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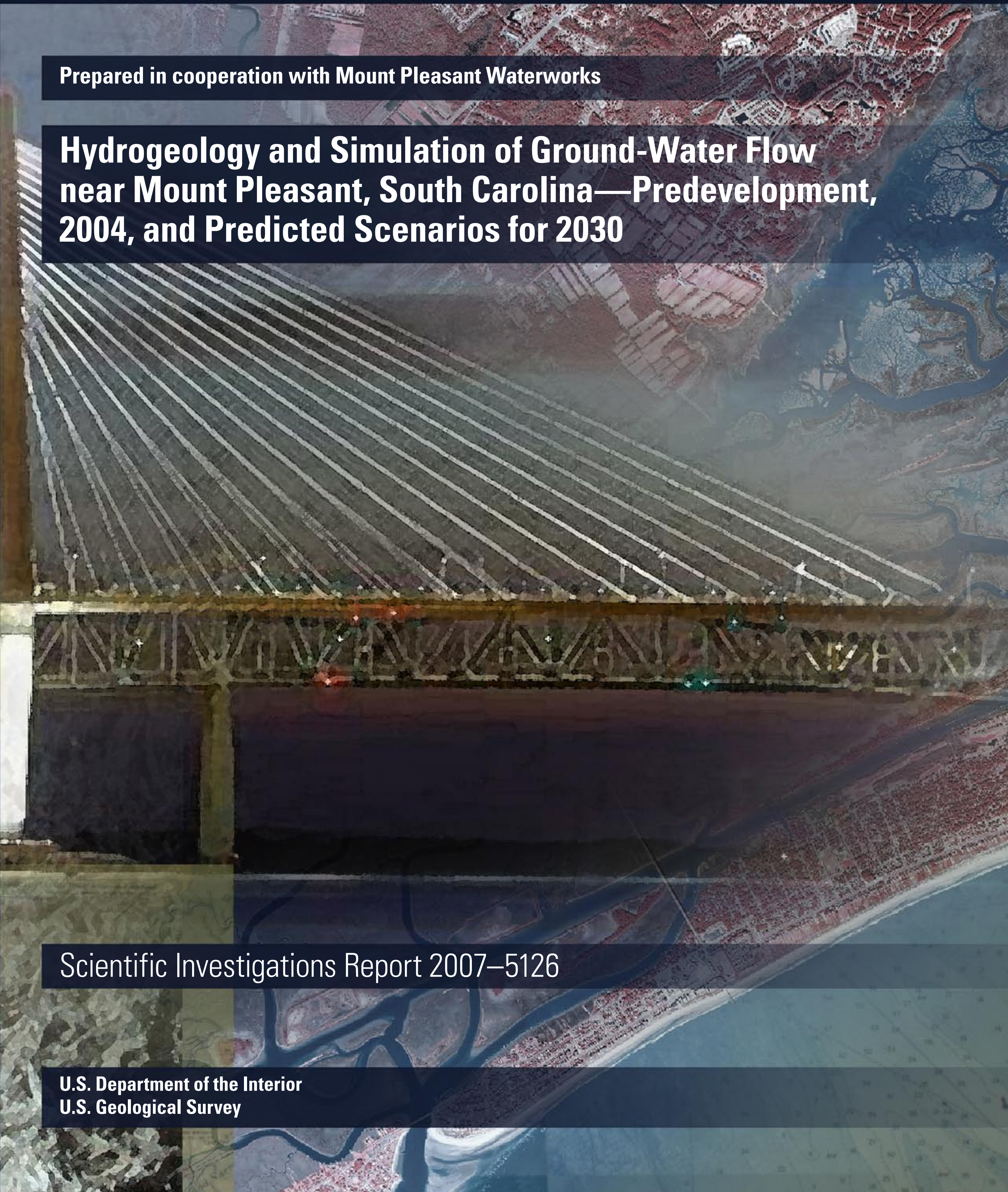
Hydrogeology and Simulation of Ground-Water Flow near Mount Pleasant, South Carolina—Predevelopment, 2004, and Predicted Scenarios for 2030



Scientific Investigations Report 2007–5126

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

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By Matthew D. Petkewich and Bruce G. Campbell

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Conversion Factors, Abbreviations, Datums, and Acronyms

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	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)

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.

*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.

Acronyms

A	Anisotropy
CBD	Charleston, Berkeley, and Dorchester
CWS	Charleston Water System
GPS	Global Positioning System
HC	Hydraulic conductivity
MPW	Mount Pleasant Waterworks
NED	National Elevation Dataset
NWIS	National Water Information System
R	Recharge
RASA	Regional Aquifer System Analysis
RB	Riverbed conductance
RMSE	Root-mean-square error
RO	Reverse osmosis
SCDHEC	South Carolina Department of Health and Environmental Control
SCDNR	South Carolina Department of Natural Resources
SCRASA	South Carolina Regional Aquifer System Analysis
SS	Specific storage
USGS	U.S. Geological Survey
VA	Vertical anisotropy

Additional Abbreviations

>	Greater than
<	Less than
Mgal/mo	Million gallons per month

Hydrogeology and Simulation of Ground-Water Flow near Mount Pleasant, South Carolina—Predevelopment, 2004, and Predicted Scenarios for 2030

By Matthew D. Petkewich and Bruce G. Campbell

Abstract

Heavy water use from the Cretaceous Middendorf aquifer in South Carolina has created a large, regional cone of depression in the potentiometric surface of the Middendorf aquifer in Charleston and Berkeley Counties, South Carolina. Water-level declines of up to 249 feet have been observed in wells over the past 125 years and are a result of ground-water use for public-water supply, irrigation, and private industry. To address the concerns of users of the Middendorf aquifer, the U.S. Geological Survey, in cooperation with Mount Pleasant Waterworks, updated an existing ground-water flow model to incorporate additional data that have been compiled since 1989. The updated ground-water flow model incorporates water-level data collected from 349 wells in 2004, base-flow data measured at 17 streams, hydraulic property data from 265 wells, and water-use data compiled for more than 2,700 wells for the period between the early 1900s to 2004.

The ground-water flow system of the Coastal Plain physiographic province of South Carolina and parts of Georgia and North Carolina was simulated using the U.S. Geological Survey finite-difference code MODFLOW-2000. The model was vertically discretized into nine layers to include the five aquifers of the surficial, the combined Floridan aquifer system and Tertiary sand aquifer, Black Creek, Middendorf, and Cape Fear, separated by four intervening confining units. Specified-head boundary conditions were used at the lateral boundaries of the model and for the lower Coastal Plain part of the surficial aquifer; no-flow boundary conditions were used at the updip and downdip extent of the model layers and at the base of the Cape Fear aquifer.

Ground-water conditions for predevelopment and 2004 were simulated using steady-state and transient approximations, respectively. Simulated water levels generally matched the observed conditions, plus or minus a 20-foot calibration target, with 56.4 and 64.8 percent of the simulated values approximating the measured values for predevelopment and 2004 hydrologic conditions, respectively. The root-mean-square error of the water-level residuals for the various model layers varied between 20.2 and 34.4 feet for predevelopment and 18.2 and 36.7 feet for 2004. The general goodness of fit also was apparent in the calculation of the ratio of standard deviation of residuals to range of observations for each modeled aquifer layer. The calculated ratios for the predevelopment and 2004 hydrologic conditions were less than 0.10 for all model layers except for the Cape Fear aquifer in both predevelopment and 2004 simulations.

The Mount Pleasant model was most sensitive to changes in simulated specific storage of most model layers, vertical anisotropy of the confining units above and below the Middendorf aquifer, hydraulic conductivity of the confining units, and the specified-head boundary conditions for the surficial aquifer. The model also is sensitive to horizontal hydraulic conductivity of the Floridan aquifer system and Tertiary sand aquifer and the Black Creek and Middendorf aquifers. Simulated water budgets indicate that the primary sources of water to the model are recharge and the specified-head boundaries in layers 1 and 3. More than 88 percent of the water that discharges from the model discharges from layers 1–3 through specified-head boundaries and rivers. Approximately 11 percent of the water budget was discharged through wells for the 2004 budget. In 2004, 8.11 million gallons of water per day was discharged from wells in the Mount Pleasant area. Water to these wells is provided predominantly by lateral flow within the Middendorf aquifer. Additional water is provided from aquifer storage and leakage from confining units located above and below the Middendorf aquifer. Downward flow through the Middendorf confining unit is a reversal of the predevelopment flow direction.

Five predictive water-management scenarios were simulated to determine the effects on the Middendorf aquifer on potential future demands in the Mount Pleasant, South Carolina, area. Simulated scenarios to the year 2030 show that continued ground-water use in the Charleston and Berkeley County area at current pumping rates will continue the overall decline in ground-water levels. Pumping Mount Pleasant wells at 75 percent the current rate reduces the rate of drawdown to less than 1.4 feet per year at two existing observation wells in the Charleston and Berkeley County area. Eliminating industrial water use from the nearest Middendorf aquifer water user in Berkeley County in the year 2010 produced water-level altitudes at the two existing observation wells for the year 2030 that were higher than the minimum reported water-level altitudes for one of the wells and within 7 feet of the other.

Introduction

The increased use of ground water following urban growth has stressed the Coastal Plain aquifers of South Carolina over the past 125 years. In particular, heavy water use from the Cretaceous Middendorf aquifer in and around Andrews, Charleston, and Florence, SC, has caused ground-water-level declines of up to 249 feet (ft). Predevelopment water-level altitudes of 126 ft in Mount Pleasant, SC (Aucott and Speiran, 1985) had declined in 2004 to an altitude of approximately –126 ft. Continued heavy use of ground water in these areas and subsequent declines in the water levels will most likely increase the cost of obtaining water from this aquifer.

Mount Pleasant, a part of the Charleston, SC, metropolitan area (fig. 1), has grown from a small fishing village of about 5,000 people in 1960 to a city of about 59,000 in 2005 (Town of Mount Pleasant, 2007). By the year 2015, the population is expected to approach about 96,000 people (Town of Mount Pleasant, 2007). This projected growth will increase demand on the currently (2007) stressed ground-water resources of the area. Mount Pleasant Waterworks (MPW), the town's independent public works agency, has produced potable water from the Middendorf aquifer since 1968. In 2004, Mount Pleasant Waterworks operated six Middendorf aquifer wells and four reverse osmosis (RO) plants and withdrew a total of 7.5 million gallons of water per day from the Middendorf aquifer. These six wells and four RO plants provided about 80 percent of the water demand in Mount Pleasant. The remaining demand was met by purchasing treated surface water from the Charleston Water System (CWS). The Bushy Park Reservoir is the primary source of surface water for CWS but is supplemented with water from the Edisto River as needed. Currently (2007), the water demand for the Town of Mount Pleasant is met by purchasing 5.5 million gallons per day (Mgal/d) of treated surface water from the CWS and supplemented by the six Middendorf wells and RO plants as needed. Mount Pleasant Waterworks currently (2007) has a total pumping capacity of 8.7 Mgal/d and a permitted capacity of 10.72 Mgal/d (J. Ouellet, Mount Pleasant Waterworks, written commun., May 2007).

Water use in Mount Pleasant, irrigation pumpage at Kiawah Island, past water use by the Town of Summerville, and use by private industry in the Charleston, SC, area have combined to create a large, regional cone of depression in the potentiometric surface of the Middendorf aquifer (fig. 2). The Charleston, Berkeley, and Dorchester (CBD) County area has been designated as a Capacity Use Area by the South Carolina Department of Health and Environmental Control (SCDHEC). In counties designated as Capacity Use Areas, ground-water withdrawals in excess of 3 million gallons per month (Mgal/mo) must be permitted and reported to SCDHEC (South Carolina Department of Health and Environmental Control, 2001).

To address the concerns of users of the Middendorf aquifer, the U.S. Geological Survey (USGS) in cooperation with the MPW, updated an existing ground-water flow model (Campbell and van Heeswijk, 1996) to incorporate data through 2004, which have been compiled since the end of the previous investigation. Simulated results produced by the model represent the water-level conditions from predevelopment to 2004 and predictive simulations of water-management scenarios to the year 2030. The results of this investigation will provide MPW and other Cretaceous-aquifer ground-water users with a tool that can be used to manage the ground-water resources of the CBD County area (fig. 1).

Alternatives to the heavily used Middendorf aquifer are the Floridan aquifer system, and the Black Creek, and Cape Fear aquifers (fig. 3). The low yield and poor water quality of the brackish Floridan aquifer system make it less appealing for water use in Mount Pleasant than the Middendorf aquifer. The depth of the Cape Fear aquifer precludes it as a viable supplemental source of ground water. Currently (2007), the Black Creek aquifer is not used in the CBD area, and its hydraulic properties and water-quality conditions are virtually unknown. The Black Creek aquifer is heavily used in other parts of South Carolina, including the Grand Strand area and the Pee Dee region. In those areas, well yields of 500 gallons per minute (gal/min) are common. As part of this investigation, a test well was installed into the Black Creek aquifer, water-quality samples were collected, and an aquifer test was conducted to evaluate the viability of the Black Creek aquifer as a supplemental water source in the Mount Pleasant area. Water-quality and aquifer-test results from the test well indicate that the Black Creek aquifer is not a practical supplemental source for use by the MPW.

Purpose and Scope

This report describes the results of an evaluation of the hydrologic system of South Carolina and parts of Georgia and North Carolina, but focuses on Mount Pleasant and the surrounding greater Charleston, SC, area. The purpose of this investigation was to update 2004 hydrologic conditions for an existing ground-water flow model that estimated ground-water flow and water use in the Cretaceous aquifers of the study area (Campbell and van Heeswijk, 1996). The newly calibrated model was used to simulate predictive water-management scenarios to the year 2030 from the Middendorf aquifer in the study area. Data used to update the previously calibrated model included hydraulic properties, water-level and water-use data for the aquifers, and ground-water contribution to rivers as baseflow in the study area. During this investigation, a test well was drilled and temporarily completed in the Black Creek aquifer to allow water-level monitoring, aquifer testing, and water-quality sampling. Aquifer-test results from the test well were incorporated in the model.

Base from U.S. Geological Survey
1:2,000,000-scale and 1:100,000-
scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 1. Location of the study area, Mount Pleasant, South Carolina.

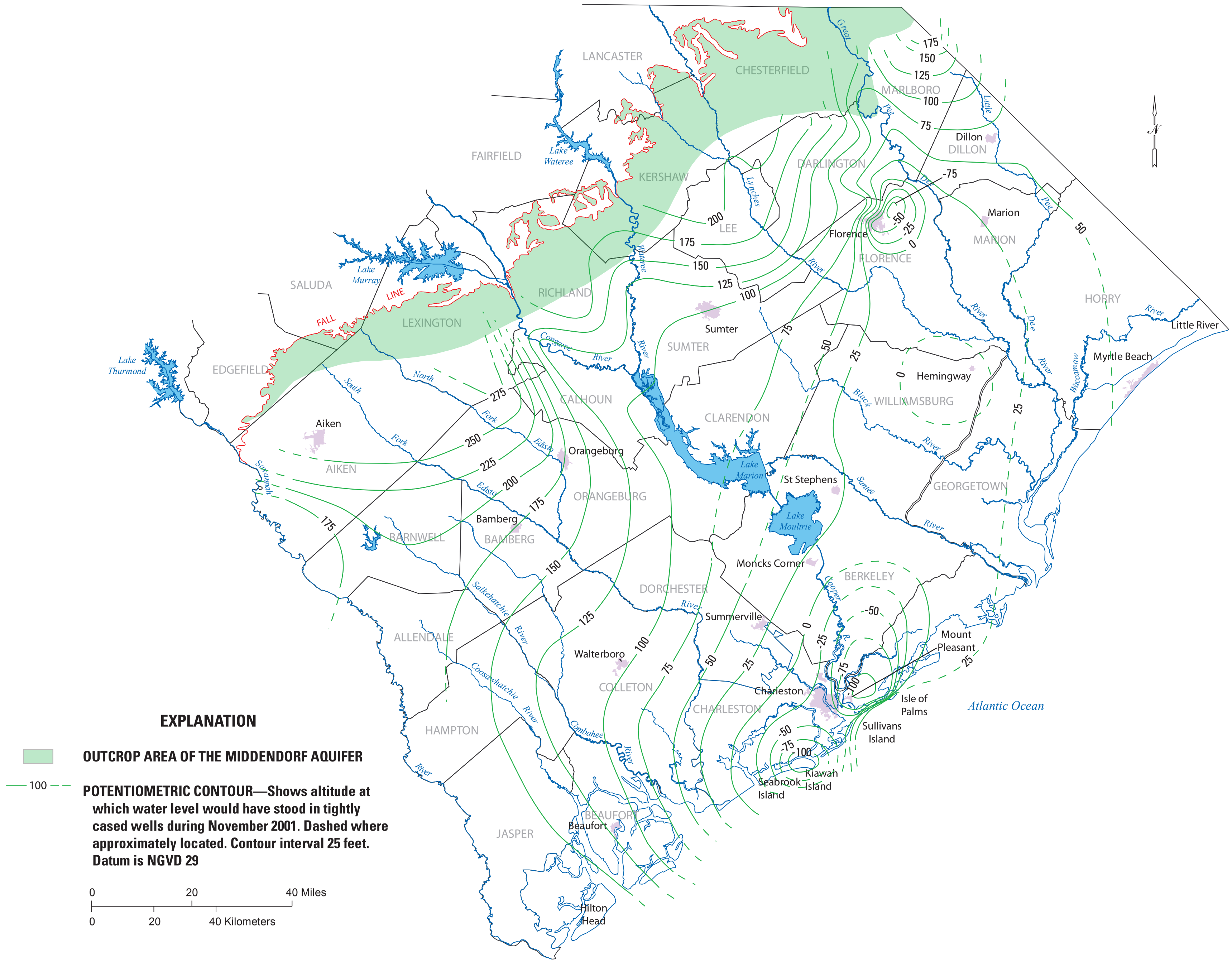


Figure 2. The potentiometric surface of the Middendorf aquifer, November 2001 (modified from Hockensmith, 2003).

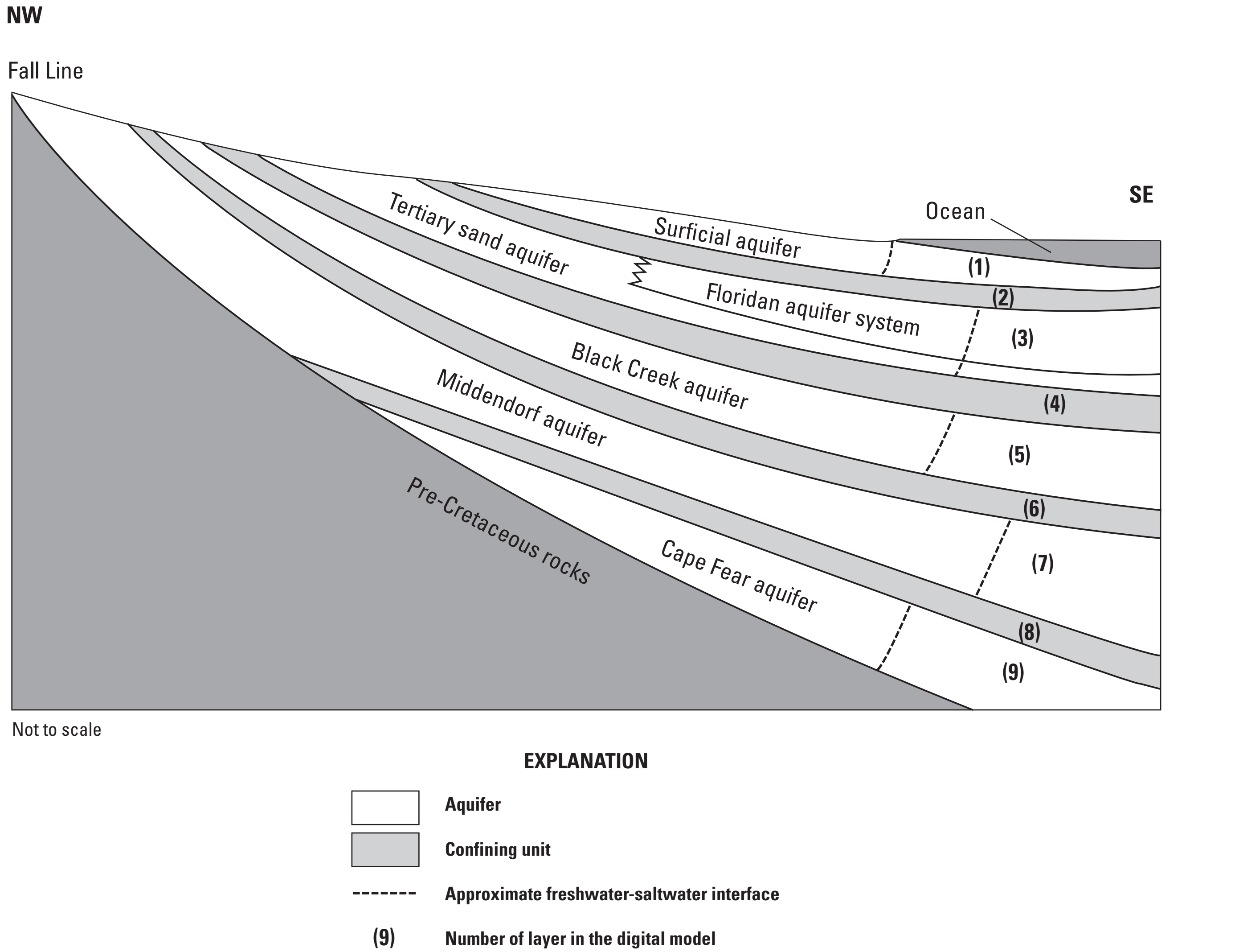


Figure 3. Schematic diagram showing geohydrologic section across the South Carolina Coastal Plain (modifed from Aucott, 1996).

Description of Study Area

The study area consists of about 49,800 square miles (mi^2), with the Fall Line as the northwestern study area (model) boundary (fig. 1). The study area comprises parts of the Southeastern and Northern Atlantic Coastal Plain aquifer systems (34,800 mi^2) and extends from the Oconee and Altamaha Rivers in Georgia to the Cape Fear River in North Carolina. The offshore part of the model area consists of 15,000 mi^2 and extends to the Florida-Hatteras Slope off the Georgia Coast (Payne and others, 2005) and freshwater-saltwater interface off the South Carolina and North Carolina coast (Lee and others, 1986). Land-surface altitude ranges from 0 at the coast to more than 600 ft in the upper Coastal Plain physiographic province (Aucott, 1996). The offshore part of the study area ranges from 0 to over 300 ft below NGVD 29.

Mean annual precipitation in Georgia, South Carolina, and North Carolina varies between about 48 and 50 inches (in.) and occurs predominantly as rainfall with occasional snowfall during the winter. The areal distribution of annual precipitation ranges from below 40 to more than 90 in. for these States, with the lowest rainfall occurring in the Coastal Plain Physiographic Province and the highest rainfall occurring in the Blue Ridge Mountains. Annual rainfall for the Coastal Plain Physiographic Province ranges from about 46 to 58 in. for Georgia, 42 to 56 in. for South Carolina, and 44 to 62 in. for North Carolina (Oregon Climate Service, 2007).

Evaporation for the Coastal Plain of South Carolina and the adjacent counties in Georgia and North Carolina ranges from about 36 to 46 in. per year (in/yr) (South Carolina Department of Natural Resources, 2007). These values were measured at 14 pan evaporation stations located in the 3 States and were adjusted using the widely accepted correction factor of 0.70, due to the fact that water is typically more readily evaporated from evaporation pans than from the surrounding area. The lower value of these estimates is similar to the range (30 to 35 in/yr) determined for the Southeastern Coastal Plain Regional Aquifer System Analysis (RASA) (Barker and Pernik, 1994).

Previous Investigations

The Southeastern Coastal Plain aquifer system in South Carolina has been modeled previously during several regional investigations (Aucott, 1988, 1996; Campbell and van Heeswijk, 1996). The systems were modeled as part of the USGS RASA program (Sun, 1986). The South Carolina RASA (SCRASA) model simulated steady-state water-level conditions in the Coastal Plain aquifers prior to development (Aucott, 1988) and transient conditions through 1982 (Aucott, 1996). Campbell and van Heeswijk (1996) refined the SCRASA model by focusing on the Charleston and Florence, SC, areas and simulating transient water-level conditions through 1989 and predictive withdrawal scenarios for the Mount Pleasant area from 1990 through 2015.

Additional modeling investigations have been completed that encompass large parts of the model area. In Georgia, the Southeastern Coastal Plain aquifer system and in North Carolina, the Northern Atlantic Coastal Plain aquifer system have been modeled as parts of the RASA program (Sun, 1986). The hydrology of Tertiary and Cretaceous aquifers of Georgia and South Carolina was evaluated as part of a model area that includes part of Florida, Alabama, and all of Mississippi (Barker and Pernik, 1994). That investigation simulated steady-state conditions for predevelopment and transient water levels to 1985. An investigation that focused on the hydrology of Georgia and parts of Alabama and South Carolina was developed to simulate steady-state predevelopment and transient water-level data to 1980 (Faye and Mayer, 1996). The North Carolina RASA model simulated steady-state predevelopment, transient water levels to 1989, and predictive transient water levels to 2000 (Giese and others, 1997). Clarke and West (1998) simulated ground-water flow and stream-aquifer relations in the vicinity of the Savannah River Site, Georgia and South Carolina. Cherry (2006) updated the Clarke and West (1998) model to include ground-water flow under 2002 conditions and four water-management scenarios from 2002 to 2020. Payne and others (2005) simulated ground-water flow in the Floridan aquifer system and the Brunswick aquifer in coastal Georgia, South Carolina, and Florida to evaluate the conceptual model of regional ground-water flow and to use the model to serve as a framework for future subregional models and to serve as a tool for future water management.

Methods of Investigation

The primary objective of this investigation was to update the existing ground-water flow model of the study area (Campbell and van Heeswijk, 1996) to evaluate five predictive management scenarios for the aquifers of the South Carolina Coastal Plain to the year 2030. Revision of the existing model was deemed necessary because additional hydrologic data were available for use in model calibration, more powerful computing capabilities allowed a more detailed evaluation of the area of interest, and the updated version of the USGS three-dimensional finite-difference modular flow model (MODFLOW-2000; Harbaugh and others, 2000) provided improved methods for simulating field conditions. Revision of the flow model included active simulation of the Floridan aquifer system and Tertiary sand aquifer (in places collectively referred to as Floridan-Tertiary sand aquifer in this report) and major confining units in the study area (fig. 3) and incorporation of hydrologic properties, water-level and water-use data, and ground-water baseflow data to rivers acquired since the previous study. After model calibration, five selected water-management scenarios were simulated to evaluate the potential effects on future water-level conditions in the aquifers.

The methods of investigation included conceptual model evaluation and revision, data compilation, model calibration, sensitivity analysis, and predictive water-management scenario simulations. The conceptual model of the existing flow model was evaluated to determine the appropriateness of boundary conditions, model layering, and methods of approximating field conditions. Revisions to the conceptual model are discussed in the section “Simulation of Ground-Water Flow.” Hydraulic properties and water-use and water-level data for 1989 to 2004 were compiled from State agencies and other USGS investigations for inclusion in the updated model. These data also included synoptic ground-water-altitude measurements made in the fall of 2004. The model was calibrated by approximating steady-state predevelopment ground-water conditions for the year 1900 and simulating transient conditions through 2004. The sensitivity of the calibrated model to the modeled parameters was evaluated to determine the relative importance of the parameters to the simulated results. Then, the calibrated model was used to simulate water-management scenarios to evaluate ground-water resources of the study area in terms of meeting future water-use demands.

Acknowledgments

The authors thank personnel of Mount Pleasant Waterworks, especially Clay Duffie, David Niesse, Jim Ouellet, Greg Hill, and Tom Milazzo, for assistance in collecting hydrologic and water-use data in the Mount Pleasant area during this investigation. This investigation benefited from a multiaquifer synoptic water-level-collection effort in 2004 that was funded by the USGS Office of Ground Water, Ground Water Resources Program. In addition, the authors thank Charles Betivas and Mary Harris from the Savannah River National Laboratory, Environmental Sciences & Biotechnology; Jack Childress, Rob Devlin, and Chuck Williams from the South Carolina Department of Health and Environmental Control; and Joe Gellici and Drennan Park from the South Carolina Department of Natural Resources, for their support during the 2004 field effort. The authors thank Karen Agerton from the South Carolina Department of Natural Resources for continuous water-level data provided for observation wells in the study area.

Hydrogeology

The sediments of the Southeastern Coastal Plain consist of a wedge-shaped accumulation of unconsolidated to poorly consolidated clay, silt, sand, and limestone of Late Cretaceous and younger ages overlying pre-Cretaceous metamorphic, igneous, and sedimentary rocks (Aucott, 1996; Miller, 1986). This sequence of deltaic and marine deposits gradually increases in thickness from the Fall Line to the present-day Atlantic Coast (fig. 1). In South Carolina, the thickness of the Coastal Plain sediments ranges from about 1,000 ft near the North Carolina border to about 4,500 ft near the Georgia border. These deposits can be divided into a series of aquifers and confining units on the basis of their relative permeabilities, areal extent, and lithologic continuity (Aucott, 1996).

Hydrogeologic Units

Aucott and Speiran (1985) described six major aquifers within the Southeastern Coastal Plain aquifer system in South Carolina. From youngest to oldest these aquifers are the surficial, Floridan aquifer system, Tertiary sand, Black Creek, Middendorf, and Cape Fear (fig. 3). The aquifers were divided into units on the basis of relative permeability and not geologic formation; therefore, aquifers may cross formation boundaries in some instances (Aucott, 1996). While previous and ongoing investigations in the study area use different nomenclature to describe these aquifers, this report uses the nomenclature described in Aucott and Speiran (1985), Aucott (1988, 1996), and Campbell and van Heeswijk (1996). The correlation between the hydrostratigraphy used in this report and that of other investigations in the study area can been seen in figure 4.

Surficial Aquifer

The uppermost aquifer in the South Carolina Coastal Plain is the unconfined surficial aquifer. This aquifer is composed of sandy marine terrace and alluvial deposits that are up to 50 ft thick along the Atlantic Coast and gradually pinch out at the boundary of the upper and lower Coastal Plain (fig. 5; Doering, 1960). The water table in the surficial aquifer varies in depth from less than 5 ft below land surface near the coast to depths up to 10 to 20 ft below land surface elsewhere (Campbell and van Heeswijk, 1996). Recharge to the surficial aquifer occurs through precipitation and upward leakage from deeper aquifers in areas of upward vertical hydraulic gradients (Campbell and van Heeswijk, 1996). Water leaves the surficial aquifer by evapotranspiration or discharge to surface-water bodies including the many rivers that truncate the aquifers. Discharge also occurs vertically through confining units of variable thickness and permeability. Hydraulic conductivity of the surficial aquifer ranges from 12 to 240 feet per day (ft/d) in the study area (table 1; Aucott and Newcome, 1986; Newcome, 1993, 2000).

Floridan Aquifer System and Tertiary Sand Aquifer

The Floridan aquifer system and Tertiary sand aquifer are composed of clastic sediments of the Tertiary sand aquifer and carbonate sediments of the Floridan aquifer system (Aucott, 1988, 1996; Campbell and van Heeswijk, 1996). These clastic and carbonate units grade laterally into one another and, having no distinctive water-level or water-quality differences, are commonly considered one aquifer (Aucott, 1988; Campbell and van Heeswijk, 1996). The Floridan aquifer system extends from south Florida through Alabama, Georgia, and South Carolina (Miller, 1986; Campbell and van Heeswijk, 1996).

Table 1. Ranges of reported aquifer transmissivity, storage coefficient, calculated hydraulic conductivity, and simulated hydraulic conductivity for the aquifers in the study area.

[ft^2/d, feet squared per day; ft/d, feet per day; —, data not available]

Aquifer	Layer	Reported transmissivity, in ft^2/d			Reported storage coefficient			Horizontal hydraulic conductivity, in ft/d					
								Calculated			Simulated		
		Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum
Surficial[a]	1	—	—	—	—	—	—	12	67	240	13	110	390
Floridan-Tertiary sand	3	180	17,000	600,000	0.00004	0.0001	0.003	4.5	150	2,000	1.1	120	2,000
Black Creek	5	50	1,600	27,000	0.00001	0.0003	0.0005	1.0	22.0	300	1.0	4.4	500
Middendorf	7	130	3,100	31,000	0.0001	0.0002	0.002	2.7	46	360	1.0	15	500
Cape Fear	9	450	900	1,300	—	—	—	8.9	11	11	1.1	3.3	56

[a] The calculated horizontal hydraulic conductivity is equal to the reported horizontal hydraulic conductivity for the surficial aquifer.

Note: The calculated and simulated hydraulic conductivities were derived from a subset of the reported transmissivities; therefore, the minimum and maximum hydraulic conductivity values may not correlate to the minimum and maximum reported transmissivities for each layer.

Series	South Carolina Geologic Units[1]	South Carolina Aquifers[1]	Georgia Aquifers[2]	North Carolina Aquifers[3]	Model layer
Holocene	Alluvium and terrace deposits	Surficial aquifer	Surficial aquifer	Surficial aquifer	1
Pleistocene					
Miocene	Hawthorn Formation	Floridan-Tertiary sand confining unit	Upper Three Runs confining unit	Yorktown confining unit	2
Eocene	Santee Limestone	Floridan aquifer system	Upper Three Runs aquifer	Yorktown aquifer	3
				Pungo River confining unit	
				Pungo River aquifer	
			Gordon confining unit	Castle Hayne confining unit	
	Barnwell Formation	Tertiary sand aquifer	Gordon aquifer	Castle Hayne aquifer	
	McBean Formation				
	Congaree Formation				
Paleocene	Black Mingo Formation		Millers Pond confining unit	Beaufort confining unit	
			Millers Pond aquifer	Beaufort aquifer	
		Black Creek confining unit	Upper Dublin confining unit	Peedee confining unit	4
Upper Cretaceous	Black Creek Formation			Peedee aquifer	
		Black Creek aquifer	Upper Dublin aquifer	Black Creek confining unit	5
			Lower Dublin confining unit	Black Creek aquifer	
			Lower Dublin aquifer		
		Middendorf confining unit	Upper Midville confining unit	Upper Cape Fear confining unit	6
	Middendorf Formation	Middendorf aquifer	Upper Midville aquifer	Upper Cape Fear aquifer	7
			Lower Midville confining unit		
	Cape Fear Formation		Lower Midville aquifer		
		Cape Fear confining unit	Confining unit	Lower Cape Fear confining unit	8
		Cape Fear aquifer		Lower Cape Fear aquifer	9
Lower Creatceous				Lower Cretaceous confining unit	Not modeled
				Lower Cretaceous aquifer	

[1] Aucott (1996)
[2] Cherry (2006)
[3] Winner and Coble (1996)

Figure 4. Generalized correlation of geologic and hydrogeologic units and model layers.

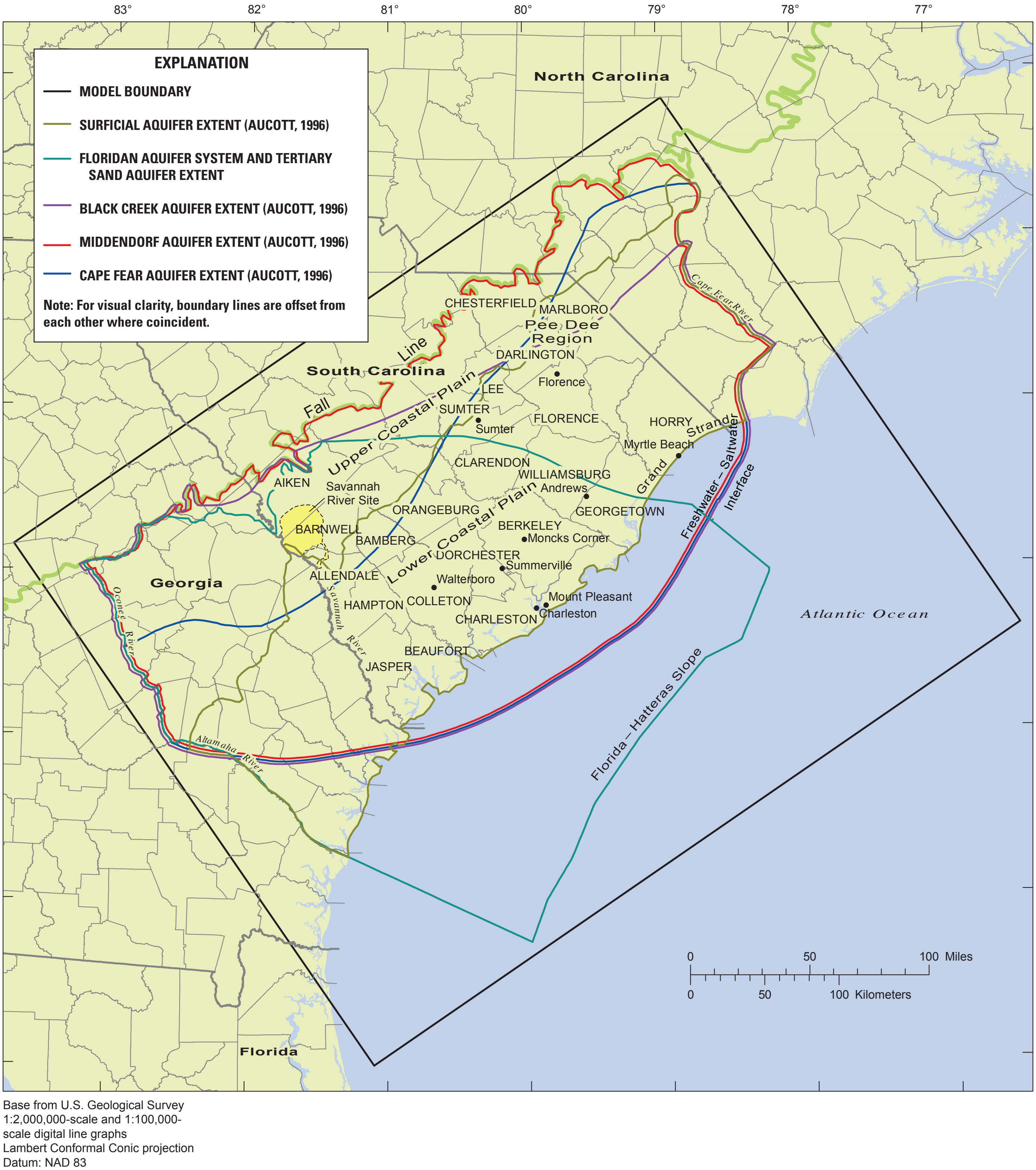


Figure 5. Areal extent of Coastal Plain aquifers in the study area.

The northernmost extent of this aquifer system occurs in South Carolina along an arc that extends from Georgetown County to the Fall Line (fig. 5). In updip areas, outcrops of the Tertiary sand aquifer are unconfined; however, the Floridan aquifer system is confined throughout the study area (Campbell and van Heeswijk, 1996). The Floridan aquifer system is the primary source of water in Beaufort and Jasper Counties and its use is common in the Charleston, Berkeley, and Dorchester County area (South Carolina Department of Health and Environmental Control, 2006).

Transmissivities for the Floridan aquifer system and Tertiary sand aquifer range from 500 to 100,000 ft^2/d in South Carolina (Aucott and Newcome, 1986; Newcome, 1993, 2000) and between 180 and 600,000 ft^2/d in Georgia (Payne and others, 2005; M. Peck, U.S. Geological Survey, written commun., December 2005; D. Payne, U.S. Geological Survey, written commun., January 2006). Transmissivities are greatest in Georgia and the southeastern part of South Carolina, where the Floridan aquifer system thickens. Reported values of the storage coefficient for the Floridan aquifer system and Tertiary sand aquifer are between 0.00004 and 0.003 (Aucott and Newcome, 1986; Newcome, 1993, 2000).

Black Creek Aquifer

The Black Creek aquifer is the uppermost regionally extensive Cretaceous aquifer (fig. 5). This system is composed of well-sorted, unconsolidated sands interbedded with organic clays (Campbell and van Heeswijk, 1996). Although absent in the northeastern part of the Coastal Plain, this aquifer extends from the Fall Line in the western part of the study area to the coast, where it thickens to approximately 900 ft (Campbell and van Heeswijk, 1996). The Black Creek aquifer is predominantly confined throughout most of its extent in the study area; however, in the eastern part of the study area, where the Floridan aquifer system and Tertiary sand and surficial aquifers are absent, the Black Creek aquifer is unconfined (fig. 5). Water use in the Black Creek aquifer is primarily concentrated in the middle to northern parts of the Coastal Plain and Georgetown and Horry Counties (South Carolina Department of Health and Environmental Control, 2006).

Transmissivities for the Black Creek aquifer range from about 50 to 27,000 ft^2/d in the study area (Aucott and Newcome, 1986; Newcome, 1993, 2000; M. Peck, U.S. Geological Survey, written commun., December 2005). The highest transmissivities occur in the western part of the study area. Transmissivities gradually decrease to the east and south as a result of increased presence of clays (Campbell and van Heeswijk, 1996). Low transmissivities also occur along the updip extent of the Black Creek aquifer, where sand deposits are thinner than in downdip areas. Reported values of the storage coefficient for the Black Creek aquifer are between 0.00001 and 0.0005 (Aucott and Newcome, 1986; Newcome, 1993, 2000).

Middendorf Aquifer

The Middendorf aquifer is the only Cretaceous-age aquifer that fully extends to the Fall Line (fig. 5). In the western part of the Coastal Plain, the Middendorf is overlain by the younger sediments of the Floridan aquifer system and Tertiary sand aquifer and the Black Creek aquifer. The Middendorf is unconfined in the eastern part of the study area where the overlying aquifers and confining units are absent. The Middendorf aquifer is the primary source of water for many upper and lower Coastal Plain communities including Florence, Sumter, Walterboro, and Mount Pleasant (Campbell and van Heeswijk, 1996). Chesterfield, Darlington, Florence, Marlboro, Orangeburg, and Sumter Counties rely heavily on the Middendorf aquifer for public water supplies (South Carolina Department of Health and Environmental Control, 2006). Over the past decade, water use from the Middendorf aquifer has increased along the coast (South Carolina Department of Health and Environmental Control, 2006).

Transmissivities for the Middendorf aquifer range from about 130 to 31,000 ft^2/d in the study area (Aucott and Newcome, 1986; Newcome, 1993, 2000; M. Peck, U.S. Geological Survey, written commun., December 2005). The highest transmissivities occur in the western part of the State and gradually decrease to the east and south (Campbell and van Heeswijk, 1996). Low transmissivities occur along the updip extent of the Middendorf aquifer, where sand deposits are thinner than in downdip areas. Reported values of the storage coefficient for the Middendorf aquifer are between 0.0001 and 0.002 (Aucott and Newcome, 1986; Newcome, 1993, 2000).

Cape Fear Aquifer

The areal extent of the Cape Fear aquifer is not well defined but probably exists only in the lower Coastal Plain and is, therefore, confined throughout the study area (Aucott, 1996). The aquifer consists of clays and sands, the continuity of which is unknown (Campbell and van Heeswijk, 1996). The Cape Fear aquifer is largely unused in South Carolina due to its high clay content and marginal drinking water quality (Campbell and van Heeswijk, 1996; South Carolina Department of Health and Environmental Control, 2006).

Transmissivities for the Cape Fear aquifer range from about 450 to 1,300 ft^2/d in the study area (Aucott and Newcome, 1986; Newcome, 1993, 2000). The existence of shallower aquifers of better water quality limits the number of wells completed in the Cape Fear aquifer. A storage coefficient of 0.0000093 is reported for the Cape Fear aquifer at Hilton Head, SC (Temples and Wadell, 1996).

Confining Units

All five aquifers are vertically separated from one another by confining units of lower permeability, the magnitude and variability of which is not well known. The confining unit between the surficial aquifer and the Floridan aquifer system and Tertiary sand aquifer is a discontinuous clayey sand to sandy clay that allows high rates of leakage between the surficial aquifer and the underlying aquifers in many areas (Hayes, 1979). The most effective confining unit in the Coastal Plain is the clay unit located between the Floridan-Tertiary sand and Black Creek aquifers (Campbell and van Heeswijk, 1996). This is evident by the differences observed in water-quality and water-level conditions between these adjacent aquifers in the Coastal Plain (Aucott and Sperian, 1985). The confining unit located between the Black Creek and Middendorf aquifers comprises silty to sandy clays, whereas the confining unit located between the Middendorf and Cape Fear aquifers comprises a massive non-calcareous clay (Gohn, 1992; Campbell and van Heeswijk, 1996).

Ground-Water Flow

The Coastal Plain aquifers in the study area are part of the extensive Southeastern Coastal Plain aquifer system and the Northern Atlantic Coastal Plain aquifer system (Sun, 1986). Predevelopment ground-water flow was generally from the southwest to the northeast and parallel to the coast, except for the Floridan aquifer system and Tertiary sand aquifer, where flow was perpendicular to the coast (fig. 6) (Aucott and Speiran, 1985; Campbell and van Heeswijk, 1996). An additional component of ground-water flow in the study area was flow from higher heads in the updip recharge areas downward into the deep flow system. In the downdip area, ground water moves vertically up through the aquifers and confining units as it approaches the freshwater-saltwater interface and discharges to the Atlantic Ocean or to the surficial aquifer (Campbell and van Heeswijk, 1996). Water leaves the surficial aquifer through evapotranspiration or by discharge to surface-water bodies (Campbell and van Heeswijk, 1996). The location of the freshwater-saltwater interface is not known, but estimates of the location are based on offshore salinity information from previous investigations (Lee and others, 1986; Smith, 1988).

Recharge to the Coastal Plain aquifers within the study area occurs predominantly in the aquifer outcrop areas in the upper Coastal Plain (Aucott, 1996). The highest water-level altitudes occur near the updip limits of the Floridan-Tertiary sand, Black Creek, and Middendorf aquifers (fig. 6).

Rivers affect ground-water flow by draining water from or adding water to aquifers that are in contact with the riverbeds. The rates at which water flows into or out of a river are dependent on the hydraulic gradient and the type of sediments in the riverbed. Riverbeds that are composed of sands are better connected to the adjacent aquifers than beds that are composed of finer material, such as silt.

Water Use

Ground-water use in the study area has increased steadily over the past century due to industrial development and increase in population (fig. 7). In 2005, Allendale, Bamberg, Barnwell, Chesterfield, Clarendon, Hampton, Lee, Orangeburg, Sumter, and Williamsburg Counties used ground water as their primary source of water supply for industrial, irrigation, and potable uses (South Carolina Department of Health and Environmental Control, 2006). Annual ground-water use for Aiken, Allendale, Beaufort, Charleston, Darlington, Florence, Hampton, Orangeburg, and Sumter Counties is greater than 2 billion gallons of ground water per county (South Carolina Department of Health and Environmental Control, 2006).

Water-use data used in this investigation included data reported for wells by State regulatory agencies (J. Childress, South Carolina Department of Health and Environmental Control, written commun., March 2005; J. Lautier, North Carolina Department of Environment and Natural Resources, written commun., March 2005), and previous investigations (Aucott, 1996; Campbell and van Heeswijk, 1996; G. Cherry, U.S. Geological Survey, written commun., March 2005; and D. Payne, U.S. Geological Survey, written commun., March 2005). As of 2001, water use exceeding 3 Mgal/mo was required to be reported to SCDHEC (South Carolina Department of Health and Environmental Control, 2006). Prior to 2001, water-use data were compiled in a South Carolina Department of Natural Resources (SCDNR) water-use database; however, reporting water-use data was not required by law and therefore was probably incomplete. Water-use data from the SCDNR database was incorporated into the water-use database currently used by the SCDHEC (J. Childress, South Carolina Department of Health and Environmental Control, oral commun., March 2005). Aucott (1996) reconstructed water-use data from predevelopment to 1982 based on population statistics and well construction dates. Campbell and van Heeswijk (1996) used data from the SCDNR water-use database and supplemental data gathered through field reconnaissance.

Water use in the study area is predominantly concentrated in the Floridan-Tertiary sand, Black Creek, and Middendorf aquifers. The distribution of wells tapping each aquifer is illustrated on figure 8. Water use in Charleston, Berkeley, and Dorchester Counties is primarily from the Floridan-Tertiary sand and Middendorf aquifers.

Mount Pleasant has utilized the Middendorf aquifer as the primary source of drinking water since 1968. In 2006, MPW operated six wells throughout its service district (fig. 9). Water use from the Middendorf has increased from 2.4 Mgal/d in 1984 to 7.5 Mgal/d in 2004 in the Mount Pleasant service district (J. Childress, South Carolina Department of Health and Environmental Control, written commun., March 2005). Other important Middendorf aquifer water uses in the Charleston, Berkeley, and Dorchester area are for drinking water and golf course irrigation on Kiawah Island, Isle of Palms, and

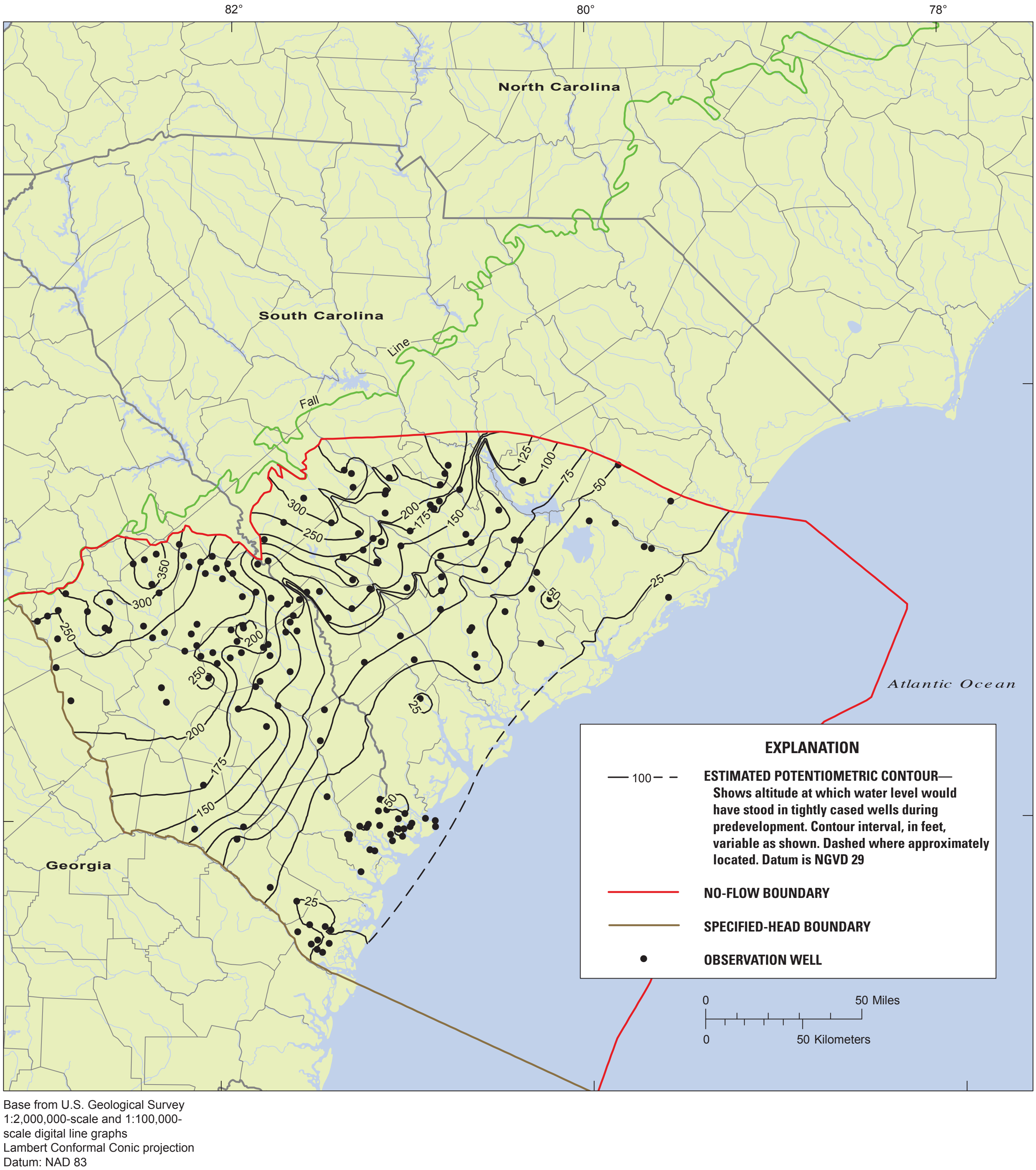
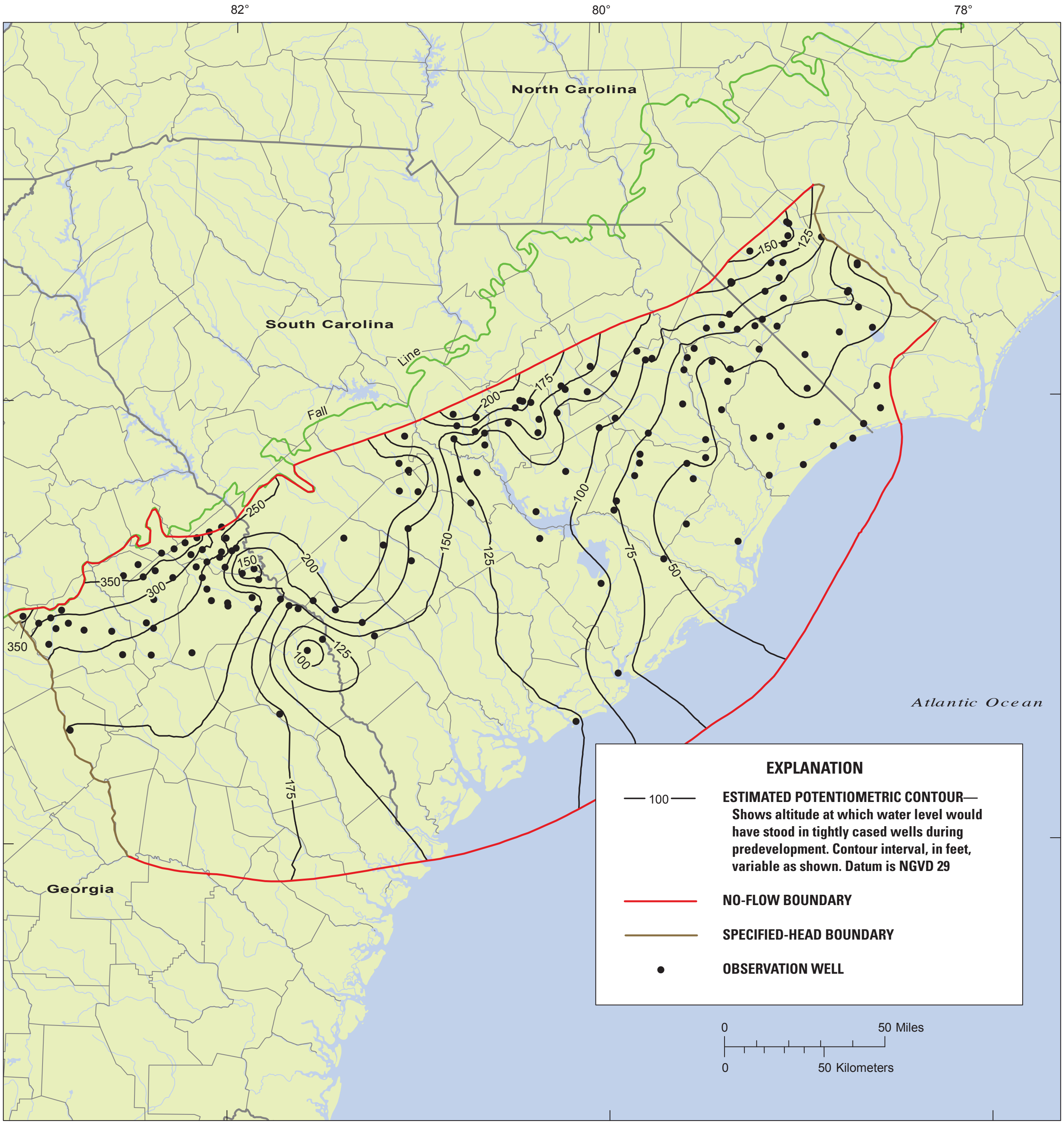


Figure 6*A*. Estimated predevelopment potentiometric surface of the Floridan aquifer system and Tertiary sand aquifer.



Base from U.S. Geological Survey
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Figure 6*B*. Estimated predevelopment potentiometric surface of the Black Creek aquifer.

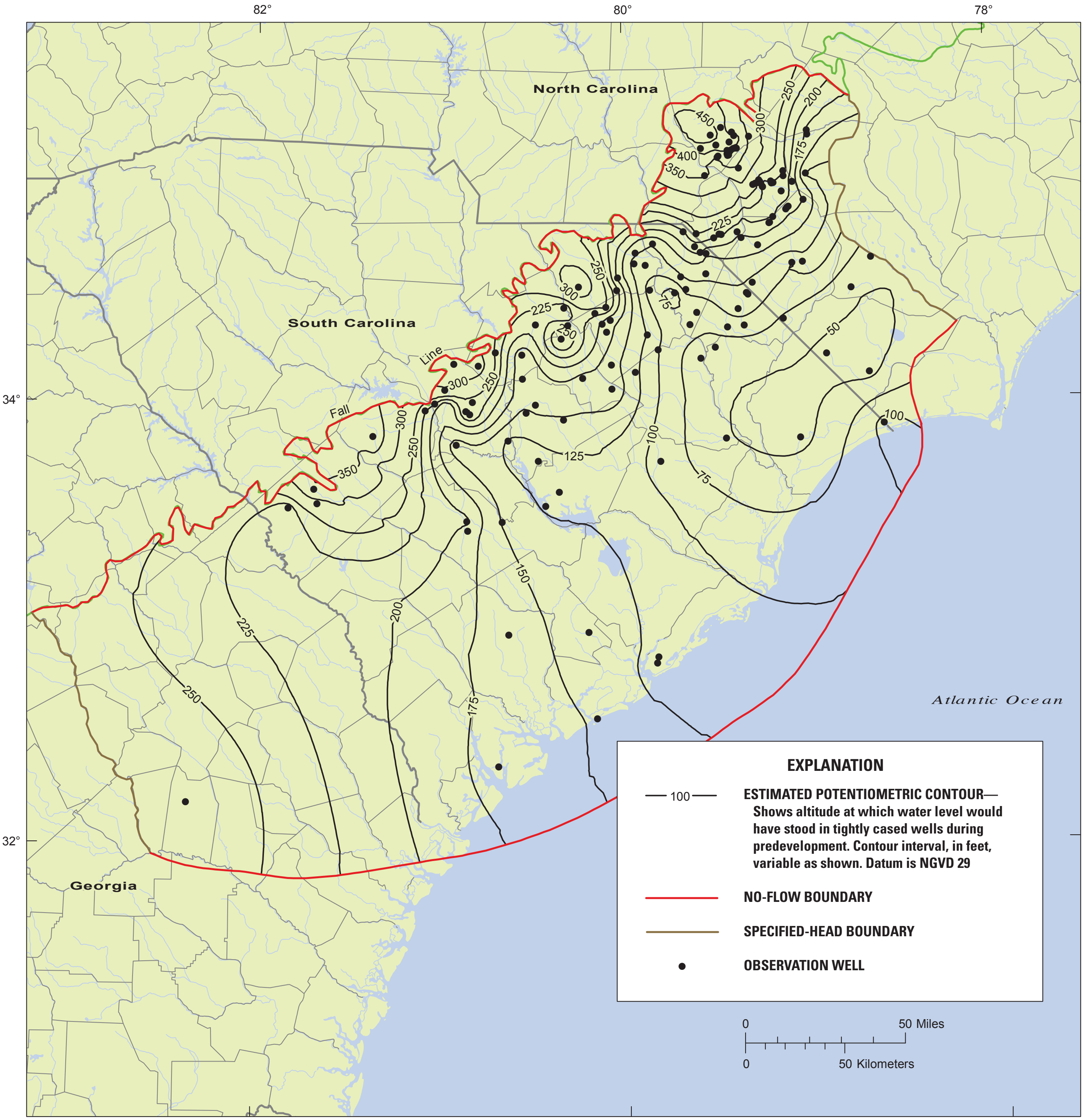

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Figure 6*C*. Estimated predevelopment potentiometric surface of the Middendorf aquifer.

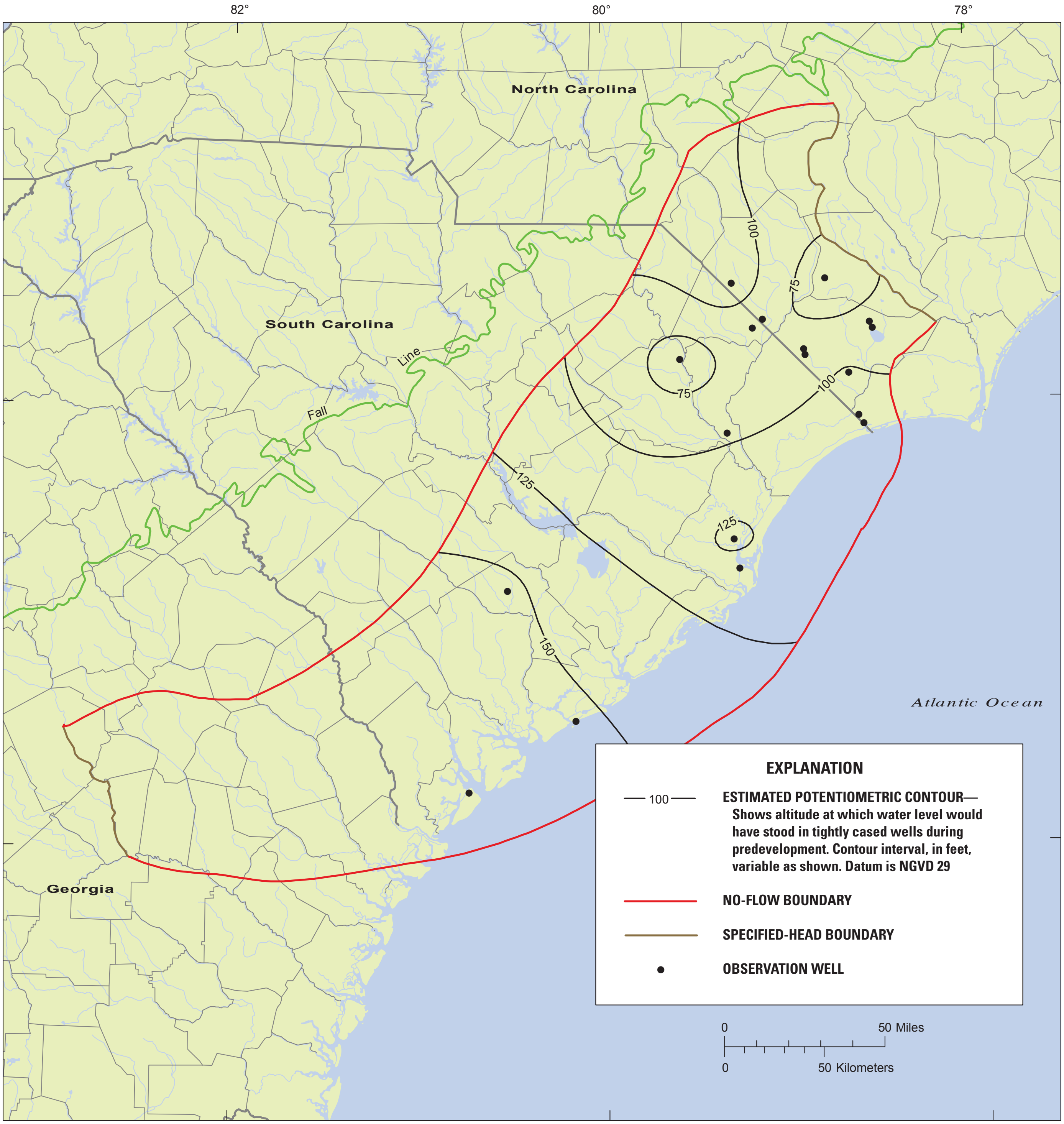

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Figure 6*D*. Estimated predevelopment potentiometric surface of the Cape Fear aquifer.

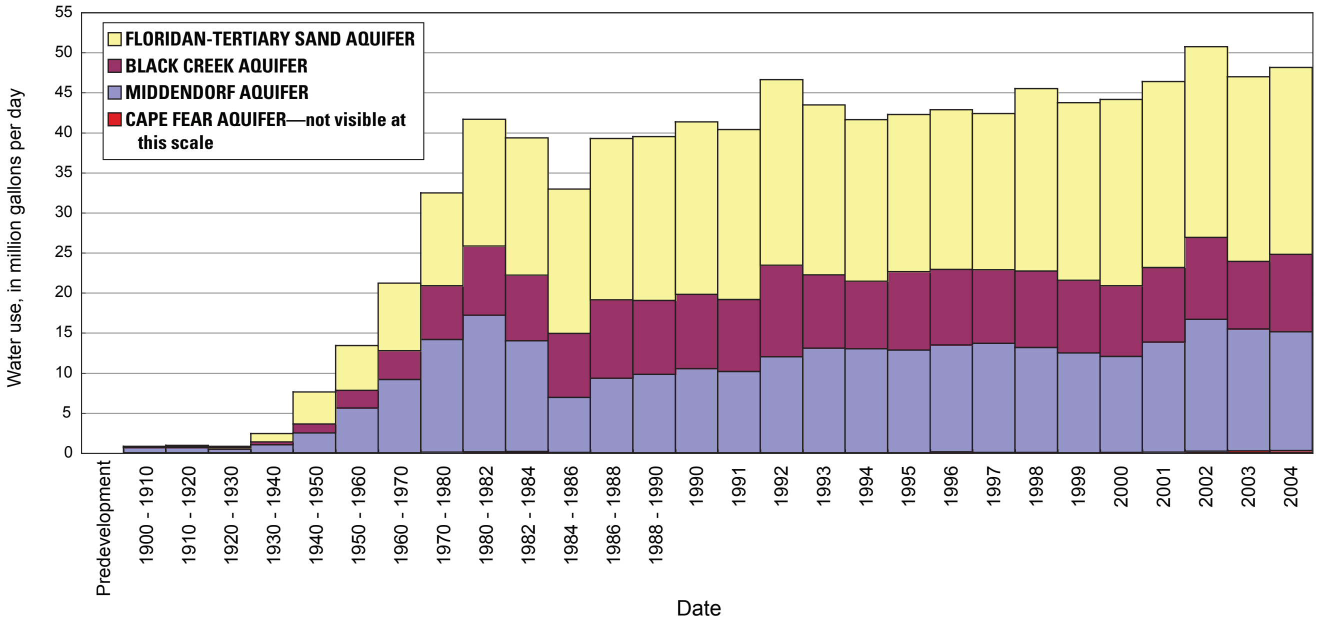


Figure 7. Estimated ground-water use in the Tertiary and Cretaceous aquifers, predevelopment (1900) to 2004.

Seabrook Island in Charleston County, and for industrial use in Berkeley County. Significant ground-water use by the city of Summerville was discontinued in 1994, when the city converted to a surface-water supply.

Mount Pleasant Ground-Water Conditions

The effect of ground-water use in the Mount Pleasant, SC, area is readily apparent in hydrographs of observation wells CHN-14 and BRK-431 screened in the Middendorf aquifer (fig. 10). At CHN-14, located in Charleston, SC (fig. 9), the water-level altitude has declined more than 90 ft during the period of record (1990–2004). The water-level altitude recovered some between late 2004 and early 2006 because of reduced water use during that period. At BRK-431, located near Moncks Corner, SC (fig. 9), water-level altitudes have declined more than 60 ft during the period of record (1989–2006). There are no reported Middendorf aquifer water users in the immediate vicinity of this well; therefore, the steady water-level decline at this location indicates that water is being removed from storage due to large withdrawals in the Charleston and Berkeley County area (Campbell and van Heeswijk, 1996).

Simulation of Ground-Water Flow

The ground-water flow system of the South Carolina Coastal Plain was simulated using the USGS finite-difference code MODFLOW-2000 (Harbaugh and others, 2000). The code allows simulation of single-density flow in three dimensions. The conceptual model for this investigation was similar to the previously documented model (Campbell and van Heeswijk, 1996) and to the SCRASA model (Aucott, 1988, 1996). For this investigation, the Floridan aquifer system and Tertiary sand aquifer were simulated actively as they were for the SCRASA model. Campbell and van Heeswijk (1996) assigned the combined Floridan aquifer system and Tertiary sand aquifer, in conjunction with the surficial aquifer, as a source-sink layer. As in the previous models, all layers in this model were simulated as confined. Unconfined conditions were not simulated in this model because the focus of this investigation was the deep flow system of the Coastal Plain. The large cell sizes required to simulate the entire model area precluded simulation of the shallow flow system. Omission of the unconfined portion of the study area is justified because water-level changes in the unconfined parts of the aquifers are small compared to the total saturated thicknesses of the aquifers (Campbell and van Heeswijk, 1996).

Spatial Discretization

Ground-water flow in the study area was simulated by creating a discretization network of model cells that extend from the area of interest out to hydrologic boundaries (fig. 11). The model encompasses 49,800 mi^2 and is discretized using 204 rows and 238 columns with a maximum of 26,609 active cells per model layer. Cell dimensions vary from a minimum area of 1,000 by 1,000 ft (0.04 mi^2) in Mount Pleasant to a maximum area of 10,000 by 10,000 ft (3.6 mi^2) at the model boundaries. Discretization in this manner enhances the ability to simulate the steep hydraulic gradients of the cones of depression in the area of interest while minimizing the total number of model cells required to simulate outward to natural hydrologic boundaries.

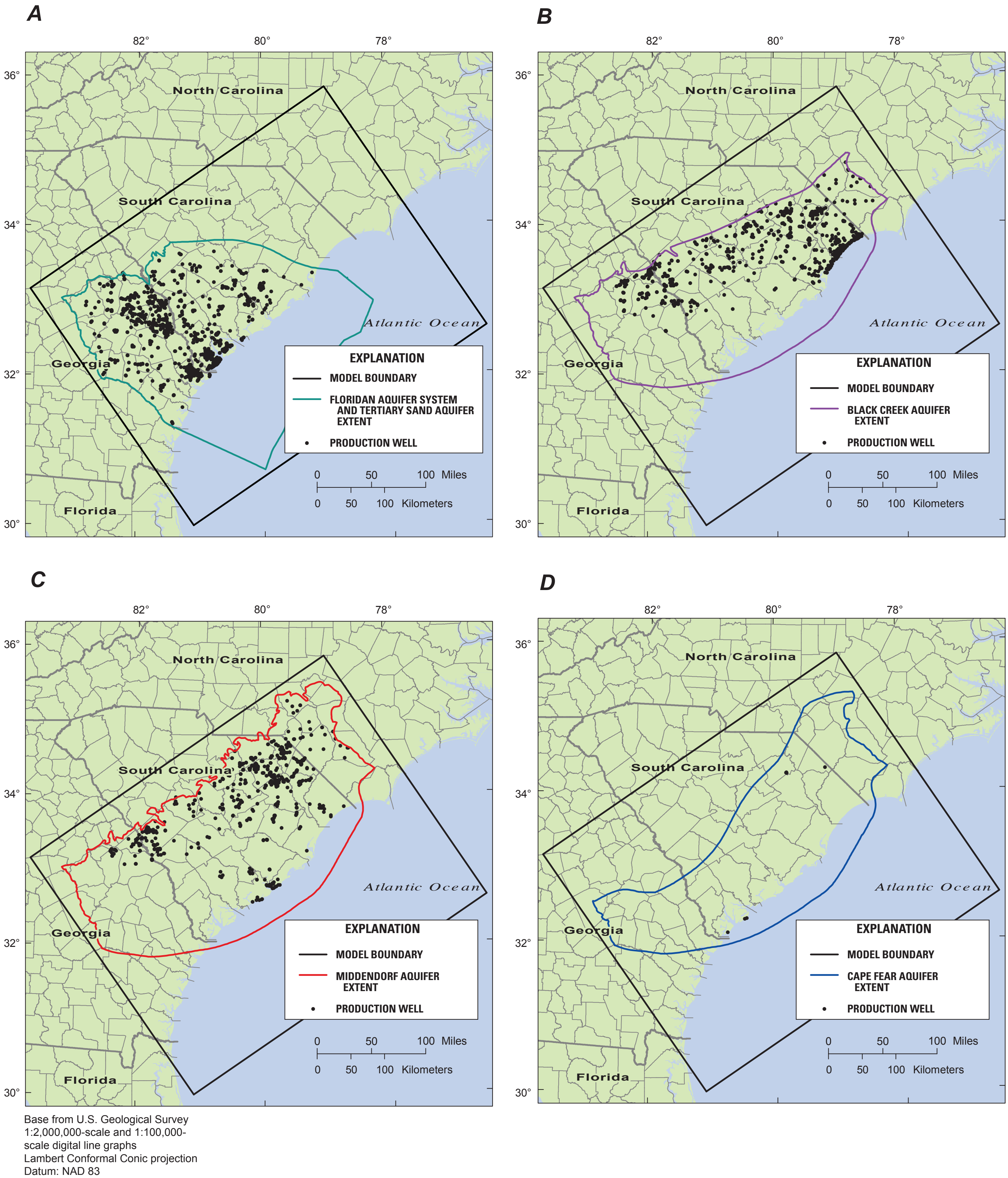


Figure 8. Distribution of production wells by model layer: (*A*) layer 3, Floridan aquifer system and Tertiary sand aquifer; (*B*) layer 5, Black Creek aquifer; (*C*) layer 7, Middendorf aquifer; and (*D*) layer 9, Cape Fear aquifer.

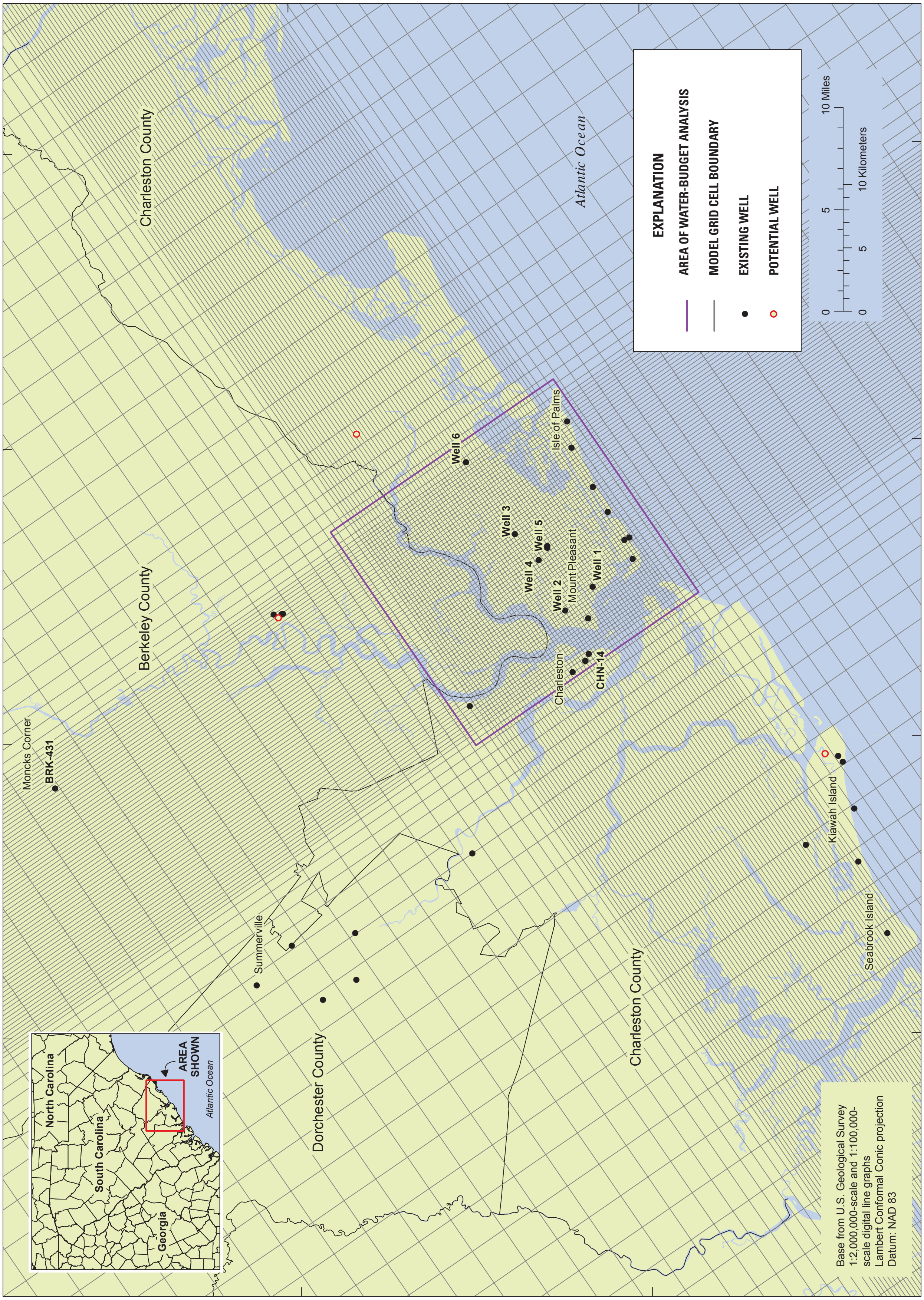


Figure 9. Existing and potential Middendorf aquifer wells, model grid, and area of water-budget analysis in the Mount Pleasant, South Carolina, area.

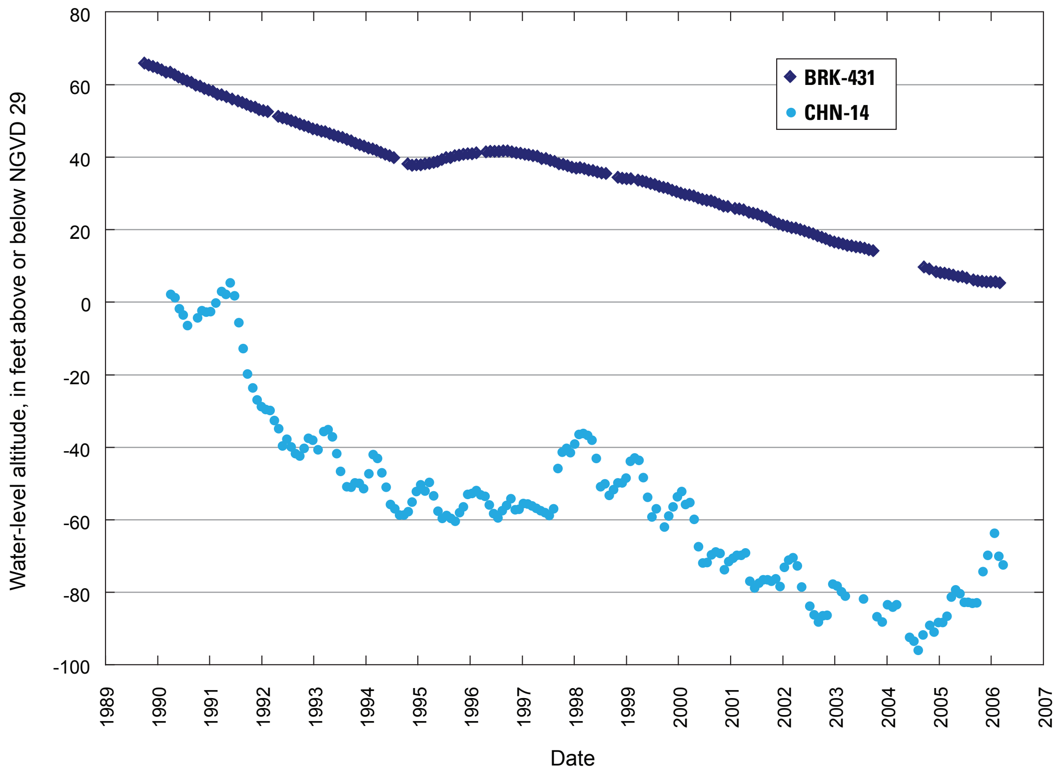


Figure 10. Hydrographs of BRK-431, observation well near Moncks Corner, South Carolina, and CHN-14, observation well in Charleston, South Carolina.

Model Layering

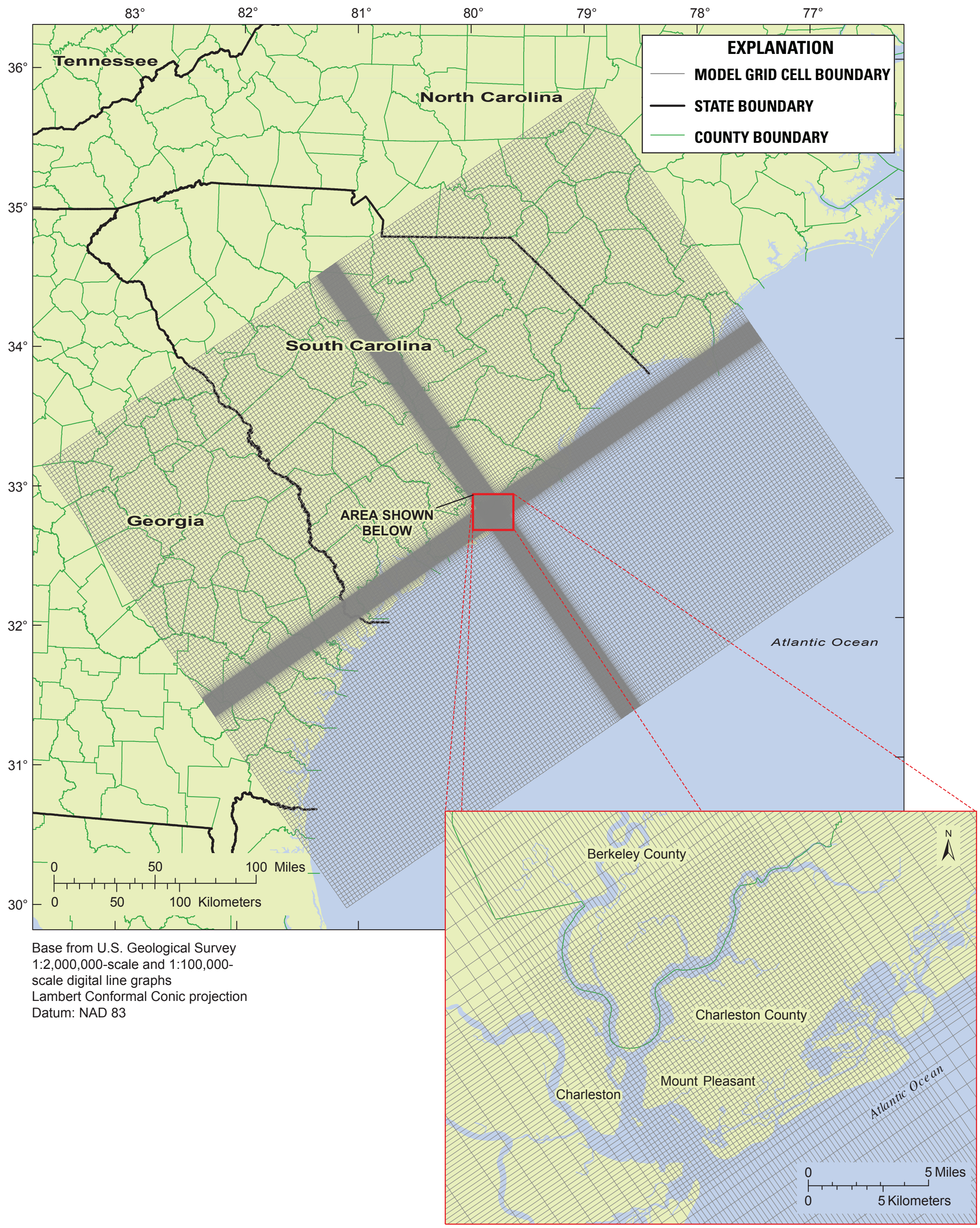
The model was vertically discretized into five aquifers separated by four confining units for a total of nine active model layers (fig. 12). The aquifers include the surficial aquifer (layer 1), a composite Floridan aquifer system and Tertiary sand aquifer (layer 3), the Black Creek aquifer (layer 5), the Middendorf aquifer (layer 7), and the Cape Fear aquifer (layer 9). The aquifers are vertically separated from one another by confining units (layers 2, 4, 6, and 8). Low-permeability pre-Cretaceous rocks below these aquifers and confining units are assumed to have no hydraulic connection to the overlying units and, therefore, are not actively simulated.

The top of layer 1 was created using 30-meter (m) National Elevation Dataset (NED; U.S. Geological Survey, 1999) cells located within the model area (fig. 13). For each model cell, the top of layer 1 was calculated by averaging the land-surface altitude for all NED grid cells that fell within that model cell.

The altitudes of the tops of each model layer were based on lithologic data from 67 boreholes described in Aucott and others (1987) and supplemented with an additional 29 boreholes (Clarke and West, 1998; Falls and others, 2005; J. Gellici, South Carolina Department of Natural Resources, written commun., March 2005) to fill in data gaps (figs. 13 and 14). To establish a common vertical datum at all boreholes and wells used in the model, land-surface altitudes were estimated from 30-m NED cells. The altitudes of layer tops were interpolated from these boreholes and extrapolated offshore, where data are not available. The altitude of the top of the surficial aquifer was arbitrarily set to 0 ft (NGVD 29) offshore. As required by the MODFLOW-2000 (Harbaugh and others, 2000) code, a nominal thickness of at least 2 ft was maintained for all model layers throughout the model extent. In areas where aquifers or confining units are, in reality, absent, hydraulic properties for that nominal thickness were assigned values equal to the hydrologic units that are, in fact, present. For example, at borehole W48-r1, located in the northeastern part of the model (fig. 14), the Middendorf confining unit is the uppermost lithologic unit described by Aucott and others (1987). To maintain a nominal thickness of all layers in this area of the model, layers 1–5 were modeled with a thickness of at least 2 ft each.

Boundary Conditions

Simulation of ground-water flow requires that the model aquifer boundaries either conceptually represent natural flow boundaries or are located at a distance far enough from the area of interest so that the choice of boundary conditions does not influence the model results in the area of interest. Boundary conditions used in this model are generally similar to the ones used in Campbell and van Heeswijk (1996) and depicted



Base from U.S. Geological Survey
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Figure 11. Model grid.

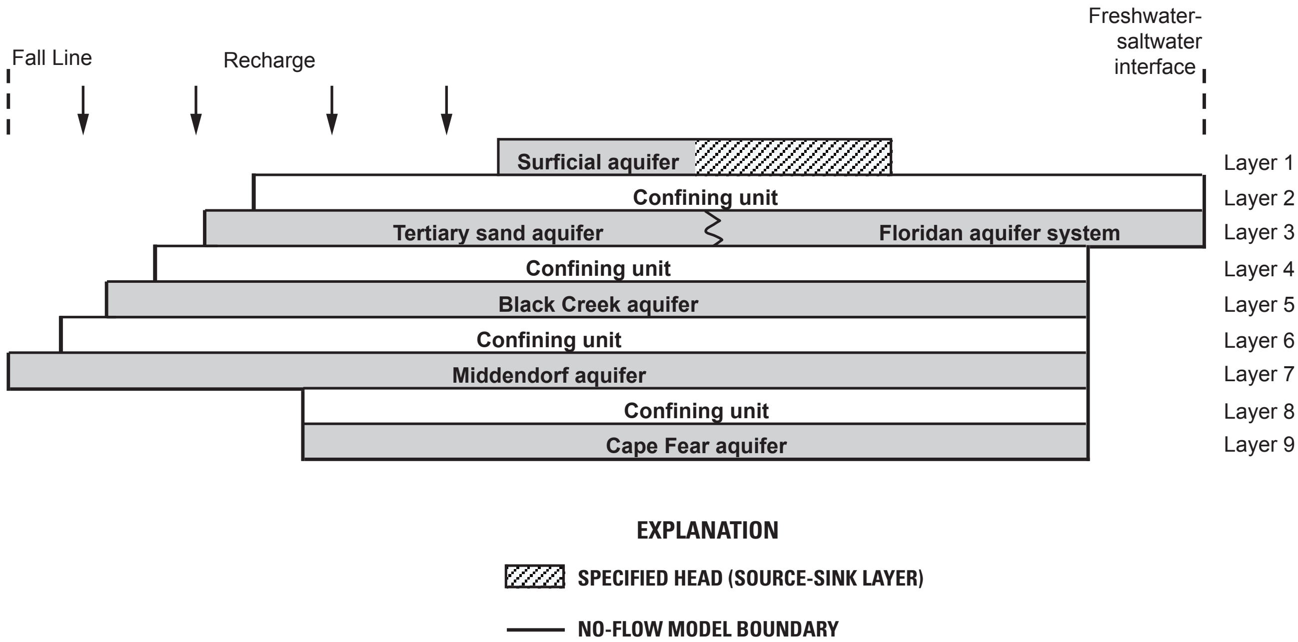


Figure 12. Conceptual model of the South Carolina Coastal Plain and model layers.

in figures 6 and 12. Spatial data do not exist for the heads in the confining units of the modeled area. Therefore, all confining units were simulated with the same boundary conditions as the aquifers beneath them. Deviations from the boundary conditions used by Campbell and van Heeswijk (1996) are discussed below.

Vertical Boundaries

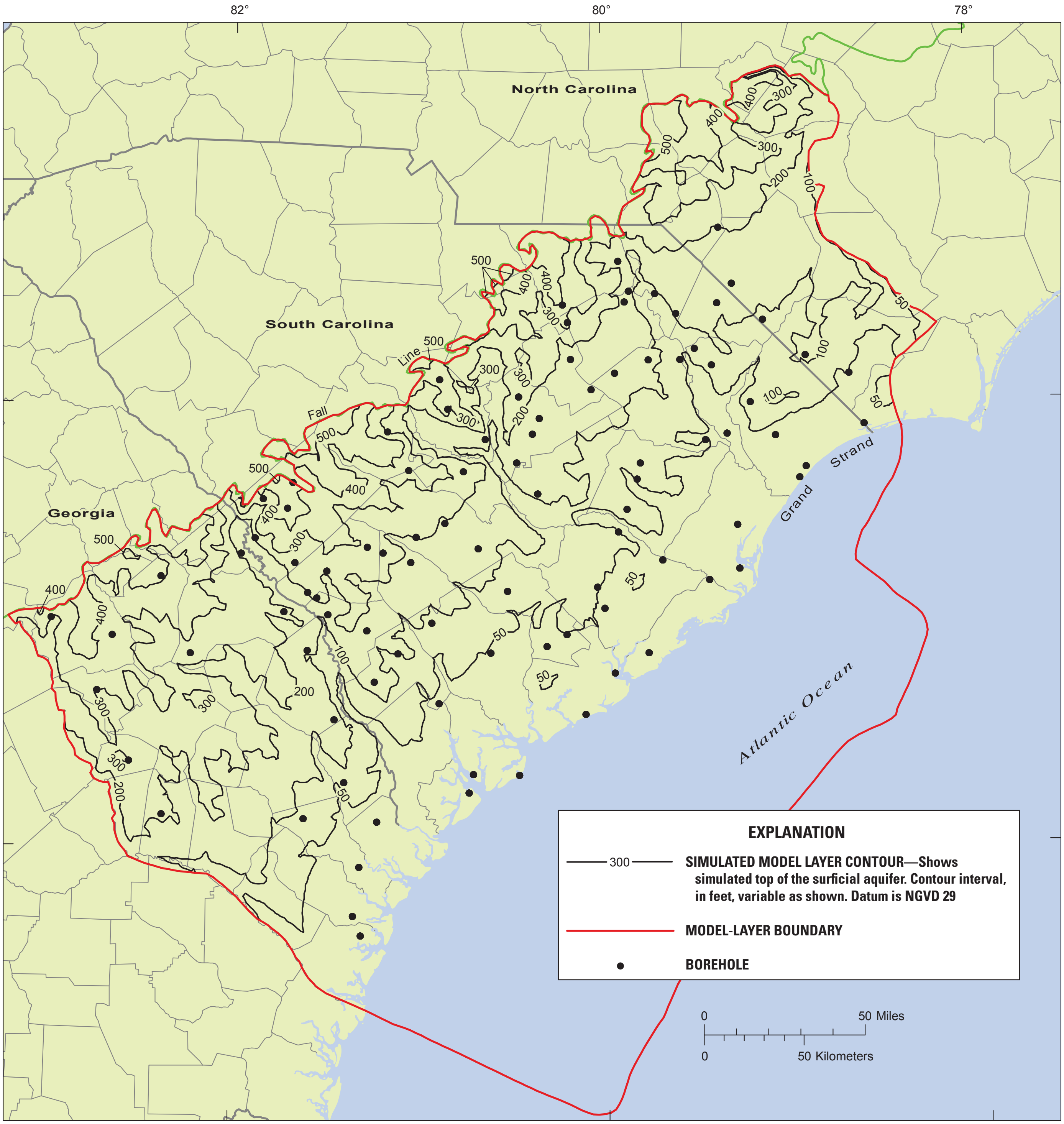
Boundary conditions for the uppermost layer of the model are set as specified-head boundaries. Due to the unavailability of extensive water-level altitude data for the surficial aquifer, the specified head for each of the cells in the uppermost layer was set equal to the top of the unit. Using the land-surface altitude as a specified-head boundary condition is reasonable considering the lack of spatial water-level data for the surficial aquifer and the method of interpolating the land-surface altitude for each cell using the NED. The number of NED cells used to approximate land-surface altitude generally varied between about 98 to 9,860 for model cell sizes that ranged from 1,000 by 1,000 ft to 10,000 by 10,000 ft, respectively. The effect of this boundary condition on the model calibration will be discussed in the section “Sensitivity Testing and Analysis.”

As in previous models of this area (Aucott, 1988, 1996; Campbell and van Heeswijk, 1996), the top of the pre-Cretaceous-age rocks is simulated as the base of the model using a no-flow boundary. This boundary condition is justified, given the fact that ground-water flow within the pre-Cretaceous rocks and between them and the overlying aquifers is much less than that occurring within the Coastal Plain aquifers (Aucott, 1996).

Lateral Boundaries

Lateral boundary locations and types for each of the model layers are depicted in figures 5 and 6. The updip extents of all aquifers are simulated as no-flow boundaries. Specified-head boundary conditions were used to simulate the lateral boundary conditions in Georgia (onshore and offshore) for layers 2–9 and in North Carolina for layers 4–9. Lateral boundary locations in this model varied from the locations used by Campbell and van Heeswijk (1996) in that the western model boundary was moved from the Savannah River to an area near the Oconee and Altamaha Rivers in Georgia; the eastern model boundary was moved from approximately 20 mi northeast of the South Carolina–North Carolina border to an area near the Cape Fear River (fig. 5). The model boundary location for the Floridan aquifer system and Tertiary sand aquifer was approximately equal to that used in Aucott (1996) for the updip and eastern boundaries (fig. 6). The updip and eastern boundary for the Floridan aquifer system and Tertiary sand aquifer was simulated using a no-flow boundary condition. The western model boundary location for the Floridan aquifer system and Tertiary sand aquifer was set at the Oconee and Altamaha Rivers in Georgia and simulated as a specified-head boundary out to the offshore downdip boundary.

Transient heads were used to simulate the specified-head boundary conditions at the lateral boundaries of the model. Potentiometric-surface maps of the Floridan aquifer system and Tertiary sand aquifer, Black Creek aquifer, Middendorf aquifer, and the Cape Fear aquifer show that the heads at these boundaries have changed over time. Transient heads along the western model boundary were derived from published potentiometric-surface maps representing predevelopment



Base from U.S. Geological Survey
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Figure 13*A*. Top of simulated model layer for the surficial aquifer.

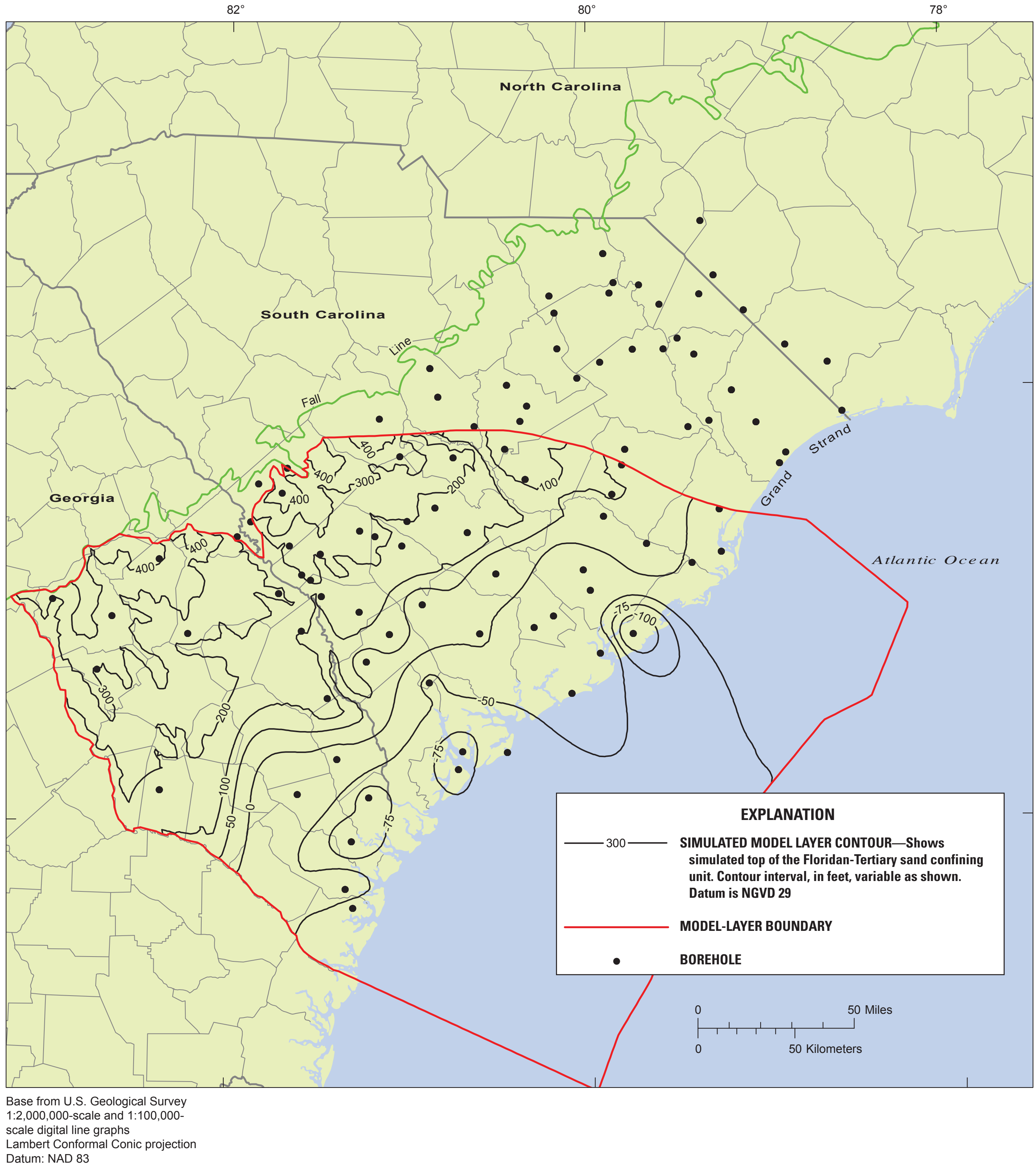

Figure 13*B*. Top of simulated model layer for the Floridan-Tertiary sand confining unit.

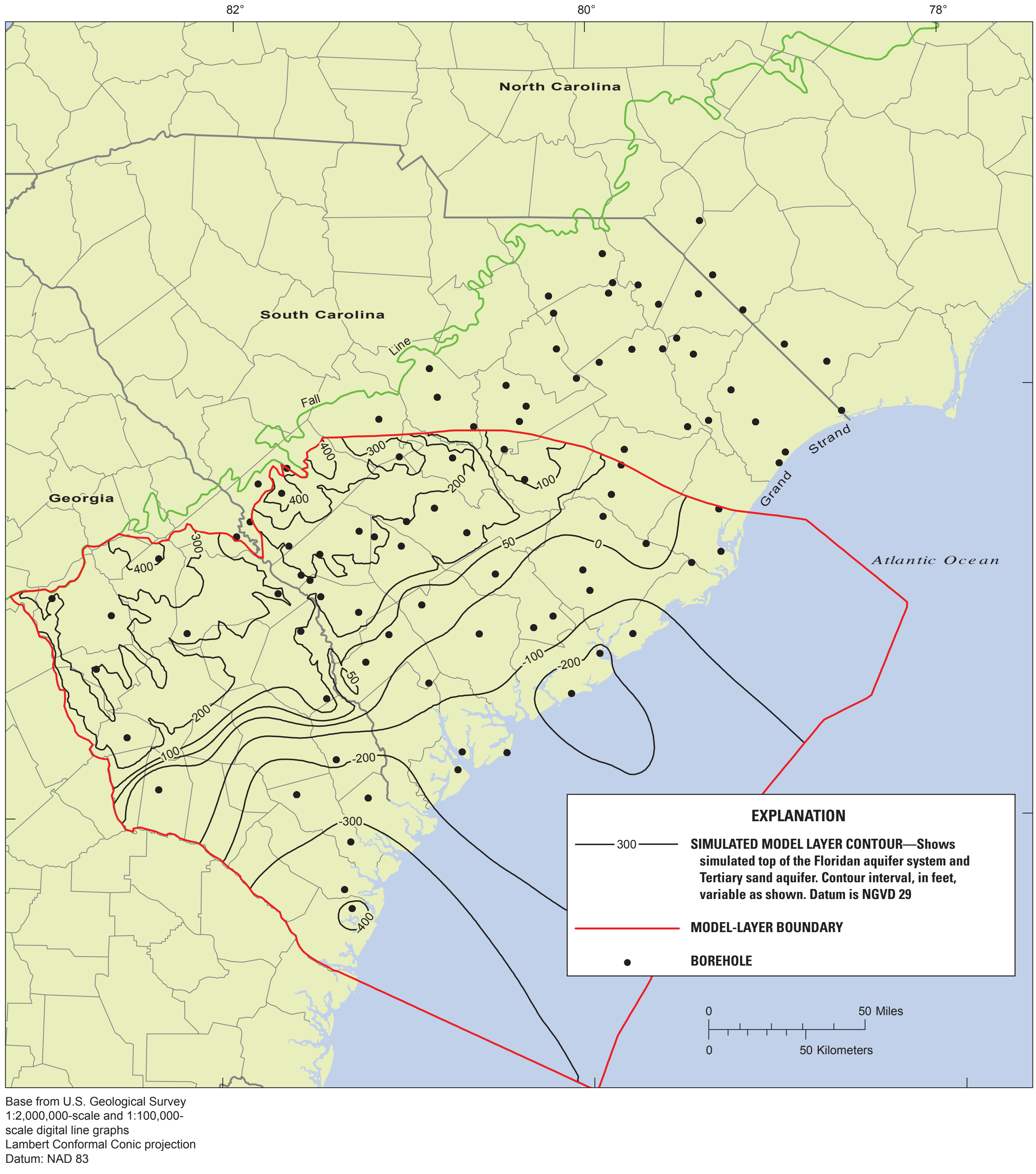

Figure 13*C*. Top of simulated model layer for the Floridan aquifer system and Tertiary sand aquifer.

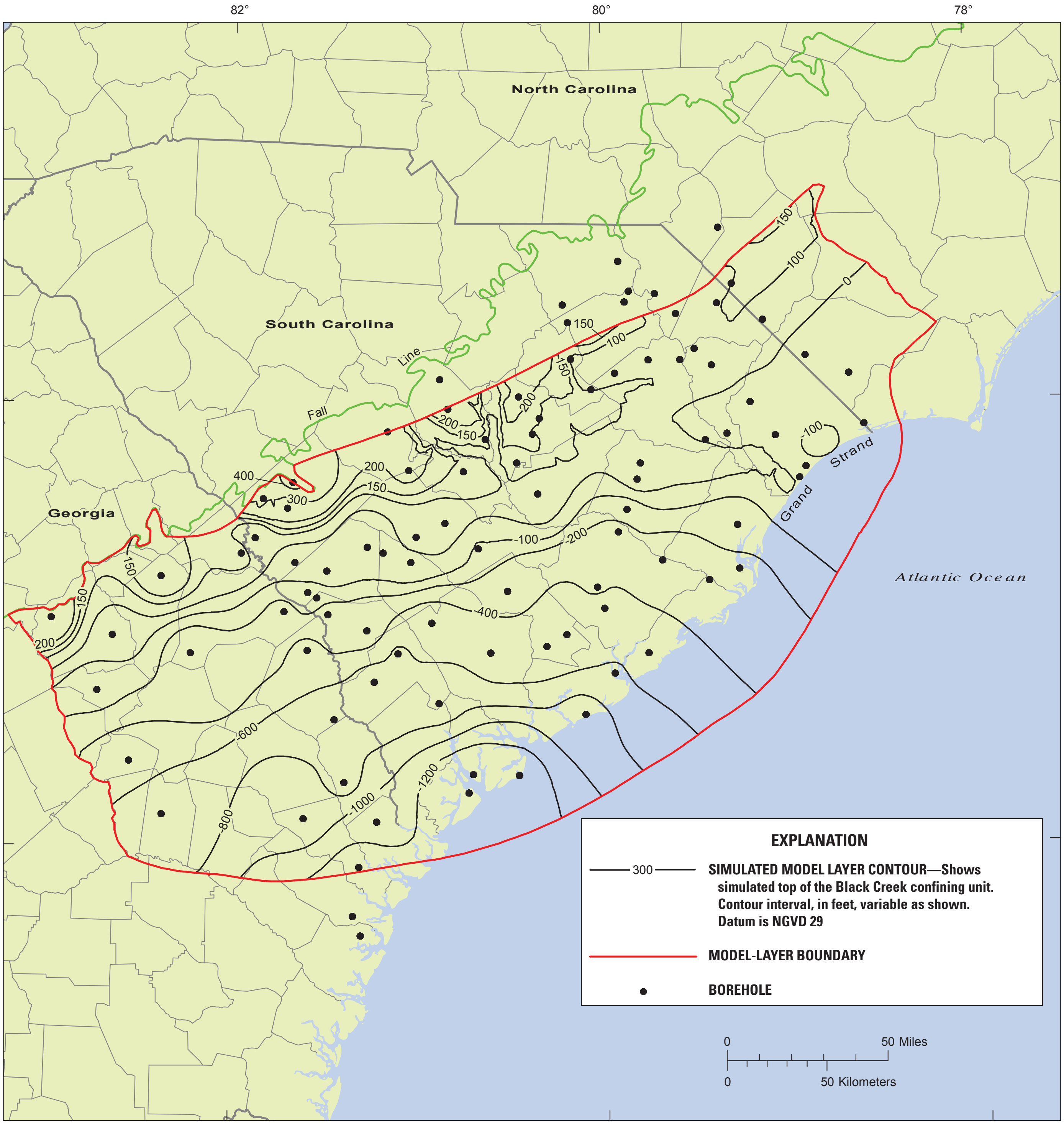

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Figure 13*D*. Top of simulated model layer for the Black Creek confining unit.

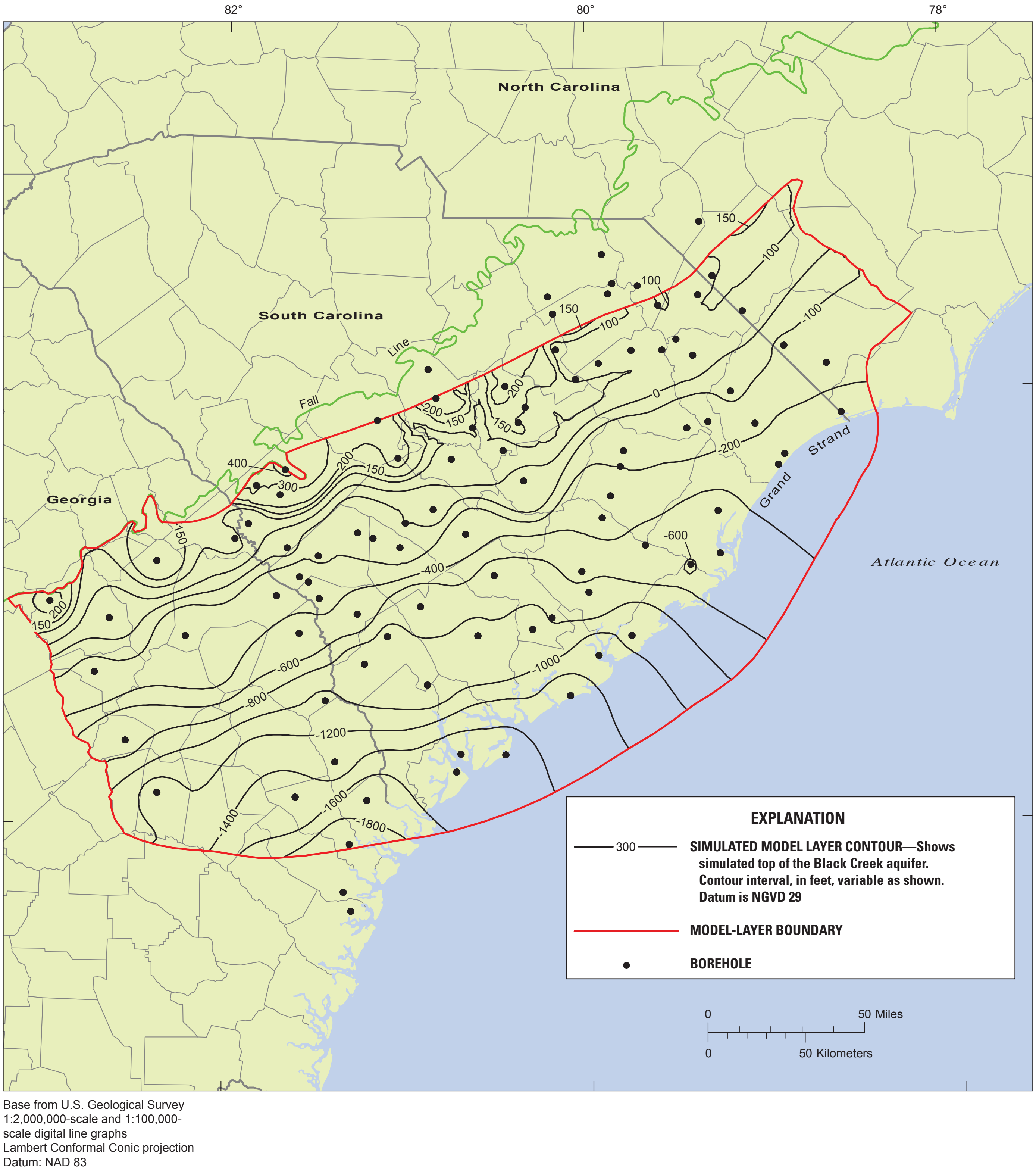
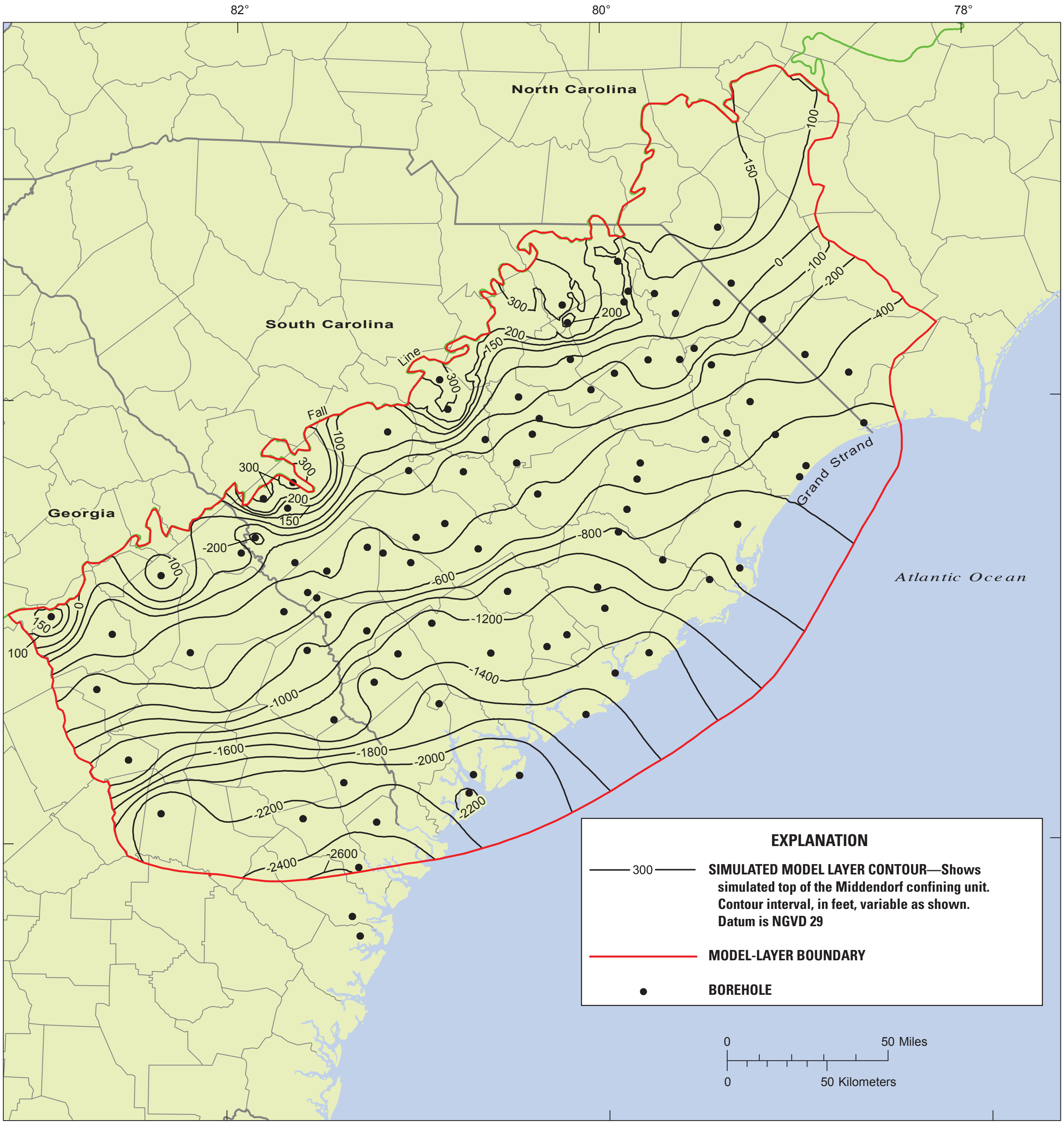


Figure 13*E*. Top of simulated model layer for the Black Creek aquifer.



Base from U.S. Geological Survey
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Figure 13*F*. Top of simulated model layer for the Middendorf confining unit.

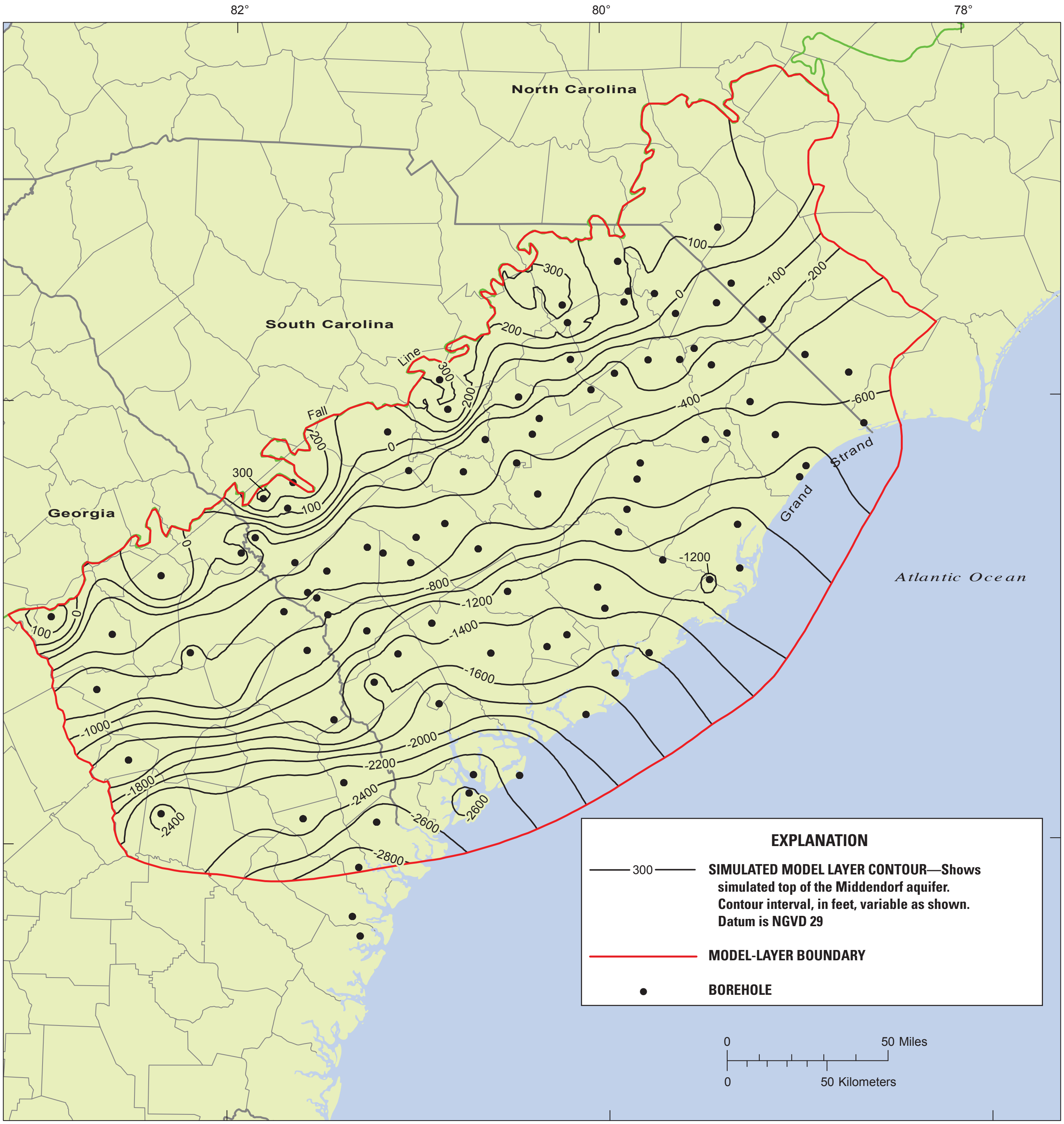

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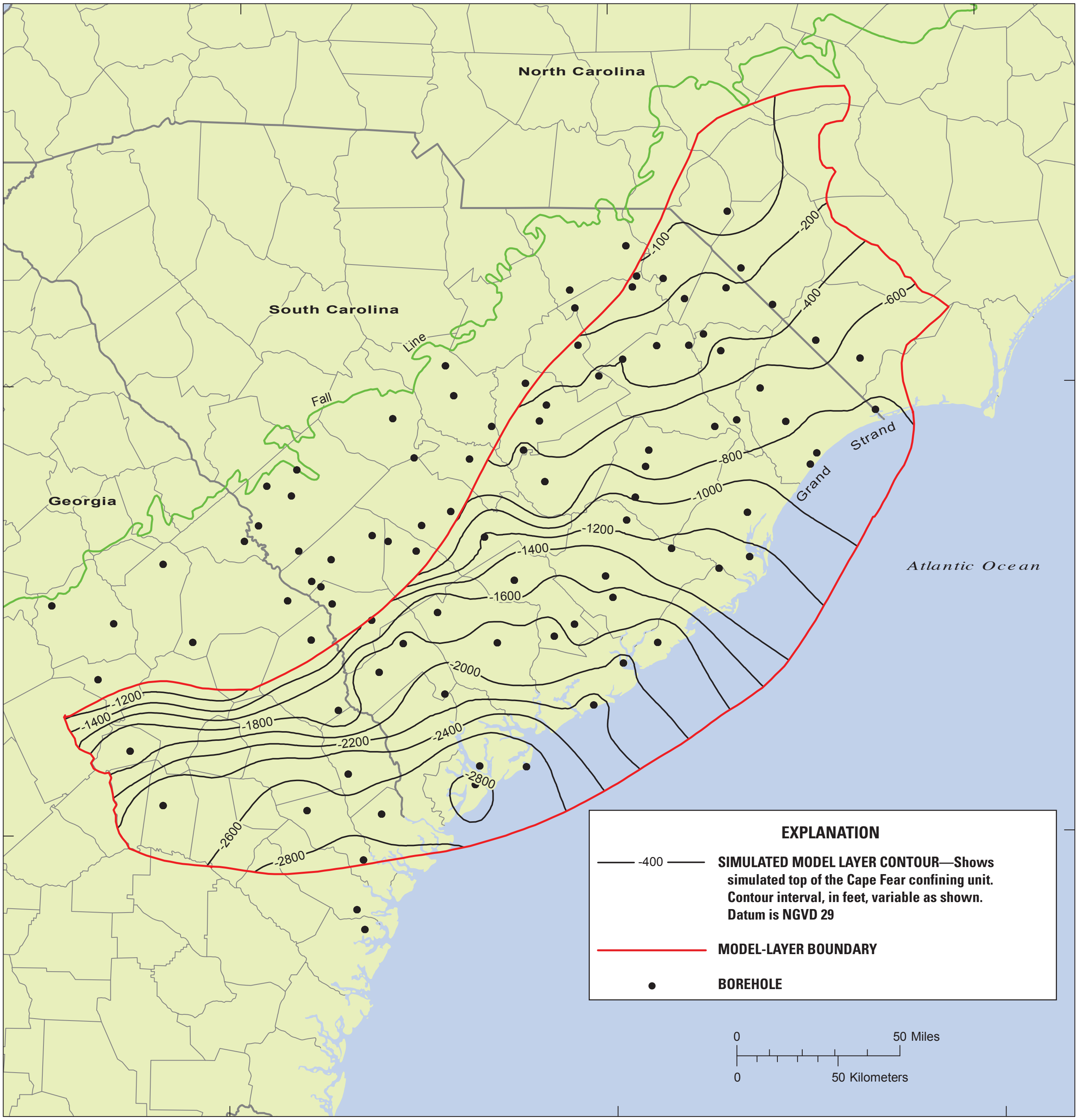
Figure 13*G*. Top of simulated model layer for the Middendorf aquifer.



Base from U.S. Geological Survey
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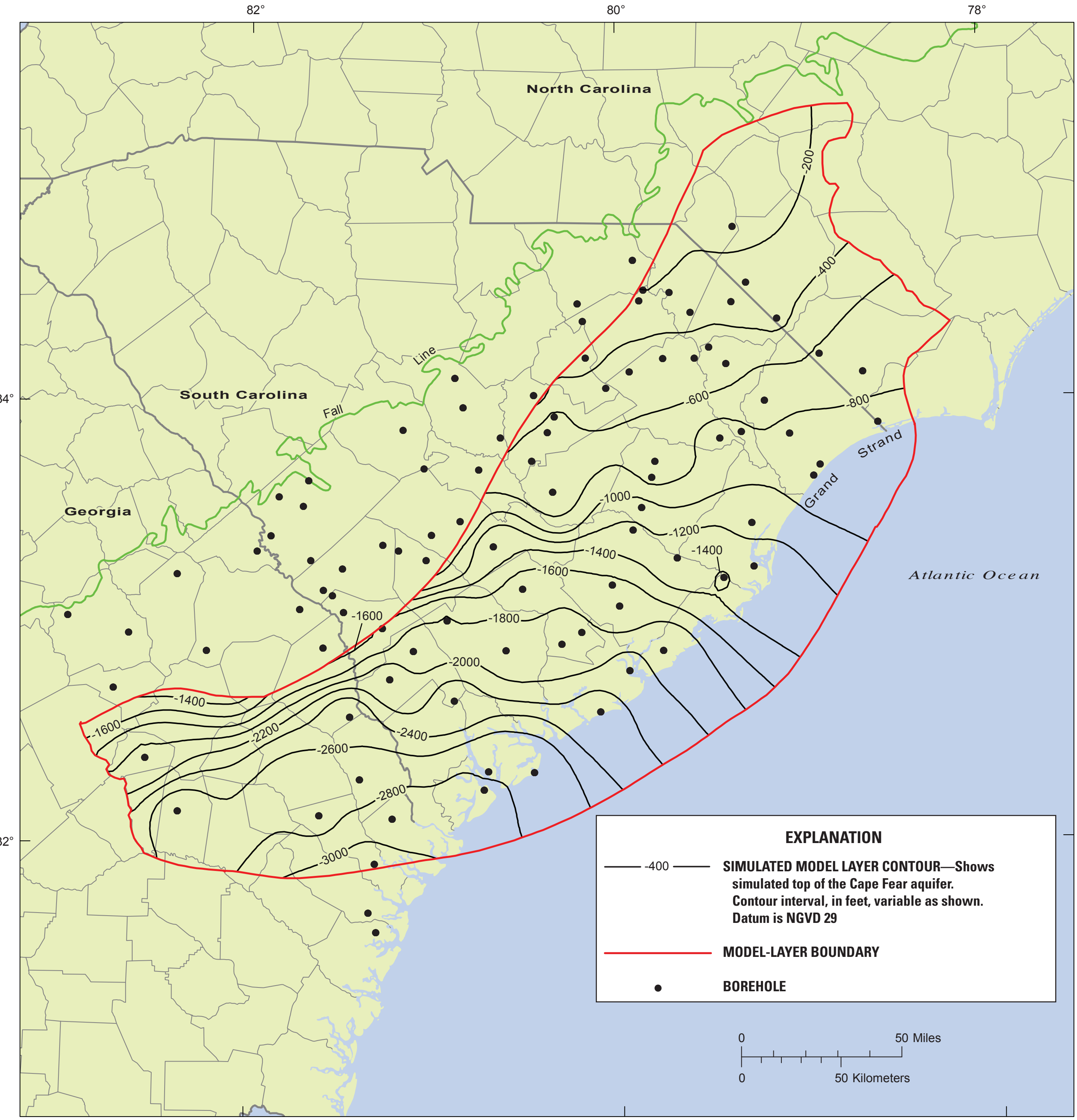
Figure 13*H*. Top of simulated model layer for the Cape Fear confining unit.



Base from U.S. Geological Survey
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Figure 13*I*. Top of simulated model layer for the Cape Fear aquifer.

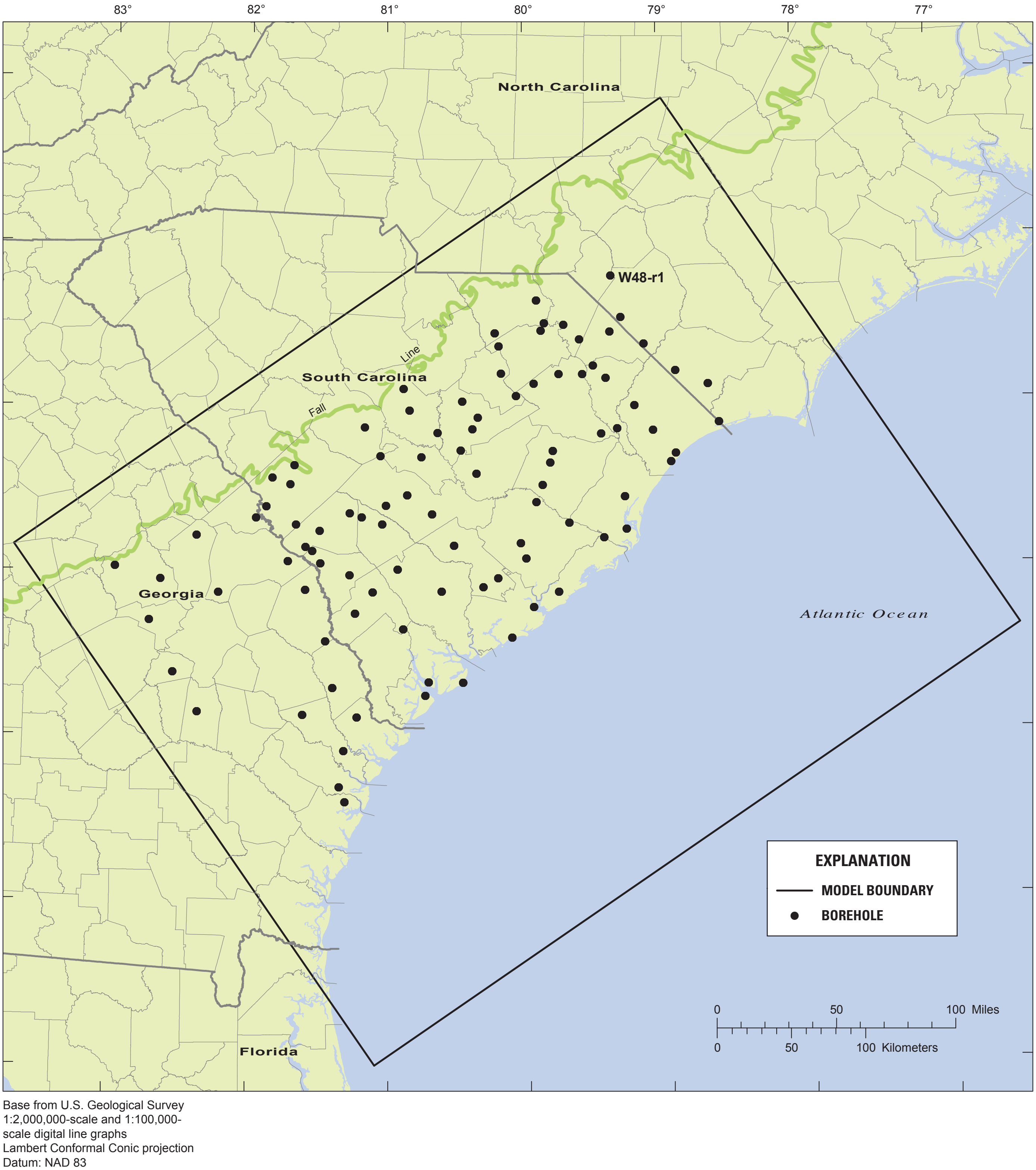


Figure 14. Borehole locations used to develop model layering.

and 1980 (Faye and Mayer, 1996; Payne and others, 2005) and approximated in 2004. Transient heads along the eastern model boundary were derived from potentiometric-surface maps representing predevelopment and 1980 (Giese and others, 1997) and from published 2005 potentiometric-surface maps (Lautier, 2006) as an approximation of 2004 conditions. Again, because spatial head data for the confining units do not exist, the transient specified-head boundary conditions for all confining units were simulated with the same boundary conditions as the aquifers beneath them.

Offshore Boundaries

The offshore boundaries in this model are similar to previously modeled boundaries for the model study area (figs. 5 and 6) (Aucott, 1996; Campbell and van Heeswijk, 1996; Payne and others, 2005). In particular, the boundary location for layers 4–9 was set equal to the freshwater-saltwater interface described by Lee and others (1986) and used for the Black Creek, Middendorf, and Cape Fear aquifers in Aucott (1996) and Campbell and van Heeswijk (1996). A no-flow boundary condition was used to simulate this boundary for these layers. Aucott (1996) used general-head boundaries for the Black Creek and Middendorf aquifers near Myrtle Beach, SC. The location of the offshore boundary for the Floridan aquifer system and Tertiary sand aquifer (layer 3) and the surficial aquifer (layer 1) was set to be similar to that modeled in Payne and others (2005) for the area located off the Georgia coast and extended up to the northeastern lateral boundary used by Aucott (1996). Payne and others (2005) found that a no-flow boundary condition modeled at a location approximately equal to the continental shelf margin (Florida-Hatteras slope) was a reasonable boundary condition for the Floridan aquifer system. Aucott (1996) used a no-flow boundary condition to simulate the offshore boundary of the Floridan aquifer system and Tertiary sand aquifer. The offshore boundary conditions of the confining units (layers 2, 4, 6, and 8) were equal to those of the simulated aquifers located directly beneath them.

Hydraulic Properties

Hydraulic properties required in the model include vertical and horizontal hydraulic conductivity, specific storage, riverbed conductance, and recharge. While adequate published data for transmissivities and storage coefficients for the model area (for most of the aquifers) exist, no data exist for hydraulic properties of the confining units and limited to no data exist for vertical hydraulic conductivity of the aquifers, riverbed conductance, and recharge.

Horizontal hydraulic conductivity and specific storage values were derived from published transmissivity and storage coefficient data and adjusted during model calibration (Aucott and Newcome, 1986; Newcome, 1993, 2000). Additional data were obtained from previous investigations in the model area (D. Payne, U.S. Geological Survey, written commun., January 2006; M. Peck, U.S. Geological Survey, written commun., December 2005). Horizontal hydraulic conductivities were calculated by dividing the published transmissivity value at a well by either the thickness of the aquifer, if known, the total length of the well screen, or an assumed aquifer thickness if the aquifer thickness was not known. The specific storage was calculated in a similar manner using the reported storage coefficient. Calculated hydraulic property values were not used when the resultant values were not representative of the aquifer being simulated. For example, if the calculated hydraulic conductivity of an aquifer at a given well was in the range more typical of a confining unit than an aquifer, that specific well was not used in the model. Using the total length of well screen for the aquifer thickness should provide an appropriate estimate because it is assumed that the owners of the well would screen the most productive part of the aquifer of interest. Inclusion of only those hydraulic property values in which the aquifer thickness was reported was not deemed necessary because the values were used as initial estimates and would be adjusted during the calibration procedure.

In the general absence of data, horizontal hydraulic conductivity and specific storage of the confining units, vertical hydraulic conductivity of the aquifers and confining units, recharge, and riverbed conductance were calibrated during the modeling process. Vertical hydraulic conductivity was simulated using an anisotropy factor tied to the horizontal hydraulic conductivity values for the individual layers. Initial values for these model inputs were set within the range of reasonable values for the given material (aquifer or confining unit) being simulated.

Water Use

Water use for the model was simulated using data that spanned the period from predevelopment to 2004 (fig. 7). Water-use data in this investigation included data reported for more than 2,700 wells (or well groups when a single water-use volume was reported for multiple wells) by State regulatory agencies (J. Childress, South Carolina Department of Health and Environmental Control, written commun., March 2005; J. Lautier, North Carolina Department of Environment and Natural Resources, written commun., March 2005), and by previous model investigations (Aucott, 1996; Campbell and van Heeswijk, 1996; G. Cherry, U.S. Geological Survey, written commun., March 2005; D. Payne, U.S. Geological Survey, written commun., March 2005). In many instances water-use data did not have an aquifer associated with the reported well. Therefore, all wells were assigned aquifers based on well construction information and the interpolated altitudes of the model layers. If it was determined that a well was screened in more than one aquifer, the total water use from that well was divided equally among the aquifers screened. While division into parts that represented the combined effect of permeability and percentage of total screen within each aquifer would have been a more accurate method of distributing the water use, this information often was not available, so the consistent methodology of equal division among aquifers was used. Approximately 10 percent of the total volume of reported water use for South Carolina was not used in the model because either the aquifer was unknown and determination of the aquifer(s) tapped by the specific water-use wells was not possible, or horizontal coordinates were not reported for the well. Water-use wells included in this investigation are depicted in figure 8.

The compiled water-use data from the State agencies are only for wells that typically pump more than 3 Mgal/mo (South Carolina Department of Health and Environmental Control, 2006). Water-use data for wells that pump less than this amount were not reported to the State agencies. Therefore, this model simulates less ground-water withdrawals than actually occurred during the period of investigation. Overall, however, it is believed that the unreported water use is much less than that reported by the major ground-water users in the study area.

Recharge

Recharge rates for the study area were determined from historic precipitation data and model calibrations. Historical precipitation data from six stations located in the upper Coastal Plain (fig. 15) were used to construct the model inputs (table 2; fig. 16). Recharge is applied to the model area representing the higher altitude land surface of the upper Coastal Plain area of the model (fig. 15). The recharge rate applied to the Mount Pleasant model varies temporally but not spatially from 2.89 to 4.17 in/yr (fig. 16). The variability of these data over time is reflected in the modeled recharge rate.

River Baseflow

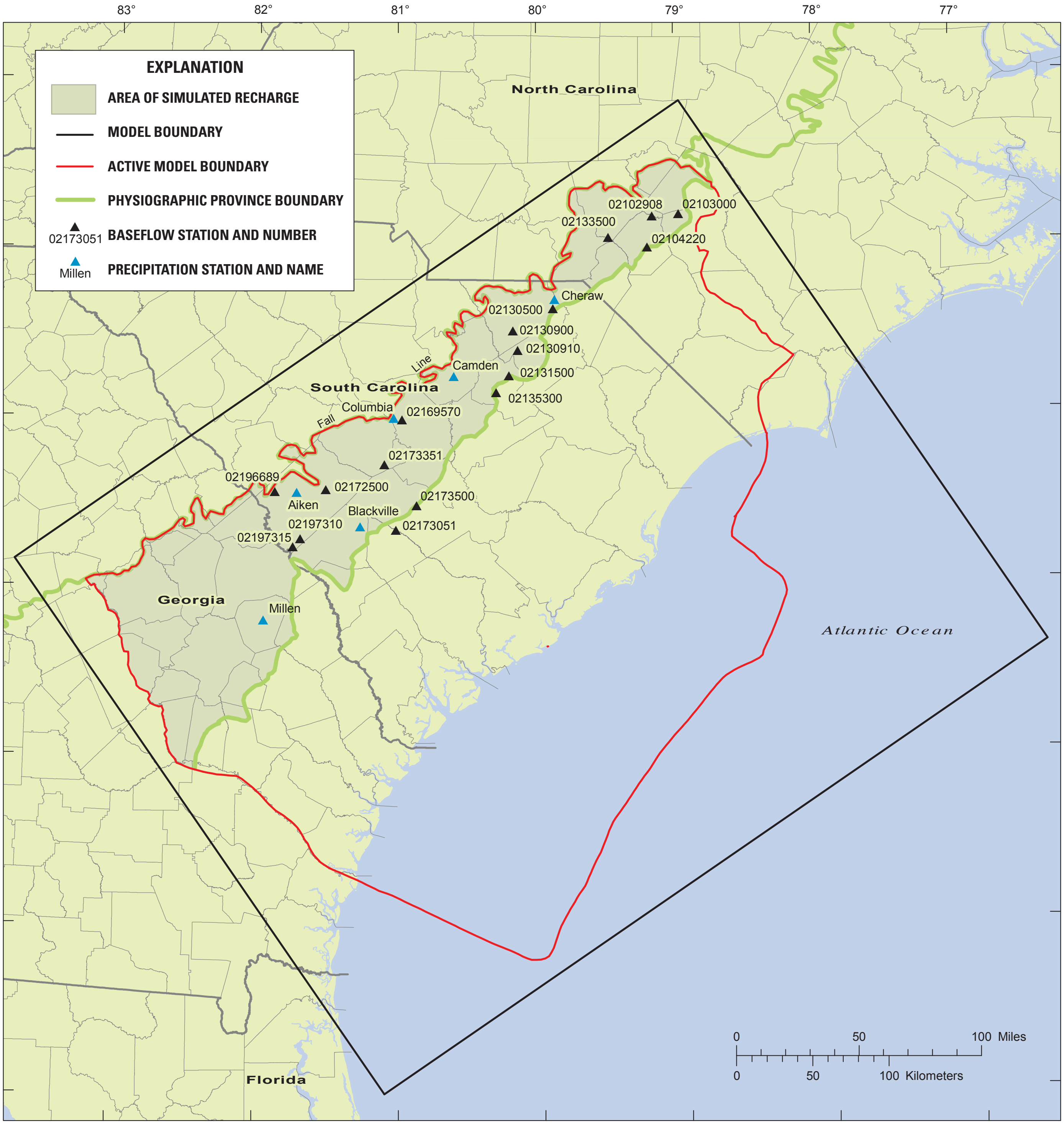
Daily streamflow data from 17 sites in the upper Coastal Plain of North and South Carolina (table 3; fig. 15) were used to estimate the ground-water discharge component of the overall streamflow. These ground-water discharge rates were calculated using the USGS computerized stream baseflow estimation program PART (Rutledge, 1998). The PART program develops a mathematical expression for recession of ground-water discharge and estimates mean ground-water recharge and discharge. The assumptions for use of the program include that all, or nearly all, ground-water discharges to the stream except that which is lost to riparian evapotranspiration and that there is limited or no regulation or diversion of streamflow within the basin. The PART program uses streamflow partitioning to estimate a daily record of baseflow under the streamflow record. The method designates baseflow to be equal to streamflow on days that fit a requirement of antecedent recession. The PART program linearly interpolates baseflow for other days and is applied to a long period of record to obtain an estimate of the mean rate of ground-water discharge (Rutledge, 1998).

The streamflow data utilized in data analysis and model calibration are from 17 USGS gaging stations that have both recent and historic data (table 3; fig. 15). The upstream basin sizes range from 7.63 to 807 mi^2. Data used in the analysis were collected at the different sites from various time periods ranging from 1939 to 2003. The mean streamflow at these sites ranged from 6.47 to 964 cubic feet per second (ft^3/s) (table 3). Mean baseflow for the sites ranged from 5.26 to 823 ft^3/s. The baseflow index, or percentage of the overall flow derived from ground-water discharge to the stream, ranged from a low of 64 percent to a high of 87 percent.

Table 2. Precipitation station descriptions.

[NOAA, National Oceanic & Atmospheric Administration; ft NGVD 29, feet above or below (–) National Geodetic Vertical Datum of 1929]

NOAA station name and location	Latitude	Longitude	Altitude, in ft NGVD 29	Period of record	Mean precipitation, inches	Maximum precipitation, inches	Minimum precipitation, inches
95882—Millen, GA	32° 48' 06"	81° 56' 49"	195	1882–2004	46.21	74.67	28.92
380074—Aiken, SC	33° 33' 01"	81° 42' 40"	400	1854–2004	47.11	71.36	22.38
380764—Blackville, SC	33° 21' 22"	81° 16' 04"	324	1884–2004	47.32	75.10	27.85
381310—Camden, SC	34° 14' 40"	80° 36' 14"	140	1849–2004	47.27	83.41	27.16
381588—Cheraw, SC	34° 41' 03"	79° 53' 48"	140	1882–2004	47.30	67.93	29.72
381944—University of South Carolina, Columbia, SC	33° 58' 10"	81° 06' 51"	242	1872–2004	43.92	74.49	27.11



Base from U.S. Geological Survey
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Figure 15. Locations of precipitation stations and baseflow stations in Georgia and North and South Carolina.

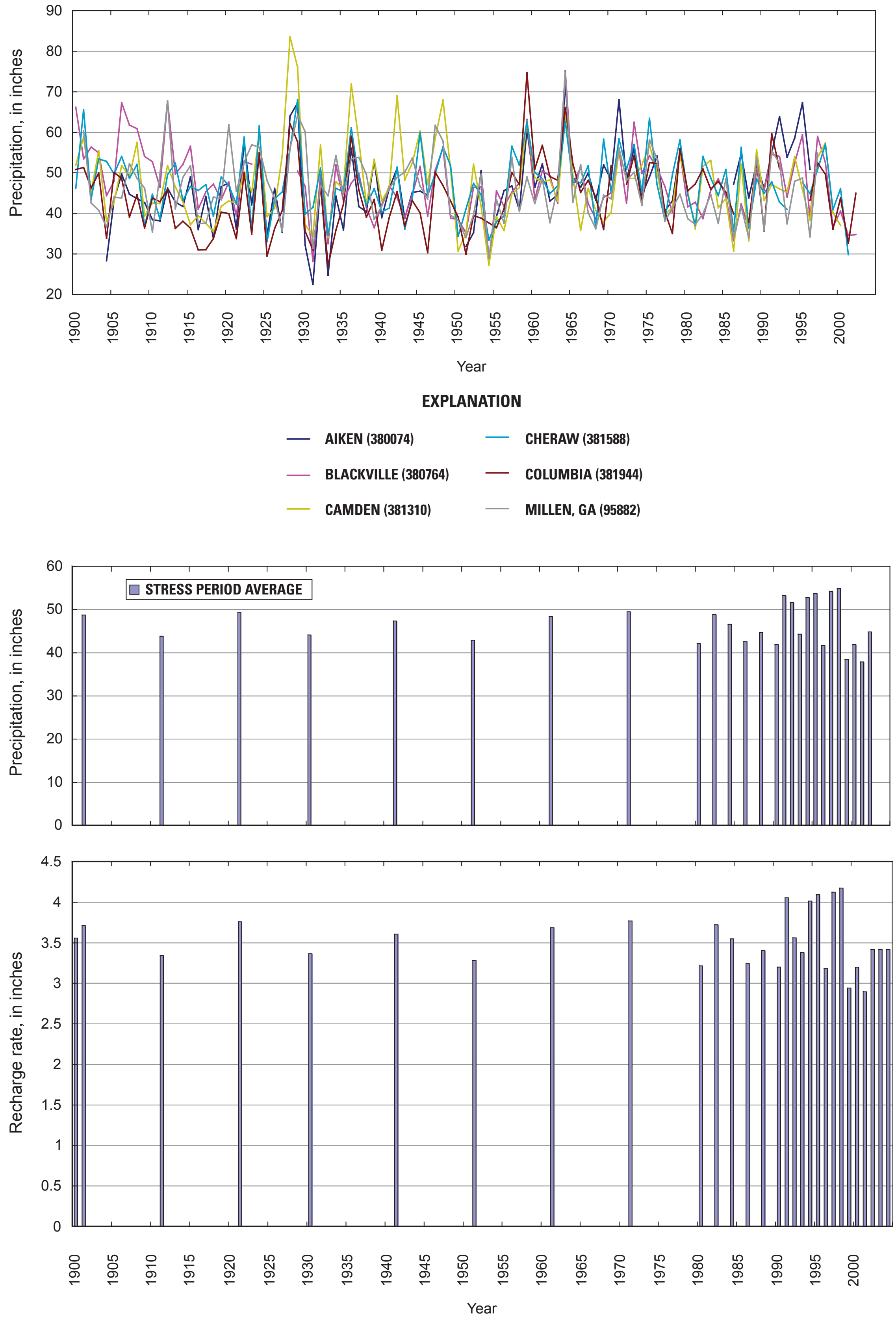


Figure 16. Annual total precipitation for six stations in the upper Coastal Plain of Georgia and South Carolina and calculated annual mean precipitation and simulated recharge per stress period.

Table 3. Streamflow gaging stations and streamflow rates used in model calibration.

[USGS, U.S. Geological Survey; mi², square mile; ft³/s, cubic feet per second; in/yr, inches per year]

USGS station number	Station name	Drainage area, in mi²	Period of record, in years	Mean streamflow, in ft³/s	Mean streamflow, in in/yr	Mean baseflow, in ft³/s	Mean baseflow, in in/yr	Baseflow index, in percent of total flow
2130900	Black Creek near McBee, SC	108	1960–2002	152	19.2	122	15.3	80
2130910	Black Creek near Hartsville, SC	173	1961–1998	226	17.7	197	15.5	87
2130500	Juniper Creek near Cheraw, SC	64.0	1941–1957	70.4	14.9	55.3	11.7	79
2196689	Little Horse Creek near Graniteville, SC	26.6	1990–1998	34.2	17.5	29.9	15.3	87
2197310	Upper Three Runs Creek above Road C	176	1975–1997	212	16.4	179	13.8	85
2197315	Upper Three Runs Creek at Road A	203	1980–2001	231	15.4	196	13.1	85
2173351	Bull Swamp Creek near Swansea, SC	34.4	2002–2002	6.47	2.55	5.26	2.08	81
2169570	Gills Creek near Columbia, SC	59.6	1967–2002	74.4	16.9	47.4	10.8	64
2131500	Lynches River near Bishopville, SC	675	1943–1970	769	15.5	525	10.6	68
2173500	North Edisto River near Orangeburg, SC	638	1939–1999	781	16.6	682	14.5	87
2135300	Scape Ore Swamp near Bishopville, SC	96.0	1969–2002	98.0	13.9	74.7	10.6	76
2173051	South Fork Edisto River near Bamberg, SC	807	1992–2002	964	16.2	823	13.9	85
2172500	South Fork Edisto River near Montmorenci, SC	198	1941–1965	244	16.7	196	13.5	80
2133500	Drowning Creek near Hoffman, NC	183	1940–2003	252	18.7	195	14.5	78
2104220	Rockfish Creek at Raeford, NC	93.1	1993–2003	117	17.1	95.8	14.0	82
2102908	Flat Creek near Inverness, NC	7.63	1969–2003	11.9	21.2	9.41	16.8	79
2103000	Little River at Manchester, NC	348	1939–1949	440	17.2	301	11.8	69

Model Calibration

The Southeastern Coastal Plain aquifer system in South Carolina has an extensive and lengthy history of use dating back to at least the earliest European settlers in the 1670s. Shallow wells were dug to produce potable water in the coastal areas that contained no fresh surface water. Deeper wells were drilled in the middle to late 1800s, but production of significant volumes of ground water in localized parts of the State did not begin until the early 20th century.

The ground-water flow model was calibrated to a time period beginning in 1900 and extending through 2004. Several sets of water-level data were available to calibrate the ground-water model. Selected predevelopment water levels during the period prior to 1979 and synoptic ground-water levels from November 2004 were utilized. The predevelopment ground-water levels compiled by Aucott and others (1984) are considered to be unaffected by ground-water pumping.

The model has 29 stress periods representing times of equal ground-water withdrawals. The stress periods are longest (10-year increments), from 1900 to 1980, when the accuracy (both locations and volumes) of the withdrawal data is poorest. Beginning in 1980, development of water-use databases allowed the collection, compilation, and storage of more accurate ground-water withdrawal data (J. Childress, South Carolina Department of Health and Environmental Control, written commun., March 2005). The stress periods are reduced to 2-year increments from 1980 to 1990, reflecting the availability of larger volumes and increased accuracy of ground-water withdrawal data. Beginning in 1990 and continuing to 2004, the stress periods are in 1-year increments and reflect relatively high-quality water-use data available for the Coastal Plain aquifers in the study area.

The model was calibrated using a technique of parameter estimation that uses regularized inversion (Doherty, 2003). This approach allowed a relatively large number (434) of parameters to be estimated for many of the model inputs including hydraulic conductivities, specific storage, recharge, riverbed conductance, and vertical anisotropy. This calibration methodology differs from the usual approach to inverse modeling by using relatively large numbers of parameters along with an alternative method of using prior information to constrain the parameter estimation process (R. Hunt, U.S. Geological Survey, written commun., January 2007). This methodology employs "pilot points" for spatial hydraulic property characterization. Pilot points are a method of spatial parameterization for model inputs, in this case, various hydraulic properties typically used in ground-water flow models. These hydraulic properties are assigned to sets of pilot points distributed throughout the model domain rather than directly to the grid elements of the MODFLOW model (Doherty, 2003). Hydraulic properties of the MODFLOW model are then assigned to model elements through spatial interpolation from the pilot points to the model grid. The result is a smooth variation of the hydraulic property over the MODFLOW grid. Pilot points have been used in ground-water model calibration by a number of authors (de Marsily and others, 1984; LaVenue and Pickens, 1992) and have proven to be a powerful and flexible way to attempt to represent spatial heterogeneity in various types of aquifer hydraulic properties.

The goal of inverse modeling is to attempt to minimize the objective function, which is the weighted sum of squares differences between model-generated observation values and those measured in the field (Doherty, 2005). Observations were weighted differently to reflect their importance in determining the optimization outcome. For example, ground-water levels collected from the Mount Pleasant area from Middendorf aquifer wells were weighted slightly higher than others to reflect their importance in the calibration process and the results. Similarly, ground-water levels for the Black Creek aquifer in the Grand Strand area (fig. 1) and Middendorf aquifer near Florence, SC (fig. 1), were weighted slightly higher to overcome difficulties encountered matching the cones of depression in these areas during model calibration. In general, weights for synoptic ground-water levels were assigned a value of 1.0. Weight values for the continuous ground-water-level data were assigned on the basis of the standard deviation of the ground-water levels. Again, the water-level measurements from the Middendorf aquifer for the Charleston and Florence, SC, areas and from the Black Creek aquifer for the Grand Strand area were assigned a slightly higher weight value to reflect their importance in the calibration process.

Parameters selected for estimation during model calibration were (1) aquifer and confining unit hydraulic conductivity (HC), (2) aquifer and confining unit specific storage (SS), (3) aquifer and confining unit anisotropy (A), (4) riverbed conductance (RB), and (5) recharge (R). Riverbed conductance and recharge were estimated only during the steady-state calibration phase. Published HC values from the South Carolina Coastal Plain aquifers were used as a starting point for the HC pilot points. These HC values were allowed to vary within limits during the calibration process in an attempt to fit the steady-state and transient observation data. No HC data are known to exist for the confining units within the Southeastern Coastal Plain aquifer system of South Carolina; therefore, previous model-derived values (Aucott, 1996) were used as a starting point for the parameter estimation process and varied within a multiplier of 5 and a divisor of 5. These limits are within the confidence limits of the aquifer test data (E. Kuniansky, U.S. Geological Survey, oral commun., December 2006). Numerous additional pilot points were added to the model in areas with sparse aquifer test data to assist in the parameter estimation process.

During calibration of the ground-water flow model, and especially when evaluating the results, it is important to understand the accuracy and uncertainty of the various kinds of data utilized in the calibration process. The match between simulated and measured data should never be closer than the accuracy of the data. Matching inaccurate observations exactly is termed "overfitting" and should be avoided (Hill and Tiedeman, 2007). Two types of data were used in the model calibration process: ground-water-level measurements (synoptic and continuous-record measurements) and results of stream baseflow analysis from selected upper Coastal Plain streams.

Abundant ground-water-level data were available for the South Carolina Coastal Plain aquifers for the study period. These data are available within the USGS National Water Information System (NWIS) database (*http://water.usgs.gov/nwis*). Whereas land-surface data are associated with all of the ground-water-level data in NWIS, the accuracy of the data associated with the land-surface altitudes is highly variable. Locations and land-surface altitudes for older wells were generally hand picked from topographic maps and likely have substantial error associated with the horizontal and vertical data. In South Carolina, topographic maps can have contour intervals ranging from 5 to 20 ft. The accuracy of the altitude of a point located on these maps would be one-half of the contour interval, or from 2.5 to 10 ft. The horizontal accuracy of a hand-picked point on a topographic map can vary widely. Recently constructed wells or wells that have been relocated are located using Global Positioning System (GPS) equipment and tend to be much more accurately positioned (within 2 centimeters or less) both horizontally and vertically. In this study, use of USGS NED values to provide a consistent land-surface altitude for the ground-water well locations minimized some of the uncertainties associated with using the data (U.S.

Geological Survey, 1999). These 30-m-spaced NED values used the North American Datum of 1983 (U.S. Geological Survey, 1999) for a horizontal datum.

Several methods of conceptualization of the ground-water flow system in the Coastal Plain aquifers within the study area were attempted. The one that gave the best fit of the measured data (water-level and baseflow measurements) was the "pilot point" method. The use of zones of uniform aquifer hydraulic properties produced a relatively poorer fit of the measured data. Many combinations of HC pilot points were modeled with the results of the one that gave the best fit to the measured data presented here. The calibration procedure for the pilot point method is described below. Many combinations of parameter values were formulated and evaluated for fit to the measured data. The combination that gave the lowest objective function is presented in this report.

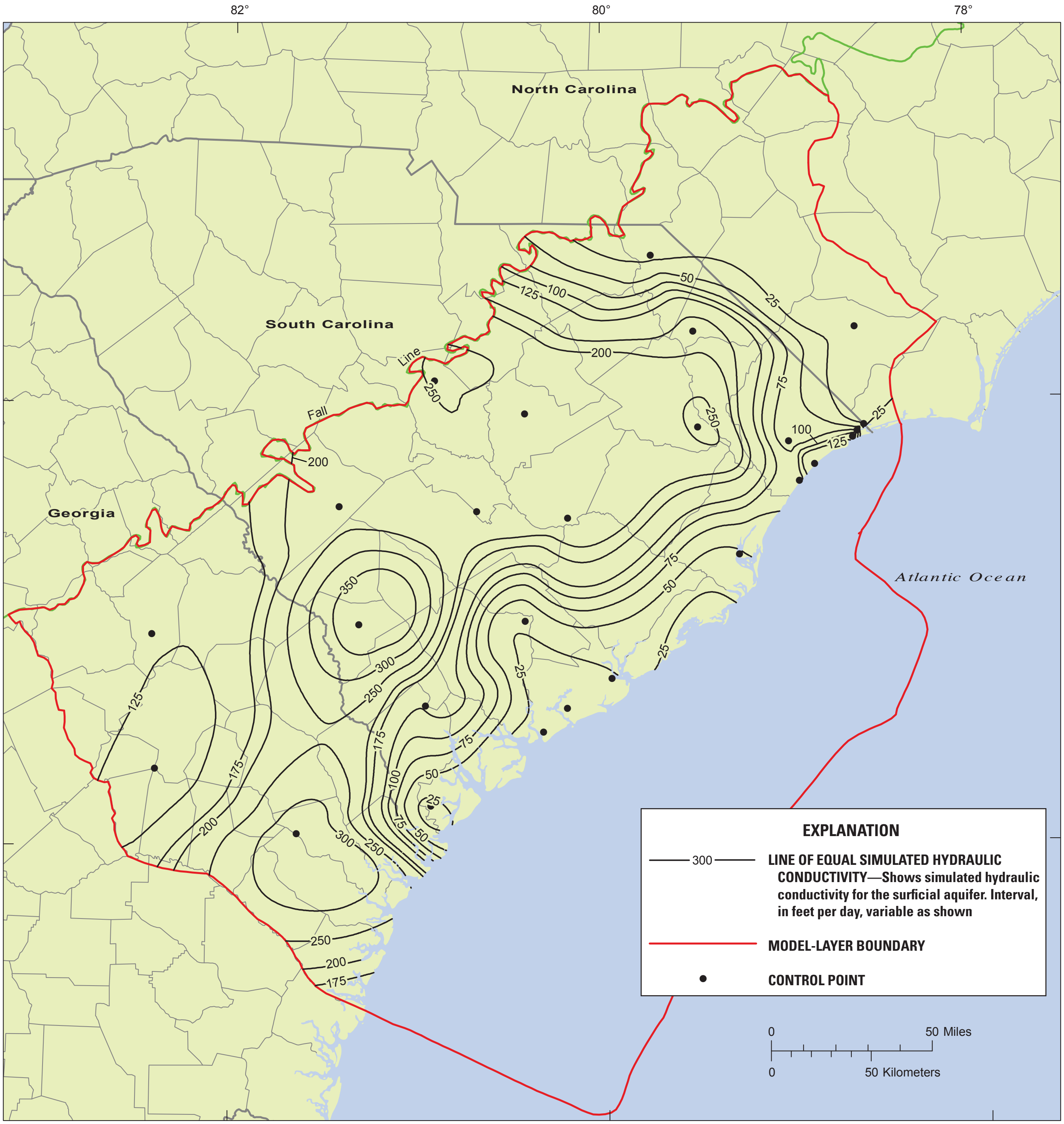
Calibrated hydraulic property values are listed in table 4 and presented in figure 17 for hydraulic conductivity of the various model layers. Horizontal hydraulic conductivity values for the aquifers ranged from 1 to 2,000 ft/d with the highest values occurring in the Floridan aquifer system and Tertiary sand aquifer. Horizontal hydraulic conductivity values for the confining units ranged from 0.000001 to 0.00095 ft/d. Horizontal to vertical anisotropy ranged from 1 to 3 for all of the model layers. Core samples of clays and shale indicate that horizontal to vertical anisotropy is typically less than 3:1 (Freeze and Cherry, 1979). Heterogeneity in model layers can lead to greater differences between horizontal and vertical anisotropy. The best fit calibration required specific storage values that were equal to the minimum value allowed (0.0000025) for all layers except the surficial aquifer, where a value of 0.00045 provided a reasonable fit.

Recharge estimates used in the model calibration contain uncertainty that is not easily quantifiable. Historical precipitation data from the National Weather Service (United States Historical Climatology Network) were used as a basis for the recharge rates in the model (Williams and others, 2005). Data from six precipitation sites in the upper Coastal Plain were used to estimate recharge rates. Uncertainty in the data comes from the collection methods for the period of 1900 to 2004 and also in extrapolation of the site data over the upper Coastal Plain area that results in the lack of spatial variability in the recharge rate. Additionally, net recharge is applied to the model, but rainfall runoff and evapotranspiration are not simulated. These uncertainties most likely result in at least a 20 to 30 percent uncertainty in the calibrated recharge rates.

Horizontal hydraulic conductivity of the aquifers is probably the best understood property of the model. Aquifer test results were not available for any of the confining units within the study area, so model inputs and results have a greater uncertainty for the horizontal hydraulic conductivities of the confining units than the aquifers. Results of the aquifer tests

Table 4. Statistics of calibrated hydraulic conductivity values, and calibrated values of specific storage and vertical anisotropy.

Hydraulic property	Layer	1	2	3	4	5	6	7	8	9
	Unit name	Surficial aquifer	Floridan-Tertiary sand confining unit	Floridan-Tertiary sand aquifer	Black Creek confining unit	Black Creek aquifer	Middendorf confining unit	Middendorf aquifer	Cape Fear confining unit	Cape Fear aquifer
	Statistic									
Horizontal hydraulic conductivity (feet/day)	Minimum	13.3	1.50×10^{-05}	1.07	1.00×10^{-06}	1.00	1.00×10^{-06}	1.00	1.00×10^{-06}	1.09
	Maximum	388	6.00×10^{-04}	2,000	4.00×10^{-04}	500	9.50×10^{-04}	500	9.10×10^{-05}	56.0
	Range	374	5.85×10^{-04}	1,999	3.99×10^{-04}	499	9.49×10^{-04}	499	9.00×10^{-05}	54.9
	Mean	133	1.41×10^{-04}	341	1.88×10^{-04}	27.5	3.55×10^{-04}	58.4	1.11×10^{-05}	13.2
	Median	122	1.00×10^{-04}	125	2.01×10^{-04}	4.38	6.50×10^{-05}	15.3	1.00×10^{-06}	3.70
	Standard deviation	114	1.75×10^{-04}	468	1.92×10^{-04}	69.0	4.37×10^{-04}	102	2.81×10^{-05}	19.6
Specific storage (dimensionless)	(calibrated values)	4.51×10^{-04}	2.50×10^{-06}	2.50×10^{-06}	2.50×10^{-06}	2.50×10^{-06}	2.50×10^{-06}	2.50×10^{-06}	2.50×10^{-06}	2.50×10^{-06}
Horizontal to vertical anisotropy (dimensionless)	(calibrated values)	1.2	1.0	1.3	1.0	3.0	3.0	1.1	3.0	1.1



Base from U.S. Geological Survey
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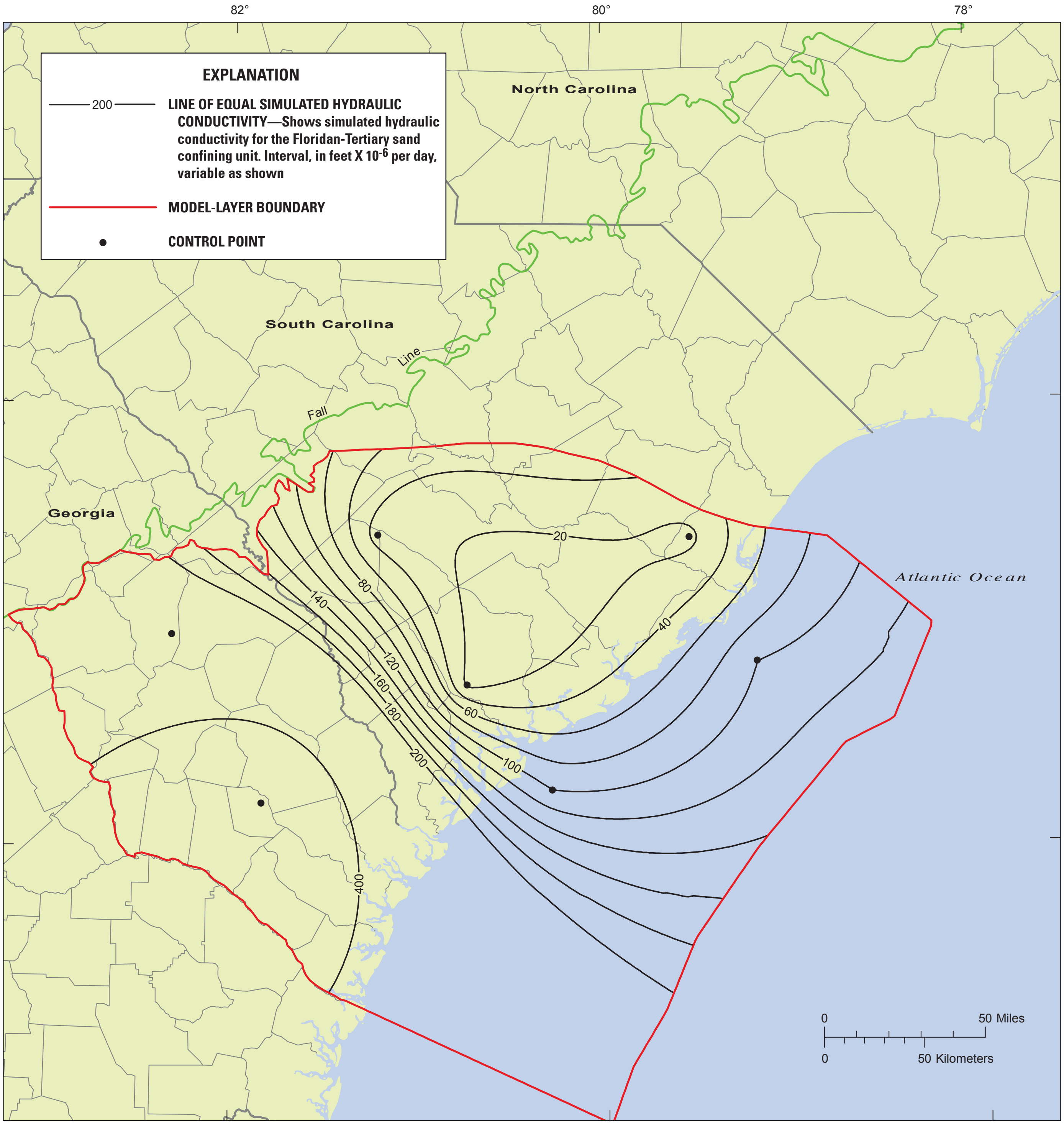
Lambert Conformal Conic projection
Datum: NAD 83

Figure 17*A*. Simulated distribution of hydraulic conductivity for the surficial aquifer.



Base from U.S. Geological Survey
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Figure 17*B*. Simulated distribution of hydraulic conductivity for the Floridan-Tertiary sand confining unit.

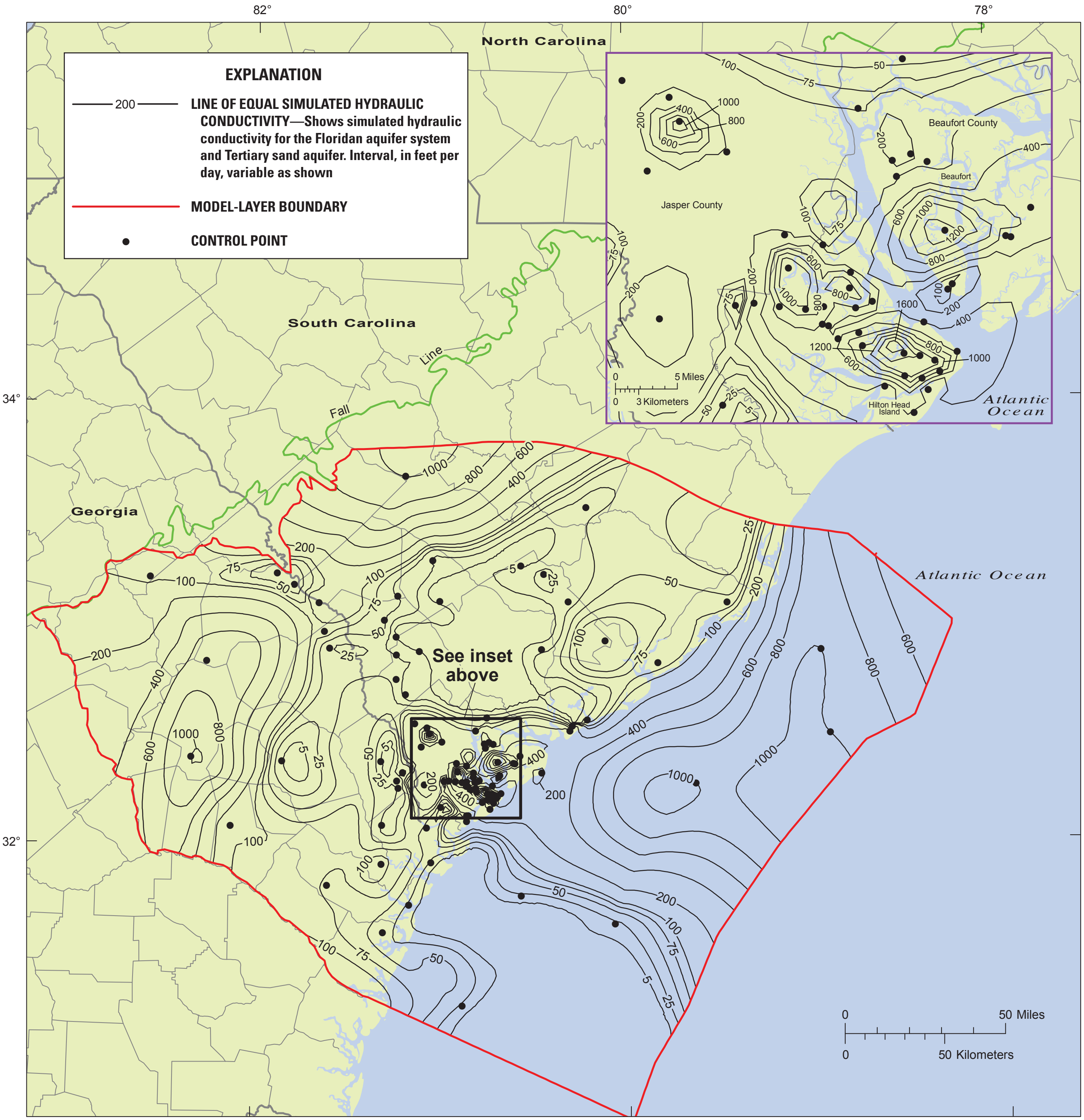

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Figure 17*C*. Simulated distribution of hydraulic conductivity for the Floridan aquifer system and Tertiary sand aquifer.

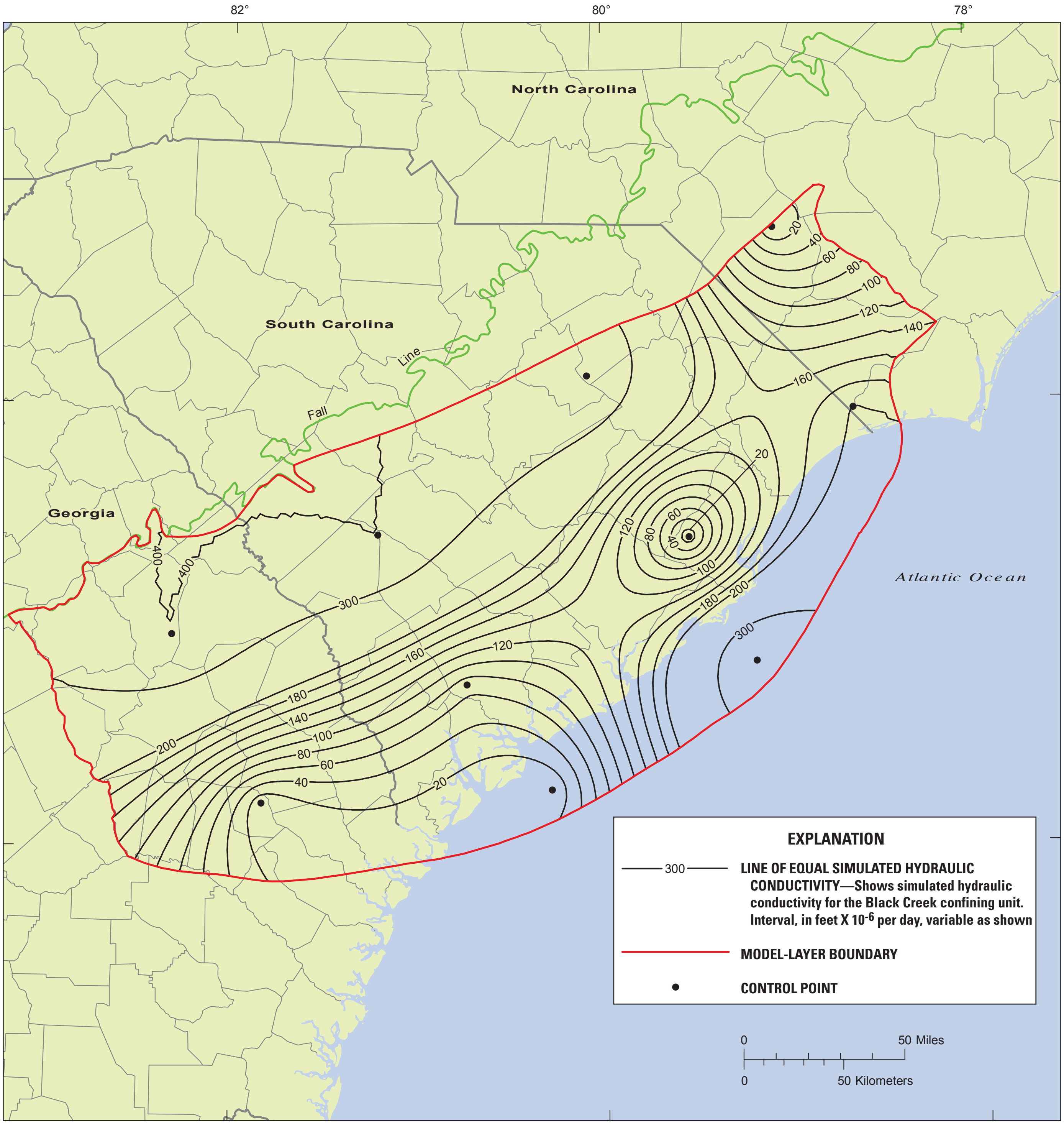

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Figure 17*D*. Simulated distribution of hydraulic conductivity for the Black Creek confining unit.

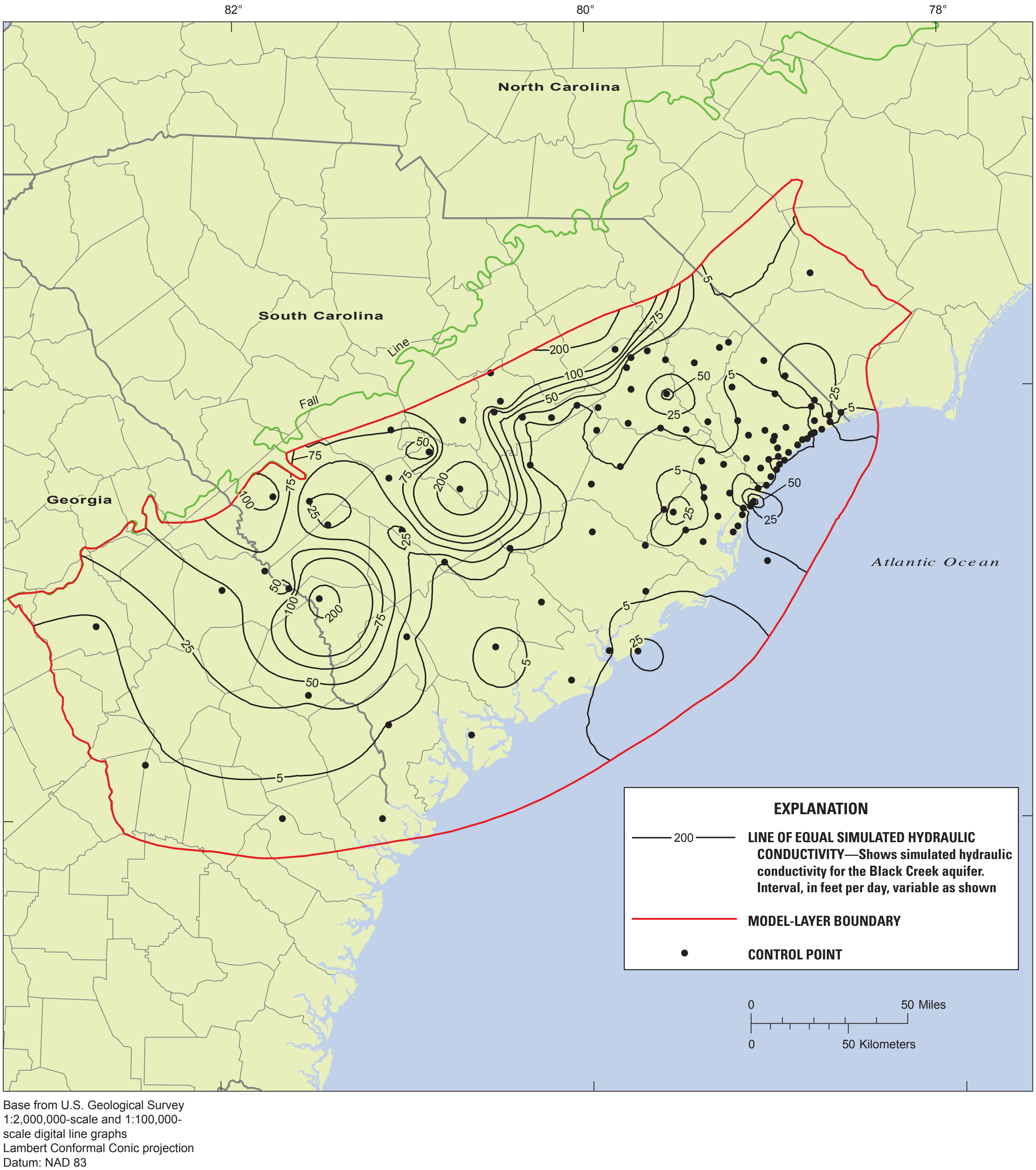
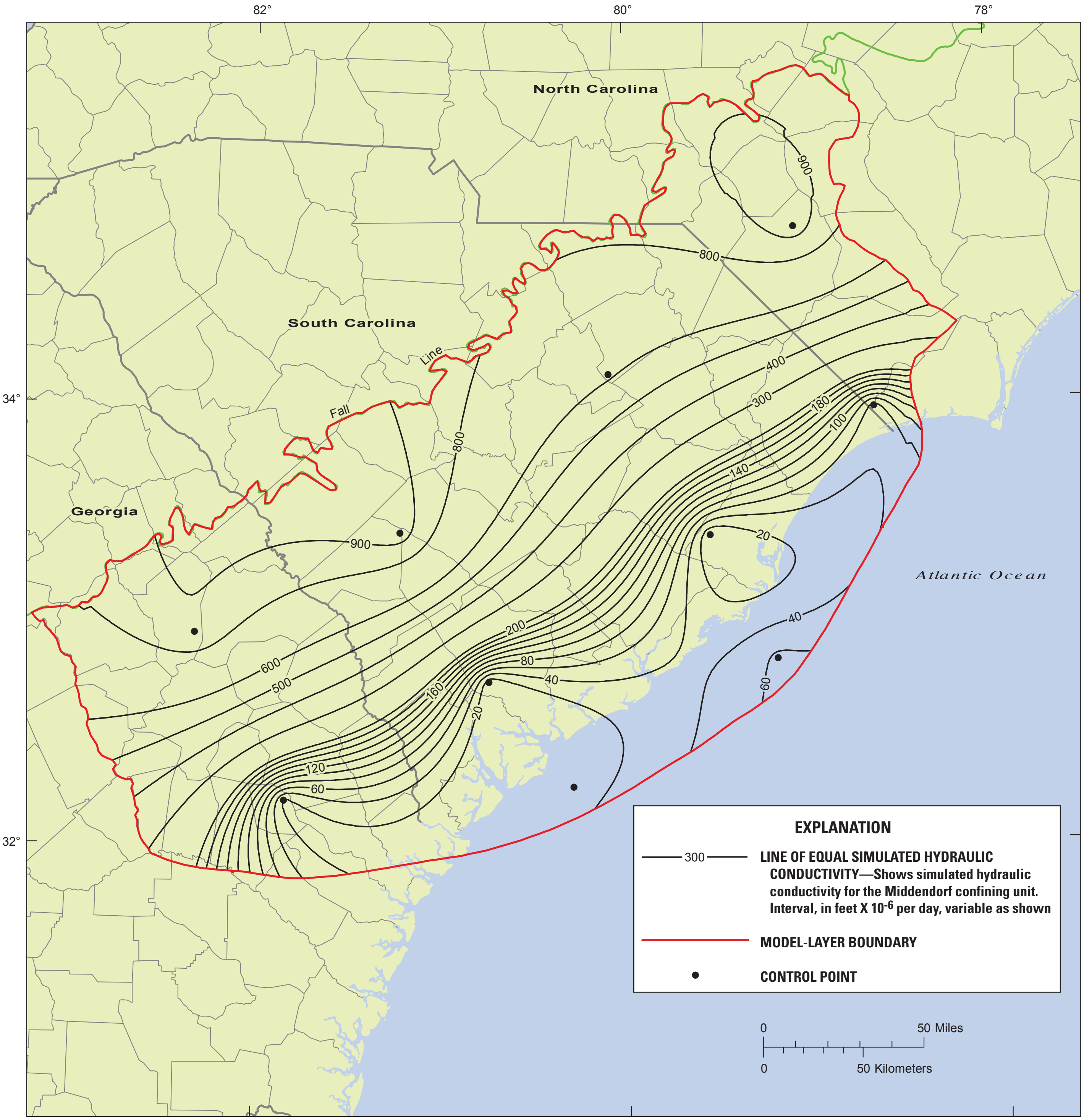


Figure 17*E*. Simulated distribution of hydraulic conductivity for the Black Creek aquifer.



Base from U.S. Geological Survey
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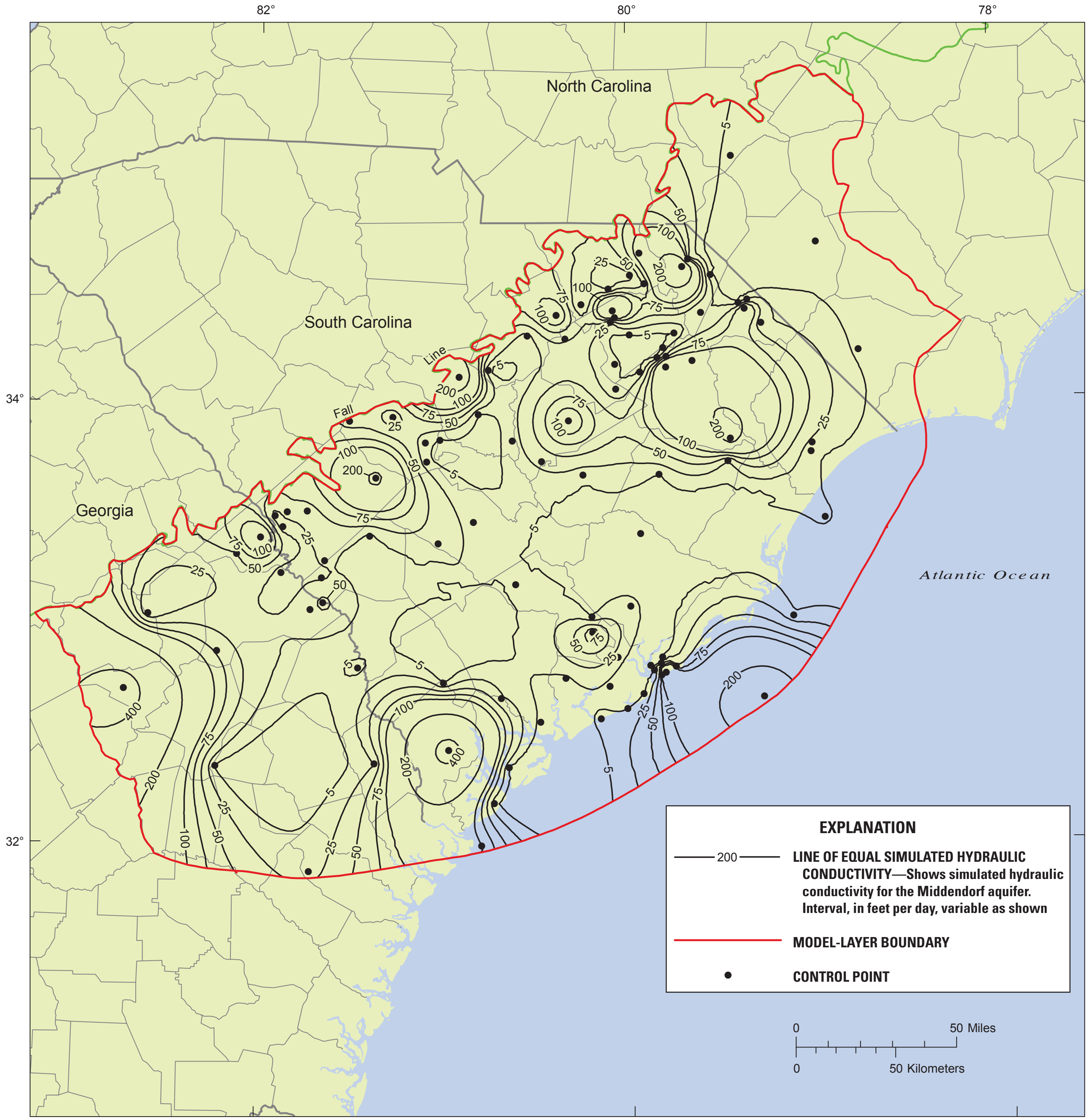
Datum: NAD 83

Figure 17*F*. Simulated distribution of hydraulic conductivity for the Middendorf confining unit.



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Datum: NAD 83

Figure 17*G*. Simulated distribution of hydraulic conductivity for the Middendorf aquifer.

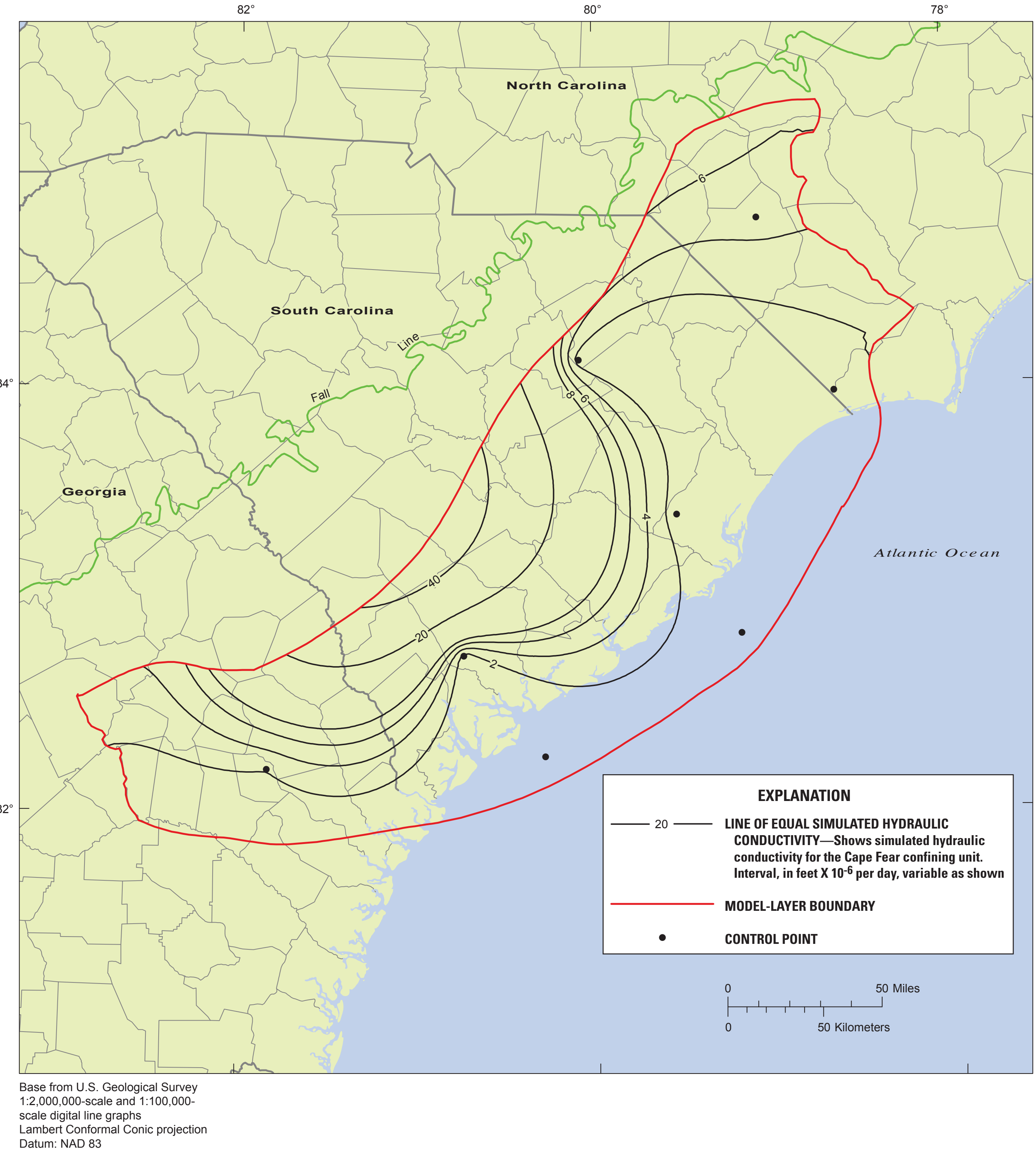
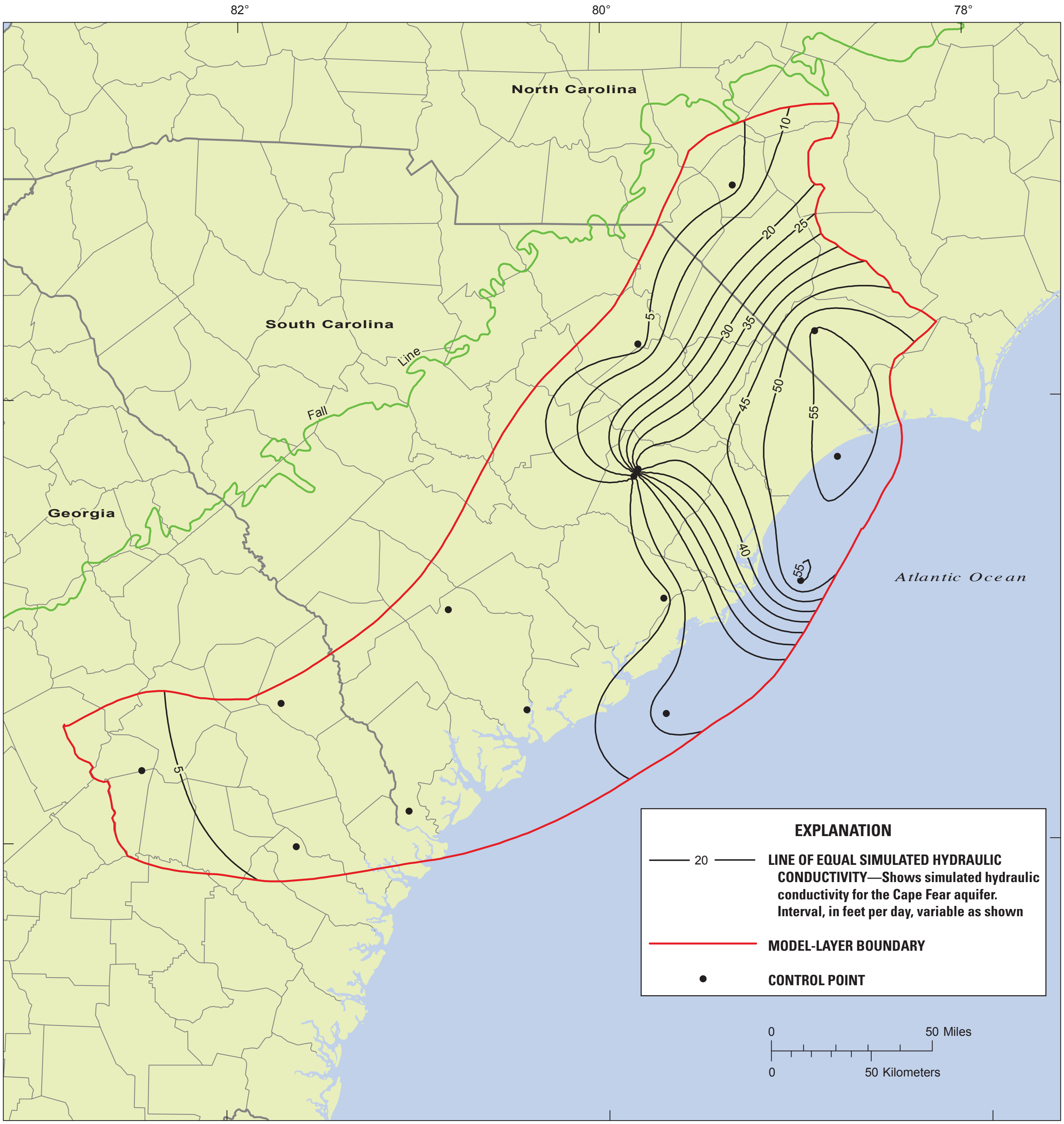


Figure 17*H*. Simulated distribution of hydraulic conductivity for the Cape Fear confining unit.



Base from U.S. Geological Survey
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scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 17*I*. Simulated distribution of hydraulic conductivity for the Cape Fear aquifer.

utilized in the model calibration have an uncertainty of at least an increase or decrease of a factor of 5 (E. Kuniansky, U.S. Geological Survey, oral commun., December 2006). More aquifer tests are available for the upper aquifers than for the deeper aquifers.

Riverbed conductance is an unknown hydraulic parameter in the South Carolina Coastal Plain. The values presented in this report were model-calibration derived, and the uncertainty associated with the values is unknown. Aquifer and confining unit vertical anisotropy values also were model derived, and there are no known published values. The uncertainty associated with these data is unknown.

Specific storage values were determined from model calibration. The calibrated numbers are within the range of values calculated from published aquifer test results available from the South Carolina Coastal Plain aquifers (Aucott and Newcome, 1986; Newcome, 1993, 2000). The range of calibrated values of specific storage is 0.000002 to 0.0003. Uncertainty associated with the values of specific storage results from the aquifer-test data-collection and data-analysis methodology, which is subject to a significant degree of uncertainty. Additionally, aquifer thicknesses reported from aquifer-test wells in the South Carolina Coastal Plain can be very accurate or roughly accurate or no data are presented, and an assumption of the thickness was made based on hydrologic judgment. Because there are no aquifer-test data available from the confining units, the values for specific storage presented are based on model calibration, and the uncertainty associated with these values is unknown.

Ground-water withdrawal locations and rates were obtained from the various State agencies tasked with collecting the data. Horizontal well locations are subject to the same uncertainty described above in this section of the report for ground-water well locations. The more recent withdrawal data are thought to be more accurate and complete than the older data. Withdrawal data prior to 1980 are derived mainly from a previous ground-water flow model calibration (Aucott, 1996) and contain a high degree of uncertainty. All of the data are subject to uncertainties associated with the measurement of flows from the wells and with general record-keeping errors.

Stream baseflow analyses were performed on selected records from streamflow gaging stations in the upper Coastal Plain of North and South Carolina. The accuracy of the daily streamflow records depends primarily on (1) the stability of the stage-streamflow relations or, if the control is unstable, the frequency of streamflow measurements, and (2) the accuracy of the observations of stage, measurements of streamflow, and interpretation of records (Cooney and others, 2003). A rating is made for the daily streamflow data and is included in the records for each station. These ratings are defined in terms of being "excellent," which means that 95 percent of the daily streamflow data are within 5 percent of the true streamflow; "good," which are within 10 percent; "fair" are within 15 percent; and "poor" means that the daily streamflow data have less than "fair" accuracy. Data from gages selected for inclusion in the model calibration are all from relatively small basins (less than 30 mi^2) in the upper Coastal Plain. These upper Coastal Plain streams have unstable sand beds that tend to shift with time and high-flow events, and therefore, tend to give "poor" ratings. Therefore, it is assumed that all of the streamflow data used in the model calibration are rated "poor."

The water-level calibration target selected for use in the model was the largest land-surface contour interval mapped in the study area, or 20 ft. Even though the NED data were used in the model input, the variation in the types and accuracies of the NED coverage over the study area makes establishing a single accuracy criterion uncertain; therefore, the contour map interval was selected. All the stream baseflow measurements are considered to be rated "poor," and the accuracy is essentially unknown.

Simulation of Predevelopment and 2004 Flow System

Ground-water conditions for predevelopment and 2004 were simulated using steady-state and transient approximations, respectively. The steady-state predevelopment water-level altitudes were used as initial conditions for the transient simulation. The simulated water levels, stream baseflows, and water budgets for the two time periods are summarized and compared.

Ground-water conditions during predevelopment were calibrated using 499 water-level measurements (table 5; fig. 18). The calibration included 175 water levels from the Floridan aquifer system and Tertiary sand aquifer, 164 from the Black Creek aquifer, 142 from the Middendorf aquifer, and 19 from the Cape Fear aquifer. The residuals, or the differences between the measured and simulated ground-water levels, are normally distributed for all aquifers and had a maximum range from –112 to 95.8 ft, with mean residuals of –3.65, –11.3, –19.2, and 5.45 ft for the Floridan-Tertiary sand, Black Creek, Middendorf, and Cape Fear aquifers, respectively (table 5; fig. 19*A*). The percent of simulated values within the 20-ft calibration target varied between 43 and 64 percent for the individual aquifers, with the simulated Middendorf aquifer water levels having the poorest fit. The root-mean-square error (RMSE) for aquifers ranged from 20.2 to 34.4 for the predevelopment calibration.

Another method of evaluating the fit of calibration is to divide the standard deviation of model residuals by the overall range of water-level observations for a particular aquifer. The lower the ratio the better, with ratios less than 0.10 representing a good model fit (Kuniansky and others, 2004). Calculated ratios of 0.10 or less indicate that residuals are less than 10 percent of the altitude range of the observations. The fit of calibration was equal to 0.154 for the Cape Fear aquifer and less than 0.10 for the other three aquifers (table 5). The poorer fit for the Cape Fear aquifer is probably due to the limited number of observations for this model layer.

Ground-water conditions during 2004 were calibrated on the basis of 349 water-level measurements (table 6; fig. 20). These measurements included 147 from the Floridan aquifer system and Tertiary sand aquifer, 110 from the Black Creek aquifer, 89 from the Middendorf aquifer, and 3 from the Cape Fear aquifer. The decrease in the number of water-level measurements from those used in the predevelopment calibration reflects the fewer number of wells available to measure in the South Carolina Coastal Plain. Many water systems have moved from ground-water to surface-water sources and have chosen to abandon production wells. Calculated residuals for the 2004 water-level data were normally distributed for all aquifers. Calculated residuals for all aquifers had a maximum range from –104 to 70.6 ft, with mean residuals of –8.24, –11.1, –11.7, and 0.298 ft for the Floridan-Tertiary sand, Black Creek, Middendorf, and Cape Fear aquifers, respectively (table 6; fig. 19*B*). The percent of simulated values within the 20-ft calibration target varied between 56.2 and 70.1 percent for the individual aquifers, with the simulated Middendorf aquifer water levels having the poorest fit. The RMSE for aquifers ranged from 18.2 to 36.7 ft for the 2004 calibration. Only three water-level measurements were collected from the Cape Fear aquifer during 2004; therefore, statistics are presented but with a low degree of confidence in the results.

The fit of calibration for the 2004 data was equal to 0.241 for the Cape Fear aquifer and less than 0.10 for the other three aquifers (table 6). The poorer fit for the Cape Fear aquifer is probably due to the limited number of observations for this model layer, as was the case for the predevelopment calibration. Simulated changes in water levels in the Mount Pleasant area for the Middendorf aquifer generally match measured values, as evident in hydrographs for observation wells CHN-14 and BRK-431 (fig. 21).

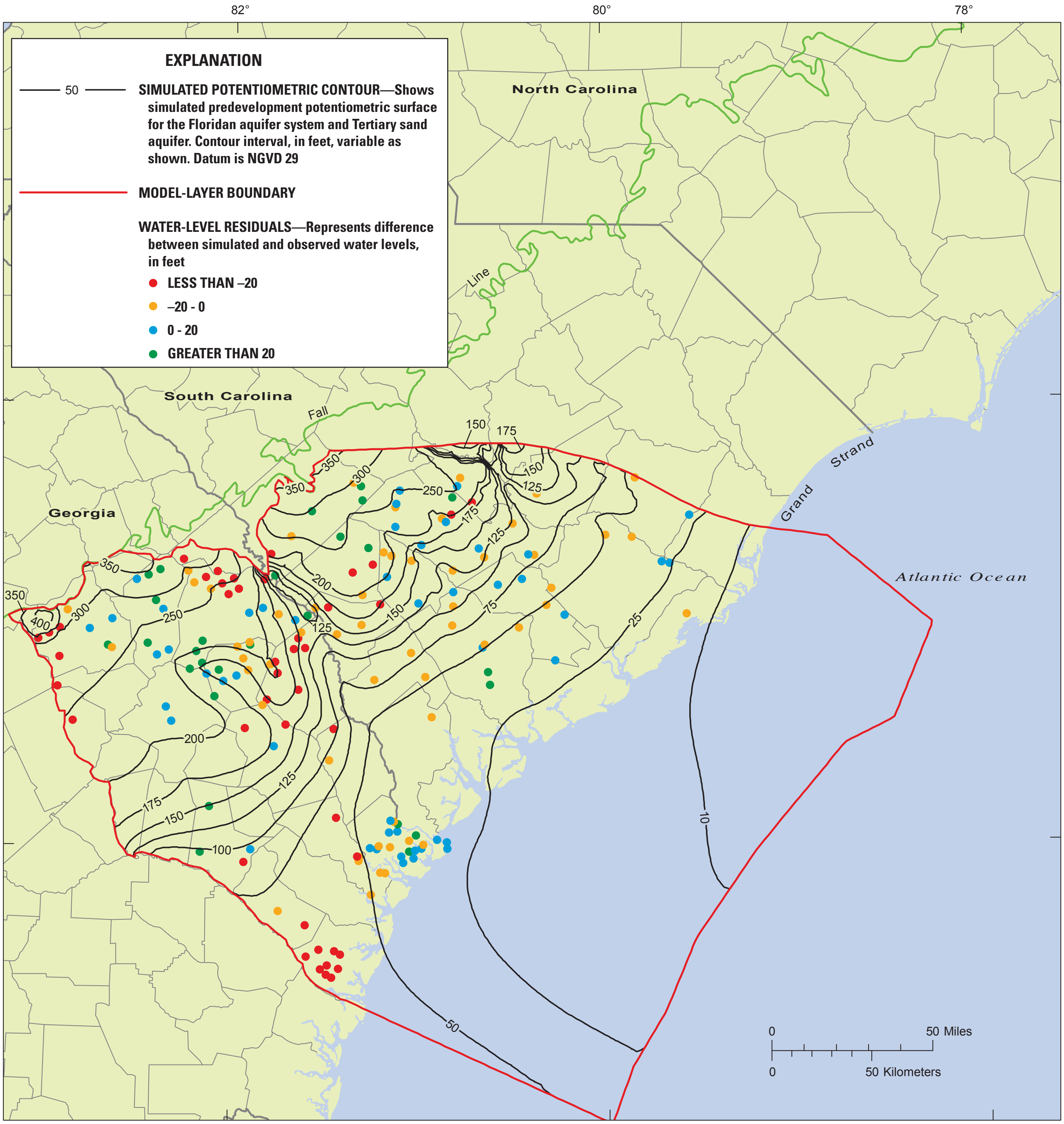
Evaluating whether or not a calibrated model is biased can be accomplished by completing a linear regression analysis and graphing the simulated residuals. Simulated and observed water levels for predevelopment and 2004 conditions are shown in figure 19 along with histograms of the overall

Table 5. Calibration statistics for simulated predevelopment ground-water levels.

	Floridan-Tertiary sand aquifer system (Layer 3)	Black Creek aquifer (Layer 5)	Middendorf aquifer (Layer 7)	Cape Fear aquifer (Layer 9)
Number of observations	175	164	142	19
Residual minimum, in feet	–94.7	–112	–105	–40.7
Residual maximum, in feet	95.8	93.6	68.4	33.0
Mean residual, in feet	–3.65	–11.3	–19.2	5.45
Percent of observations with +/– 20 feet calibration criteria	59.4	64.0	43.0	63.2
Root-mean-square error	27.9	31.0	34.4	20.2
Standard deviation of residuals	27.8	29.0	28.6	20.0
Water-level range, in feet	385	393	445	130
Calibration fit	0.0721	0.0738	0.0642	0.154

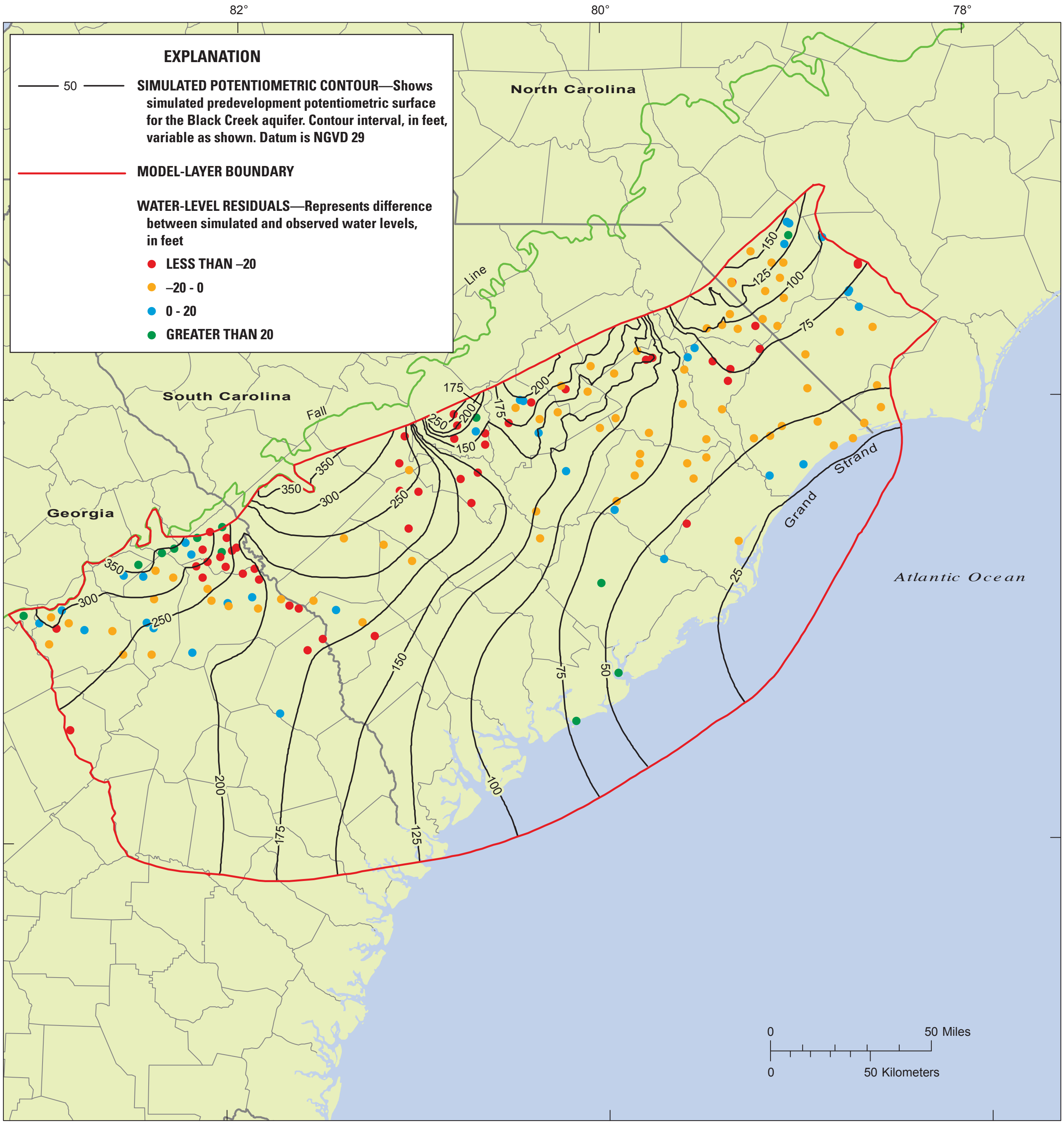
Table 6. Calibration statistics for simulated 2004 ground-water levels.

	Floridan-Tertiary sand aquifer system (Layer 3)	Black Creek aquifer (Layer 5)	Middendorf aquifer (Layer 7)	Cape Fear aquifer (Layer 9)
Number of observations	147	110	89	3
Residual minimum, in feet	–69.9	–94.1	–104	–24.7
Residual maximum, in feet	44.3	70.6	66.0	17.5
Mean residual, in feet	–8.24	–11.1	–11.7	0.298
Percent of observations with +/– 20 feet calibration criteria	70.1	64.5	56.2	66.7
Root-mean-square error	20.2	28.5	36.7	18.2
Standard deviation of residuals	18.5	26.4	35.0	22.2
Water-level range, in feet	317	449	510	92.3
Calibration fit	0.0584	0.0588	0.0686	0.241



Base from U.S. Geological Survey
1:2,000,000-scale and 1:100,000-scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 18*A*. Simulated predevelopment potentiometric surface for the Floridan aquifer system and Tertiary sand aquifer.



Base from U.S. Geological Survey
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Datum: NAD 83

Figure 18*B*. Simulated predevelopment potentiometric surface for the Black Creek aquifer.

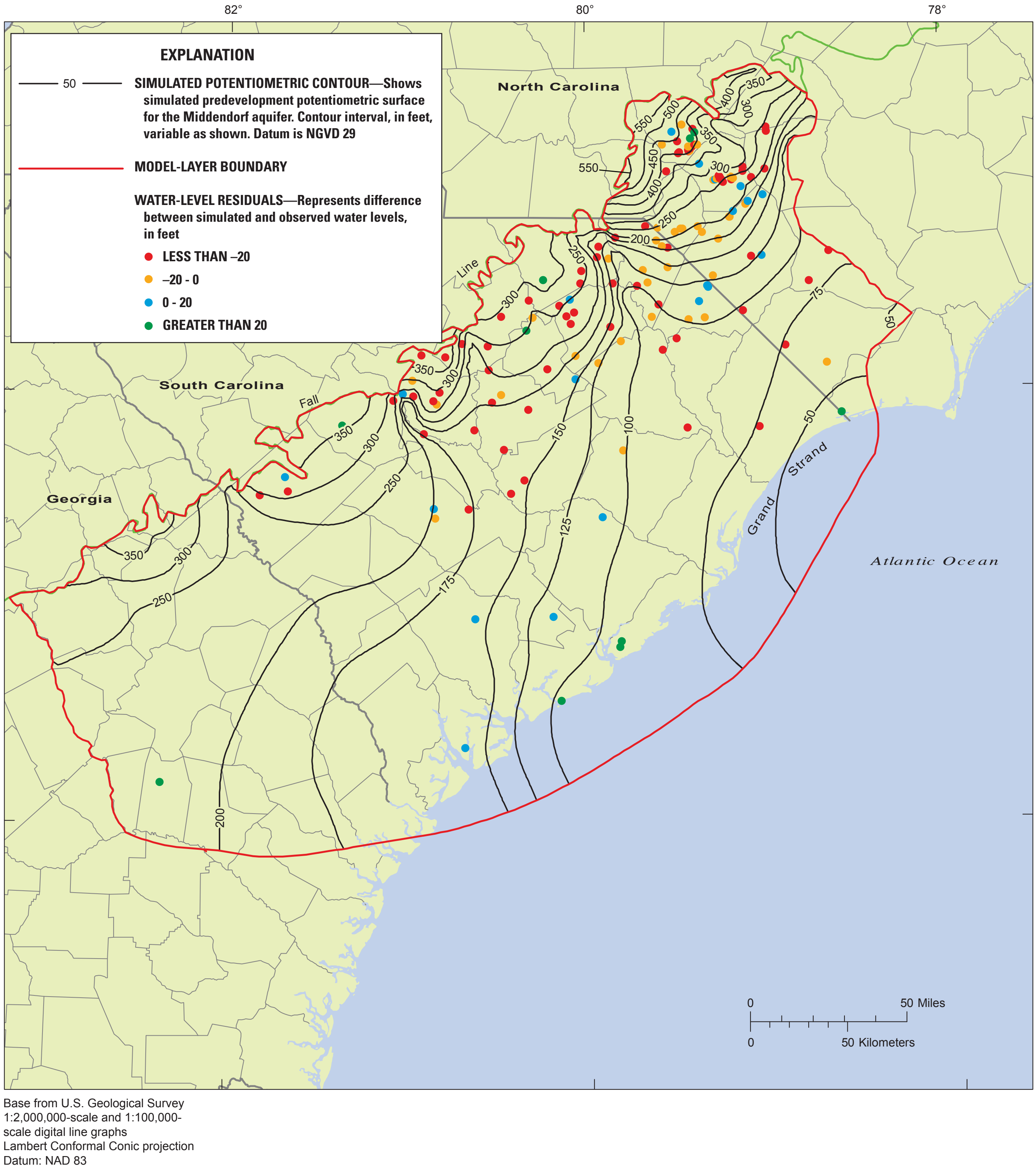
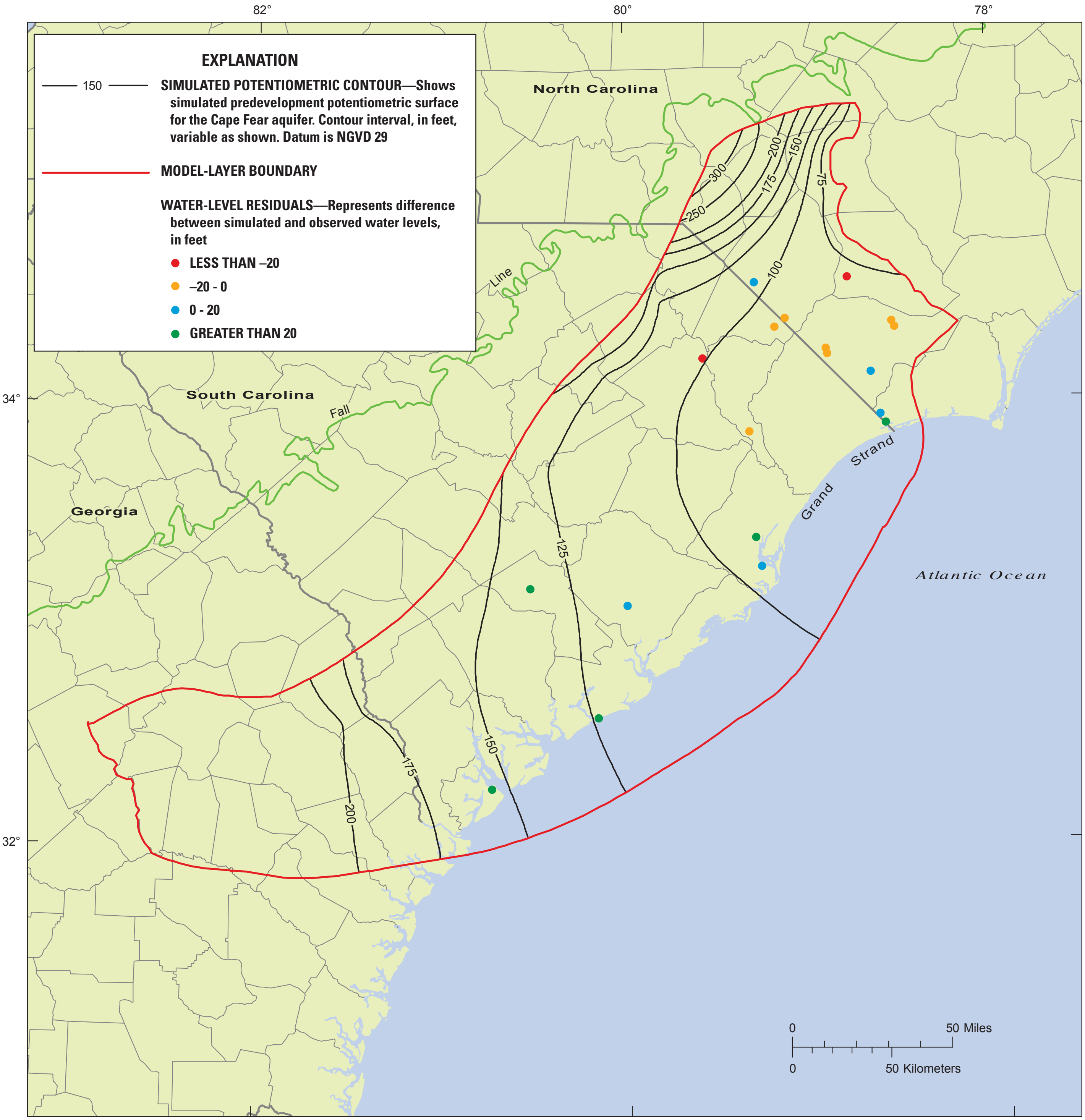


Figure 18*C*. Simulated predevelopment potentiometric surface for the Middendorf aquifer.



Base from U.S. Geological Survey
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Figure 18*D*. Simulated predevelopment potentiometric surface for the Cape Fear aquifer.

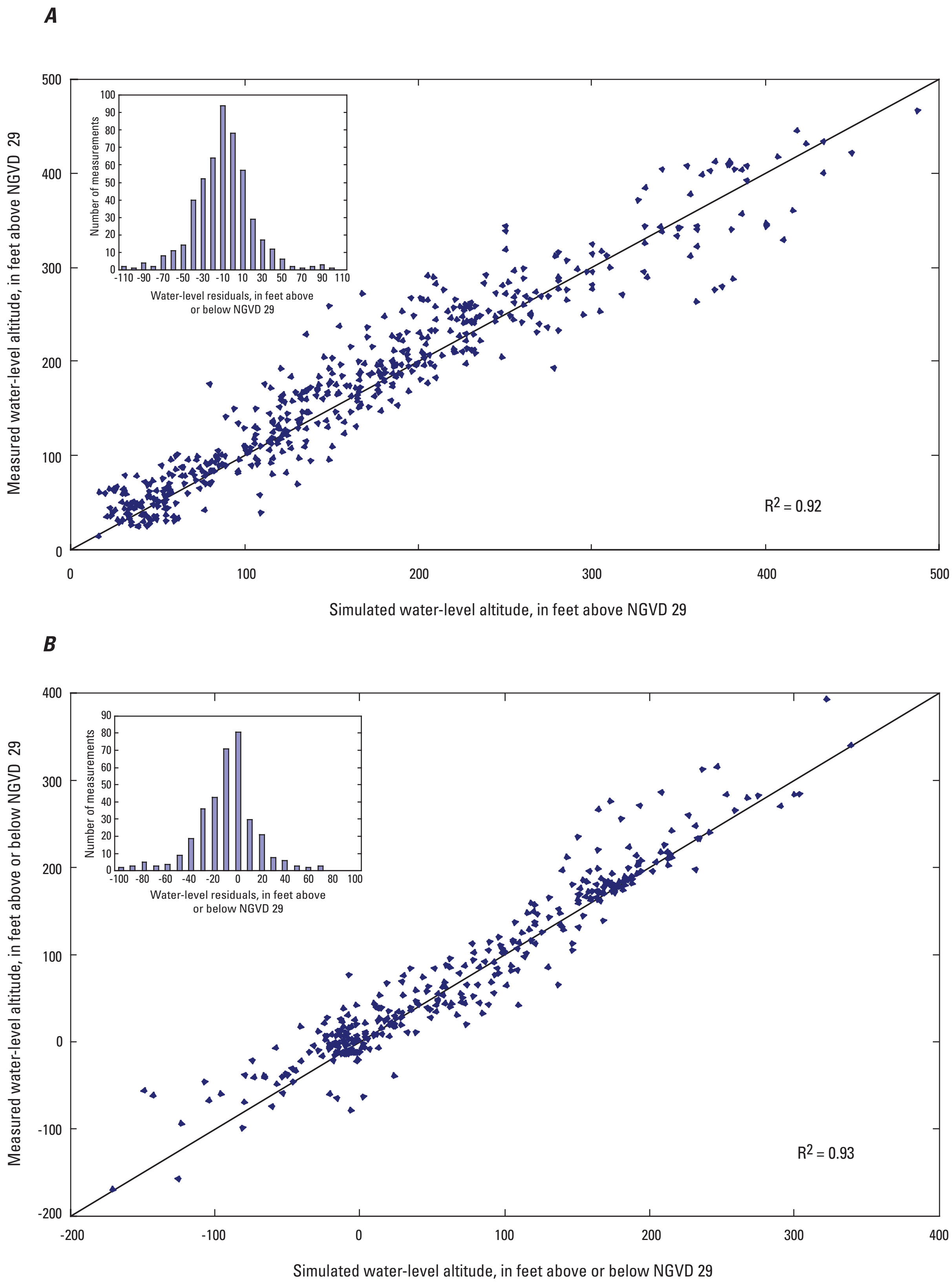
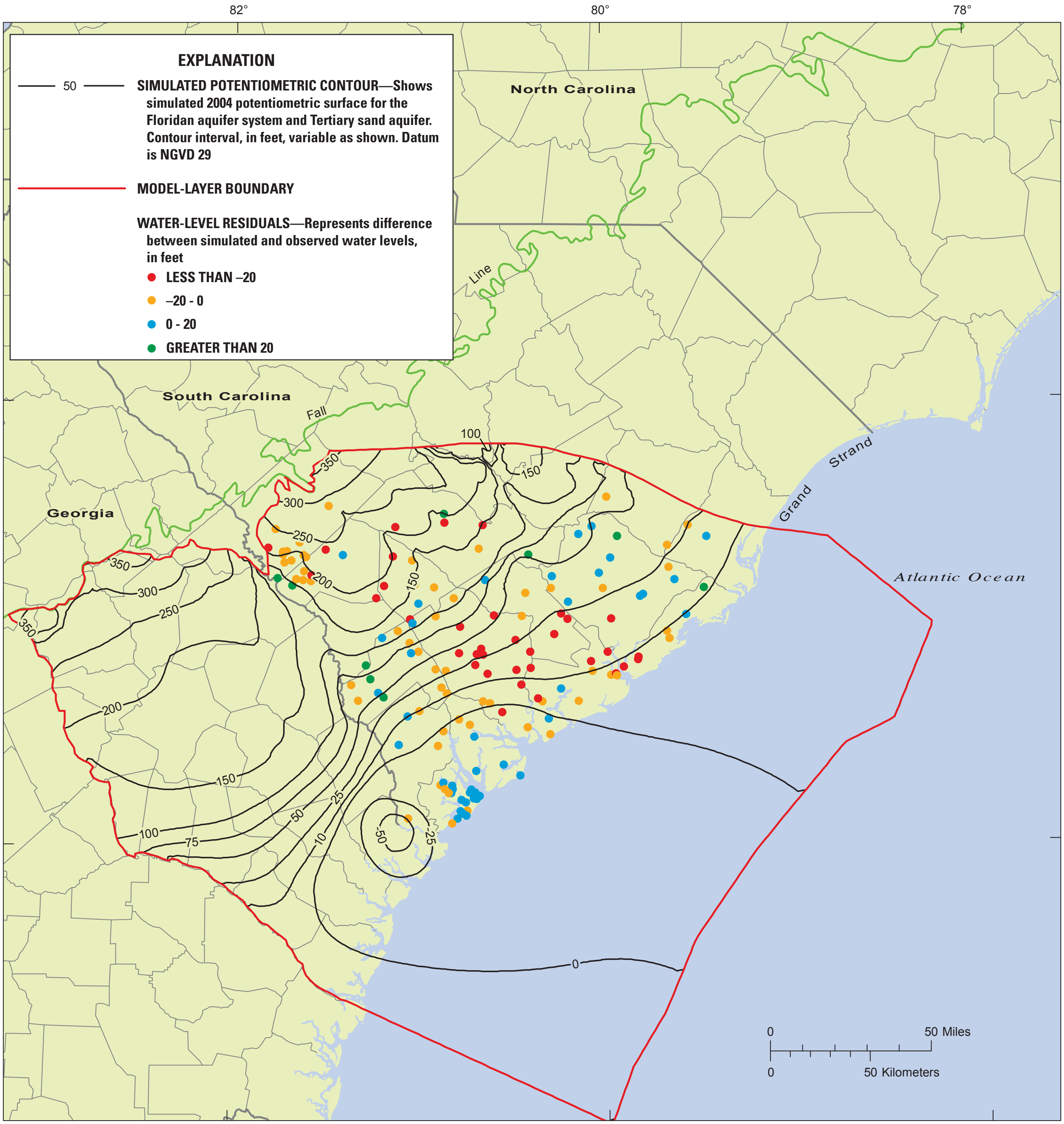
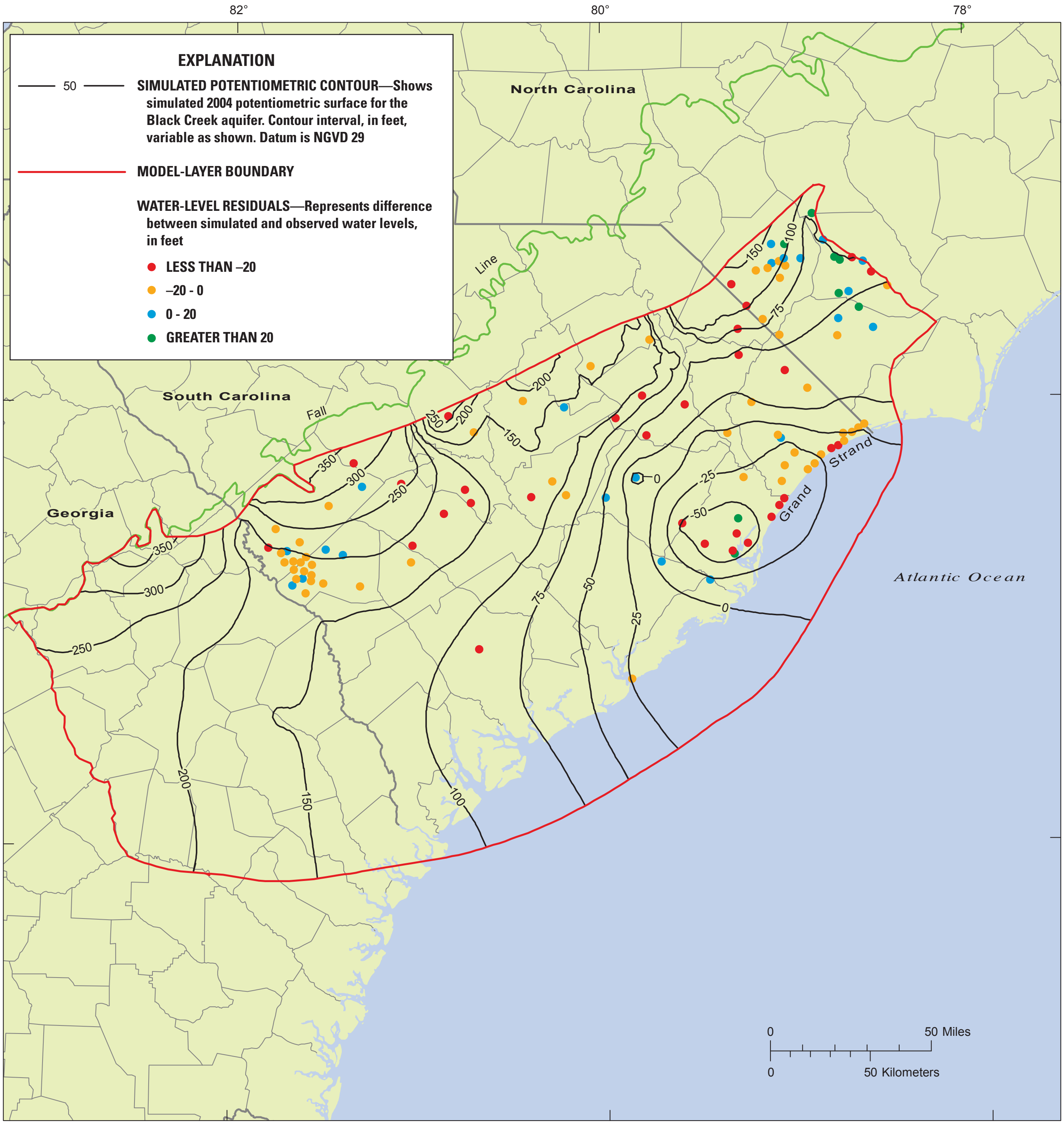


Figure 19. Measured and simulated water-level altitudes for (*A*) predevelopment and (*B*) 2004.



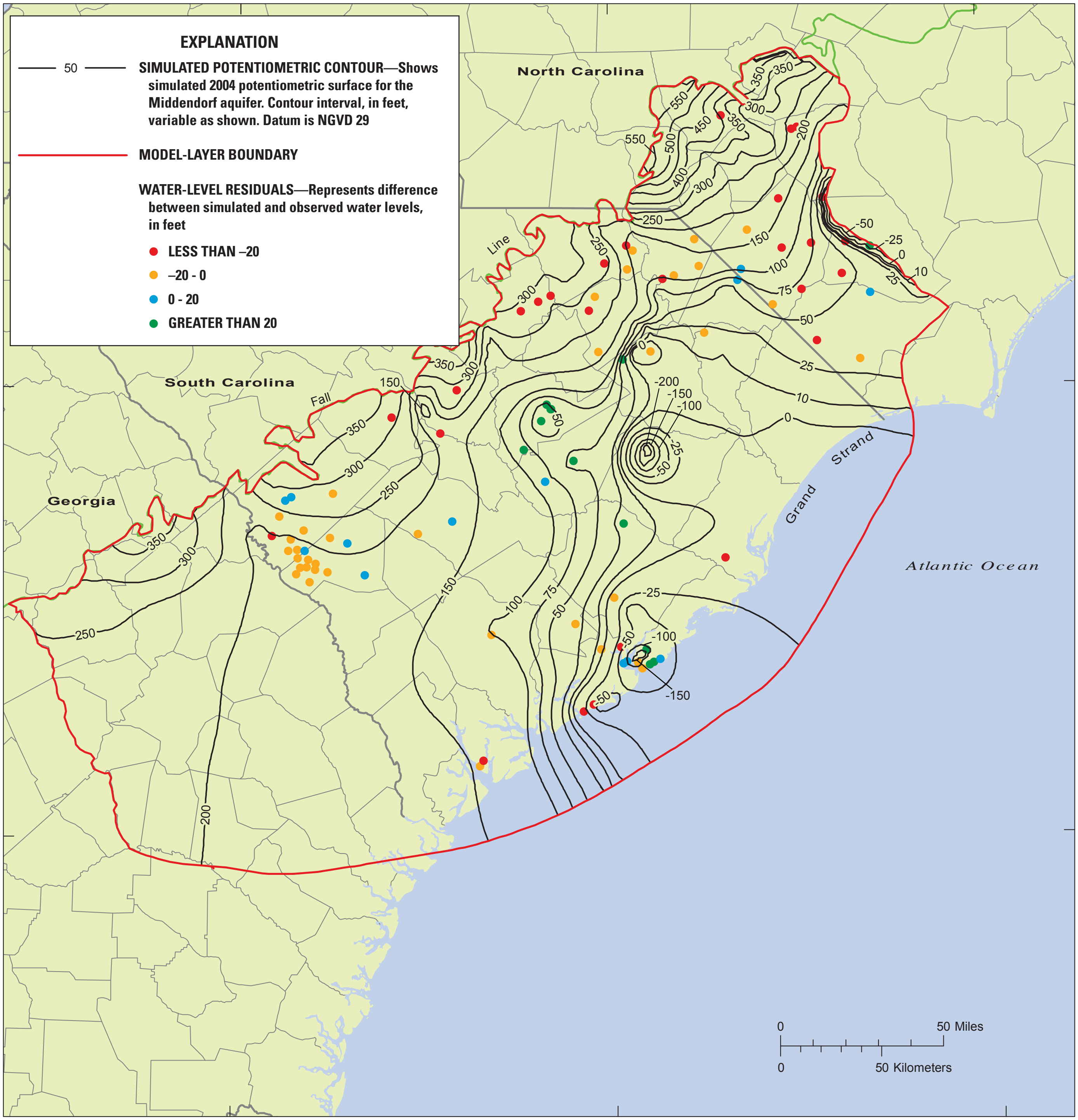
Base from U.S. Geological Survey
1:2,000,000-scale and 1:100,000-scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 20*A*. Simulated 2004 potentiometric surface for the Floridan aquifer system and Tertiary sand aquifer.



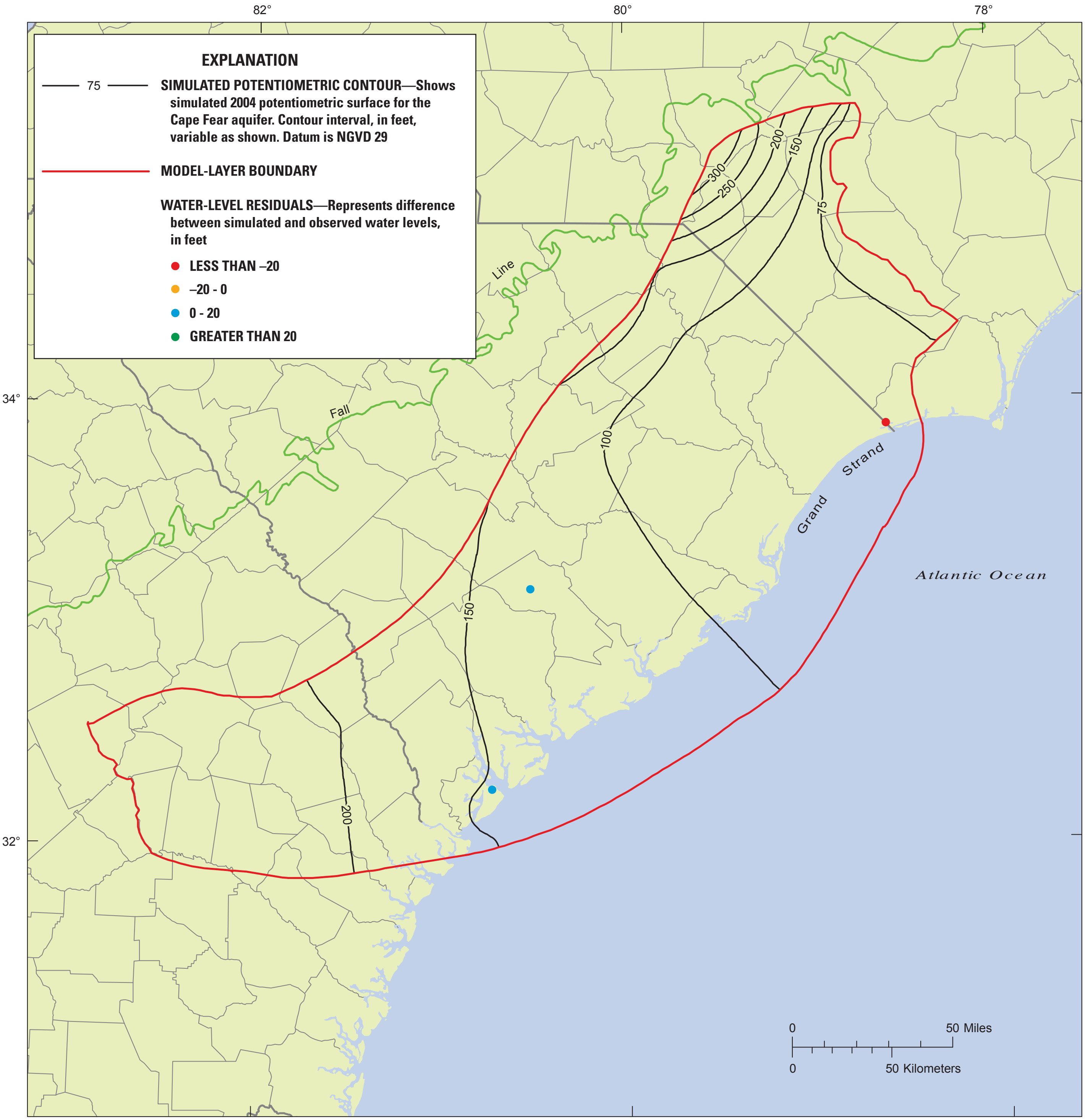
Base from U.S. Geological Survey
1:2,000,000-scale and 1:100,000-scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 20*B*. Simulated 2004 potentiometric surface for the Black Creek aquifer.



Base from U.S. Geological Survey
1:2,000,000-scale and 1:100,000-scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 20*C*. Simulated 2004 potentiometric surface for the Middendorf aquifer.



Base from U.S. Geological Survey
1:2,000,000-scale and 1:100,000-scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 20*D*. Simulated 2004 potentiometric surface for the Cape Fear aquifer.

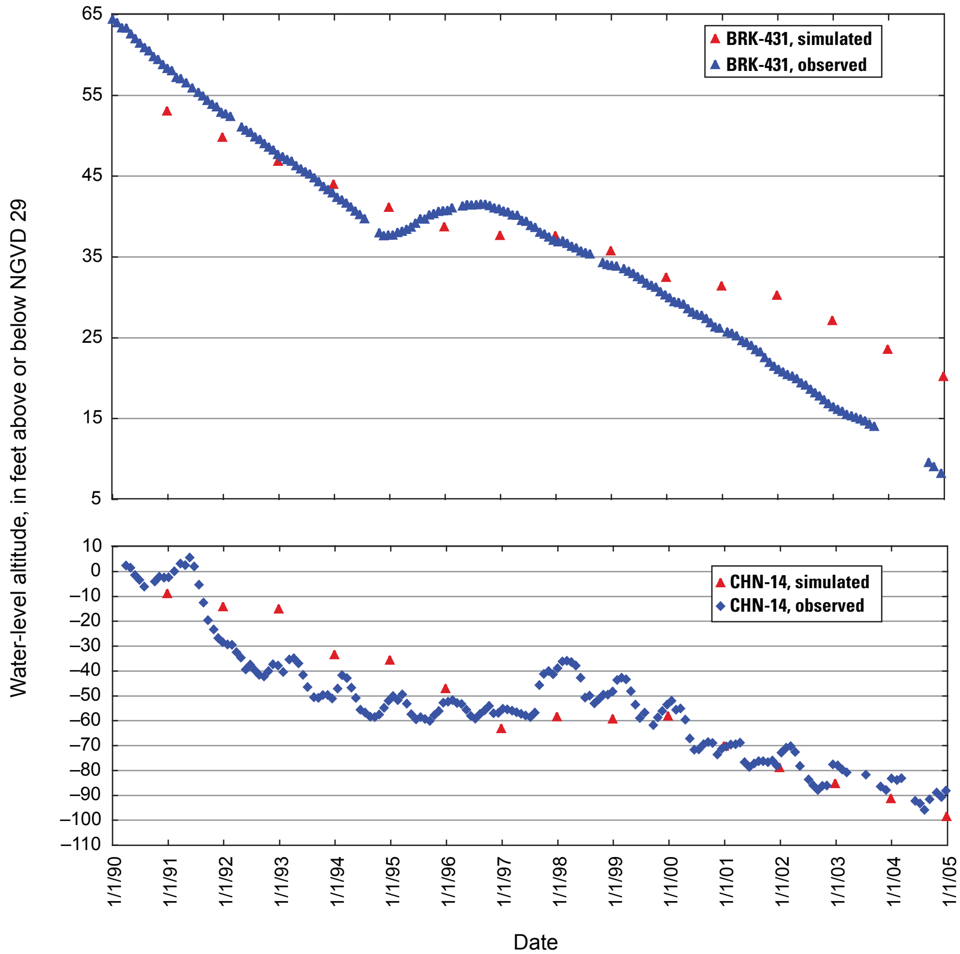


Figure 21. Measured and simulated water-level altitudes for BRK-431, observation well near Moncks Corner, South Carolina, and CHN-14, observation well in Charleston, South Carolina.

distribution of the residuals. Residuals for the predevelopment conditions are normally distributed and produce a coefficient of determination (R^2) from the linear regression analysis of 0.92. Residuals for 2004 conditions are normally distributed and produce an R^2 of 0.93. The percentages of simulated values for all aquifers within the 20-ft calibration target were 56.4 and 64.8 percent for the predevelopment and 2004 simulations, respectively.

Simulation of Baseflow

Observed and simulated stream baseflows were compared at 17 locations in the upper Coastal Plain of North and South Carolina (fig. 15 and table 7). Overall, the model did not simulate the baseflows well. Of the 17 gaging stations, 15 of the model fits undersimulated the baseflow, while 2 oversimulated the baseflow. Generally, the calibration fits on the smaller streams with lower baseflows were simulated more closely, with a better fit on the observed data than the larger streams. The best fit on the observed and simulated data occurred at Rockfish Creek at Raeford, NC (table 7), the stream with the lowest baseflow in the model. The poorest fit occurred at the South Fork Edisto River near Bamberg, the stream with the largest baseflows simulated in the model.

Streambed conductance was estimated during the modeling process. This was done with a geographic information system process that used the location of the river, represented as arcs that intersected the model finite-difference cells. The arcs with relatively longer lengths in a cell had a higher streambed conductance than arcs of relatively shorter lengths in a cell. The streambed conductance terms ranged from a low of 400 ft^2/d to a high of 254,000 ft^2/d.

Sensitivity Testing and Analysis

Ground-water-modeling results can be affected by many model parameters, assumptions, and system stresses. These can include, among others, aquifer and confining unit geometry, model grid size and spacing, model boundary types and locations, and magnitude and areal distributions of stresses, such as ground-water recharge and withdrawals. Riverbed conductance terms along with the vertical and horizontal hydraulic conductivities of the aquifers and confining units

Table 7. Streamflow gaging stations, observed baseflow, and calibrated model results.

[ft³/s, cubic foot per second; ft²/d, square foot per day]

USGS station number	Station name	Period of record, in years	Observed mean baseflow, in ft³/s	Calculated mean baseflow, in ft³/s	Simulated streambed conductance, in ft²/d		
					Mean	Maximum	Minimum
2130900	Black Creek near McBee, SC	1960–2002	122	54.7	89,000	184,000	12,000
2130910	Black Creek near Hartsville, SC	1961–1998	197	3.89	61,000	155,000	8,000
2130500	Juniper Creek near Cheraw, SC	1941–1957	55.3	44.1	48,000	106,000	11,000
2196689	Little Horse Creek near Graniteville, SC	1990–1998	29.9	0.92	34,000	85,000	19,000
2197310	Upper Three Runs Creek above Road C	1975–1997	179	53.4	92,000	168,000	44,000
2197315	Upper Three Runs Creek at Road A	1980–2001	196	97.7	46,000	71,000	13,000
2173351	Bull Swamp Creek near Swansea, SC	2002–2002	5.26	16.7	97,000	196,000	7,000
2169570	Gills Creek near Columbia, SC	1967–2002	47.4	35.3	23,000	79,000	400
2131500	Lynches River near Bishopville, SC	1943–1970	525	109	79,000	185,000	2,700
2173500	North Edisto River near Orangeburg, SC	1939–1999	682	110	107,000	178,000	5,000
2135300	Scape Ore Swamp near Bishopville, SC	1969–2002	74.7	30.0	157,000	254,000	8,000
2173051	South Fork Edisto River near Bamberg, SC	1992–2002	823	7.23	84,000	211,000	20,000
2172500	South Fork Edisto River near Montmorenci, SC	1941–1965	196	10.6	104,000	154,000	3,000
2133500	Drowning Creek near Hoffman, NC	1940–2003	195	74.2	64,000	158,000	8,000
2104220	Rockfish Creek at Raeford, NC	1993–2003	95.8	78.1	87,000	139,000	11,000
2102908	Flat Creek near Inverness, NC	1969–2003	9.41	95.0	86,000	140,000	1,500
2103000	Little River at Manchester, NC	1939–1949	301	31.4	69,000	159,000	5,000

also can significantly affect the results of ground-water models (Kuniansky, 2004). Models that simulate transient flow also are susceptible to effects from the time-step size, number of stress periods, and the aquifer and confining unit storage terms used in the simulation. A complete sensitivity analysis would determine the model sensitivity to all of these parameters and stresses; however, sensitivities within the Mount Pleasant model were tested in a more general way due to the large number of parameters estimated (434). Most of these parameters are horizontal hydraulic conductivities associated with the pilot points, but numerous other parameters were estimated. Sensitive parameters are more likely to be accurately estimated through the modeling process than less sensitive parameters. Insensitive parameters may or may not be close to their corresponding field values and are unlikely to be estimated accurately during the parameter estimation process.

Relative composite sensitivities are a measure of composite changes in model outputs that are caused by small changes in the value of a modeled parameter (Doherty, 2005). For a given modeled parameter, the larger the value of the associated relative composite sensitivity the more sensitive the model is to that parameter. Relative composite sensitivities were calculated and analyzed for 434 parameters used in the model calibration process (table 8). These 434 parameters include 416 hydraulic conductivity (HC) pilot point values, 9 specific storage (SS) values, and 9 vertical anisotropy (VA) values. The results are presented by layer for each of the parameter types (HC, SS, and VA). Median relative composite sensitivity values are presented for the HC arrays because the total number of pilot points varied between 10 and 114 for each of the model layers. To differentiate between sensitive and insensitive parameters, the overall range of relative sensitivities was divided into quartiles. For this investigation, the model is considered sensitive to a parameter if the relative composite sensitivity of that parameter falls within the range of the highest quartile (0.0039–0.41). The model is considered insensitive to a parameter if the relative composite sensitivity falls within the range of the lowest quartile (<0.00035).

Table 8. Distribution of relative sensitivities for 434 model parameters.

[<, less than; —, no data]

Parameter name	Description	Number of parameters	Relative sensitivity (or median of relative sensitivity for number of parameters >1)	Quartile number, range of relative sensitivities in each quartile, and count of parameters in each quartile			
				Quartile 4	Quartile 3	Quartile 2	Quartile 1
				(0.0039–0.41)	(0.0012–0.0039)	(0.00035–0.0012)	<0.00035
HC1	Layer 1 hydraulic conductivity	30	$4.2x10^{-04}$	3	3	8	16
HC2	Layer 2 hydraulic conductivity	10	$6.4x10^{-03}$	7	2	1	0
HC3	Layer 3 hydraulic conductivity	106	$1.3x10^{-03}$	24	30	26	26
HC4	Layer 4 hydraulic conductivity	10	$2.0x10^{-02}$	10	0	0	0
HC5	Layer 5 hydraulic conductivity	114	$7.3x10^{-04}$	8	35	37	34
HC6	Layer 6 hydraulic conductivity	10	$1.9x10^{-02}$	10	0	0	0
HC7	Layer 7 hydraulic conductivity	104	$1.6x10^{-03}$	31	33	25	15
HC8	Layer 8 hydraulic conductivity	10	$6.4x10^{-03}$	6	2	2	0
HC9	Layer 9 hydraulic conductivity	22	$3.2x10^{-04}$	1	1	9	11
SS1	Layer 1 specific storage	1	$9.0x10^{-04}$	—	—	1	—
SS2	Layer 2 specific storage	1	$8.6x10^{-04}$	—	—	1	—
SS3	Layer 3 specific storage	1	$2.0x10^{-02}$	1	—	—	—
SS4	Layer 4 specific storage	1	$2.0x10^{-02}$	1	—	—	—
SS5	Layer 5 specific storage	1	$1.6x10^{-01}$	1	—	—	—
SS6	Layer 6 specific storage	1	$3.2x10^{-02}$	1	—	—	—
SS7	Layer 7 specific storage	1	$2.9x10^{-01}$	1	—	—	—
SS8	Layer 8 specific storage	1	$7.8x10^{-03}$	1	—	—	—
SS9	Layer 9 specific storage	1	$7.4x10^{-03}$	1	—	—	—
VA1	Layer 1 anisotropy	1	$3.3x10^{-07}$	—	—	—	1
VA2	Layer 2 anisotropy	1	$<1.0x10^{-08}$	—	—	—	1
VA3	Layer 3 anisotropy	1	$6.2x10^{-07}$	—	—	—	1
VA4	Layer 4 anisotropy	1	$<1.0x10^{-08}$	—	—	—	1
VA5	Layer 5 anisotropy	1	$9.9x10^{-06}$	—	—	—	1
VA6	Layer 6 anisotropy	1	$1.2x10^{-02}$	1	—	—	—
VA7	Layer 7 anisotropy	1	$9.1x10^{-08}$	—	—	—	1
VA8	Layer 8 anisotropy	1	$4.0x10^{-03}$	1	—	—	—
VA9	Layer 9 anisotropy	1	$1.6x10^{-08}$	—	—	—	1

Overall, the model is most sensitive to specific storage of all layers except 1 and 2; anisotropy of layers 6 and 8; and the hydraulic conductivity pilot points in the confining units (layers 2, 4, 6, and 8; table 8). The model also is sensitive to some of the hydraulic conductivity pilot points for the other model layers; however, the range of the relative composite sensitivities for these layers generally varies across the four quartiles. The model is least sensitive to all anisotropy layers except layer 6 and layer 8, and to the hydraulic conductivity pilot points of layer 9. The model is insensitive to some of the hydraulic conductivity pilot points in the model layers representing aquifers (layers 1, 3, 5, and 7); however, the range of the relative composite sensitivities for these layers generally varies across the four quartiles.

A simple sensitivity analysis of the specified heads in the surficial aquifer model layer was performed to quantify the model sensitivity to changes in the altitude of the specified heads. Simulated water budgets were analyzed after raising and lowering the specified heads in the surficial aquifer by 1 ft to determine the model sensitivity to these changes. Lowering the specified heads in the surficial layer by 1 ft produced an 11-percent decrease in the net water budget component for the specified heads in the surficial layer. A 1-ft increase in the specified heads in the surfical aquifer layer increased the net water budget component for the specified heads by 11 percent for the predevelopment time period. These results indicate that the model is sensitive to changes in the altitude of the specified heads in the surficial layer. The overall model budget, however, was changed very little by this increase and decrease in the specified heads in the surficial aquifer. Increasing the specified heads by 1 ft increased the overall model budget by 0.63 percent, while decreasing the specified heads by 1 ft decreased the overall water budget by 0.32 percent.

Simulated Water Budgets

Water budgets representing inflow and outflow of water for the entire modeled area are presented in figures 22 and 23. These budgets show the inflow and outflow of water to and from the ground-water flow system for modeled hydrologic component per stress period (fig. 22) and per model layer (fig. 23). The water budget components include inflow through recharge, inflow and outflow through specified-head boundaries or rivers, inflow and outflow through storage, and outflow through withdrawal by wells.

The two largest components of the water budget are recharge into the model and discharge to rivers out of the model (fig. 22). While the magnitudes of these two components are approximately equal during the steady-state simulation, recharge exceeds discharge to rivers for all transient stress periods (fig. 22). The next largest component of the water budget is a net flux out of the model through the specified-head boundaries. Water flow into the model from rivers is an additional source of water that exists for each stress period. Removal of water from the model through well discharge begins in stress period 2 and increases over time (fig. 22). At the regional model scale, the net flux of water into or out of the model from storage is tied to the variability in the recharge rate. During periods of relatively higher recharge (for example, stress period 16, fig. 22), water flows out of the model into storage. During periods of relatively lower recharge (for example, stress period 10, fig. 22) water flows into the model through storage.

For both steady-state predevelopment and transient 2004 water budgets (fig. 23) the primary source of water to the model (more than 2,100 Mgal/d) is recharge to layers 1 and 3 (fig. 23). The next highest source of water is from

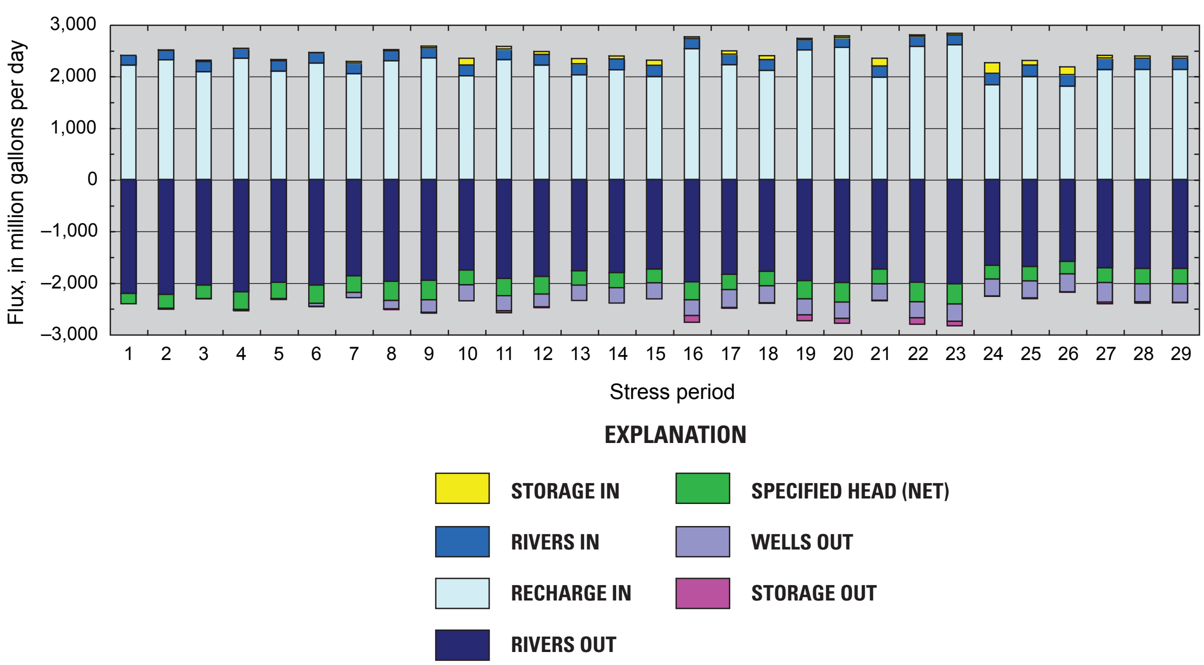


Figure 22. Simulated water budget per stress period from predevelopment to 2004.

specified-head boundaries, which provide a combined 881 and 834 Mgal/d from layers 1 to 3 for the predevelopment and 2004 budgets, respectively. River inflow (layers 1–3) accounts for 186 and 217 Mgal/d for the predevelopment and 2004 water budgets, respectively. For both water budgets, more than 88 percent of the water that discharges from the model discharges from layers 1–3 through specified-head boundaries (greater than 1,080 Mgal/d) and rivers (greater than 1,720 Mgal/d). The overall magnitude of flow between model layers generally decreases with depth (fig. 23). Downward leakage is generally greater than upward leakage for the 2004 budget. Approximately 11 percent (360 Mgal/d) of the water budget is discharged through wells for the 2004 budget.

Water budgets for an area concentrated at Mount Pleasant (fig. 9) were calculated for the calibrated model so that the source of water produced from the Middendorf wells could be understood. Predevelopment flow within this area is predominantly lateral flow within the Middendorf aquifer, with 365,000 gal/d flowing into this zone and 340,000 gal/d flowing out. The vertical component of flow for this zone consists of 6,250 gal/d flowing up from the confining unit located below the Middendorf aquifer and 31,700 gal/d flowing out into the confining unit located above the aquifer. The largest flow component in the 2004 water budget for the Mount Pleasant area is discharge through wells at a rate of 8.11 Mgal/d. Additionally, 27,000 gal/d flows laterally out of this zone to the Middendorf aquifer. Flow into this zone consists predominantly of lateral flow within the Middendorf aquifer at 7.54 Mgal/d. Additionally, 412,000 gal/d is released into this zone from storage. Vertically, 118,000 gal/d flows down from the confining unit located above the Middendorf aquifer and 60,300 gal/d flows up from the confining unit below. Downward flow from the Middendorf confining unit is a reversal of the predevelopment flow direction.

Model Limitations

Ground-water models are simplified numerical approximations of actual ground-water flow systems. The many assumptions incorporated in the development of the model result in limitations to the accuracy of the model and ability of the simulated system to predict actual hydraulic conditions at any given point in the model over time. Factors that could affect the reliability of this model include model scale, the method of stratifying the model into layers, the accuracy and method of distributing the available hydraulic data, the location of and method of simulating aquifer boundaries, and methods of simulating recharge and baseflow in rivers.

The flow model was calibrated to simulate regional ground-water flow throughout the study area. The model uses a variably spaced grid with the best resolution located at Mount Pleasant, where the minimum cell size is 1,000 by 1,000 ft. Elsewhere, the model cell sizes are as large as 10,000 by 10,000 ft. The size of the large cells limits the ability of the model to accurately simulate local conditions such as discharge to wells or rivers.

Lack of knowledge of the altitude and configuration of the water-table altitude within the surficial aquifer is a limitation of the model. Knowledge of these altitudes would result in a more accurate simulation of the specified-head boundary within the surficial aquifer. Sensitivity testing of this boundary condition indicates that the errors in estimating the specified-head altitudes could result in some overall budget error. Sensitivity testing showed an 11-percent increase in the simulated predevelopment water budget component for the specified heads in layer 1 with a 1-ft increase in the surficial aquifer specified-head boundary. A 1-ft decrease in the specified heads in layer 1 resulted in an 11-percent decrease in the simulated predevelopment budget component for the surficial aquifer specified-head boundary. The overall model budget, however, was changed very little by this increase and decrease in the specified heads in the surficial aquifer. Increasing the specified heads by 1 ft increased the overall model budget by 0.63 percent, whereas decreasing the specified heads by 1 ft decreased the overall water budget by 0.32 percent.

The flow model was developed by interpolating data from 96 boreholes into nine continuous layers throughout the study area. Interpolation in areas of limited data or extrapolation of the layers to the model boundaries may produce undesired results such as thinning or thickening of units inappropriately.

Hydraulic data incorporated in the model include hydraulic conductivity values that were approximated using reported transmissivity values and reported and assumed aquifer thicknesses. Hydraulic conductivity values also were estimated during model calibration where actual values were absent. Incorporation of hydraulic conductivity values in the model is further complicated by allowing the measured values to vary up to a factor of 5 during the model calibration process. The absence of reliable hydraulic conductivity data for the confining units limits the overall accuracy of the model. The calibrated distribution of hydraulic conductivity is a large-scale approximation of measured and estimated values; the calibrated results should be considered approximate estimates only.

Water-use data incorporated in the model probably underrepresent the actual historic water use. Specifically, water-use data from the SCDHEC include only those wells that pump at a rate that exceeds 3 Mgal/mo. Historic water use is more uncertain for the earliest years of pumping and more reliable for the more recent water-use years. In addition, water use was assigned to specific aquifers when the aquifer was designated by the water-use provider or when the aquifer could be ascertained from well construction information and interpolated model layering. Water-use data were not used from wells for which well construction information was not available.

Assumptions regarding type and location of model boundaries affect the reliability of the model. Model boundaries for this study were chosen to be similar to the boundaries of previous models of the South Carolina Coastal Plain. In general, model boundaries were placed at natural hydraulic boundaries or at distances far enough from the primary area of focus (Mount Pleasant) so that the choice of boundary did not greatly affect the simulated water levels in Mount Pleasant, SC. Care should be taken when evaluating predicted simulated results outside of this area of focus.

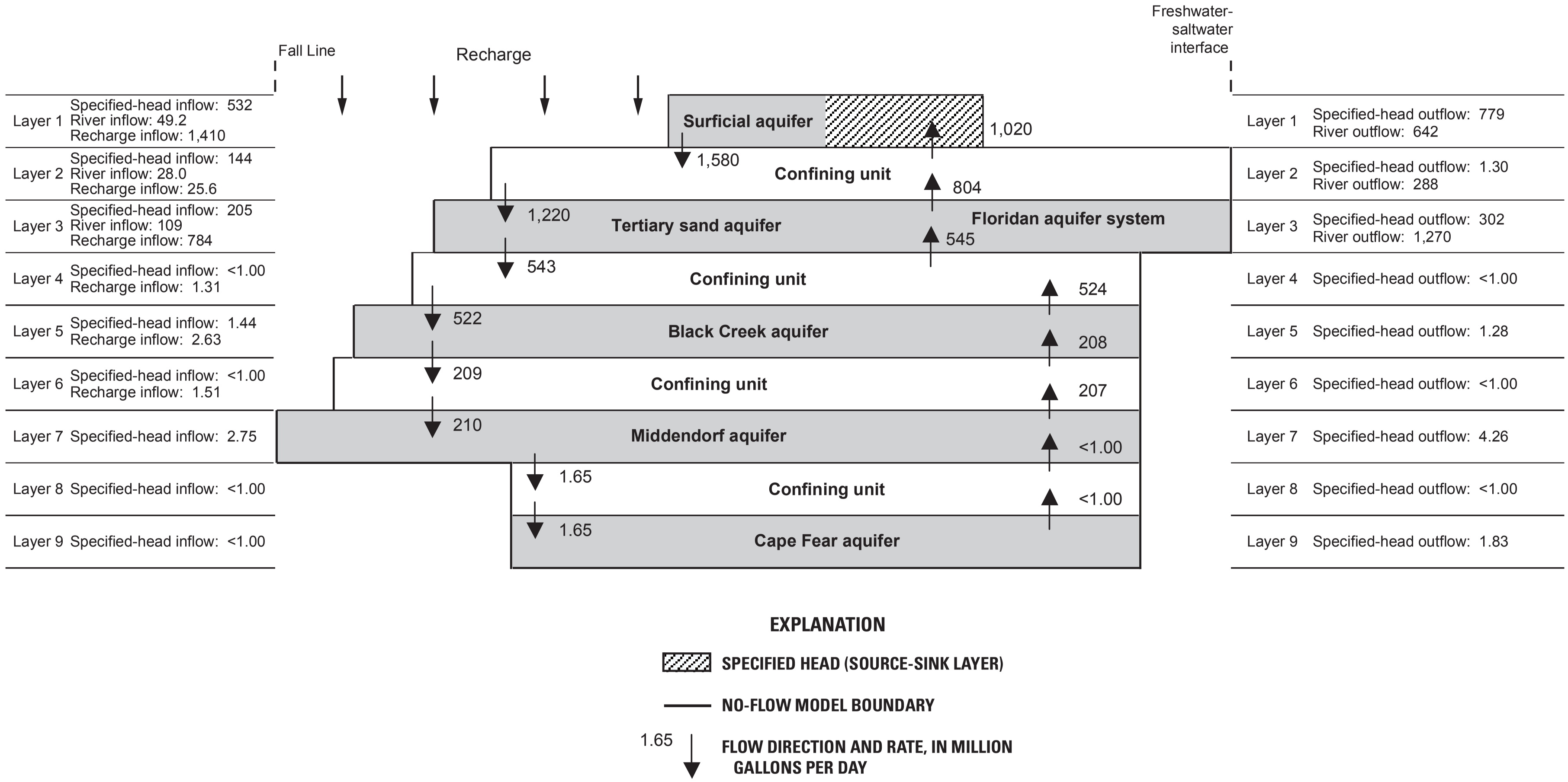


Figure 23A. Simulated water budget per model layer for predevelopment. (Units are in million gallons per day; values are rounded to three significant digits.)

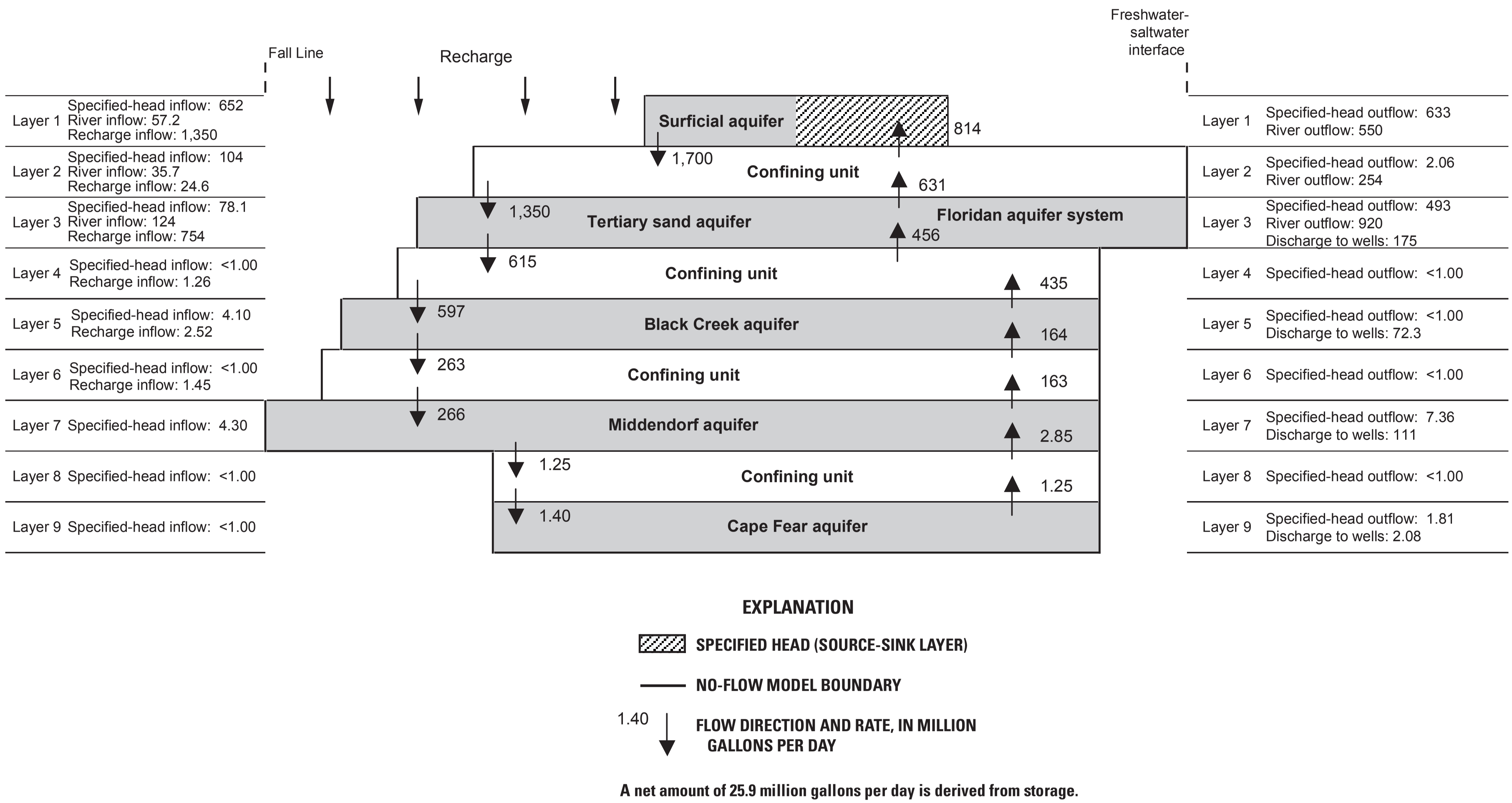


Figure 23*B*. Simulated water budget per model layer for 2004. (Units are in million gallons per day; values are rounded to three significant digits.)

Recharge rates used in the model are net recharge only. Rainfall runoff and evapotranspiration are not simulated in the model, and the six precipitation stations used in the model represent a small fraction of the large area in the model where recharge is simulated. The precipitation data used to estimate the recharge rates and recharge rate variability were collected over a 104-year period and are, most likely, subject to an unknown degree of uncertainty.

The analysis of the stream baseflow data represents only an approximation of actual ground-water baseflow. Daily discharge data from 17 stations located in the upper Coastal Plain of North and South Carolina were used in the model. The periods of record available for analysis varied substantially for each station. Streambed conductance terms simulated in the model are derived from model calibration, as there are no published values or field measurements of streambed conductance available for the study area.

The calibrated model is one representation of the study area over the time simulated. This solution is not unique, and similar results could be achieved through different grid discretizations, model boundary types or locations, and interpolation of model layering or hydraulic properties. The calibrated model is a reasonable solution and can be used for the purpose described in this report.

Model Applications

The calibrated ground-water flow model was used to simulate five predictive water-management scenarios to the year 2030 for the Middendorf aquifer in the Mount Pleasant, SC (Charleston, Berkeley, and Dorchester County), area (fig. 9). The simulations of these scenarios will help MPW understand the effects of and plan for future Middendorf aquifer water use. Mount Pleasant Waterworks currently (2007) operates six wells that withdraw water from the Middendorf aquifer. The predictive simulations use a variety of wells and pumping schedules in the Charleston and Berkeley County area. The following are the scenarios that were simulated from 2005 to 2030:

1. Continue water use from the MPW wells at the annual average rate for years 2000–2004 (table 9);

2. Maximize use of existing wells—withdrawals from existing MPW wells to be at the present design capacity of 10.5 Mgal/d (table 10);

3. Increase withdrawal through additional wells—same as Scenario 2, but three new wells are added in the Charleston and Berkeley County areas (one each in Mount Pleasant, Berkeley County, and Kiawah Island) (table 11; fig. 9);

4. Eliminate drawdown in the Middendorf aquifer—proportionally reduce the withdrawal rate from Scenario 1 so that future drawdown at observations wells CHN-14 and BRK-431 is minimized (table 12); and

5. Decrease industrial water use in the future—same as Scenario 4 but eliminate future industrial water use in Berkeley County in 2010 (table 13).

Numerical results from the five predictive water-management scenarios were evaluated to determine the effects on the Middendorf aquifer. To compare predictive scenario results, the minimum simulated water levels in the Charleston and Berkeley County area for each scenario were tabulated (table 14), and the simulated water levels at observation wells CHN-14 and BRK-431 were plotted (fig. 24). Simulated water-level results at the observation wells were evaluated with respect to the historical data for these wells to ascertain the overall effect of the scenarios in the Mount Pleasant, SC, area. The minimum historical water level for CHN-14 and BRK-431 was –96.08 ft (August 7, 2004) and 5.06 ft (March 7, 2006), respectively.

Table 9. Simulated pumping rates for production wells in the Mount Pleasant, South Carolina, area for model Scenario 1.

[Mgal/d, million gallons per day]

Well name (see figure 25 for well locations)	2004 reported pumping rate, in Mgal/d	Simulated pumping rates, in Mgal/d						
		2005	2006	2008	2010	2015	2020	2025
Well 1	1.34	1.33	1.33	1.33	1.33	1.33	1.33	1.33
Well 2	2.01	1.87	1.87	1.87	1.87	1.87	1.87	1.87
Well 3	0.89	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Well 4	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Well 5	1.12	0.94	0.94	0.94	0.94	0.94	0.94	0.94
Well 6	1.24	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Total	7.51	6.65	6.65	6.65	6.65	6.65	6.65	6.65

Table 10. Simulated pumping rates for production wells in the Mount Pleasant, South Carolina, area for model Scenario 2.

[Mgal/d, million gallons per day]

Well name (see figure 26 for well locations)	2004 reported pumping rate, in Mgal/d	Simulated pumping rates, in Mgal/d						
		2005	2006	2008	2010	2015	2020	2025
Well 1	1.34	2.10	2.10	2.10	2.10	2.10	2.10	2.10
Well 2	2.01	2.94	2.94	2.94	2.94	2.94	2.94	2.94
Well 3	0.89	1.39	1.39	1.39	1.39	1.39	1.39	1.39
Well 4	0.91	1.44	1.44	1.44	1.44	1.44	1.44	1.44
Well 5	1.12	1.49	1.49	1.49	1.49	1.49	1.49	1.49
Well 6	1.24	1.13	1.13	1.13	1.13	1.13	1.13	1.13
Total	7.51	10.50	10.50	10.50	10.50	10.50	10.50	10.50

Table 11. Simulated pumping rates for production wells in the Mount Pleasant, South Carolina, area for model Scenario 3.

[Mgal/d, million gallons per day]

Well name (see figure 27 for well locations)	2004 reported pumping rate, in Mgal/d	Simulated pumping rates, in Mgal/d						
		2005	2006	2008	2010	2015	2020	2025
Well 1	1.34	2.10	2.10	2.10	2.10	2.10	2.10	2.10
Well 2	2.01	2.94	2.94	2.94	2.94	2.94	2.94	2.94
Well 3	0.89	1.39	1.39	1.39	1.39	1.39	1.39	1.39
Well 4	0.91	1.44	1.44	1.44	1.44	1.44	1.44	1.44
Well 5	1.12	1.49	1.49	1.49	1.49	1.49	1.49	1.49
Well 6	1.24	1.13	1.13	1.13	1.13	1.13	1.13	1.13
New Mount Pleasant well	0.00	1.75	1.75	1.75	1.75	1.75	1.75	1.75
New Kiawah Island well	0.00	0.44	0.44	0.44	0.44	0.44	0.44	0.44
New industrial well in Berkeley County	0.00	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Total (Mount Pleasant wells only)	7.51	12.25	12.25	12.25	12.25	12.25	12.25	12.25

Table 12. Simulated pumping rates for production wells in the Mount Pleasant, South Carolina, area for model Scenario 4.

[Mgal/d, million gallons per day]

Well name (see figure 28 for well locations)	2004 reported pumping rate, in Mgal/d	Simulated pumping rates, in Mgal/d						
		2005	2006	2008	2010	2015	2020	2025
Well 1	1.34	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Well 2	2.01	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Well 3	0.89	0.66	0.66	0.66	0.66	0.66	0.66	0.66
Well 4	0.91	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Well 5	1.12	0.71	0.71	0.71	0.71	0.71	0.71	0.71
Well 6	1.24	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Total	7.51	4.99	4.99	4.99	4.99	4.99	4.99	4.99

Table 13. Simulated pumping rates for production wells in the Mount Pleasant, South Carolina, area for model Scenario 5.

[Mgal/d, million gallons per day]

Well name (see figure 29 for well locations)	2004 reported pumping rate, in Mgal/d	Simulated pumping rates, in Mgal/d						
		2005	2006	2008	2010	2015	2020	2025
Well 1	1.34	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Well 2	2.01	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Well 3	0.89	0.66	0.66	0.66	0.66	0.66	0.66	0.66
Well 4	0.91	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Well 5	1.12	0.71	0.71	0.71	0.71	0.71	0.71	0.71
Well 6	1.24	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Industrial wells in Berkeley County	2.35	2.35	2.35	2.35	0.00	0.00	0.00	0.00
Total (Mount Pleasant wells only)	7.51	4.99	4.99	4.99	4.99	4.99	4.99	4.99

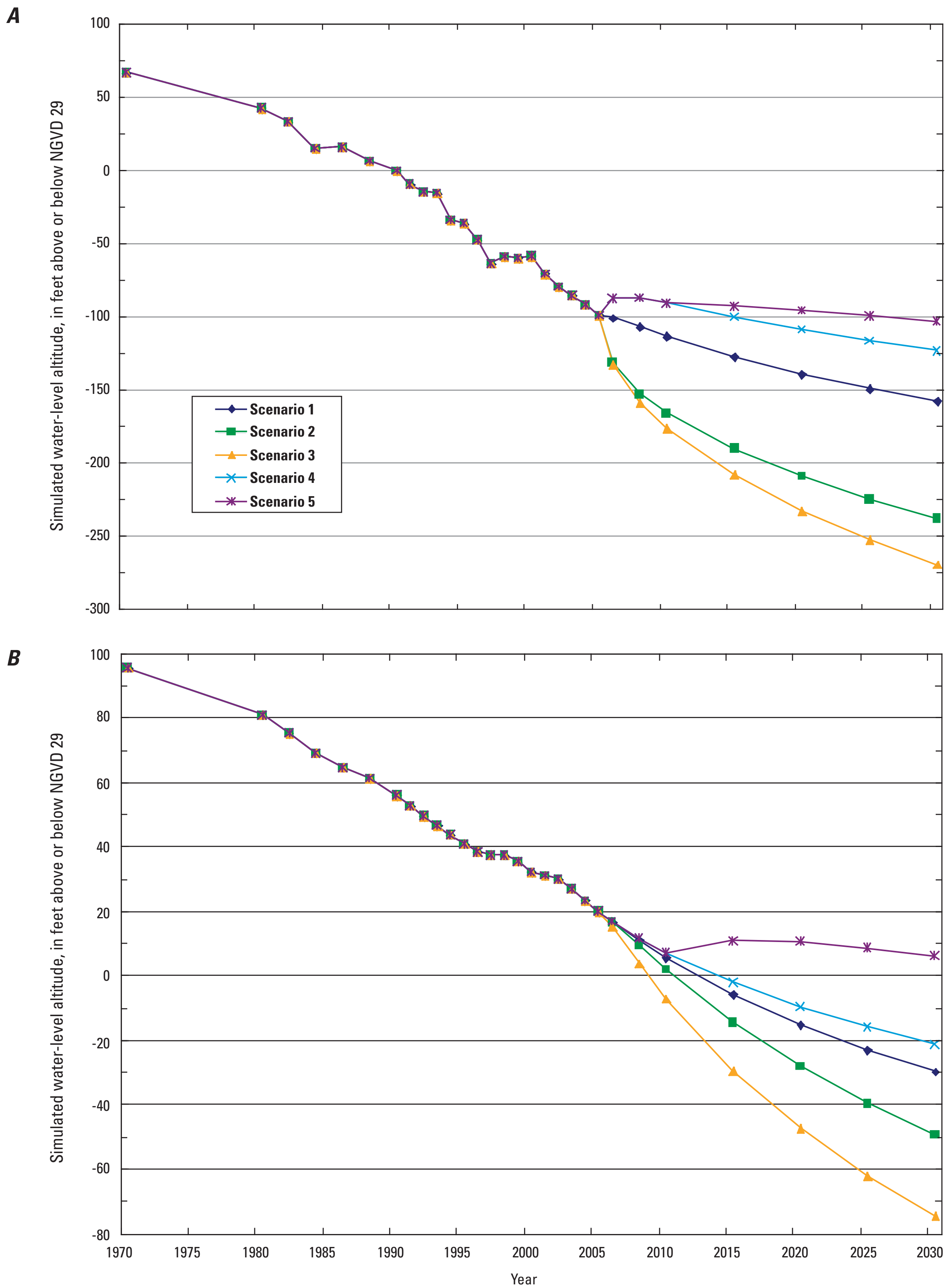


Figure 24. Simulated hydrographs from 1970 to 2030 for wells (*A*) CHN-14 and (*B*) BRK-431 for five model scenarios.

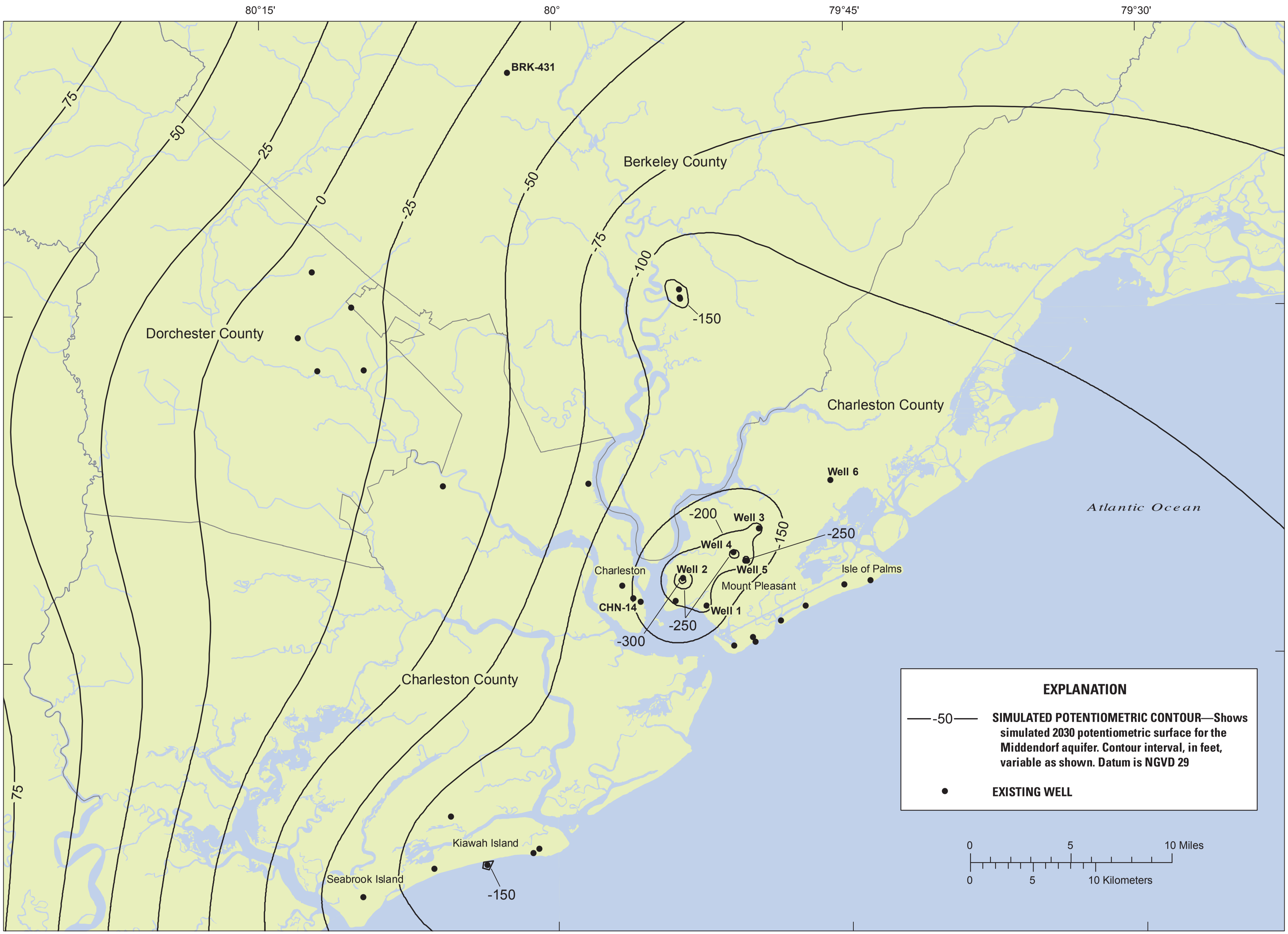
The five predictive scenarios were simulated with the calibrated transient model. Future Middendorf aquifer water use at annual average rates (table 9, Scenario 1) indicates continued drawdown in observation wells CHN-14 and BRK-431 (fig. 24). In the year 2030 simulation (Scenario 1), a minimum water-level altitude of –356 ft is predicted for the Mount Pleasant, SC, area (table 14; fig. 25). Simulated increases in water use at Mount Pleasant to the design capacity of the existing wells (Scenario 2) produce a minimum 2030 water-level altitude of –549 ft (table 14; fig. 26) and sharper declines in the hydrographs of observation wells CHN-14 and BRK-431 (fig. 24). Adding the three additional wells in the Charleston and Berkeley County area (Scenario 3) produces the lowest water-level altitude (–582 ft) of all simulated scenarios for the Mount Pleasant area (table 14; fig. 27). Minimum 2030 water-level altitudes of about –269 and –74.4 ft were predicted for CHN-14 and BRK-431 (fig. 24), respectively, under Scenario 3 (fig. 27).

Scenarios 4 and 5 simulate an initial recovery of water levels from 2004 conditions for observation well CHN-14 and higher 2030 water levels than all other scenarios (figs. 24, 28, and 29; table 14). Both scenarios use pumping rates at 75 percent of the average annual rates reported for the Mount Pleasant wells (tables 12 and 13). While pumping at 75 percent of the average annual rate (Scenario 4) does not eliminate simulated drawdown at observation wells CHN-14 or BRK-431 for year 2030, it does reduce the drawdown to a rate of less than 1.4 ft/yr for both Scenarios 4 and 5. Eliminating industrial water use in Berkeley County in year 2010 (Scenario 5) produced 2030 water-level altitudes at CHN-14 and BRK-431 of –103 and 6.4 ft, respectively. For Scenario 5, the 2030 simulated water-level altitude for BRK-431 was higher than the minimum historic water-level altitude for this well. The simulated 2030 water-level altitude for CHN-14 was within 7 ft of the minimum historic water-level altitude for this well.

Table 14. Minimum simulated water levels for the year 2030 and total drawdown from predevelopment to the year 2030 in the Middendorf aquifer for the Mount Pleasant, South Carolina, area.

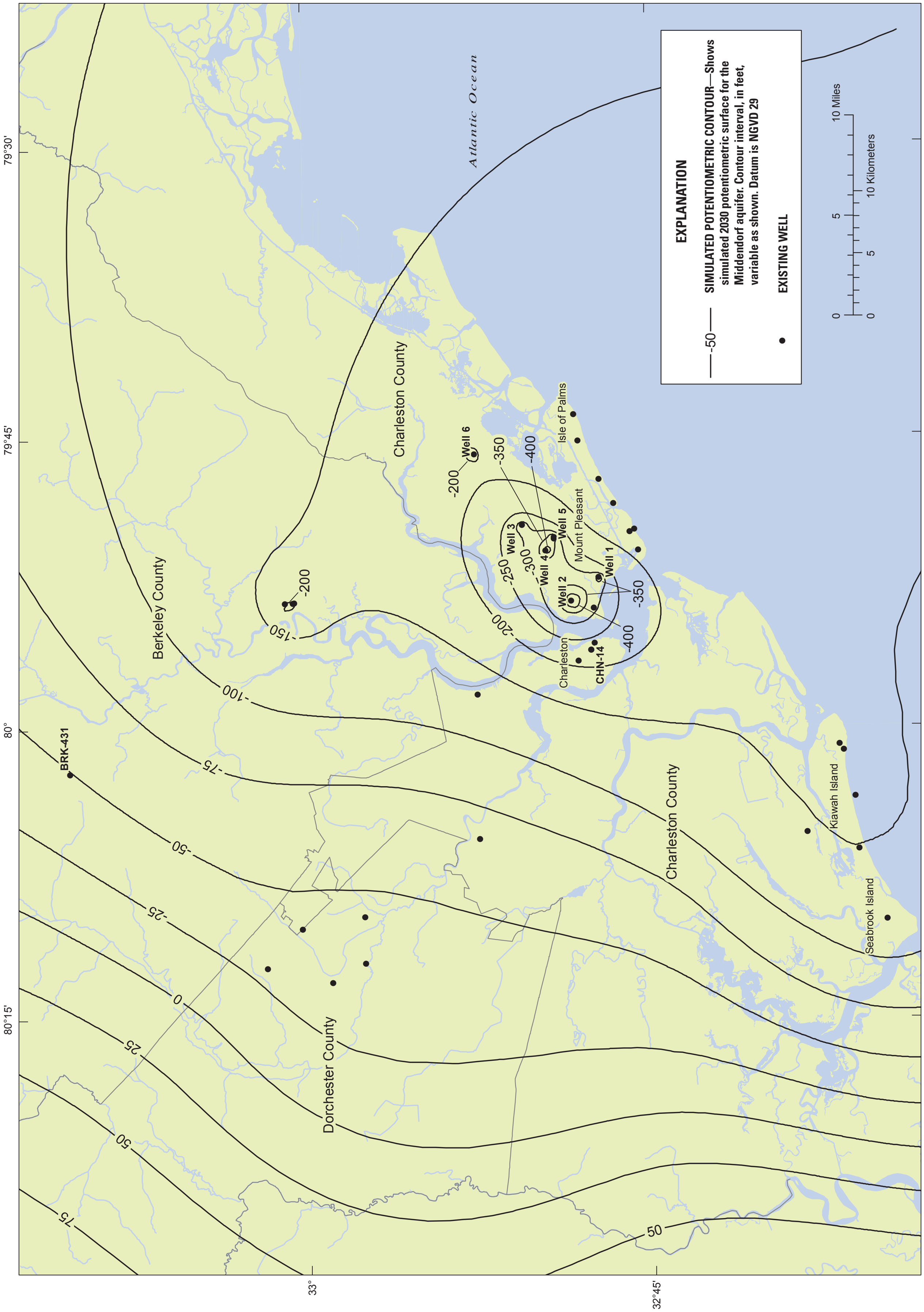
[ft NGVD 29, feet above or below (–) National Geodetic Vertical Datum of 1929]

Scenario	Minimum water level (ft NGVD 29)	Total drawdown from predevelopment (ft)
1	–356	–482
2	–549	–675
3	–582	–708
4	–273	–399
5	–253	–379



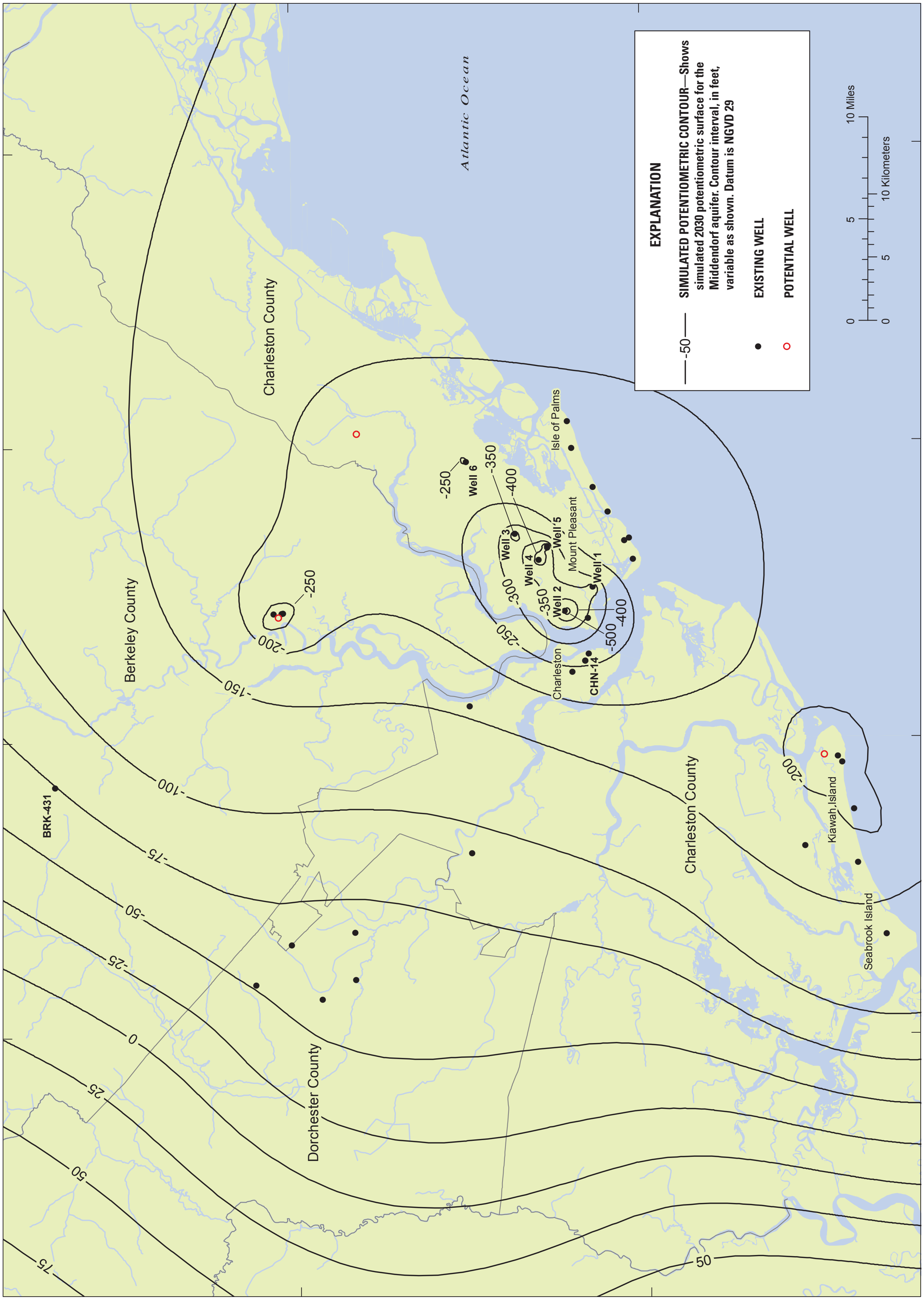
Base from U.S. Geological Survey
1:2,000,000-scale and 1:100,000-scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 25. Simulated potentiometric surface for the Middendorf aquifer in the year 2030 using Scenario 1.



Base from U.S. Geological Survey
1:2,000,000-scale and 1:100,000-scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 26. Simulated potentiometric surface for the Middendorf aquifer in the year 2030 using Scenario 2.



Base from U.S. Geological Survey
1:2,000,000-scale and 1:100,000-scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 27. Simulated potentiometric surface for the Middendorf aquifer in the year 2030 using Scenario 3.

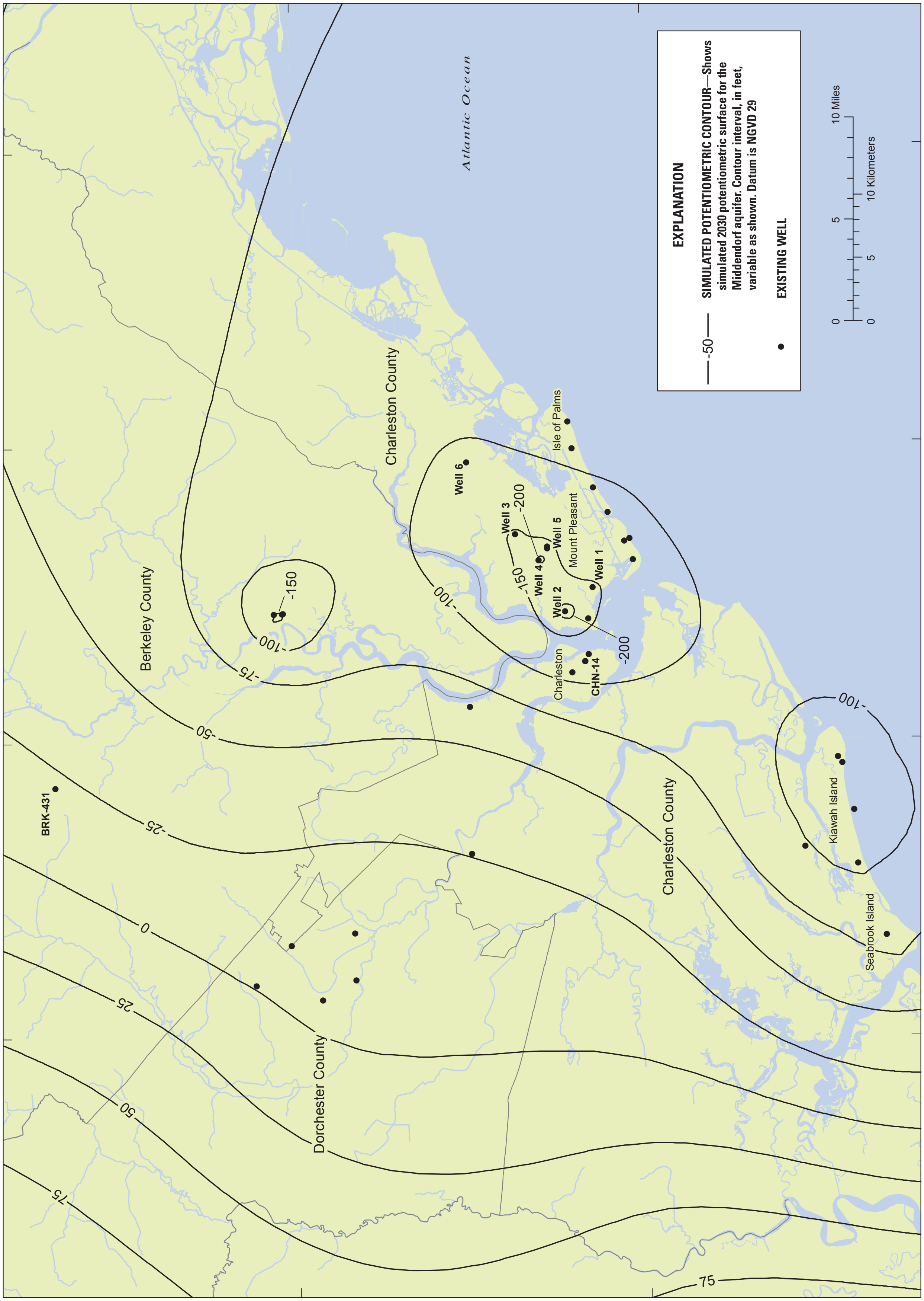
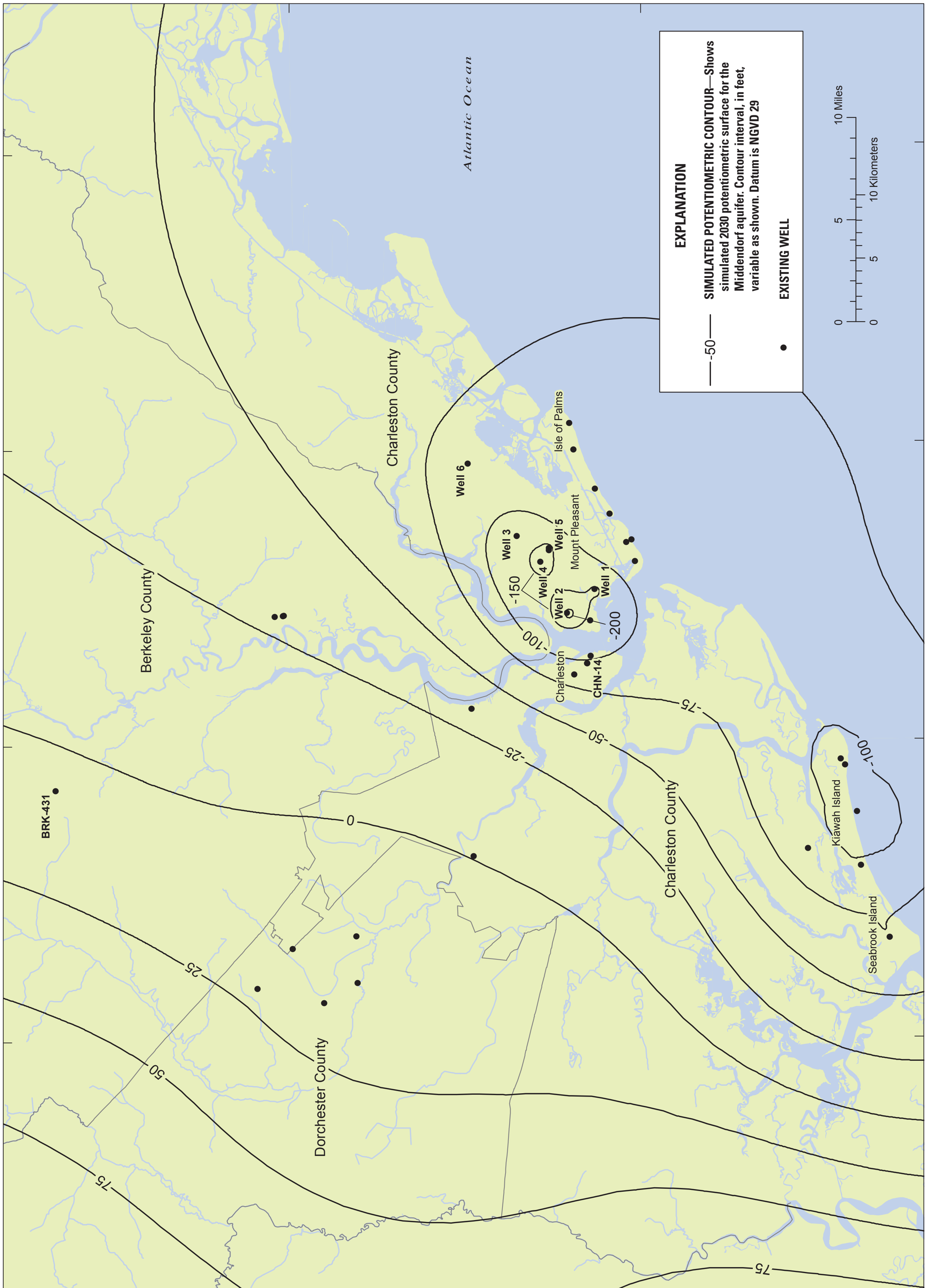


Figure 28. Simulated potentiometric surface for the Middendorf aquifer in the year 2030 using Scenario 4.



Base from U.S. Geological Survey 1:2,000,000-scale and 1:100,000-scale digital line graphs
Lambert Conformal Conic projection
Datum: NAD 83

Figure 29. Simulated potentiometric surface for the Middendorf aquifer in the year 2030 using Scenario 5.

Summary

Water use in Mount Pleasant, along with irrigation pumpage at Kiawah Island, past use by the Town of Summerville, and private industry's use in the Charleston, South Carolina, area have combined to create a large, regional cone of depression in the potentiometric surface of the Middendorf aquifer. To address the concerns of users of the Middendorf aquifer, the U.S. Geological Survey (USGS), in cooperation with Mount Pleasant Waterworks (MPW), updated an existing ground-water flow model to incorporate data through 2004, which have been compiled since a previous investigation. Simulated results produced by the model represent the water-level conditions from predevelopment to 2004 and predictive simulations of water-management scenarios to the year 2030. The results of this investigation will provide MPW and other Charleston, South Carolina, area users of Cretaceous-aquifer ground water with a tool that can be used to manage the ground-water resources of the Charleston, Berkeley, and Dorchester County area. Data used to update the previously calibrated model included hydraulic properties, water-level and water-use data for the aquifers, and ground-water base-flow data to rivers in the study area.

The ground-water flow system of the South Carolina Coastal Plain was simulated using the USGS finite-difference code MODFLOW-2000. The study area consists of about 49,800 square miles in South Carolina, adjacent parts of Georgia and North Carolina, and offshore. Ground-water conditions for predevelopment and 2004 were simulated using steady-state and transient approximations, respectively. The model was vertically discretized into nine layers including the surficial aquifer, Floridan aquifer system and Tertiary sand aquifer, Black Creek aquifer, Middendorf aquifer, and Cape Fear aquifer, separated by four intervening confining units. Specified-head boundary conditions were used at the lateral boundaries of the model and for the lower Coastal Plain part of the surficial aquifer; no-flow boundary conditions were used at the updip and downdip extent of the model layers and at the base of the Cape Fear aquifer.

The model was calibrated using a technique of parameter estimation that uses regularized inversion, an approach that allowed a relatively large number of parameters to be estimated for many of the model inputs, including hydraulic conductivities, specific storage, recharge, riverbed conductance, and vertical anisotropy. Calibrated horizontal hydraulic conductivity values for the aquifers ranged from 1 to 2,000 feet per day (ft/d), with the highest values occurring in the Floridan aquifer system and Tertiary sand aquifer. Horizontal hydraulic conductivity values for the confining units ranged from 0.000001 to 0.00095 ft/d. Horizontal to vertical anisotropy ranged from 1 to 3 for all of the layers modeled. The best fit calibration required specific storage values that were equal to the minimum value allowed (0.0000025) for all layers except the surficial aquifer, where a value of 0.00045 was calibrated.

Ground-water conditions during predevelopment were calibrated using 499 water-level measurements. Residuals for the predevelopment conditions were normally distributed and produce a coefficient of determination (R^2) from the linear regression analysis of 0.92. Simulated residuals had a maximum range from –112 to 95.8 feet (ft), with mean residuals of –3.65, –11.3, –19.2, and 5.45 ft for the Floridan-Tertiary sand, Black Creek, Middendorf, and Cape Fear aquifers, respectively. The percentage of simulated values within the 20-ft calibration target varied between 43 and 64 percent for the individual aquifers with the simulated Middendorf aquifer water levels having the poorest fit. The root-mean-square error (RMSE) for aquifers ranged from 20.2 to 34.4 for the predevelopment calibration. Dividing the standard deviation of model residuals by the overall range of water-level observations for a particular aquifer yielded a fit of calibration equal to 0.154 for the Cape Fear aquifer and less than 0.10 for the other three aquifers. The poorer fit for the Cape Fear aquifer is probably due to the limited number of observations for this model layer.

Ground-water conditions during 2004 were calibrated on the basis of 349 water-level measurements. Residuals for all of the 2004 water-level data are normally distributed and produce a coefficient of determination (R^2) of 0.93. Calculated residuals for all aquifers had a maximum range from –104 to 70.6 ft, with mean residuals of –8.24, –11.1, –11.7, and 0.298 ft for the Floridan-Tertiary sand, Black Creek, Middendorf, and Cape Fear aquifers, respectively. The percentage of simulated values within the 20-ft calibration target varied between 56.2 and 70.1 percent, with the simulated Middendorf water levels having the poorest fit. The RMSE for aquifers ranged from 18.2 to 36.7 ft for the 2004 calibration. Only three water-level measurements were collected from the Cape Fear aquifer during 2004; therefore, statistics are presented but with a low degree of confidence in the results. The fit of calibration for the 2004 data was equal to 0.241 for the Cape Fear aquifer and less than 0.10 for the other three aquifers. The poorer fit for the Cape Fear aquifer is probably due to the limited number of observations for this model layer, as was for the predevelopment calibration.

Overall, the model is most sensitive to specific storage of all layers except 1 and 2; anisotropy of layers 6 and 8; and the hydraulic conductivity in layers 2, 4, 6, and 8. The model also is sensitive to some of the hydraulic conductivity values for the other model layers; however, the range of the relative composite sensitivities for these layers generally varies across the four quartiles representing the full range of values for the individual layers. The model is least sensitive to all anisotropy layers except layer 6 and layer 8 and the hydraulic conductivity of layer 9. Additionally, the model is sensitive to changes in the specified-head boundary conditions of the surficial aquifer.

For both water budgets, the primary source of water to the model (more than 2,100 million gallons per day [Mgal/d]) is recharge to layers 1 and 3. Specified-head boundaries located in layers 1–3 also are significant water sources to the model

and provide combined inflow rates of greater than 881 and 834 Mgal/d, for predevelopment and 2004 water budgets, respectively. More than 88 percent of the water that discharges from the model discharges from layers 1–3 through specified-head boundaries (more than 1,080 Mgal/d) and rivers (more than 1,720 Mgal/d). The overall magnitude of flow between model layers generally decreases with depth. Downward leakage is generally greater than upward leakage for the 2004 budget. Approximately 11 percent (360 Mgal/d) of the water budget is discharged through wells for the 2004 budget.

Predevelopment and 2004 water budgets were calculated for an area concentrated on Mount Pleasant, South Carolina, to help understand the source of water produced by the Middendorf aquifer wells. The predevelopment water budget indicates that lateral flow into this zone accounts for the majority of flow prior to pumping in the Mount Pleasant area. In the 2004 simulation, 8.11 Mgal/d of water is discharged from wells in the Mount Pleasant area. Water to these wells is provided predominantly by lateral flow (7.54 Mgal/d) within the Middendorf aquifer. Additionally, 412,000 gallons per day of water is released into this zone from storage. Leakage from the confining units located above and below the Middendorf aquifer increased from predevelopment to support the pumping demand in the area and provided 179,000 gallons of water per day. Downward flow from the Middendorf confining unit is a reversal of the predevelopment flow direction.

Predictive water-management scenarios to the year 2030 show that continued water use in the Charleston and Berkeley County area at current annual average rates will continue the overall decline in water levels in the area. Pumping Mount Pleasant wells at 75 percent of the annual average rate reduces the rate of drawdown to less than 1.4 ft per year at two existing observation wells in the Charleston and Berkeley County area. Eliminating industrial water use from the nearest Middendorf aquifer water user in Berkeley County in the year 2010 produced 2030 water-level altitudes that were higher than the minimum reported water-level altitudes for one of these wells and within 7 ft of the other.

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