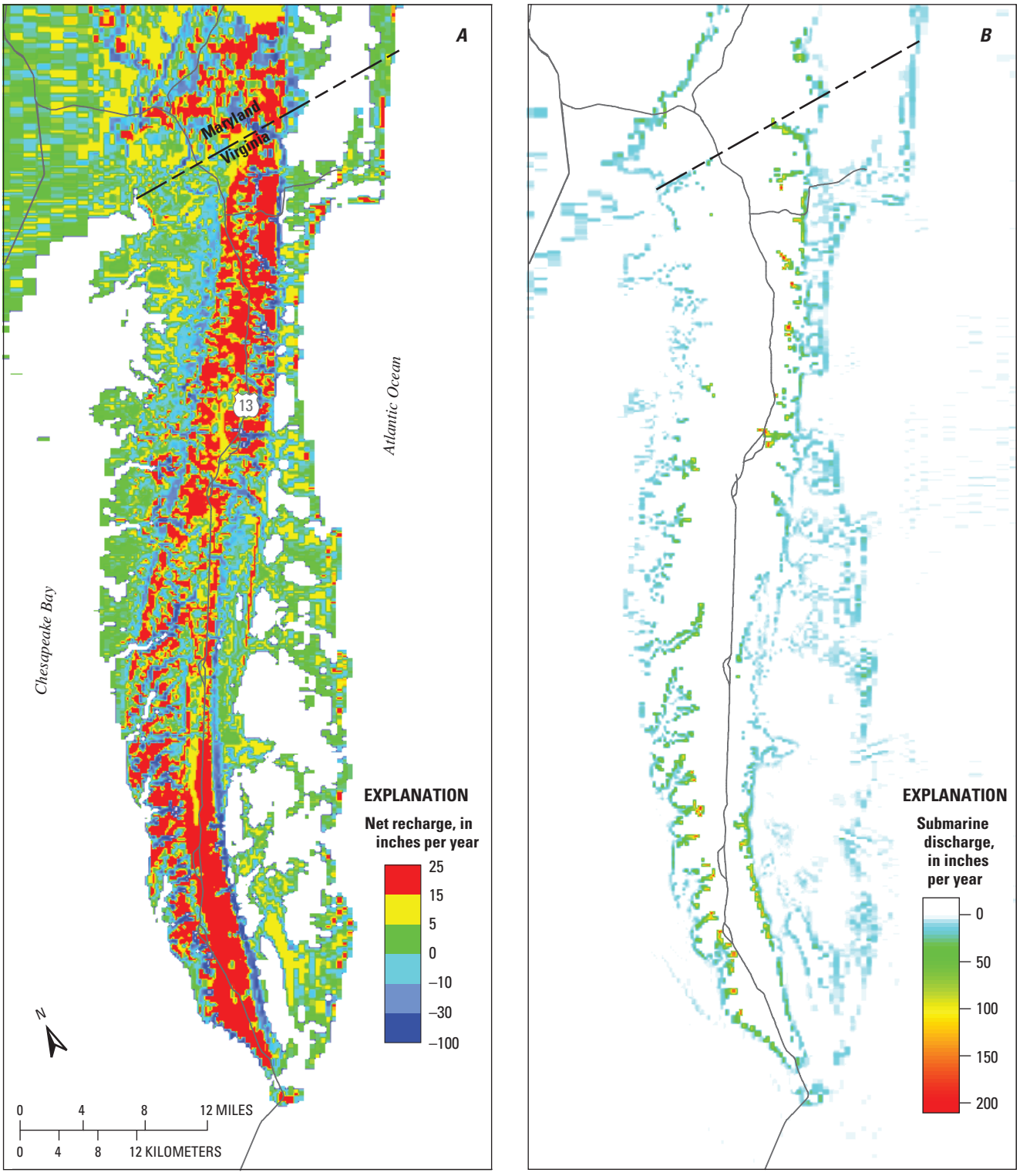


Figure 23. Simulated *(A)* net recharge and *(B)* submarine discharge in the top layer of the model of the Eastern Shore of Virginia.

General Head

A general-head boundary condition contains a conductance term that, when adjusted to a very high value, causes the boundary to behave as a constant-head boundary but, when adjusted to a very low level, allows the boundary to behave as a no-flow boundary. For the cells in the top layer of the model that are overlain by water, a general-head boundary condition was used to allow the conductance term to represent the fraction of water covering the cell. As geographic information system (GIS) data on land cover are available at a resolution finer than the grid cells, it is possible to represent the fraction that each model cell area is covered by water with the conductance term (fig. 24). This affects the discharge distribution of the groundwater along the coastal regions. The head for each general-head cell is adjusted for density internally by SEAWAT by using the specified head value (zero for sea level), the altitude of the cell below sea level, and the surface-water chloride concentration at that cell.

The northern land boundary of the model is not a hydrologic boundary and cannot accurately be represented by either a no-flow or constant-head condition. In order to prevent unrealistic effects on simulated heads in the model, a general-head boundary was assigned to the northern land boundary. The conductance term can be adjusted along the boundary to control the simulated water levels in the region. Currently, the conductance term is set relatively low, so the northern boundary is contributing negligible water to the model. Hydrologic conditions in Maryland have only a small influence on water levels in Virginia, thus the northern boundary conductance term was not adjusted to create the best fit for observed water levels in Maryland. The term may be refined if an improved simulation of water levels in the Maryland part of the model is desired in the future.

Historical Withdrawals

Historically, most groundwater in the Eastern Shore was extracted from shallow wells in the surficial aquifer for domestic and small-business use. During the 20th century, as drilling became more practical and affordable, more wells were drilled in the confined aquifers and fewer wells were drilled in the unconfined aquifer. Deeper wells allowed for larger drawdowns and protection from surface contamination. To create a model that is reliable for assessing current pumping effects on water levels, it was first necessary to simulate observed historical water levels and historical withdrawals. A data set was created that represents the best estimates of historical withdrawals. Industrial, commercial, public-supply, and some agricultural withdrawals from individual wells were assigned to the model using the multi-node-well package (Halford and Hanson, 2002). Pre-1982 pumping estimates were taken from the model of Richardson (1994). Domestic withdrawals have not been reported, so estimates were made and assigned using the well package in MODFLOW in the manner described below.

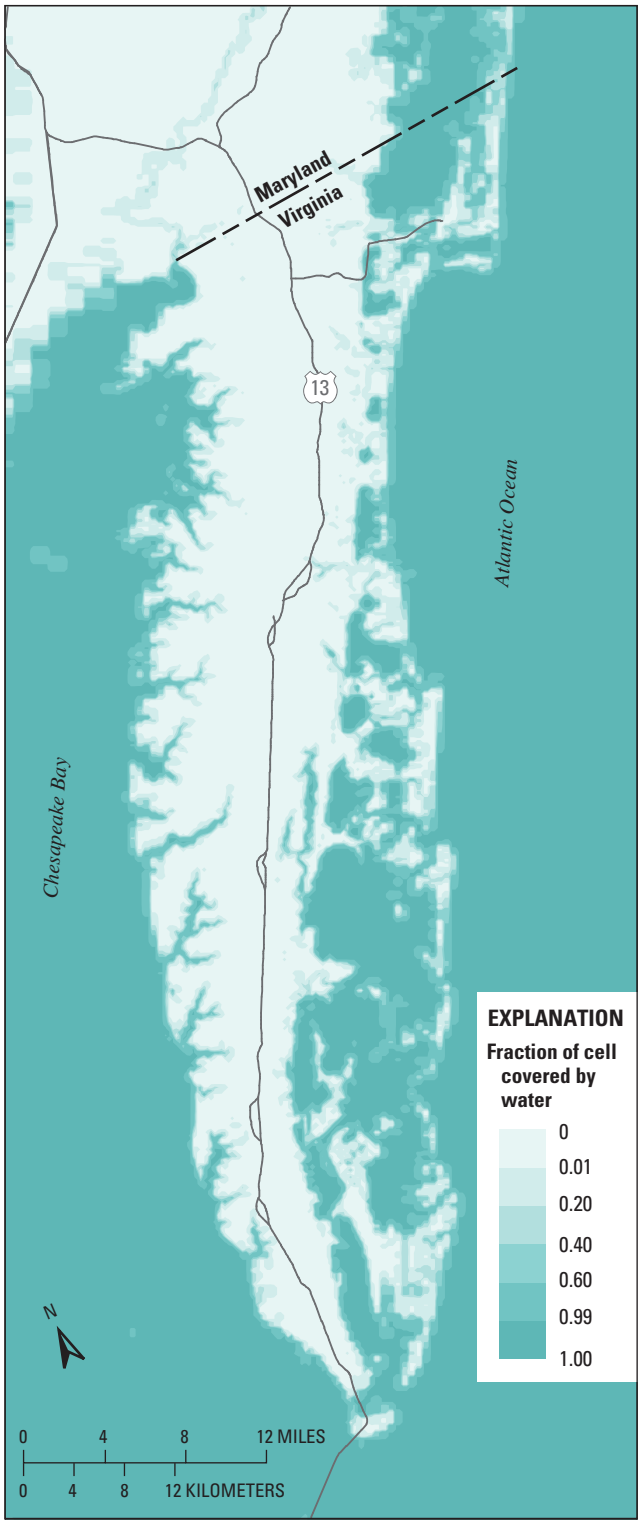


Figure 24. Fraction of general-head boundary cells covered by water on the Eastern Shore of Virginia.

Withdrawals from the surficial aquifer were not included in the historical simulations for several reasons. First, records of withdrawals from the surficial aquifer are sparse. Second, much of the domestic withdrawal has migrated to the confined aquifers to avoid surficial contamination. Third, recharge rates in the surficial aquifer are quite large compared to individual withdrawals, so water-level declines usually are limited to near the withdrawal wells and are less likely to be present in observation wells. It is recognized, however, that large agricultural withdrawals during drought periods are a concern to water managers, and this model has the capability of simulating withdrawals from the surficial aquifer if that effect needs to be assessed in the future.

Permitted Withdrawals

Beginning in 1982, permits were required by the Virginia DEQ for withdrawals greater than 300,000 gallons per month. A list of the actual reported withdrawals under these permits was compiled. These withdrawals were entered into the model, and the withdrawal rates and model locations are summarized in table 3. The historical pumping record is illustrated in figure 25. Withdrawal rates increased dramatically in the late 1960s, and the rates have been approximately evenly distributed between the three confined aquifers; however, Accomack County withdrawals have exceeded those of Northampton County by a factor of about 3 to 4. The withdrawal rates of the Maryland counties within the model area are similar to or less than those of Northampton County in Virginia.

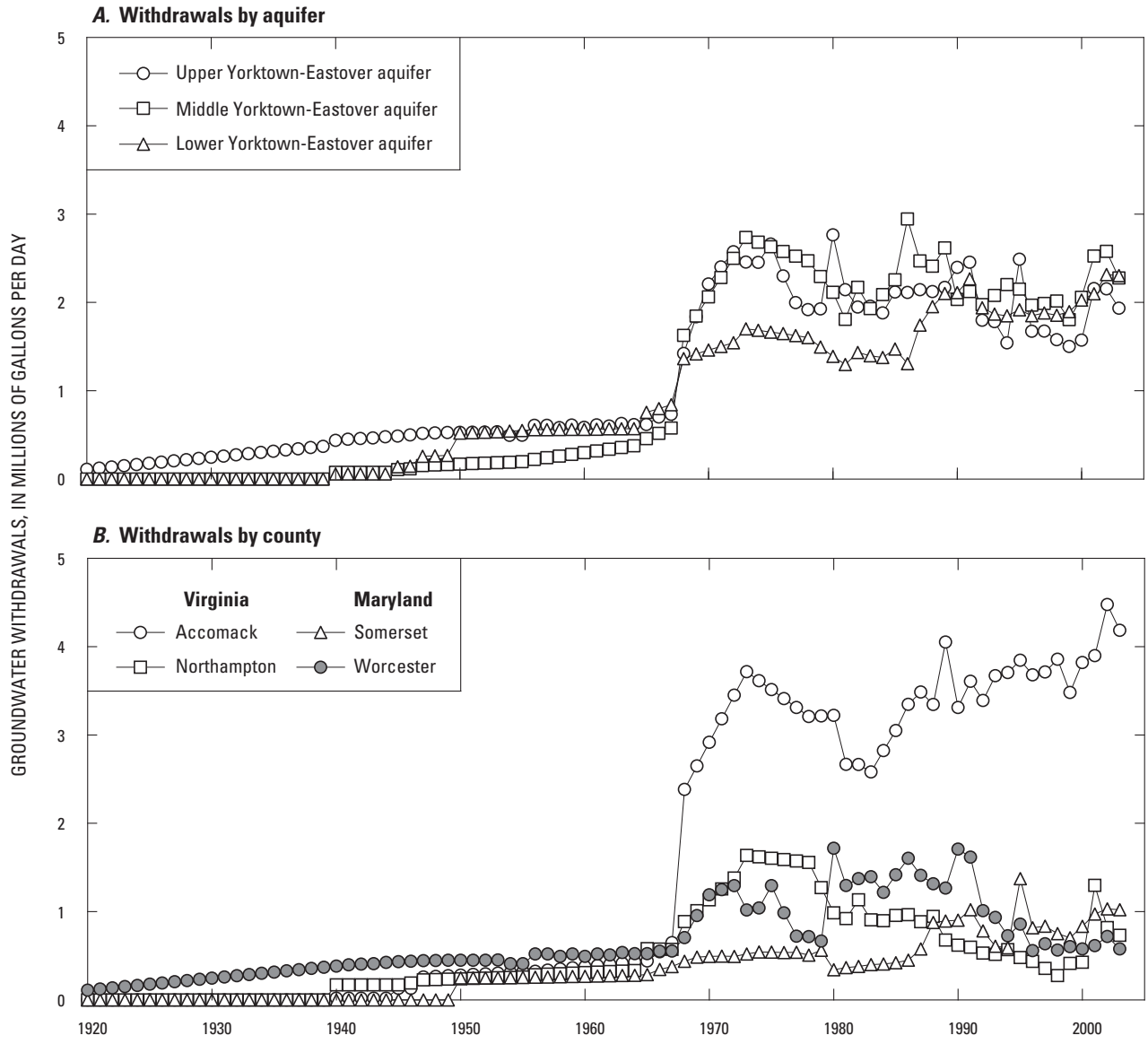


Figure 25. Reported confined withdrawals in the model through time by *(A)* aquifer and *(B)* county.

Table 3. Reported groundwater withdrawals in the model of the Eastern Shore of Virginia since reporting began in 1982.

First year of pumping	Last year of pumping included in model	Average annual pumping rate, in thousands of gallons per day	Name	Model row	Model column	Yorktown-Eastover aquifer
1982	1985	616.9	Tyson Foods	62	55	All
1982	2003	562.2	Pocomoke City	21	23	Upper
1982	2003	551.5	Somerset County	9	1	Lower
1982	2003	508.6	Perdue	122	52	Mid-low
2001	2001	432.0	Bailey	319	51	Middle
1982	2003	426.2	Perdue	121	51	Mid-low
1987	2003	360.9	Perdue	122	51	Mid-low
1987	2003	322.0	Tyson Foods	61	52	All
1982	1993	291.9	Campbell Soup	23	20	Upper
1982	2003	231.4	Perdue	120	58	Mid-low
1986	1991	202.2	Tyson Foods	62	55	Middle
1982	1990	201.4	KMC Foods	305	43	Middle
1987	2003	199.5	Tyson Foods	61	53	All
1987	2003	190.3	Tyson Foods	62	54	All
2001	2001	184.7	Guy	226	33	Upper
1998	2003	171.4	Perdue	123	50	Mid-low
1982	2003	168.2	Chincoteague	35	71	Middle
1982	2003	154.3	Chincoteague	35	71	Upper
1987	2003	147.8	Tyson Foods	60	52	All
1982	1998	145.2	Perdue	122	50	Mid-low
1987	1993	127.5	Apex Chemtech	35	42	Lower
1995	1998	126.1	Long	20	2	Upper
1988	2003	121.8	Tyson Foods	62	53	Middle
1995	1998	116.0	Long	21	3	Upper
1984	2003	111.0	Apex Chemtech	35	44	Middle
1982	2001	109.0	U.S. Government	62	70	Middle
1982	2003	103.9	Cape Charles	320	34	Up-mid
1982	1991	98.4	American Original Foods	215	48	Middle
1988	2003	93.3	Onancock	142	34	Middle
1982	1997	89.0	Maryland Stone	26	14	Upper
1988	2003	86.5	Cape Charles	320	35	Up-mid
1982	1989	77.9	Onancock	142	34	Middle
1995	2003	74.7	Butler Farms	36	16	Upper
1982	2003	74.7	Exmore	207	40	Up-mid
1982	2003	68.0	Perdue	124	51	All
1982	1003	67.6	Parksley	106	46	Middle
1984	2003	66.9	Exmore	207	40	Middle
2001	2003	66.1	Tankard	221	20	Upper
1982	1988	63.4	Taylor Packing	69	47	Middle
2002	2002	61.1	Kuzzens	217	25	Middle

Table 3. Reported groundwater withdrawals in the model of the Eastern Shore of Virginia since reporting began in 1982.—Continued

First year of pumping	Last year of pumping included in model	Average annual pumping rate, in thousands of gallons per day	Name	Model row	Model column	Yorktown-Eastover aquifer
1982	2003	58.6	Shore Health Services	234	39	Mid-low
1995	1995	58.0	Cape Charles	320	35	Middle
1988	2003	52.3	Onancock	142	34	Upper
1982	1999	51.4	Eastville	284	37	Upper
1995	2003	51.0	Butler Farms	36	11	Upper
1986	2002	50.8	Apex Chemtech	35	44	Upper
2001	2002	49.7	Tankard	221	21	Upper
2002	2003	47.0	Hall	143	67	Upper
1982	2003	46.7	Chincoteague	38	71	Upper
1982	1994	45.2	Chesapeake Wood Treating	22	18	Upper
1990	2003	43.7	Eastville	284	39	Upper
1995	2002	40.7	Holland & Sons	29	22	Upper
1982	1991	40.5	C&D Seafood	304	53	Middle
1982	1999	40.0	Eastville	284	37	Upper
1995	2002	37.5	Butler Farms	34	8	Upper
2000	2002	37.0	Holland & Sons	29	18	Upper
1995	2002	34.2	Butler Farms	34	27	Upper
2003	2003	33.9	Taylor & Fulton	80	47	Lower
1982	1999	32.7	Bayshore Concrete	324	32	Middle
2000	2000	32.1	Tankard	326	54	Upper
1988	2003	31.2	Chincoteague	37	71	Upper
1982	2003	30.7	Shore Seafood	72	10	Middle
2001	2003	30.2	Tankard	221	22	Upper
2002	2003	29.4	Hall	142	66	Middle
2001	2003	29.0	Tankard	222	21	Upper
2002	2003	27.4	Eastern Shore Seafood	71	59	Lower
2002	2003	24.2	Hall	144	61	Middle
2002	2003	23.9	Eastern Shore Seafood	72	60	Lower
2002	2003	23.4	Hall	144	62	Middle
1982	2003	23.1	Byrd Foods	116	45	Lower
2002	2003	22.9	U.S. Government	37	68	Middle
1982	1995	22.8	Seawatch International	303	53	Middle
1982	1995	22.8	Seawatch International	303	53	Middle
1982	2003	22.3	Captains Cove Utility	24	73	Upper
2001	2003	21.6	Tankard	221	23	Upper
1985	2003	21.4	Apex Chemtech	35	44	Lower
1982	2003	21.2	Shore Health Services	234	39	Mid-low
2001	2003	21.1	Trails & Utility	32	70	Upper
1990	1999	21.0	Smith Bull	289	31	Middle
2001	2003	20.4	Tankard	220	23	Upper

Table 3. Reported groundwater withdrawals in the model of the Eastern Shore of Virginia since reporting began in 1982.—Continued

First year of pumping	Last year of pumping included in model	Average annual pumping rate, in thousands of gallons per day	Name	Model row	Model column	Yorktown-Eastover aquifer
2002	2003	20.2	U.S. Government	37	66	Middle
1990	2003	19.4	U.S. Government	64	70	Middle
2002	2003	18.4	U.S. Government	37	65	Middle
1985	2003	18.2	Perdue	15	3	Lower
2002	2003	18.0	Eastern Shore Seafood	71	59	Lower
2002	2003	17.4	Eastern Shore Seafood	71	59	Middle
2002	2003	16.7	U.S. Government	37	64	Middle
1988	2003	16.4	Captains Cove Utility	23	69	Middle
2002	2003	16.3	U.S. Government	37	69	Middle
1988	1994	15.7	Bayshore Concrete	325	32	Upper
2002	2003	15.4	Tankard	221	20	Upper
1985	2003	15.1	Mountaire Farms	12	3	Lower
2003	2003	15.1	Taylor & Fulton	87	48	Upper
1982	2003	14.7	Chincoteague	36	71	Middle
1983	2003	14.3	Shore Health Services	111	57	Upper
2001	2003	13.8	Nottingham	337	49	Upper
2001	2001	13.6	Papetti	169	28	Upper
2001	2001	13.5	Papetti	170	28	Upper
2001	2003	13.0	East Coast Brokers & Packers	81	55	Lower
1989	2000	12.8	U.S. Government	63	70	Middle
2002	2002	12.6	Eastern Shore Seafood	71	58	Lower
2002	2003	12.2	Tankard	220	24	Upper
2001	2001	11.6	Bayshore Concrete	324	31	Middle
1996	2003	11.6	Bayshore Concrete	325	32	Middle
2002	2003	11.4	Eastern Shore Seafood	71	58	Middle
2002	2003	11.3	Hall	155	57	Middle
2003	2003	10.6	Taylor & Fulton	80	48	Lower
1991	2003	9.6	Chincoteague	37	71	Middle
1982	2003	8.7	Patel	23	31	Upper
1988	1998	8.6	Onancock	141	31	Middle
1982	2003	8.6	Shore Landvest	350	65	Upper
1982	2003	8.3	Maryland Dnr	2	48	Lower
1988	1999	8.2	U.S. Government	62	70	Upper
1988	2003	7.7	Bayshore Concrete	325	31	Middle
2001	2001	7.6	Bailey	315	49	Middle
1985	1985	7.5	C.J. Scarborough	18	76	Lower
1986	2003	7.5	Naco Virginia Landing	223	57	Upper
2003	2003	7.1	Taylor & Fulton	80	47	Middle
2003	2003	7.0	Eastern Shore Yacht	170	22	Middle
2002	2003	6.9	Ballard Brothers Fish	314	30	Mid-low

Table 3. Reported groundwater withdrawals in the model of the Eastern Shore of Virginia since reporting began in 1982.—Continued

First year of pumping	Last year of pumping included in model	Average annual pumping rate, in thousands of gallons per day	Name	Model row	Model column	Yorktown-Eastover aquifer
1987	2003	6.8	Pocomoke Hosptiality	27	34	Lower
2003	2003	6.7	Eastern Shore Yacht	171	22	Middle
1995	2003	6.6	Dennis	40	64	Upper
2003	2003	6.5	Bayshore Concrete	325	32	Up-mid
2002	2003	6.5	Virginia Commonwealth	345	59	Middle
1995	2003	6.0	Butler Farms	36	13	Upper
2003	2003	5.7	Eastern Shore Yacht	130	51	Middle
2002	2003	5.7	Cape Charles	320	34	Middle
2001	2003	5.6	East Coast Brokers & Packers	81	56	Lower
1988	2003	5.2	Captains Cove Utility	26	72	Middle
1995	2003	5.1	Bayshore Concrete	324	32	Upper
1995	2002	5.1	Bayshore Concrete	325	31	Upper
1988	1994	5.0	Bayshore Concrete	325	32	Middle
1988	1998	4.8	Onancock	141	31	Middle
1998	1998	4.7	Holland	8	15	Upper
1982	1987	4.6	Vighnesh	27	36	Lower
2001	2003	4.6	Zieger Floral	276	47	Upper
1999	2002	4.3	Bayshore Concrete	325	32	Middle
2001	2003	4.1	Zieger Floral	276	47	Upper
1995	2002	3.2	Vessey	29	10	Lower
2003	2004	3.0	Maryland Dnr	2	48	Lower
2003	2003	2.8	Naco Virginia Landing	221	57	Upper
2002	2003	2.7	YMCA	240	14	Lower
2002	2003	2.6	Eastern Shore Seafood	71	58	Middle
2003	2003	1.9	Eastern Shore Yacht	170	20	Middle
1996	2001	1.8	Bayshore Concrete	324	31	Middle
1990	1994	1.3	Klingenberg	2	46	Lower
2003	2003	1.1	Eastern Shore Yacht	170	20	Middle
2001	2003	1.0	East Coast Brokers & Packers	80	56	Lower
2002	2002	0.7	Ballard Brothers Fish	314	30	All
1995	1997	0.6	Overholt	25	8	Lower
1997	1997	0.5	Somerset Growers	19	4	Lower
2001	2003	0.2	Commonwealth Chesapeake	33	42	Upper
2002	2003	0.2	Eastern Shore Seafood	72	59	Lower
2003	2003	0.1	Eastern Shore Yacht	170	23	Upper
2002	2003	0.1	Virginia Commonwealth	344	57	Middle

Domestic Withdrawals

Domestic withdrawals are not reported, so they were estimated on the basis of the temporal and spatial distribution of the population of the Eastern Shore (table 4). The following algorithm, also used for the entire Virginia Coastal Plain in another study (Pope and others, 2007), was used to determine the magnitude and distribution of domestic pumpage. Each individual is assumed to use 75 gallons of water a day. The population was mapped on the basis of census block groups from the 2000 census. People within a census block group are assumed to live along roads. Areas serviced by public-supply wells were excluded. Coverages representing public-supply areas, roads, and population were combined in a GIS to assign flow rates to model grid cells (fig. 26). This allowed the withdrawals to be distributed where people are likely to be living rather than uniformly across the entire Eastern Shore. The spatial distribution of domestic pumping is shown in figure 27. It was assumed that beginning in the 1940s greater numbers of domestic wells were completed in the deeper aquifers in greater numbers in the 1940s, and that by the 1960s, most domestic wells were completed in the confined aquifers. Thus, domestic pumping did not begin in the model until 1940, and it increased linearly until 1960 when it reached the rate for the entire self-supplied population. The pumping is distributed between the upper, middle, and lower aquifers on the bases of the distribution of well screens from a sampling of well installation records from Accomack and Northampton Counties (Pope and others, 2007).

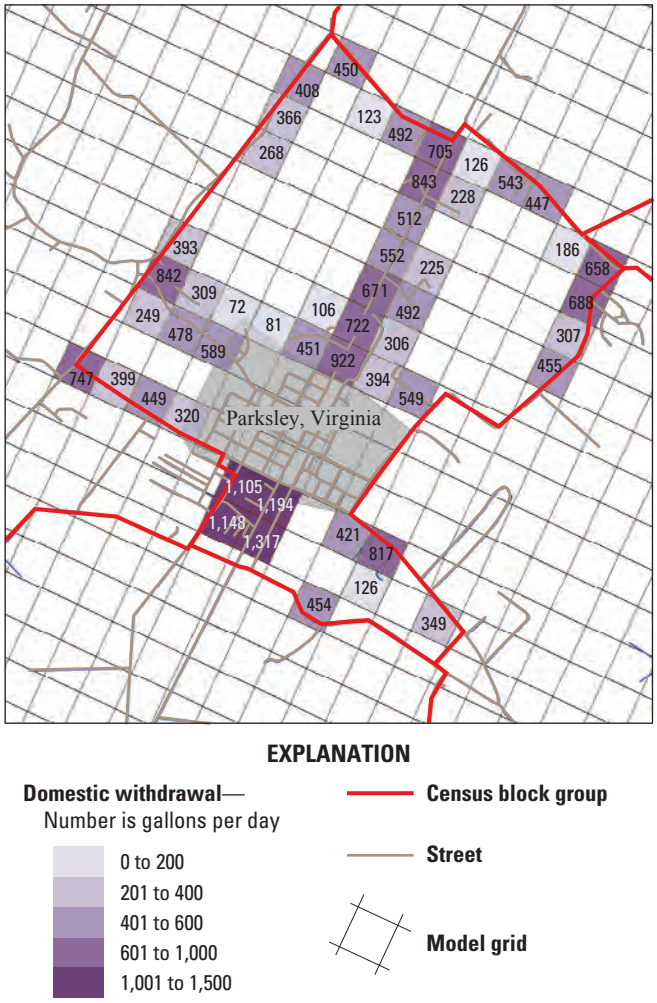


Figure 26. Example of how domestic withdrawals were assigned in the model. Gray area is supplied with public water.

Table 4. Estimated self-supplied withdrawals, by county, used to estimate confined withdrawals from the groundwater model.

Year	Withdrawals, in thousands of gallons per day				
	Somerset, Maryland	Worcester, Maryland	Accomack, Virginia	Northampton, Virginia	Total
2000	706	295	1,999	742	3,742
1990	669	222	1,654	740	3,285
1980	548	196	1,632	828	3,204
1970	540	155	1,514	818	3,027
1960	560	150	1,599	961	3,270
1950	592	147	1,765	980	3,484
1940	598	135	1,724	997	3,454
1930	667	137	1,871	1,052	3,727
1920	702	141	1,816	1,011	3,671
1910	598	135	1,724	997	3,454
1900	667	137	1,871	1,052	3,727

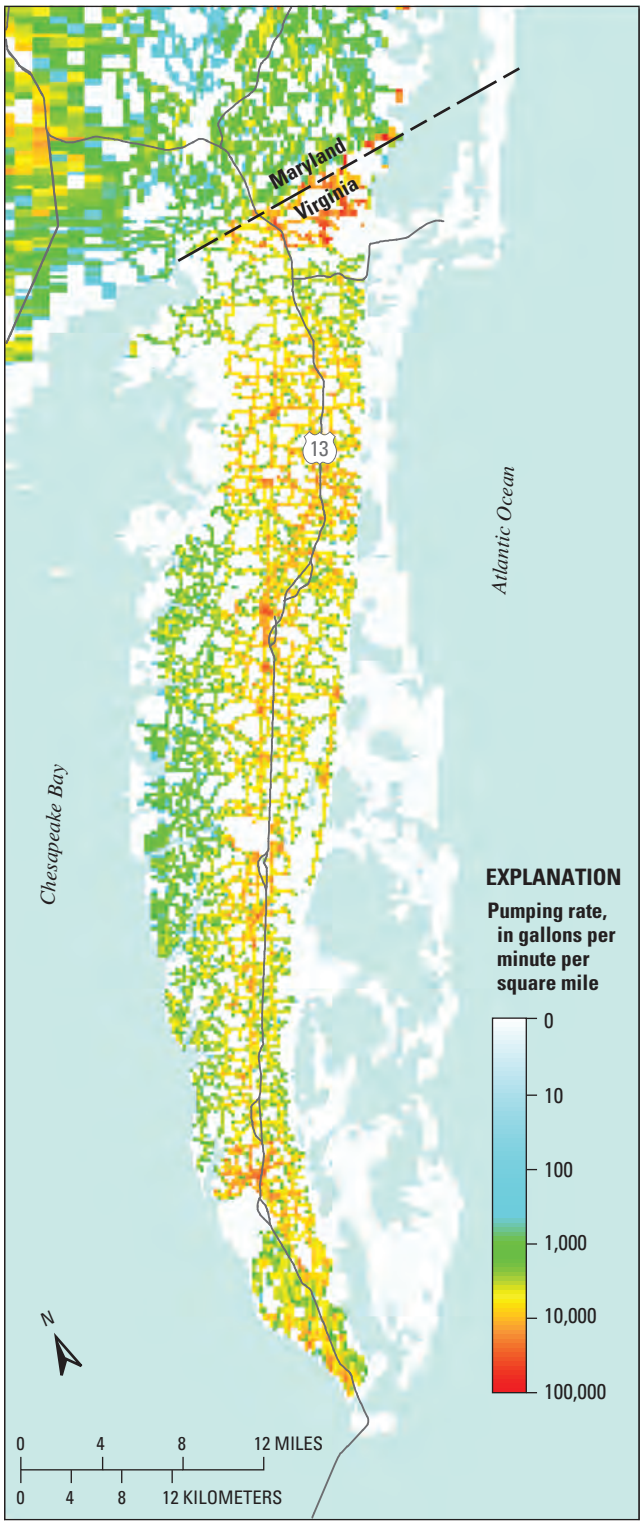


Figure 27. Distribution of domestic well withdrawals as assigned in the model of the Eastern Shore of Virginia.

Hydraulic Parameters

For this model to successfully assess the effects of pumping on water levels and salinity changes, it was necessary to set the model parameters to best represent the hydraulic properties of the hydrogeologic units of the Eastern Shore. To accomplish this, individual field measurements were used only as a guide, as they usually represent values of the hydraulic properties in cores or, at best, a few hundred yards from a well. For a scale of many miles, which the model represents, long-term water-level declines from regional pumping areas yield the best data for calibrating the model. The system is complex, however, as the properties vary not only between but within hydrogeologic units. An approach was adopted that used the automated inverse model calibration tool UCODE to adjust the parameter values until a best fit was obtained between the observed and simulated water levels. The 189 observation wells with data that were used in this calibration are listed in table 5. The water-level observations in both space and time that were used for the calibration are listed in Appendix 1 (table 1–1). Depending on the sensitivity, parameters representing hydraulic conductivity, specific storage, and porosity throughout the model domain were either estimated or assigned reasonable values. Some parameter values could not be constrained by the calibration procedure because the simulated observations were not sensitive enough to constrain the parameter values. Values for these insensitive parameters were specified within the reasonable range of values that might be expected to occur in the study area.

Spatial Distribution

To account for the fact that hydraulic parameter values vary in space, a paradigm had to be chosen to determine how these values should occur in the model as a function of space. For this study, it was decided that values between hydrogeologic units would vary discretely, but that the values within the units would vary gradually. The bulk vertical anisotropy of the system was represented by the difference in hydraulic conductivity values between the aquifers and confining units. Within each unit, the hydraulic conductivity was assumed to be isotropic both in vertically and horizontally. To vary the values gradually in space, a technique was used that combined pilot points with kriging. Pilot points are specific locations within the model area where values of the parameters are assigned during the calibration process. Values at all other locations are calculated by a smoothing function that interpolates and extrapolates values based on the pilot-point values and locations. In this model, 21 pilot-point locations were selected (fig. 28). The locations of the points are coincident with observation-well locations. The degree to which each pilot point's value influences the values in the areas surrounding the point is illustrated by contours of percentage influence as shown in figure 28. The kriged fields of parameter values (hydraulic conductivity and specific storage) were calculated on the basis of the log values of the actual parameter values. An ancillary program (Appendix 2) was written to calculate

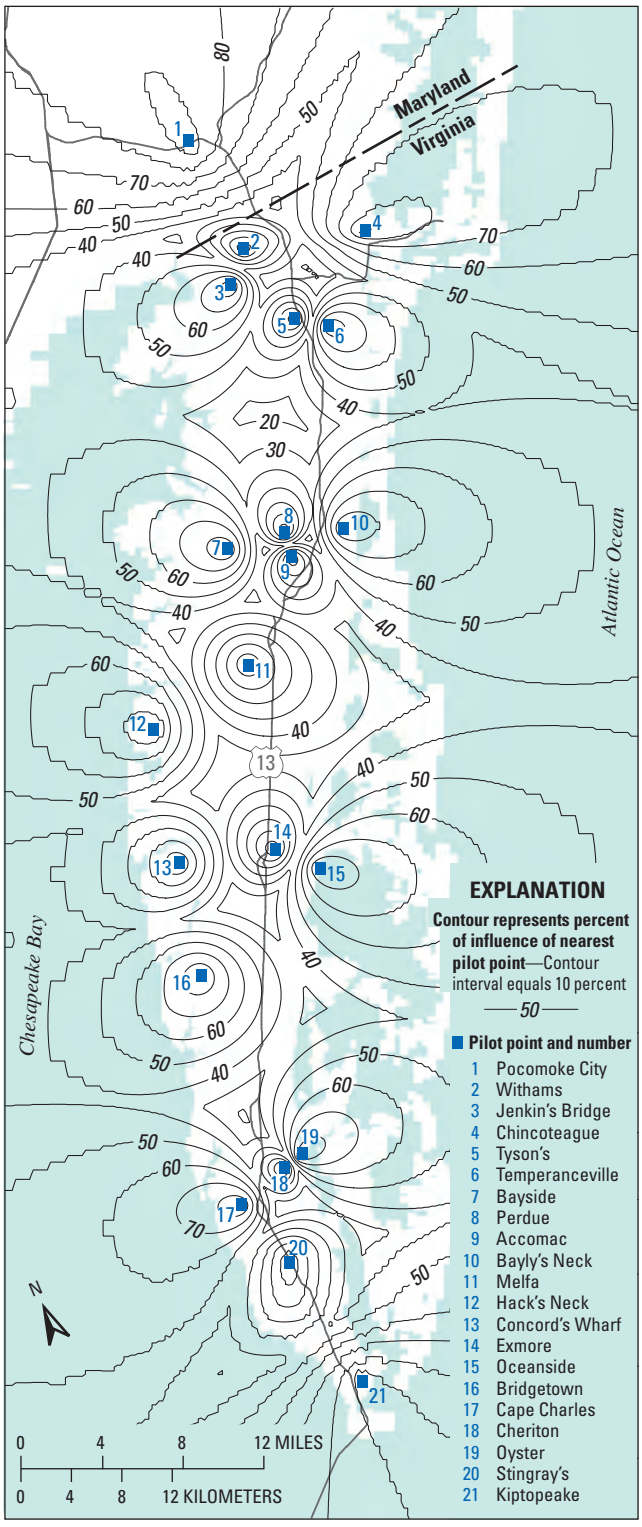


Figure 28. Percent of influence near each of the parameter pilot points used for model calibration of the Eastern Shore of Virginia.

these fields and print out the required input data sets before each SEAWAT run. This program is no longer required for use of the model, as a calibrated set of parameter values is now available.

Porosity

Porosity does not directly enter the flow equation, nor does it affect the water-level calculations. It does, however, directly affect solute transport and the timing of the movement of saltwater within the system. There are few data that allow for calibration of the porosity values as a function of space within the Eastern Shore. Direct measurements are available, however, and the values are not likely to differ much from those typically expected for unconsolidated sediment. In the spring of 2006, cores were obtained from the entire vertical thickness of the flow system in Northampton County. Porosity values of these cores were measured (fig. 29) by weighing them both wet and dry to determine the bulk and water volumes. Based on these data the aquifers were assigned a porosity value of 40 percent and the confining units a value of 50 percent. The surficial aquifer appears to have an average porosity of about 47 percent, but little saltwater movement occurs in that aquifer. These values are total porosity values and are not to be confused with effective porosity values. These two values may be close in regional systems where groundwater movement is slow and where effective and total porosity become indistinguishable at low velocities in homogeneous material (Neretnieks, 1981). A value close to total porosity is used in this study, as saltwater encroachment

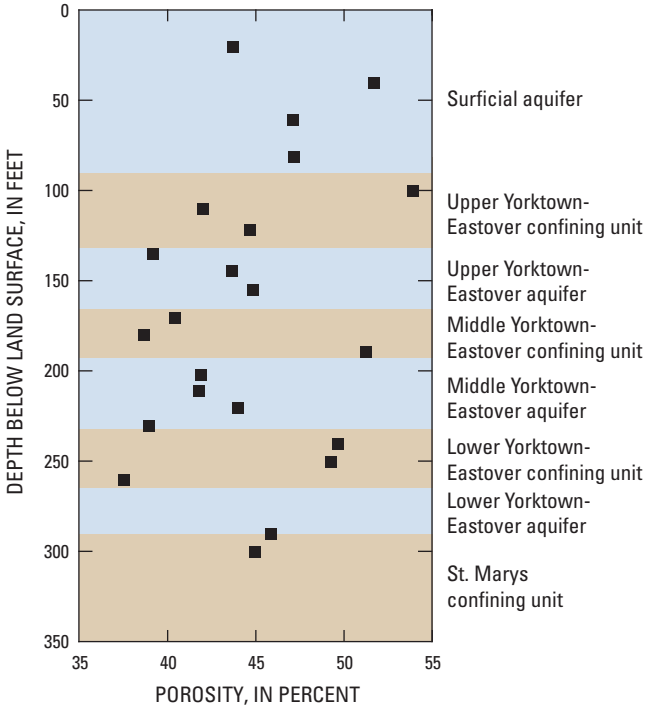


Figure 29. Porosity values of core samples taken approximately 5 miles north of the town of Cape Charles, Virginia.

Table 5. Information on observation (non-supply) wells on the Eastern Shore of Virginia used in this study.

[USGS, U.S. Geological Survey; aquifer: upper, middle, and lower refers to Yorktown-Eastover aquifer; °, degrees; ', minutes; ", seconds; —, unavailable]

USGS well number	Virginia State well number	Well name, owner, or source of data	Latitude (NAD 83)	Longitude (NAD 83)	Well depth, in feet	Aquifer
63G 20	SOW 075	Webster Co. G L	37°17'35"	75°57'25"	240	Middle
66K 4	SOW 101A	Bayly's Neck	37°43'19"	75°36'55"	152	Upper
66K 3	SOW 101B	Bayly's Neck	37°43'19"	75°36'55"	218	Middle
66K 2	SOW 101C	Bayly's Neck	37°43'19"	75°36'55"	292	Lower
64H 6	SOW 102A	Oceanside	37°29'25"	75°47'03"	154	Upper
64H 7	SOW 102B	Oceanside	37°29'21"	75°47'04"	220	Middle
64H 5	SOW 102C	Oceanside Campground	37°29'21"	75°47'04"	306	Lower
63H 6	SOW 103A	PC Kellam	37°27'05"	75°55'58"	37	Surficial
63H 5	SOW 103B	PC Kellam	37°27'05"	75°55'58"	132	Upper
63H 4	SOW 103C	PC Kellam	37°27'06"	75°55'58"	235	Middle
63G 17	SOW 104A	Doughty's Grocery	37°17'09"	75°56'07"	140	Upper
63G 16	SOW 104B	Doughty's Grocery	37°17'09"	75°56'07"	240	Middle
63G 15	SOW 104C	Doughty's Grocery	37°17'09"	75°56'06"	310	Lower
63G 21	SOW 104S	Doughty's Grocery	37°17'09"	75°56'07"	36	Surficial
63F 15	SOW 105A	Cape Center	37°13'08"	75°58'34"	130	Upper
63F 17	SOW 105B	Cape Center	37°13'08"	75°58'34"	196	Middle
63F 16	SOW 105C	Cape Center	37°13'08"	75°58'34"	285	Lower
64K 9	SOW 106A	Hack's Neck	37°38'45"	75°52'24"	37	Upper
64K 8	SOW 106B	Hack's Neck	37°38'45"	75°52'24"	94	Upper
64K 7	SOW 106C	Hack's Neck	37°38'45"	75°52'24"	164	Middle
66L 2	SOW 107A	Chesser Brothers	37°52'25"	75°32'16"	139	Upper
66L 3	SOW 107B	Chesser Brothers	37°52'25"	75°32'16"	201	Middle
66L 1	SOW 107C	Chesser Brothers	37°52'25"	75°32'16"	305	Lower
64K 10	SOW 108A	Melfa	37°39'32"	75°45'26"	50	Surficial
64K 11	SOW 108B	Melfa	37°39'32"	75°45'26"	175	Upper
64K 12	SOW 108C	Melfa	37°39'32"	75°45'26"	284	Lower
65K 24	SOW 109A	Bayside	37°44'42"	75°43'24"	130	Upper
65K 25	SOW 109B	Bayside	37°44'42"	75°43'24"	228	Lower
65K 23	SOW 109C	Bayside	37°44'42"	75°43'27"	290	Lower
65K 26	SOW 109S	Bayside	37°44'42"	75°43'24"	25	Surficial

Table 5. Information on observation (non-supply) wells on the Eastern Shore of Virginia used in this study.—Continued

[USGS, U.S. Geological Survey; aquifer: upper, middle, and lower refers to Yorktown-Eastover aquifer; °, degrees; ', minutes; ", seconds; —, unavailable]

USGS well number	Virginia State well number	Well name, owner, or source of data	Latitude (NAD 83)	Longitude (NAD 83)	Well depth, in feet	Aquifer
66M 16	SOW 110A	Withams	37°57'23"	75°34'43"	130	Upper
66M 17	SOW 110B	Withams	37°57'23"	75°34'43"	178	Middle
66M 18	SOW 110C	Withams	37°57'23"	75°34'44"	240	Lower
66M 19	SOW 110S	Withams	37°57'23"	75°34'43"	36	Surficial
63G 22	SOW 111A	Cheriton	37°16'53"	75°58'47"	150	Upper
63G 23	SOW 111B	Cheriton	37°16'53"	75°58'47"	280	Lower
63G 24	SOW 111C	Cheriton	37°16'53"	75°58'47"	330	Lower
63G 25	SOW 111S	Cheriton	37°16'53"	75°58'47"	56	Surficial
64J 9	SOW 112A	Willis' Wharf	37°30'59"	75°48'44"	135	Upper
64J 10	SOW 112B	Willis' Wharf	37°30'59"	75°48'44"	210	Middle
64J 11	SOW 112C	Willis' Wharf	37°30'59"	75°48'44"	313	Lower
64J 12	SOW 112S	Willis' Wharf	37°30'59"	75°48'44"	47	Surficial
63J 1	SOW 113A	Concord's Wharf	37°32'16"	75°54'06"	120	Upper
63J 2	SOW 113B	Concord's Wharf	37°32'16"	75°54'06"	236	Lower
63J 3	SOW 113C	Concord's Wharf	37°32'16"	75°54'06"	290	Lower
65K 27	SOW 114A	Perdue	37°44'25"	75°39'59"	160	Upper
65K 28	SOW 114B	Perdue	37°44'25"	75°39'59"	230	Middle
65K 29	SOW 114C	Perdue	37°44'27"	75°39'59"	315	Lower
65K 30	SOW 114S	Perdue	37°44'25"	75°39'59"	40	Surficial
67M 10	SOW 115A	Chincoteague	37°56'35"	75°27'14"	51	Surficial
67M 11	SOW 115B	Chincoteague	37°56'35"	75°27'14"	138	Upper
67M 12	SOW 115C	Chincoteague	37°56'35"	75°27'14"	222	Middle
67M 13	SOW 115D	Chincoteague	37°56'35"	75°27'14"	249	Middle
67M 14	SOW 115E	Chincoteague	37°56'17"	75°27'36"	280	Middle
64J 13	SOW 120	Corp Amer Original	37°30'46"	75°48'24"	105	Upper
62G 15	SOW 121	Cape Charles	37°15'43"	76°00'33"	190	Middle
63G 26	SOW 160	Corp KMC Foods Inc	37°17'27"	75°57'27"	320	Lower
63G 27	SOW 161	Smith HA	37°17'10"	75°55'21"	185	Middle
66M 25	SOW 181C	Jenkin's Bridge	37°56'10"	75°36'17"	303	Lower
66M 26	SOW 181D	Jenkin's Bridge	37°56'10"	75°36'17"	230	Lower

Table 5. Information on observation (non-supply) wells on the Eastern Shore of Virginia used in this study.—Continued

[USGS, U.S. Geological Survey; aquifer: upper, middle, and lower refers to Yorktown-Eastover aquifer; °, degrees; ', minutes; ", seconds; —, unavailable]

USGS well number	Virginia State well number	Well name, owner, or source of data	Latitude (NAD 83)	Longitude (NAD 83)	Well depth, in feet	Aquifer
63F 53	SOW 182C	Kiptopeake	37°08'08"	75°57'07"	256	Lower
63F 54	SOW 182D	Kiptopeake	37°08'08"	75°57'07"	55	Upper
65K 59	SOW 183A	Accomac	37°43'14"	75°40'13"	285	Lower
65K 60	SOW 183B	Accomac	37°43'14"	75°40'13"	233	Middle
65K 61	SOW 183C	Accomac	37°43'14"	75°40'13"	134	Upper
65K 62	SOW 183D	Accomac	37°43'14"	75°40'13"	20	Surficial
62G 8	none	Bayshore Concrete	37°15'40"	76°01'20"	200	Middle
63F 1	none	School Northampton	37°11'60"	75°57'31"	453	Lower
63F 9	none	Hotel Holiday Inn	37°10'58"	75°58'13"	115	Upper
63F 10	none	Hotel Holiday Inn	37°10'58"	75°58'13"	203	Middle
63F 34	none	U.S. Geological Survey	37°13'08"	75°58'35"	13	Surficial
63F 44	none	—	37°11'26"	75°57'01"	26	Surficial
63F 55	none	VASWCB Res St	37°08'08"	75°57'07"	20	Surficial
63G 13	none	—	37°21'06"	75°56'18"	165	Upper
63G 18	none	VA Ag Prod	37°21'44"	75°55'20"	190	Upper
63G 29	none	Corp KMC Foods Inc	37°17'26"	75°57'37"	330	Middle
63H 3	none	School Machipongo	37°24'14"	75°54'32"	67	Surficial
63J 4	none	Busn Busy B's Grocery	37°32'20"	75°54'14"	40	Surficial
64H 2	none	Hosp Accomack	37°28'34"	75°51'43"	300	Middle
64J 1	none	School Accomack Brd	37°36'00"	75°46'37"	337	Lower
64J 4	none	Busn Exmore Foods Inc	37°32'01"	75°49'12"	285	Middle
64J 19	none	Corp Exmore Foods Inc	37°32'03"	75°49'15"	218	Middle
64J 27	none	School Hare Valley Elem	37°30'13"	75°51'11"	225	Middle
64J 29	none	U.S. Geological Survey	37°33'30"	75°49'45"	40	Surficial
64K 5	none	School Comm College	37°38'28"	75°45'08"	290	Lower
65J 4	none	Gulf Stream Nuresy	37°35'28"	75°42'07"	267	Middle
65K 6	none	Town of Onley	37°41'23"	75°42'58"	179	Upper
65K 9	none	Town of Onancock	37°42'34"	75°44'31"	110	Upper
65K 20	none	Accomack Co. Jail	37°43'11"	75°40'14"	295	Lower
65K 22	none	Busn Acme Grocery	37°41'53"	75°43'08"	178	Upper

Table 5. Information on observation (non-supply) wells on the Eastern Shore of Virginia used in this study.—Continued

[USGS, U.S. Geological Survey; aquifer: upper, middle, and lower refers to Yorktown-Eastover aquifer; °, degrees; ', minutes; ", seconds; —, unavailable]

USGS well number	Virginia State well number	Well name, owner, or source of data	Latitude (NAD 83)	Longitude (NAD 83)	Well depth, in feet	Aquifer
65K 34	none	Knight Joe	37°39'04"	75°40'33"	218	Middle
65K 39	none	U.S. Geological Survey	37°39'16"	75°41'07"	22	Surficial
65L 3	none	Town of Parksley	37°47'04"	75°38'60"	153	Upper
65L 4	none	Town of Parksley	37°47'03"	75°38'60"	63	Surficial
65L 6	none	Busn Byrd Packing Co.	37°45'30"	75°40'09"	266	Middle
66M 2	none	Corp Kelley Co H E	37°58'30"	75°32'15"	229	Middle
66L 6	none	Corp Messick & Wessills	37°49'00"	75°35'23"	246	Middle
66L 12	none	U.S. Geological Survey	37°47'55"	75°37'09"	28	Surficial
66M 9	none	Busn Holly Farms Inc	37°52'56"	75°33'22"	289	Middle
66M 14	none	School Atlantic High	37°55'34"	75°32'58"	290	Lower
66M 15	none	Busn Kelley Company	37°58'42"	75°32'18"	226	Middle
66M 22	none	Highways VA Dept of	37°59'20"	75°32'04"	132	Upper
67M 7	none	—	37°56'26"	75°28'43"	225	Upper
67M 24	none	Town of Chincoteague	37°56'38"	75°27'19"	245	Middle
SO Cf 2	none	Maryland	38°06'16"	75°38'06"	15	Surficial
WO Fb 2	none	Maryland	38°04'07"	75°33'57"	121	Upper
WO Fc 50	none	Maryland	38°01'28"	75°25'35"	50	Surficial
WO Fc 51	none	Maryland	38°01'28"	75°25'35"	20	Surficial
WO Fc 52	none	Maryland	38°01'42"	75°25'57"	50	Surficial
WO Fc 53	none	Maryland	38°01'42"	75°25'57"	25	Surficial
WO Fc 54	none	Maryland	38°00'58"	75°27'16"	18	Surficial
WO Fc 56	none	Maryland	38°02'09"	75°27'17"	25	Surficial
WO Fc 57	none	Maryland	38°02'54"	75°27'45"	49	Surficial
WO Fc 58	none	Maryland	38°02'54"	75°27'45"	25	Surficial
none	100-1008	Tyson's	37°53'15"	75°33'18"	305	Lower
none	100-1009	Tyson's	37°53'15"	75°33'20"	245	Middle
none	100-1010	Tyson's	37°53'15"	75°33'19"	180	Upper
none	100-0011	Tyson's	37°53'34"	75°33'55"	300	Lower
none	100-0012	Tyson's	37°53'34"	75°33'55"	230	Middle
none	100-0013	Tyson's	37°53'33"	75°33'55"	165	Upper

Table 5. Information on observation (non-supply) wells on the Eastern Shore of Virginia used in this study.—Continued

[USGS, U.S. Geological Survey; aquifer: upper, middle, and lower refers to Yorktown-Eastover aquifer; °, degrees; ', minutes; ", seconds; —, unavailable]

USGS well number	Virginia State well number	Well name, owner, or source of data	Latitude (NAD 83)	Longitude (NAD 83)	Well depth, in feet	Aquifer
S&T 03b	none	Sinnott & Tibbits (1954)	—	—	189	Upper
S&T 07	none	Sinnott & Tibbits (1954)	—	—	235	Middle
S&T 08j	none	Sinnott & Tibbits (1954)	—	—	228	Middle
S&T 13	none	Sinnott & Tibbits (1954)	—	—	168	Upper
S&T 15	none	Sinnott & Tibbits (1954)	—	—	140	Upper
S&T 18	none	Sinnott & Tibbits (1954)	—	—	173	Upper
S&T 21	none	Sinnott & Tibbits (1954)	—	—	123	Upper
S&T 23	none	Sinnott & Tibbits (1954)	—	—	180	Middle
S&T 25	none	Sinnott & Tibbits (1954)	—	—	123	Upper
S&T 30	none	Sinnott & Tibbits (1954)	—	—	190	Lower
S&T 33	none	Sinnott & Tibbits (1954)	—	—	162	Middle
S&T 35	none	Sinnott & Tibbits (1954)	—	—	174	Upper
S&T 36	none	Sinnott & Tibbits (1954)	—	—	133	Upper
S&T 39	none	Sinnott & Tibbits (1954)	—	—	174	Upper
S&T 43	none	Sinnott & Tibbits (1954)	—	—	200	Middle
S&T 44b	none	Sinnott & Tibbits (1954)	—	—	304	Lower
S&T 46	none	Sinnott & Tibbits (1954)	—	—	248	Lower
S&T 48	none	Sinnott & Tibbits (1954)	—	—	232	Lower
S&T 49	none	Sinnott & Tibbits (1954)	—	—	128	Upper
S&T 50b	none	Sinnott & Tibbits (1954)	—	—	172	Upper
S&T 53	none	Sinnott & Tibbits (1954)	—	—	240	Lower
S&T 54	none	Sinnott & Tibbits (1954)	—	—	365	Lower
S&T 56	none	Sinnott & Tibbits (1954)	—	—	190	Middle
S&T 57	none	Sinnott & Tibbits (1954)	—	—	256	Lower
S&T 59	none	Sinnott & Tibbits (1954)	—	—	255	Middle
S&T 61	none	Sinnott & Tibbits (1954)	—	—	147	Upper
S&T 62	none	Sinnott & Tibbits (1954)	—	—	153	Upper
S&T 64	none	Sinnott & Tibbits (1954)	—	—	138	Upper
S&T 65	none	Sinnott & Tibbits (1954)	—	—	220	Middle
S&T 65	none	Sinnott & Tibbits (1954)	—	—	111	Upper
S&T 67	none	Sinnott & Tibbits (1954)	—	—	189	Middle
S&T 68	none	Sinnott & Tibbits (1954)	—	—	302	Lower
S&T 69	none	Sinnott & Tibbits (1954)	—	—	230	Middle
S&T 71	none	Sinnott & Tibbits (1954)	—	—	296	Lower

Table 5. Information on observation (non-supply) wells on the Eastern Shore of Virginia used in this study.—Continued

[USGS, U.S. Geological Survey; aquifer: upper, middle, and lower refers to Yorktown-Eastover aquifer; °, degrees; ', minutes; ", seconds; —, unavailable]

USGS well number	Virginia State well number	Well name, owner, or source of data	Latitude (NAD 83)	Longitude (NAD 83)	Well depth, in feet	Aquifer
S&T 80	none	Sinnott & Tibbits (1954)	—	—	299	Lower
S&T 82	none	Sinnott & Tibbits (1954)	—	—	123	Upper
S&T 84	none	Sinnott & Tibbits (1954)	—	—	228	Middle
S&T 85	none	Sinnott & Tibbits (1954)	—	—	165	Upper
S&T 88	none	Sinnott & Tibbits (1954)	—	—	220	Upper
S&T 88	none	Sinnott & Tibbits (1954)	—	—	300	Lower
S&T 94	none	Sinnott & Tibbits (1954)	—	—	123	Upper
S&T 95	none	Sinnott & Tibbits (1954)	—	—	105	Upper
S&T 97	none	Sinnott & Tibbits (1954)	—	—	267	Lower
S&T 100	none	Sinnott & Tibbits (1954)	—	—	220	Middle
S&T 102	none	Sinnott & Tibbits (1954)	—	—	160	Upper
S&T 104	none	Sinnott & Tibbits (1954)	—	—	115	Upper
S&T 106	none	Sinnott & Tibbits (1954)	—	—	160	Upper
S&T 108c	none	Sinnott & Tibbits (1954)	—	—	210	Middle
S&T 111	none	Sinnott & Tibbits (1954)	—	—	127	Upper
S&T 117	none	Sinnott & Tibbits (1954)	—	—	287	Lower
S&T 119	none	Sinnott & Tibbits (1954)	—	—	187	Middle
S&T 119	none	Sinnott & Tibbits (1954)	—	—	144	Upper
S&T 125	none	Sinnott & Tibbits (1954)	—	—	104	Upper
S&T 126	none	Sinnott & Tibbits (1954)	—	—	128	Upper
S&T 139	none	Sinnott & Tibbits (1954)	—	—	194	Upper
S&T 139	none	Sinnott & Tibbits (1954)	—	—	112	Upper
S&T 146	none	Sinnott & Tibbits (1954)	—	—	140	Upper
S&T 152	none	Sinnott & Tibbits (1954)	—	—	222	Middle
S&T 156	none	Sinnott & Tibbits (1954)	—	—	265	Lower
S&T 158	none	Sinnott & Tibbits (1954)	—	—	120	Upper
S&T 164	none	Sinnott & Tibbits (1954)	—	—	179	Middle
S&T 167	none	Sinnott & Tibbits (1954)	—	—	230	Middle
S&T 168	none	Sinnott & Tibbits (1954)	—	—	173	Upper
S&T 169	none	Sinnott & Tibbits (1954)	—	—	154	Middle
S&T 170	none	Sinnott & Tibbits (1954)	—	—	123	Upper
S&T 174	none	Sinnott & Tibbits (1954)	—	—	134	Upper
S&T 178	none	Sinnott & Tibbits (1954)	—	—	202	Middle
S&T 180	none	Sinnott & Tibbits (1954)	—	—	202	Middle

is a long-term, slow process on a regional scale. For smaller-spatially scaled contaminant-transport problems, the effective porosity may be somewhat less than the total porosity. This may include the seasonal movement of saline water in proximity to a well or well field. A lower value of effective porosity would result in an increase in seepage velocity and a faster migration of saline water toward wells.

Storage Coefficients

The storage coefficient, or specific storage, affects water levels near wells under transient conditions. It was determined during the calibration procedure that the water levels were very insensitive to the specific storage of the aquifer and were only sensitive to specific storage of confining units near areas where substantial pumping was occurring. Consequently, the specific storage for all of the aquifers was assigned a value of 4×10^{-6} ft^{-1}. The values for the confining units were assigned upper and lower bounds of 3×10^{-4} and 1×10^{-5} ft^{-1}, beyond which the values were not adjusted to improve fits. These values are typical of the specific-storage values for sediment types in these units (Domenico and Mifflin, 1965). Values for all estimated and specified values of specific storage and hydraulic conductivity at pilot points are given in table 6.

Table 6. Estimated and specified values of hydraulic parameters for the model of the Eastern Shore of Virginia.

[No., number; aquifer or confining unit refers to the Yorktown-Eastover; values in italic are specified; values in bold are estimated]

Pilot point		Hydraulic conductivity (feet per day)			Specific storage (1/feet)		Hydraulic conductivity (feet per day)				
		Confining unit					Aquifer				
No.	Name	Upper	Middle	Lower	All confining units	All aquifers	Upper	Middle	Lower	Surficial aquifer	
1	Pocomoke	**7.80E-04**	**3.00E-05**	**9.00E-03**	*1.00E-05*	*4.00E-06*	**18.0**	**19.0**	*75.0*	*75*	
2	Withams	**7.20E-04**	**3.70E-05**	**8.00E-05**	*1.00E-05*	*4.00E-06*	*0.5*	**1.0**	*0.5*	*75*	
3	Jenkin's Bridge	**3.60E-03**	**2.10E-05**	**2.00E-03**	*1.00E-05*	*4.00E-06*	*0.5*	*75.0*	*1.0*	*75*	
4	Chincoteague	**1.00E-03**	**1.00E-05**	**4.70E-03**	**1.60E-04**	*4.00E-06*	**23.0**	**4.8**	*75.0*	**75**	
5	Tyson's	**5.50E-04**	**6.00E-03**	**1.30E-04**	**1.50E-04**	*4.00E-06*	**7.2**	**8.3**	**13.9**	*75*	
6	Temperanceville	**6.00E-04**	**7.50E-03**	**2.00E-03**	**1.30E-04**	*4.00E-06*	**6.0**	**60.0**	**1.5**	*75*	
7	Bayside	**6.60E-04**	**6.50E-04**	**9.00E-05**	*1.00E-05*	*4.00E-06*	*0.5*	*75.0*	**10.4**	*50*	
8	Perdue	**8.40E-04**	**1.00E-03**	**5.20E-04**	*1.00E-05*	*4.00E-06*	**2.3**	*0.5*	**7.4**	*50*	
9	Accomac	**1.00E-03**	**2.60E-03**	**5.30E-05**	*1.00E-05*	*4.00E-06*	**28.0**	**19.0**	**7.2**	**50**	
10	Bayly's Neck	**1.46E-03**	**6.30E-04**	**7.10E-04**	*1.00E-05*	*4.00E-06*	**52.0**	**3.1**	**4.9**	*50*	
11	Melfa	**2.00E-03**	**7.00E-04**	**9.00E-05**	*1.00E-05*	*4.00E-06*	*1.0*	*1.0*	*1.0*	*50*	
12	Hack's Neck	**3.80E-05**	*5.00E-02*	*5.00E-02*	*1.00E-05*	*4.00E-06*	*75.0*	**32.0**	**3.0**	*50*	
13	Concord's Wharf	**4.00E-05**	*5.00E-02*	*5.00E-02*	*1.00E-05*	*4.00E-06*	*75.0*	**30.0**	**3.0**	*25*	
14	Exmore	**5.20E-05**	*5.00E-02*	**3.00E-03**	**5.00E-05**	*4.00E-06*	*1.0*	*75.0*	*75.0*	**25**	
15	Oceanside	**8.80E-05**	**2.00E-02**	**2.60E-02**	*1.00E-05*	*4.00E-06*	*75.0*	*75.0*	*75.0*	*25*	
16	Bridgetown	**6.20E-04**	**7.50E-04**	**7.00E-05**	**2.00E-05**	*4.00E-06*	*0.5*	*0.5*	*75.0*	*25*	
17	Cape Charles	**3.40E-04**	**5.00E-03**	*5.00E-02*	*3.00E-04*	*4.00E-06*	*75.0*	*0.5*	**7.0**	*100*	
18	Cheriton	**5.30E-04**	**3.30E-03**	*5.00E-02*	*3.00E-04*	*4.00E-06*	*0.5*	*0.5*	*0.5*	**100**	
19	Oyster	**4.60E-03**	**6.10E-04**	**3.10E-05**	**8.50E-05**	*4.00E-06*	*1.0*	*1.0*	*0.5*	*100*	
20	Stingray's	**1.30E-04**	**4.00E-03**	**3.40E-06**	*3.00E-04*	*4.00E-06*	*0.5*	*0.5*	**0.8**	*100*	
21	Kiptopeake	**9.80E-04**	*5.00E-02*	**1.60E-02**	*3.00E-04*	*4.00E-06*	*75.0*	*0.5*	*0.5*	*100*	
Median value		**6.60E-04**	**2.60E-03**	**2.00E-03**	**9.07E-05**	*4.00E-06*	**6.0**	**4.8**	**4.9**	**75**	
Mean value		**9.82E-04**	**1.20E-02**	**1.26E-02**	**9.07E-05**	*4.00E-06*	**25**	**23**	**21**	**64**	
											Total
Number estimated		**21**	**17**	**17**	**6**	**0**	**7**	**9**	**10**	**4**	**91**
Number specified		*0*	*4*	*4*	*15*	*21*	*14*	*12*	*11*	*17*	*81*

Yorktown-Eastover Aquifer Transmissive Properties

Hydraulic conductivity values for the confined aquifers were estimated at the pilot-point locations by the calibration procedure. Observations and historical pumping enabled many values in Accomack and northernmost Northampton Counties to be estimated, but values could not be estimated reliably for much of Northampton County. The values of hydraulic conductivity were given upper and lower bounds of 75 and 0.5 ft/d, respectively. The estimated hydraulic conductivity and transmissivity fields of the lower Yorktown-Eastover aquifer are shown in figure 30. Areas with higher values include the northeastern part of the study area and the area around the town of Exmore. The estimated hydraulic conductivity and transmissivity fields of the middle Yorktown-Eastover aquifer are shown in figure 31. Areas with higher values include the northwestern part of the study area and the area around the town of Exmore. The estimated hydraulic conductivity and transmissivity fields of the upper Yorktown-Eastover aquifer are shown in figure 32. Areas with higher values generally are located in local areas along the coasts. The simulated locations of the paleochannels are discernable in figures 30–32 because the paleochannels were assigned hydraulic conductivity values disctinct from the aquifer and confining units that they transect.

Surficial Aquifer Transmissive Properties

The hydraulic conductivity values of the surficial aquifer were estimated with the aid of water-level and groundwater age (SF_6) data (fig. 33). As fewer data were available for the surficial aquifer than the confined aquifers, only four separate values were estimated independently for the pilot points (table 5). Several pilot points were assigned to each of four sections from north to south through the study area, and only one value was estimated for each area. From north to south, the estimated values were 75, 50, 25, and 100 ft/d. Kriging was used in the same manner as for the confined aquifers to create the smoothly varying field. The transmissivity (T) values for the surficial aquifer reflect the aquifer saturated thickness (b) in addition to the hydraulic conductivity (K) values (T = K*b).

Yorktown-Eastover Confining Unit Leakance Properties

Hydraulic conductivity values for the Yorktown-Eastover confining units also were estimated for the pilot-point locations by the calibration procedure. As a whole, the simulated water levels were more sensitive to the hydraulic conductivity of the confining units than of the aquifers. This likely is because the predevelopment water levels are controlled more by the confining units than the aquifers. Values for the majority of the pilot points were obtained by the calibration procedure. The values of hydraulic conductivity were given an upper bound of 0.05 ft/d; no lower bound was required. The upper bound (0.05 ft/d) was chosen to be one order of magnitude below the lower bound for the aquifers in order to be consistent with the conceptual model of differentiating three aquifers and three confining layers. The hydraulic conductivity and vertical leakance fields of the lower Yorktown-Eastover confining unit are shown in figure 34. Areas with high leakance include the northeastern part of the study area and the areas around the towns of Exmore and Cape Charles. The hydraulic conductivity and vertical leakance fields of the middle Yorktown-Eastover confining unit are shown in figure 35. Areas with high leakage include the central area around the town of Exmore and the southernmost part of the peninsula. The hydraulic conductivity and vertical leakance fields of the upper Yorktown-Eastover confining unit are shown in figure 36. This confining unit tends to be somewhat thicker than the lower and middle confining units and therefore is more ubiquitous and less leaky across the Eastern Shore.

Paleochannel Aquifer Properties

The paleochannels were assigned hydraulic conductivity values that were unrelated to values of the other confined aquifers. The paleochannels were delineated in the model on the basis of estimates of their depth and location (D.S. Powars, U.S. Geological Survey, written commun., 2004). The calibration procedure indicated that there are too few water-level observation data in the paleochannels to estimate the values of hydraulic conductivity for the channels; therefore, a value of 100 ft/d was assigned to the northern, Exmore channel, and a value of 5 ft/d was assigned to the southern, Eastville channel. The upper parts of the channels were capped by finer-grained material as the sea levels rose and flooding occurred. To account for this, channel deposits were assumed to have hydraulic conductivities similar to confining units in their uppermost sections. Therefore, within the model layers representing the upper Yorktown-Eastover confining unit, the paleochannels were not considered to have independent hydraulic conductivities; their values were treated as part of the smoothly varying hydraulic conductivity field of the confining unit.

St. Marys Confining Unit Properties

The bottom four layers of the model represent the St. Marys confining unit. These were included so that the model could simulate the potential release of saline water from beneath the confined-aquifer system and upward seepage into pumping centers. They were also included to simulate release of water from storage from this unit that may affect water levels in the lower aquifer. As no observation data are present within the St. Marys confining unit, there are no estimates of it is hydraulic properties independent from core measurements. For this reason, the unit was assigned a hydraulic conductivity of 1×10^{-5} ft/d (Richardson, 1994), and the specific storage was assigned a value of 3×10^{-4} ft^{-1}, which is the upper bound value used for the other confining units and a value typical of the clayey-silty sediment that is common in the unit.

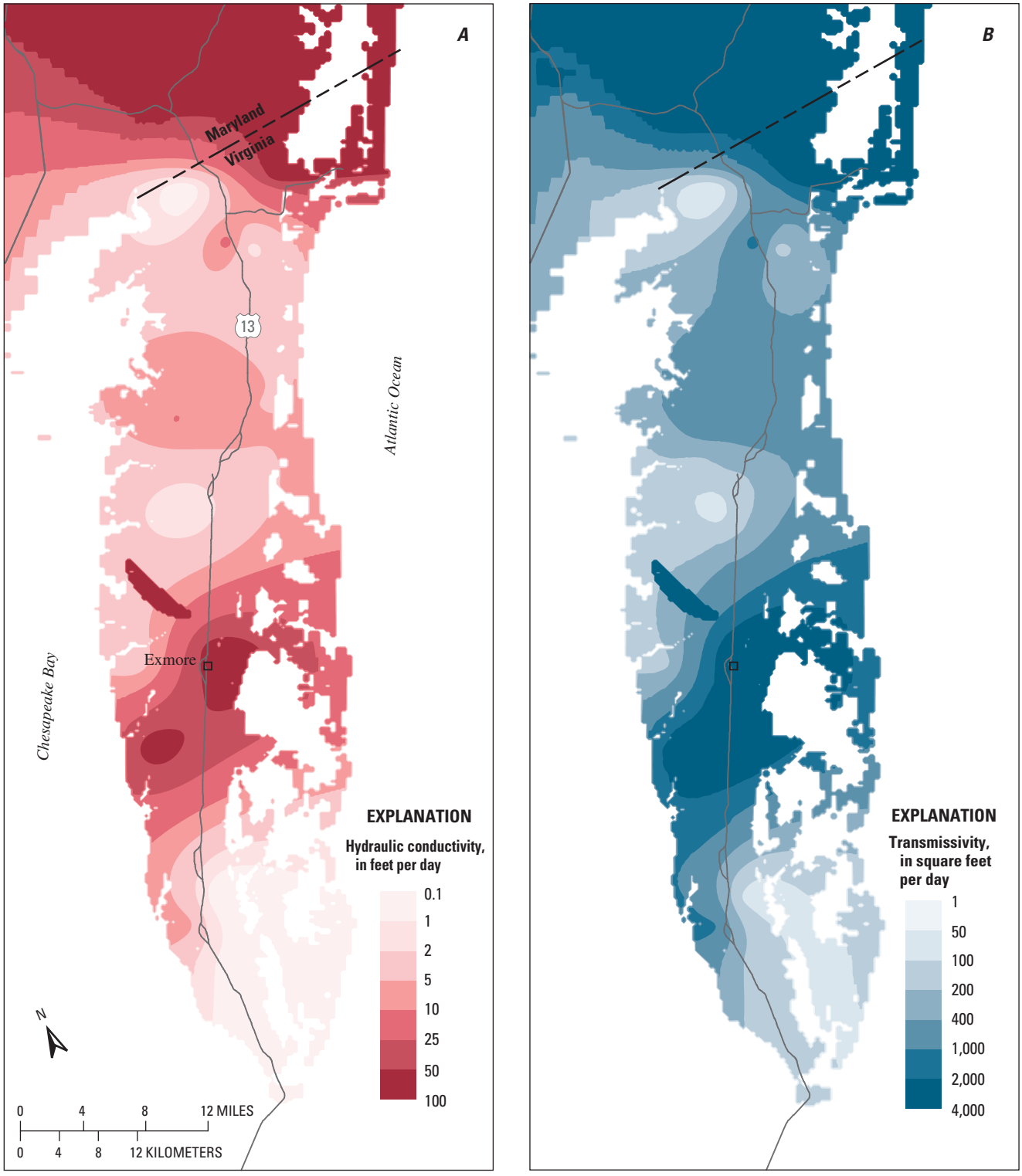


Figure 30. The calibrated *(A)* hydraulic conductivity and *(B)* transmissivity of the lower Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

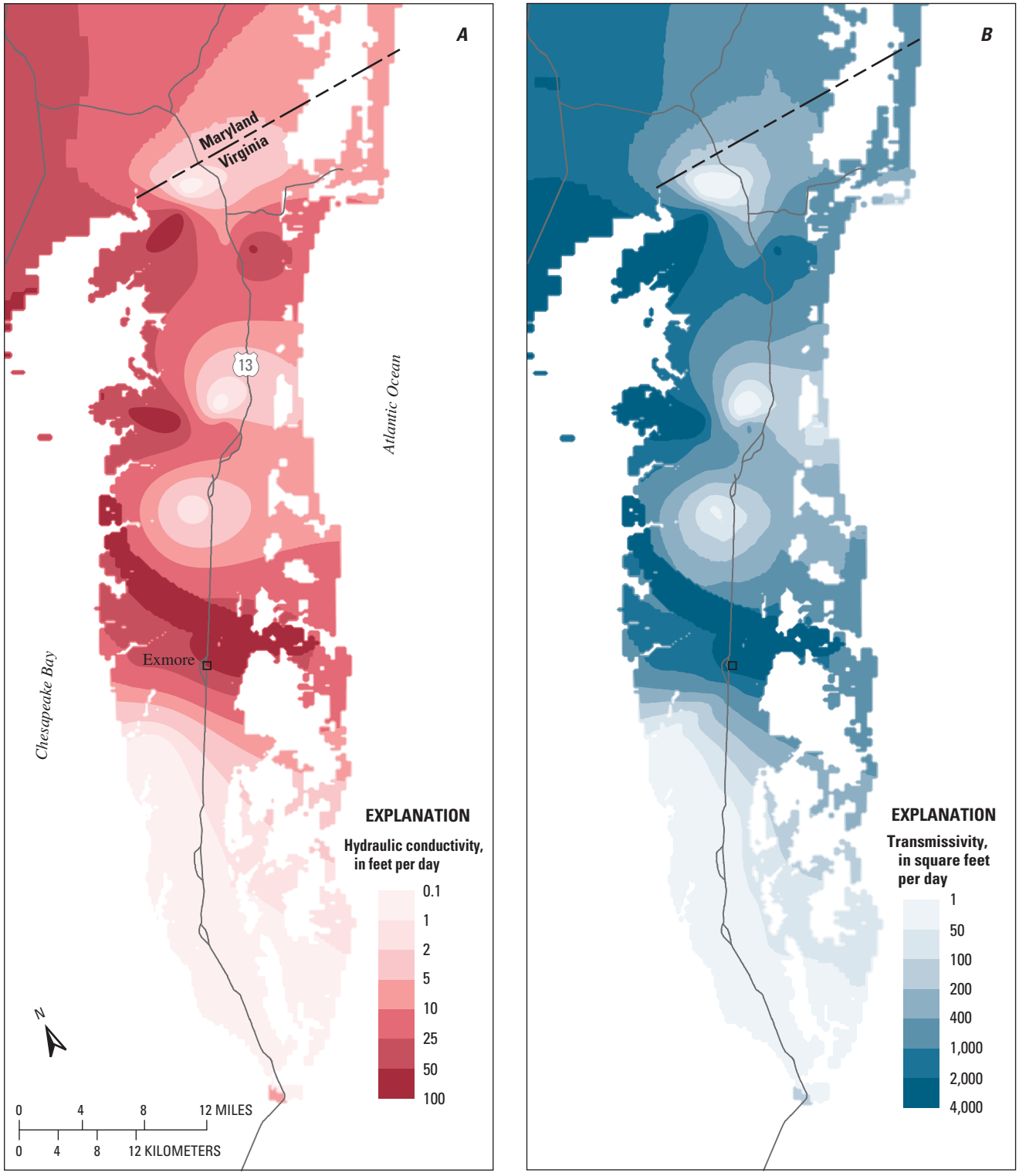


Figure 31. The calibrated *(A)* hydraulic conductivity and *(B)* transmissivity of the middle Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

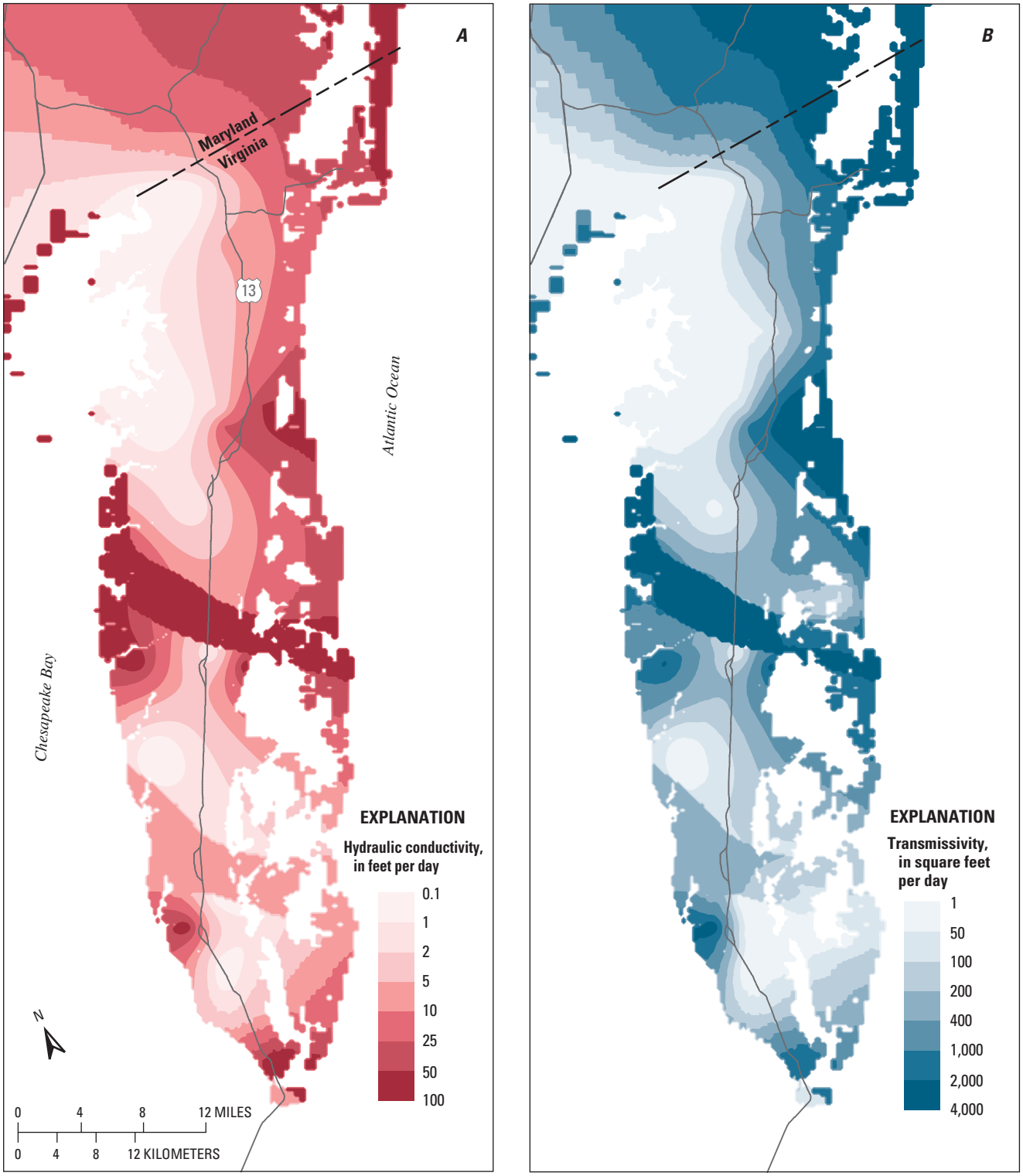


Figure 32. The calibrated *(A)* hydraulic conductivity and *(B)* transmissivity of the upper Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

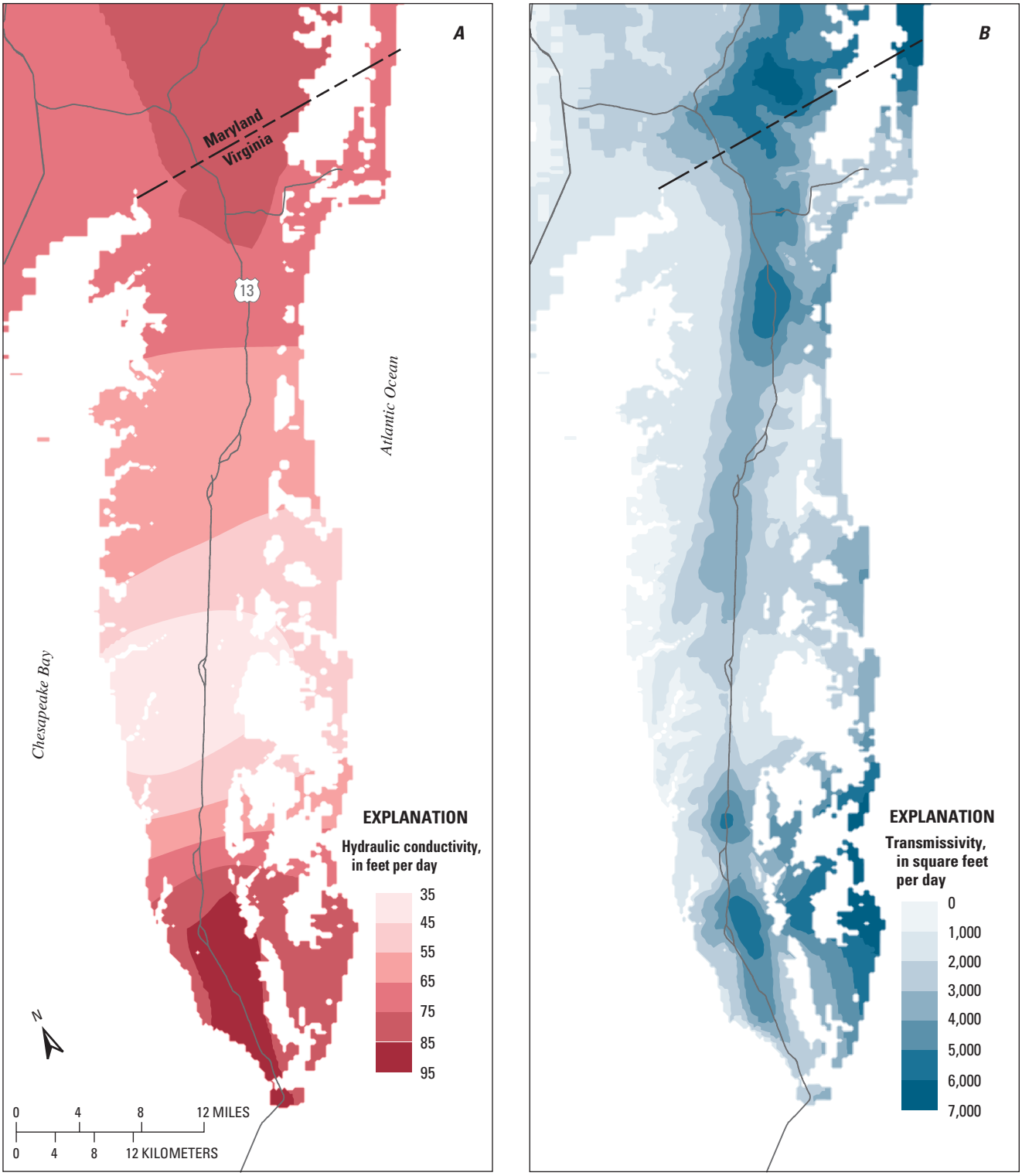


Figure 33. The calibrated *(A)* hydraulic conductivity and *(B)* transmissivity of the surficial aquifer of the Eastern Shore of Virginia.

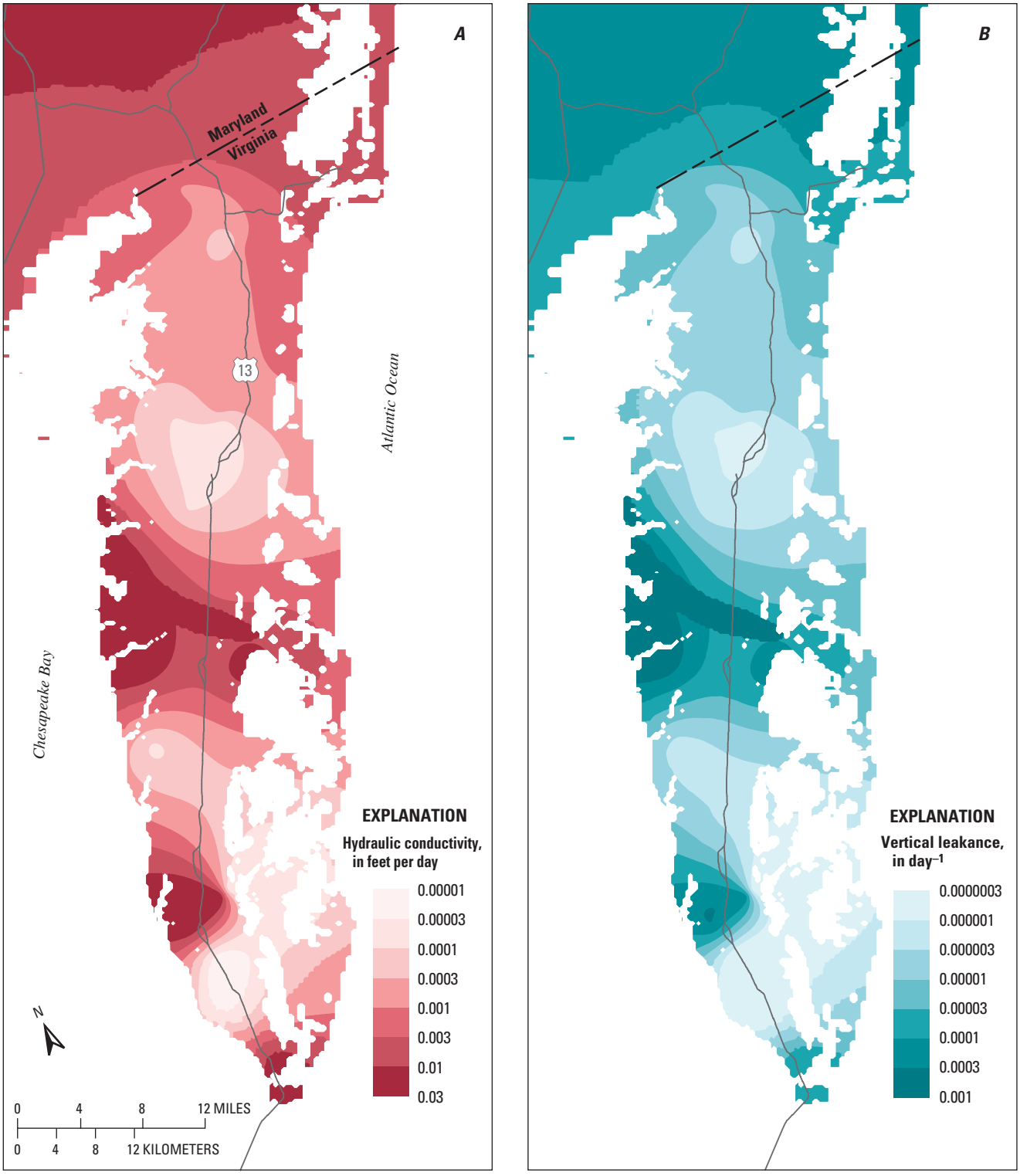


Figure 34. The calibrated *(A)* hydraulic conductivity and *(B)* vertical leakance of the lower Yorktown-Eastover confining unit of the Eastern Shore of Virginia.

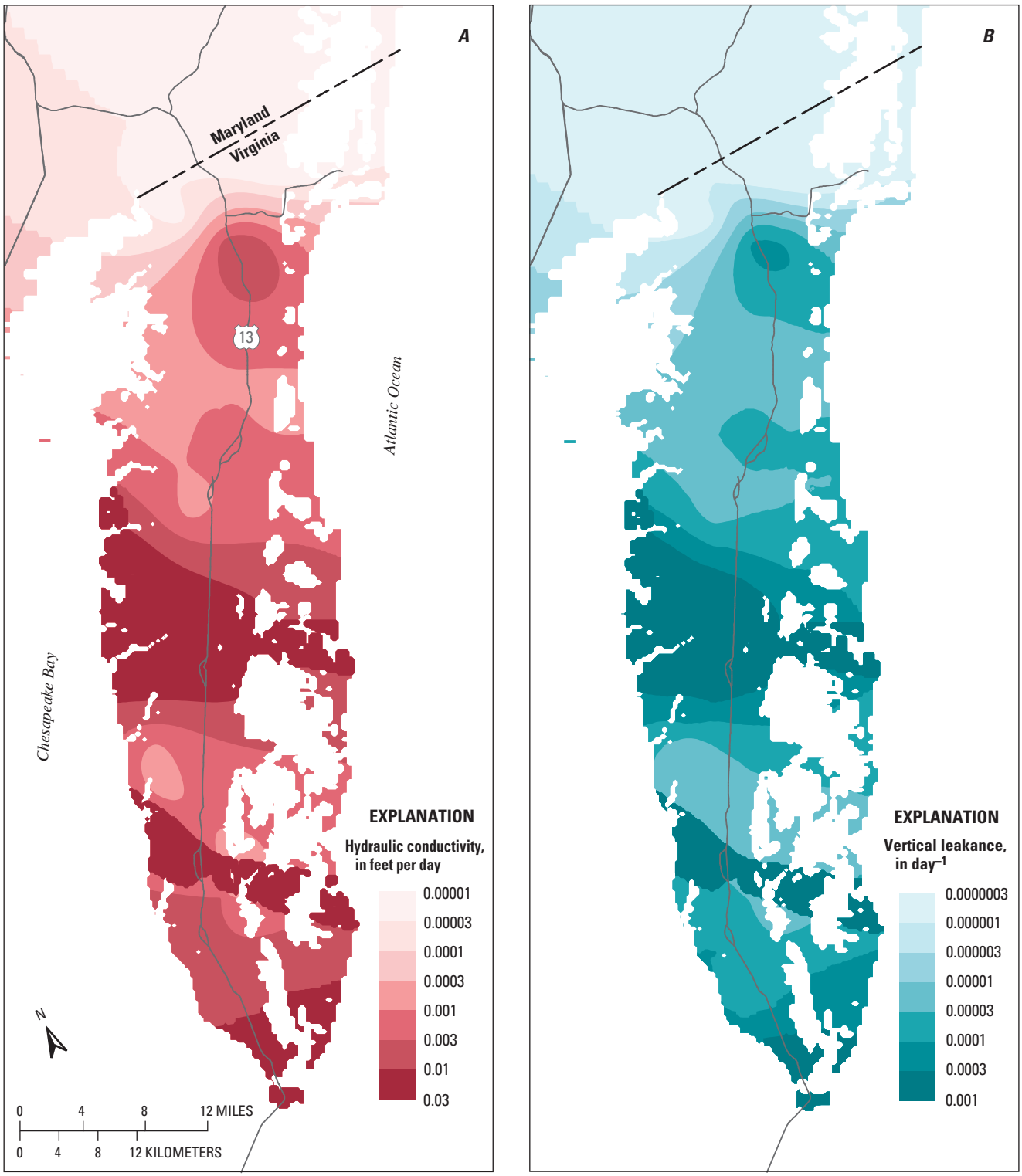


Figure 35. The calibrated *(A)* hydraulic conductivity and *(B)* vertical leakance of the middle Yorktown-Eastover confining unit of the Eastern Shore of Virginia.

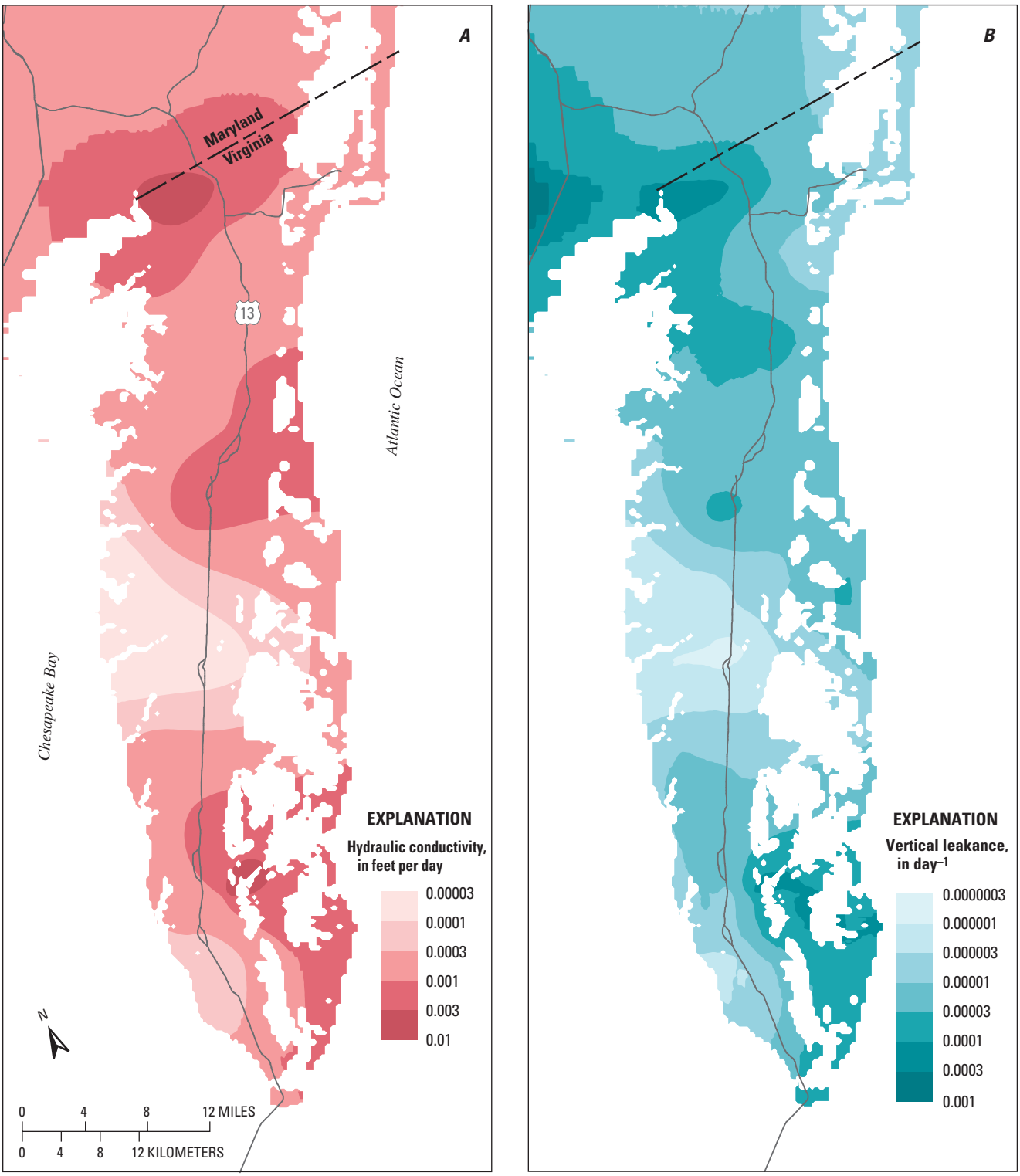


Figure 36. The calibrated *(A)* hydraulic conductivity and *(B)* vertical leakance of the upper Yorktown-Eastover confining unit of the Eastern Shore of Virginia.

Groundwater Model Simulations

Model-calibration simulations had a start time at the beginning of 1900 and an end time at the end of 2003. Each year was considered to be a separate stress period in SEAWAT, and each stress period was divided into four time steps. The time-step lengths increased geometrically within each stress period in order to have a smaller time step at the beginning of a new stress period immediately after the stresses were changed. The time-step multiplier was adjusted so that the end of time-step 3 was always half way through the given year. The model was calibrated by running flow simulations with an approximate representation of the saltwater transition zone. Transient transport was simulated after the hydraulic parameters had been estimated, during which the chloride-concentration field was adjusted to fit the known conditions beneath the Eastern Shore. Further calibration following the adjustment of the chloride-concentration field did not create any significant changes in the estimates of the parameter values. A summary of the simulated hydrologic budget through time is given in table 7.

Historical Water Levels

Simulated water levels for predevelopment conditions (the year 1900) are shown in figures 37 and 38. Overall, the highest water levels are beneath the central-upland ridge. Water levels in the surficial aquifer most closely resemble the land-surface topography, and water levels decrease with increasing depth beneath the central ridge, reflecting a downward gradient and recharge. Water levels in the surficial aquifer exceed 20 ft above mean sea level (amsl) along the ridge, whereas water levels in the lower aquifer usually do not exceed 15 ft amsl.

Simulated water levels for 1980 and 2000 are shown in figures 39–41. A small cone-of-depression had developed in southern Northampton County by 1980, but water levels in that area recovered by 2000 because much of the withdrawals in that area had ceased. In central Accomack County, two simulated cones of depression persist through 2000 because of pumping associated with two large poultry-processing facilities. These cones are larger in 2000 than in 1980 and are of greater lateral extent in the lower Yorktown-Eastover aquifer. Simulated water levels in Maryland near the northwest corner of the model area are below sea level in the lower and middle aquifers, especially in 2000, but uncertainties in the aquifer properties there and the proximity to the northern general-head boundary make it uncertain how closely these water levels reflect actual conditions. The simulated drawdowns in Maryland are sufficiently far from Virginia that the effect on simulated water levels in Virginia is relatively small. Increasing the conductance term to the northern general-head boundary would increase the simulated water levels in Maryland.

Simulated water levels in the surficial aquifer show little to no difference between 1980 and 2000 (fig. 42). A comparison of these water levels to 1900 (fig. 38*B*) also indicates that there is little change in simulated water levels in the surficial aquifer since predevelopment time. This is because drawdowns in the confined aquifers resulting from pumping in recent decades have not propogated upward across the upper confining unit. Simulated water levels in some coastal areas are slightly below sea level. This is caused by evapotranspiration in the marsh areas, which also have low recharge and low hydraulic conductivity. The relative hydraulic isolation of the surficial aquifer from the confined aquifers can be seen in cross-sectional views of the simulated water levels (fig. 43).

Table 7. Hydrologic budget components of the model of the Eastern Shore of Virginia through time.

[All values are in millions of gallons per day]

Year	Groundwater inflows		Groundwater outflows			
	Recharge	Release from storage	Evapo-transpiration	Coastal discharge	Production wells	Domestic wells
1901	574.55	0.00	477.94	92.94	0.00	0.00
1910	574.55	0.00	478.07	96.41	0.00	0.00
1920	574.55	0.06	478.01	96.49	0.10	0.00
1930	574.55	0.07	477.91	96.48	0.23	0.00
1940	574.55	0.26	477.79	96.45	0.54	0.03
1950	574.55	0.59	477.20	96.13	1.14	0.66
1960	574.55	0.58	476.74	95.82	1.35	1.21
1970	574.55	1.66	474.54	94.64	5.36	1.67
1980	574.55	0.85	473.37	93.81	5.86	2.35
1990	574.55	0.81	472.83	93.41	6.12	2.99
2000	574.55	0.97	473.08	93.72	5.29	3.42

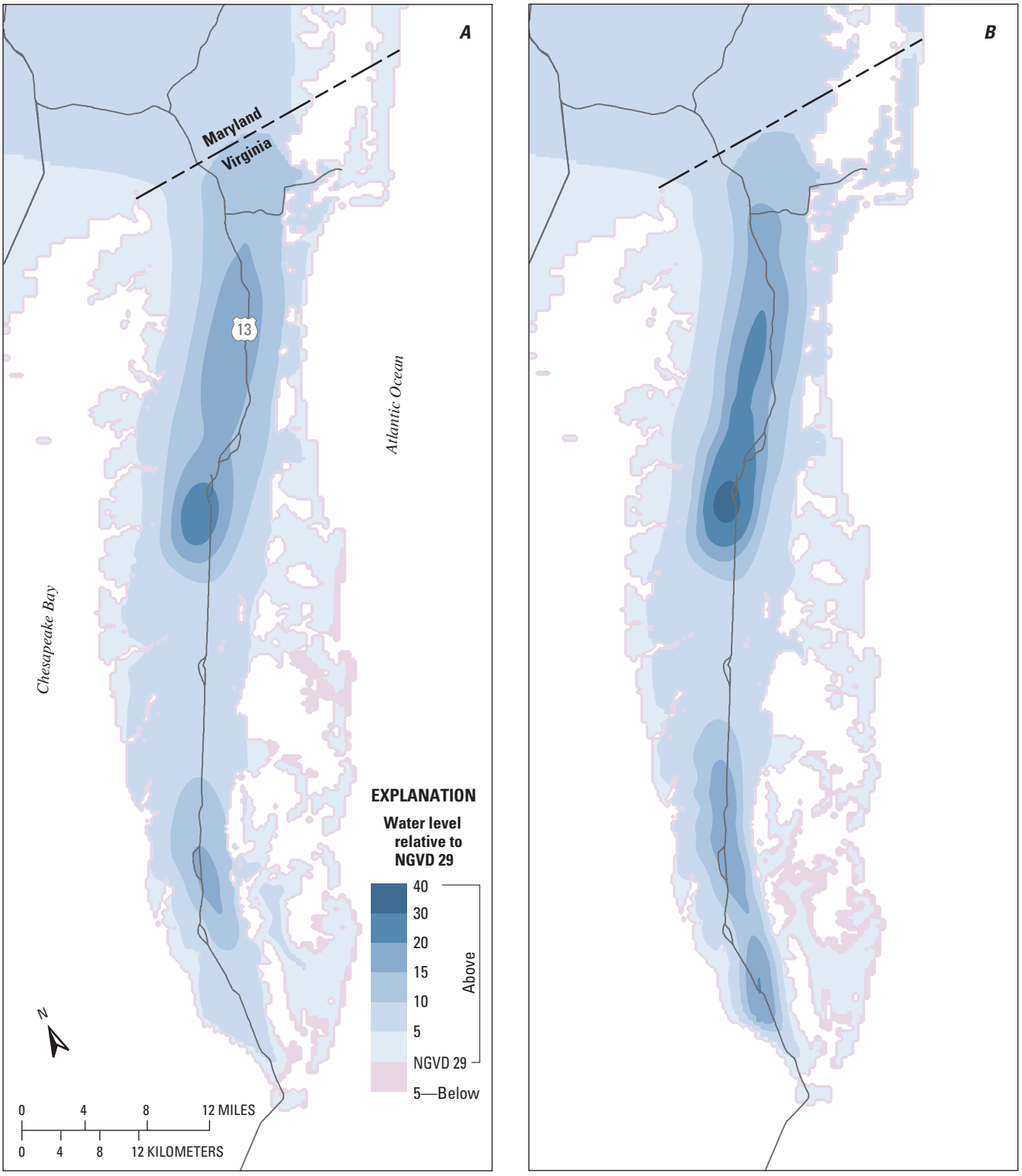


Figure 37. Simulated 1900 water levels in the *(A)* lower and *(B)* middle Yorktown-Eastover aquifers of the Eastern Shore of Virginia.

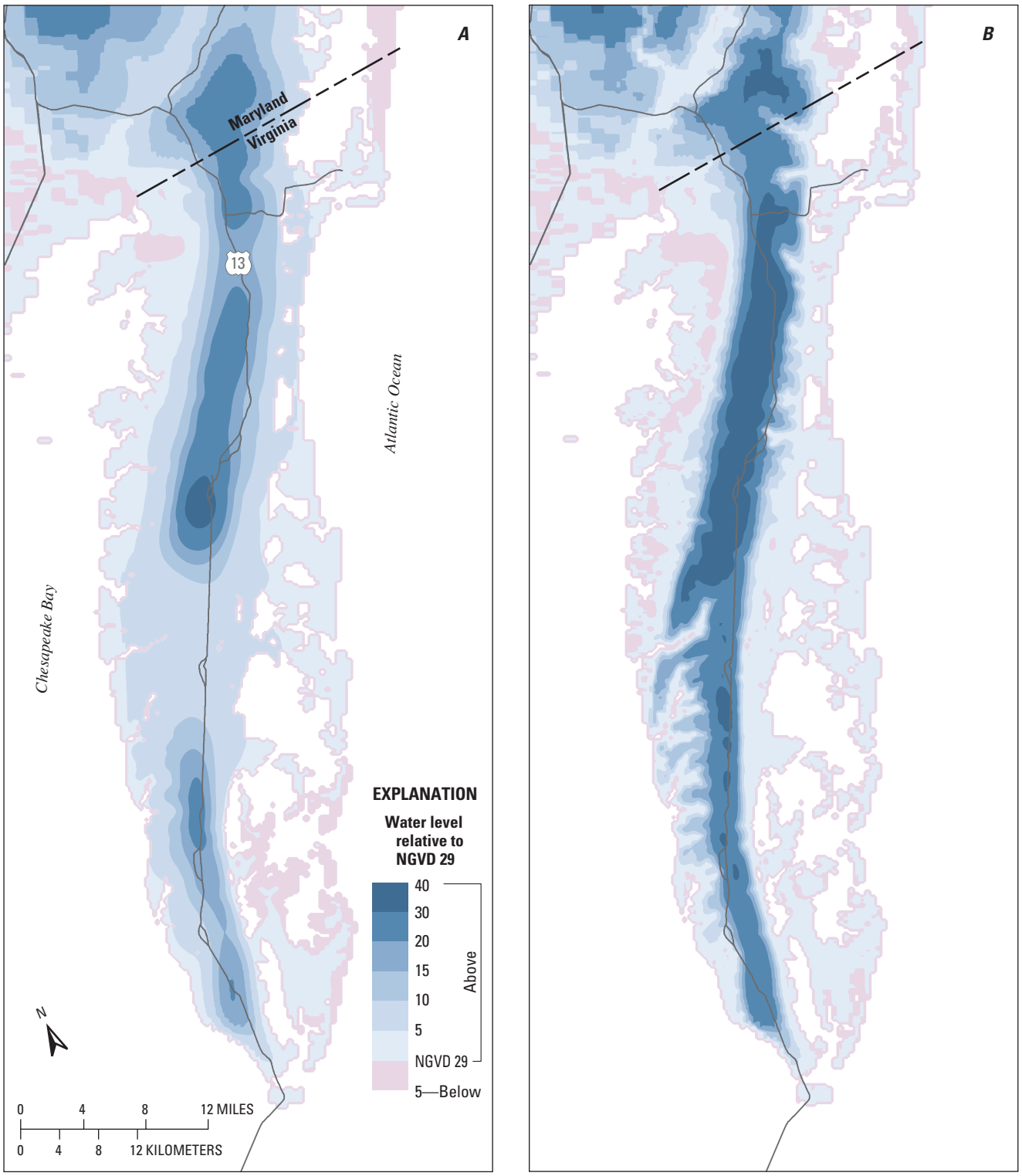


Figure 38. Simulated 1900 water levels in the *(A)* upper Yorktown-Eastover and *(B)* surficial aquifers of the Eastern Shore of Virginia.

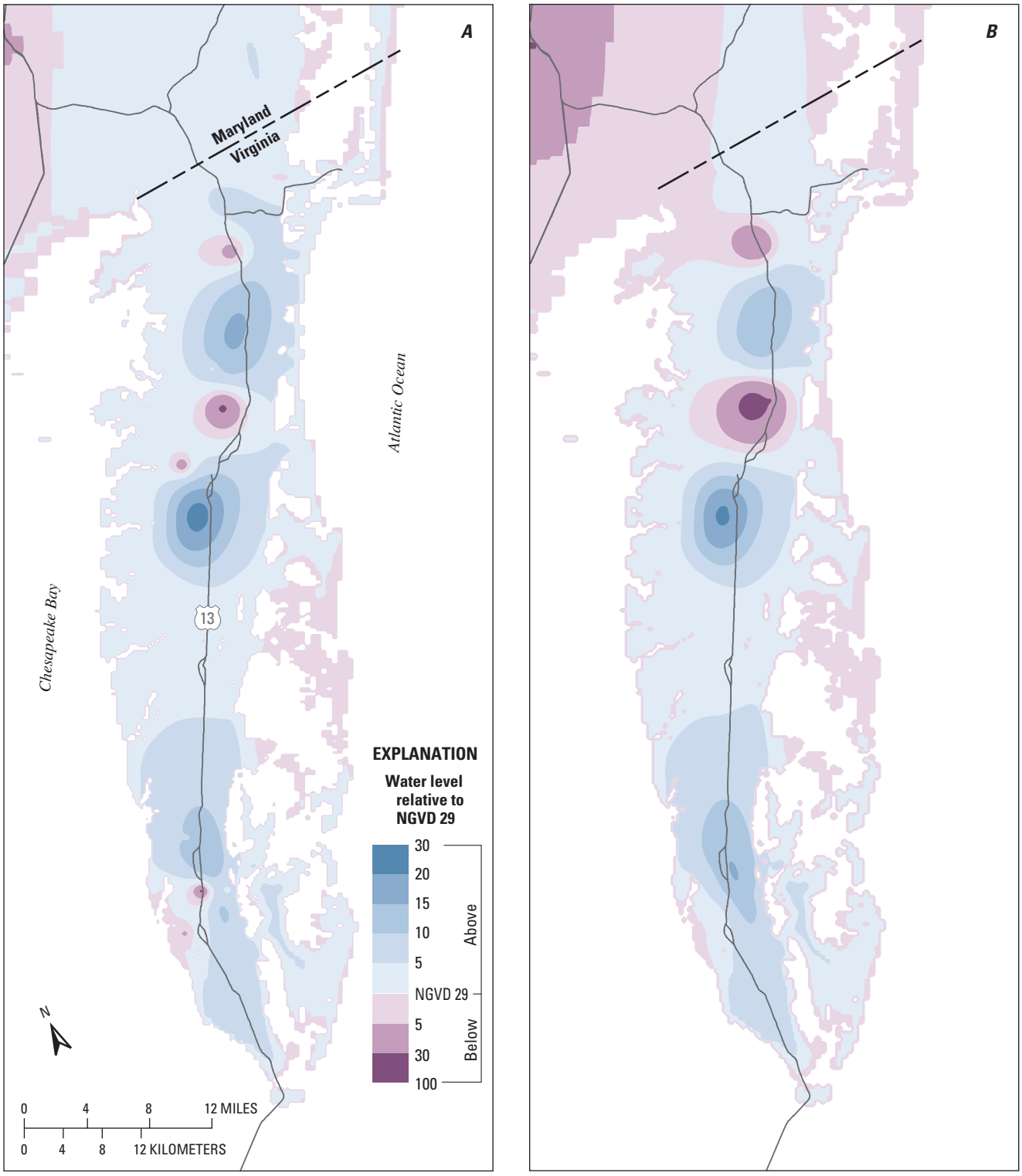


Figure 39. Simulated *(A)* 1980 and *(B)* 2000 water levels in the lower Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

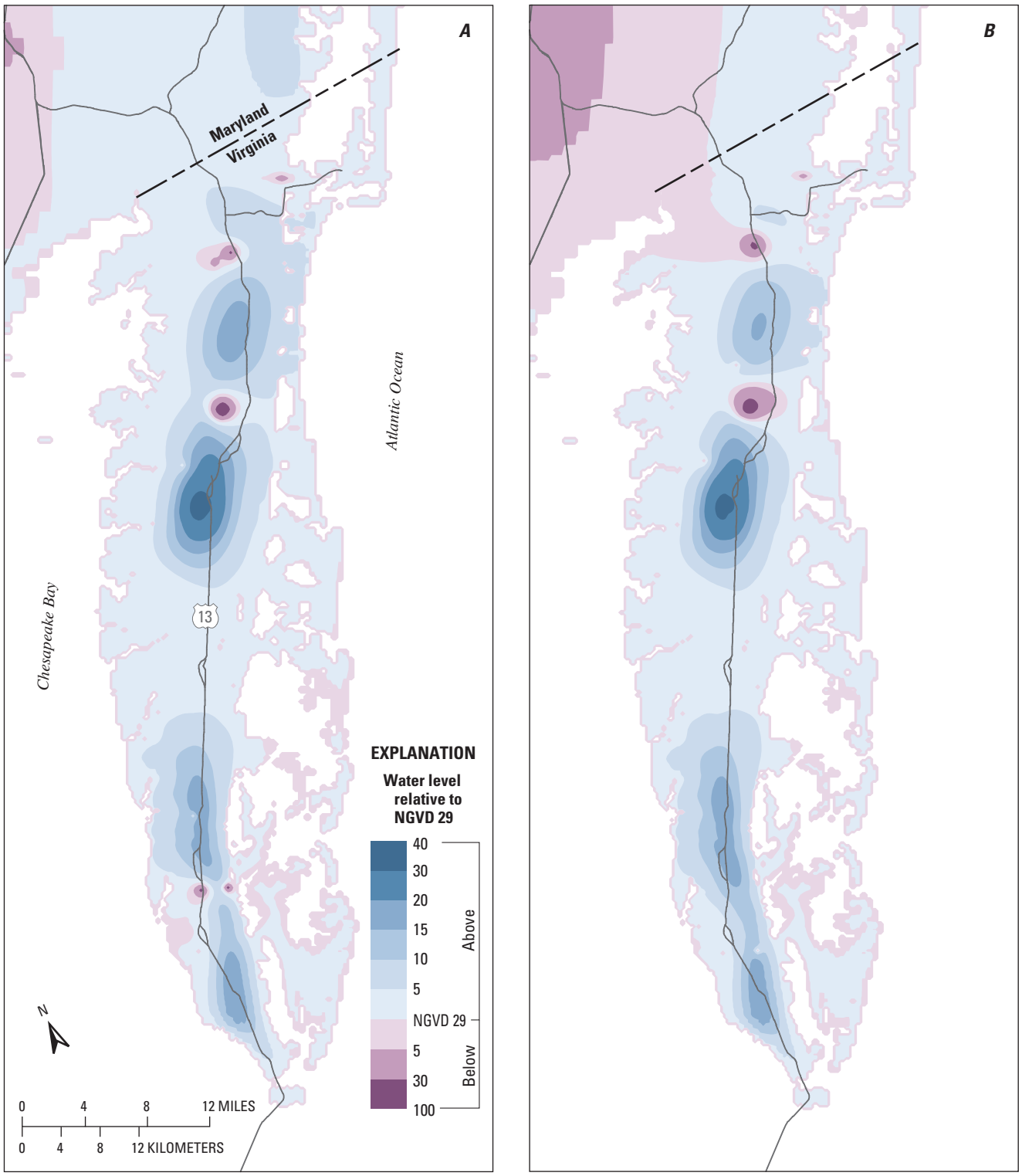


Figure 40. Simulated *(A)* 1980 and *(B)* 2000 water levels in the middle Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

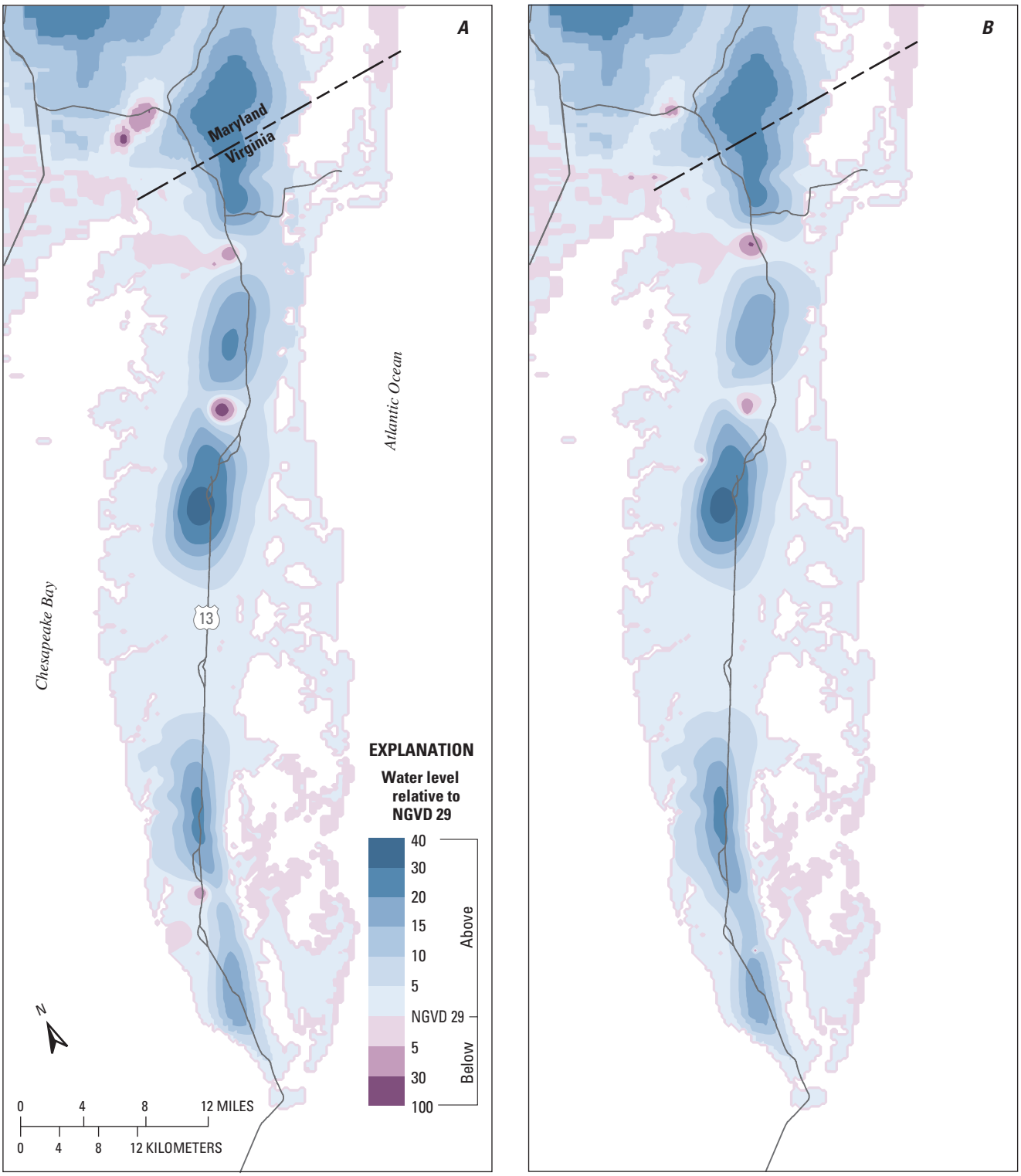


Figure 41. Simulated *(A)* 1980 and *(B)* 2000 water levels in the upper Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

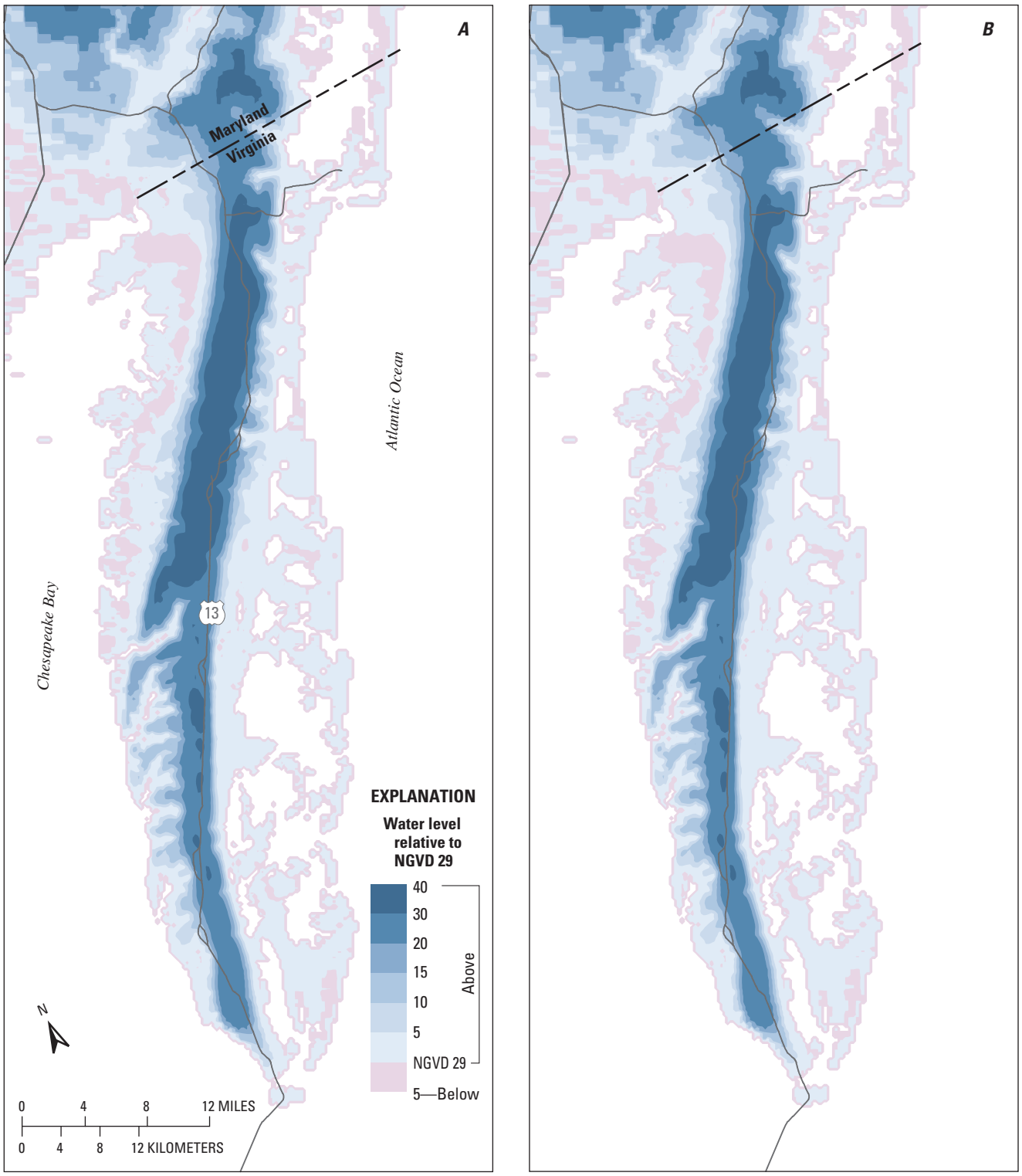


Figure 42. Simulated *(A)* 1980 and *(B)* 2000 water levels in the surficial aquifer of the Eastern Shore of Virginia.

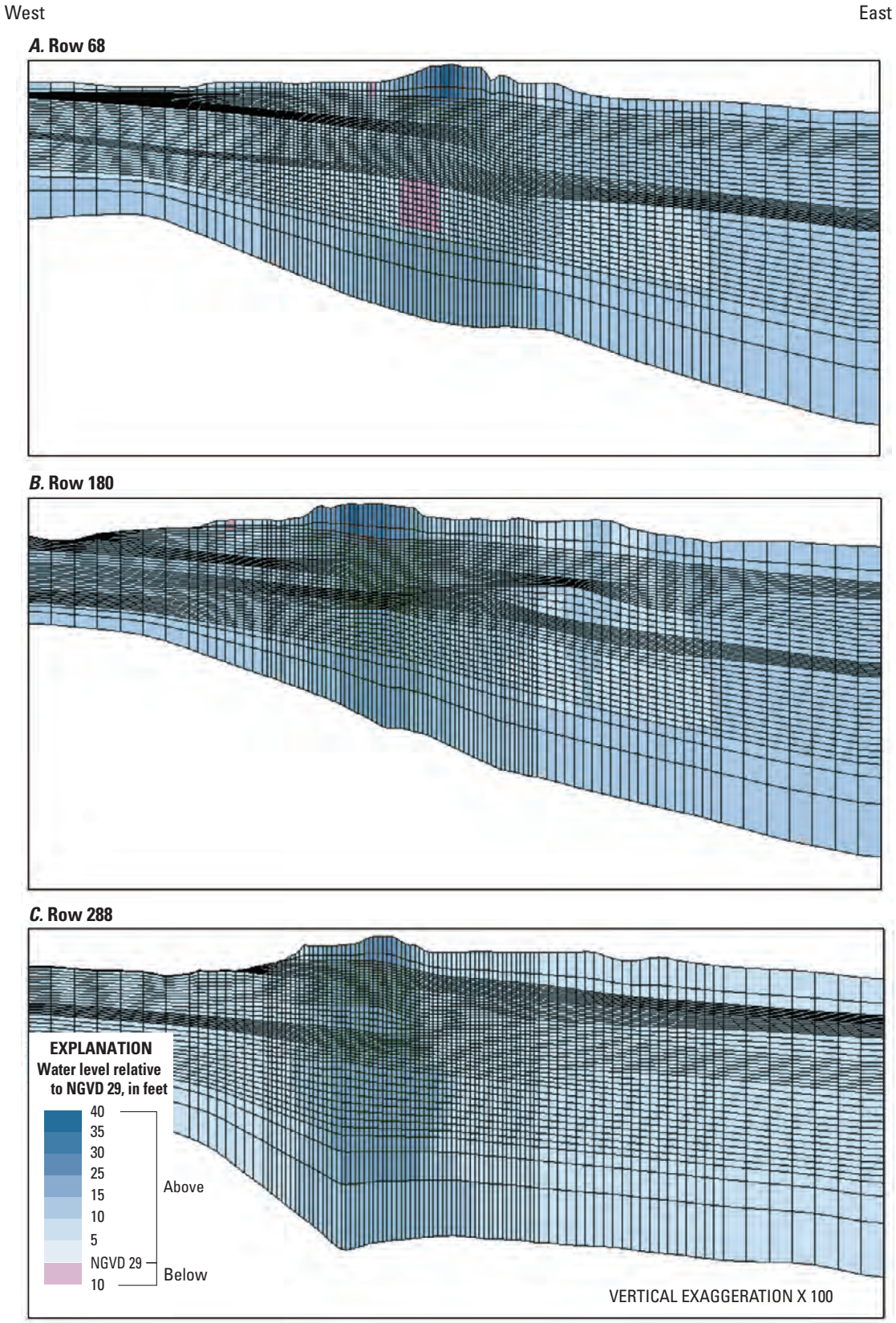


Figure 43. Cross-sectional views of simulated water levels in 2000 at model rows *(A)* 68, *(B)* 180, and *(C)* 288 of the Eastern Shore of Virginia. See figure 20 for locations.

Groundwater Age

The age of the groundwater beneath the Eastern Shore was simulated using the USGS code MODPATH, which tracks backward-flow path lines and computes associated transport times from any given point in the model to its point of recharge. By beginning such path lines at every cell in a model layer, the advective transport times can be plotted for different aquifers. A porosity of 40 percent was used for the aquifers in these calculations. The lower and middle confined aquifers (fig. 44) have simulated ages typically between 3,000 and 30,000 years, and 1,000 and 10,000 years, respectively. The upper confined aquifer (fig. 45*A*) has simulated ages that typically are between 300 and 3,000 years. The simulated age distributions of all the confined aquifers show clearly there is younger water in the model beneath the recharge zones of the central ridge and older water along the coastline and around the border between the two counties. This age distribution is consistent with the conceptual model of flow in the system. The simulated ages for the surficial aquifer (fig. 45*B*) are all less than 300 years in the recharge zone of the central upland. Ages measured there with the environmental tracer SF_6 (table 2) indicate that most of these ages are likely to be less than 50 years. In the coastal areas of the surficial aquifers the ages vary but are all much older than along the central ridge, as these areas typically receive older water that is leaking upward from the confined aquifers. Simulated ages in the confined aquifers of thousands to tens of thousands of years are similar to the ^{14}C-based ages measured in water sampled from the observation wells.

Chloride Distribution

Chloride concentrations are used as a proxy for salinity in the model, where the chloride concentration of seawater was set at the mean ocean value of 19 grams per liter (g/L). Establishing an initial chloride distribution for predevelopment conditions in the model is not a straightforward process. Frequently it is assumed that such systems are at equilibrium with respect to current sea level and the current groundwater-flow system. During the last ice age, the entire Chesapeake Bay and the Atlantic Continental Shelf were above sea level and were receiving freshwater recharge. The subsequent rise of sea level to present-day conditions was accompanied by the migration of the freshwater-seawater transition zone toward the present-day coastline. One can simulate a transition zone in an equilibrium position starting with freshwater conditions everywhere beneath the present-day land surface and letting the simulation run long enough to reach equilibrium. This typically requires tens of thousands of years of simulation time. Such a simulation was run with the Eastern Shore model. A problem with this approach is that usually the resulting simulated equilibrium transition zone does not have chloride concentrations at the observation wells that match any of the observed chloride concentrations in the wells (table 2). Such was the case with the Eastern Shore model; some of the simulated chloride observations were too high, and others were too low. An alternative approach might be to try to create a three-dimensional transition zone in the model that matches the observations; however, there are not enough observations to do this, and there is no easy way to make such a field reflect the flow conditions in the system without simulating its position and distribution.

A different, but related, approach was taken in this study that attempted to make a natural transition zone that also reflected the concentrations that were measured at the observation wells. An initial simulation was run starting with freshwater under all land cells and seawater under all water cells. This simulation was run to equilibrium, but snapshots of the chloride-concentration field were saved at various time steps. A comparison then was made between each observed chloride-concentration value above 100 mg/L and the simulated values. A time snapshot of the entire transition zone was assigned to each observation well according to the time at which the simulated-chloride level best fit the chloride observation at that well. Some observation wells (especially on the bay side) never matched because observed chlorinity values exceeded all simulated values (the simulated transition zone never encroached far enough inland at equilibrium). For these wells, a snapshot of the entire transition zone was used that translated the equilibrium-simulated transition zone inland in a due easterly or westerly direction (along model rows) until a best match could be made to the observed chloride-concentration level. At this point in the process each well had associated with it a snapshot of a chloride-concentration field for the entire model area that best fit the value observed at the well. These multiple fields then were combined into one smoothly varying field (that was still a best-fit at each observation well) by using the kriging routine (Appendix 3) that was used for the pilot points described earlier. In this context, the location of each observation well became the equivalent of the pilot-point location. The resulting predevelopment chloride-concentration field is shown for the lower and middle aquifers (fig. 46) and the upper and surficial aquifers (fig. 47). These illustrations show that, along the coast, the chloride concentrations are typically higher in each successively lower aquifer.

Once the predevelopment chloride-concentration field was established, historical simulations were run to simulate the change in the chloride concentration that may have occurred because of pumping over the past century. Results for the lower, middle, and upper aquifers are shown in figures 48, 49, and 50, respectively. In general, it is difficult to see the difference in chloride simply by comparing the concentration fields for 1900 (figs. 46 and 47) and 2003 (figs. 48*A*, 49*A*, and 50*A*); thus, the changes in concentration between the two different years are shown in figures 48*B*, 49*B*, and 50*B*. In the lower aquifer (fig. 48*B*), increases in simulated chloride concentrations of greater than 0.1 g/L (100 mg/L) can be observed around Cape Charles, east of Exmore, and near Chincoteague. In the middle aquifer (fig. 49*B*), increases

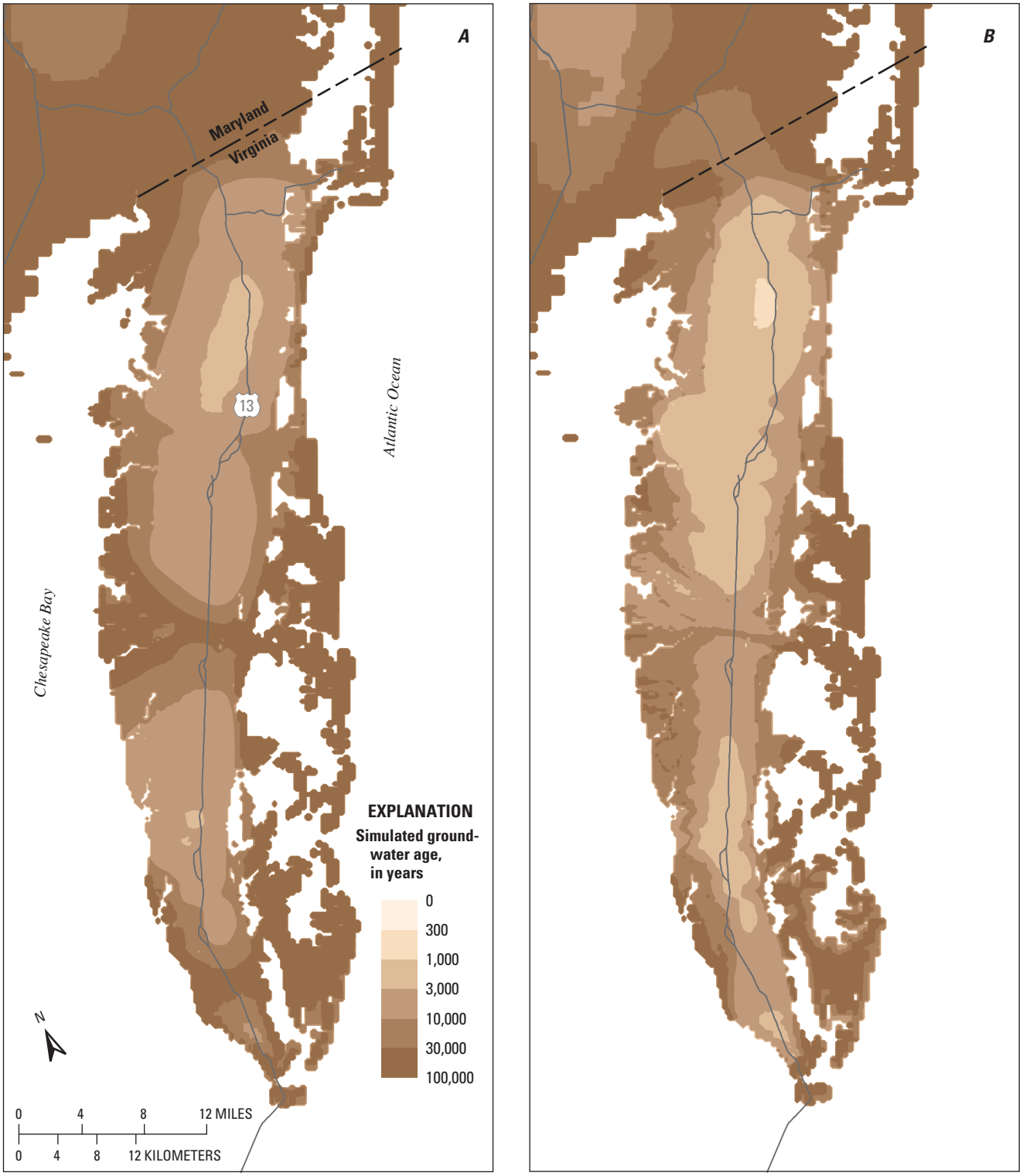


Figure 44. Simulated groundwater age in the *(A)* lower and *(B)* middle Yorktown-Eastover aquifers of the Eastern Shore of Virginia.

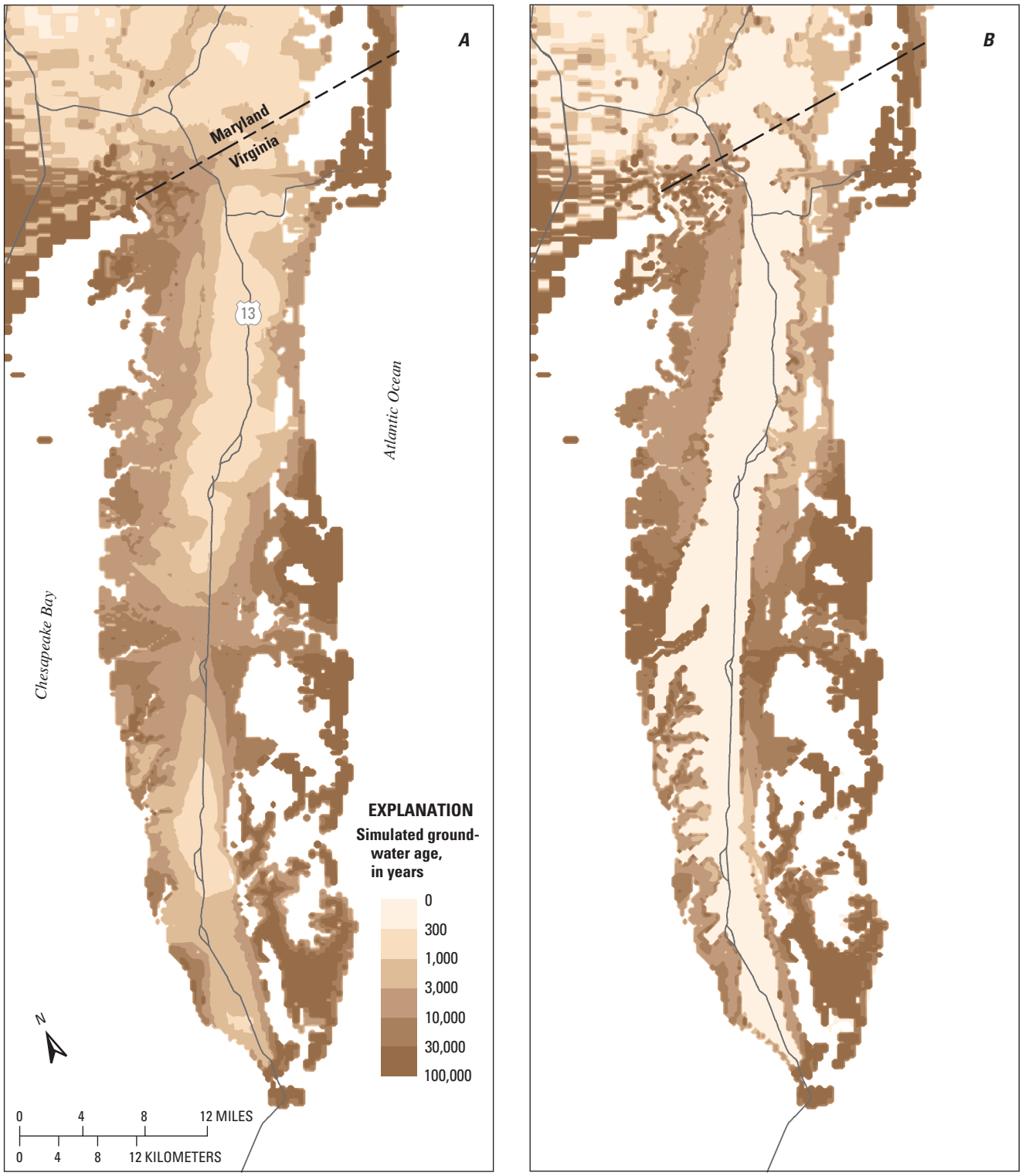


Figure 45. Simulated groundwater age in the *(A)* upper Yorktown-Eastover and *(B)* surficial aquifers of the Eastern Shore of Virginia.

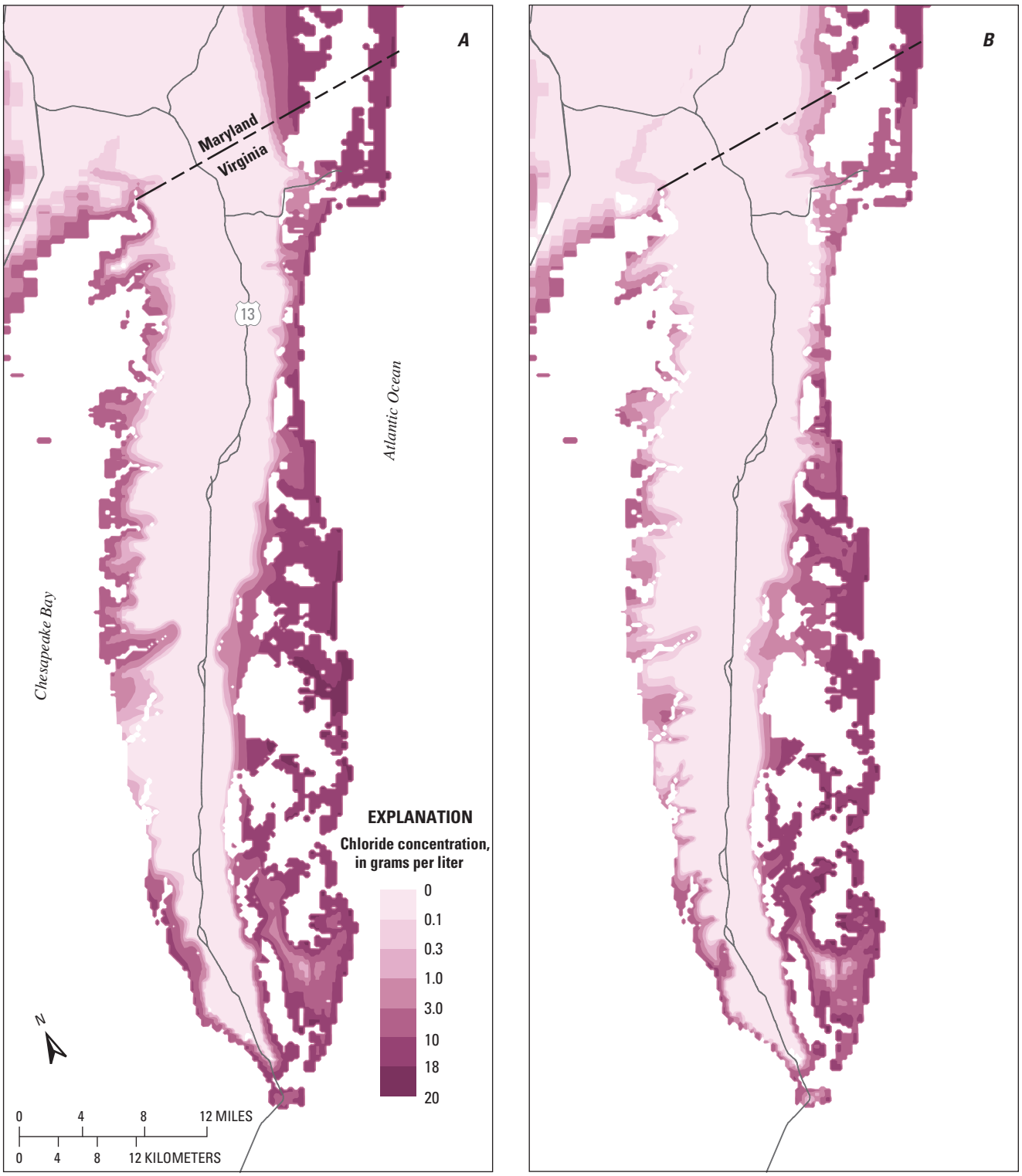


Figure 46. Simulated 1900 chloride concentrations in the *(A)* lower and *(B)* middle Yorktown-Eastover aquifers of the Eastern Shore of Virginia.

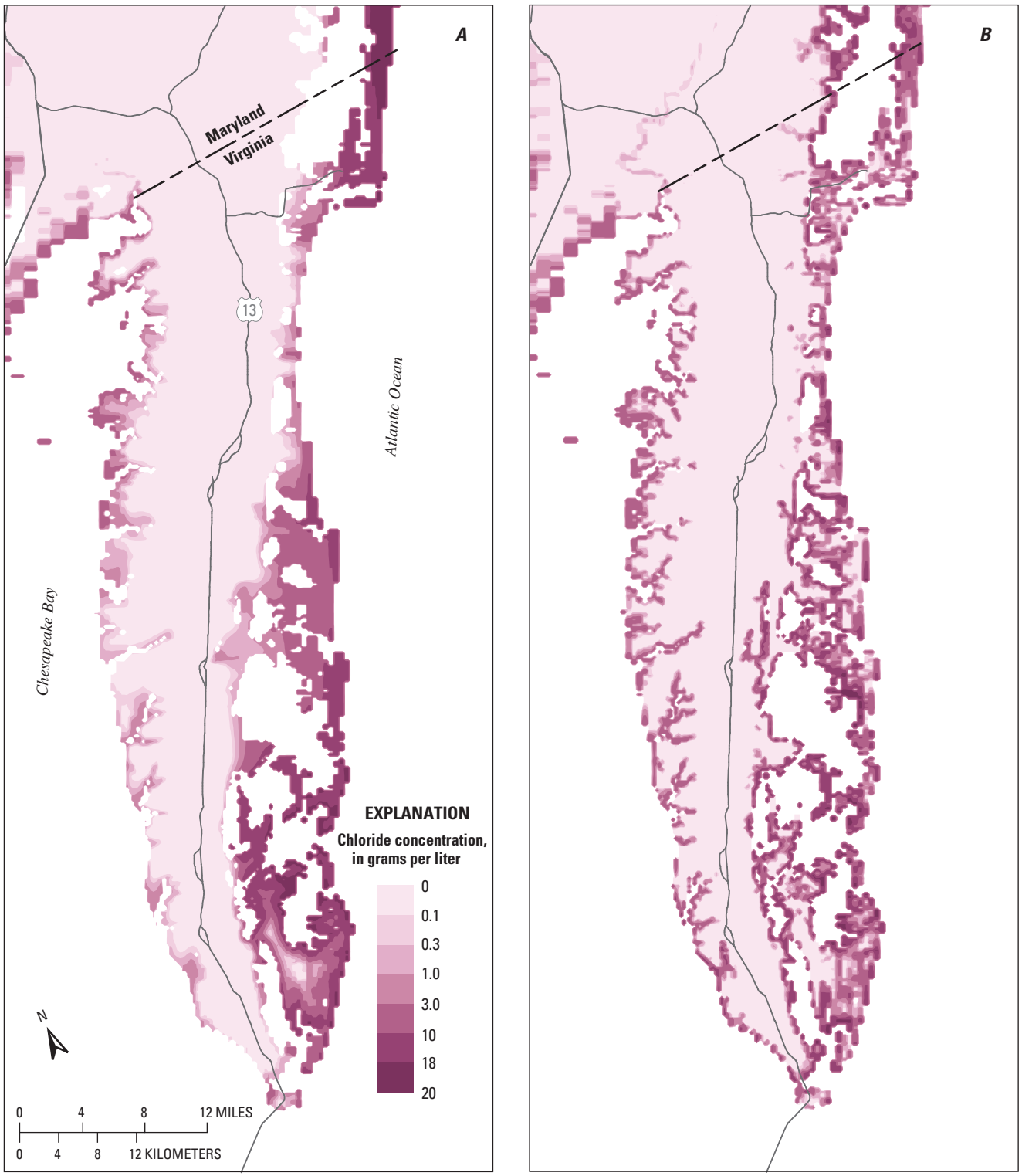


Figure 47. Simulated 1900 chloride concentrations in the *(A)* upper Yorktown-Eastover and *(B)* surficial aquifers of the Eastern Shore of Virginia.

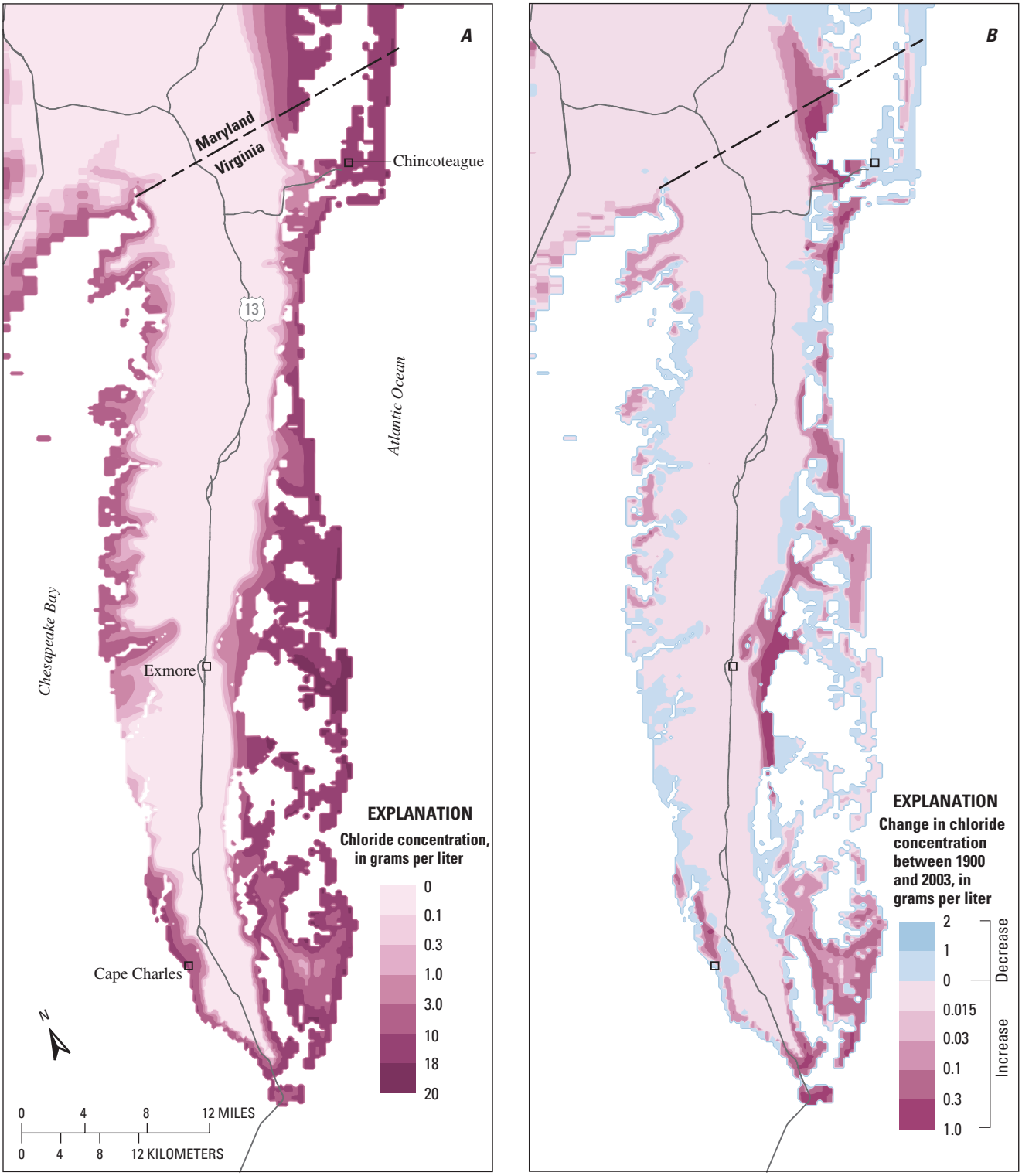


Figure 48. Simulated *(A)* chloride concentrations in 2003 and *(B)* changes in chloride concentrations between 1900 and 2003 in the lower Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

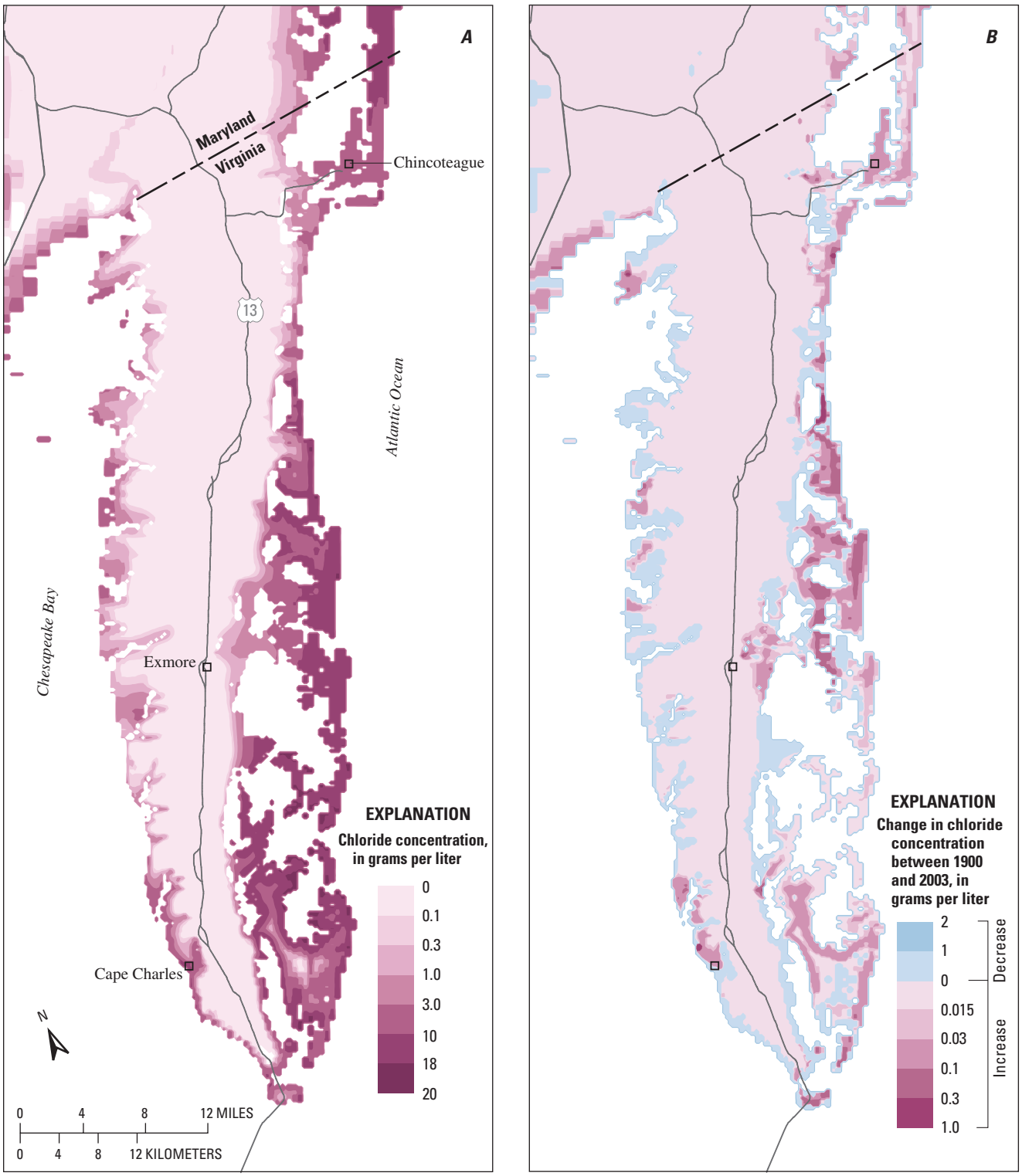


Figure 49. Simulated *(A)* chloride concentrations in 2003 and *(B)* changes in chloride concentrations between 1900 and 2003 in the middle Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

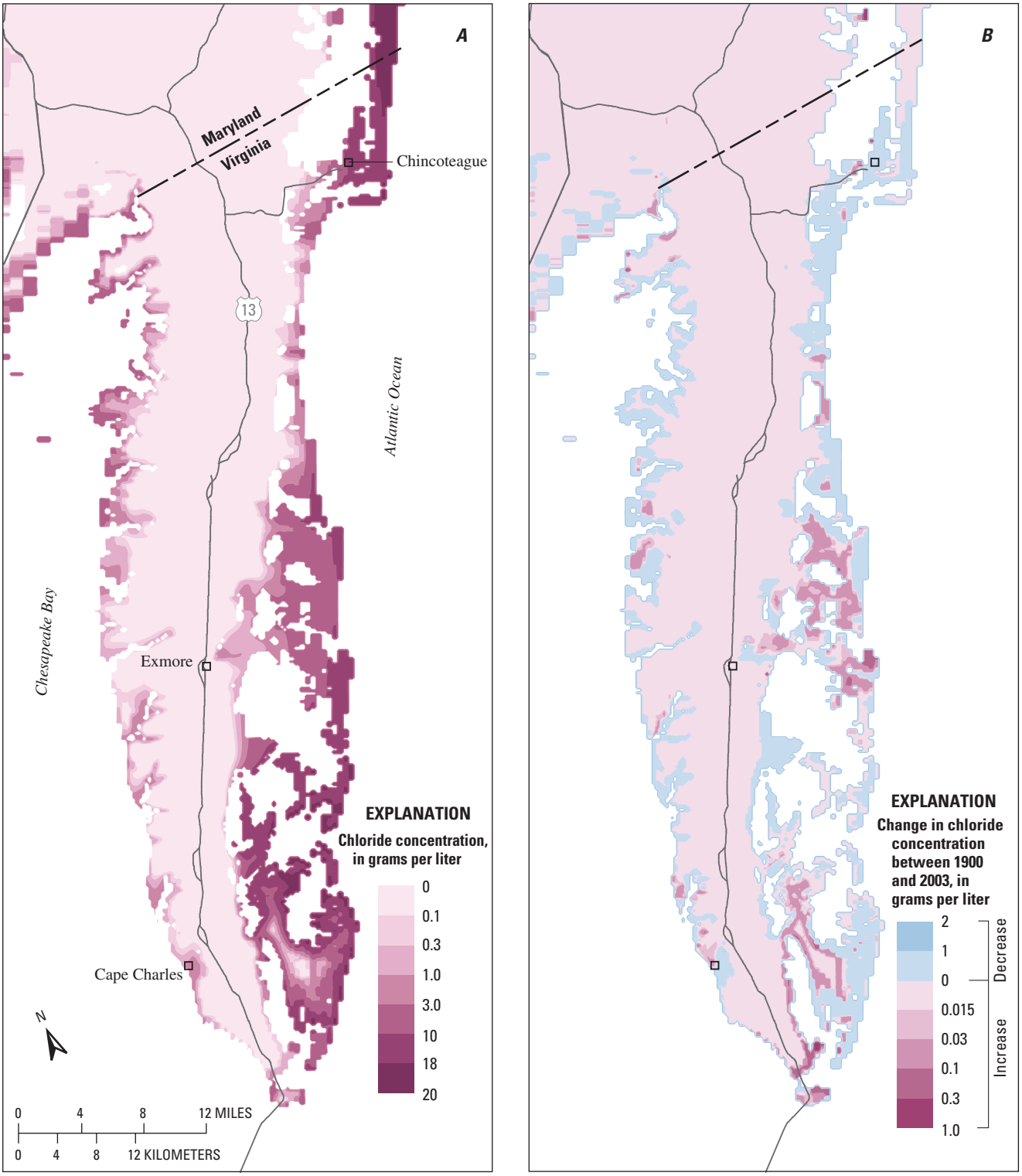


Figure 50. Simulated *(A)* chloride concentrations in 2003 and *(B)* changes in chloride concentrations between 1900 and 2003 in the upper Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

in simulated chloride concentrations of only 0.03 g/L or less can be observed in these same areas. In the upper aquifer (fig. 50*B*), little to no increases can be seen except in the coastal bays, where small increases are associated with very local flow systems around the islands. Some simulated decreases in concentration occur in these areas where regional flow may displace saltwater in bays with freshwater from islands. Changes in concentrations in these coastal-bay regions are not reliably simulated in this model partly because of numerical dispersion, but also because there are no chloride concentration data for the aquifer system in these regions.

The distribution of chloride (and thus seawater) beneath the Eastern Shore is three-dimensional, and vertical cross sections illustrate its distribution with depth (fig. 51). Three cross sections are shown along rows 68, 180, and 288 of the model. The first section (fig. 51*A*) is in the northern area near Chincoteague. The second section (fig. 51*B*) is near Exmore, and the third section (fig. 51*C*) is near Cape Charles. In areas where the land surface is above sea level, chloride concentrations within the St. Marys confining unit were specified to increase slowly with depth in a manner similar to the salinity profile in a core collected near Eastville (Gohn and others, 2008). There are few data from the Eastern Shore that indicate how salinity increases beneath the lower aquifer. Upconing of saline water from the St. Marys confining unit could be simulated with this model; however, the results would not be reliable without salinity or chloride observations from within the St. Marys with which to calibrate simulated concentrations.

Future Water-Level Changes

The model developed in this study is intended to be used by State and local water managers to assess the effects of future withdrawals on water conditions of the Eastern Shore. One condition of interest is the response of water levels to continued or increased pumpage. In order to test the model in these types of future-scenario simulations, two different pumping rates were simulated until 2050: (1) pumping that continues at 2003 levels and (2) pumping that is set at the total permitted withdrawal rates for the Eastern Shore. The latter pumping rates are greater than the former.

Current Withdrawal Rate Scenario

The effect of pumping at the 2003 rates (nondomestic total of 6.5 Mgal/d) until 2050 is shown for the lower aquifer in figure 52*A*. Lowering of water levels is predicted to continue in Accomack County, but in most places this additional drawdown after 50 years is less than 1 ft. This suggests that the current system has already nearly reached a new equilibrium state, where extracted water is being balanced by water leaking down through overlying confining units. In the southern part of Northampton County, water levels are predicted to increase because there was a particular user who had relatively large extractions during the drought of 2002, then little during the wet year of 2003. The "current-withdrawal" simulation projected this lower extraction rate, and water levels were predicted to recover from the 2002 levels. Water levels in 2050 in the middle aquifer (fig. 53*A*) are predicted to have changes similar to those in the lower aquifer. One difference is that in central Accomack County, the additional drawdowns typically will be slightly less than in the lower aquifer. In the upper aquifer, similar changes are predicted for the water levels in 2050 (fig. 54*A*). In this case little additional drawdown is predicted in Maryland and near the Virginia State border.

Total Permitted Withdrawal Rate Scenario

Simulations from 2003–2050 with total permitted withdrawals indicated greater drawdowns than those with 2003 withdrawal rates (figs. 52–54). These greater simulated drawdowns are a result of higher simulated pumping rates (nondomestic total of 9.1 Mgal/d). Patterns of drawdown are the same in all three confined aquifers except in Maryland, where the drawdowns are limited to the lower and middle aquifers. Projected drawdowns in Accomack County typically are 1–3 ft and never exceed about 10 ft. In Northampton County an area of drawdown greater than 3 ft is at the northwest end of the county; this is a result of the permitted withdrawal of one particular user. If the numerous water users in the southern part of the county withdraw at the total permitted amount until 2050, substantial areas with >10 ft of drawdown and some areas with >30 ft would result. The future-scenario simulation results are not shown for the surficial aquifer, as the drawdowns in the confined aquifers do not sufficiently propagate upward through the upper confining unit to cause observable drawdowns there.

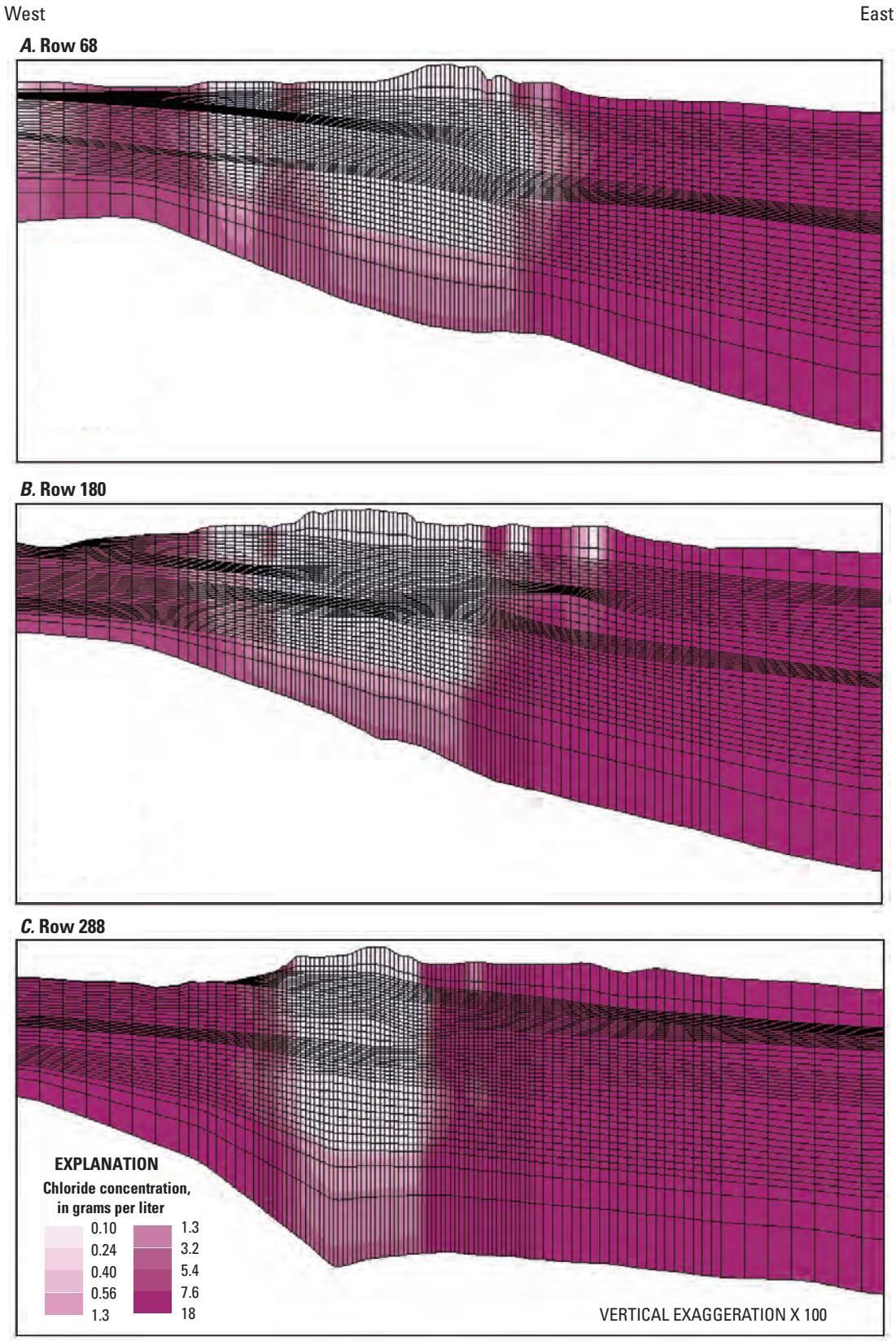


Figure 51. Cross-sectional views of simulated chloride concentrations in 2003 at model rows *(A)* 68, *(B)* 180, and *(C)* 288 of the Eastern Shore of Virginia. See figure 20 for locations.

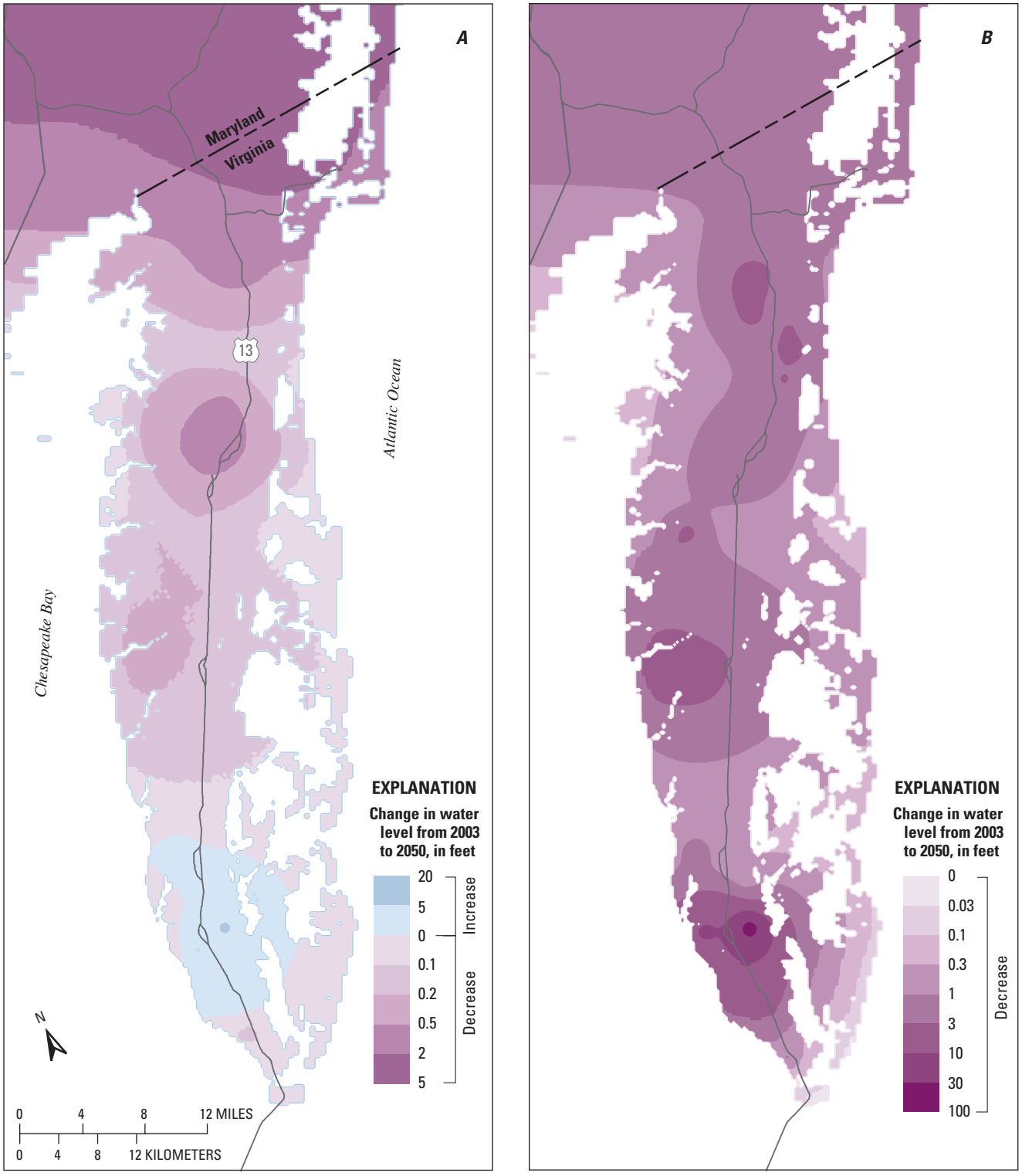


Figure 52. Changes in water levels from 2003 to 2050 assuming pumping after 2003 is for *(A)* 2003 pumping rates and *(B)* total permitted withdrawal rates in the lower Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

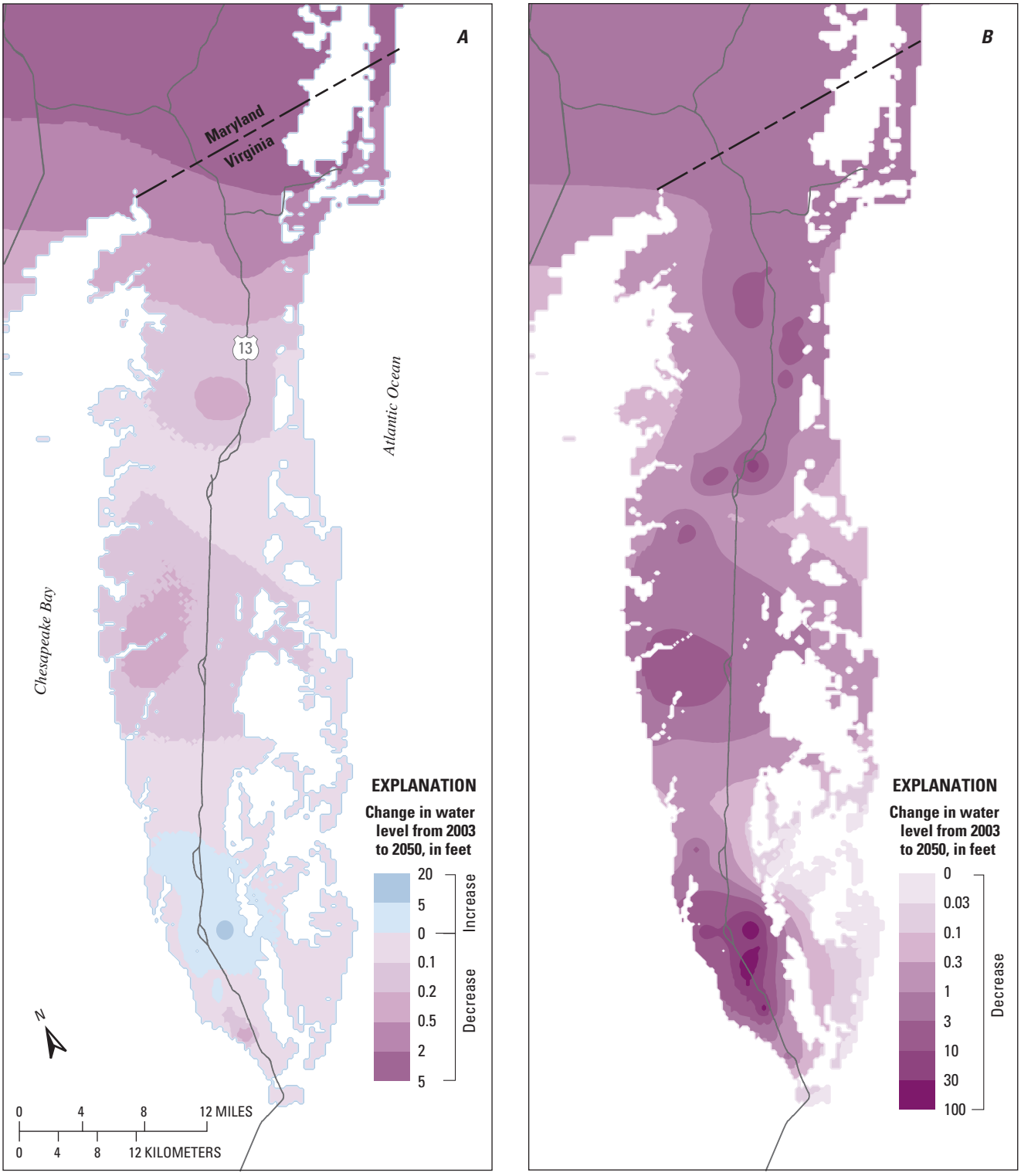


Figure 53. Changes in water levels from 2003 to 2050 assuming pumping after 2003 is for *(A)* 2003 pumping rates and *(B)* total permitted withdrawal rates in the middle Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

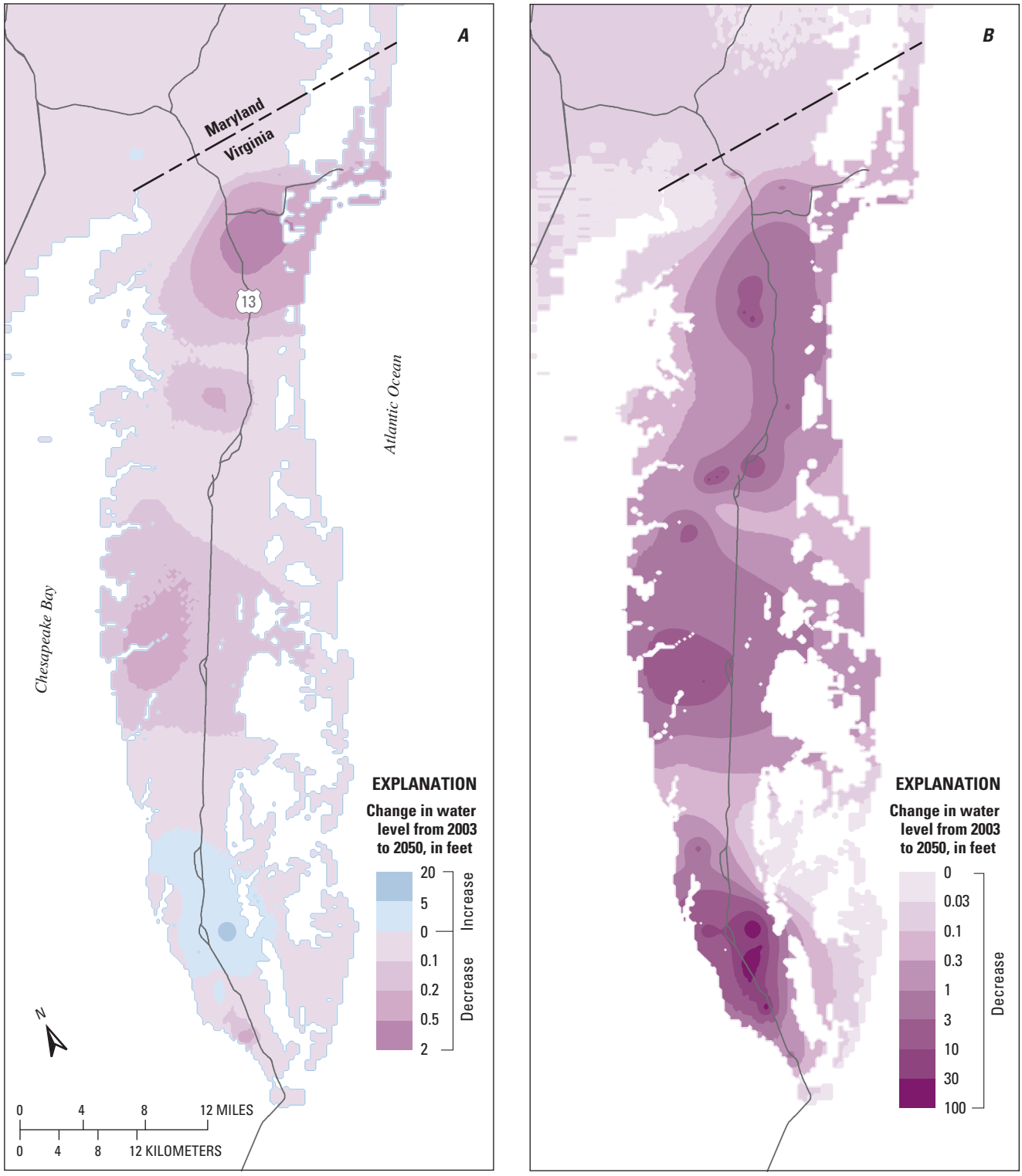


Figure 54. Changes in water levels from 2003 to 2050 assuming pumping after 2003 is for *(A)* 2003 pumping rates and *(B)* total permitted withdrawal rates in the upper Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

Future Salinity Changes

The model developed for this study is also intended to be used by State and local water managers to assess the effects of future withdrawals on saltwater encroachment. To test the model for these types of future-scenario simulations, two different pumping rates were simulated until 2050 as before: (1) pumping that continues at 2003 levels and (2) pumping that is set at the total- permitted withdrawal rates for the Eastern Shore.

Current Withdrawal Rate Scenario

The effect of pumping at the 2003 rates until 2050 is shown for the lower aquifer in figure 55*A*. The simulated chloride increases between 2003 and 2050 for the coastal region around Cape Charles has, between 2003 and 2050 are more than 0.1 gm/L (100 mg/L) in 2050. The very southern tip of the peninsula and Fisherman's Island have increases of more than 0.3 g/L (300 mg/L). The region just east of Exmore also has a simulated increase in chlorinity of more than 0.3 g/L. Other areas near Chincoteague also have a simulated increases of over 0.3 g/L. Given that the USEPA drinking guideline for water for chloride is 250 mg/L, these increases have the potential to adversely affect some local wells near the coasts in these locations. Simulated increases in chloride concentrations in 2050 in the middle aquifer (fig. 56*A*) are smaller but follow similar patterns as those in the lower aquifer. In the upper aquifer in 2050, the simulated increases on chloride concentration since 2003 are less than 0.03 g/L (fig. 57*A*) in almost all areas.

Total Permitted Withdrawal Rate Scenario

Simulations until the year 2050 with total permitted withdrawal rates typically predict greater increases in chloride than those with 2003 withdrawal rates (figs. 55–57). Greater simulated increases in chloride are a result of higher simulated pumping rates. Patterns of chlorinity increases are somewhat similar to those from the 2003 pumping-rate scenario. The areas near Cape Charles, east of Exmore, and west of Chincoteague show very similar chlorinity increase patterns to those of the 2003-rate scenario. Two additional areas of potential intrusion are evident, however, in the lower aquifer (fig. 55*B*). Increases in chloride concentration near the eastern coastal area of central Accomack County is likely an effect from the two large cones-of-depression. Also, the entire southern end of the peninsula in Northampton County shows increases in simulated chlorinity of more than 0.1 gm/L. The middle aquifer (fig. 56*B*) shows increases in chloride concentration in the Accomack coastal area, but not the Atlantic Coastal area in Northampton County. As for water levels, the future-scenario simulation results for chloride increases are not shown for the surficial aquifer, as there are no substantial simulated amounts of seawater intrusion. Only a few of the observation wells show simulated chloride-concentration values that have a substantial rise between 1900 and 2050 (fig. 58) under either 2003 or total-permitted withdrawal scenarios, including the wells near Chincoteague (SOW 115), south of Cape Charles (SOW 121), and east of Exmore (SOW 112). The well east of Exmore shows an additional increase in simulated chloride concentration when the total-permitted-withdrawal scenario is simulated.

Areas Contributing Water to Public-Supply Wells

Groundwater models often are used to delineate the source of recharge water that contributes to a particular well. This information can be informative in terms of protecting drinking-water supplies. Five such wells were identified in the Eastern Shore, and an analysis was performed for each well using the USGS code MODPATH to delineate the contributing areas. A large number of path lines were traced from each well backward to its recharge area, and the ending locations of these path lines were highlighted as the recharge area (fig. 59). For this study, wells at Chincoteague, Onancock, Exmore, Eastville, and Cape Charles were analyzed. The path lines were traced to the bottom of the surficial aquifer but not all the way to the water table. The water-table zones should be close to the zones at the base of the surficial aquifer, although each one might be shifted slightly closer to the spine of the central ridge. The Chincoteague recharge zones are west of the well field in multiple locations because of multiple screened zones for the wells. The Onancock recharge zone extends away from the production wells to the south-south-east. The Exmore recharge zone extends to the northeast of the production well. The Eastville zone is close to, and just east of, the well. The Cape Charles zone extends to the east of the well and east of the central highway. Although these zones suggest possible areas to protect from contamination, the travel times from recharge to well associated with nearly all of these zones were greater than 1,000 years and often several thousand years. Long transport times, therefore, protect most of these wells from any recent contamination originating at the land surface.

Travel Time of Water to the Confined Aquifer

Although the wells in the confined aquifer are fairly well protected from contamination by long travel times (in the thousands of years), it is possible that lower water levels, especially in the upper confined aquifer, may increase the rate at which dissolved contaminants migrate vertically downward through the upper confining unit where they could potentially contaminate wells. Given that high nitrate concentrations are widespread throughout the surficial aquifer, a map that shows

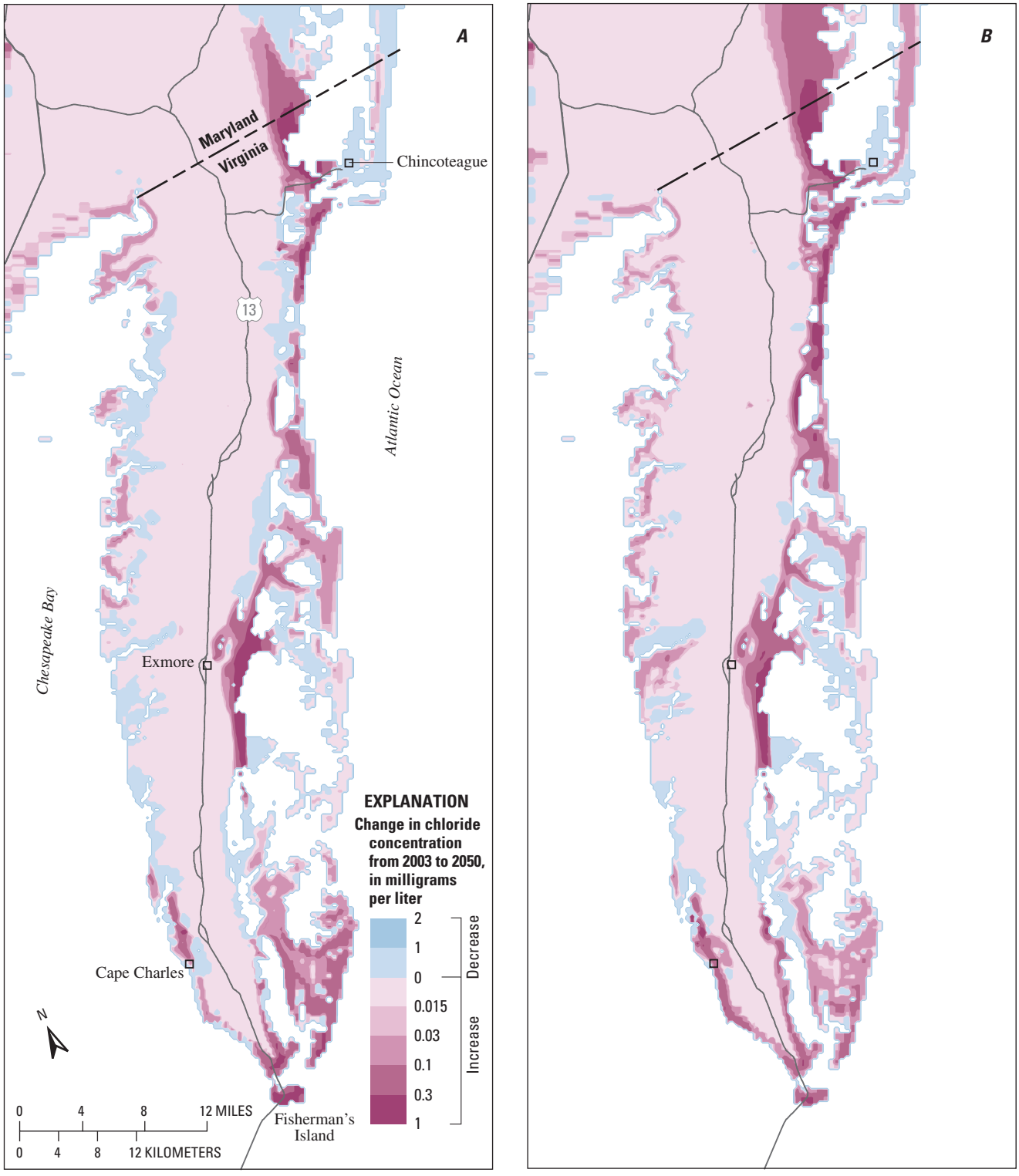


Figure 55. Changes in chloride concentrations from 2003 to 2050 assuming pumping after 2003 is for *(A)* 2003 pumping rates and *(B)* total permitted withdrawal rates in the lower Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

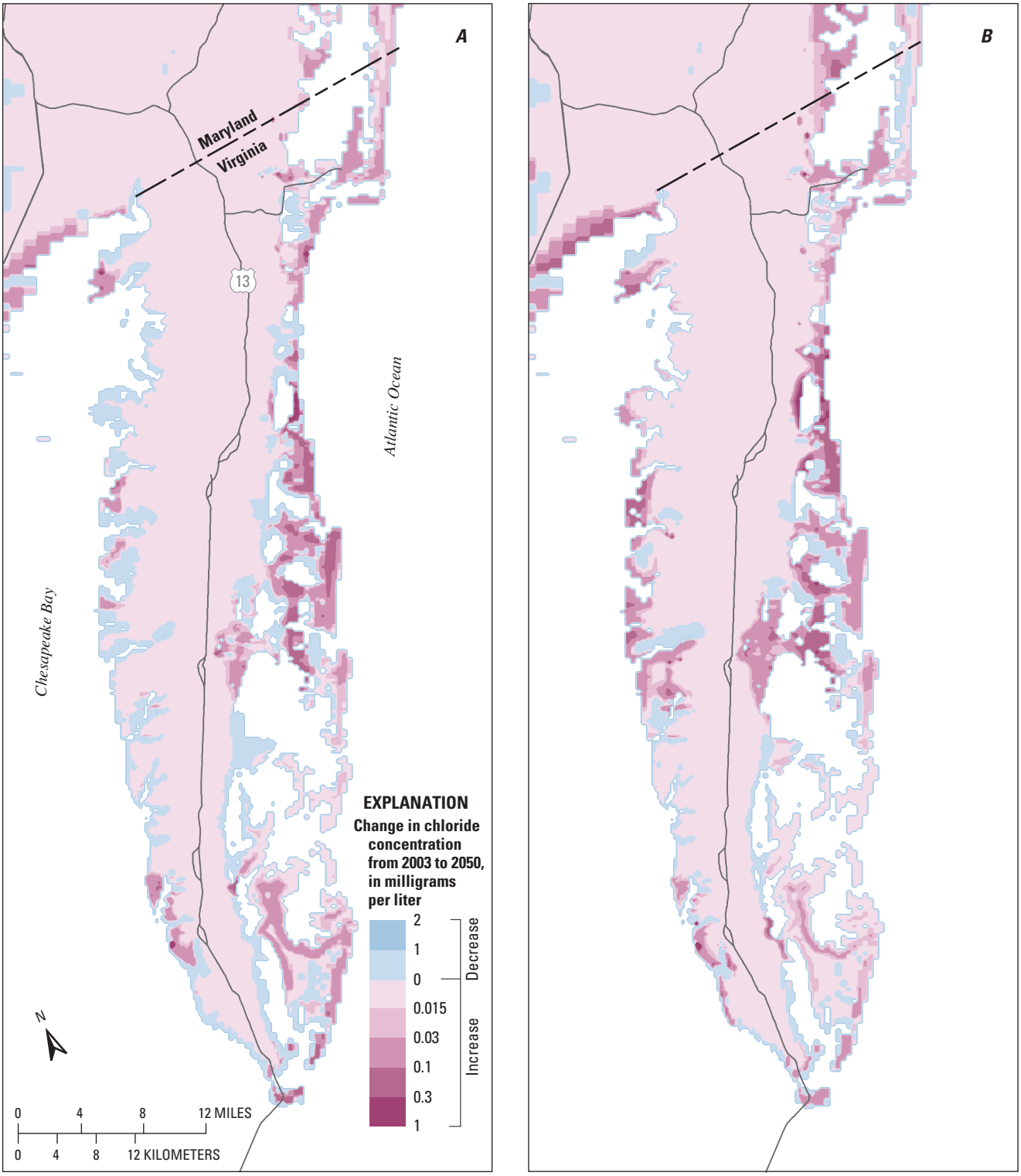


Figure 56. Changes in chloride concentrations from 2003 to 2050 assuming pumping after 2003 is for *(A)* 2003 pumping rates and *(B)* total permitted withdrawal rates in the middle Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

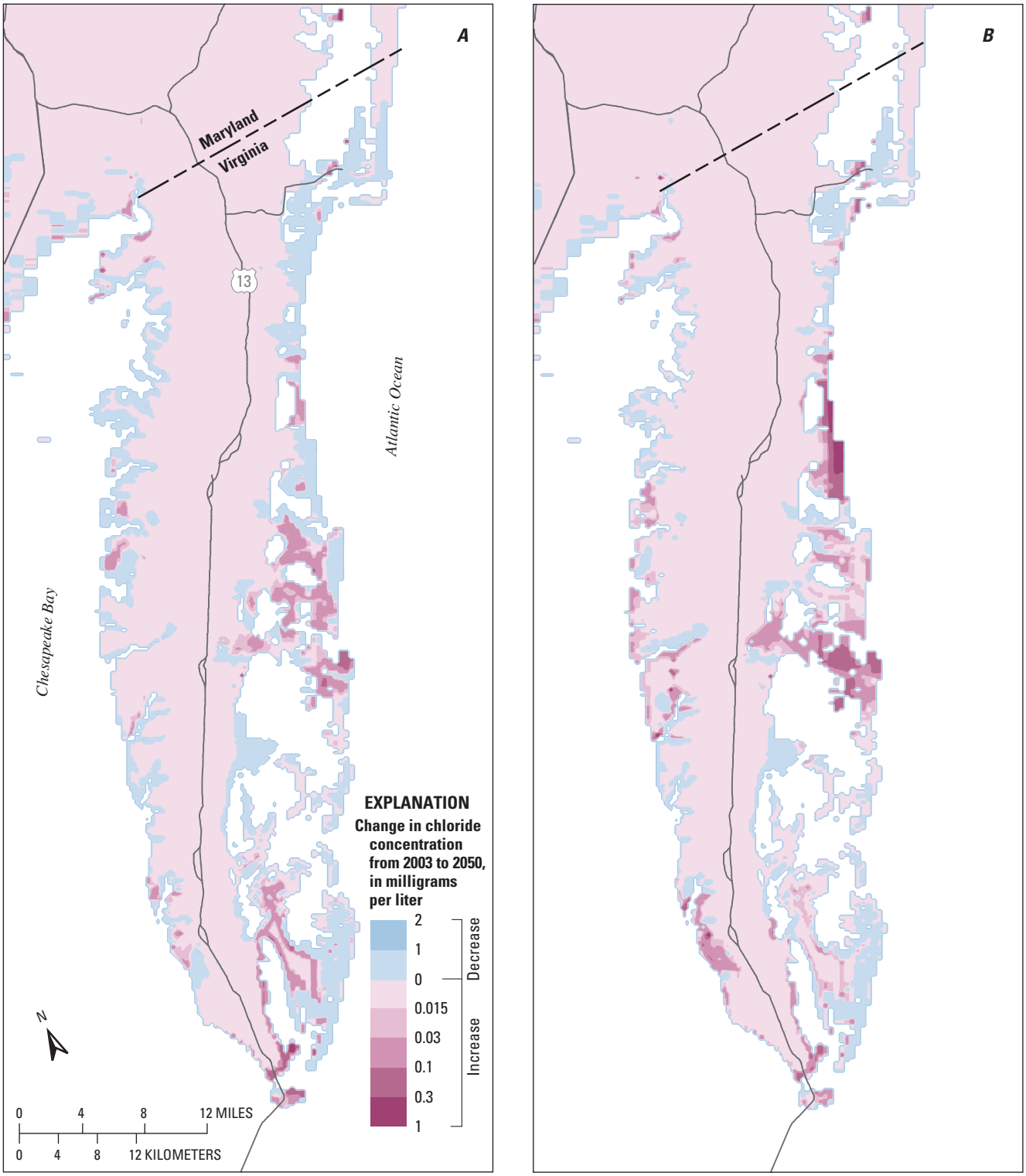


Figure 57. Changes in chloride concentrations from 2003 to 2050 assuming pumping after 2003 is for *(A)* 2003 pumping rates and *(B)* total permitted withdrawal rates in the upper Yorktown-Eastover aquifer of the Eastern Shore of Virginia.

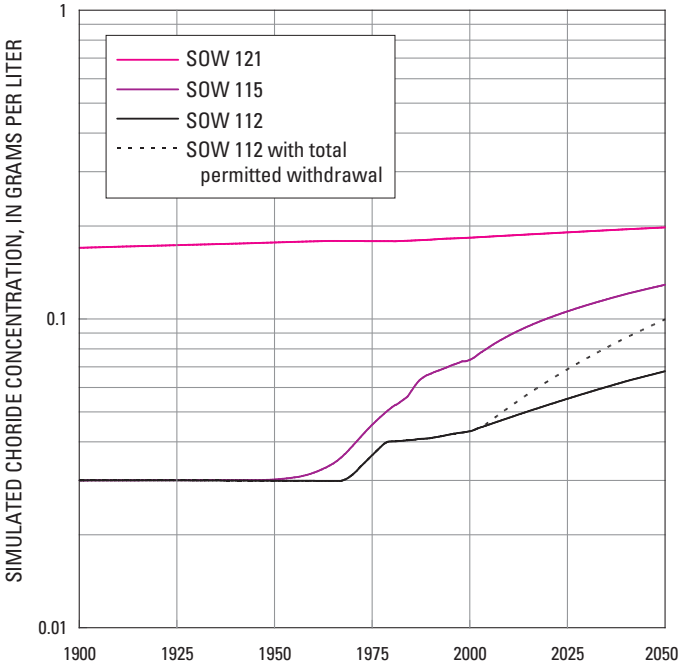


Figure 58. Simulated increases in chloride concentrations in selected wells. See figure 3 for well locations.

the downward transit time of dissolved solutes through the upper confining layer is useful and is shown in figure 60. The map was generated using Darcy's law, a porosity of 40 percent, and values of the thickness of the confining unit, the hydraulic conductivity of the confining unit, and water levels on both sides of the confining unit for the conditions described below.

The downward transit times through the confining unit are shown for predevelopment conditions in 1900 (fig. 60*A*). The recharge area along the central topographic ridge is clearly delineated, and the typical transit times range from several hundred to a few thousand years. The simulated lower water levels for 2003 have resulted in decreased transit times (fig. 60*B*). The area of downward migration has widened substantially, especially in Accomack County, compared to the area shown if figure 60*A* for 1900. Also, the simulated transit time has decreased to 200–300 years for wide areas in both counties. A few locations directly over withdrawal wells had simulated transit times less than 100 years. The uncertainties in these transit times are a function of the uncertainties in the porosity, the surficial and upper aquifer water levels, the thickness of the uppermost confining layer, and the vertical hydraulic conductivity of the uppermost confining layer. The last parameter has the highest uncertainty of the four, and its value will vary spatially at a scale that is more local than what is represented in this model.

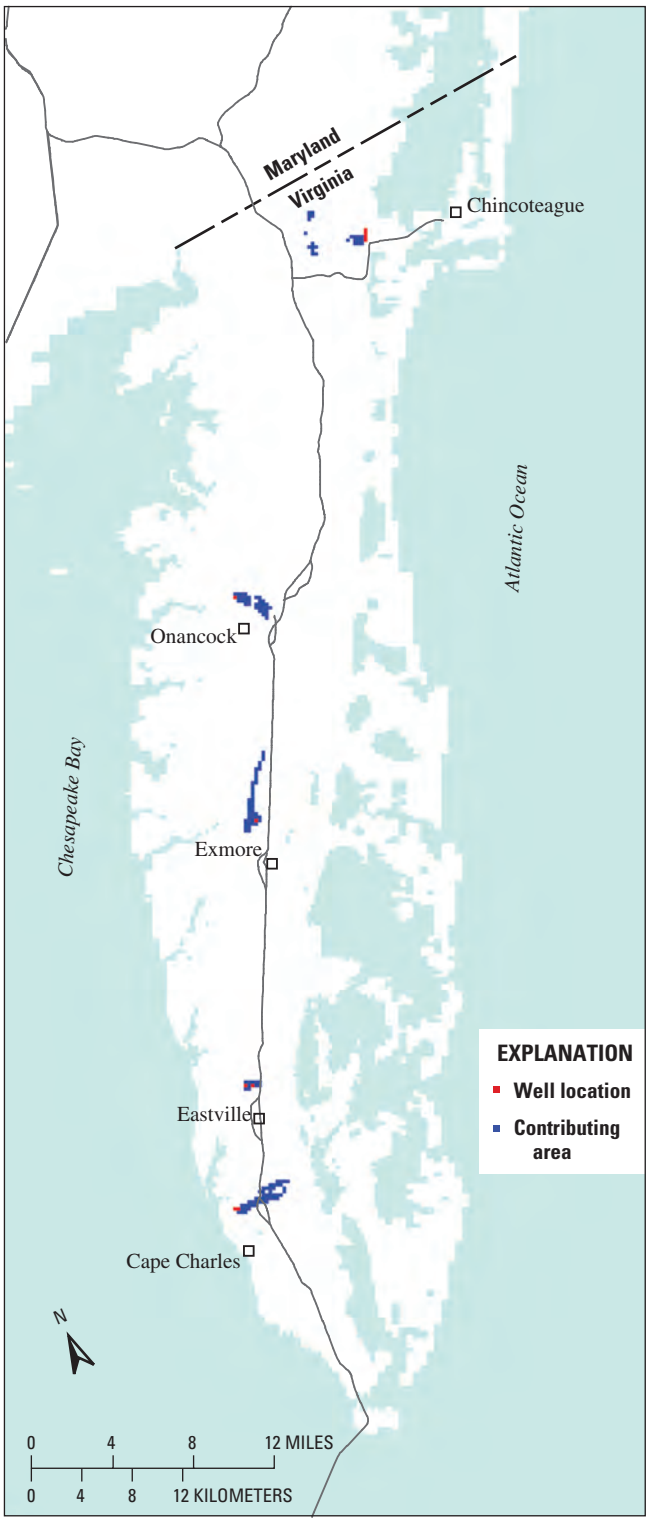


Figure 59. Areas at the base of the surficial aquifer contributing water to selected public-supply wells on the Eastern Shore of Virginia.

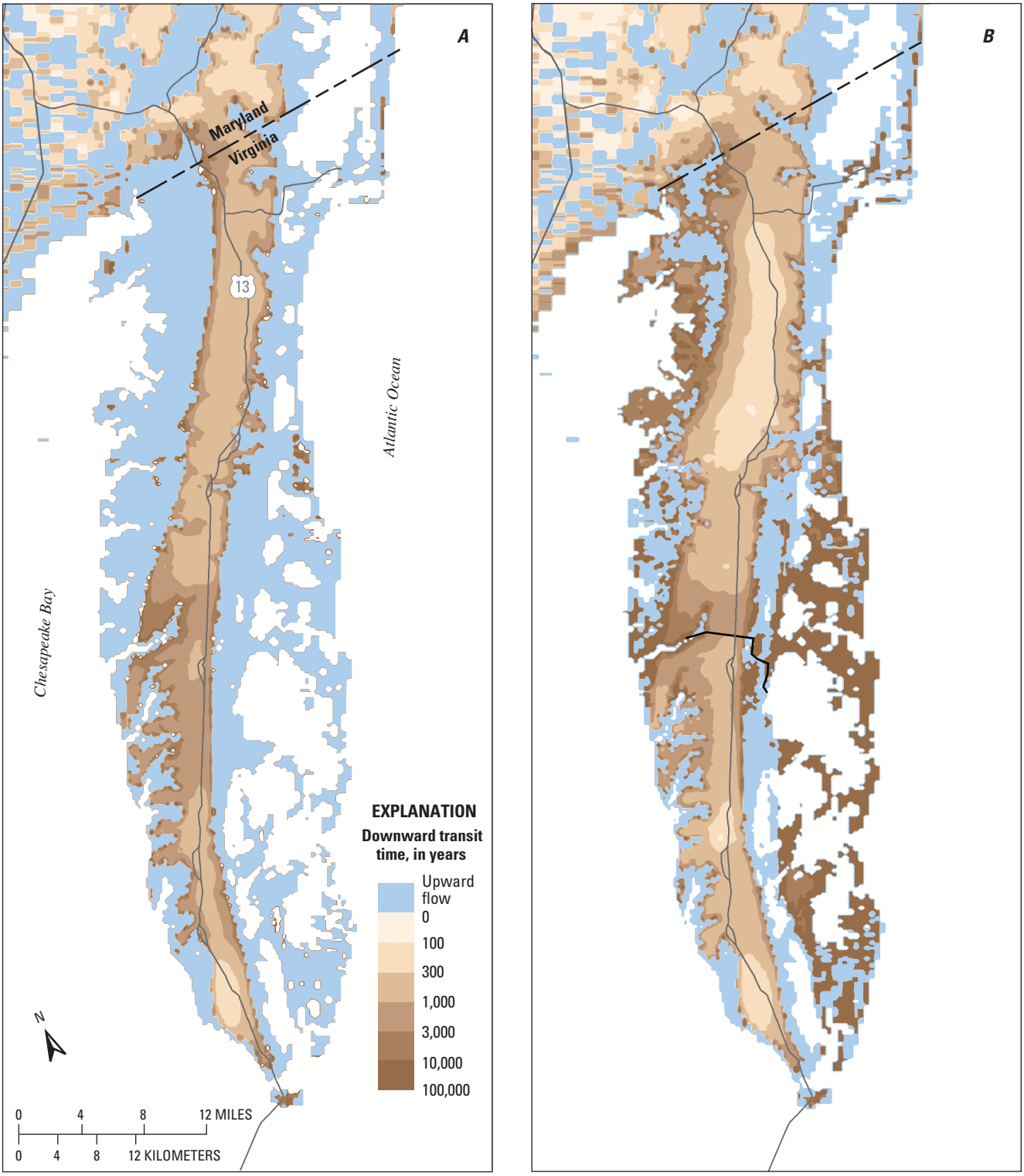


Figure 60. Downward transit time of water for *(A)* 1900 and *(B)* 2003 hydraulic conditions through the upper Yorktown-Eastover confining unit of the Eastern Shore of Virginia.

Groundwater Model Reliability

The model in this study was made with certain assumptions about the geology, the way in which subsurface units are heterogeneous, and the historical rates and patterns of withdrawal. The result is that the model produced is only an approximation of the real system. It was created in such a way as to reproduce the historical water-level observations with as much precision as possible, but many aspects of the model will be inaccurate because of the limited knowledge we have of the subsurface. It is important, therefore, to attempt to address the reliability of the model as it might be used to assess future changes in water levels or salinities within the Eastern Shore.

Model Error

One way of quantifying the model reliability is to examine the errors associated with reproducing the historical set of observations. A plot of observed versus simulated observations is a simple way to examine these errors. In this study, simulated water levels at all observation points were plotted against the observed values (fig. 61*A*). For a perfectly calibrated model, all such points should plot on the unit diagonal line. In this study, the water levels all fall reasonably close to the line ($R^2 = 0.93$) with no significant outliers. During the calibration process, each observation was given a weight based on the degree of accuracy with which the observation was thought to be reported. Typically, the water-levels reported from the observation-well network (SOW-numbered wells) were given a higher weight (by a factor of 10) than most other data, which had either limited information on land-surface elevations or limited data points in time, where seasonal fluctuations could not be accounted for. The weighted-simulated values can also be plotted against the weighted residuals (observed minus simulated) to discern any bias in the model (Hill, 1998). The pattern of weighted residuals about the abscissa appears essentially random (fig. 61*B*), suggesting a lack of bias in the model results.

Chloride data were also used to try to adjust the simulated predevelopment chlorinity field to a reasonable location. These data were not used in the calibration procedure, so they were not weighted. A simple observed versus simulated chloride value plot (fig. 62) still, however, gives good information. The scale in the plot is log-log, which improves the way the fit to the diagonal might look, although in this case there are a number of points that do not fall near the diagonal ($R^2 = 0.16$). A number of points have observed chloride values ranging from 100 to greater than 1,000 mg/L, but the simulated values

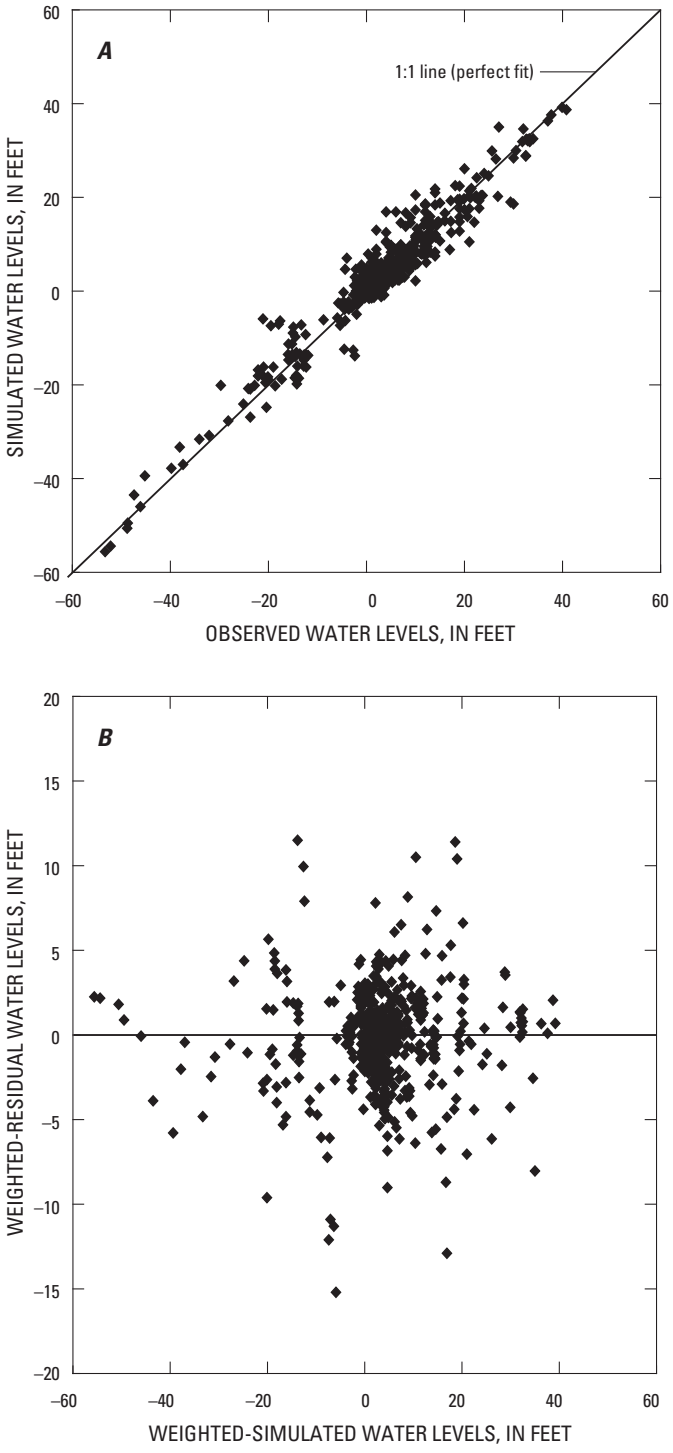


Figure 61. *(A)* Observed versus simulated water levels and *(B)* weighted-simulated versus weighted-residual water levels from the model of the Eastern Shore of Virginia.

are near background at freshwater concentrations (100 mg/L). These mismatches may be because the sources of chloride in the confined aquifer are other than seawater, the presence of very small percentages of very old saline water in the system, or the inability of the transport simulation to adequately represent dispersion. No matter what the reason, it underlines the important fact that any concentrations predicted by this model are going to have a much higher degree of uncertainty associated with them than water-level predictions.

Spatial distribution of errors can also be informative. Plots have been created that show how the errors are distributed across the Eastern Shore (figs. 63 and 64). Trends in such data can suggest sections of the model where the hydrogeologic framework or model parameters may have to be adjusted in a different way than was done during the model calibration. In the plots, the filled circles represent where the simulated water levels are too high, and the open circles represent where the simulated water levels are too low. The size of the circle is proportional to the size of the error. Although circles of one type or another may be clustered in one or two locations in the two figures, in general there is little trend to where the different types of errors are located. There is also no particular region where the errors are high or where they are low. This suggests that there is no spatial bias in the model.

Another way of assessing model error was to plot observed and simulated water levels for that have a lot of historical data (hydrographs). Hydrographs are plotted for four well clusters in Northampton County (figs. 65 and 66). In general, the transient simulated observations match the observed data with a few exceptions. Simulated water levels near Kiptopeake did not match the observations closely, and the data suggest there might be low levels of pumping in this region that were not included in the simulations. Hydrographs are also plotted for 10 well clusters in Accomack County (figs. 67–69). In general, the simulated water levels match the observed water-level data relatively well. It should be noted that the Perdue and Accomac clusters (fig. 68*C* and 68*D*), which are near major pumping centers, show drawdowns of tens of feet over decades, and the model reproduces these drawdowns fairly well. The cluster at Chincoteague (fig. 69*C*) shows great seasonal fluctuations because of high summertime groundwater use during the tourist season. The model did not simulate seasonal variations in pumping, thus the model did not generate seasonal water-level fluctuations.

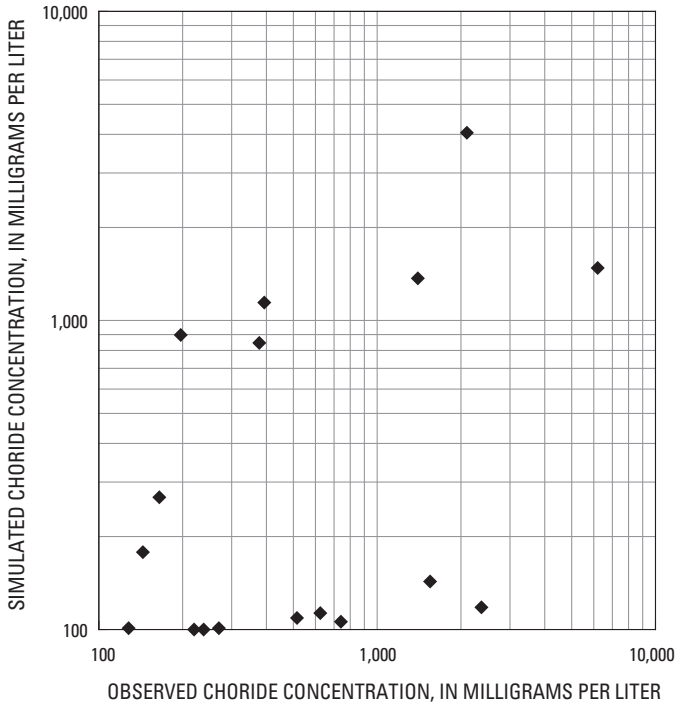


Figure 62. Observed versus simulated chloride concentrations in wells from the model of the Eastern Shore of Virginia.

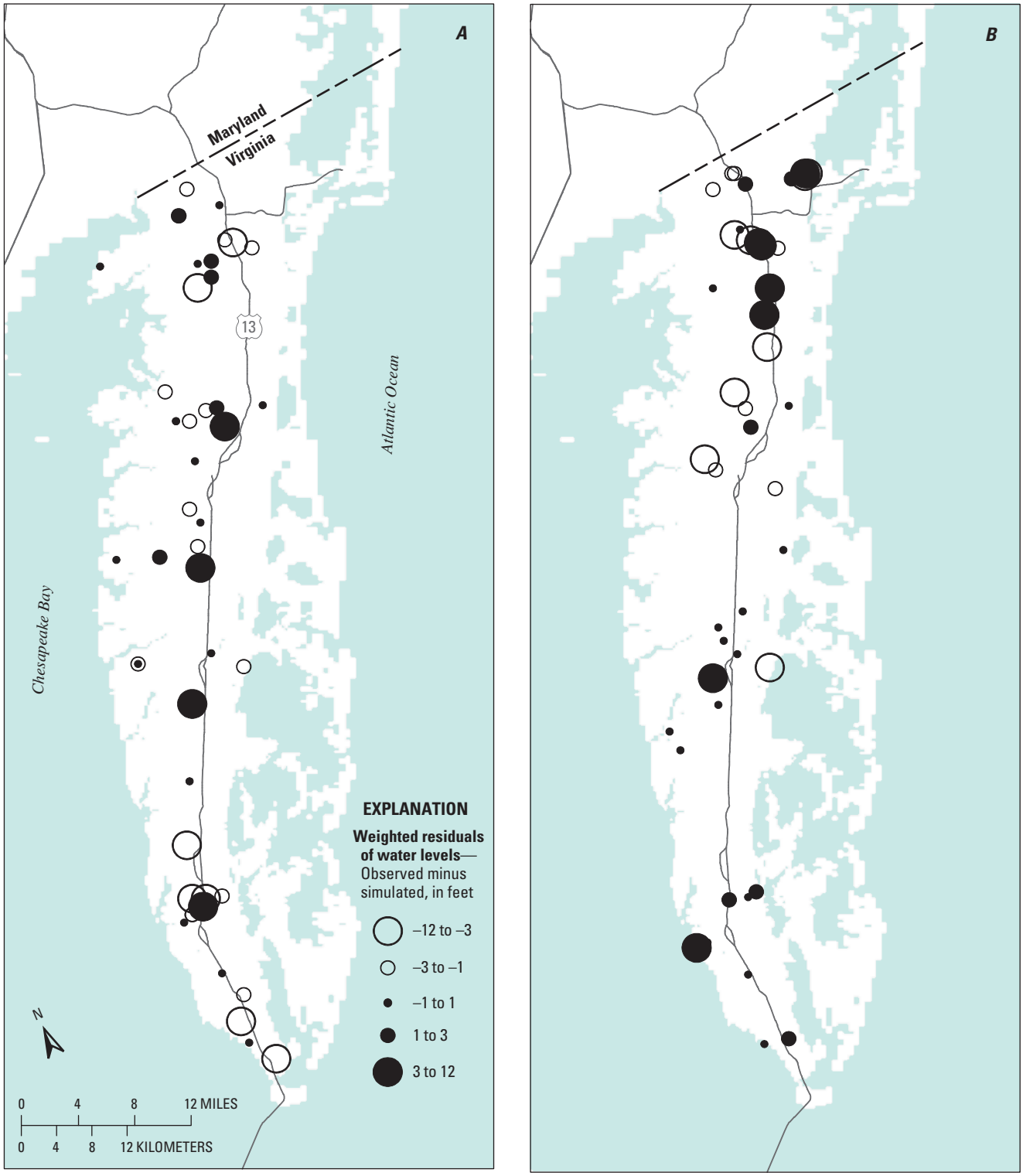


Figure 63. Spatial distribution of water-level simulation errors in the *(A)* lower and *(B)* middle Yorktown-Eastover aquifers of the Eastern Shore of Virginia.

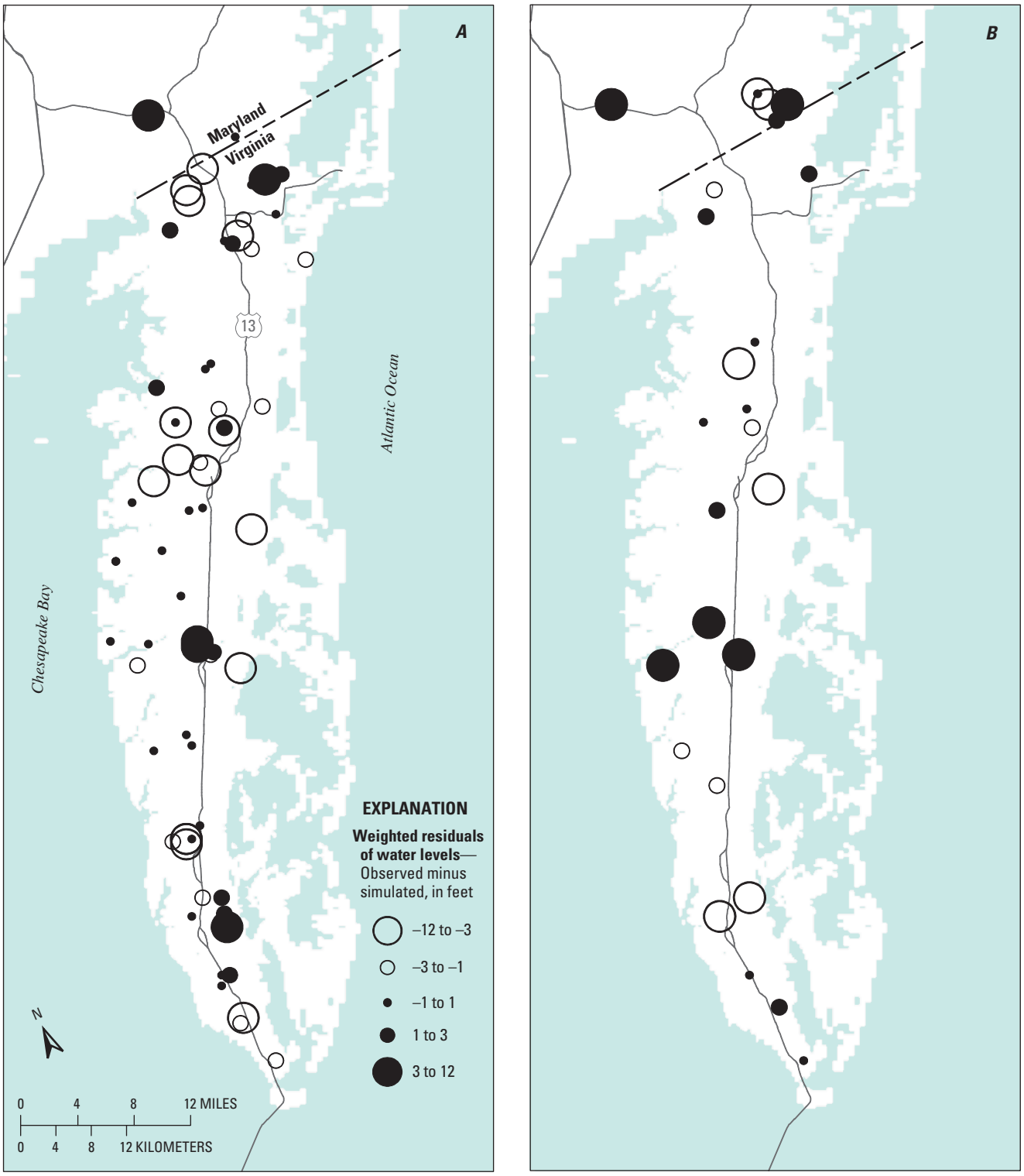


Figure 64. Spatial distribution of water-level simulation errors in the *(A)* upper Yorktown-Eastover and *(B)* surficial aquifers of the Eastern Shore of Virginia.

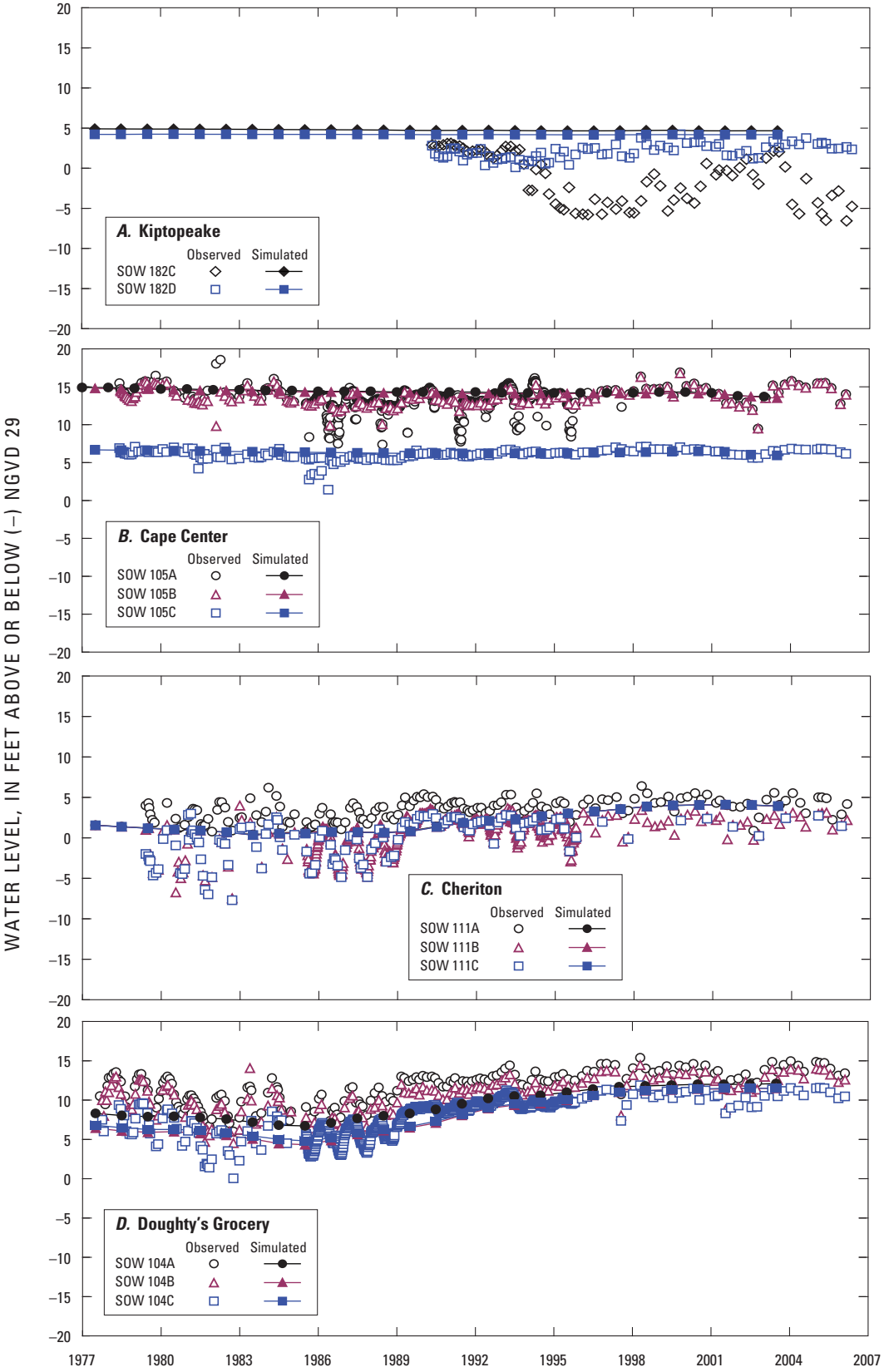


Figure 65. Observed and simulated water levels in southern Northampton County, Virginia, for well clusters *(A)* SOW 182, *(B)* SOW 105, *(C)* SOW 111, and *(D)* SOW 104. See figure 3 for well locations.

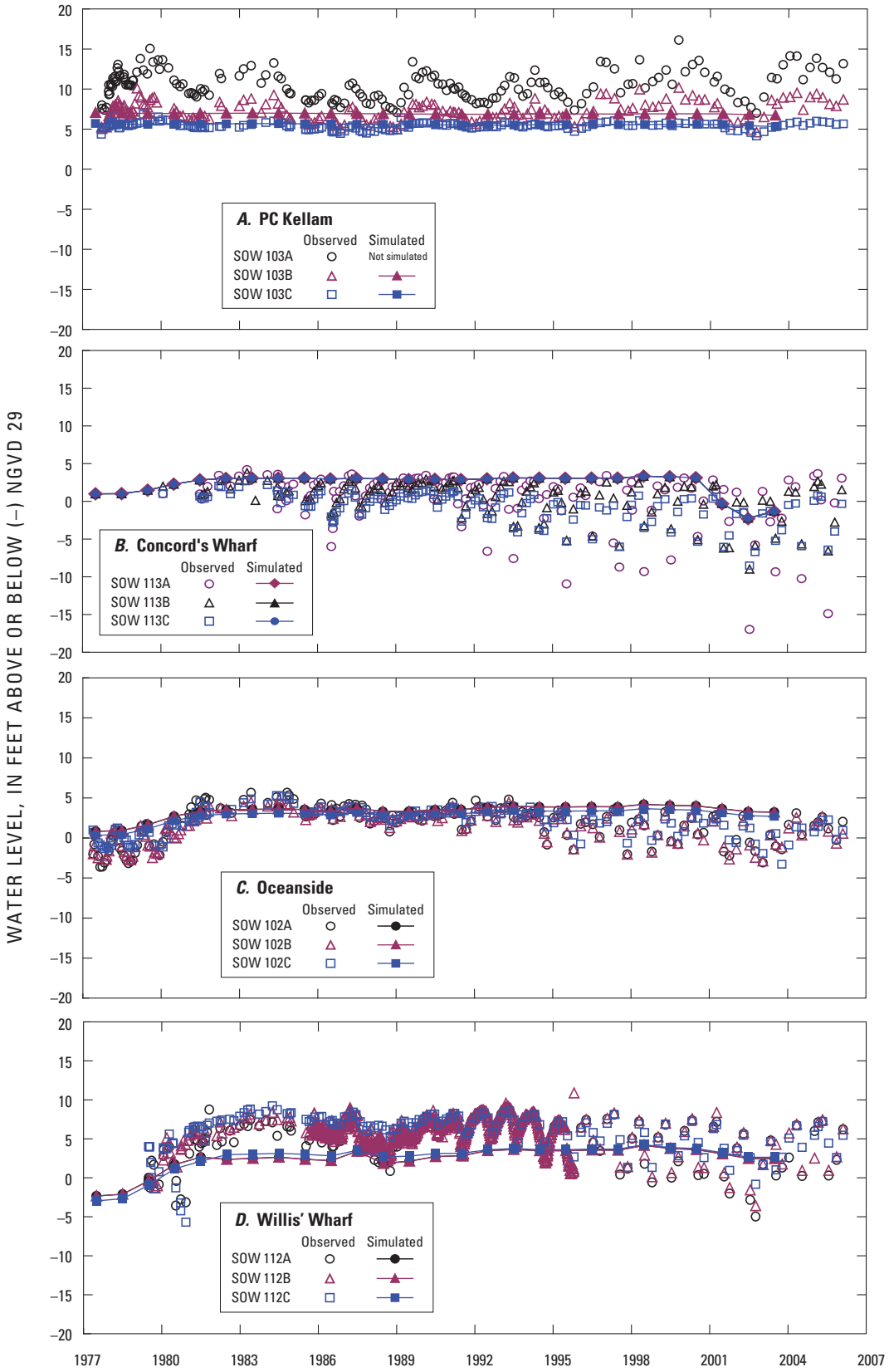


Figure 66. Observed and simulated water levels in southern Northampton County, Virginia, for well clusters *(A)* SOW 103, *(B)* SOW 113, *(C)* SOW 102, and *(D)* SOW 112. See figure 3 for well locations.

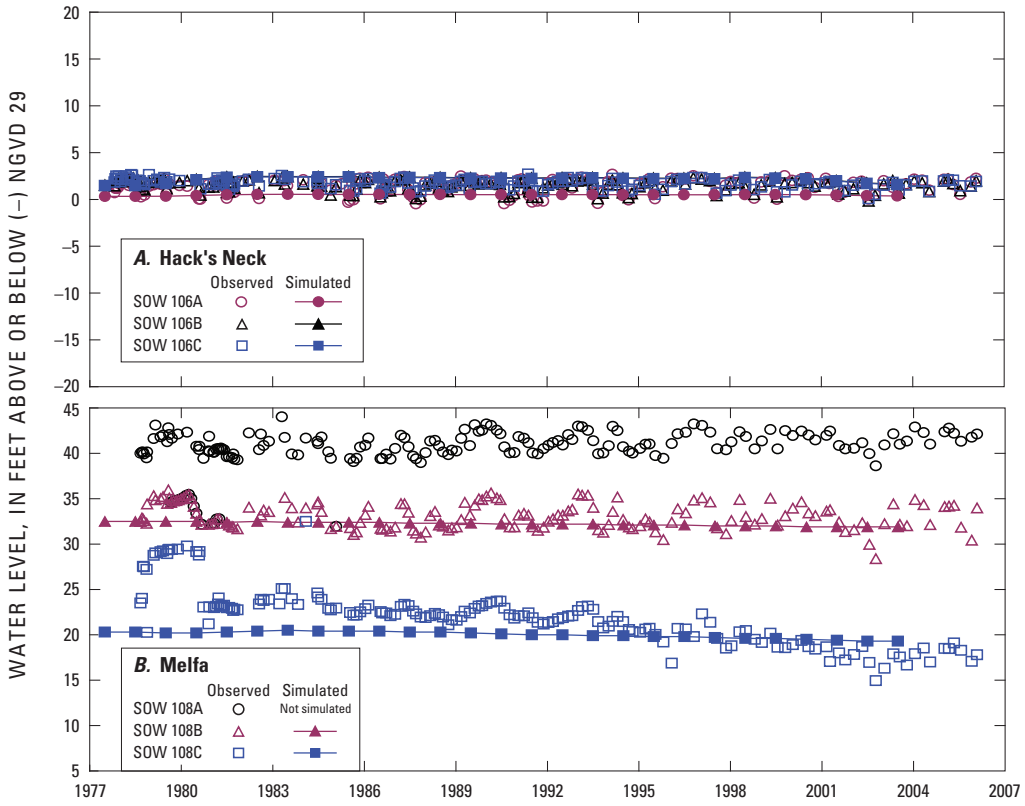


Figure 67. Observed and simulated water levels in central Accomack County, Virginia, for well clusters *(A)* SOW 106 and *(B)* SOW 108. See figure 3 for well locations.

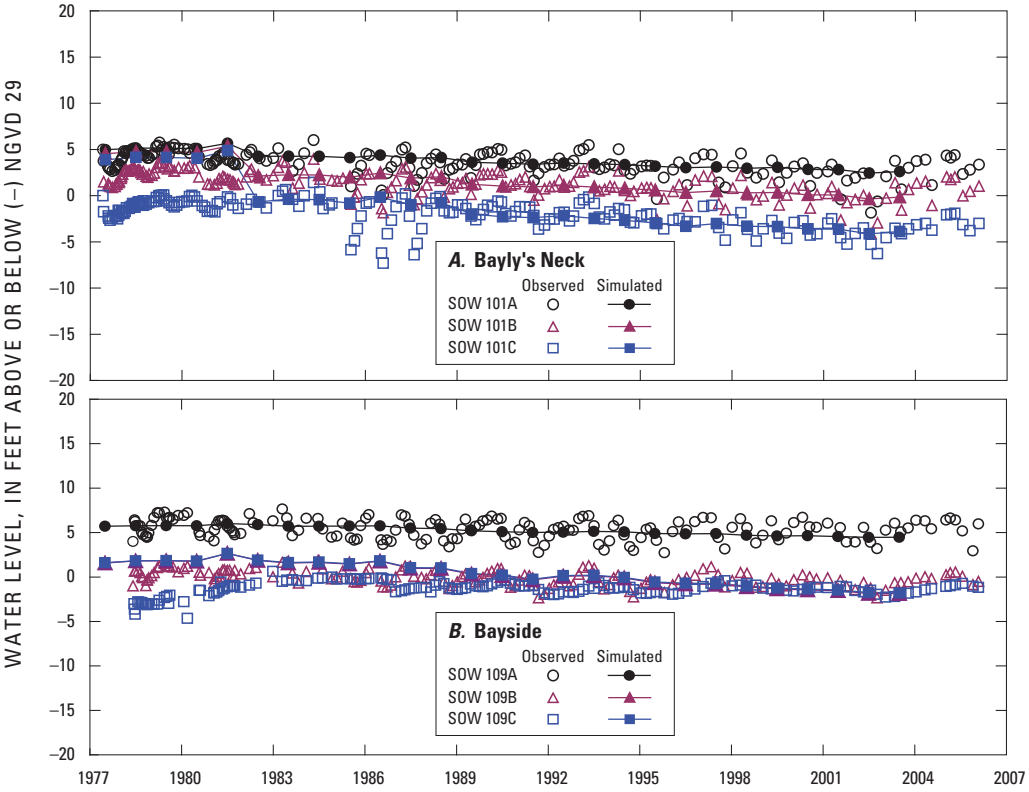


Figure 68. Observed and simulated water levels in central Accomack County, Virginia, for well clusters *(A)* SOW 101, *(B)* SOW 109, *(C)* SOW 114, and *(D)* SOW 183. See figure 3 for well locations.

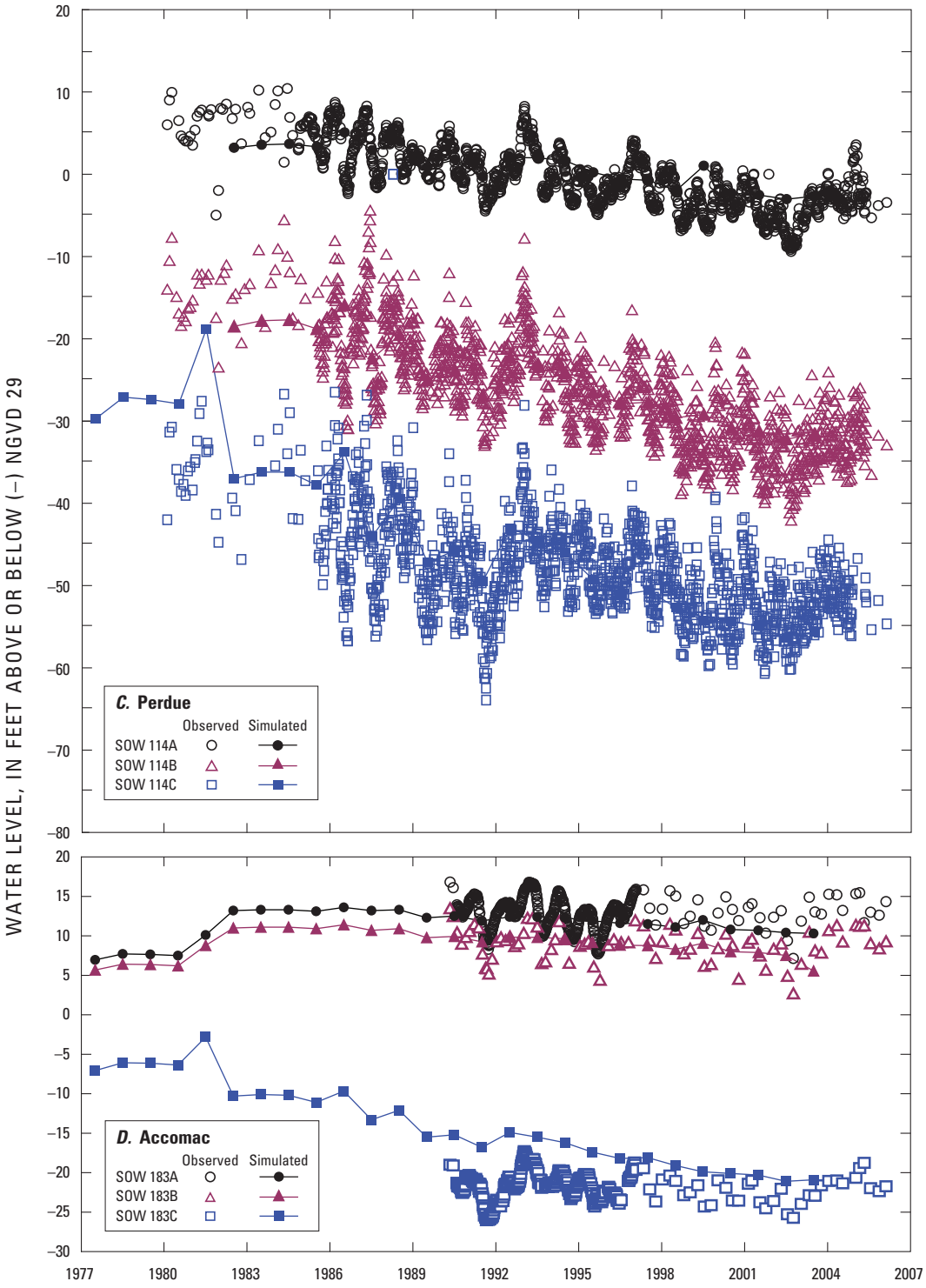


Figure 68. Observed and simulated water levels in central Accomack County, Virginia, for well clusters *(A)* SOW 101, *(B)* SOW 109, *(C)* SOW 114, and *(D)* SOW 183. See figure 3 for well locations. —Continued

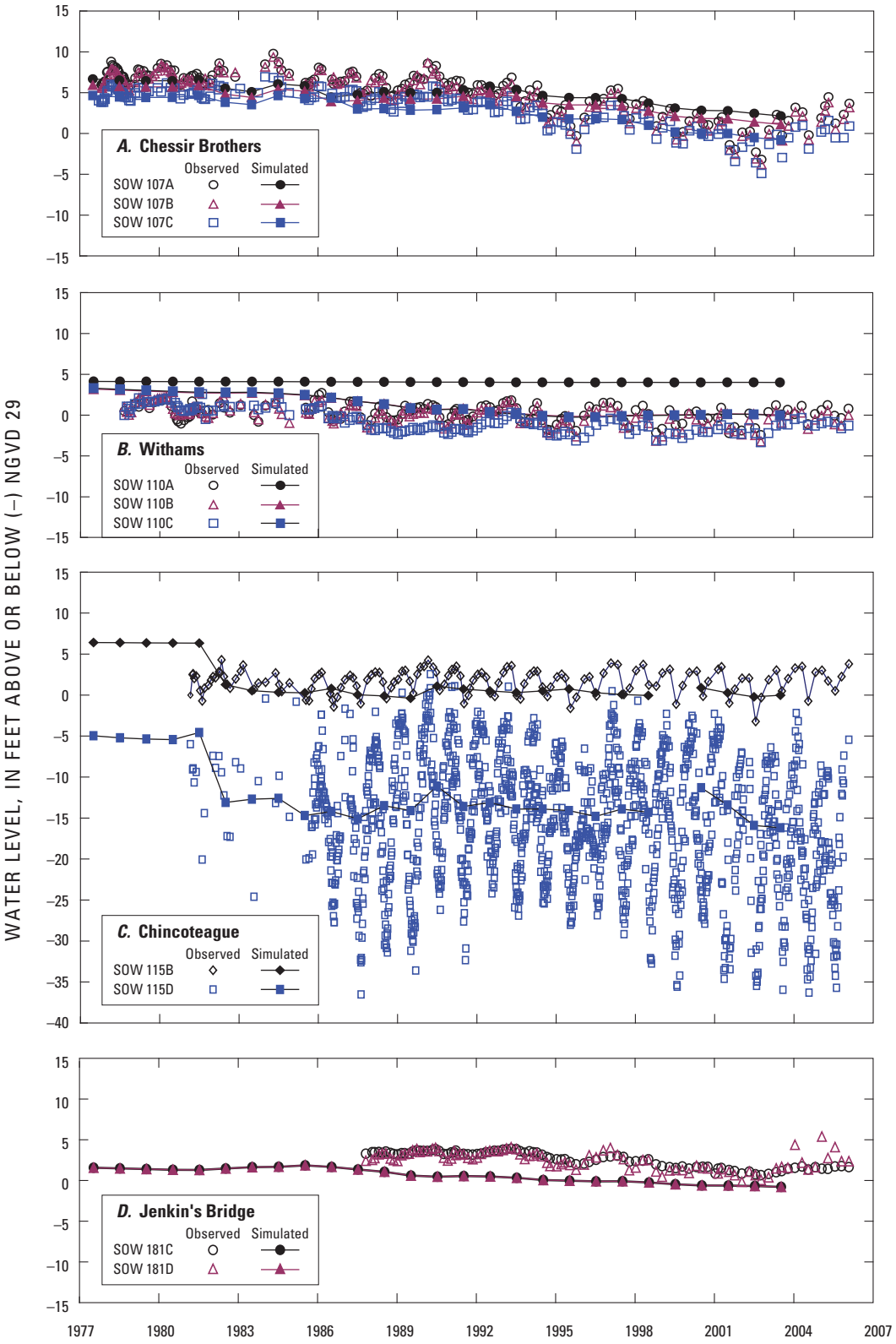


Figure 69. Observed and simulated water levels in northern Accomack County, Virginia, for well clusters *(A)* SOW 107, *(B)* SOW 110, *(C)* SOW 115, and *(D)* SOW 181. See figure 3 for well locations.

Model Parameter Sensitivity

The calibration procedure used to create the model of the Eastern Shore calculates a composite scaled sensitivity (Hill, 1998) for each parameter that is specified or estimated. The composite scaled sensitivity indicates the magnitude to which a change in the value of the parameter causes a change in the simulated water-level observations. Highly sensitive parameters, therefore, exert greater control over the simulated water levels, whereas relatively insensitive parameters have less control over the simulated water levels. The relative differences in the composite scaled sensitivities reflect the importance the parameter plays in the system to control water levels and also the distribution of the observations (a cluster of observations are more likely to be affected by a nearby parameter). A plot of the composite scaled sensitivities of the hydraulic conductivity values at the pilot-point locations (fig. 28) for the aquifer is shown in figure 70. Each pilot-point location represents a separate parameter. These graphs illustrate clearly which parameters have greater control over the simulated equivalents to observations and which ones have little to no control. The lower aquifer has sensitive parameters in central Accomack County around the pumping centers, especially the Perdue center. The middle aquifer has its most sensitive parameters near Chincoteague, Tysons, and Oyster. The upper aquifer has its most sensitive parameter near Pocomoke, with somewhat sensitive parameters near Chincoteague and Perdue.

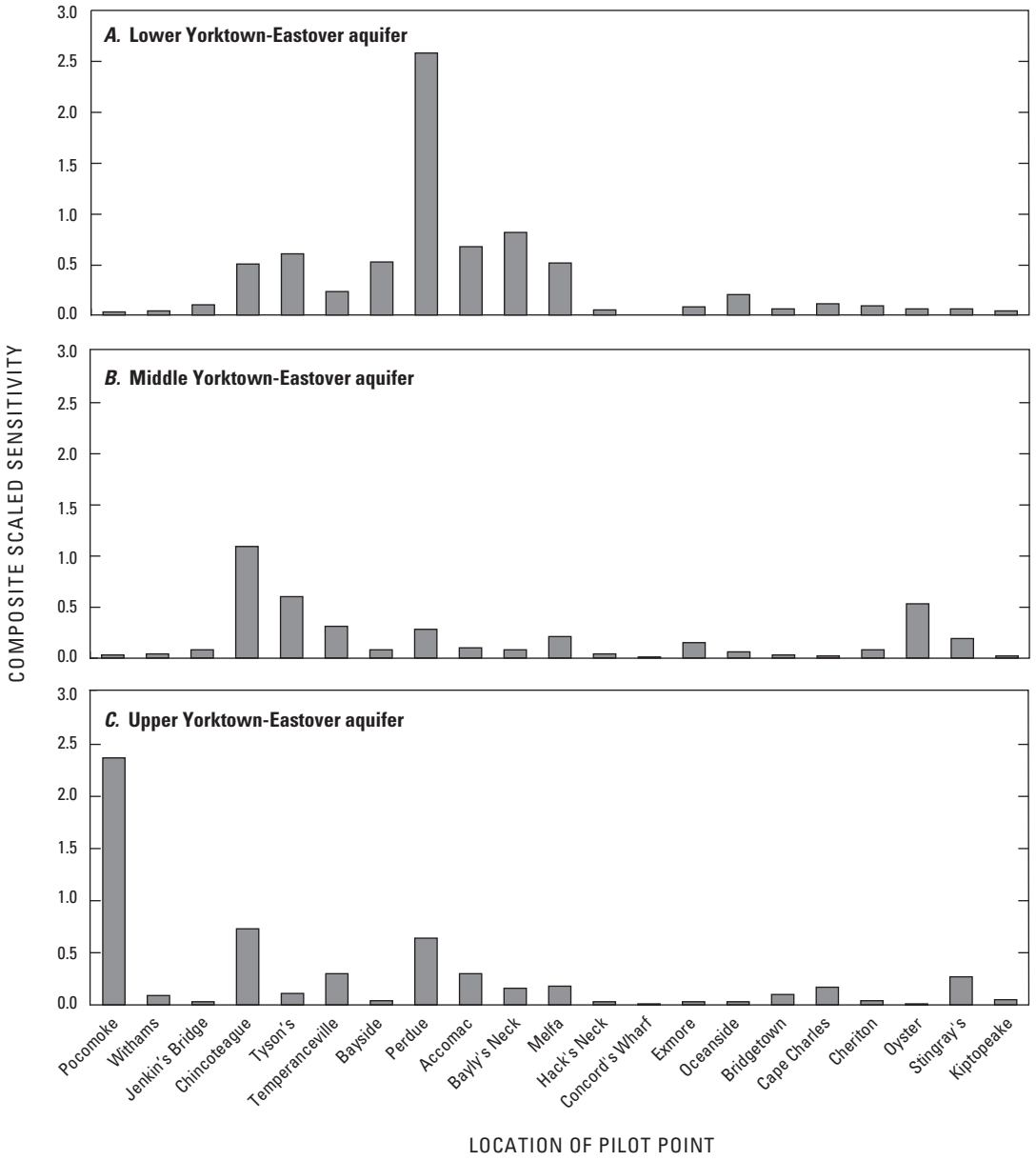


Figure 70. Relative sensitivities of water levels to hydraulic conductivities in the *(A)* lower, *(B)* middle, and *(C)* upper Yorktown-Eastover aquifers of the Eastern Shore of Virginia. See figure 28 for locations.

The composite scaled sensitivities of the hydraulic conductivity of the confining units at the pilot-point locations are plotted in figure 71. Considering all pilot points as a group, the upper confining unit has a greater effect on water levels than any other confining unit or aquifer. The Perdue–Accomac region has high confining-unit sensitivities, especially for the upper and lower confining units because of the large number of observations in that vicinity and the large hydraulic stress on the aquifer system. Overall, Northampton County has fewer parameters that have substantial composite sensitivities because less pumping has taken place.

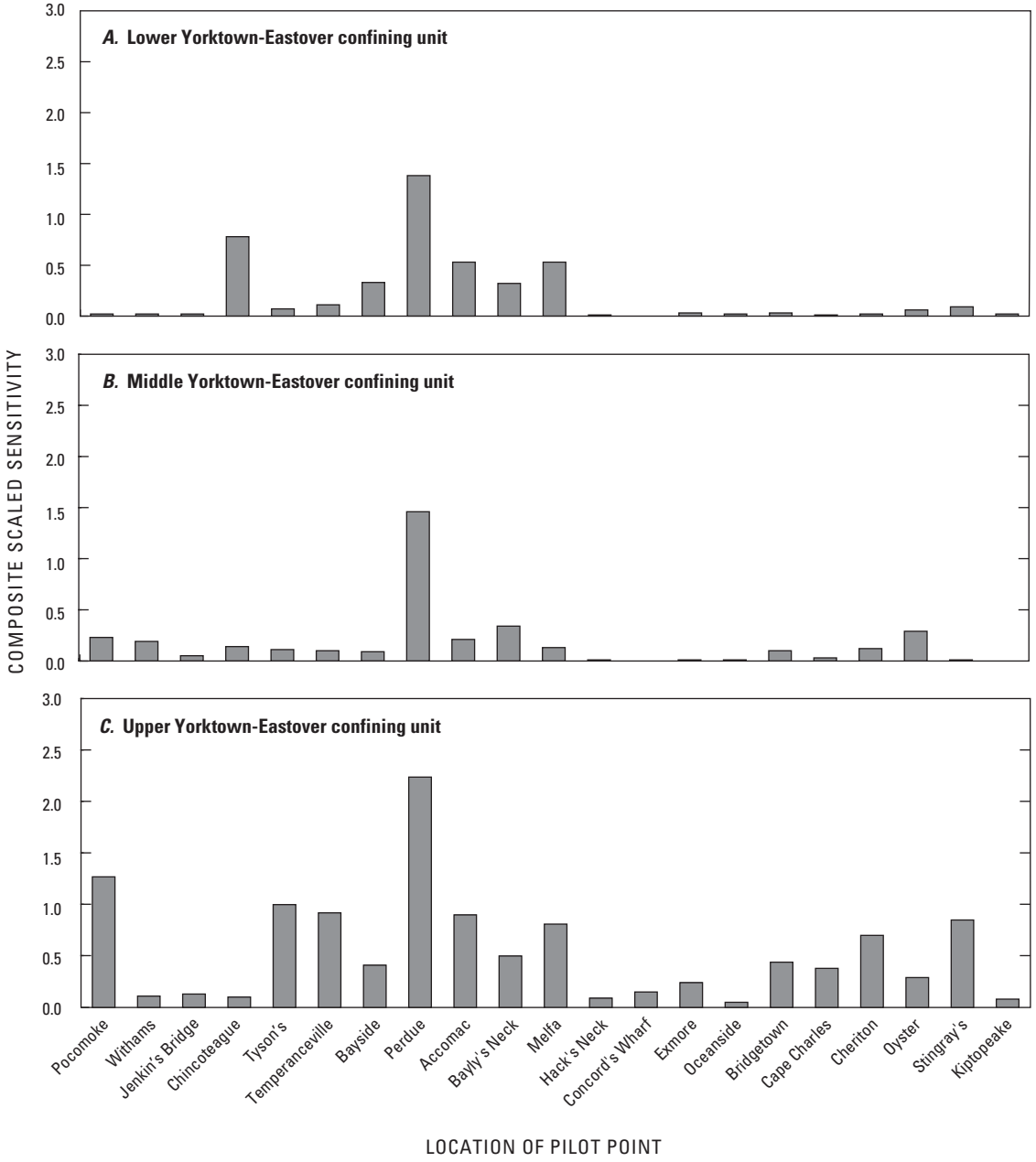


Figure 71. Relative sensitivities of water levels to hydraulic conductivities in the *(A)* lower, *(B)* middle, and *(C)* upper Yorktown-Eastover confining units of the Eastern Shore of Virginia. See figure 28 for locations.

Confidence Intervals

Another way of examining the relative importance of different parameters and the degree of confidence in an estimated parameter value is to calculate 95 percent linear confidence intervals. These limits are calculated partly on the basis of the sensitivity of the parameter (Hill, 1998), and indicate a range of values to which the parameter value could be set that might still give similar simulated equivalents to observations. Such confidence intervals have been plotted for the three confined aquifers (fig. 72). The vertical axes cover many orders of magnitude, so it can be seen that any parameter whose confidence interval covers more than one or two orders of magnitude has a large degree of uncertainty. Essentially, there was not enough information in the observations to constrain such a parameter value with any reasonable certainty. Relatively high certainty in a parameter value is associated with narrow ranges of the 95 percent confidence intervals, which are limited to the parameters in central Accomack County for the lower aquifer, a few of these parameters for the middle aquifer, and few similar

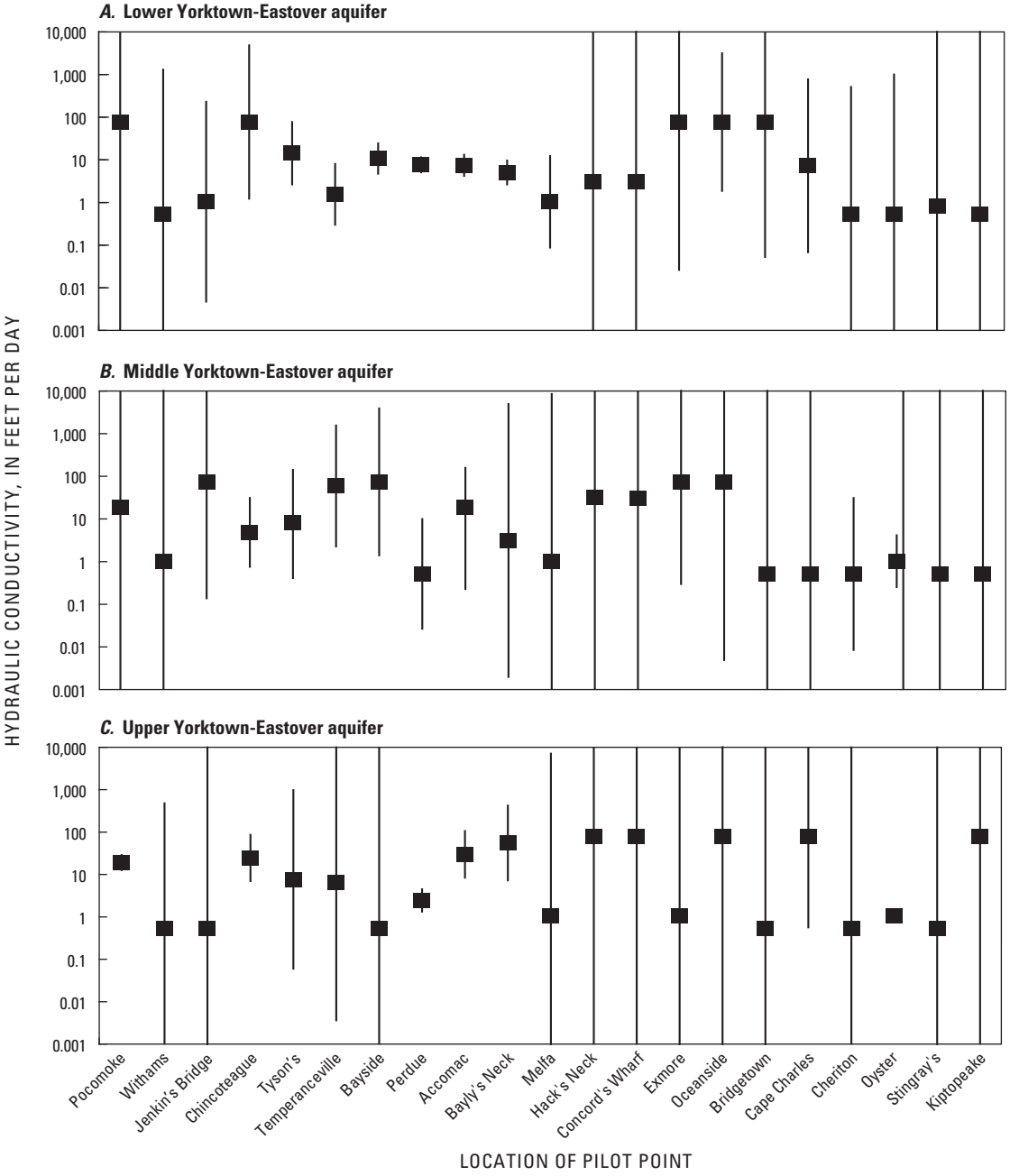


Figure 72. Calculated 95 percent linear confidence intervals of hydraulic conductivities in the *(A)* lower, *(B)* middle, and *(C)* upper Yorktown-Eastover aquifers of the Eastern Shore of Virginia. Line segment indicates range of confidence interval. See figure 28 for locations.

parameters in the upper aquifer. The confidence intervals for the confining units are shown in figure 73. The pattern of parameters with narrow 95 percent confidence intervals is similar to that for sensitivities in figure 71. The upper con fining unit and the central Accomack County region have the narrowest confidence intervals and the best constrained values. The upper confining unit has the most control on regional predevelopment water levels, so its values are typically better constrained than lower confining units or aquifers. Also, the more highly stressed long-term records of central Accomack County have provided observation data that are suited to estimate parameters for that region. Future data-collection efforts could focus on areas where parameter values are not well constrained. If the goal of future studies is to reduce uncertainty in model forecasting, then reducing the uncertainty in the currently unconstrained parameter values in the areas of interest may be the most cost-efficient approach (Tiedeman and others, 2003, 2004; Hill and Tiedeman, 2007).

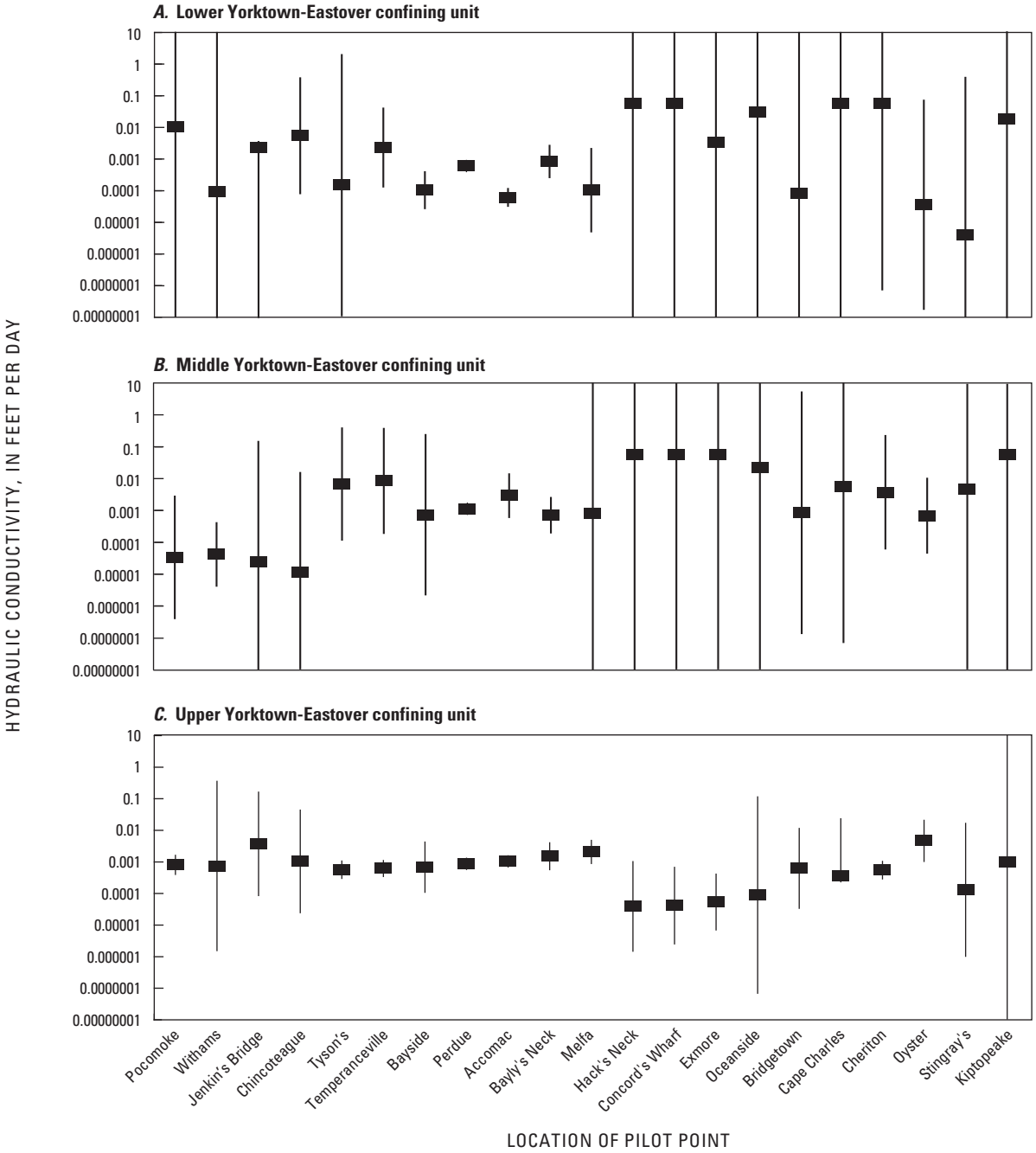


Figure 73. Calculated 95 percent linear confidence intervals of hydraulic conductivities in the *(A)* lower, *(B)* middle, and *(C)* upper Yorktown-Eastover confining units of the Eastern Shore of Virginia. Line segment indicates range of confidence interval. See figure 28 for locations.

Summary and Conclusions

The Eastern Shore of Virginia relies solely on groundwater for its water supply. Consequently, effective management of the aquifer system is needed to protect the supply from overextraction and seawater intrusion. In order for water managers to consider the current knowledge and data on the aquifer system in their decision making, a numerical model that incorporates all of this information may be used to assess the effect of current and future stresses on the aquifer system. Recent increases in the computational speed and memory capabilities of computers, and the development of more sophisticated groundwater modeling software have motivated this study, in which a new numerical model of the Eastern Shore has been assembled and calibrated using the latest available techniques. The geologic framework was not updated substantially from the most recent model (Richardson, 1994), but the model was refined spatially. The new, refined model can simulate water levels in the surficial aquifer and chloride concentrations in the entire system. The model calibration procedure produced fields of hydraulic parameters values, based on 21 pilot-point locations, which vary smoothly across the study area and are bounded by reasonable limits for the parameter values.

Future simulations to the year 2050 with both 2003 and total-permitted-withdrawal pumping rates indicate that at 2003 rates drawdowns may stabilize, but at total-permitted-withdrawal rates drawdowns may accelerate at locations not presently being affected. Future simulations of chloride concentrations indicate areas near the coast that are most likely to be affected by saltwater intrusion. These include locations near Chincoteague, east of Exmore, and near Cape Charles. The deepest aquifer is consistently more susceptible to intrusion than the shallower aquifers.

Although the model has been created using the latest observation data and modeling software, results from the model and error analyses identify areas where the model still has limitations. Results from the chloride transport simulations indicate that the model identifies potential locations susceptible to seawater intrusion and the timeframes associated with that intrusion. The ability to accurately forecast changes in chloride concentrations at individual locations is for the most part still beyond the capability of this model ($R^2 = 0.16$). The historical water levels observed on the Eastern Shore can be matched by the model relatively well ($R^2 = 0.93$) for most locations, suggesting that future assessments of water-level changes are likely to be more accurate than those of salinity changes. The sensitivity and confidence interval analyses indicate where model parameters are well constrained and perhaps more importantly, where they are not well constrained and, thus, where future data collection may improve the reliability of the model.

Acknowledgments

This study was supported by the Virginia Department of Environmental Quality, the Accomack-Northampton Planning District Commission, the U.S. Geological Survey Office of Groundwater, and the U.S. Geological Survey National Research Program. Most of the chemical analyses were performed in the laboratories of the USGS National Research Program in Reston, Virginia. Several members of the Virginia DEQ and the USGS Virginia Water Science Center provided helpful comments and suggestions throughout the course of the study.

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Appendixes 1–3

Appendix 1. Observation Wells with Observed and Simulated Water Levels Used to Calibrate the Model of the Eastern Shore of Virginia

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia.

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
63G 20	SOW 075	Corp Webster Co. G L	2–23	306	43	1976	–0.02	9.75
63G 20	SOW 075	Corp Webster Co. G L	2–23	306	43	1979	–2.35	8.31
63G 20	SOW 075	Corp Webster Co. G L	2–23	306	43	1982	–4.31	–1.10
63G 20	SOW 075	Corp Webster Co. G L	2–23	306	43	1985	1.53	4.06
63G 20	SOW 075	Corp Webster Co. G L	2–23	306	43	1988	3.61	4.33
63G 20	SOW 075	Corp Webster Co. G L	2–23	306	43	1991	11.04	16.53
63G 20	SOW 075	Corp Webster Co. G L	2–23	306	43	1994	11.68	17.55
66K 4	SOW 101A	Bayly's Neck	16–17	122	65	1979	4.69	4.45
66K 4	SOW 101A	Bayly's Neck	16–17	122	65	1982	3.96	3.46
66K 4	SOW 101A	Bayly's Neck	16–17	122	65	1985	3.32	3.28
66K 4	SOW 101A	Bayly's Neck	16–17	122	65	1988	3.33	3.28
66K 4	SOW 101A	Bayly's Neck	16–17	122	65	1991	3.63	2.56
66K 4	SOW 101A	Bayly's Neck	16–17	122	65	1994	3.19	2.51
66K 4	SOW 101A	Bayly's Neck	16–17	122	65	1997	2.91	2.26
66K 4	SOW 101A	Bayly's Neck	16–17	122	65	2000	2.28	1.99
66K 4	SOW 101A	Bayly's Neck	16–17	122	65	2003	1.32	1.74
66K 3	SOW 101B	Bayly's Neck	30	122	65	1979	2.66	3.90
66K 3	SOW 101B	Bayly's Neck	30	122	65	1982	2.11	1.10
66K 3	SOW 101B	Bayly's Neck	30	122	65	1985	1.22	0.88
66K 3	SOW 101B	Bayly's Neck	30	122	65	1988	1.30	0.90
66K 3	SOW 101B	Bayly's Neck	30	122	65	1991	1.31	–0.23
66K 3	SOW 101B	Bayly's Neck	30	122	65	1994	0.87	–0.42
66K 3	SOW 101B	Bayly's Neck	30	122	65	1997	0.56	–0.73
66K 3	SOW 101B	Bayly's Neck	30	122	65	2000	–0.08	–1.14
66K 3	SOW 101B	Bayly's Neck	30	122	65	2003	–1.00	–1.42
66K 2	SOW 101C	Bayly's Neck	37–38	122	65	1979	–0.81	3.25
66K 2	SOW 101C	Bayly's Neck	37–38	122	65	1982	–0.63	–2.13
66K 2	SOW 101C	Bayly's Neck	37–38	122	65	1985	–2.67	–2.31
66K 2	SOW 101C	Bayly's Neck	37–38	122	65	1988	–1.84	–2.24
66K 2	SOW 101C	Bayly's Neck	37–38	122	65	1991	–1.91	–3.96
66K 2	SOW 101C	Bayly's Neck	37–38	122	65	1994	–1.95	–4.30
66K 2	SOW 101C	Bayly's Neck	37–38	122	65	1997	–2.86	–4.68
66K 2	SOW 101C	Bayly's Neck	37–38	122	65	2000	–3.69	–5.30
66K 2	SOW 101C	Bayly's Neck	37–38	122	65	2003	–4.43	–5.59
64H 6	SOW 102A	Oceanside	14–16	220	57	1979	–0.24	0.44

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
64H 6	SOW 102A	Oceanside	14–16	220	57	1982	4.15	2.37
64H 6	SOW 102A	Oceanside	14–16	220	57	1985	3.84	2.43
64H 6	SOW 102A	Oceanside	14–16	220	57	1988	2.84	2.17
64H 6	SOW 102A	Oceanside	14–16	220	57	1991	2.99	2.34
64H 6	SOW 102A	Oceanside	14–16	220	57	1994	2.25	2.67
64H 6	SOW 102A	Oceanside	14–16	220	57	1997	1.23	2.64
64H 6	SOW 102A	Oceanside	14–16	220	57	2000	0.76	2.77
64H 6	SOW 102A	Oceanside	14–16	220	57	2003	–0.58	1.91
64H 7	SOW 102B	Oceanside	27–29	220	58	1979	–0.38	0.44
64H 7	SOW 102B	Oceanside	27–29	220	58	1982	3.34	2.40
64H 7	SOW 102B	Oceanside	27–29	220	58	1985	3.46	2.45
64H 7	SOW 102B	Oceanside	27–29	220	58	1988	2.75	2.22
64H 7	SOW 102B	Oceanside	27–29	220	58	1991	2.90	2.38
64H 7	SOW 102B	Oceanside	27–29	220	58	1994	2.09	2.71
64H 7	SOW 102B	Oceanside	27–29	220	58	1997	1.09	2.69
64H 7	SOW 102B	Oceanside	27–29	220	58	2000	0.62	2.80
64H 7	SOW 102B	Oceanside	27–29	220	58	2003	–0.89	1.94
64H 5	SOW 102C	Oceanside Campground	36–37	220	58	1979	0.26	0.47
64H 5	SOW 102C	Oceanside Campground	36–37	220	58	1982	3.74	2.46
64H 5	SOW 102C	Oceanside Campground	36–37	220	58	1985	3.84	2.52
64H 5	SOW 102C	Oceanside Campground	36–37	220	58	1988	2.98	2.31
64H 5	SOW 102C	Oceanside Campground	36–37	220	58	1991	3.25	2.45
64H 5	SOW 102C	Oceanside Campground	36–37	220	58	1994	2.73	2.77
64H 5	SOW 102C	Oceanside Campground	36–37	220	58	1997	1.53	2.76
64H 5	SOW 102C	Oceanside Campground	36–37	220	58	2000	1.51	2.85
64H 5	SOW 102C	Oceanside Campground	36–37	220	58	2003	–0.02	1.99
63H 6	SOW 103A	PC Kellam	2–3	251	25	1990	10.33	13.27
63H 5	SOW 103B	PC Kellam	15–17	251	25	1979	7.69	7.29
63H 5	SOW 103B	PC Kellam	15–17	251	25	1982	7.52	7.33
63H 5	SOW 103B	PC Kellam	15–17	251	25	1985	6.36	7.29
63H 5	SOW 103B	PC Kellam	15–17	251	25	1988	6.44	7.23
63H 5	SOW 103B	PC Kellam	15–17	251	25	1991	6.81	7.17
63H 5	SOW 103B	PC Kellam	15–17	251	25	1994	6.98	7.21
63H 5	SOW 103B	PC Kellam	15–17	251	25	1997	8.01	7.21
63H 5	SOW 103B	PC Kellam	15–17	251	25	2000	8.15	7.22
63H 5	SOW 103B	PC Kellam	15–17	251	25	2003	6.60	7.03
63H 4	SOW 103C	PC Kellam	28–29	251	25	1979	5.83	5.55
63H 4	SOW 103C	PC Kellam	28–29	251	25	1982	5.36	5.65
63H 4	SOW 103C	PC Kellam	28–29	251	25	1985	5.14	5.61
63H 4	SOW 103C	PC Kellam	28–29	251	25	1988	5.12	5.53

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
63H 4	SOW 103C	PC Kellam	28–29	251	25	1991	5.48	5.45
63H 4	SOW 103C	PC Kellam	28–29	251	25	1994	5.42	5.50
63H 4	SOW 103C	PC Kellam	28–29	251	25	1997	5.66	5.50
63H 4	SOW 103C	PC Kellam	28–29	251	25	2000	5.56	5.52
63H 4	SOW 103C	PC Kellam	28–29	251	25	2003	4.85	5.23
63G 17	SOW 104A	Doughty's Grocery	14–16	306	50	1979	11.26	9.44
63G 17	SOW 104A	Doughty's Grocery	14–16	306	50	1982	9.55	9.20
63G 17	SOW 104A	Doughty's Grocery	14–16	306	50	1985	9.38	8.40
63G 17	SOW 104A	Doughty's Grocery	14–16	306	50	1988	9.71	9.65
63G 17	SOW 104A	Doughty's Grocery	14–16	306	50	1991	12.43	11.02
63G 17	SOW 104A	Doughty's Grocery	14–16	306	50	1994	12.84	11.92
63G 17	SOW 104A	Doughty's Grocery	14–16	306	50	1997	13.26	12.85
63G 17	SOW 104A	Doughty's Grocery	14–16	306	50	2000	14.10	13.06
63G 17	SOW 104A	Doughty's Grocery	14–16	306	50	2003	13.35	13.09
63G 16	SOW 104B	Doughty's Grocery	28–29	306	50	1979	10.36	8.03
63G 16	SOW 104B	Doughty's Grocery	28–29	306	50	1982	8.66	7.74
63G 16	SOW 104B	Doughty's Grocery	28–29	306	50	1985	8.70	6.63
63G 16	SOW 104B	Doughty's Grocery	28–29	306	50	1988	8.37	8.35
63G 16	SOW 104B	Doughty's Grocery	28–29	306	50	1991	11.00	10.17
63G 16	SOW 104B	Doughty's Grocery	28–29	306	50	1994	11.71	11.40
63G 16	SOW 104B	Doughty's Grocery	28–29	306	50	1997	12.20	12.67
63G 16	SOW 104B	Doughty's Grocery	28–29	306	50	2000	13.17	12.97
63G 16	SOW 104B	Doughty's Grocery	28–29	306	50	2003	12.37	13.00
63G 15	SOW 104C	Doughty's Grocery	35–36	306	50	1979	7.12	8.65
63G 15	SOW 104C	Doughty's Grocery	35–36	306	50	1982	5.16	8.36
63G 15	SOW 104C	Doughty's Grocery	35–36	306	50	1985	5.40	7.38
63G 15	SOW 104C	Doughty's Grocery	35–36	306	50	1988	5.65	8.77
63G 15	SOW 104C	Doughty's Grocery	35–36	306	50	1991	8.81	10.54
63G 15	SOW 104C	Doughty's Grocery	35–36	306	50	1994	9.72	11.82
63G 15	SOW 104C	Doughty's Grocery	35–36	306	50	1997	10.09	12.91
63G 15	SOW 104C	Doughty's Grocery	35–36	306	50	2000	10.87	13.23
63G 15	SOW 104C	Doughty's Grocery	35–36	306	50	2003	10.12	13.26
63G 21	SOW 104S	Doughty's Grocery	1–2	306	50	1990	14.00	18.39
63F 15	SOW 105A	Cape Center	17–18	333	50	1979	14.69	15.06
63F 15	SOW 105A	Cape Center	17–18	333	50	1982	14.45	14.91
63F 15	SOW 105A	Cape Center	17–18	333	50	1985	13.06	14.80
63F 15	SOW 105A	Cape Center	17–18	333	50	1988	13.00	14.71
63F 15	SOW 105A	Cape Center	17–18	333	50	1991	13.14	14.64
63F 15	SOW 105A	Cape Center	17–18	333	50	1994	13.47	14.61
63F 15	SOW 105A	Cape Center	17–18	333	50	1997	14.28	14.60

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
63F 15	SOW 105A	Cape Center	17–18	333	50	2000	14.49	14.60
63F 15	SOW 105A	Cape Center	17–18	333	50	2003	13.00	14.03
63F 17	SOW 105B	Cape Center	26–27	333	50	1979	14.54	14.93
63F 17	SOW 105B	Cape Center	26–27	333	50	1982	13.35	14.78
63F 17	SOW 105B	Cape Center	26–27	333	50	1985	12.98	14.66
63F 17	SOW 105B	Cape Center	26–27	333	50	1988	12.81	14.57
63F 17	SOW 105B	Cape Center	26–27	333	50	1991	13.06	14.51
63F 17	SOW 105B	Cape Center	26–27	333	50	1994	13.52	14.48
63F 17	SOW 105B	Cape Center	26–27	333	50	1997	14.29	14.46
63F 17	SOW 105B	Cape Center	26–27	333	50	2000	14.42	14.47
63F 17	SOW 105B	Cape Center	26–27	333	50	2003	12.98	13.89
63F 16	SOW 105C	Cape Center	36	333	50	1979	6.64	8.04
63F 16	SOW 105C	Cape Center	36	333	50	1982	6.07	7.92
63F 16	SOW 105C	Cape Center	36	333	50	1985	5.26	7.82
63F 16	SOW 105C	Cape Center	36	333	50	1988	5.79	7.71
63F 16	SOW 105C	Cape Center	36	333	50	1991	6.24	7.66
63F 16	SOW 105C	Cape Center	36	333	50	1994	6.46	7.62
63F 16	SOW 105C	Cape Center	36	333	50	1997	6.82	7.62
63F 16	SOW 105C	Cape Center	36	333	50	2000	6.73	7.64
63F 16	SOW 105C	Cape Center	36	333	50	2003	6.25	7.09
64K 9	SOW 106A	Hack's Neck	4–5	180	13	1979	1.25	0.25
64K 9	SOW 106A	Hack's Neck	4–5	180	13	1982	1.51	0.43
64K 9	SOW 106A	Hack's Neck	4–5	180	13	1985	1.24	0.43
64K 9	SOW 106A	Hack's Neck	4–5	180	13	1988	1.47	0.41
64K 9	SOW 106A	Hack's Neck	4–5	180	13	1991	1.22	0.39
64K 9	SOW 106A	Hack's Neck	4–5	180	13	1994	1.29	0.39
64K 9	SOW 106A	Hack's Neck	4–5	180	13	1997	1.76	0.37
64K 9	SOW 106A	Hack's Neck	4–5	180	13	2000	1.60	0.37
64K 9	SOW 106A	Hack's Neck	4–5	180	13	2003	1.21	0.24
64K 8	SOW 106B	Hack's Neck	12–15	180	13	1979	1.65	1.37
64K 8	SOW 106B	Hack's Neck	12–15	180	13	1982	1.71	2.04
64K 8	SOW 106B	Hack's Neck	12–15	180	13	1985	1.26	2.03
64K 8	SOW 106B	Hack's Neck	12–15	180	13	1988	1.45	1.94
64K 8	SOW 106B	Hack's Neck	12–15	180	13	1991	1.35	1.84
64K 8	SOW 106B	Hack's Neck	12–15	180	13	1994	1.34	1.85
64K 8	SOW 106B	Hack's Neck	12–15	180	13	1997	1.58	1.79
64K 8	SOW 106B	Hack's Neck	12–15	180	13	2000	1.48	1.76
64K 8	SOW 106B	Hack's Neck	12–15	180	13	2003	1.13	1.17
64K 7	SOW 106C	Hack's Neck	30	180	13	1979	1.86	1.37
64K 7	SOW 106C	Hack's Neck	30	180	13	1982	1.95	2.04

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
64K 7	SOW 106C	Hack's Neck	30	180	13	1985	1.49	2.03
64K 7	SOW 106C	Hack's Neck	30	180	13	1988	1.64	1.94
64K 7	SOW 106C	Hack's Neck	30	180	13	1991	1.67	1.84
64K 7	SOW 106C	Hack's Neck	30	180	13	1994	1.48	1.85
64K 7	SOW 106C	Hack's Neck	30	180	13	1997	1.69	1.79
64K 7	SOW 106C	Hack's Neck	30	180	13	2000	1.43	1.76
64K 7	SOW 106C	Hack's Neck	30	180	13	2003	1.20	1.17
66L 2	SOW 107A	Chesser Brothers	14–15	63	61	1979	7.44	6.49
66L 2	SOW 107A	Chesser Brothers	14–15	63	61	1982	7.56	5.51
66L 2	SOW 107A	Chesser Brothers	14–15	63	61	1985	7.19	5.68
66L 2	SOW 107A	Chesser Brothers	14–15	63	61	1988	6.10	4.92
66L 2	SOW 107A	Chesser Brothers	14–15	63	61	1991	6.12	5.09
66L 2	SOW 107A	Chesser Brothers	14–15	63	61	1994	3.74	4.43
66L 2	SOW 107A	Chesser Brothers	14–15	63	61	1997	3.46	3.96
66L 2	SOW 107A	Chesser Brothers	14–15	63	61	2000	0.96	2.49
66L 2	SOW 107A	Chesser Brothers	14–15	63	61	2003	–0.22	1.75
66L 3	SOW 107B	Chesser Brothers	23	63	61	1979	7.04	5.78
66L 3	SOW 107B	Chesser Brothers	23	63	61	1982	7.27	4.72
66L 3	SOW 107B	Chesser Brothers	23	63	61	1985	7.02	4.96
66L 3	SOW 107B	Chesser Brothers	23	63	61	1988	5.85	4.21
66L 3	SOW 107B	Chesser Brothers	23	63	61	1991	5.48	4.38
66L 3	SOW 107B	Chesser Brothers	23	63	61	1994	2.98	3.63
66L 3	SOW 107B	Chesser Brothers	23	63	61	1997	2.88	3.16
66L 3	SOW 107B	Chesser Brothers	23	63	61	2000	0.39	1.63
66L 3	SOW 107B	Chesser Brothers	23	63	61	2003	–0.79	0.83
66L 1	SOW 107C	Chesser Brothers	37–38	63	61	1979	5.17	4.81
66L 1	SOW 107C	Chesser Brothers	37–38	63	61	1982	5.17	4.19
66L 1	SOW 107C	Chesser Brothers	37–38	63	61	1985	5.16	4.53
66L 1	SOW 107C	Chesser Brothers	37–38	63	61	1988	4.24	3.29
66L 1	SOW 107C	Chesser Brothers	37–38	63	61	1991	3.95	3.35
66L 1	SOW 107C	Chesser Brothers	37–38	63	61	1994	1.87	2.34
66L 1	SOW 107C	Chesser Brothers	37–38	63	61	1997	1.73	1.91
66L 1	SOW 107C	Chesser Brothers	37–38	63	61	2000	–0.38	0.19
66L 1	SOW 107C	Chesser Brothers	37–38	63	61	2003	–2.13	–0.61
64K 10	SOW 108A	Melfa	2	161	38	1989	40.76	38.72
64K 11	SOW 108B	Melfa	17–18	161	38	1979	33.99	32.74
64K 11	SOW 108B	Melfa	17–18	161	38	1982	33.24	32.71
64K 11	SOW 108B	Melfa	17–18	161	38	1985	32.57	32.65
64K 11	SOW 108B	Melfa	17–18	161	38	1988	32.85	32.55
64K 11	SOW 108B	Melfa	17–18	161	38	1991	33.21	32.45

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
64K 11	SOW 108B	Melfa	17–18	161	38	1994	32.85	32.36
64K 11	SOW 108B	Melfa	17–18	161	38	1997	33.34	32.26
64K 11	SOW 108B	Melfa	17–18	161	38	2000	33.29	32.16
64K 11	SOW 108B	Melfa	17–18	161	38	2003	31.76	32.11
64K 12	SOW 108C	Melfa	37	161	38	1979	26.84	22.57
64K 12	SOW 108C	Melfa	37	161	38	1982	23.68	22.65
64K 12	SOW 108C	Melfa	37	161	38	1985	23.40	22.62
64K 12	SOW 108C	Melfa	37	161	38	1988	22.38	22.43
64K 12	SOW 108C	Melfa	37	161	38	1991	22.22	22.22
64K 12	SOW 108C	Melfa	37	161	38	1994	21.21	22.04
64K 12	SOW 108C	Melfa	37	161	38	1997	19.91	21.82
64K 12	SOW 108C	Melfa	37	161	38	2000	18.58	21.60
64K 12	SOW 108C	Melfa	37	161	38	2003	17.18	21.42
65K 24	SOW 109A	Bayside	17–18	128	33	1979	5.86	5.95
65K 24	SOW 109A	Bayside	17–18	128	33	1982	6.02	6.02
65K 24	SOW 109A	Bayside	17–18	128	33	1985	5.19	5.84
65K 24	SOW 109A	Bayside	17–18	128	33	1988	5.37	5.53
65K 24	SOW 109A	Bayside	17–18	128	33	1991	5.13	5.10
65K 24	SOW 109A	Bayside	17–18	128	33	1994	4.82	5.15
65K 24	SOW 109A	Bayside	17–18	128	33	1997	5.44	4.94
65K 24	SOW 109A	Bayside	17–18	128	33	2000	5.41	4.69
65K 24	SOW 109A	Bayside	17–18	128	33	2003	4.81	4.51
65K 25	SOW 109B	Bayside	35–36	128	33	1979	0.55	2.59
65K 25	SOW 109B	Bayside	35–36	128	33	1982	0.58	2.45
65K 25	SOW 109B	Bayside	35–36	128	33	1985	0.09	1.96
65K 25	SOW 109B	Bayside	35–36	128	33	1988	0.09	1.47
65K 25	SOW 109B	Bayside	35–36	128	33	1991	–0.53	0.98
65K 25	SOW 109B	Bayside	35–36	128	33	1994	–0.46	0.30
65K 25	SOW 109B	Bayside	35–36	128	33	1997	–0.03	–0.47
65K 25	SOW 109B	Bayside	35–36	128	33	2000	–0.43	–1.12
65K 25	SOW 109B	Bayside	35–36	128	33	2003	–1.16	–1.59
65K 23	SOW 109C	Bayside	42	128	33	1979	–1.77	2.61
65K 23	SOW 109C	Bayside	42	128	33	1982	0.35	2.49
65K 23	SOW 109C	Bayside	42	128	33	1985	0.80	2.02
65K 23	SOW 109C	Bayside	42	128	33	1988	–0.20	1.54
65K 23	SOW 109C	Bayside	42	128	33	1991	–0.22	0.19
65K 23	SOW 109C	Bayside	42	128	33	1994	–0.38	0.38
65K 23	SOW 109C	Bayside	42	128	33	1997	–0.09	–0.37
65K 23	SOW 109C	Bayside	42	128	33	2000	–0.27	–1.02
65K 23	SOW 109C	Bayside	42	128	33	2003	–0.90	–1.48

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
65K 26	SOW 109S	Bayside	2	128	33	1990	8.40	8.27
66M 16	SOW 110A	Withams	14–16	41	37	1979	0.72	4.22
66M 16	SOW 110A	Withams	14–16	41	37	1982	0.42	4.14
66M 16	SOW 110A	Withams	14–16	41	37	1985	0.91	4.06
66M 16	SOW 110A	Withams	14–16	41	37	1988	0.34	3.84
66M 16	SOW 110A	Withams	14–16	41	37	1991	0.35	3.71
66M 16	SOW 110A	Withams	14–16	41	37	1994	–0.23	3.55
66M 16	SOW 110A	Withams	14–16	41	37	1997	0.28	3.50
66M 16	SOW 110A	Withams	14–16	41	37	2000	–0.58	3.48
66M 16	SOW 110A	Withams	14–16	41	37	2003	–0.44	3.48
66M 17	SOW 110B	Withams	27–29	41	37	1979	1.17	4.24
66M 17	SOW 110B	Withams	27–29	41	37	1982	0.65	3.97
66M 17	SOW 110B	Withams	27–29	41	37	1985	0.49	3.76
66M 17	SOW 110B	Withams	27–29	41	37	1988	–0.06	2.64
66M 17	SOW 110B	Withams	27–29	41	37	1991	–0.08	2.02
66M 17	SOW 110B	Withams	27–29	41	37	1994	–0.57	1.24
66M 17	SOW 110B	Withams	27–29	41	37	1997	–0.37	1.13
66M 17	SOW 110B	Withams	27–29	41	37	2000	–1.20	1.12
66M 17	SOW 110B	Withams	27–29	41	37	2003	–1.24	1.05
66M 18	SOW 110C	Withams	35–36	41	37	1979	1.20	5.69
66M 18	SOW 110C	Withams	35–36	41	37	1982	0.90	5.33
66M 18	SOW 110C	Withams	35–36	41	37	1985	0.65	4.96
66M 18	SOW 110C	Withams	35–36	41	37	1988	–1.44	3.62
66M 18	SOW 110C	Withams	35–36	41	37	1991	–1.52	2.87
66M 18	SOW 110C	Withams	35–36	41	37	1994	–1.40	1.88
66M 18	SOW 110C	Withams	35–36	41	37	1997	–1.57	1.76
66M 18	SOW 110C	Withams	35–36	41	37	2000	–2.13	1.89
66M 18	SOW 110C	Withams	35–36	41	37	2003	–1.95	1.80
66M 19	SOW 110S	Withams	2	41	37	1992	1.40	4.28
63G 22	SOW 111A	Cheriton	14–15	313	39	1979	2.67	5.54
63G 22	SOW 111A	Cheriton	14–15	313	39	1982	3.07	5.35
63G 22	SOW 111A	Cheriton	14–15	313	39	1985	2.03	5.54
63G 22	SOW 111A	Cheriton	14–15	313	39	1988	3.66	5.47
63G 22	SOW 111A	Cheriton	14–15	313	39	1991	3.82	6.21
63G 22	SOW 111A	Cheriton	14–15	313	39	1994	3.78	6.51
63G 22	SOW 111A	Cheriton	14–15	313	39	1997	4.64	6.82
63G 22	SOW 111A	Cheriton	14–15	313	39	2000	4.69	6.90
63G 22	SOW 111A	Cheriton	14–15	313	39	2003	3.83	6.71
63G 23	SOW 111B	Cheriton	35	313	39	1979	–2.48	5.37
63G 23	SOW 111B	Cheriton	35	313	39	1982	–0.88	5.19

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
63G 23	SOW 111B	Cheriton	35	313	39	1985	–1.21	5.37
63G 23	SOW 111B	Cheriton	35	313	39	1988	–0.21	5.30
63G 23	SOW 111B	Cheriton	35	313	39	1991	2.12	6.12
63G 23	SOW 111B	Cheriton	35	313	39	1994	1.41	6.43
63G 23	SOW 111B	Cheriton	35	313	39	1997	1.88	6.76
63G 23	SOW 111B	Cheriton	35	313	39	2000	1.97	6.85
63G 23	SOW 111B	Cheriton	35	313	39	2003	1.62	6.65
63G 24	SOW 111C	Cheriton	38	313	39	1982	–1.23	5.19
63G 24	SOW 111C	Cheriton	38	313	39	1985	–1.26	5.37
63G 24	SOW 111C	Cheriton	38	313	39	1988	–0.52	5.30
63G 24	SOW 111C	Cheriton	38	313	39	1991	1.92	6.12
63G 24	SOW 111C	Cheriton	38	313	39	1994	1.40	6.43
63G 24	SOW 111C	Cheriton	38	313	39	1997	0.91	6.76
63G 24	SOW 111C	Cheriton	38	313	39	2000	1.96	6.85
63G 24	SOW 111C	Cheriton	38	313	39	2003	1.34	6.65
63G 25	SOW 111S	Cheriton	2	313	39	1988	5.52	9.11
64J 9	SOW 112A	Willis' Wharf	11–12	215	46	1979	0.26	–1.10
64J 9	SOW 112A	Willis' Wharf	11–12	215	46	1982	5.83	1.50
64J 9	SOW 112A	Willis' Wharf	11–12	215	46	1985	5.41	1.51
64J 9	SOW 112A	Willis' Wharf	11–12	215	46	1988	4.51	1.02
64J 9	SOW 112A	Willis' Wharf	11–12	215	46	1991	6.73	1.91
64J 9	SOW 112A	Willis' Wharf	11–12	215	46	1994	5.93	2.53
64J 9	SOW 112A	Willis' Wharf	11–12	215	46	1997	4.37	2.56
64J 9	SOW 112A	Willis' Wharf	11–12	215	46	2000	3.35	2.64
64J 9	SOW 112A	Willis' Wharf	11–12	215	46	2003	1.34	1.45
64J 10	SOW 112B	Willis' Wharf	25–27	215	46	1979	1.38	–1.10
64J 10	SOW 112B	Willis' Wharf	25–27	215	46	1982	6.44	1.50
64J 10	SOW 112B	Willis' Wharf	25–27	215	46	1985	6.68	1.51
64J 10	SOW 112B	Willis' Wharf	25–27	215	46	1988	5.31	1.02
64J 10	SOW 112B	Willis' Wharf	25–27	215	46	1991	6.94	1.92
64J 10	SOW 112B	Willis' Wharf	25–27	215	46	1994	6.11	2.53
64J 10	SOW 112B	Willis' Wharf	25–27	215	46	1997	4.73	2.56
64J 10	SOW 112B	Willis' Wharf	25–27	215	46	2000	3.84	2.64
64J 10	SOW 112B	Willis' Wharf	25–27	215	46	2003	2.37	1.45
64J 11	SOW 112C	Willis' Wharf	38–39	215	46	1979	1.51	–1.27
64J 11	SOW 112C	Willis' Wharf	38–39	215	46	1982	7.41	2.20
64J 11	SOW 112C	Willis' Wharf	38–39	215	46	1985	7.76	2.25
64J 11	SOW 112C	Willis' Wharf	38–39	215	46	1988	6.89	1.97
64J 11	SOW 112C	Willis' Wharf	38–39	215	46	1991	7.34	2.23
64J 11	SOW 112C	Willis' Wharf	38–39	215	46	1994	6.49	2.64

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
64J 11	SOW 112C	Willis' Wharf	38–39	215	46	1997	5.26	2.66
64J 11	SOW 112C	Willis' Wharf	38–39	215	46	2000	4.65	2.74
64J 11	SOW 112C	Willis' Wharf	38–39	215	46	2003	2.55	1.58
64J 12	SOW 112S	Willis' Wharf	1–2	215	46	1980	20.60	15.90
63J 1	SOW 113A	Concord's Wharf	14–16	219	19	1982	2.71	2.24
63J 1	SOW 113A	Concord's Wharf	14–16	219	19	1985	0.77	2.27
63J 1	SOW 113A	Concord's Wharf	14–16	219	19	1988	1.68	2.16
63J 1	SOW 113A	Concord's Wharf	14–16	219	19	1991	0.98	2.05
63J 1	SOW 113A	Concord's Wharf	14–16	219	19	1994	–0.30	2.20
63J 1	SOW 113A	Concord's Wharf	14–16	219	19	1997	–1.14	2.17
63J 1	SOW 113A	Concord's Wharf	14–16	219	19	2000	0.09	2.20
63J 1	SOW 113A	Concord's Wharf	14–16	219	19	2003	–4.67	–2.40
63J 2	SOW 113B	Concord's Wharf	35	219	19	1982	1.90	2.25
63J 2	SOW 113B	Concord's Wharf	35	219	19	1985	0.60	2.28
63J 2	SOW 113B	Concord's Wharf	35	219	19	1988	1.51	2.17
63J 2	SOW 113B	Concord's Wharf	35	219	19	1991	1.12	2.05
63J 2	SOW 113B	Concord's Wharf	35	219	19	1994	–0.30	2.20
63J 2	SOW 113B	Concord's Wharf	35	219	19	1997	–0.48	2.18
63J 2	SOW 113B	Concord's Wharf	35	219	19	2000	–0.87	2.20
63J 2	SOW 113B	Concord's Wharf	35	219	19	2003	–2.67	–2.37
63J 3	SOW 113C	Concord's Wharf	42	219	19	1982	1.64	2.25
63J 3	SOW 113C	Concord's Wharf	42	219	19	1985	–0.09	2.28
63J 3	SOW 113C	Concord's Wharf	42	219	19	1988	0.14	2.17
63J 3	SOW 113C	Concord's Wharf	42	219	19	1991	–0.11	2.05
63J 3	SOW 113C	Concord's Wharf	42	219	19	1994	–1.51	2.20
63J 3	SOW 113C	Concord's Wharf	42	219	19	1997	–1.89	2.18
63J 3	SOW 113C	Concord's Wharf	42	219	19	2000	–1.83	2.20
63J 3	SOW 113C	Concord's Wharf	42	219	19	2003	–3.65	–2.37
65K 27	SOW 114A	Perdue	15–16	123	49	1982	6.34	2.79
65K 27	SOW 114A	Perdue	15–16	123	49	1985	4.54	3.04
65K 27	SOW 114A	Perdue	15–16	123	49	1988	2.54	3.57
65K 27	SOW 114A	Perdue	15–16	123	49	1991	0.88	–0.94
65K 27	SOW 114A	Perdue	15–16	123	49	1994	–0.17	1.03
65K 27	SOW 114A	Perdue	15–16	123	49	1997	–1.28	–1.45
65K 27	SOW 114A	Perdue	15–16	123	49	2000	–3.67	–3.09
65K 27	SOW 114A	Perdue	15–16	123	49	2003	–5.39	–3.52
65K 28	SOW 114B	Perdue	23–26	123	49	1982	–14.10	–18.18
65K 28	SOW 114B	Perdue	23–26	123	49	1985	–17.28	–18.35
65K 28	SOW 114B	Perdue	23–26	123	49	1988	–20.61	–18.95
65K 28	SOW 114B	Perdue	23–26	123	49	1991	–23.70	–26.50

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
65K 28	SOW 114B	Perdue	23–26	123	49	1994	–25.14	–23.70
65K 28	SOW 114B	Perdue	23–26	123	49	1997	–28.24	–27.39
65K 28	SOW 114B	Perdue	23–26	123	49	2000	–32.06	–30.46
65K 28	SOW 114B	Perdue	23–26	123	49	2003	–34.10	–31.36
65K 29	SOW 114C	Perdue	39–40	123	48	1982	–37.40	–36.75
65K 29	SOW 114C	Perdue	39–40	123	48	1985	–39.84	–37.61
65K 29	SOW 114C	Perdue	39–40	123	48	1988	–45.19	–38.99
65K 29	SOW 114C	Perdue	39–40	123	48	1991	–48.66	–49.33
65K 29	SOW 114C	Perdue	39–40	123	48	1994	–46.08	–45.76
65K 29	SOW 114C	Perdue	39–40	123	48	1997	–48.82	–50.50
65K 29	SOW 114C	Perdue	39–40	123	48	2000	–52.19	–54.23
65K 29	SOW 114C	Perdue	39–40	123	48	2003	–53.32	–55.44
65K 30	SOW 114S	Perdue	1–3	123	49	1991	37.67	37.55
67M 10	SOW 115A	Chincoteague	2	35	72	1994	4.03	2.56
67M 11	SOW 115B	Chincoteague	12–14	35	72	1982	1.93	0.55
67M 11	SOW 115B	Chincoteague	12–14	35	72	1985	0.80	–0.11
67M 11	SOW 115B	Chincoteague	12–14	35	72	1988	1.77	–0.49
67M 11	SOW 115B	Chincoteague	12–14	35	72	1991	1.93	0.30
67M 11	SOW 115B	Chincoteague	12–14	35	72	1994	1.48	0.12
67M 11	SOW 115B	Chincoteague	12–14	35	72	1997	2.03	–0.36
67M 11	SOW 115B	Chincoteague	12–14	35	72	2000	1.62	0.29
67M 11	SOW 115B	Chincoteague	12–14	35	72	2003	0.98	–0.43
67M 12	SOW 115C	Chincoteague	23–24	35	72	1982	–14.26	–11.95
67M 12	SOW 115C	Chincoteague	23–24	35	72	1985	–15.87	–13.81
67M 12	SOW 115C	Chincoteague	23–24	35	72	1988	–15.06	–12.41
67M 12	SOW 115C	Chincoteague	23–24	35	72	1991	–12.73	–13.14
67M 12	SOW 115C	Chincoteague	23–24	35	72	1994	–14.52	–13.56
67M 12	SOW 115C	Chincoteague	23–24	35	72	1997	–12.20	–13.30
67M 12	SOW 115C	Chincoteague	23–24	35	72	2000	–15.17	–10.96
67M 13	SOW 115D	Chincoteague	25–27	35	72	1982	–12.31	–15.87
67M 13	SOW 115D	Chincoteague	25–27	35	72	1985	–12.77	–13.80
67M 13	SOW 115D	Chincoteague	25–27	35	72	1988	–16.01	–12.40
67M 13	SOW 115D	Chincoteague	25–27	35	72	1991	–12.29	–13.13
67M 13	SOW 115D	Chincoteague	25–27	35	72	1994	–15.03	–13.56
67M 13	SOW 115D	Chincoteague	25–27	35	72	1997	–14.83	–13.29
67M 13	SOW 115D	Chincoteague	25–27	35	72	2000	–15.86	–10.95
67M 13	SOW 115D	Chincoteague	25–27	35	72	2003	–18.97	–15.87
67M 14	SOW 115E	Chincoteague	27–29	36	71	1982	–2.97	–1.79
67M 14	SOW 115E	Chincoteague	27–29	36	71	1985	–2.00	–3.80
67M 14	SOW 115E	Chincoteague	27–29	36	71	1988	–3.90	–2.03

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
67M 14	SOW 115E	Chincoteague	27–29	36	71	1991	–1.79	–1.84
67M 14	SOW 115E	Chincoteague	27–29	36	71	1994	–3.61	–2.31
67M 14	SOW 115E	Chincoteague	27–29	36	71	1997	–3.60	–3.01
67M 14	SOW 115E	Chincoteague	27–29	36	71	2000	–5.73	–2.03
64J 13	SOW 120	Corp Amer Original	11	215	48	1979	–4.67	–0.85
64J 13	SOW 120	Corp Amer Original	11	215	48	1982	–0.31	–0.38
64J 13	SOW 120	Corp Amer Original	11	215	48	1985	–0.76	–0.14
64J 13	SOW 120	Corp Amer Original	11	215	48	1988	–0.70	–1.13
64J 13	SOW 120	Corp Amer Original	11	215	48	1991	2.92	1.38
64J 13	SOW 120	Corp Amer Original	11	215	48	1994	3.81	2.53
62G 15	SOW 121	Cape Charles	26–27	323	35	1978	1.69	1.24
62G 15	SOW 121	Cape Charles	26–27	323	35	1982	1.05	0.78
62G 15	SOW 121	Cape Charles	26–27	323	35	1985	–0.18	1.11
62G 15	SOW 121	Cape Charles	26–27	323	35	1988	0.53	0.98
62G 15	SOW 121	Cape Charles	26–27	323	35	1991	1.67	1.47
62G 15	SOW 121	Cape Charles	26–27	323	35	1994	1.51	1.58
62G 15	SOW 121	Cape Charles	26–27	323	35	1997	2.08	2.27
62G 15	SOW 121	Cape Charles	26–27	323	35	2000	1.10	2.07
62G 15	SOW 121	Cape Charles	26–27	323	35	2003	1.00	1.92
63G 26	SOW 160	Corp KMC Foods Inc	36	307	44	1982	–14.47	–2.75
63G 26	SOW 160	Corp KMC Foods Inc	36	307	44	1984	–8.76	1.03
63G 26	SOW 160	Corp KMC Foods Inc	36	307	44	1988	–5.94	1.22
63G 26	SOW 160	Corp KMC Foods Inc	36	307	44	1991	4.5	12.66
63G 26	SOW 160	Corp KMC Foods Inc	36	307	44	1994	4.8	14.00
63G 27	SOW 161	Smith HA	24–25	304	53	1982	–38.12	–33.55
63G 27	SOW 161	Smith HA	24–25	304	53	1985	–47.37	–43.83
63G 27	SOW 161	Smith HA	24–25	304	53	1988	–29.74	–20.30
63G 27	SOW 161	Smith HA	24–25	304	53	1991	–21.12	–6.02
63G 27	SOW 161	Smith HA	24–25	304	53	1994	–5.37	–7.52
63G 27	SOW 161	Smith HA	24–25	304	53	1997	6.41	5.25
63G 27	SOW 161	Smith HA	24–25	304	53	2000	3.37	5.47
63G 27	SOW 161	Smith HA	24–25	304	53	2003	6.71	5.49
66M 25	SOW 181C	Jenkin’s Bridge	42	51	34	1988	3.38	2.14
66M 25	SOW 181C	Jenkin’s Bridge	42	51	34	1991	3.46	1.57
66M 25	SOW 181C	Jenkin’s Bridge	42	51	34	1994	3.11	1.06
66M 25	SOW 181C	Jenkin’s Bridge	42	51	34	1997	2.53	0.87
66M 25	SOW 181C	Jenkin’s Bridge	42	51	34	2000	1.51	0.32
66M 25	SOW 181C	Jenkin’s Bridge	42	51	34	2003	0.91	0.11
66M 26	SOW 181D	Jenkin’s Bridge	36	51	34	1988	2.88	2.14
66M 26	SOW 181D	Jenkin’s Bridge	36	51	34	1991	3.3	1.57

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
66M 26	SOW 181D	Jenkin's Bridge	36	51	34	1994	2.72	1.06
66M 26	SOW 181D	Jenkin's Bridge	36	51	34	1997	2.53	0.87
66M 26	SOW 181D	Jenkin's Bridge	36	51	34	2000	1.17	0.32
66M 26	SOW 181D	Jenkin's Bridge	36	51	34	2003	0.8	0.11
66M 27	SOW 181E	Jenkin's Bridge	2	51	34	1996	3.25	1.98
63F 53	SOW 182C	Kiptopeake	35	349	70	1991	2.44	1.96
63F 53	SOW 182C	Kiptopeake	35	349	70	1994	–1.31	1.89
63F 53	SOW 182C	Kiptopeake	35	349	70	1997	–4.35	1.91
63F 53	SOW 182C	Kiptopeake	35	349	70	2000	–2.17	1.90
63F 53	SOW 182C	Kiptopeake	35	349	70	2003	0.7	1.89
63F 54	SOW 182D	Kiptopeake	4–6	349	70	1991	1.4	3.30
63F 54	SOW 182D	Kiptopeake	4–6	349	70	1994	1.65	3.28
63F 54	SOW 182D	Kiptopeake	4–6	349	70	1997	2.51	3.30
63F 54	SOW 182D	Kiptopeake	4–6	349	70	2000	2.3	3.28
63F 54	SOW 182D	Kiptopeake	4–6	349	70	2003	2.22	3.28
65K 59	SOW 183A	Accomac	37	130	51	1991	–22.14	–17.78
65K 59	SOW 183A	Accomac	37	130	51	1994	–20.99	–17.02
65K 59	SOW 183A	Accomac	37	130	51	1997	–21.15	–19.12
65K 59	SOW 183A	Accomac	37	130	51	2000	–22.77	–21.28
65K 59	SOW 183A	Accomac	37	130	51	2003	–23.71	–22.05
65K 60	SOW 183B	Accomac	28–30	130	51	1991	9.52	9.39
65K 60	SOW 183B	Accomac	28–30	130	51	1994	8.86	9.74
65K 60	SOW 183B	Accomac	28–30	130	51	1997	9.67	8.89
65K 60	SOW 183B	Accomac	28–30	130	51	2000	7.95	8.15
65K 60	SOW 183B	Accomac	28–30	130	51	2003	7.32	6.34
65K 61	SOW 183C	Accomac	12–13	130	51	1991	13.02	12.08
65K 61	SOW 183C	Accomac	12–13	130	51	1994	12.47	12.46
65K 61	SOW 183C	Accomac	12–13	130	51	1997	14.06	11.70
65K 61	SOW 183C	Accomac	12–13	130	51	2000	12.7	11.06
65K 61	SOW 183C	Accomac	12–13	130	51	2003	11.89	10.49
65K 62	SOW 183D	Accomac	1	130	51	1998	32.04	0.59
62G 8	none	Bayshore Concrete	27–29	325	31	1973	3.00	10.74
63F 1	none	School Northampton	42	337	58	1953	7.00	12.28
63F 9	none	Hotel Holiday Inn	16	342	57	1965	13.00	12.16
63F 10	none	Hotel Holiday Inn	30	342	57	1968	9.00	—
63F 34	none	U.S. Geological Survey	1	333	50	1995	24.94	24.54
63F 44	none	Unknown	1	339	61	1993	17.16	14.87
63F 55	none	VASWCB Res St	1–2	349	70	1996	4.05	3.27
63G 13	none	Unknown	15–18	284	39	1972	19.00	20.97
63G 18	none	VA Ag Prod	2–10	279	42	1966	21.40	23.50

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
63G 29	none	Corp KMC Foods Inc	6–26	307	43	1973	4.00	8.54
63H 3	none	School Machipongo	2	264	38	1953	24.00	25.12
63J 4	none	Busn Busy B's Grocery	2	219	18	1990	21.00	17.58
64H 2	none	Hosp Accomack	16–29	234	39	1952	15.00	7.20
64J 1	none	School Accomack Brd	42	183	42	1953	19.00	12.58
64J 4	none	Busn Exmore Foods Inc	27–33	210	41	1941	7.67	7.37
64J 19	none	Corp Exmore Foods Inc	13–24	210	41	1967	12.20	5.55
64J 27	none	School Hare Valley Elem	26–29	224	37	1972	10.00	1.72
64J 29	none	U.S. Geological Survey	1–2	203	35	1989	29.40	19.03
64K 5	none	School Comm College	35–37	166	42	1974	21.00	22.92
65J 4	none	Gulf Stream Nursery	23–32	176	63	1968	5.00	4.68
65K 6	none	Town of Onley	16–18	146	44	1971	20.00	26.04
65K 9	none	Town of Onancock	12	142	34	1952	8.00	13.90
65K 20	none	Accomack Co. Jail	36–38	130	51	1968	13.00	9.18
65K 22	none	Acme Grocery Store	17–18	143	42	1969	22.50	24.12
65K 34	none	Knight Joe	26–28	153	60	1970	6.00	8.28
65K 39	none	U.S. Geological Survey	2	153	57	1988	5.00	8.29
65L 3	none	Town of Parksley	11–18	106	46	1947	21.00	21.60
65L 4	none	Town of Parksley	2	106	46	1946	27.00	35.05
65L 6	none	Busn Byrd Packing Co.	23–33	117	45	1966	12.00	18.01
66L 6	none	Corp Messick & Wessills	27–28	88	56	1969	23.00	19.51
66L 12	none	U.S. Geological Survey	1	98	52	1989	39.90	39.22
66M 2	none	Corp Kelley Co H E	15–26	35	45	1947	10.00	15.01
66M 9	none	Busn Holly Farms Inc	11–28	62	55	1966	19.00	16.00
66M 14	none	School Atlantic High	37	47	49	1969	8.00	9.79
66M 15	none	Busn Kelley Company	11–26	35	44	1947	11.00	14.87
66M 22	none	Highways VA Dept of	11–13	33	43	1967	9.00	14.60
67M 7	none	Unknown	11–20	37	66	1953	21.00	10.47
67M 24	none	Town of Chincoteague	23–26	35	71	1964	9.00	7.07
SO Cf 2	none	Maryland	1	20	7	1977	17.28	12.48
WO Fb 2	none	Maryland	15–18	22	23	1947	–15	–9.02
WO Fb 2	none	Maryland	15–18	22	23	1955	–14.92	–7.77
WO Fb 2	none	Maryland	15–18	22	23	1958	–19.5	–7.58
WO Fb 2	none	Maryland	15–18	22	23	1961	–17.94	–7.28
WO Fb 2	none	Maryland	15–18	22	23	1964	–17.61	–6.60
WO Fb 2	none	Maryland	15–18	22	23	1967	–13.29	–7.50
WO Fb 2	none	Maryland	15–18	22	23	1970	–12.84	–16.86
WO Fb 2	none	Maryland	15–18	22	23	1973	–11.88	–14.46
WO Fb 2	none	Maryland	15–18	22	23	1976	–13.6	–14.15
WO Fb 2	none	Maryland	15–18	22	23	1979	–12.4	–9.72

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
WO Fb 2	none	Maryland	15–18	22	23	1982	–13.8	–19.14
WO Fb 2	none	Maryland	15–18	22	23	1985	–14.33	–18.49
WO Fb 2	none	Maryland	15–18	22	23	1988	–14.06	–16.42
WO Fb 2	none	Maryland	15–18	22	23	1991	–14.19	–20.38
WO Fb 2	none	Maryland	15–18	22	23	1994	–14.64	–18.77
WO Fb 2	none	Maryland	15–18	22	23	1997	–4.54	–12.64
WO Fb 2	none	Maryland	15–18	22	23	2000	–2.68	–12.83
WO Fb 2	none	Maryland	15–18	22	23	2003	–2.38	–14.06
WO Fc 50	none	Maryland	2	20	66	2000	26.40	28.18
WO Fc 51	none	Maryland	1	20	66	2000	30.00	28.35
WO Fc 52	none	Maryland	2	20	64	2000	32.48	28.76
WO Fc 53	none	Maryland	1	20	64	2000	32.48	28.93
WO Fc 54	none	Maryland	1	23	60	2000	12.00	9.66
WO Fc 56	none	Maryland	1	20	57	2000	18.12	22.52
WO Fc 57	none	Maryland	2	18	53	2000	25.62	29.89
WO Fc 58	none	Maryland	1	18	53	2000	30.50	30.03
none	100-1008	Tyson’s	35–37	61	54	2004	–22.13	–20.38
none	100-1009	Tyson’s	24–30	61	54	2004	–20.40	–23.81
none	100-1010	Tyson’s	11–18	61	54	2004	–18.64	–20.83
none	100-1011	Tyson’s	35–37	60	51	2004	–20.07	–19.94
none	100-1012	Tyson’s	23–30	60	51	2004	–24.10	–20.87
none	100-1013	Tyson’s	12–18	60	51	2004	–19.85	–19.62
S&T 03b	none	Sinnott & Tibbits (1954)	16–18	26	55	1944	19.00	20.37
S&T 07	none	Sinnott & Tibbits (1954)	26–30	39	49	1953	15.00	14.05
S&T 08j	none	Sinnott & Tibbits (1954)	23–24	37	66	1953	14.00	11.23
S&T 13	none	Sinnott & Tibbits (1954)	15–17	212	41	1938	12.00	7.53
S&T 15	none	Sinnott & Tibbits (1954)	15–17	45	38	1952	1.00	7.13
S&T 18	none	Sinnott & Tibbits (1954)	15–17	39	61	1953	6.00	15.72
S&T 21	none	Sinnott & Tibbits (1954)	18	56	31	1948	3.00	1.89
S&T 23	none	Sinnott & Tibbits (1954)	23–24	56	47	1951	10.00	12.42
S&T 25	none	Sinnott & Tibbits (1954)	11–13	214	47	1948	9.00	6.57
S&T 30	none	Sinnott & Tibbits (1954)	35–37	70	10	1950	2.00	3.02
S&T 33	none	Sinnott & Tibbits (1954)	23	58	45	1950	4.00	11.02
S&T 35	none	Sinnott & Tibbits (1954)	14–17	52	58	1949	10.00	20.55
S&T 36	none	Sinnott & Tibbits (1954)	11	50	70	1946	10.00	10.44
S&T 39	none	Sinnott & Tibbits (1954)	14–17	58	56	1948	12.00	18.62
S&T 43	none	Sinnott & Tibbits (1954)	23–26	244	21	1949	10.00	5.29
S&T 44b	none	Sinnott & Tibbits (1954)	36–38	234	39	1952	14.00	6.92
S&T 46	none	Sinnott & Tibbits (1954)	35–36	68	46	1948	13.00	12.86
S&T 48	none	Sinnott & Tibbits (1954)	35–36	69	41	1948	6.00	9.84

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
S&T 49	none	Sinnott & Tibbits (1954)	11–12	245	37	1949	11.00	11.46
S&T 50b	none	Sinnott & Tibbits (1954)	15–18	249	39	1950	13.00	14.03
S&T 53	none	Sinnott & Tibbits (1954)	35	74	46	1950	14.00	13.12
S&T 54	none	Sinnott & Tibbits (1954)	39–40	263	38	1953	7.00	9.01
S&T 56	none	Sinnott & Tibbits (1954)	28–30	78	37	1936	7.00	7.15
S&T 57	none	Sinnott & Tibbits (1954)	37–38	78	41	1936	5.00	10.65
S&T 59	none	Sinnott & Tibbits (1954)	26–29	74	58	1951	19.00	18.38
S&T 61	none	Sinnott & Tibbits (1954)	11–13	67	78	1946	2.00	5.28
S&T 62	none	Sinnott & Tibbits (1954)	18–20	285	32	1952	4.00	10.16
S&T 64	none	Sinnott & Tibbits (1954)	12–15	284	37	1952	10.00	18.56
S&T 65	none	Sinnott & Tibbits (1954)	23–25	78	58	1945	30.00	19.76
S&T 65	none	Sinnott & Tibbits (1954)	8–11	284	37	1950	12.00	19.66
S&T 67	none	Sinnott & Tibbits (1954)	19–21	286	37	1951	8.00	17.91
S&T 68	none	Sinnott & Tibbits (1954)	35	287	37	1950	2.00	12.68
S&T 69	none	Sinnott & Tibbits (1954)	24–27	87	56	1948	19.00	21.32
S&T 71	none	Sinnott & Tibbits (1954)	35–36	307	39	1949	2.00	7.86
S&T 80	none	Sinnott & Tibbits (1954)	35	310	43	1951	17.00	12.18
S&T 82	none	Sinnott & Tibbits (1954)	17–18	115	26	1950	5.00	3.82
S&T 84	none	Sinnott & Tibbits (1954)	24–27	100	57	1950	15.00	21.03
S&T 85	none	Sinnott & Tibbits (1954)	17–18	108	44	1950	20.00	18.36
S&T 88	none	Sinnott & Tibbits (1954)	36–37	316	36	1950	5.00	5.05
S&T 88	none	Sinnott & Tibbits (1954)	35–37	117	29	1951	5.00	7.59
S&T 94	none	Sinnott & Tibbits (1954)	14–17	128	33	1948	2.00	9.19
S&T 95	none	Sinnott & Tibbits (1954)	11	312	51	1949	19.00	17.14
S&T 97	none	Sinnott & Tibbits (1954)	35–36	124	44	1948	12.00	16.65
S&T 100	none	Sinnott & Tibbits (1954)	30	128	38	1952	4.00	12.83
S&T 102	none	Sinnott & Tibbits (1954)	14–18	317	52	1949	22.00	17.37
S&T 104	none	Sinnott & Tibbits (1954)	11	316	54	1953	12.00	12.92
S&T 106	none	Sinnott & Tibbits (1954)	13–16	131	51	1950	14.00	21.18
S&T 108	none	Sinnott & Tibbits (1954)	28–30	142	34	1927	7.00	14.89
S&T 111	none	Sinnott & Tibbits (1954)	15–18	150	25	1951	3.00	6.20
S&T 117	none	Sinnott & Tibbits (1954)	35–38	143	40	1950	16.00	17.17
S&T 119	none	Sinnott & Tibbits (1954)	23–24	146	38	1949	14.00	21.73
S&T 119	none	Sinnott & Tibbits (1954)	16–18	333	53	1951	23.00	18.90
S&T 125	none	Sinnott & Tibbits (1954)	11–14	335	50	1950	16.00	15.99
S&T 126	none	Sinnott & Tibbits (1954)	17–18	158	17	1936	6.00	3.75
S&T 139	none	Sinnott & Tibbits (1954)	15–18	160	43	1948	37.00	36.61
S&T 139	none	Sinnott & Tibbits (1954)	11–15	341	58	1952	4.00	13.75
S&T 146	none	Sinnott & Tibbits (1954)	14–18	176	28	1951	7.00	9.82
S&T 152	none	Sinnott & Tibbits (1954)	30	179	27	1951	10.00	8.52

Table 1–1. Observation wells with observed and simulated water levels used to calibrate the model of the Eastern Shore of Virginia. —Continued

[USGS, U.S. Geological Survey; water level above or below (–) NGVD 29]

USGS well number	Virginia State well number	Well name, owner, or source of data	Model layer(s)	Model row	Model column	Year	Altitude of water level, in feet	Simulated water level, in feet
S&T 156	none	Sinnott & Tibbits (1954)	35–37	175	41	1948	12.00	18.80
S&T 158	none	Sinnott & Tibbits (1954)	11–13	168	61	1949	1.00	5.88
S&T 164	none	Sinnott & Tibbits (1954)	27–30	346	56	1950	–1.00	5.38
S&T 167	none	Sinnott & Tibbits (1954)	30	346	60	1949	2.00	5.73
S&T 168	none	Sinnott & Tibbits (1954)	14–17	193	35	1952	9.00	7.08
S&T 169	none	Sinnott & Tibbits (1954)	23–26	345	65	1946	8.00	5.05
S&T 170	none	Sinnott & Tibbits (1954)	18	210	12	1948	2.00	4.16
S&T 174	none	Sinnott & Tibbits (1954)	13–18	211	23	1949	4.00	6.03
S&T 178	none	Sinnott & Tibbits (1954)	18–25	205	39	1950	7.00	6.77
S&T 180	none	Sinnott & Tibbits (1954)	23–28	199	48	1949	–4.00	6.74

Appendix 2. Fortran Program Used to Create Hydraulic Parameter Fields Based on Paleochannels and Kriging-Based Multiplier Arrays

This program was called every run before SEAWAT from UCODE during the calibration procedure.

See Appendix 3 for the Fortran program that created the multiplier arrays.

```
PROGRAM HPFIELD
common wt(21,102,370),pk(8,21),ps(8,21),hk(102),ss(102)
      common izc(102,370,46),nlay(8)
      data nlay/2,8,8,4,8,4,8,4/
c
c This has the values of the parameters at pilot points
c It is created with Ucode's prepare file
c
      OPEN(unit= 5,file='pilot-points2',status='unknown')
c
c This is a map of the paleochannels
c
      OPEN(unit= 6,file='zonecodes',status='unknown')
c
c These are the multiplier arrays--one for each pilot point
c
      OPEN(unit= 7,file='mp-pocomoke-k ',status='unknown')
      OPEN(unit= 8,file='mp-withams-k',status='unknown')
      OPEN(unit= 9,file='mp-jenkins-k',status='unknown')
      OPEN(unit=10,file='mp-chincoteague-k',status='unknown')
      OPEN(unit=11,file='mp-tysons-k',status='unknown')
      OPEN(unit=12,file='mp-temperanceville-k',status='unknown')
      OPEN(unit=13,file='mp-bayside-k',status='unknown')
      OPEN(unit=14,file='mp-perdue-k',status='unknown')
      OPEN(unit=15,file='mp-accomac-k',status='unknown')
      OPEN(unit=16,file='mp-baylysneck-k',status='unknown')
      OPEN(unit=17,file='mp-melfa-k',status='unknown')
      OPEN(unit=18,file='mp-hacksneck-k',status='unknown')
      OPEN(unit=19,file='mp-concordswharf-k',status='unknown')
      OPEN(unit=20,file='mp-exmore-k',status='unknown')
      OPEN(unit=21,file='mp-oceanside-k',status='unknown')
      OPEN(unit=22,file='mp-bridgetown-k',status='unknown')
      OPEN(unit=23,file='mp-capecharles-k',status='unknown')
      OPEN(unit=24,file='mp-cheriton-k',status='unknown')
      OPEN(unit=25,file='mp-oyster-k',status='unknown')
      OPEN(unit=26,file='mp-capecenter-k',status='unknown')
      OPEN(unit=27,file='mp-kiptopeake-k',status='unknown')
c
c One hydraulic conductivity output file for each of the geologic formations
c
      OPEN(unit=28,file='k-columbia  ',status='unknown')
      OPEN(unit=29,file='k-upper-confining ',status='unknown')
      OPEN(unit=30,file='k-upper-aquifer ',status='unknown')
      OPEN(unit=31,file='k-middle-confining',status='unknown')
      OPEN(unit=32,file='k-middle-aquifer ',status='unknown')
      OPEN(unit=33,file='k-lower-confining ',status='unknown')
```

```
      OPEN(unit=34,file='k-lower-aquifer ',status='unknown')
      OPEN(unit=35,file='k-saint-marys  ',status='unknown')
c
c One specific storage output file for each of the geologic formations
c
      OPEN(unit=36,file='ss-columbia  ',status='unknown')
      OPEN(unit=37,file='ss-upper-confining ',status='unknown')
      OPEN(unit=38,file='ss-upper-aquifer ',status='unknown')
      OPEN(unit=39,file='ss-middle-confining',status='unknown')
      OPEN(unit=40,file='ss-middle-aquifer ',status='unknown')
      OPEN(unit=41,file='ss-lower-confining ',status='unknown')
      OPEN(unit=42,file='ss-lower-aquifer ',status='unknown')
      OPEN(unit=43,file='ss-saint-marys  ',status='unknown')
c
c One vertical conductivity output file for each of the geologic formations
c
      OPEN(unit=44,file='v-columbia  ',status='unknown')
      OPEN(unit=45,file='v-upper-confining ',status='unknown')
      OPEN(unit=46,file='v-upper-aquifer ',status='unknown')
      OPEN(unit=47,file='v-middle-confining',status='unknown')
      OPEN(unit=48,file='v-middle-aquifer ',status='unknown')
      OPEN(unit=49,file='v-lower-confining ',status='unknown')
      OPEN(unit=50,file='v-lower-aquifer ',status='unknown')
      OPEN(unit=51,file='v-saint-marys  ',status='unknown')
c
c nforms is the number of geologic formations
c nlay is the number of modflow layers per formation
c ncol is the number of model columns
c nrow is the number of model rows
c npilot is the number of pilot points
c
      npilot=21
      nforms=8
      nrows=370
      ncols=102
c
c Read the zonecode array
c
      do 65 k=1,46
       do 35 j=1,nrows
       read(6,950) (izc(i,j,k),i=1,ncols)
 35 continue
 65 continue
c
c Read in the kriging multiplier arrays
c Read in the values of K for the pilot points
c Take the log of the K values
c
  read(5,*) pchkn
      read(5,*) pchks
  do 300 ifm=1,nforms
  do 200 ip=1,npilot
           read(5,*) pk(ifm,ip)
           read(5,*) ps(ifm,ip)
       pk(ifm,ip)=log10(pk(ifm,ip))
       ps(ifm,ip)=log10(ps(ifm,ip))
```

```
       if (ifm.eq.1) then
        iunit=ip+6
        do 100 iz=1,nrows
        read(iunit,*) (wt(ip,ix,iz),ix=1,ncols)
 100  continue
   endif
 200   continue
 300 continue
c
c Make the kriged surfaces using the weighting arrays
c Convert back from log values
c Write to the output files
c
  k=0
  do 800 ifm=1,nforms
       do 700 ilay=1,nlay(ifm)
       k=k+1
       do 600 j=1,nrows
        do 500 i=1,ncols
        hk(i)=0.
        ss(i)=0.
        do 400 ip=1,npilot
              hk(i)=hk(i)+wt(ip,i,j)*pk(ifm,ip)
                   ss(i)=ss(i)+wt(ip,i,j)*ps(ifm,ip)
 400    continue
        hk(i)=10**hk(i)
        ss(i)=10**ss(i)
c
c Make the paleochannel parameters equal to either the north
c vlue or the south value if it is below the upper confining unit
c
        if (ifm.gt.2) then
         if(izc(i,j,k).eq.8.or.izc(i,j,k).eq.9) then
         if(j.le.250) then
          hk(i)=pchkn
         elseif(j.ge.251) then
          hk(i)=pchks
         endif
         endif
                  endif
 500    continue
   write(ifm+27,900) (hk(i),i=1,ncols)
       write(ifm+35,900) (ss(i),i=1,ncols)
       write(ifm+43,900) (hk(i),i=1,ncols)
 600        continue
 700   continue
 800 continue
     stop
 900  format(1P10E12.4)
 950 format(102I1)
     end
```

Appendix 3. Fortran Program Used to Create Kriging-Based Multiplier Arrays Based on the Location of the Pilot Points and the Grid Cells

```
      PROGRAM KRIGING
c
c Find the weight arrays for Punctual Kriging
c with Linear Semivariogram, Slope=1
c NP is the number of pilot points
c NX is the number of grid points in the x-eirection
c NY is the number of grid points in the y-direction
c
  PARAMETER(NP=9,NX=102,NY=370)
  COMMON dist(NP+1,NP+1),vector(np+1),distp(NP+1)
  COMMON xx(NX),yy(NY),xp(NP),yp(NP)
  common weight(nx,ny,np+1),total(nx,ny)
  OPEN (unit=5,file="cellcenters.txt",status="unknown")
  OPEN (unit=6,file="xypcoords",status="unknown")
  OPEN (unit=7,file="krig-arrays",status="unknown")
  OPEN (unit=8,file="krig.debug",status="unknown")
  OPEN (unit=9,file="krig.xylist",status="unknown")
c
c Read in the coordinate data
c
  do 50 iy=1,370
  do 25 ix=1,102
   read(5,*) ir,ic,xx(ic),yy(ir)
   xx(ic)=xx(ic)/1000.
   yy(ir)=yy(ir)/1000.
 25  continue
 50 continue
  write(8,*) "x and y grid coordinates"
  do 60 ix=1,nx
  write(8,*) ix, xx(ix)
 60 continue
  do 70 iy=1,ny
  write(8,*) iy, yy(iy)
 70 continue
  write(8,*) "parameter node coordinates"
  do 100 ip=1,np
  read(6,*) icellx,icelly
  xp(ip)=xx(icellx)
  yp(ip)=yy(icelly)
  write(8,*) xp(ip),yp(ip)
 100 continue
c
c Sweep through all of the nodes nx through ny
c
  do 2000 iy=1,ny
  do 1000 ix=1,nx
c
c Assemble the "intra-distance between observations" array
c
  do 500 ip1=1,np
```

```
   do 400 ip2=1,np
   dist(ip1,ip2)=sqrt((xp(ip1)-xp(ip2))**2+(yp(ip1)-yp(ip2))**2)
 400  continue
 500 continue
c
c Add the Lagrangian multiplier
c
  do 600 ip=1,np
   dist(np+1,ip)=1.0
   dist(ip,np+1)=1.0
 600 continue
  dist(np+1,np+1)=0.0
c
c Fill in the right-hand side
c
  distp(np+1)=1.0
  do 900 ip=1,np
   distp(ip)=sqrt((xp(ip)-xx(ix))**2+(yp(ip)-yy(iy))**2)
 900 continue
c
c write echo the 10x10 array
c
  write(8,*) "left-hand side array"
  do 625 ip=1,np+1
   write(8,626) (dist(ipp,ip),ipp=1,np+1)
 625 continue
 626 format(10f9.2)
c
c write echo the right-hand side
c
  write(8,*) "right-hand side vector for ", ix,iy
  write(8,626) (distp(ipp),ipp=1,np+1)
c
c solve the matrix for the weights
c
   call gauss (np+1,dist,vector,distp)
   do 950 ip=1,np
   if (ip.eq.1) total(ix,iy)=0.
   weight(ix,iy,ip)=vector(ip)
   total(ix,iy)=total(ix,iy)+weight(ix,iy,ip)
 950  continue
 1000 continue
 2000 continue
  do 3000 ip=1,np
  do 2500 iy=1,370
   write(7,4000) (weight(ix,iy,ip),ix=1,102)
 2500 continue
 3000 continue
  do 3333 iy=1,370
  do 3111 ix=1,102
   write(9,5000) xx(ix),yy(iy),(weight(ix,iy,ip),ip=1,np),
  1     total(ix,iy)
 3111 continue
 3333 continue
  stop
 4000 format (10f13.5)
```

```
 5000 format (2F8.2,10f13.5)
  end
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c                   c
c Please Note:               c
c                   c
c (1) This computer program is part of the book, "An Introduction to c
c  Computational Physics," written by Tao Pang and published and c
c  copyrighted by Cambridge University Press in 1997.    c
c                   c
c (2) No warranties, express or implied, are made for this program. c
c                   c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
  SUBROUTINE GAUSS(N,A,X,B)
C
C An example of solving linear equation set A(N,N)*X(N) = B(N)
C with the partial-pivoting Gaussian elimination scheme. The
C numerical values are for the Wheatstone bridge example discussed
C in Section 4.1 in the book with all resistances being 100 ohms
C and the voltage 200 volts.
C
  DIMENSION X(N),B(N),A(N,N),INDX(N)
C  DATA B/200.0,0.0,0.0/,
C  *  ((A(I,J), J=1,N),I=1,N) /100.0,100.0,100.0,-100.0,
C  *     300.0,-100.0,-100.0,-100.0, 300.0/
C
  write(8,*) "N,B"
  write(8,*) N,B
  CALL LEGS (A,N,B,X,INDX)
C
C  WRITE (6, 999) (X(I), I=1,N)
C  STOP
  RETURN
 999 FORMAT (F16.8)
  END
C
  SUBROUTINE LEGS(A,N,B,X,INDX)
C
C Subroutine to solve the equation A(N,N)*X(N) = B(N) with the
C partial-pivoting Gaussian elimination scheme.
C
  DIMENSION A(N,N),B(N),X(N),INDX(N)
C
  CALL ELGS(A,N,INDX)
C
  DO  100 I = 1, N-1
  DO 90 J = I+1, N
   B(INDX(J)) = B(INDX(J))
  *     -A(INDX(J),I)*B(INDX(I))
 90   CONTINUE
 100   CONTINUE
C
  X(N) = B(INDX(N))/A(INDX(N),N)
  DO  200 I = N-1, 1, -1
  X(I) = B(INDX(I))
```

```
  DO 190 J = I+1, N
   X(I) = X(I)-A(INDX(I),J)*X(J)
 190   CONTINUE
   X(I) = X(I)/A(INDX(I),I)
 200  CONTINUE
C
  RETURN
  END
C
  SUBROUTINE ELGS(A,N,INDX)
C
C Subroutine to perform the partial-pivoting Gaussian elimination.
C A(N,N) is the original matrix in the input and transformed
C matrix plus the pivoting element ratios below the diagonal in
C the output. INDX(N) records the pivoting order.

C
  DIMENSION A(N,N),INDX(N),C(N)
C
C Initialize the index
C
  DO  50 I = 1, N
  INDX(I) = I
 50  CONTINUE
C
C Find the rescaling factors, one from each row
C
  DO  100 I = 1, N
   C1= 0.0
   DO 90 J = 1, N
   C1 = AMAX1(C1,ABS(A(I,J)))
 90    CONTINUE
   C(I) = C1
 100   CONTINUE
C
C Search the pivoting (largest) element from each column
C
  DO  200 J = 1, N-1
  PI1 = 0.0
  DO 150 I = J, N
   PI = ABS(A(INDX(I),J))/C(INDX(I))
   IF (PI.GT.PI1) THEN
   PI1 = PI
   K = I
   ELSE
   ENDIF
 150   CONTINUE
C
C Interchange the rows via INDX(N) to record pivoting order
C
  ITMP = INDX(J)
  INDX(J) = INDX(K)
  INDX(K) = ITMP
  DO 170 I = J+1, N
   PJ = A(INDX(I),J)/A(INDX(J),J)
C
```

```
C Record pivoting ratios below the diagonal
C
   A(INDX(I),J) = PJ
C
C Modify other elements accordingly
C
   DO 160 K = J+1, N
   A(INDX(I),K) = A(INDX(I),K)-PJ*A(INDX(J),K)
 160    CONTINUE
 170    CONTINUE
 200     CONTINUE
C
  RETURN
  END
```

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