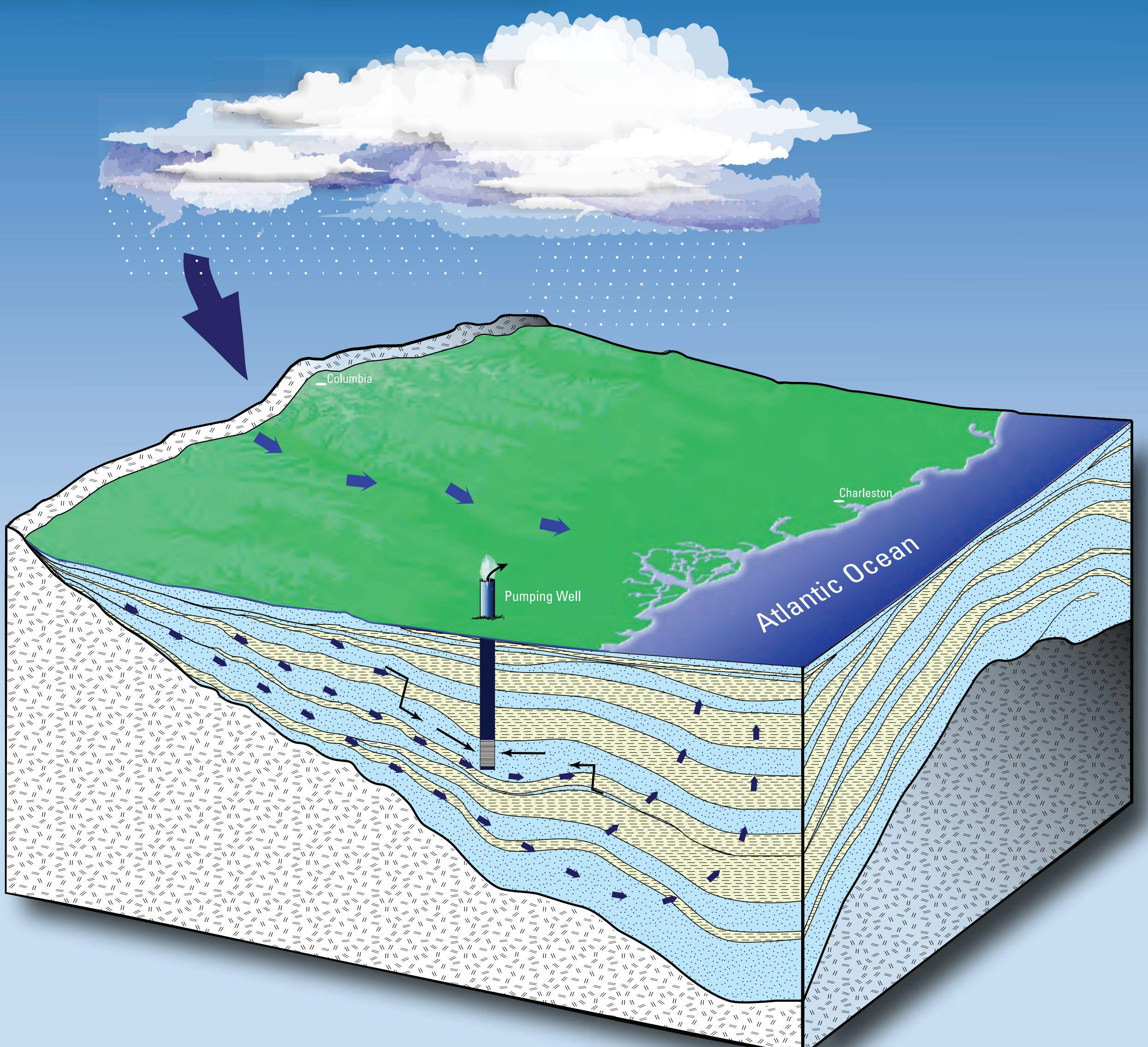
GROUNDWATER RESOURCES PROGRAM

# Groundwater Availability in the Atlantic Coastal Plain of North and South Carolina




Professional Paper 1773

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

**Cover.** Generalized block diagram showing hydrogeology of the Atlantic Coastal Plain, North and South Carolina.

# Groundwater Availability in the Atlantic Coastal Plain of North and South Carolina

Edited by Bruce G. Campbell and Alissa L. Coes

Chapter A

**Groundwater Availability in the Atlantic Coastal Plain of North and South Carolina**

By Bruce G. Campbell, Jason M. Fine, Matthew D. Petkewich, Alissa L. Coes, and Silvia Terziotti

Chapter B

**Hydrogeologic Framework of the Atlantic Coastal Plain, North and South Carolina**

By Joseph A. Gellici and Jeff C. Lautier

Chapter C

**Simulation of Groundwater Flow in the Atlantic Coastal Plain, North and South Carolina and Parts of Eastern Georgia and Southern Virginia, Predevelopment to 2004**

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

**U.S. Geological Survey**
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

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# Foreword

An adequate supply of groundwater is essential for the Nation's health and economic well being. Increased use of groundwater resources and the effects of drought have led to concerns about the future availability of groundwater to meet domestic, agricultural, industrial, and environmental needs. The resulting effects of competition for groundwater from human and environmental uses need to be better understood to respond to the following basic questions that are being asked about the Nation's ability to meet current and future demands for groundwater. Do we have enough groundwater to meet the needs of the Nation? Where are these groundwater resources? Is groundwater available where it is needed? To help answer these questions, the U.S. Geological Survey's (USGS) Groundwater Resources Program is conducting large-scale multidisciplinary regional studies of groundwater availability, such as this study of the Atlantic Coastal Plain aquifer system in North and South Carolina.

Regional groundwater availability studies quantify current groundwater resources, evaluate how those resources have changed through time, and provide tools that decision makers can use to forecast system responses to future development and climate variability and change. These quantitative studies are, by design, large in scope, can include multiple aquifers, and address critical groundwater issues. The USGS has previously identified the Nation's principal aquifers, and they will be used as a framework to classify and study regional groundwater systems.

The groundwater availability studies being conducted for each regional groundwater flow system emphasize the use of long-term groundwater monitoring data, in conjunction with groundwater models, to improve understanding of the flow systems and assess the status and trends in groundwater resources in the context of a changing water budget for the aquifer system. The results of these individual groundwater availability studies will be used collectively as building blocks towards a national assessment of groundwater availability. In addition, these studies will provide the foundational information and modeling tools needed to help State and local resource managers make water availability decisions based on the latest comprehensive quantitative assessment given their regional water-management constraints and goals.

Matthew C. Larsen, Associate Director for Water
U.S. Geological Survey

# Acknowledgments

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Funding for the coring work in South Carolina was provided through the USGS National Geologic Cooperative Mapping Program. David C. Prowell (retired) of the USGS initiated the study, coordinated the drilling activities, described the cores, and determined allostratigraphic and geologic contacts. Jean M. Self-Trail (USGS) described and assigned ages to Cretaceous calcareous nannofossils. Raymond A. Christopher (Clemson University, retired) described and assigned ages to Cretaceous palynomorphs. Laurel M. Bybell (USGS) described and assigned ages to Tertiary calcareous nannofossils. Norman O. Frederiksen (USGS) and Lucy E. Edwards (USGS) described and assigned ages to Tertiary palynomorphs. Karen E. Agerton (SCDNR) assisted in the collection and description of the cores and in the particle-size analyses. Andrew Wachob (SCDNR) obtained the geophysical logs. Eugene Cobbs, II, Eugene Cobbs, III, and Donald Queen (all of the USGS) drilled the cores and constructed some of the monitor wells used in the study.

# Executive Summary


The Atlantic Coastal Plain aquifers and confining units of North and South Carolina are composed of crystalline carbonate rocks, sand, clay, silt, and gravel and contain large volumes of high-quality groundwater. The aquifers have a long history of use dating back to the earliest days of European settlement in the late 1600s. Although extensive areas of some of the aquifers have or currently (2009) are areas of groundwater level declines from large-scale, concentrated pumping centers, large areas of the Atlantic Coastal Plain contain substantial quantities of high-quality groundwater that currently (2009) are unused.

Groundwater use from the Atlantic Coastal Plain aquifers in North Carolina and South Carolina has increased during the past 60 years as the population has increased along with demands for municipal, industrial, and agricultural water needs. While North Carolina and South Carolina work to increase development of water supplies in response to the rapid growth in these coastal populations, both States recognize that they are facing a number of unanswered questions regarding availability of groundwater supplies and the best methods to manage these important supplies.

An in-depth assessment of groundwater availability of the Atlantic Coastal Plain aquifers of North and South Carolina has been completed by the U.S. Geological Survey Groundwater Resources Program. This assessment includes (1) a determination of the present status of the Atlantic Coastal Plain groundwater resources; (2) an explanation for how these resources have changed over time; and (3) development of tools to assess the system's response to stresses from potential future climate variability. Results from numerous previous investigations of the Atlantic Coastal Plain by Federal and State agencies have been incorporated into this effort.

The primary products of this effort are (1) comprehensive hydrologic datasets such as groundwater levels, groundwater use, and aquifer properties; (2) a revised hydrogeologic framework; (3) simulated water budgets of the overall study area along with several subareas; and (4) construction and calibration of a numerical modeling tool that is used to forecast the potential effects of climate change on groundwater levels.

### Hydrogeologic Framework

Interpretations of the hydrogeologic frameworks of the North and South Carolina Coastal Plain have evolved separately during the past 100 years but are combined in this report. Hydrostratigraphic correlations of the Atlantic Coastal Plain sediments at the North Carolina–South Carolina border are presented. Data from 309 boreholes located in North and South Carolina, eastern Georgia, and southern Virginia were used to define the hydrogeologic framework of the Atlantic Coastal Plain aquifers and confining units in the study area. The study area encompasses several formal aquifer systems contained within the sediments of the Atlantic Coastal Plain. Aquifers and confining units located in North Carolina and Virginia are part of the Northern Atlantic Coastal Plain aquifer system. In South Carolina, aquifers and confining units in the Atlantic Coastal Plain sediments are part of either the Southeastern Coastal Plain aquifer system or the Floridan aquifer system. Because the study area crosses the boundaries of these formal aquifer systems, no new formal regional aquifer system will be designated, and the units under study will be referred to as the North and South Carolina Atlantic Coastal Plain aquifers and confining units.

The hydrogeologic framework of the North Carolina Atlantic Coastal Plain aquifers and confining units consists of nine aquifers separated by eight confining units. From top to bottom, the aquifers are the surficial aquifer, Yorktown aquifer, Castle Hayne aquifer, Beaufort aquifer, Peedee aquifer, Black Creek aquifer, Upper Cape Fear aquifer, Lower Cape Fear aquifer, and Early Cretaceous aquifer. The uppermost aquifer (the surficial aquifer in most places) is a water-table aquifer, and the bottom of the system is underlain by various types of crystalline bedrock. Sedimentary deposits forming the aquifers are of Holocene to Cretaceous age and are composed mostly of sand, with lesser amounts of gravel and limestone. The confining units between the aquifers are composed primarily of clay and silt. Total thickness of the aquifers and confining units ranges from 0 feet along the Fall Line to more than 10,000 feet at Cape Hatteras, North Carolina. The most prominent structural feature of the study area is the Cape Fear Arch, the axis of which trends in a southeast direction. The hydrostratigraphy was primarily determined from correlations of geophysical logs and drill cutting descriptions from 149 wells distributed across the North Carolina Coastal Plain. Aquifers were defined using these logs and cuttings, as well as water-level and water-quality data and evidence of the continuity of pumping effects. Structure contour and thickness maps delineate the aquifers and confining units. Hydrogeologic sections depict the correlation of these aquifers throughout the North Carolina Coastal Plain.

The hydrogeologic framework of the South Carolina Coastal Plain consists of 15 hydrostratigraphic units (eight aquifers and seven intervening confining units) that are delineated from records of 38 core holes and 68 water wells. Isopach and structure-contour maps, together with hydrogeologic cross sections, depict the thickness, altitude, and geographic extent of each of the aquifers and confining units in the South Carolina Coastal Plain. The aquifers and confining units are composed of sedimentary materials, such as gravel, sand, silt, clay, and limestone, and range from Late Cretaceous to Tertiary in age. Thickness of the materials ranges from 0 feet at the Fall Line to approximately 4,000 feet in southernmost South Carolina. Biostratigraphic and allostratigraphic data and borehole geophysical logs were used to identify and correlate aquifers and confining units from well to well. Aquifers and confining units are characterized in terms of their lithology, hydrologic properties, and geophysical-log signature. A new hydrostratigraphic nomenclature, first introduced at the Savannah River Site in western South Carolina, is extended across the entire South Carolina Coastal Plain. The aquifers are, in descending order, the surficial aquifer, Upper Floridan aquifer, Middle Floridan aquifer, Gordon aquifer, Crouch Branch aquifer, McQueen Branch aquifer, Charleston aquifer, and Gramling aquifer. Each aquifer, except for the unconfined surficial aquifer, has an associated confining unit of the same name located stratigraphically above the aquifer.

Hydrostratigraphic correlations of the Atlantic Coastal Plain aquifers and confining units at the North Carolina–South Carolina border were made to resolve differences between data used to delineate the hydrogeologic framework within the two States. Detailed hydrostratigraphic cross sections at two locations—between Marietta, North Carolina, and Little Peedee State Park, South Carolina, and between Calabash, North Carolina, and Myrtle Beach, South Carolina—indicate that the downdip area correlates well but the updip area is more complex.

### Hydrologic System Modeling

A three-dimensional finite-difference numerical code (MODFLOW-2000) was used to simulate groundwater flow within the aquifers and confining units of the Coastal Plain of North and South Carolina and parts of Georgia and Virginia. A new groundwater flow model of this area was deemed necessary because previous groundwater models had hydrogeologic inconsistencies at the North Carolina–South Carolina border, and a large amount of new hydraulic, geologic, water-level, and water-use data was available for analysis.

The approximately 70,500-square-mile study area was represented in the model by a grid of 130 rows and 275 columns made up of 4-square-mile cells. The hydrogeologic system of alternating layers of permeable sand or crystalline carbonate rocks separated by confining units of silt, clay, or low-permeability crystalline carbonate rocks was represented by 16 deformed grid model layers. Model layer 1 was designated as a specified-head boundary in areas where the surficial aquifer is underlain by confining units, and recharge was defined by variable-head cells in areas where the aquifers crop out. The no-flow lower model boundary at the bottom of model layer 16 simulates the top of bedrock. The northwestern and southeastern no-flow boundaries of all layers were located at a geologic boundary and the saltwater transition zone, respectively; the northeastern and southwestern boundaries were simulated as specified-head boundaries and were located along large rivers.

The flow simulation began with a steady-state stress period representing predevelopment flow conditions prior to 1900; transient stress periods represent subsequent pumping and variable recharge through 2004. The model was calibrated to conditions representing the three flow systems of pre-1900, 1980, and 2004. The model was calibrated with a type of parameter estimation using pilot points and regularized inversion.

Future uses of the numerical flow model could include optimization techniques to assist in the management of local or subregional groundwater problems such as substantial water-level declines at concentrated pumping centers. The potential effects of new wells on existing groundwater users could be simulated and evaluated. The model could be converted to a variable-density type to simulate saltwater encroachment problems. The local grid refinement package available for MODFLOW-2000 could be used to assist with either of these uses.

**Water Budget Analysis**

The groundwater budgets for the Atlantic Coastal Plain aquifers and confining units of North and South Carolina have changed over time as a result of withdrawals superimposed on the original, natural flow system and from natural variability in the climate, which results in variable recharge rates. Simulation results indicate that high rates of withdrawals produce outflows from storage within the aquifers and confining units and decreases in baseflows to rivers in the inner Coastal Plain. High rates of precipitation cause increases in storage rates within the aquifer system and higher baseflows to the rivers. Overall, the 2004 rates of groundwater withdrawals changed the flow system in subregional areas, but the flow system in large parts of the area’s aquifers and confining units remains relatively unchanged from predevelopment. Concentrated withdrawals combined with poor aquifer properties, however, have produced large groundwater level declines in some areas.

The calibrated groundwater flow model of the Atlantic Coastal Plain aquifers and confining units of North and South Carolina (presented in Chapter C of this report) was used to calculate an overall budget and several local groundwater budgets for the study area. The largest component of the predevelopment and 2004 water budgets is vertical interlayer flow. The next largest budget component is the volume of water that flows into and out of the specified-head boundaries. The total inflow through all specified-head boundaries is approximately equal to the outflow and is approximately 3,700 and 3,600 million gallons per day (Mgal/d) for the predevelopment and 2004 model budgets, respectively. Two other sources of water for the model are (1) a specified recharge rate of about 1,230 Mgal/d for predevelopment and 2004 and (2) inflow from rivers at 13.5 Mgal/d for predevelopment and 16.4 Mgal/d for 2004. Water is removed from the model area by discharge to rivers at rates of 1,051 Mgal/d for predevelopment and 964 Mgal/d for 2004. Discharge of water through pumping wells is another large component of groundwater flow for the model and accounts for 482 Mgal/d in the 2004 water budget. Additionally, during the time simulated by the model (1900–2004), water enters and is released from storage. For the 2004 water budget, rates of flow into and out of storage are 43 and 56 Mgal/d, respectively.

A detailed, simulated groundwater flow budget is presented for the North Carolina Central Coastal Plain Capacity Use Area, a 15-county area in which groundwater levels have been declining since before 1960 in the Black Creek and Upper Cape Fear aquifers. The budget analysis for this area revealed that most predevelopment groundwater flow is concentrated in the upper aquifers of Tertiary age. Predevelopment groundwater flow occurs primarily into and out of the surficial aquifer, which is simulated as a specified-head boundary. These rates of flow are 98.2 Mgal/d into the specified head boundary and 85.4 Mgal/d out of the boundary. Predevelopment groundwater flows within the aquifers and confining units of Cretaceous age are characterized as sluggish because of low water-level gradients. In 2004, the largest water budget component for the area is specified-head flow into and out of the surficial aquifer at 199 and 55.6 Mgal/d, respectively. Vertical flow is highest in the upper layers and decreases with depth for both predevelopment and 2004 conditions. The decrease from predevelopment to 2004 is not as pronounced as in the predevelopment budget. Additional downward flow of water replaces water that is removed from the aquifers by pumping. Water is removed from storage from the Black Creek, Upper Cape Fear, and Lower Cape Fear aquifers at rates of 3.52, 2.85, and 1.73 Mgal/d, respectively, as a result of pumping from these aquifers. Lateral groundwater flow into this area increased from predevelopment rates for some of the model layers and most significantly to 5.52 Mgal/d through the Upper Cape Fear aquifer because of pumping.

Simulated groundwater flow budgets for predevelopment conditions in the Sumter, South Carolina area, indicate that recharge and specified-head inflow rates were 8.01 and 4.03 Mgal/d, respectively. Lateral flow within the model layers was less than 1 Mgal/d for each layer, except within the Crouch Branch aquifer (2.81 Mgal/d) and McQueen Branch aquifer (2.21 Mgal/d). The simulated 2004 groundwater budget for the Sumter area includes pumping from the Crouch Branch and McQueen Branch aquifers at rates of 1.20 and 8.53 Mgal/d, respectively. Recharge to the surficial aquifer (8.01 Mgal/d), specified-head flow into the surficial aquifer (5.13 Mgal/d), and lateral flow into the Crouch Branch and McQueen Branch aquifers at rates of 2.88 and 7.65 Mgal/d, respectively, are the major sources of water to the Sumter area. Changes in storage are insignificant in the Sumter area in 2004.

For the Aiken, South Carolina area, recharge is by far the greatest source of groundwater at a rate of 33.6 Mgal/d. Water flows into the surficial aquifer through rivers and lateral groundwater flow at rates of 1.47 and 2.67 Mgal/d, respectively. Lateral flow also occurs in the Upper Floridan confining unit and the Crouch Branch aquifer at rates of 1.68 and 1.39 Mgal/d, respectively. Discharge of groundwater from the surficial aquifer to rivers is the most substantial loss of water in the Aiken area at 16.2 Mgal/d. Water also flows out of the Aiken area through lateral flow within the surficial aquifer, Upper Floridan confining unit, Upper Floridan aquifer, Middle Floridan aquifer, Gordon confining unit, Crouch Branch aquifer, and McQueen Branch aquifer at rates that vary between 1.33 and 8.50 Mgal/d, with the highest rate occurring in the surficial aquifer. Pumping during 2004 in the Aiken area caused an increase in the downward flow of water within all of the aquifers present in the area. Most of the groundwater withdrawals in the Aiken area are from pumping the Crouch Branch and McQueen Branch aquifers at rates of 1.27 and 5.41 Mgal/d, respectively. With the exception of a decrease in discharge to rivers in the surficial aquifer of 6.1 Mgal/d for the 2004 water budget, all other budget terms are similar to those of predevelopment. Changes in storage are insignificant in the Aiken area.

# Contents

## Chapter B

*Hydrogeologic Framework of the Atlantic Coastal Plain, North and South Carolina*

## Chapter C

*Simulation of Groundwater Flow in the Atlantic Coastal Plain, North and South Carolina and Parts of Georgia and Virginia, Predevelopment to 2004*



# Plates

[In pocket]

# Figures

## Chapter A

**Chapter B**

**Chapter C**

# Tables

# Conversion Factors

Inch/pound to SI

| 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 ($mi^2$) | 2.58998 | square kilometer ($km^2$) |
| | Flow rate | |
| inch per year (in/yr) | 2.54 | centimeter per year (cm/yr) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| cubic foot per day ($ft^3/d$) | 0.67944 | cubic meter per day ($m^3/d$) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3/s$) |
| gallons per minute (gal/min) | 0.06309 | liter per second (L/s) |
| | 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 ($m^2/d$) |
| | Riverbed conductance | |
| foot squared per day per foot [$(ft^2/d)/ft$] | 0.09290 | meter squared per day per meter [$(m^2/d)/m$] |
| | Hydraulic gradient | |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer (m/km) |

SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |

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

°F=(1.8×°C)+32

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

°C=(°F–32)/1.8

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

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.

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

## Acronyms and Abbreviations

| | |
|---|---|
| ACP | Atlantic Coastal Plain |
| CCPCUA | Central Coastal Plain Capacity Use Area |
| CUA | Capacity Use Area |
| DEM | Digital Elevation Model |
| DWR | Division of Water Resources |
| ENSO | El Niño/Southern Oscillation |
| FL | Florida |
| GA | Georgia |
| GCM | Global Climate Model |
| GIS | Geographic Information System |
| GPS | Global Positioning System |
| Ma | Mega annum (million years) |
| MAGICC | Model for the Assessment of Greenhouse Gas Induced Climate Change |
| MODFLOW-2000 | Modular Flow Model |
| NC | North Carolina |
| NCCPCUA | North Carolina Central Coastal Plain Capacity Use Area |
| NED | National Elevation Dataset |
| NWIS | National Water Information System |
| Ohm-m | Ohm-meters |
| $\Phi$ | The logarithmic transformation of the ratio of a grain diameter in millimeters to a standard grain diameter of 1 millimeter |
| $R^2$ | Coefficient of determination of a linear regression |
| RASA | Regional Aquifer-System Analysis |
| SC | South Carolina |
| SCDHEC | South Carolina Department of Health and Environmental Control |
| SCDNR | South Carolina Department of Natural Resources |
| SCENGEN | Scene Generator |
| SP | Spontaneous Potential |
| SRS | Savannah River Site |
| TDEM | Time Domain Electromagnetic |
| USGS | U.S. Geological Survey |
| VA | Virginia |

# Chapter A. Groundwater Availability in the Atlantic Coastal Plain of North and South Carolina

By Bruce G. Campbell, Jason M. Fine, Matthew D. Petkewich, Alissa L. Coes, and Silvia Terziotti

## Introduction

Groundwater withdrawals from Atlantic Coastal Plain (ACP) aquifers in North Carolina (NC) and South Carolina (SC) have increased during the past 30 years in response to demands for water by a rapidly increasing population. The combined populations of counties in the NC and SC ACP totaled nearly 6 million people, with 3.2 million located in NC and 2.5 million in SC (Campbell, 1997; Perry and Mackun, 2001). These respective populations composed about 40 percent of the total NC population and about 60 percent of the total SC population. In NC, the population increased 21.4 percent from 1990 to 2000 (Perry and Mackun, 2001) and is projected to increase another 13.7 percent by the year 2015 (Campbell, 1997). The population in SC increased 15.1 percent from 1990 to 2000 and is projected to increase an additional 13.2 percent by 2015. While NC and SC endeavor to meet water-supply needs in response to rapid coastal population growth, both States recognize that better information is needed regarding groundwater supplies.

Historically, groundwater use from the ACP aquifers in North and South Carolina dates to at least 1670 when European settlers arrived in what is now Charleston, SC, and constructed shallow, hand-dug wells (Lynch and others, 1882; *fig. A1*). With time and increasing population, Charleston began to have water-quality problems with the surficial aquifer, so other sources of water supply were sought, especially deeper, confined aquifers. Developing these deeper aquifers for adequate groundwater supplies led to declining water levels in the study area, which in some cases, date back to the latter part of the 19th century.

The recent drought (1998–2002) in the Eastern United States highlighted the problem of declining groundwater levels. During the drought, surficial aquifer groundwater levels in the ACP and Piedmont of the Carolinas declined to some of the lowest levels on record (Gellici and others, 2004; Weaver, 2005). While drought conditions do not affect the deeper, confined aquifers to the same extent as the shallow aquifers, additional water was pumped from the deep aquifers during the drought to supply increased water demands in the area resulting from the lack of precipitation. During the 1998–2002 drought, ACP groundwater levels declined an average of 8.7 feet (ft) in SC, and record-low groundwater levels were recorded at many of the groundwater monitoring stations (Gellici and others, 2004; *fig. A2*). In NC, record-low groundwater levels were observed during water year 2002[1] in 100 of 137 wells monitored in the State (Weaver, 2005).

North and South Carolina water-resource regulatory agencies recognize the need for cooperation in addressing critical groundwater issues. The States further recognize the need for current groundwater management tools, such as an updated groundwater flow model for the ACP region. Currently (2009), neither NC nor SC has an up-to-date groundwater flow model of the ACP. However, since the completion of the U.S. Geological Survey (USGS) Regional Aquifer System Analysis (RASA) models in both States in the 1980s, an abundance of groundwater use, water-level, and hydrogeologic framework data have been collected.

One approach taken by NC and SC for dealing with water demands in critical areas is to manage groundwater resources on a smaller scale (subregional) by way of establishing Capacity Use Areas in which groundwater withdrawals are individually permitted and groundwater levels are regularly monitored (*fig. A3*). However, there remains a need to examine all the competing demands across the ACP to better understand the cumulative effects on the regional groundwater resources now and in the future. The situation in the ACP is not unlike what is occurring in areas across the United States that use other major aquifers (Reilly and others, 2008). Groundwater systems under stress from population increases and climatic variability accentuate the need for an updated status on the availability of groundwater resources throughout the United States. An assessment of the current status of the groundwater flow in principal aquifers, such as the ACP aquifers and confining units, could be invaluable for assessing groundwater availability.

The USGS Groundwater Resources Program is using the quantitative work previously conducted by the RASA Program and other water-related investigations conducted by local, State, and other Federal agencies to provide updated quantitative assessments of groundwater availability in areas of critical importance. The focus of this study is to define a consistent hydrogeologic framework spanning the two States within the ACP aquifers and confining units and to improve the fundamental knowledge of groundwater availability in the ACP aquifers of North and South Carolina, including water fluxes, storage, and water use by a variety of human activities.

[1] Water year is the period October 1 through September 30 and is identified by the year in which the period ends. For example, water year 2002 began on October 1, 2001, and ended on September 30, 2002.

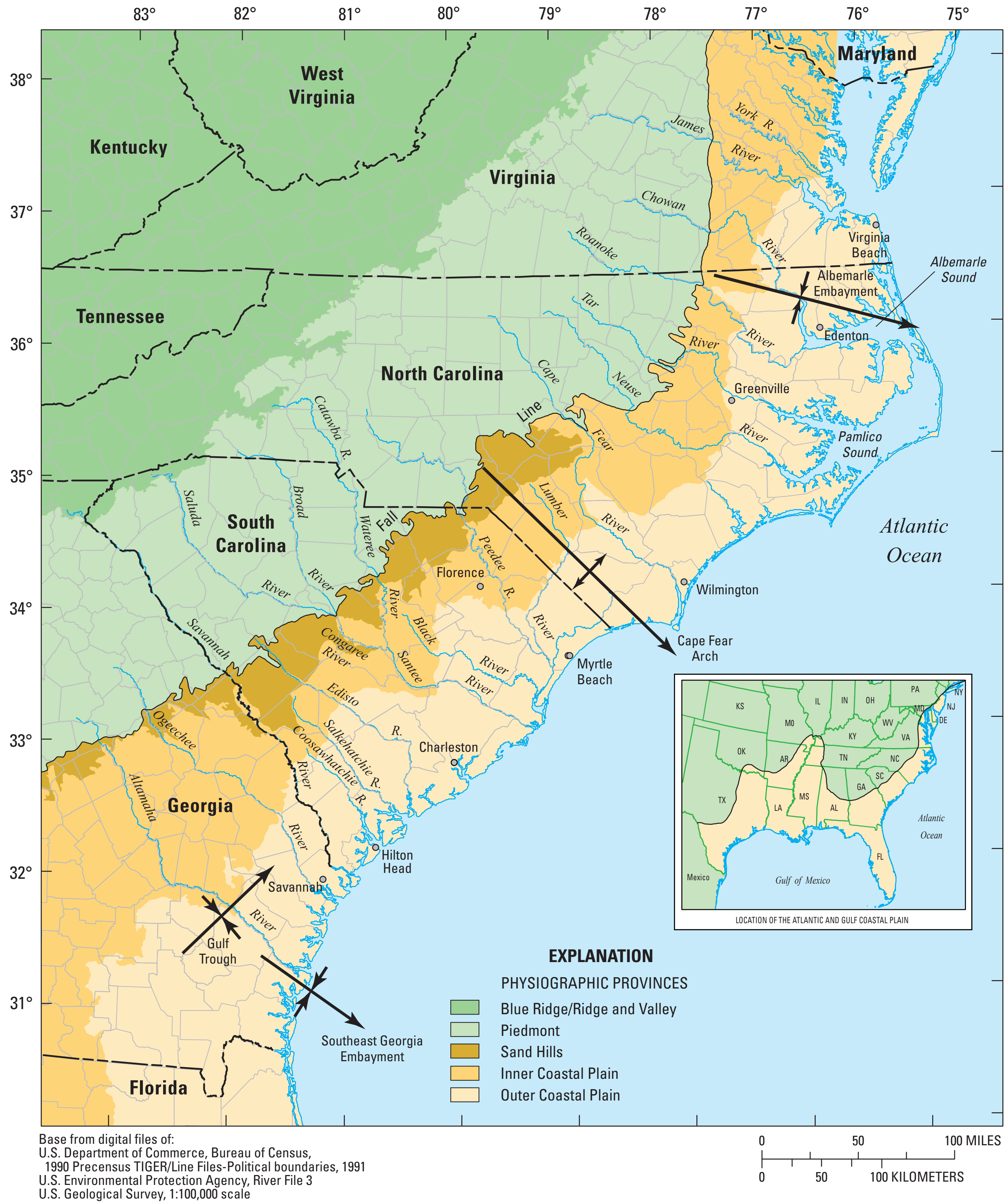
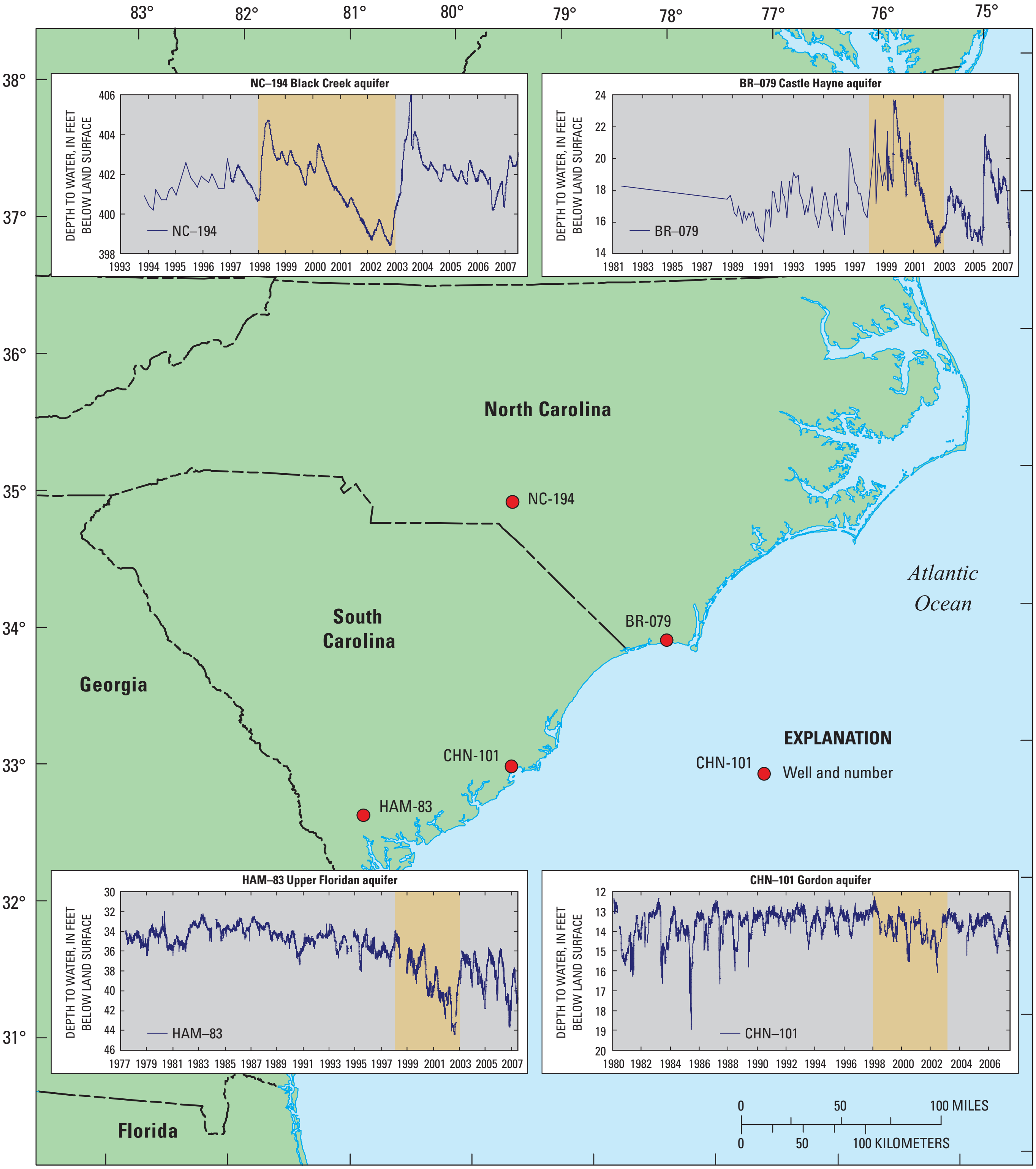



**Figure A1.** The Atlantic Coastal Plain along the Atlantic Coast of North and South Carolina and parts of northern Florida, Georgia, Virginia, and Maryland.




Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure A2.** Locations of selected groundwater level monitoring sites and hydrographs showing the effects of the 1998–2002 drought in North and South Carolina.

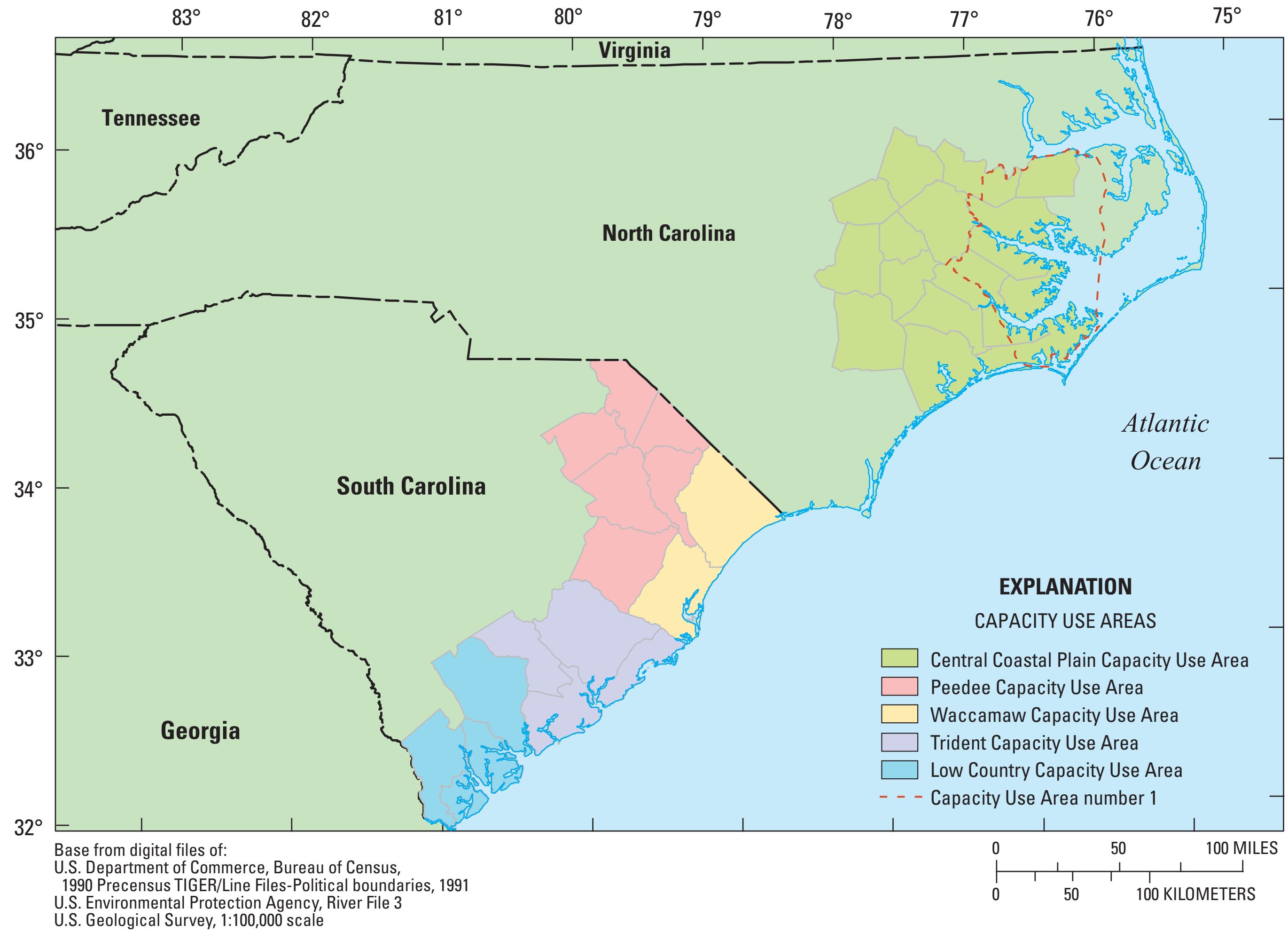



**Figure A3.** Capacity Use Areas in North and South Carolina.

## Purpose and Scope

The purpose of this report is to describe the status and trends of groundwater availability on a regional scale within the ACP aquifers and confining units underlying NC, SC, and parts of eastern Georgia (GA) and southern Virginia (VA). Study results presented here build on previous, related investigations that have involved the ACP aquifers and confining units and have included numerical modeling. This report is organized into three chapters accompanied by a series of plates that detail the hydrostratigraphy of the aquifers and confining units.This chapter, *Chapter A*, summarizes background information on the groundwater resources of the study area and focuses on providing an analysis and assessment of groundwater availability in the ACP aquifers of North and South Carolina. Included are descriptions of the effects of development on the flow system (hydrologic budget analysis), groundwater sustainability and management, and an evaluation of the adequacy of monitoring networks to assess effects of groundwater use and climate variations at a regional scale. The results of a numerical modeling tool are used to develop an understanding of how groundwater conditions can be affected by a variety of natural (climatic) and anthropogenic developments now (2009) and in the future. *Chapter B* brings together the current available geologic, lithologic, and hydrologic properties, as well as geophysical information to define a regional hydrogeologic framework for the ACP aquifers and confining units system of NC and SC. Also included in *Chapter B* is a presentation of hydrostratigraphic correlations of the ACP aquifers and confining units at the NC–SC border using detailed cross sections. The framework described in *Chapter B* was used to develop the numerical modeling tool. *Chapter C* documents the development of a three-dimensional finite-difference numerical model of the regional groundwater flow within the ACP aquifers and confining units. The numerical model is used to evaluate the groundwater availability described in *Chapter A*. Previous groundwater modeling efforts of the study area were not comprehensive, and the area simulated was restricted to either the NC or SC Coastal Plain. The current groundwater modeling effort fully simulates the aquifers and confining units in three dimensions as opposed to previous efforts that did not fully simulate the confining units within the flow system.

Specific objectives of the NC and SC ACP regional groundwater availability analysis are to (1) develop a better understanding of the three-dimensional nature of the hydrogeologic framework including the confining units of the ACP of NC and SC and resolve differences between disparate forms of information regarding delineation of the hydrogeologic framework within the two States; (2) determine groundwater flow directions and use enhanced groundwater budget analysis techniques to estimate the water budget components (recharge, discharge, change in storage) for the aquifers and confining units; (3) quantify the groundwater resources of the study area to enable the forecasting (assessment of groundwater sustainability) of the response (effects on groundwater levels) to potential future climate variations at scales relevant to making water-management decisions; and (4) conduct a geospatial analysis of the groundwater level monitoring networks in the ACP aquifers in North and South Carolina.

Groundwater flow models are commonly used analytical tools for quantifying groundwater flow and budgets. Modeling results also can be used to evaluate future stresses given likely management scenarios and the design of monitoring networks that address specific long-term questions. In this case, study objectives were met by developing a numerical groundwater flow model of the aquifers and confining units that make up the flow system using the USGS modular finite-difference groundwater flow model, MODFLOW-2000 (Harbaugh and others, 2000). The ACP groundwater flow model of NC and SC represents transient three-dimensional groundwater flow from 1900 to 2004 and includes several enhancements over previous modeling efforts owing to additional data availability, improved MODFLOW capabilities, and improved computer technology. Tasks undertaken to construct the groundwater flow model and evaluate groundwater availability include:

1. Compilation of geologic and hydrologic data collected since publication of previous models discussed in the "*Previous Investigations*" section;
2. Construction of model input and calibration datasets based on the data compilation.
3. Calibration of the groundwater flow model and evaluation of model fit;
4. Evaluation of model results including hydraulic head, water budget, and changes in head and water budget through time;
5. Predictive simulations and evaluation of hypothetical future groundwater conditions given selected climatic scenarios; and
6. Evaluation of current and historic groundwater level monitoring networks.

The first task is accomplished through data and interpretations developed from a series of core holes drilled in the SC Coastal Plain over the past decade along with slightly revised interpretations of the hydrostratigraphy of the NC Coastal Plain from geophysical log interpretations and analysis of continuous groundwater levels. Also, detailed hydrostratigraphic cross sections have been developed at the NC–SC border to connect the hydrostratigraphies. The second task is achieved through the use of historical data such as groundwater levels, aquifer properties, and water-use data. These data were compiled and converted to groundwater flow model input and utilized for model calibration. The third task was achieved by use of both manual and automated model calibration and parameter estimation techniques until a satisfactory fit was achieved between simulated and observed groundwater levels and stream baseflow estimates. Model calibration was completed for predevelopment, 1980, and 2004 conditions. The fourth task was achieved with the presentation of groundwater flow simulation results including potentiometric surface maps of the aquifer for the calibration periods, detailed analysis of the overall groundwater budget over time along with areas of local groundwater budgets. Changes in groundwater levels and water budgets over time are extracted from the model and presented for the three calibration periods along with various periods of record of groundwater levels available from selected long-term observation wells. The fifth task was achieved through the use of a climatic model that was used to simulate possible precipitation variability to the year 2100. These predicted precipitation rates were then converted to groundwater model input, and the model was used to predict possible groundwater levels at selected sites. The sixth task was achieved with the use of geostatistical techniques to evaluate the adequacy of the groundwater level monitoring network in the study area.

## Methods of Investigation

Knowledge of groundwater resources and how they are assessed has changed substantially since the last groundwater modeling efforts were undertaken for the ACP aquifers and confining units of NC and SC. The groundwater flow simulation and visualization tools are much improved over ones used in past efforts. Much new data are available from parts of the study area that were not monitored in the past along with extended records from sites that have been monitored for long periods of time. A current assessment of groundwater availability of the ACP aquifers of NC and SC would include basic information on the hydrostratigraphic framework, aquifer and confining unit boundaries, potentiometric surfaces of the units, aquifer and confining unit hydraulic properties, and quantification of human-induced changes to the flow system and water budgets related to groundwater pumping.

This assessment of groundwater availability of the ACP aquifers of NC and SC consisted of the collection, integration, and use of both new and existing data along with the construction and calibration of a groundwater flow model. The model is the primary tool used in the assessment of groundwater availability of the study area. The results, conclusions, and limitations discussed in this report are based on the analyses of these data along with the interpretation of results from the groundwater flow model.

## Data Compilation

Major types of data used in the study include (1) groundwater levels, both synoptic and continuous types; (2) groundwater use data, consisting of both estimated and recorded groundwater pumping rates, locations, and aquifer assignments; (3) hydrostratigraphic data such as aquifer and confining unit extents, along with top and bottom altitudes; and (4) estimates of stream baseflows derived from the analysis of streamflow records at selected sites.

The regional hydrogeologic framework of the ACP was constructed by examining strata outcrops, core and drill cuttings samples, micro and macro fossils, and geophysical logs obtained from numerous boreholes. These data were integrated into detailed descriptions of the lithology, thickness, geometry, and relative permeability of the ACP sediments at 309 borehole locations within the study area. The top and bottom altitudes of the ACP aquifers and confining units from the 309 boreholes were extrapolated over the study area to the known extents of the units. This hydrostratigraphy is described in detail in *Chapter B* of this report. Historical groundwater level, groundwater use, and stream flows, were compiled from 1900 to 2004 and used in the model construction and calibration process.

## Numerical Model

A finite-difference numerical modeling technique (MODFLOW-2000, Harbaugh and others, 2000) was used to simulate groundwater flow in the ACP aquifers and confining units over a 104-year period from 1900 to 2004. This model is described in detail in *Chapter C* of this report. The methods of investigation used in the modeling effort included conceptual model evaluation and revision, data compilation, model construction and calibration, and sensitivity analysis. The existing conceptual models were evaluated to determine the appropriateness of boundary conditions, model layering, and methods of approximating field conditions. Hydraulic, water-use, and water-level data for 1900 to 2004 were compiled from various State agencies and other USGS investigations for inclusion in the model. These data also included synoptic groundwater altitude and groundwater baseflow measurements made in the fall of 2004. The model was calibrated by approximating steady-state, predevelopment groundwater conditions for 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 simulated results.

The updated version of the USGS three-dimensional finite-difference modular flow model (MODFLOW-2000; Harbaugh and others, 2000) provided a more robust method for simulating field conditions than the numerical codes used in the NC and SC RASA models. Revision of the flow model included active simulation of the ACP aquifers and confining units in the study area and incorporation of hydraulic properties, water-level and water-use data, and groundwater baseflow data acquired since the previous studies.

These modeling techniques produced groundwater altitudes and flow directions that were compared to both synoptic and continuous field measurements of groundwater altitudes and evaluated with statistical methods. Global climate models (GCMs) were employed to predict future variations in precipitation rates that were then converted into variations in net recharge rates and input into the groundwater model. Geographic information system (GIS) techniques were used to analyze the groundwater level monitoring networks in North and South Carolina to quantify the extents of the coverage distributions.

# Previous Investigations

Although many recent investigations related to ACP geology and groundwater have taken place in North and South Carolina, only investigations of regional extent will be cited here. One of the first regional studies of groundwater resources in the study area was by Darton (1896), who described existing artesian wells and the prospects for additional artesian wells. A comprehensive study of the geology and groundwater resources of the NC ACP was conducted by Clark and others (1913). Winner and Coble (1996) described the hydrogeologic framework of the NC ACP. Lautier (1998, 2002, 2006) describes parts of the hydrogeology of the NC ACP. The Winner and Coble report contains an extensive listing of previous hydrologic and geologic investigations of the NC ACP. Giese and others (1997) described the simulation of groundwater flow in the NC ACP using a finite-difference groundwater flow model. Eimers and others (1990) presented a model that simulated groundwater flow in the Cretaceous aquifers of NC.

Numerous local and subregional hydrologic and geologic investigations of the SC ACP have been conducted. The first comprehensive study of the geology of the SC ACP was by Cooke (1936). Colquhoun and others (1983) described the surface and subsurface stratigraphy, structure, and aquifers of the SC ACP. Aucott (1996) produced a comprehensive report on the hydrology of the SC ACP. The Aucott report contains an extensive listing of previous hydrologic and geologic investigations of the SC ACP. Campbell and van Heeswijk (1996) described the simulation of groundwater flow within the Cretaceous aquifers of the SC ACP. A recent addition to the stratigraphic delineation of the Atlantic and Gulf Coastal Plain is the identification of Supergroups of Coastal Plain sediments by Weems and others (2004). A surficial geologic map of the ACP was compiled by Newell and others (2002).

Several important regional-scale groundwater modeling investigations of the ACP have taken place in both NC and SC. The NC RASA model was one of the first developed in the National RASA Program (Giese and others, 1997). The computer model used the Trescott (1975) code as modified by Leahy (1982), and was calibrated to 1980 groundwater conditions. The NC RASA model was updated by Eimers and others (1990). The SC RASA model was developed by Aucott (1988, 1996), calibrated to predevelopment and 1982 conditions, and later recalibrated by Campbell and van Heeswijk (1996) using data collected in 1989.

## Study Area

The ACP area extends from eastern Georgia through South and North Carolina and into southern Virginia (*fig. A1*). The study area extends from the Fall Line to areas both on and offshore that contain fresh groundwater. Vertically, the study includes all of the ACP aquifers and confining units.

The ACP aquifers underlie an area of approximately 25,000 square miles ($mi^2$) in NC and 22,500 $mi^2$ in SC. The study area extends into eastern GA and encompasses approximately 5,000 $mi^2$ there, along with approximately 3,000 $mi^2$ in southern VA; additionally, the study area includes approximately 15,000 $mi^2$ offshore. This entire study area lies approximately between latitude 31° and 37° 30′ N and longitude 76° and 30′ and 83° W (*fig. A1*).

### Physiography and Climate

The ACP of North and South Carolina is characterized by rolling hills and deeply incised river valleys in the inner Coastal Plain and gently rolling to flat topography in the outer Coastal Plain, which generally slopes toward the Atlantic Ocean (*fig. A1*). Major river valleys, such as the Savannah, Congaree, Wateree, Pee Dee, Cape Fear, Neuse, Tar, and Roanoke Rivers dominate the inner Coastal Plain topography. These river valleys within the inner Coastal Plain typically contain extensive wetlands and are flanked by broad, relatively flat uplands in the interstream areas. The inner Coastal Plain is characterized by relatively high land-surface altitudes, which range from about 50 ft to more than 700 ft above the National Geodetic Vertical Datum of 1929 (NGVD 29) at the Fall Line. The Sand Hills region is characterized by long gentle slopes, rounded summits cut by stream valleys, and well-defined flood plains along rivers. Dense networks of tributaries that extend across the entire study area contribute runoff to the major rivers.

The outer Coastal Plain is characterized by low land-surface altitudes, which range from 0 to about 50 ft and average 20 ft above NGVD 29 throughout most of the area. The outer Coastal Plain is characterized as a low, broad plain with numerous coastal terraces. Parts of the area are swampy, and large streams and their tributaries are affected by oceanic tides. Two major estuaries are on the NC coast within the outer Coastal Plain—Albemarle and Pamlico Sounds (*fig. A1*).

The climate in the SC and NC ACP is temperate and is characterized by hot, humid summers and moderate winters. Annual precipitation rates for the study area in SC are about 50 to 52 inches (in.) (South Carolina State Climatology Office, 2007), and rates in NC are 40 to 55 in. (State Climate Office of North Carolina, 2007). The precipitation is relatively uniformly distributed and is seasonal in nature with wet winters, springs, and summers and with dry autumns. Streamflow is greatest during the winter months and decreases during spring and summer when evapotranspiration rates are highest.

### Capacity Use Areas

As a way of managing declining groundwater levels, both NC and SC began establishing Capacity Use Areas (CUA) in which groundwater withdrawals are permitted and groundwater levels are monitored. CUA1 (*fig. A3*) was established in 1967 in NC because of groundwater level declines related to phosphate mine de-watering in the Castle Hayne aquifer (North Carolina Division of Water Resources, 2005). In 2002, the NC Central Coastal Plain CUA (CCPCUA) was established to regulate withdrawals from the Black Creek and Upper Cape Fear aquifers. Under the 2002 CCPCUA regulations, several counties and municipalities were required to reduce withdrawals by 25 percent by 2008 and by 75 percent by 2018. Overall groundwater level declines are estimated to be as much as 200 ft near pumping centers in the CCPCUA.

In 1979, the first CUA in SC was established as the Waccamaw CUA, to monitor 200-ft drawdowns from predevelopment levels in the Black Creek aquifer (*fig. A3*). In 1981, the Low Country area was designated as a CUA because of saltwater encroachment in the Upper Floridan aquifer. More recently, in 2002, the Trident area was designated as a CUA because of 225-ft drawdowns in one of the sand aquifers of Late Cretaceous age underlying the area. The five-county Peedee area of SC was designated as a CUA in 2003 because of declining groundwater levels in several of the Cretaceous sand aquifers.

## Geologic History and Setting

The ACP sediments that underlie the study area consist of unconsolidated sand, silts, and clays along with crystalline carbonate units of Late Cretaceous, Tertiary, and Quaternary age that unconformably overlie consolidated crystalline bedrock of Paleozoic and Triassic age. These sediments are part of the Atlantic Continental margin that extends over most of the length of the eastern United States (Gohn, 1988). The ACP sediments are bordered to the west by the Piedmont rocks of Precambrian and Paleozoic age at the Fall Line (*fig. A1*). The study area has a long and complex tectonic history related to the opening and continued extension of the Atlantic Ocean. The geologic history of ACP sediments begins with the continental fragmentation and rifting in the early Mesozoic, continuing with continental drifting, and progressing to the opening of the modern Atlantic Ocean in the late Mesozoic and Cenozoic Eras (Gohn, 1988).

The ACP sediments are part of the geologic evidence of the rifting and post-rifting of the Atlantic Continental margin. Major post-rift basins within the study area include the Albemarle embayment in southern VA and northern NC and the Southeast Georgia embayment in coastal GA (*fig. A1*). Between these basins is an area of relatively higher altitude called the Cape Fear Arch. Sediments on the Cape Fear Arch are thinner and less complete stratigraphically than the thicker sections of sediments in the basins (Gohn, 1988).

# Hydrogeology

Extensive areas of the ACP sediments in North and South Carolina are composed of permeable gravels, sands, and crystalline carbonate sediments that have substantial water-transmission capacity. This water-transmission capacity coupled with high precipitation rates in the study area result in large quantities of high-quality groundwater available in many parts of the North and South Carolina ACP. These groundwater resources are used for various purposes, including municipal, irrigation, and industrial supplies.

A long and complex history of sediment deposition has created a framework of aquifers and low-permeability confining units. These sediments overlie crystalline rocks of Paleozoic age and generally thicken and dip toward the Atlantic Ocean from the Fall Line. The axis of the Cape Fear Arch is located a few miles northeast and approximately parallel to the NC–SC State boundary (*fig. A1*) and produces a second dip component that causes the ACP sediments to thicken to the southwest and northeast of the arch axis (Gohn, 1988).

The aquifers and confining units of Tertiary age are found only in the southwestern and northeastern parts of the study area. These units do not extend across the Cape Fear Arch. The units of Cretaceous age extend across the Cape Fear Arch, but most do not underlie the entire study area.

Properties of the ACP aquifers and confining units, such as horizontal and vertical hydraulic conductivities and specific storage, are not well known across the study area. More information is available on the upper units compared to the deeper units, which contain fewer wells. Many hydraulic values are available that are derived from various types of aquifer or laboratory tests; however, these values are distributed randomly, and large parts of the study area have essentially no available data. The available hydraulic property data are described in detail by unit in *Chapter B* of this report. In parts of the study area without hydraulic data, parameter estimation techniques described in *Chapter C* of this report were used to estimate horizontal hydraulic conductivities, anisotropies, and specific storage values.

# Hydrologic System

In the NC and SC Atlantic Coastal Plain, the unconfined surficial aquifer is recharged by water from precipitation; then groundwater is lost by seepage to streams and evapotranspiration. A small amount of water in the surficial aquifer percolates through confining units to recharge underlying aquifers. Additional recharge to deeper underlying aquifers occurs where the confined aquifers crop out along the Fall Line in the inner Coastal Plain and Sand Hills Physiographic Provinces. In this region, streams typically gain water from the aquifers. Water is lost from the deep aquifers by upward leakage through confining units and by pumping.

## Surface Water

The major rivers in the NC and SC ACP are, from north to south, the James, Chowan, Roanoke, Tar, Neuse, Cape Fear, Lumber, Pee Dee, Black, Santee, Edisto, Salkehatchie, Savannah, Ogeechee, and Altamaha Rivers (*fig. A1*). Most of these major rivers originate in the Piedmont Physiographic Province, flow through the inner and outer Coastal Plain Physiographic Provinces and discharge to the Atlantic Ocean. Smaller rivers originate near the inner margin of the ACP sediments. All of the major rivers except the Edisto are regulated, and most of the smaller rivers are unregulated.

Where the major rivers cross the Fall Line and pass from the crystalline rock of the Piedmont to the unconsolidated ACP sediments, the rivers incise into the ACP sediments below the surfical aquifer, and most of the reaches are gaining. In general, streams in the southern part of the inner Coastal Plain are well connected to the groundwater system and are gaining. Streams in the northern part of the inner Coastal Plain are on an escarpment and are more poorly connected to the groundwater system than streams located in the southern part.

## Groundwater

The hydrogeologic units of the NC and SC Coastal Plain have been described in the following publications: Aucott (1996), Winner and Coble (1996), Lautier (1998, 2002, 2006), and Harrelson and Fine (2006). The aquifers consist of layers of permeable sand or carbonate rocks separated by confining units of silt, clay, or low-permeability carbonate rocks. The hydrogeologic units in the NC Coastal Plain differ from those in the SC Coastal Plain in number, nomenclature, age, and lithology. As part of this investigation, the hydrogeologic units at the NC–SC border were correlated (*Chapter B*), and this correlation was used as the framework for defining the hydrogeologic units/model layers used in the modeling results.

The long-term annual precipitation rate for the Coastal Plain of SC is about 48 inches per year (in/yr; Badr and others, 2004). In NC, the long-term average is about 50 in/yr (Giese and others, 1997). Much of this total precipitation is lost to evapotranspiration (in SC, 34 in., and in NC, 33 in.) and streamflow (in SC, 13 in., and in NC, 16 in.). About 1 in. is estimated to recharge the deeper aquifers in both SC and NC and eventually discharges to the Atlantic Ocean.

Recharge to the surficial aquifer of the ACP occurs in most interstream areas. Recharge to the deeper ACP aquifers, however, occurs predominantly where underlying confined aquifers crop out near the Fall Line. Published estimates of recharge rates to the surficial aquifer range from 3 to 47 in/yr (Aucott, 1996; Giese and others, 1997; Mew and others, 2002; Coes and others, 2007). The wide range of published recharge rates can be attributed to the various methods used to calculate the rates and the scales (local to regional) that the methods employ (Coes and others, 2007). Recharge rates used in regional groundwater modeling studies tend to be in the lower range of 3 to 5 in/yr. In areas where confining units restrict the vertical movement of groundwater between the surficial aquifer and the underlying aquifers, recharge rates through the confining units are estimated to be lower, ranging from 0.5 to 1.4 in/yr (Winner, 1976; Winner and Simmons, 1977; Aucott, 1996; Giese and others, 1997; Heath and Spruill, 2003).

Discharge from the predevelopment ACP aquifers occurred by seepage into streams and lakes; evapotranspiration from soil zones; and upward leakage through confining units to stream valleys, estuaries, and the Atlantic Ocean (Aucott, 1996; Winner and Coble, 1996). Recharge to and discharges from the aquifer were equal under predevelopment conditions with no changes in storage. The majority of groundwater discharged from shallow aquifers, other than the amount lost to evapotranspiration, provided the baseflow of perennial streams. Discharge from deeper aquifers was primarily upward leakage through confining units.

# Development of the Hydrologic System

Predevelopment groundwater flow through the ACP aquifers and confining units of NC and SC was generally from recharge areas to discharge areas and perpendicular to the coast, except for the deeper, confined aquifers in SC, which had a predevelopment flow direction parallel to the coast toward the northeast (Aucott, 1996; Giese and others, 1997). Predevelopment groundwater flow through confining units generally is considered to be vertically downward in recharge areas in the inner Coastal Plain and vertically upward in discharge areas in the outer Coastal Plain (Aucott, 1996; Campbell and van Heeswijk, 1996; Winner and Coble, 1996). In the inner Coastal Plain, the groundwater in the shallow aquifers generally has short flow paths from recharge areas to discharge areas along streams. In the outer Coastal Plain, where the aquifers are not hydraulically connected to the streams, groundwater flow paths are longer, and hydraulic gradients are not as steep as those in the inner Coastal Plain.

Discharge components from the postdevelopment ACP aquifers and confining units are the same as the predevelopment, plus additional discharge from groundwater pumping along with changes in storage. Pumping generally increased from 1900 to 2004. The total pumpage in 2004 is approximately 479 million gallons per day (Mgal/d) in the study area and, in some cases, has resulted in large alterations to the natural groundwater flow system. The most substantial withdrawals are for municipal and industrial supply in the cities of Aiken, Andrews, Florence, Mount Pleasant, and Sumter in SC and the Counties of Beaufort, Craven, Duplin, New Hanover, Onslow, Robeson, and Sampson in NC (*fig. B1*). These groundwater withdrawals, in some cases, have resulted in substantial drawdowns and widespread cones of depression.

## Groundwater Development History

The ACP aquifers of NC and SC have a long history of development dating back to at least the original settlements by the Spanish and British settlers in the 1500s and 1600s. Shallow wells were hand dug into the surficial aquifer that provided fresh water for early residents. Deeper, drilled wells that were able to exploit confined aquifers were constructed at Charleston, SC, and Edenton, NC, in the mid-1800s (*fig. A1*). Few records of groundwater use for the study area exist prior to about 1980, so much of the data available are estimated from well construction dates and historic population figures for cities and towns. Reconstructions of historical pumpage from the SC and NC ACP aquifers are presented in Aucott (1996) and in Giese and others (1997), respectively. Since about 1980, more complete records of withdrawals are available, and these records have been incorporated into this study.

Beginning about 1940, groundwater withdrawals began to have an effect on the potentiometric surfaces of the ACP confined aquifers of NC and SC (Aucott, 1996; Giese and others, 1997). Groundwater withdrawal estimates indicate rapid increases in the volumes of groundwater withdrawn from the ACP aquifers through the early 1980s when the increase in the rates of withdrawals began to moderate.

Groundwater withdrawals in SC in 1982 are described by Aucott (1996), and groundwater withdrawals in NC in 1980 are described by Giese and others (1997). In SC, the largest withdrawals for municipal and industrial uses are from the Sumter, Florence, Myrtle Beach, and the Savannah River sites (*fig. B1*). These withdrawals created substantial declines in the potentiometric surfaces of the pumped aquifers, especially in the Florence and Myrtle Beach, SC, areas. In NC, the 1980 potentiometric surfaces of the ACP confined aquifers indicated lower water levels in the northern part of the ACP due primarily to heavy, concentrated pumpage from the Lower Cape Fear aquifer in southern VA. There were also large declines in the potentiometric surface of the Lower Cape Fear, Upper Cape Fear, and Black Creek aquifers in the central part of the NC Coastal Plain area. Large-scale declines in the potentiometric surface of the Castle Hayne aquifer are associated with mine dewatering in the central eastern part of the NC ACP.

In 2004, in the study area, the potentiometric surfaces of the ACP aquifers were mapped in detail from a set of synoptic water-level measurements from all of the aquifers. In SC, Hockensmith (2008a, b, 2009) presents the synoptic measurements in the form of potentiometric maps. The most prominent feature within the Tertiary aquifers is the large water-level decline associated with pumping at Savannah, GA (*fig. A1*). Less severe declines occur in the Charleston, SC, area. Much of the updip area of the Tertiary aquifers is unaffected by pumping and is, therefore, close to predevelopment conditions. In the Cretaceous aquifers, a deep cone of depression is centered on the Andrews area in the southern Georgetown County area in eastern SC (*fig. B1*) along with a smaller scale depression near Sumter, SC. Other pumping centers that have developed noticeable cones of depression are centered on the Charleston and Florence, SC, areas (*fig. A1*).

During 2004, in the NC ACP aquifers, potentiometric declines occurred in the eastern NC ACP due to the mine dewatering described above, in the Cretaceous aquifers of the central NC Coastal Plain area, and along the VA–NC border. Additional areas of groundwater level declines were the southern NC Coastal Plain near the SC border within the Cretaceous aquifers.

### Water Use

Groundwater use data for the study area were obtained from various State agencies charged with collecting the information from well owners. In SC, the South Carolina Department of Health and Environmental Control (SCDHEC) collects groundwater use data from users who withdraw more than 3 million gallons in any month (SCDHEC, 2009). The SCDHEC groundwater use database was accessed, aquifer assignments were made for all wells with sufficient data (well location, depth, and screened interval), and the groundwater use data were assigned to the model stress periods. In NC, non-agricultural users are required to report groundwater use of more than 0.1 Mgal/d, and agricultural users are required to report more than 1.0 Mgal/d (North Carolina Division of Water Resources, 2009). These data were compiled and assigned to the model stress periods.

Groundwater use data for areas in southern Virginia were provided by the USGS Virginia Water Science Center (Jason Pope, U.S. Geological Survey, written commun., 2006). Groundwater use data for eastern GA were provided by the USGS Georgia Water Science Center (Dorothy Payne, U.S. Geological Survey, written commun., 2006). These data provided for VA and GA were part of ongoing groundwater modeling studies being conducted in the ACP aquifers.

## Development and Changes to the Hydrologic Budget

Groundwater availability in the ACP of North and South Carolina generally is good, in that supply exceeds demand in most areas. However, concentrated pumping combined with relatively poor aquifer properties in some areas has produced groundwater level declines, some of which are subregional in scale. In much larger parts of the study area where groundwater is plentiful, aquifer properties are good, and there is little or no groundwater use. Also, many of these areas in the ACP are underlain by several aquifers, all containing high-quality, potable groundwater (Lee, 1993; Knobel and others, 1998).

This section of the report discusses uses of the groundwater model (presented in *Chapter C* of this report) to present general and detailed groundwater flow budgets for the overall study area and three sub-areas—NC Central Coastal Plain Capacity Use Area (CCPCUA), Sumter, SC, and Aiken, SC. Climate variability, which affects precipitation and net recharge in the model, has been projected to the year 2100, and the effects on simulated groundwater levels have been analyzed.

### Simulated Groundwater Budget Analysis

The ACP aquifers of North and South Carolina contain local, intermediate, and regional groundwater flow regimes as described by Toth (1963). The inner Coastal Plain (*fig. A1*) is an area of local and intermediate flow systems in which the recharged water moves relatively quickly to discharge areas, primarily streams and rivers. A small percentage of the recharged water moves vertically into deep aquifers of the regional flow system. Groundwater flow in the outer Coastal Plain moves locally through the surficial system, but predominantly moves regionally through the deep, confined aquifers and confining units. As aquifers are developed and large volumes of water are produced from the system through wells, substantial volumes of groundwater can be diverted from the local and intermediate flow systems into the regional flow system (Johnston, 1997). Reduced baseflow to surface-water bodies and reductions in the volume of water stored in the aquifers are the primary changes to the regional groundwater budget as a result of the withdrawals.

The groundwater budgets presented are derived from the calibrated, regional groundwater flow model described in *Chapter C* of this report. The model simulates groundwater flow over an area of approximately 144,000 $mi^2$ with a constant finite-difference cell size of 4 $mi^2$. Using a regional model of this size with a relatively coarse model grid imparts assumptions and limitations into the derived groundwater budgets. With a 4-$mi^2$ grid size, the local and intermediate flow systems in the inner Coastal Plain cannot be simulated with a high degree of accuracy. This grid size also limits the accuracy of the simulation of surface-water features, such as streams and rivers. The model employs a specified-head layer to simulate the surficial aquifer in the outer Coastal Plain; however, the model does provide a reasonable simulation of the regional groundwater flow system in the deep, confined aquifers of this area.

The calibrated groundwater flow model is used to calculate groundwater budgets for the study area and for three sub-areas. These three sub-areas include the 15-county area of the NCCPCUA, and the Sumter and Aiken, SC, areas (*fig. A4*). These sub-areas were selected for detailed analysis because they have long histories of groundwater use, and detailed records of groundwater use and water-level data are available. Amounts of groundwater use are also some of the highest in the study area; this analysis could help water managers in these areas understand the resource to a better degree.

### Regional Groundwater Budget

In the simulated predevelopment groundwater flow budget, recharge from precipitation and a small amount of leakage from rivers are balanced by discharge to rivers and outflow to lateral boundaries (*fig. A5*). Because the aquifers were developed and pumping rates increased in the model, the 2004 simulated groundwater budget is different. Recharge is still the

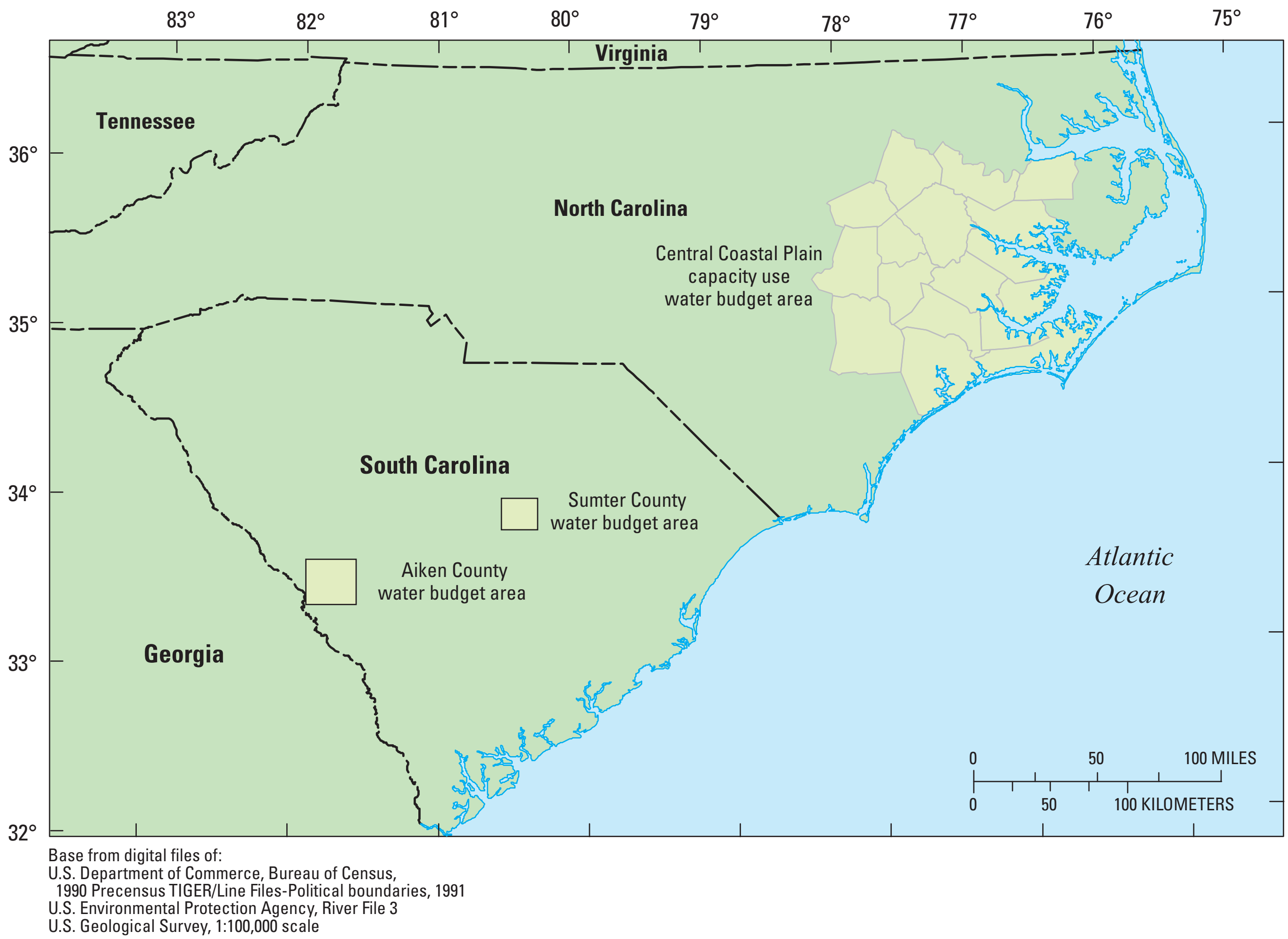



**Figure A4.** Locations of areas of detailed groundwater budgets, North and South Carolina.

primary source of water to the aquifers, but additional sources and a small volume of leakage from the rivers are present. In 2004, simulated withdrawals from the system by wells create an inflow of water to the aquifers and confining units from storage and lateral boundaries. These simulated withdrawals also result in reduced groundwater discharge to rivers.

Simulated groundwater flow budgets for the area are presented in several ways. The first is an overall view of the simulated major water-budget components in the study area for predevelopment and 2004 (*fig. A5*). Next are water budgets that quantify the inflow and outflow of water to and from the groundwater flow system for each hydrologic component and model layer for predevelopment and 2004 (*figs. A6* and *A7*, respectively). Also included is a simulated water budget for stress periods from predevelopment to 2004 (*fig. A8*). The water-budget components include inflow from recharge, inflow and outflow through specified-head boundaries and rivers, inflow to and outflow from storage, and outflow by wells. Flow rates are depicted in the figures and discussed later in this chapter in the "*Development and Changes to the Hydrologic Budget*" section.

The largest component of the predevelopment and 2004 water budgets is vertical interlayer flow (*figs. A6* and *A7*). Vertical interlayer flow is the volume of groundwater that moves from one layer within the aquifers and confining units to adjacent layers under a hydraulic gradient. This gradient can be natural, related to recharge, or manmade (related to withdrawals). The next largest budget components are the inflows and outflows through the specified-head boundaries. Flow from or to the specified-head boundaries is derived from the vertical and horizontal hydraulic gradient at the boundary. The total inflow through all specified-head boundaries is approximately equal to outflow through specified-head boundaries and is approximately 3,700 and 3,600 Mgal/d for the predevelopment and 2004 model water budgets, respectively. During the model simulation of predevelopment conditions, about 70 percent of the groundwater enters the study area through specified-head boundaries in the surficial aquifer (layer 1), Black Creek/McQueen Branch aquifer (layer 11), Lower Cape Fear/Gramling aquifer (layer 15), and Lower Cretaceous aquifer (layer 16); 74 percent flows out of the study area through specified-head boundaries in the surficial aquifer (layer 1),

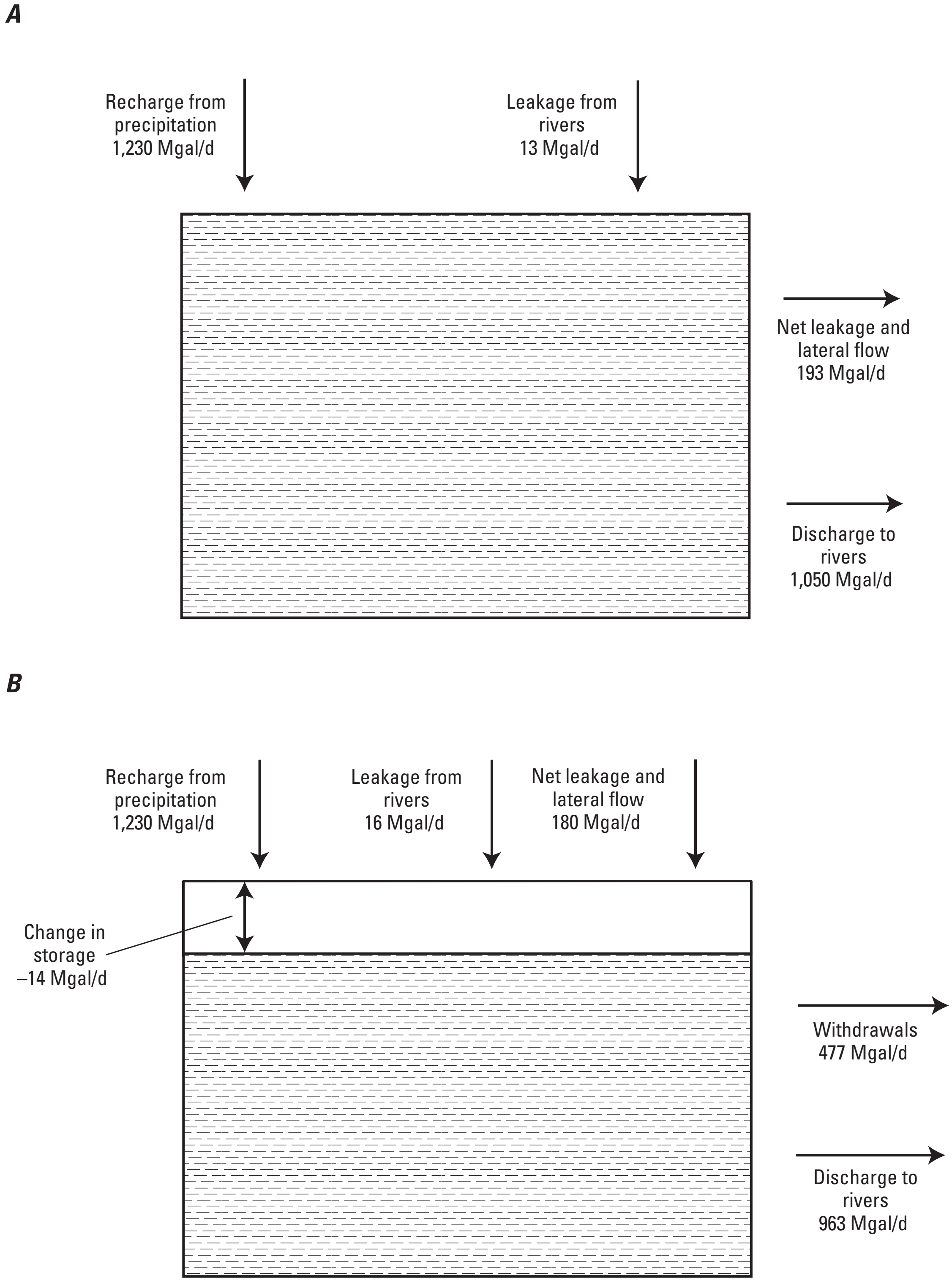



**Figure A5.** Simulated water budget in the Atlantic Coastal Plain aquifer system of North and South Carolina for *A*, predevelopment and *B*, 2004. [Mgal/d, million gallons per day]

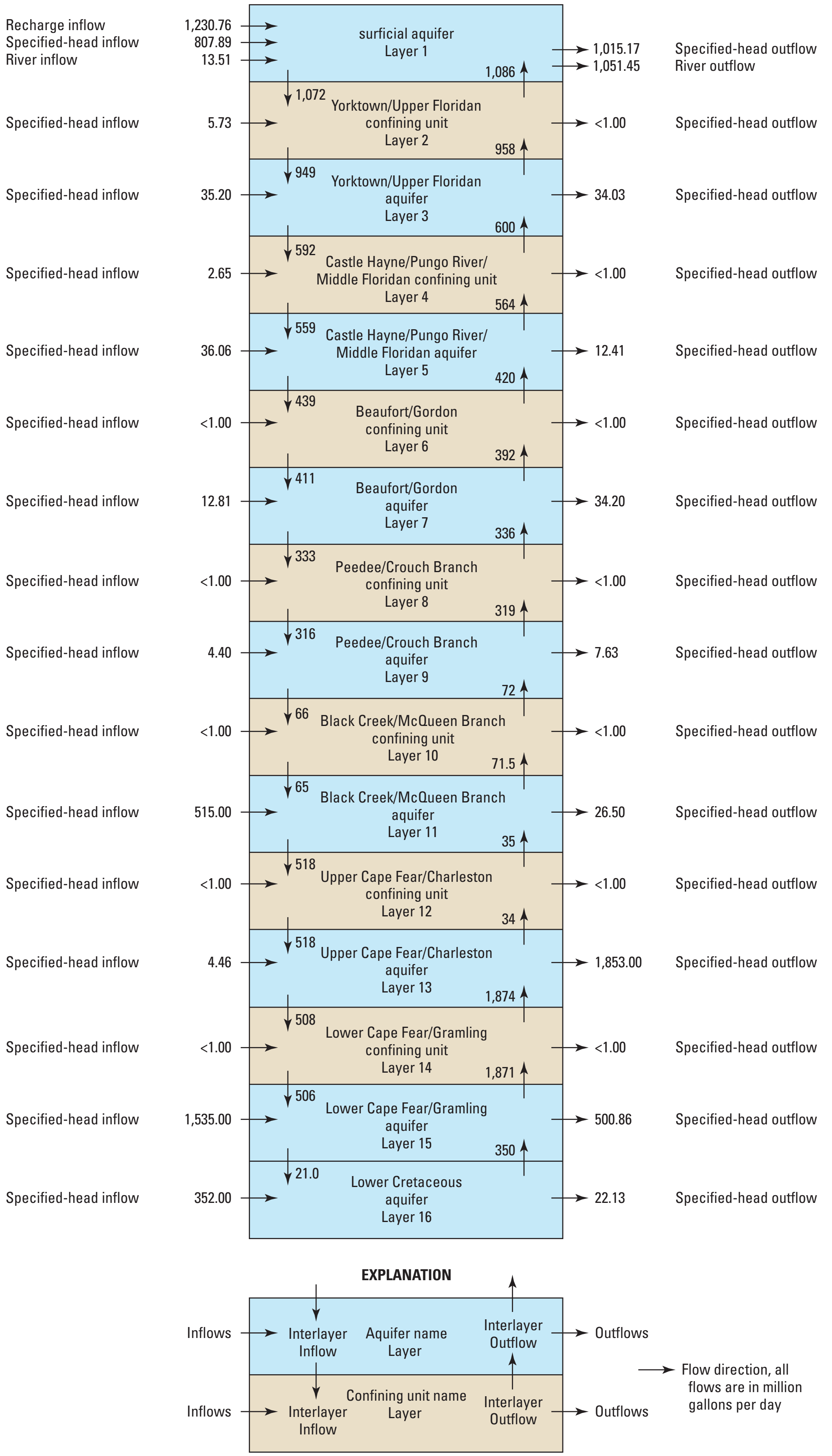



**Figure A6.** Simulated predevelopment groundwater budget for the Atlantic Coastal Plain of North and South Carolina.

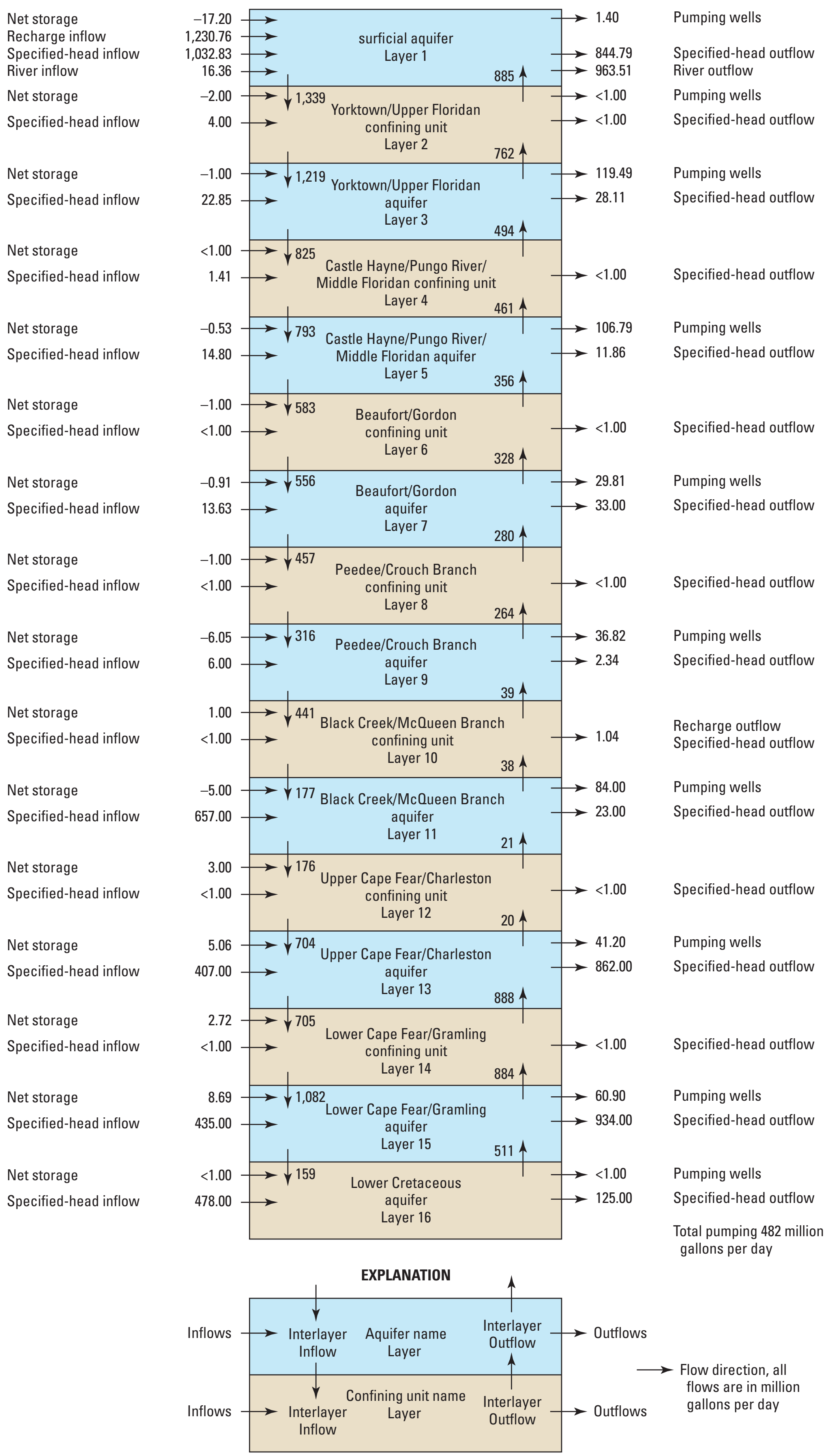



**Figure A7.** Simulated 2004 groundwater budget for the Atlantic Coastal Plain of North and South Carolina.

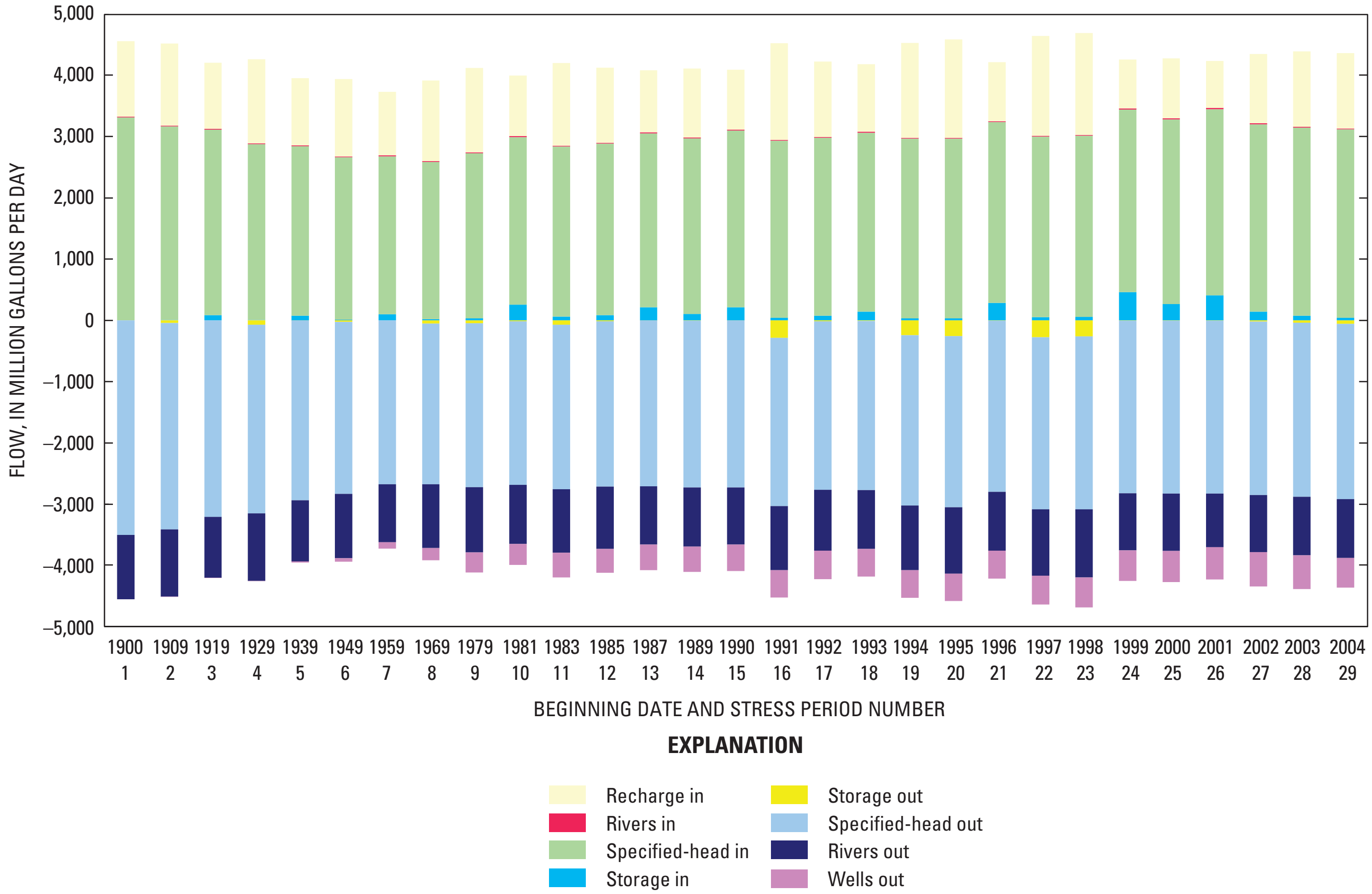



**Figure A8.** Simulated water budget per stress period from predevelopment to 2004 in the Atlantic Coastal Plain of North and South Carolina.

Upper Cape Fear/Charleston aquifer (layer 13), and the Lower Cape Fear/Gramling aquifer (layer 15; *fig. A6*). In the simulated 2004 water budget, 45 percent of the groundwater enters the study area through specified-head boundaries in the surficial aquifer (layer 1), Black Creek/McQueen Branch aquifer (layer 11), Upper Cape Fear/Charleston aquifer (layer 13), Lower Cape Fear/Gramling aquifer (layer 15), and Lower Cretaceous aquifer (layer 16); 61 percent of the groundwater flows out of the study area through specified-head boundaries in the surficial aquifer (layer 1), Upper Cape Fear/Charleston aquifer (layer 13), and Lower Cape Fear/Gramling aquifer (layer 15; *fig. A7*). Two other sources of water to the groundwater budget are recharge, which is 1,231 Mgal/d for predevelopment and 2004, and inflow through rivers at 13.5 Mgal/d for predevelopment and 16.4 Mgal/d for 2004. Water is removed from the simulated water budget through discharge to rivers at rates of 1,051 Mgal/d for predevelopment and 964 Mgal/d for 2004 (*figs. A6* and *A7*, respectively). Discharge of water through wells is another component of flow in the model and accounts for 482 Mgal/d for the 2004 water budget (*fig. A7*). Additionally, as groundwater is pumped over time, water flows into and out of storage in the simulated model. Storage is defined as the volume of water an aquifer releases or takes in per unit surface area of the aquifer per unit change in head (Theis, 1938). For the 2004 water budget, rates of flow into and out of storage are 43 and 56 Mgal/d, respectively (*fig. A8*). In *figure A7*, net storage changes are depicted for each layer. Net storage changes are negative for flow out of storage (*fig. A7*, layers 1, 2, 3, 5, 6, 7, 8, 9, and 11); net storage changes are positive for flow into storage (*fig. A7*, layers 10, 12, 13, 14, and 15). Storage changes are less than 1.0 Mgal/d for layers 4 and 16.

Changes in the water-budget components over time can be evaluated by reviewing *figure A8*, in which net changes in flow are depicted across specified-head boundaries by stress period. Prior to about 1983, there was a net flow of water out of the simulated flow regime through specified-head boundaries. After about 1983, there was a net flow of water into the simulated water budget through specified-head boundaries. The change in the net flow through specified-head boundaries roughly corresponds to an increase in total simulated water use (groundwater withdrawals), indicating that the withdrawals may intercept water that would have discharged to streams and wetlands.

The next largest components of the water budget are recharge from precipitation and discharge to rivers. Simulated groundwater discharge to rivers decreased over time from 1,051 Mgal/d for predevelopment to 964 Mgal/d for 2004. For all stress periods, the simulated recharge varies over time based on the reported annual precipitation from gaging stations in the inner Coastal Plain. In general, groundwater flows into the simulated area from storage at rates between about 2 and 455 Mgal/d for all stress periods except the steady-state predevelopment stress period when there is no contribution from storage. At the modeled regional scale, the net flow of groundwater into or out of the simulated flow regime from storage is tied to the variability in the recharge rate. During periods of relatively high recharge (above 1,500 Mgal/d), a net loss of water occurs as water flows out of the simulated flow regime into storage (for example, stress period 16, *fig. A8*). During periods of relatively low recharge (less than 1,500 Mgal/d), a net increase occurs in the volume of water flowing into the simulated flow regime from storage (for example, stress periods 24–26, *fig. A8*).

In summary, the groundwater budgets for the ACP aquifers and confining units have changed over time as a result of withdrawals superimposed on the original natural flow system and from natural variability in the climate, which results in variable recharge rates. High rates of withdrawals produce outflows from storage within the system and decreases in baseflows to the inner Coastal Plain rivers. High rates of precipitation cause increases in storage rates within the aquifers and confining units and higher baseflows to the rivers. Overall, the 2004 rates of groundwater withdrawals have not changed groundwater flow within the aquifers and confining units to any substantial degree; however, concentrated withdrawals combined with poor aquifer properties have produced large groundwater level declines in some areas.

## North Carolina Central Coastal Plain Capacity Use Area Groundwater Budget

Detailed groundwater flow budgets for three sub-areas of the study area are presented. These sub-areas were selected on the basis of relatively high groundwater withdrawals and availability of detailed water-use data. The effects of the withdrawals on groundwater levels and water budgets vary subtantially for the three areas. The NC CCPCUA has had major changes in the groundwater budget as a result of concentrated withdrawals over the past 30 years. The Aiken and Sumter, SC, areas have had less change to the groundwater flow systems because the aquifers tend to have relatively high horizontal hydraulic conductivities and transmissivities.

The CCPCUA is a 15-county area in the central part of the North Carolina ACP where the population was approximately 912,000 in 2000 (Perry and Mackun, 2001; *fig. A4*). Approximately 40 Mgal/d of groundwater was used in the CCPCUA in 2004 by public potable supply systems operated by cities and counties. Water for many residents in the area is self-supplied by domestic wells. Pumpage data from these domestic wells are unavailable (State of North Carolina, 2004). Groundwater use in the CCPCUA is regulated by NC (State of North Carolina, 2001). Groundwater levels have been declining since at least 1960 in the Black Creek and Upper Cape Fear aquifers in the vicinity of the CCPCUA as a result of concentrated withdrawals.

Simulated predevelopment groundwater flow in the CCPCUA occurs predominantly in the surficial, Yorktown, and Castle Hayne/Pungo River aquifers and their related confining units (layers 1–5; *fig. A9*). Specified-head inflow and outflow of this area occurs primarily in the surficial aquifer (layer 1) at rates of 98.20 Mgal/d and 85.40 Mgal/d, respectively. Vertical flow is highest in the upper layers. Downward rates vary from 1.28 to 97.3 Mgal/d, and upward rates vary from 1.04 to 84.00 Mgal/d. The vertical component of flow decreases substantially below the Castle Hayne/Pungo River aquifer (layer 5). Lateral flow into the CCPCUA occurs in the Yorktown aquifer (layer 3) and Upper Cape Fear aquifers (layer 13) at rates of 1.64 and 1.86 Mgal/d, respectively. Lateral flow out of the CCPCUA occurs in the Yorktown (layer 3), Castle Hayne/Pungo River (layer 5), Peedee (layer 9), and Upper Cape Fear aquifers (layer 13) at rates of 9.06, 5.12, 2.77, and 1.08 Mgal/d, respectively.

The simulated 2004 water budget for the CCPCUA includes pumping from the Yorktown aquifer (layer 3), Castle Hayne/Pungo River aquifer (layer 5), Peedee aquifer (layer 9), Black Creek aquifer (layer 11), and Upper Cape Fear aquifer (layer 13) at rates of 1.39, 97.54, 4.09, 27.8, and 20.98 Mgal/d, respectively (*fig. A10*). Specified-head inflow and outflow affecting the surficial aquifer (layer 1) were 199.32 and 55.64 Mgal/d, respectively. As in the predevelopment budget, vertical flow is highest in the upper layers and decreases with depth; however, the decrease is not as sharp as in the predevelopment budget. Additional downward flow from the specified heads in the surficial aquifer (layer 1) replaces water that is removed from the aquifers by pumping. Upward flow in the CCPCUA is substantially less than downward flow (*fig. A10*). Water is removed from storage in the Black Creek (layer 11), Upper Cape Fear (layer 13), and Lower Cape Fear aquifers (layer 15) at rates of 3.52, 2.85, and 1.73 Mgal/d, respectively, as a result of pumping from these aquifers. Simulated lateral flow into the CCPCUA increased from predevelopment rates for some of the model layers but mostly for the Upper Cape Fear aquifer (2004 rate of 5.52 Mgal/d) because of pumping. Lateral flow out of the CCPCUA for the 2004 water budget generally decreased from the predevelopment rates (*figs. A9* and *A10*).

As of 2004, large volumes of groundwater being pumped in the CCPCUA had affected groundwater levels and flow regimes (State of North Carolina, 2004) in the aquifers and confining units underlying the area. As the simulated groundwater flow budget analysis indicates, groundwater continues to be removed from storage in many of the hydrogeologic units, and groundwater level declines continue to occur. Until these reductions in groundwater storage are lowered or stopped, groundwater availability will continue to decline in this area.

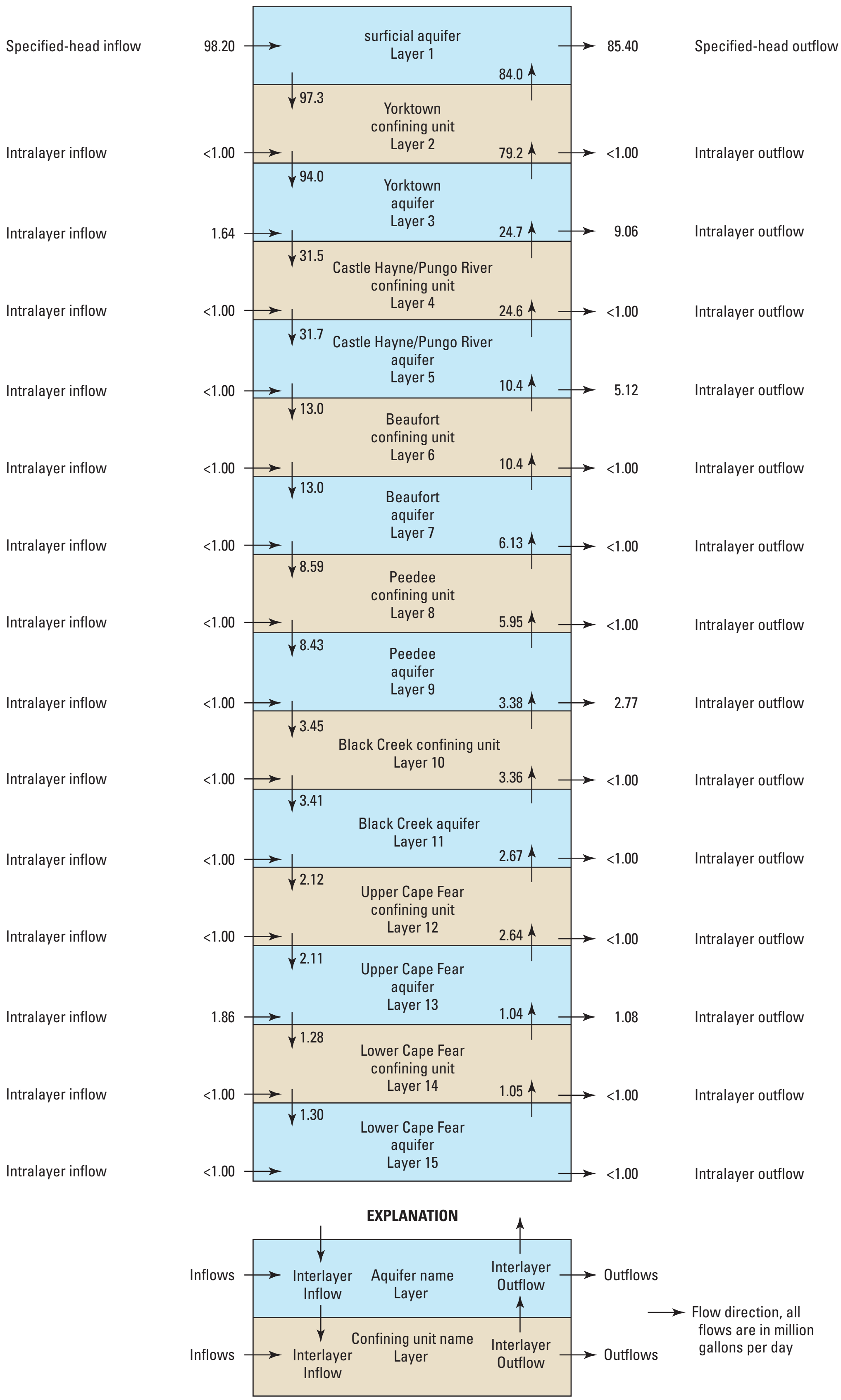



**Figure A9.** Simulated groundwater flow budget for predevelopment conditions in the North Carolina Central Coastal Plain Capacity Use Area.

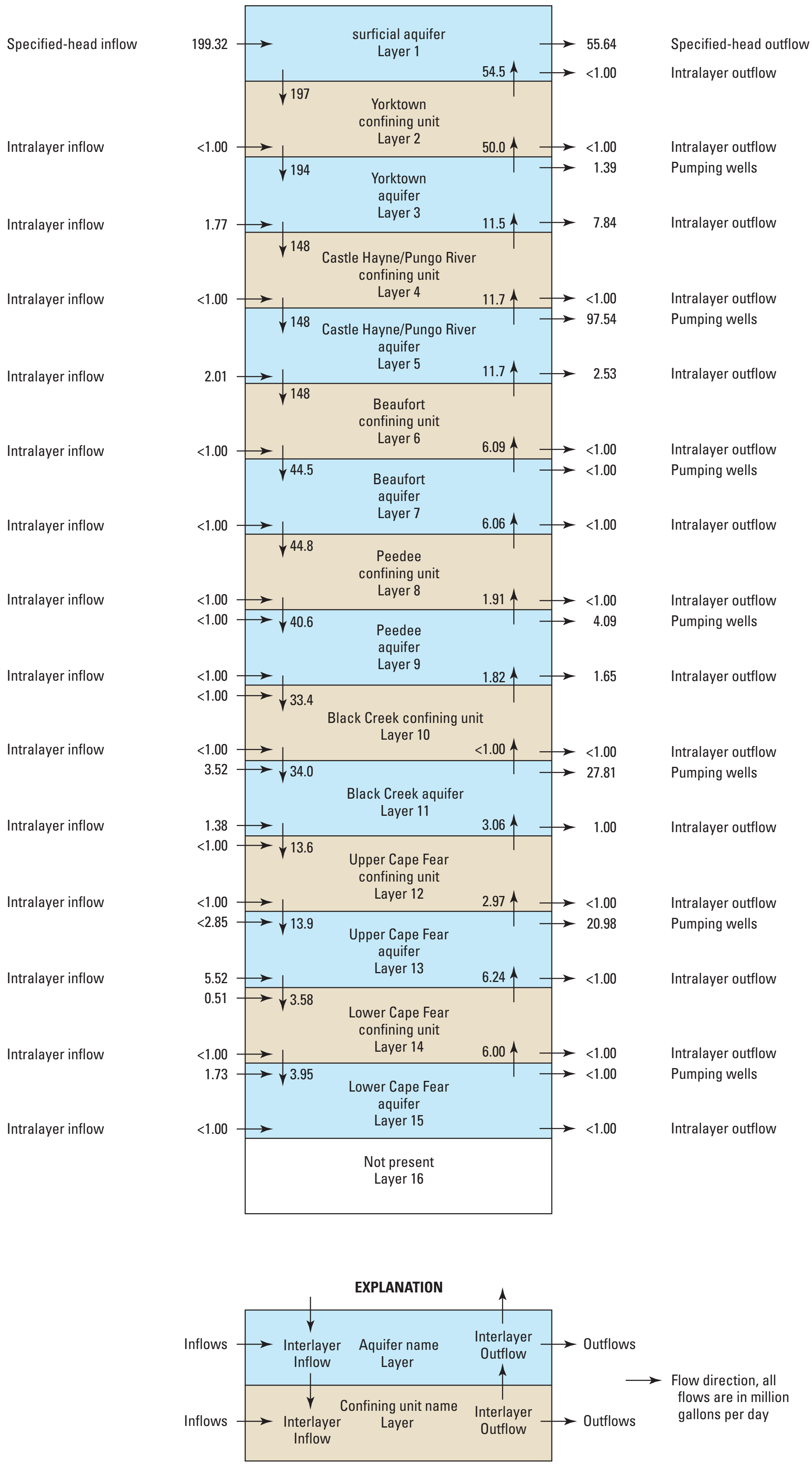



**Figure A10.** Simulated groundwater flow budget for 2004 conditions in the North Carolina Central Coastal Plain Capacity Use Area.

## Sumter, South Carolina, Groundwater Budget

Sumter, SC, is a city of approximately 45,000 people and is located in Sumter County in the central part of the SC ACP (*fig. A4*). The city depends solely on groundwater from 19 wells open to the Crouch Branch and McQueen Branch aquifers for potable water. Reported groundwater use in 2004 for Sumter County was about 18 Mgal/d (Childress and Bristol, 2005). Sumter County is not located in a capacity-use regulated area, and no major groundwater level declines are known to have occurred in the area.

The primary sources of groundwater in the Sumter area (*fig. A4*), for the simulated predevelopment water budget are recharge, specified-head boundaries, and lateral flow for all simulated aquifer and confining unit layers (*fig. A11*). Predevelopment recharge and specified-head inflow rates were 8.01 and 4.03 Mgal/d, respectively. Lateral flow was less than 1 Mgal/d for each model layer, except the Crouch Branch (layer 9) and the McQueen Branch aquifers (layer 11) for which lateral flow was 2.81 and 2.21 Mgal/d, respectively. Groundwater flow out of the Sumter area occurred through specified-head outflow for the surficial aquifer (layer 1; 5.67 Mgal/d) and through lateral flow within the surficial aquifer (layer 1; 1.57 Mgal/d), Crouch Branch aquifer (layer 9; 7.42 Mgal/d), and the McQueen Branch aquifer (layer 11; 2.27 Mgal/d). Intralayer flow generally decreases with depth from the surficial aquifer to the Crouch Branch aquifer. Below the Crouch Branch aquifer (layer 9), intralayer flow rates are less than 1 Mgal/d. Downward flow generally is twice as much as upward flow in the Sumter area (*fig. A11*).

The simulated 2004 water budget for the Sumter area includes pumping from the Crouch Branch and McQueen Branch aquifers (layers 9 and 11, respectively) at rates of 1.20 and 8.53 Mgal/d, respectively (*fig. A12*). The major sources of groundwater in the Sumter area are recharge and specified-head inflow to the surfical aquifer (layer 1) at rates of 8.01 Mgal/d and 5.13 Mgal/d, respectively, and lateral flow from outside of the Sumter water-budget area into the Crouch Branch and McQueen Branch aquifers (layers 9 and 11) at rates of 2.88 and 7.65 Mgal/d, respectively. Other than through pumping, groundwater flows from the Sumter area by discharge to specified-head boundaries in the surficial aquifer (layer 1, 3.44 Mgal/d), along with intralayer outflow from the surficial aquifer (1.56 Mgal/d), the Crouch Branch aquifer (layer 9, 6.93 Mgal/d), and the McQueen Branch aquifer (layer 11, 1.36 Mgal/d). As in the simulated predevelopment budget, vertical flow decreases with depth; however, in the 2004 water budget, reported flow is substantially greater in the McQueen Branch confining unit and aquifer (layers 10 and 11) because of pumping from the McQueen Branch aquifer. Downward flow is as much as six times greater than upward flow in the Sumter area (*fig. A12*). Changes in storage are insignificant in the Sumter area for the 2004 stress period. Simulated lateral flow into the McQueen Branch aquifer (layer 11, 7.65 Mgal/d) in the 2004 water budget tripled from the simulated predevelopment rate of 2.21 Mgal/d (*fig. A11*) as a result of increased pumping from this aquifer. Lateral groundwater flow from the Sumter area did not change greatly from the simulated predevelopment rates except for the McQueen Branch aquifer (layer 11) from which lateral flow decreased by half (*fig. A12*). The simulated 2004 water budget indicates little effect on groundwater availability from withdrawals by the city of Sumter as noted by the small changes in storage in the aquifers that are pumped.

## Aiken, South Carolina, Groundwater Budget

Aiken is a city of about 25,000 people located in Aiken County in western SC (*fig. A4*). The city of Aiken uses mostly groundwater from the Crouch Branch and McQueen Branch aquifers as a drinking-water supply source. Aiken County is not located in a capacity-use regulated area, and no major groundwater level declines are known to have occurred in the area.

The primary components of the groundwater budget in the Aiken area during simulated predevelopment groundwater flow conditions were recharge, rivers, and vertical flow through all of the model layers (*fig. A13*). Recharge is the largest source of groundwater at a rate of 33.60 Mgal/d. Water flows into the surficial aquifer (layer 1) from rivers (1.47 Mgal/d) and by lateral groundwater flow (2.67 Mgal/d). Lateral inflow also occurs through the Upper Floridan confining unit (layer 2) and Crouch Branch aquifer (layer 9) at rates of 1.68 and 1.39 Mgal/d, respectively. Discharge of groundwater from the surficial aquifer (layer 1) to rivers is the most substantial loss of groundwater from the Aiken area at 16.2 Mgal/d in the simulated predevelopment water budget. Groundwater also flows from the Aiken area by lateral flow through the surficial aquifer, the Upper Floridan confining unit and aquifer (layers 2 and 3), the Middle Floridan aquifer (layer 5), the Gordon confining unit (layer 6), the Crouch Branch aquifer (layer 9), and the McQueen Branch aquifer (layer 11) at rates that vary between 1.33 and 8.50 Mgal/d, with the highest lateral-flow rate occurring in the surficial aquifer. Downward vertical flow occurs throughout the groundwater system in the Aiken area, whereas upward vertical flow occurs in layers 1–10. Downward predevelopment water flow is considerably greater than upward predevelopment flow throughout the Aiken area.

Pumping rates during 2004 in the Aiken area increased downward groundwater flow through all of the aquifer and confining units compared to predevelopment flow rates (*fig. A14*). During 2004, withdrawals in the Aiken area from the Crouch Branch and McQueen Branch aquifers (layers 9 and 11) are at rates of 1.27 and 5.41 Mgal/d, respectively. With the exception of a decrease in discharge to rivers from the surficial aquifer (layer 1) of 6.1 Mgal/d, all other 2004 budget terms are similar to those of predevelopment (*figs. A13* and *A14*). The simulated 2004 water budget indicates little effect on groundwater availability from withdrawals by the city of Aiken as noted in the small changes in storage within the pumped aquifers.

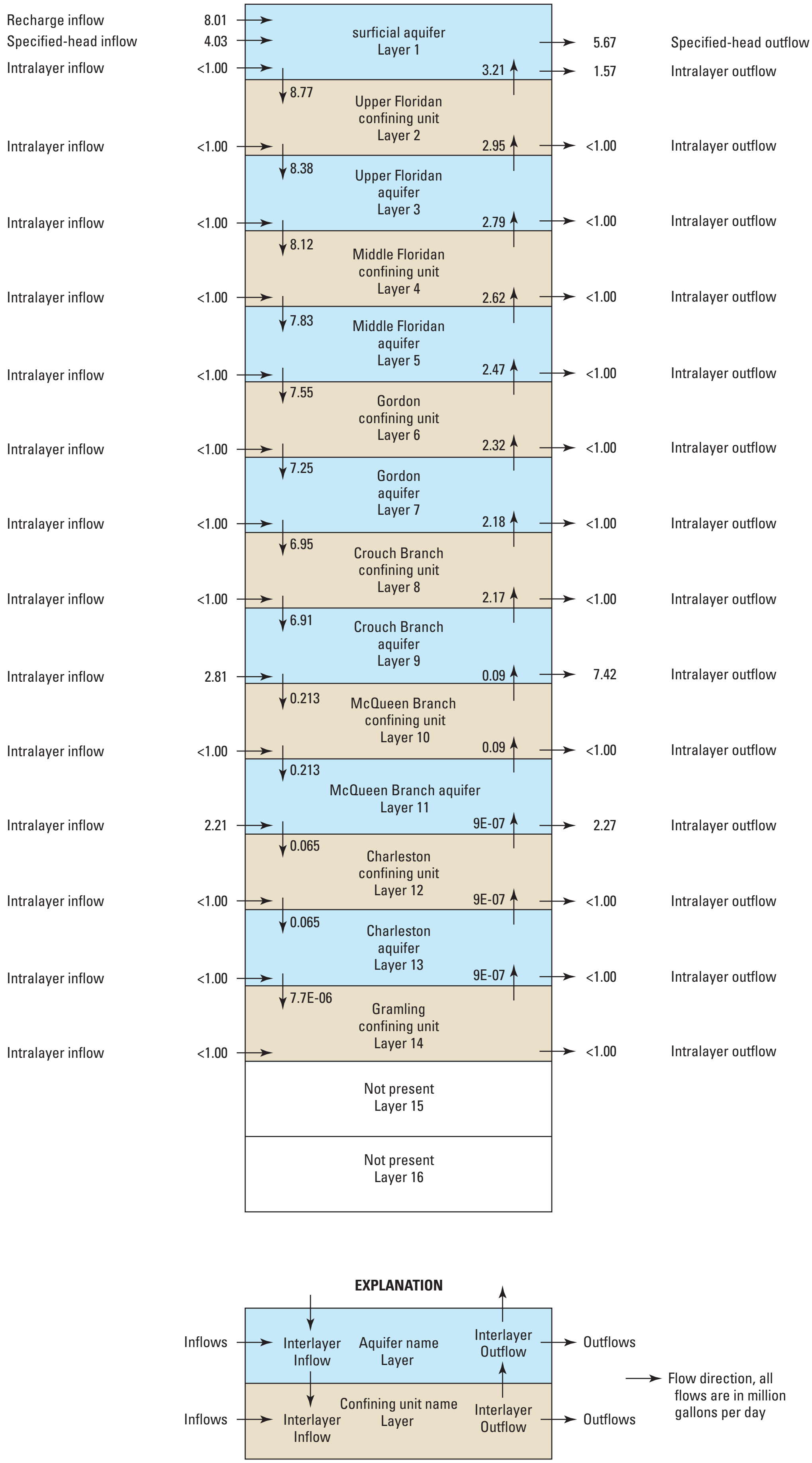



**Figure A11.** Simulated groundwater flow budget for predevelopment conditions in the Sumter, South Carolina, area.

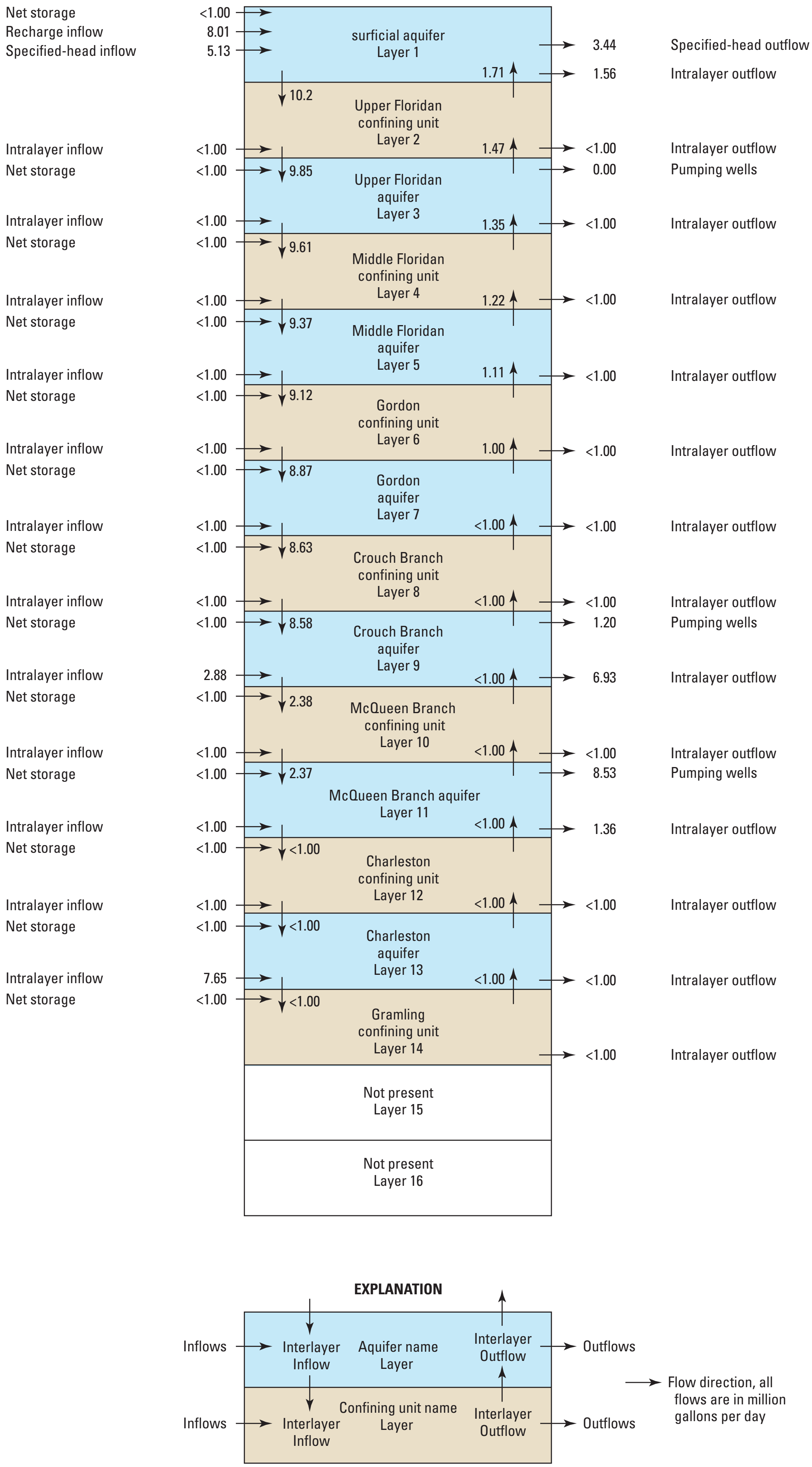



**Figure A12.** Simulated groundwater flow budget for 2004 conditions in the Sumter, South Carolina, area.

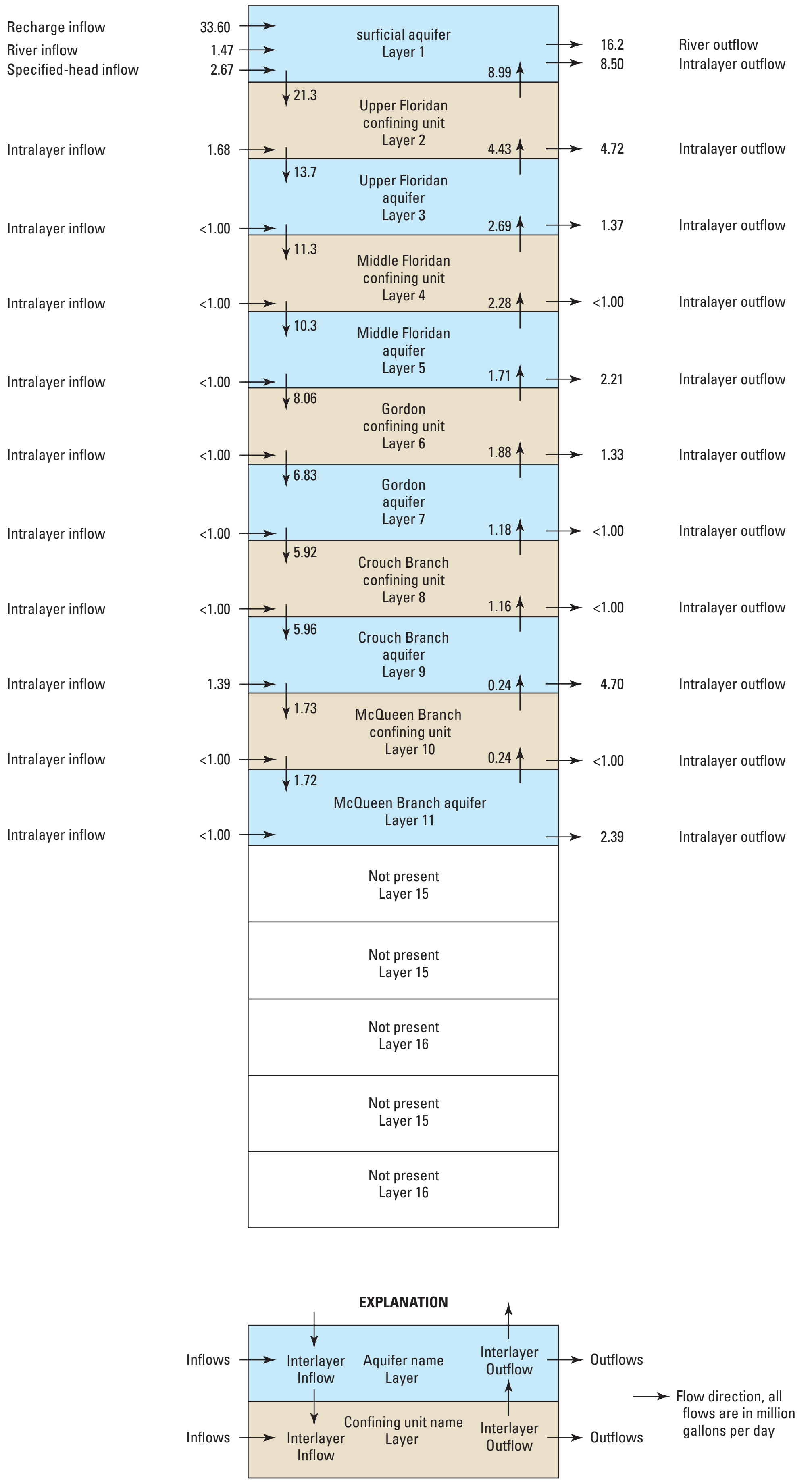



**Figure A13.** Simulated groundwater flow budget for predevelopment conditions in the Aiken, South Carolina, area.

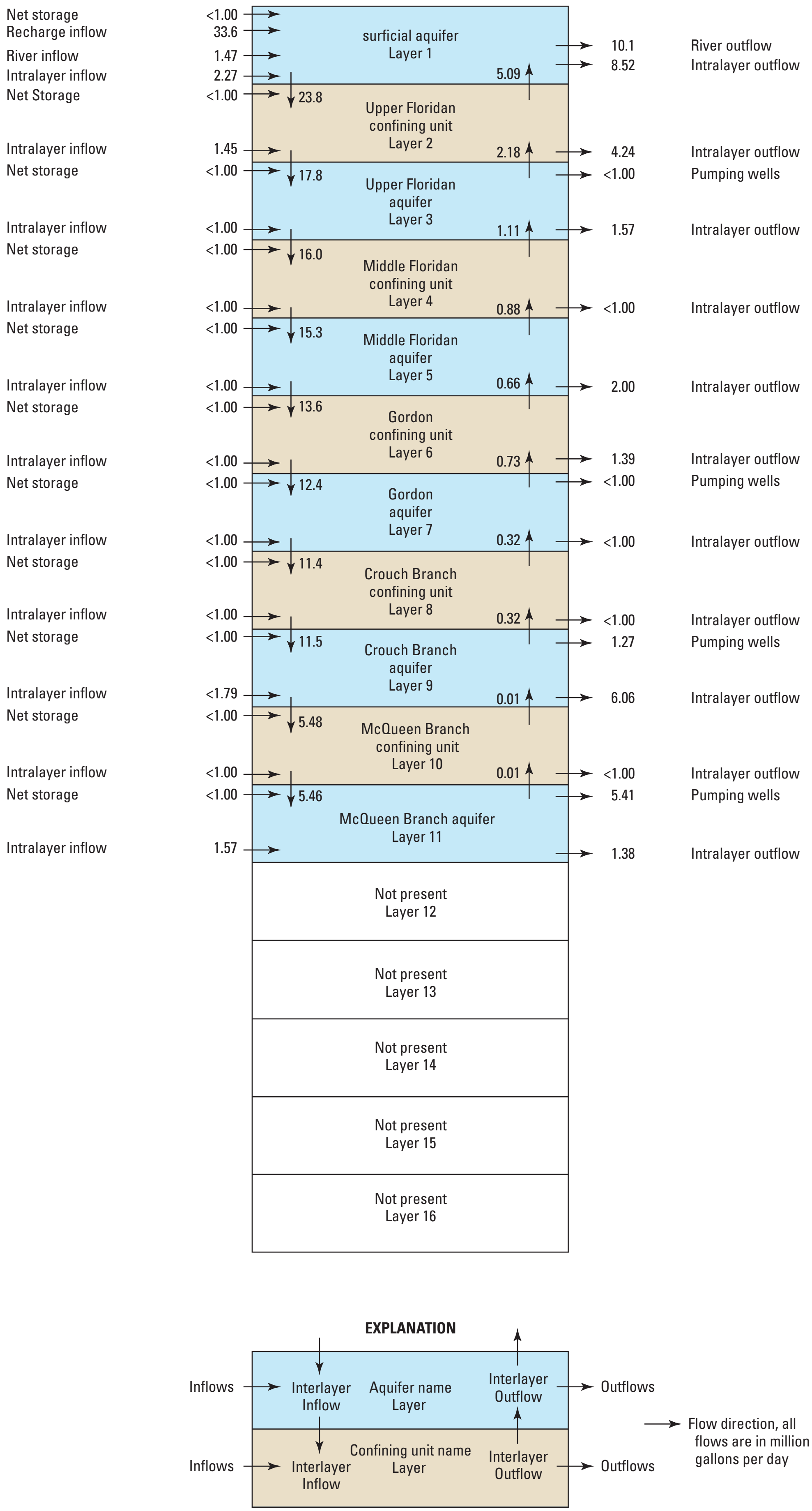



**Figure A14.** Simulated groundwater flow budget for 2004 conditions in the Aiken, South Carolina, area.

## Effects of Potential Future Climate Variability on Groundwater Levels

Groundwater levels and flows in the North and South Carolina ACP are dependent on climate and climatic variations, which must be considered for effective management of the groundwater resources. Climate tends to vary temporally and spatially in the study area based on various phenomena, including the El Niño–Southern Oscillation (ENSO), seasonal changes, and tropical events. Many groundwater management techniques rely on averages of long-term climatic conditions and underestimate the importance of variations from these averages (Alley, 2001).

In the Southeastern United States, North and South Carolina have some of the warmest climates in the United States; however, during the past 100 years, cooling periods have occurred that have given the Southeastern United States an overall cooling trend of 1 to 2 degrees Celsius (°C) (Burkett and others, 2001). Annual precipitation rates in the Southeastern States, which are among the highest in the United States, have increased by 20 to 30 percent during the past 100 years (Burkett and others, 2001). Much of the increase in annual precipitation rates can be attributed to an increase in rainfall intensity.

At least some of the variability in climate, especially temperature and precipitation rates, in the Southeastern United States is attributed to the effects of the ENSO phenomenon (Boyles and others, 2004). The ENSO phenomenon occurs as an oscillation between cold (El Niño) and warm (La Niña) water temperatures at the surface of the tropical Pacific Ocean. The ENSO cycle typically is 3–7 years. El Niño is the cooler phase of the ENSO phenomenon and results in cooler and wetter winters and drier summers for the Southeast; La Niña, the warmer phase, typically results in drier winters and wetter summers and can result in more tropical storms.

The sensitivity of groundwater resources to climate variability and change has been explored in several areas of the United States at various scales. Stockton and Boggess (1979) examined the potential geohydrologic implications of climate change on the groundwater resources of the United States. Vaccaro (1991) analyzed the sensitivity of groundwater recharge to climate variability in an area of the Columbia Plateau in Washington. Historical, synthetic, and projected climate variations, including variations resulting from global warming, were used in the analysis of recharge rates for the Ellensburg basin in the Columbia Plateau. Closer to the ACP study area, Ayers and others (1994) presented a sensitivity analysis of the potential effects of climate change on water resources in the Delaware River basin. More recently, Hanson and Dettinger (2005) evaluated the responses of both ground- and surface water in the Santa Clara–Calleguas basin in California to simulated climate variations. In the Hanson and Dettinger study (2005), Global Climate Models (GCMs) were used to predict future precipitation rates for the study area, which then were used to estimate groundwater and surface-water inflows and outflows in a regional groundwater flow model of the area. That study demonstrated that predicted climate variations from GCMs can be linked to groundwater flow models to produce realistic local-scale groundwater responses.

The calibrated groundwater flow model described in *Chapter C* of this report is used to simulate groundwater level changes as a result of possible variations in precipitation rates from 2010 to 2100. An ensemble of GCMs was used to predict the precipitation variability. The GCM is contained in an overall model developed by the National Center for Atmospheric Research (Wigley, 2003) termed the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC). MAGICC is coupled to a graphical interface named Scene Generator (SCENGEN), which can be used to visualize and extract results. The MAGICC model was run with two atmospheric emissions scenarios—a "reference" scenario, which assumes no changes are made by the global community to the 2000 atmospheric emissions, and a "policy" scenario, which assumes changes will be made that will lower the levels of greenhouse gases emitted. For instance, in 2100, the "policy" scenario assumes that the level of carbon dioxide atmospheric concentrations is reduced from about 700 to about 600 parts per million.

The MAGICC/SCENGEN model predicts the rate of change in precipitation or temperature for a user-selected area, which can be as large as the entire planet. An area within the MAGICC/SCENGEN model that encompasses the Southeastern United States was selected, and the rate of change in precipitation for this area was predicted on a decadal scale from 2010 to 2100. Reference and policy model runs were completed, and the results of the mean, maximum, and minimum precipitation-rate changes were recorded. These predicted precipitation-rate changes, in percent, were used to specify future recharge rates over decadal stress periods from 2010 to 2100 in the groundwater flow model (*fig. A15*).

Predicted groundwater level altitudes at selected observation-well sites were plotted for the Yorktown/Upper Floridan aquifers (layer 3), Castle Hayne/Pungo River/Middle Floridan aquifers (layer 5), Beaufort/Gordon aquifers (layer 7), Peedee/Crouch Branch aquifer (layer 9), Black Creek/McQueen Branch aquifer (layer 11), and Upper Cape Fear/Charleston aquifer (layer 13, *figs. A6, A16–A22*; *table A1*). The groundwater model was run in transient mode without pumpage to evaluate the difference in groundwater level altitudes attributable to simulated future variations in the recharge rates. Varying the recharge rates changes groundwater levels from 3 to 45 ft in the higher altitude areas of the southern portion of the model area where recharge is applied. The same recharge variations produce less than 0.2 ft of change in groundwater levels in the northern portion of the model area, downdip and away from the area of specified recharge.

Simulated groundwater levels for the climate-prediction scenarios were calculated for two observation wells that are in the Upper Floridan aquifer (layer 3) in South Carolina—HAM-83 and BFT-429 (*figs. A16* and *A17*). The simulated and observed groundwater levels match closely at well BFT-429 but less closely at well HAM-83. The reference and policy scenarios for well HAM-83 produce similar groundwater

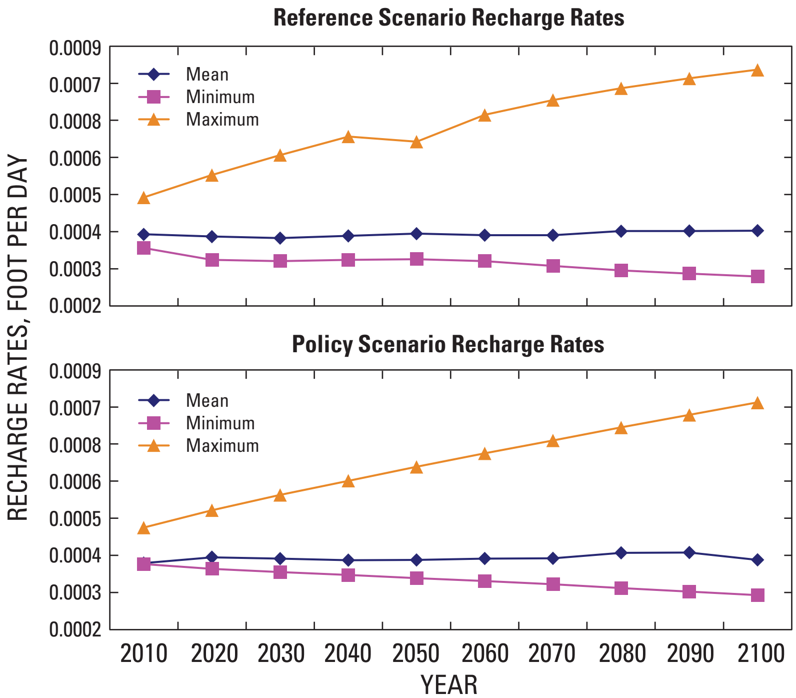



**Figure A15.** Simulated net recharge rates for decadal stress periods from 2010 to 2100 used in the climate variability scenarios for the Atlantic Coastal Plain groundwater flow model for North and South Carolina.

levels by 2100. At well BFT-429, the reference and policy scenarios produce essentially the same simulated groundwater levels by 2100 (*table A1*).

Simulated groundwater levels for the climate-prediction scenarios were calculated for two observation wells in the Castle Hayne/Pungo River/Middle Floridan aquifers (layer 5)—COL-92 and ON-227, in South and North Carolina, respectively (*figs. A16* and *A18*). The simulated and observed groundwater levels match closely at well ON-227 but less closely at well COL-92. The reference and policy scenarios for wells COL-92 and ON-227 produce essentially the same simulated groundwater levels by 2100 (*table A1*).

Simulated groundwater levels for the climate-prediction scenarios were calculated for two observation wells in the Beaufort/Gordon aquifers (layer 7)—CHN-101 and ON-265, in South and North Carolina, respectively (*figs. A16* and *A19*). The simulated and observed groundwater levels at these sites match closely at well ON-265 but less closely at well CHN-101. The reference and policy scenarios for these wells produce essentially the same groundwater levels by 2100 (*table A1*).

Simulated groundwater levels for the climate-prediction scenarios were calculated for two observation wells in the Peedee/Crouch Branch aquifer (layer 9)—AL-7 and S 22J9, in South and North Carolina, respectively (*figs. A16* and *A20*). The simulated and observed groundwater levels at these sites match closely at well S 22J9 but less closely at well AL-7. The policy scenario for well AL-7 produces a minimum groundwater level about 0.6 ft higher than the reference scenario in 2100. For well S 22J6, the reference and policy scenarios produce essentially the same groundwater levels by 2100 (*table A1*).

Simulated groundwater levels for the climate-prediction scenarios were calculated for two observation wells in the Black Creek and McQueen Branch aquifer (layer 11)—30AA04 and T 29G4, in Georgia and North Carolina, respectively (*figs. A16* and *A21*). The simulated and observed groundwater levels at these sites match closely at well T 29G4 but less closely at well 30 AA04. The policy scenario for well 30 AA04 produces a minimum groundwater level 1.73 ft lower than the reference scenario. For well T 29G4, the reference and policy scenarios produce essentially the same groundwater levels by 2100 (*table A1*).

Simulated groundwater levels for the climate-prediction scenarios were calculated for two observation wells in the Upper Cape Fear/Charleston aquifer (layer 13)—FLO-128 and M 30L3, in South and North Carolina, respectively (*figs. A16* and *A22*). The simulated and observed groundwater levels at these sites are presented, and the results match closely at both wells. The reference and policy scenarios for these wells produce essentially the same groundwater levels by 2100 (*table A1*).

These simulations of the potential effects of future climate variability indicate that groundwater resources in some places in the study area are susceptible to substantial fluctuations in groundwater levels. The more susceptible areas are in the inner Coastal Plain, and the less susceptible areas are in the outer Coastal Plain (*fig. A1*). Simulation results indicate that groundwater availability should not be substantially affected by potential future climate variations related to changes in precipitation rates in the outer Coastal Plain. Simulation results, however, do indicate that these potential precipitation variations could have an effect on groundwater availability in the inner Coastal Plain, especially if the precipitation rates tend to be lower than the reference scenario.

## Groundwater Level Monitoring Network Analysis in North and South Carolina

Knowledge of current and historical groundwater levels is a key component of the assessment of groundwater availability in the North and South Carolina ACP. Without groundwater level data, it would be difficult to evaluate changes over time and, therefore, groundwater availability. Groundwater level data have been collected in the study area since about 1840, but networks of wells for collecting groundwater level data systematically were not established in the North and South Carolina ACP aquifers until 1931 in NC (Burchard, 1936) and


**Figure A16.** Locations of wells used in the climate variability scenarios in the Atlantic Coastal Plain of North Carolina, South Carolina, and Georgia.

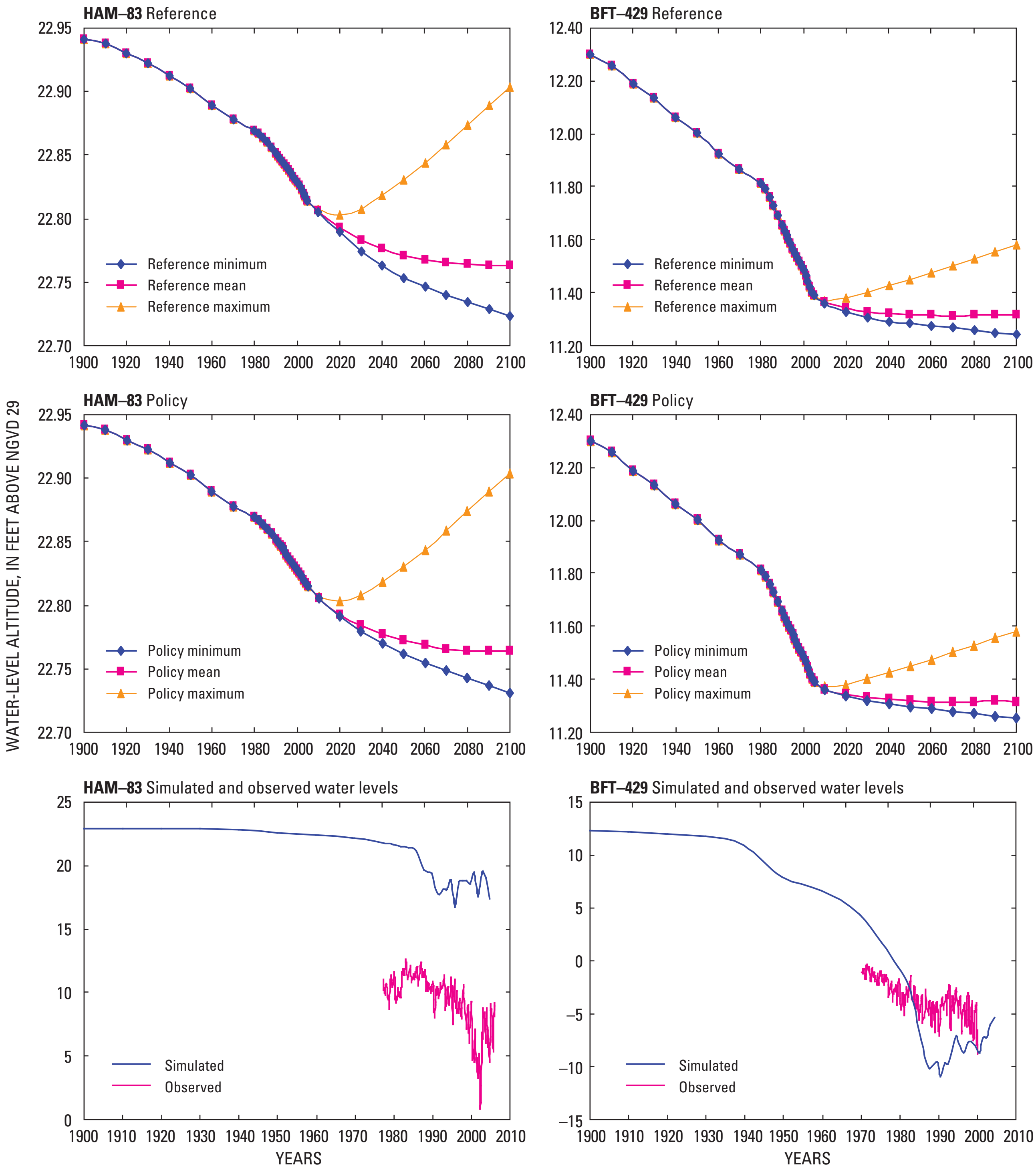



**Figure A17.** Simulated and observed groundwater levels for observation wells in the Upper Floridan aquifer, 1900–2100, in the Atlantic Coastal Plain of South Carolina.

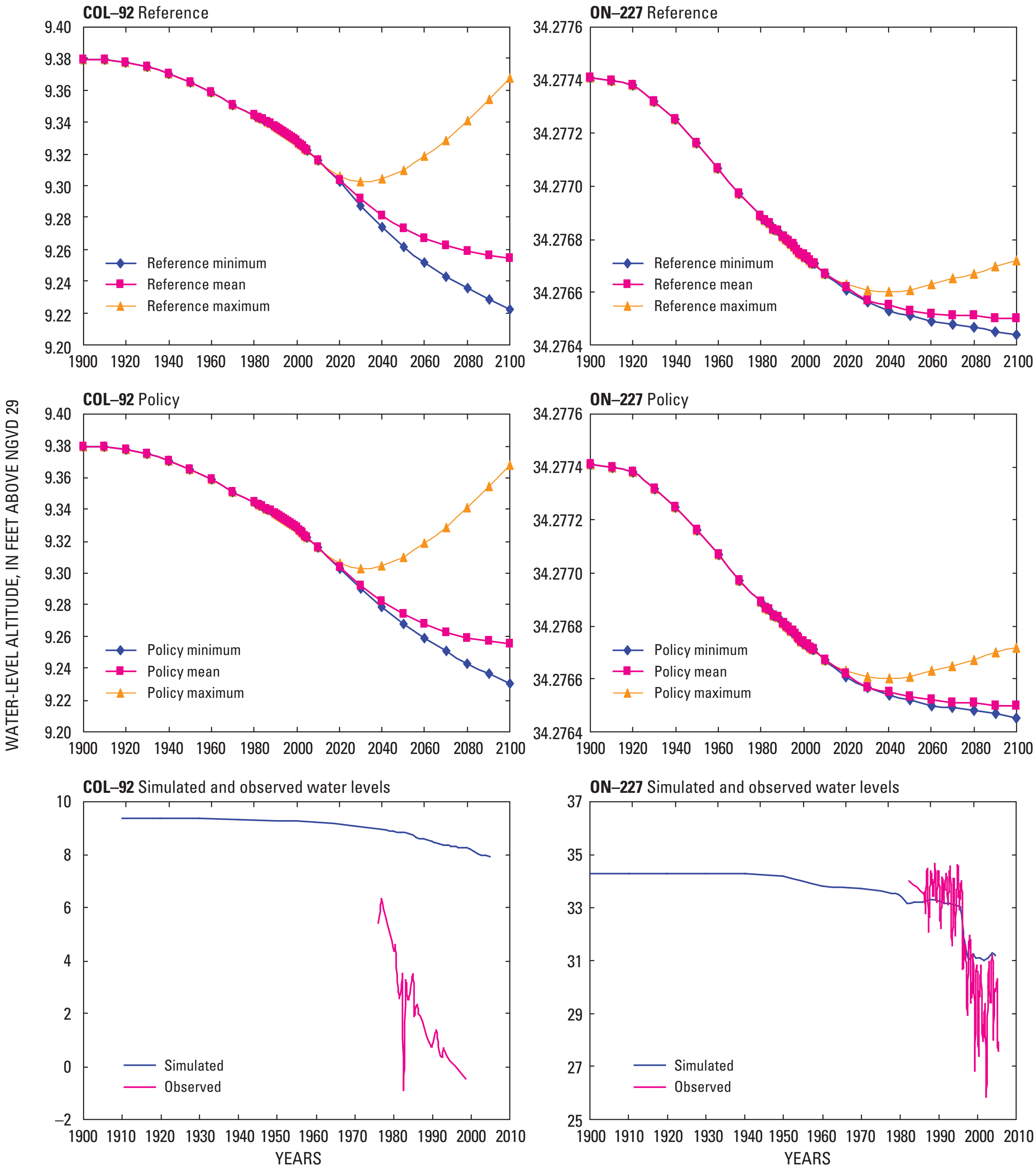



**Figure A18.** Simulated and observed groundwater levels for observation wells in the Castle Hayne/Pungo River/Middle Floridan aquifer, 1900–2100, in the Atlantic Coastal Plain of North and South Carolina.

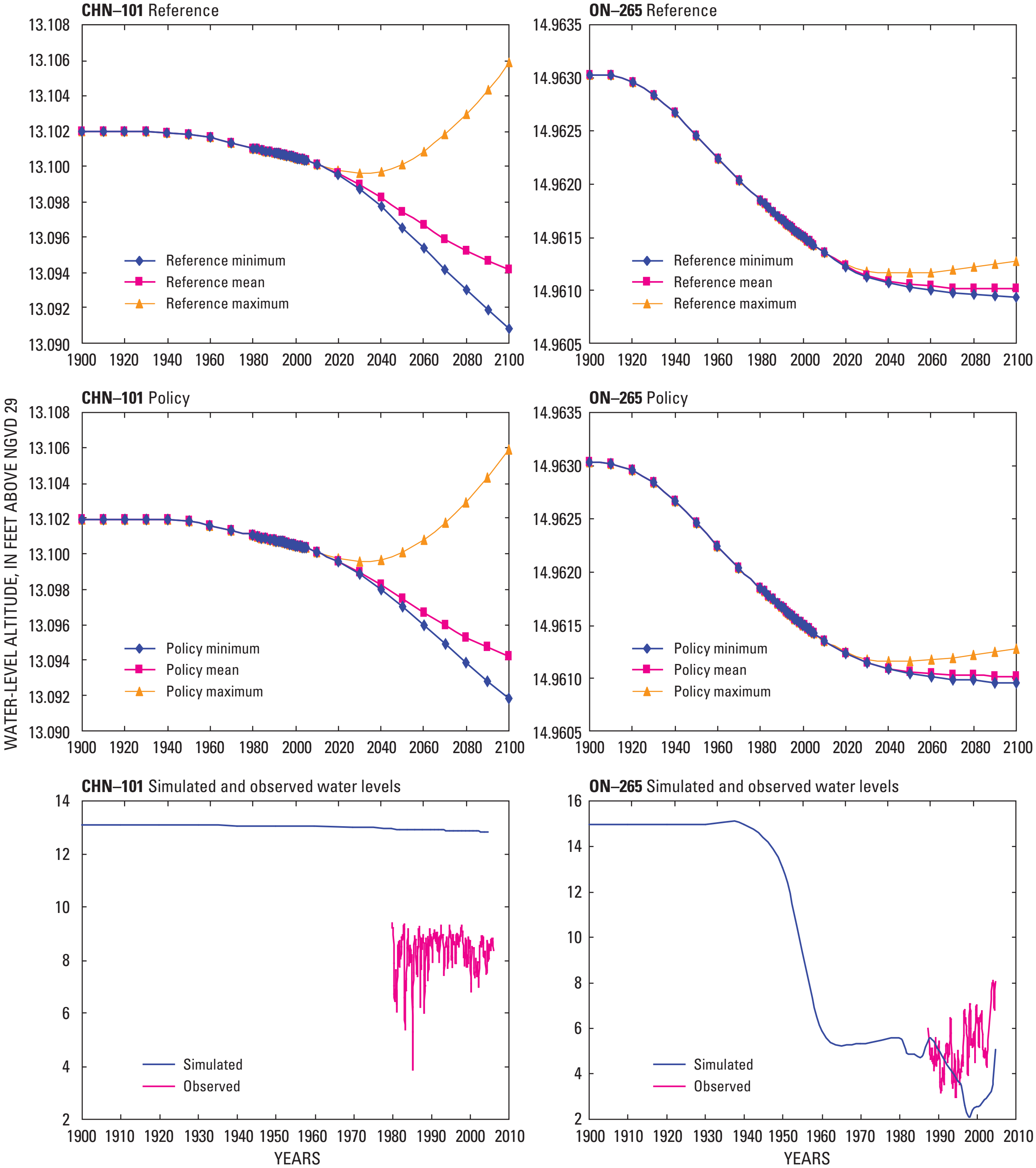



**Figure A19.** Simulated and observed groundwater levels for observation wells in the Beaufort/Gordon aquifer, 1900–2100, in the Atlantic Coastal Plain of North and South Carolina.

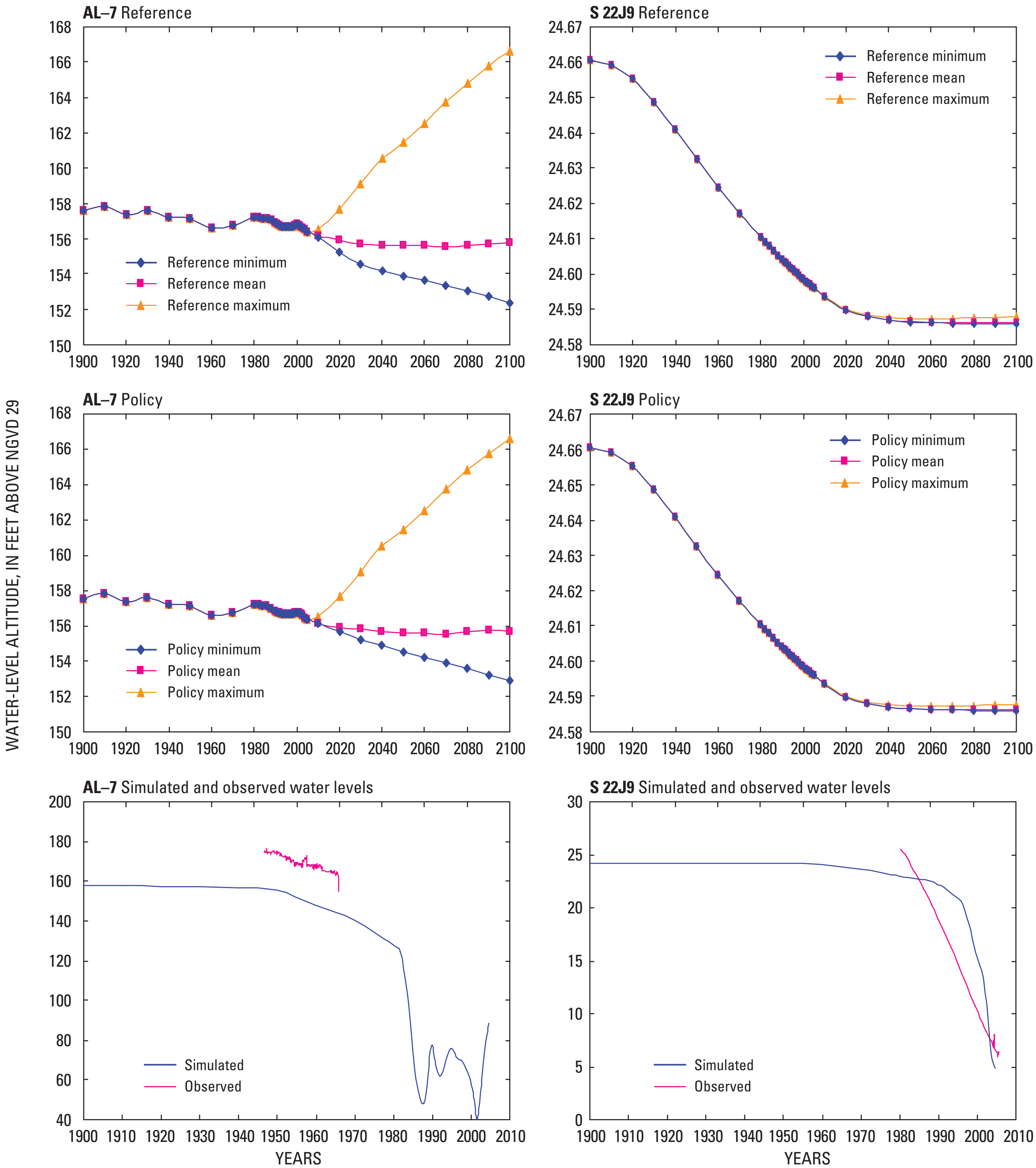



**Figure A20.** Simulated and observed groundwater levels for observation wells in the Peedee/Crouch Branch aquifer, 1900–2100, in the Atlantic Coastal Plain of North and South Carolina.

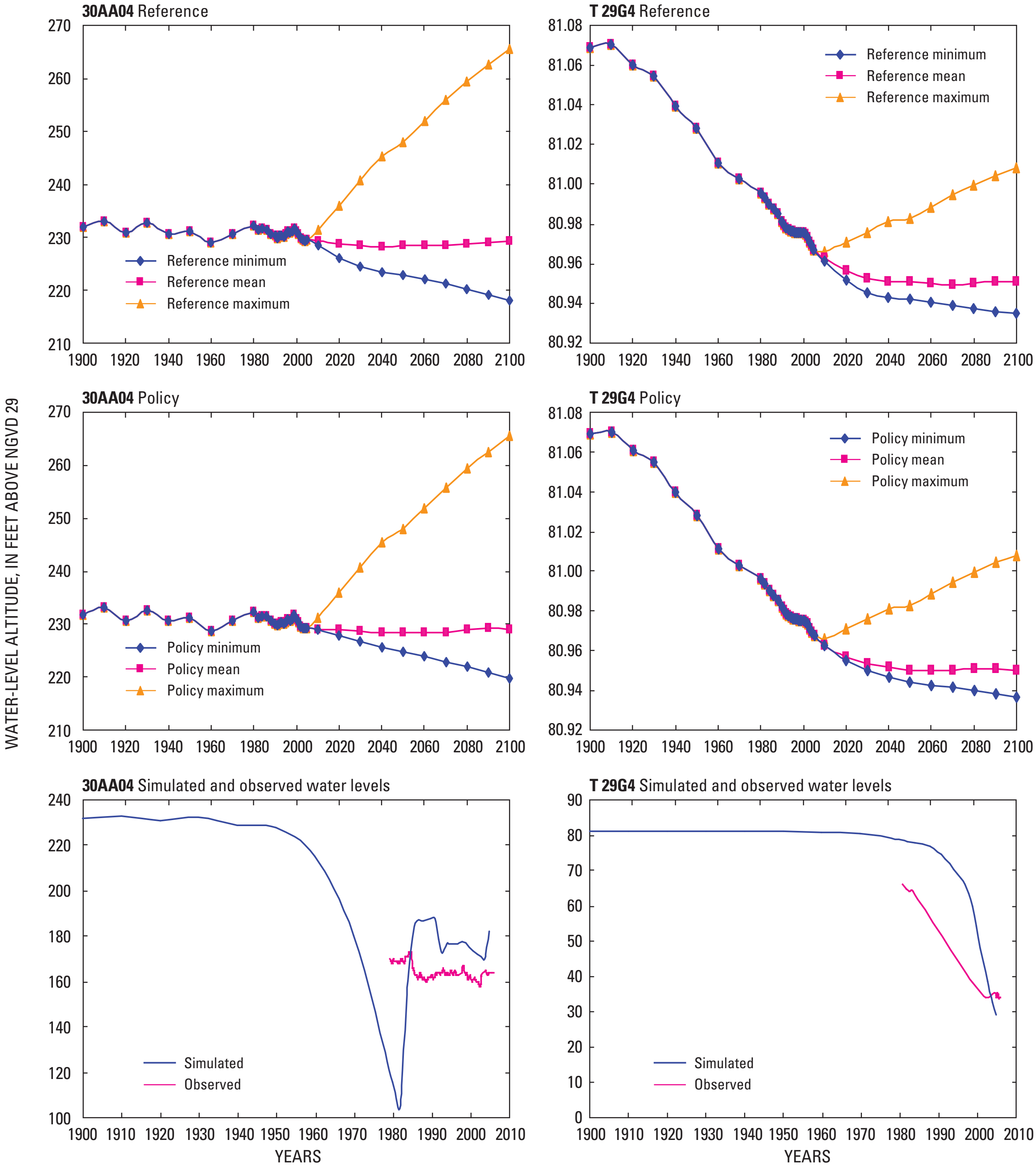



**Figure A21.** Simulated and observed groundwater levels for observation wells in the Black Creek/McQueen Branch aquifer, 1900–2100, in the Atlantic Coastal Plain of North Carolina and Georgia.

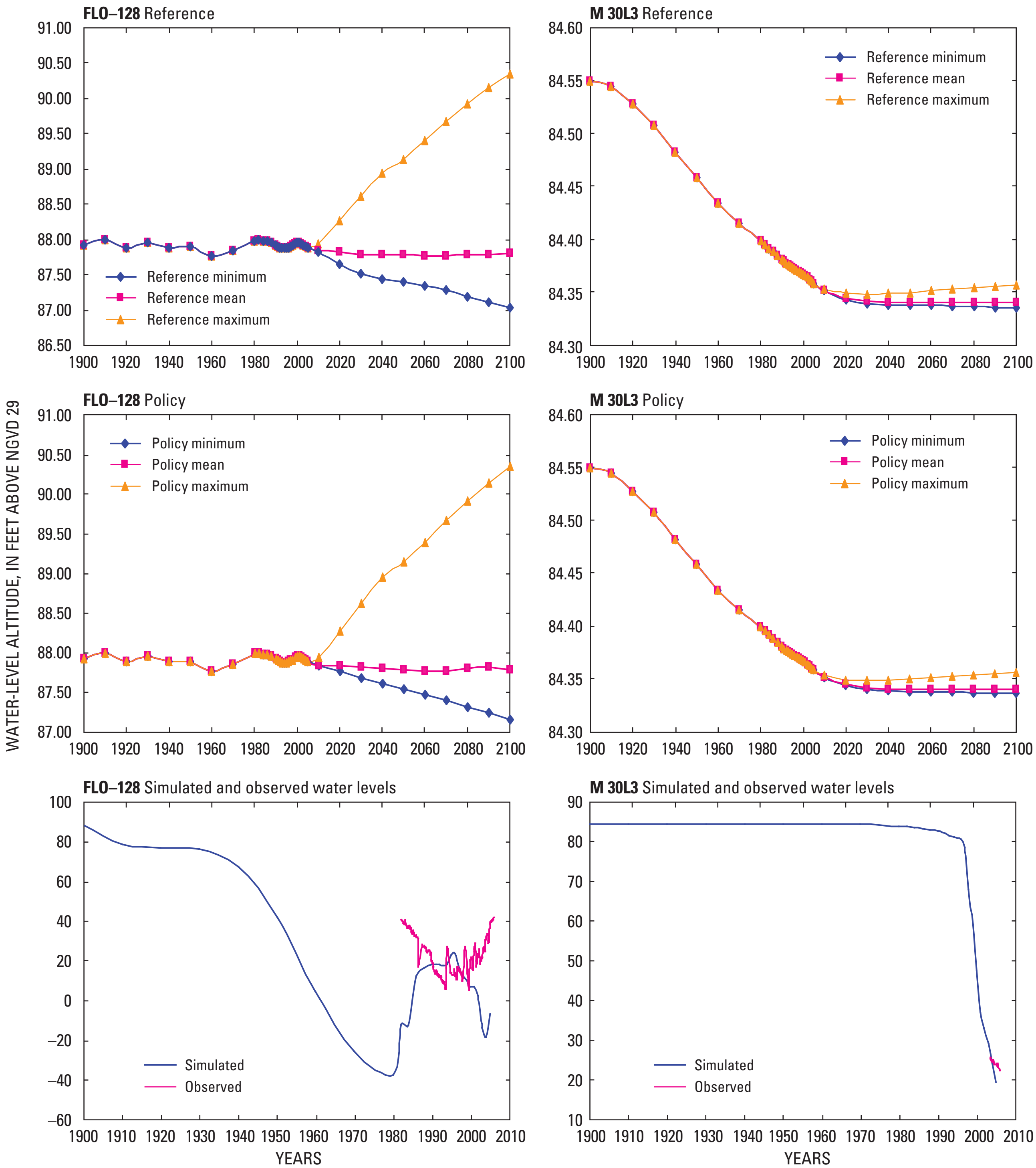



**Figure A22.** Simulated and observed groundwater levels for observation wells in the Upper Cape Fear/Charleston aquifers, 1900–2100, in the Atlantic Coastal Plain of North and South Carolina.

**Table A1.** Statistics for analysis of effects of climate variability on groundwater levels in the Atlantic Coastal Plain of North and South Carolina.

[Water levels are in feet above NGVD 29]

| Well number | Model layer | Aquifer | Reference—2010 | | | Reference—2100 | | | Policy—2010 | | | Policy—2100 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Minimum water level | Mean water level | Maximum water level | Minimum water level | Mean water level | Maximum water level | Minimum water level | Mean water level | Maximum water level | Minimum water level | Mean water level | Maximum water level |
| BFT-429 | 3 | Upper Floridan | 12.30 | 12.30 | 12.30 | 11.24 | 11.32 | 11.58 | 12.30 | 12.30 | 12.30 | 11.25 | 11.31 | 11.58 |
| HAM-83 | 3 | Upper Floridan | 22.94 | 22.94 | 22.94 | 22.72 | 22.76 | 22.90 | 22.94 | 22.94 | 22.94 | 22.73 | 22.76 | 22.90 |
| COL-92 | 5 | Middle Floridan | 9.38 | 9.38 | 9.38 | 9.22 | 9.25 | 9.37 | 9.38 | 9.38 | 9.38 | 9.23 | 9.26 | 9.37 |
| ON-227 | 5 | Castle Hayne | 34.28 | 34.28 | 34.28 | 34.28 | 34.28 | 34.28 | 34.28 | 34.28 | 34.28 | 34.28 | 34.28 | 34.28 |
| ON-265 | 7 | Beaufort | 14.96 | 14.96 | 14.96 | 14.96 | 14.96 | 14.96 | 14.96 | 14.96 | 14.96 | 14.96 | 14.96 | 14.96 |
| CHN-101 | 7 | Gordon | 13.10 | 13.10 | 13.10 | 13.09 | 13.09 | 13.11 | 13.10 | 13.10 | 13.10 | 13.09 | 13.09 | 13.11 |
| AL- 7 | 9 | Lynches | 157.56 | 157.56 | 157.56 | 152.38 | 155.76 | 166.62 | 157.56 | 157.56 | 157.56 | 152.93 | 155.73 | 166.62 |
| S 22J9 | 9 | Peedee | 24.66 | 24.66 | 24.66 | 24.66 | 24.66 | 24.66 | 24.59 | 24.59 | 24.59 | 24.59 | 24.59 | 24.59 |
| T 29G4 | 11 | Black Creek | 81.07 | 81.07 | 81.07 | 81.07 | 81.07 | 81.07 | 80.93 | 80.95 | 81.01 | 80.94 | 80.95 | 81.01 |
| 30AA04 | 11 | McQueen Branch | 231.85 | 231.85 | 231.85 | 218.11 | 229.11 | 265.42 | 231.85 | 231.85 | 231.85 | 219.84 | 228.85 | 265.42 |
| FLO- 128 | 13 | Charleston | 87.92 | 87.92 | 87.92 | 87.04 | 87.80 | 90.35 | 87.92 | 87.92 | 87.92 | 87.16 | 87.79 | 90.35 |
| M 30L3 | 13 | Upper Cape Fear | 84.55 | 84.55 | 84.55 | 84.34 | 84.34 | 84.36 | 84.55 | 84.55 | 84.55 | 84.34 | 84.34 | 84.36 |

1940 in SC (Warren, 1944). A compilation of groundwater level measurements for the NC ACP (Stephenson and Johnson, 1912) included many individual groundwater level measurements from various ACP aquifers.

Groundwater level compilations for North and South Carolina that include recent (2005–2006) and earlier groundwater levels can be found in Waters (2003), Webb (2006), Agerton and others (2007), and DePaul and others (2008). Substantial resources have been and continue to be expended in both States to monitor groundwater levels, but no quantitative effort has been made to assess the efficacy of the respective groundwater level network coverage.

Several studies have been conducted to evaluate groundwater level networks (Swain and Sonenshein, 1994; Olea and Davis, 1999; Prinos, 2005). Swain and Sonenshein (1994) used “confidence polygons” to define the monitoring area for each observation well in Broward County, Florida. The boundaries of these polygons were determined by the endpoints of radial lines from each well oriented toward other neighboring wells. The lengths of these lines were statistically estimated distances to the points at which groundwater levels can be predicted within specified criteria. The water-level data were analyzed for temporal variations, and the results of the spatial and temporal analysis were combined into a single coefficient that was used to evaluate the network and for future management decisions. Prinos (2005) took a similar approach using the Miami–Dade County, Florida, groundwater level network. While this type of analysis is appropriate at a county scale, it is not useful at a regional scale. Olea and Davis (1999) used a geostatistical approach to analyze the High Plains aquifer groundwater level observation network in western Kansas. In their study, the kriging standard deviation of the well locations was used as a measure of reliability in spatial estimation. The larger kriging standard deviations of the well locations were considered to be less reliable estimates, while the smaller kriging standard deviations were considered to be more reliable estimates.

The groundwater level monitoring network of the North and South Carolina ACP was characterized in a method similar to that of Olea and Davis (1999). Continuous groundwater level well-location maps were generated for each aquifer using data from 609 current and historical wells: 174 wells completed in the Yorktown/Upper Floridan aquifers (layer 3, *fig. A23*), 87 wells completed in the Castle Hayne/Pungo River/Middle Floridan aquifers (layer 5, *fig. A24*), 73 wells completed in the Beaufort/Gordon aquifers (layer 7, *fig. A25*), 97 wells completed in the Peedee/Crouch Branch aquifer (layer 9, *fig. A26*), 95 wells completed in the Black Creek/McQueen Branch aquifer (layer 11, *fig. A27*), 52 wells completed in the Upper Cape Fear/Charleston aquifer (layer 13, *fig. A28*), and 31 wells completed in the Lower Cape Fear/Gramling aquifer (layer 15, *fig. A29*). Groundwater level data for NC were obtained from the North Carolina Division of Water Resources (2007), and groundwater level data for SC were obtained from Waters (2003). Groundwater level

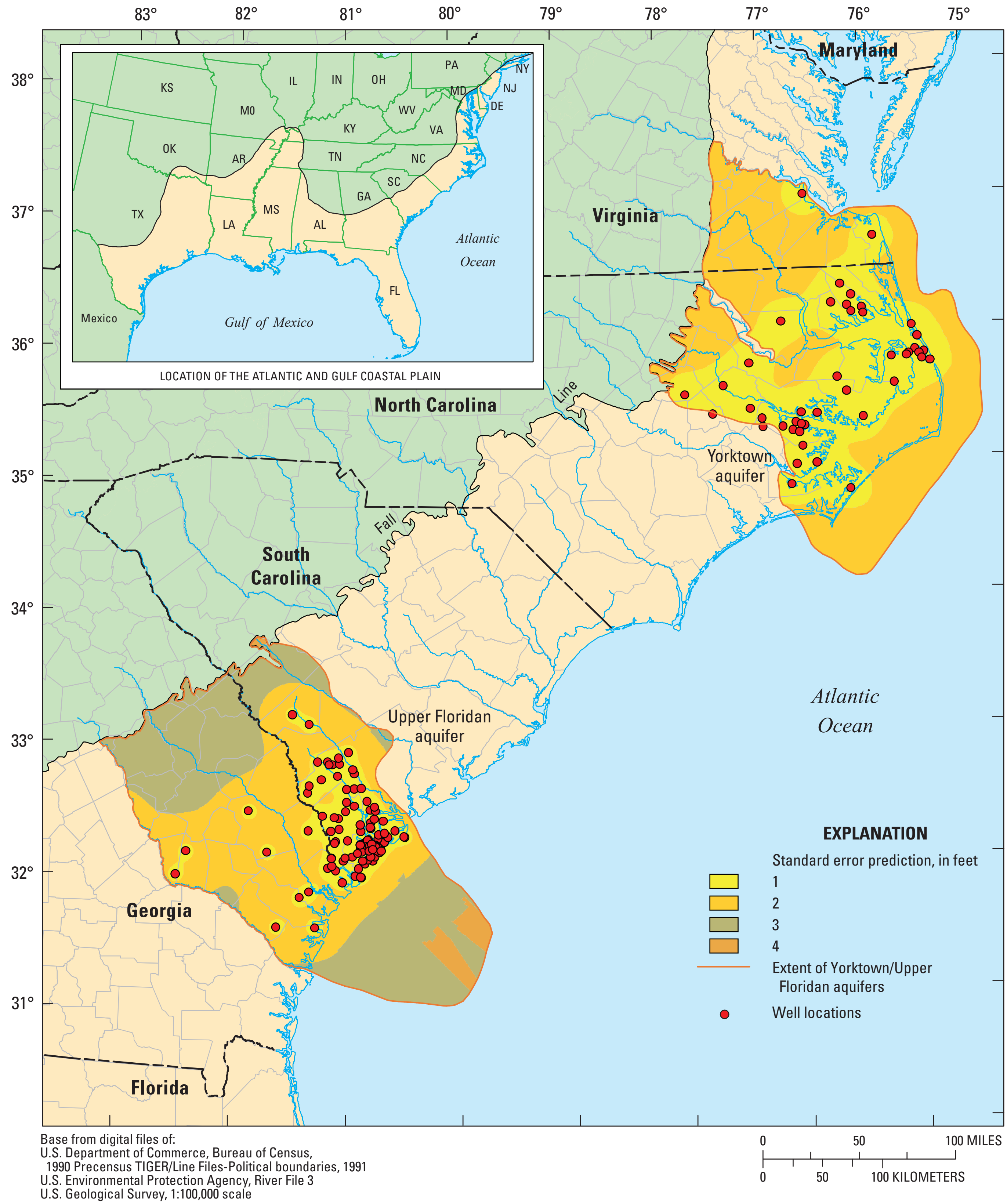



**Figure A23.** Prediction standard error of the groundwater level monitoring network in the Yorktown/Upper Floridan aquifers in the Atlantic Coastal Plain of North and South Carolina.

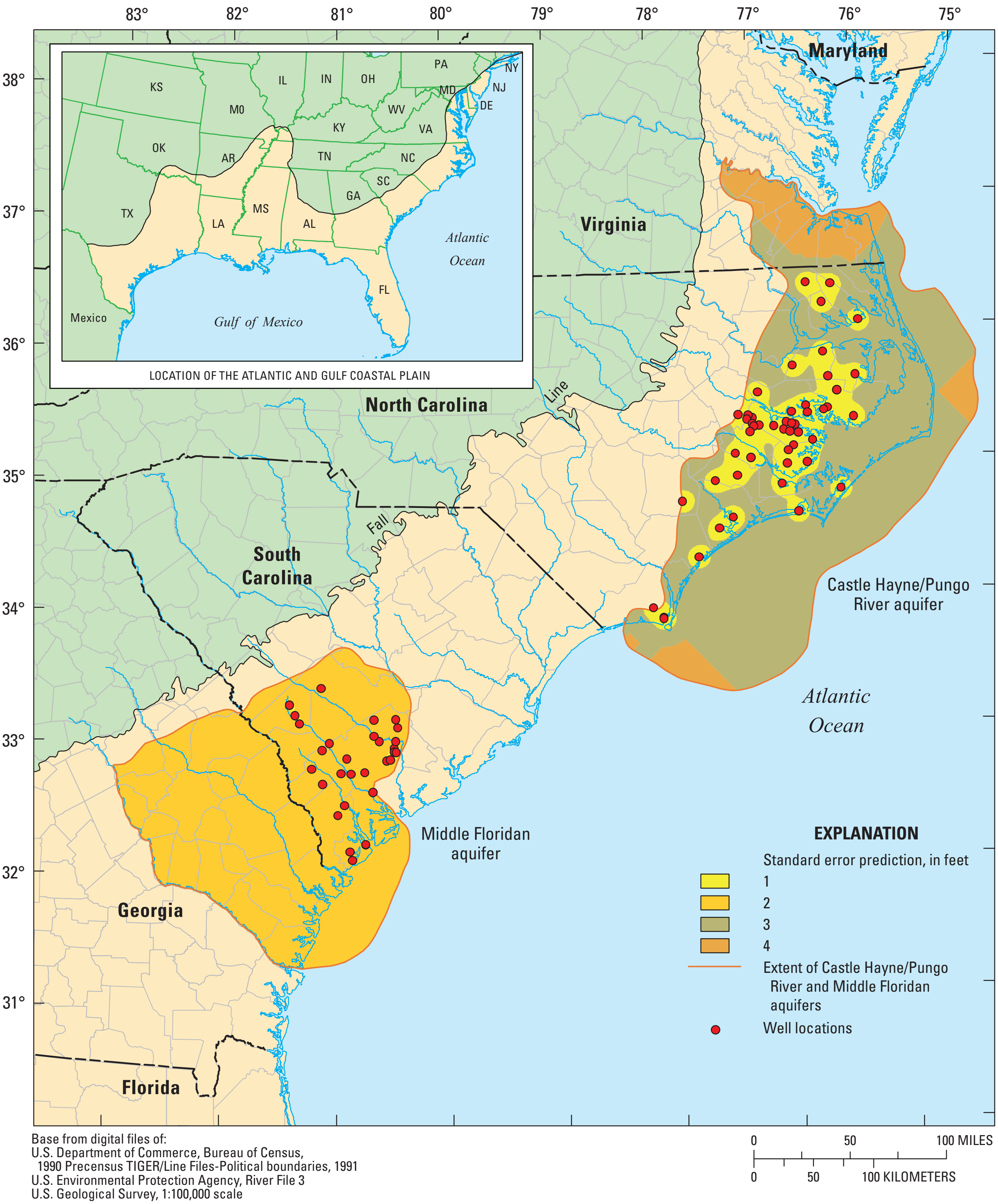



**Figure A24.** Prediction standard error of the groundwater level monitoring network in the Castle Hayne/Pungo River/Middle Floridan aquifers in the Atlantic Coastal Plain of North and South Carolina.

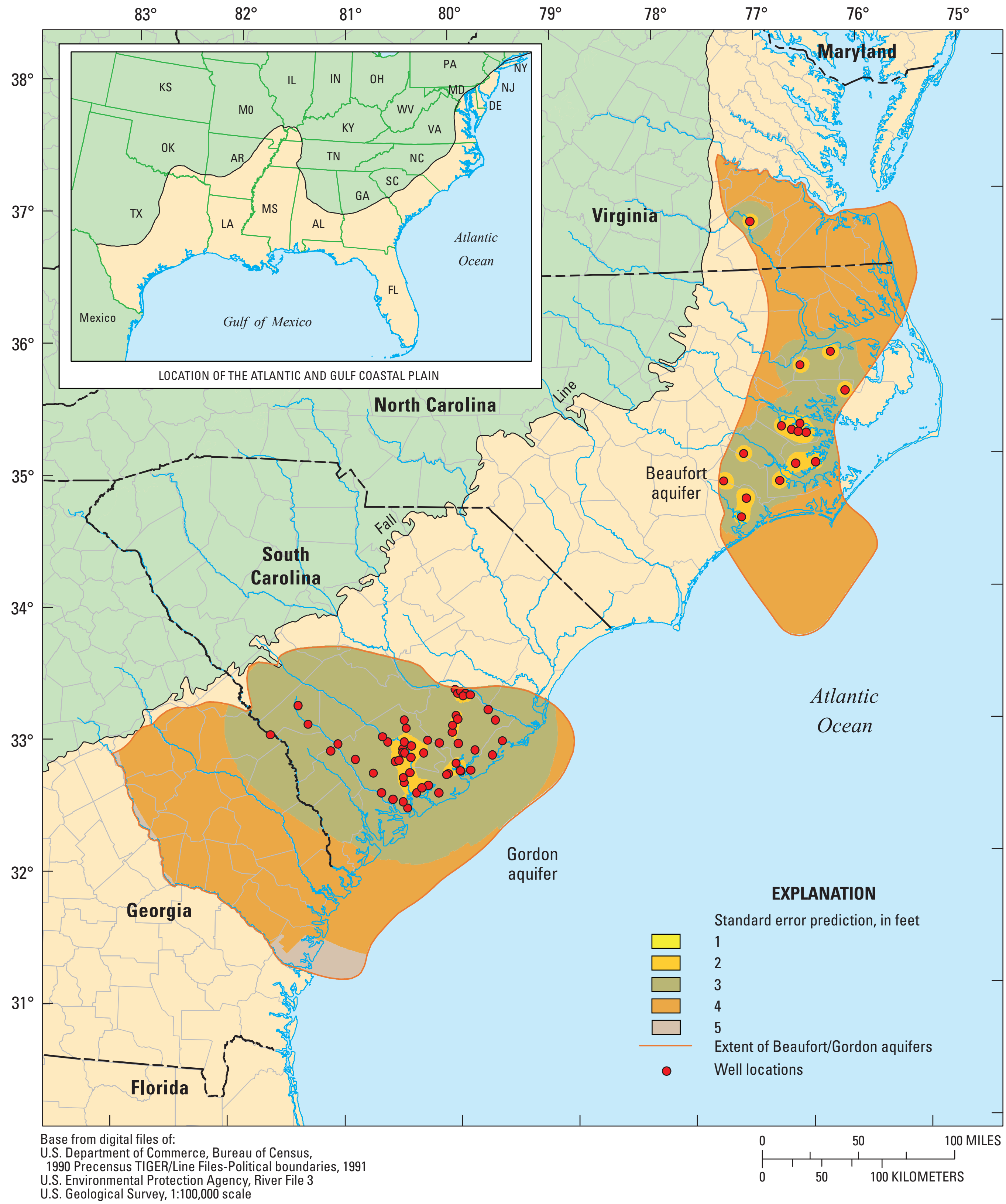
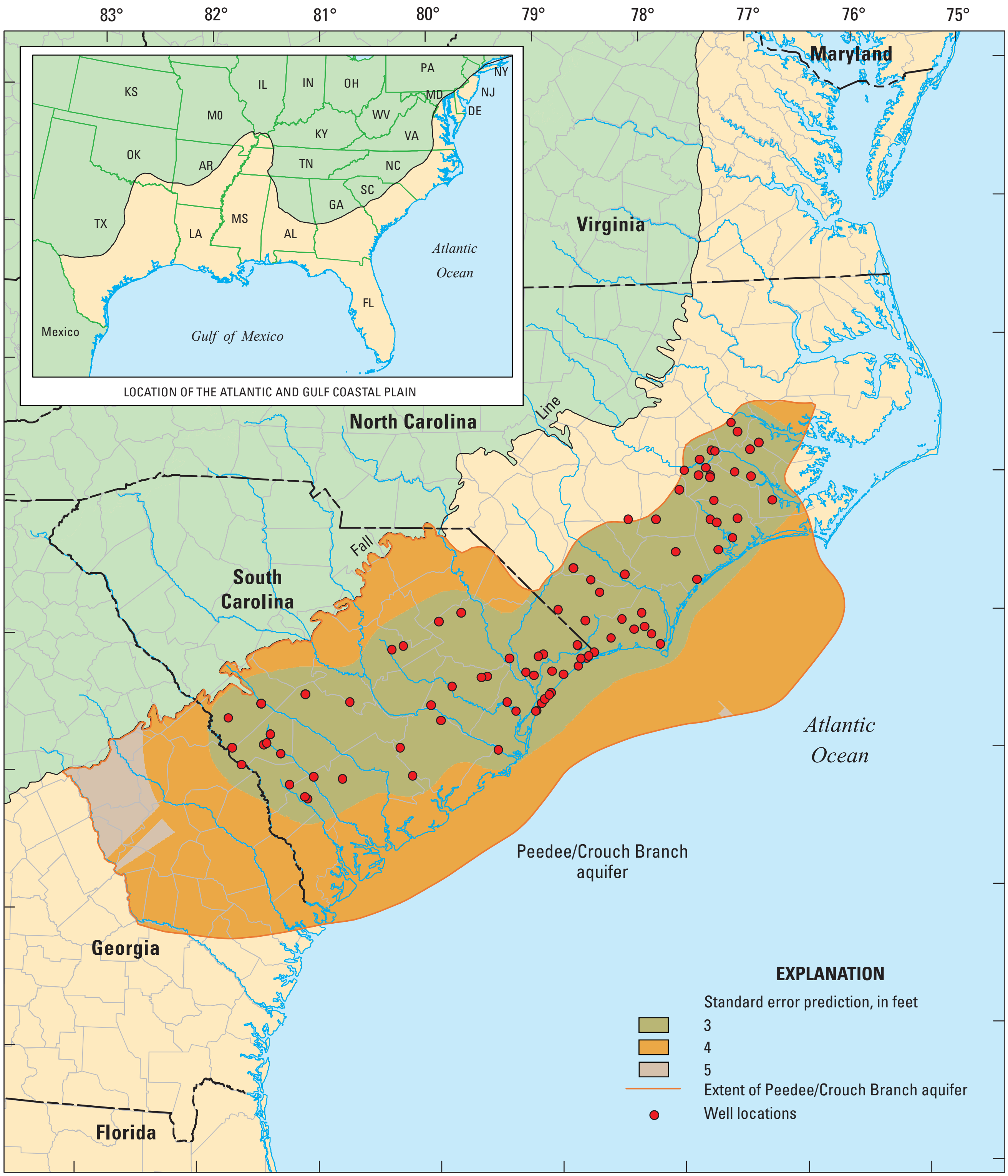



**Figure A25.** Prediction standard error of the groundwater level monitoring network in the Beaufort/Gordon aquifers in the Atlantic Coastal Plain of North and South Carolina.




Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure A26.** Prediction standard error of the groundwater level monitoring network in the Peedee/Crouch Branch aquifer in the Atlantic Coastal Plain of North and South Carolina.

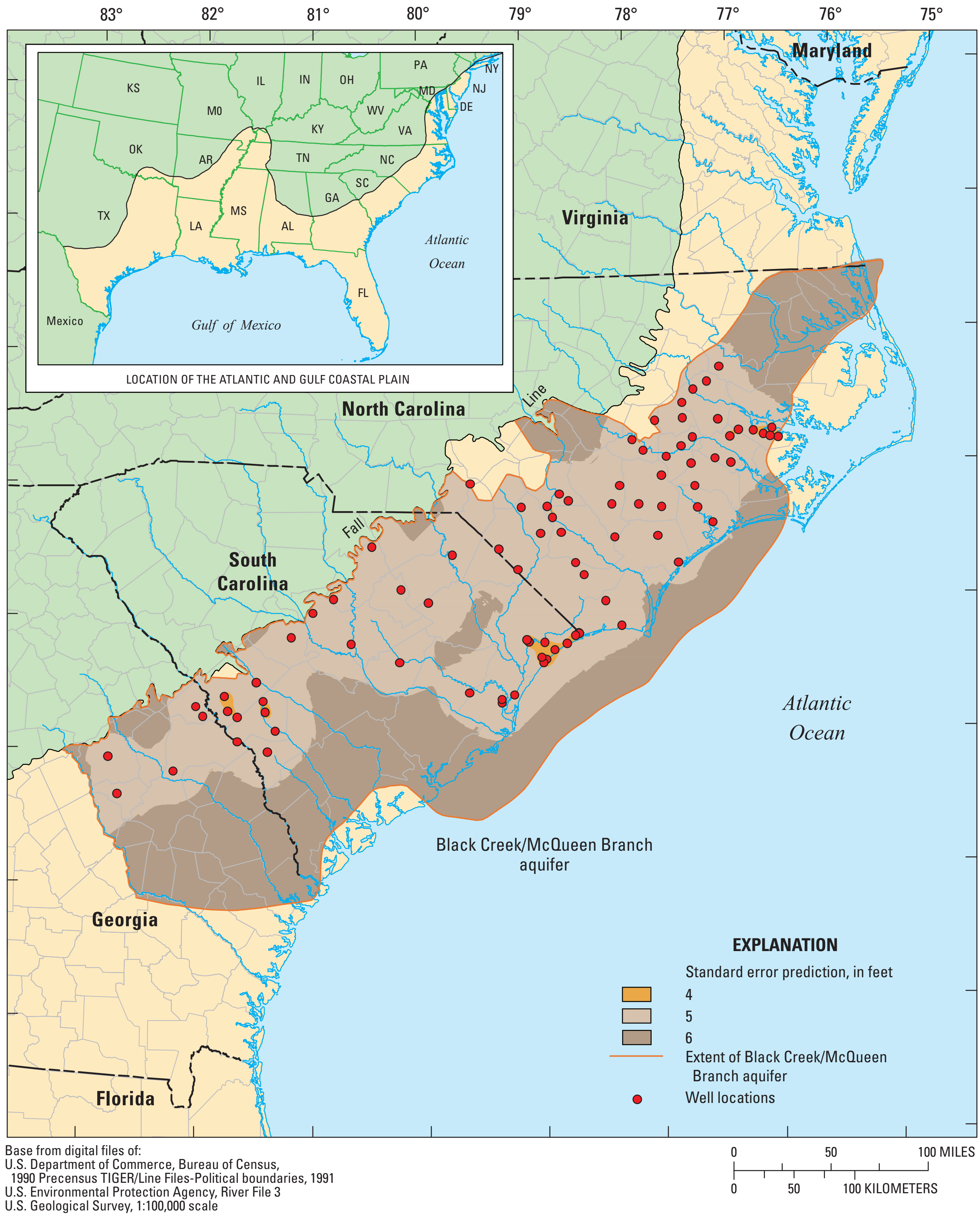



**Figure A27.** Prediction standard error of the groundwater level monitoring network in the Black Creek/McQueen Branch aquifer in the Atlantic Coastal Plain of North and South Carolina.

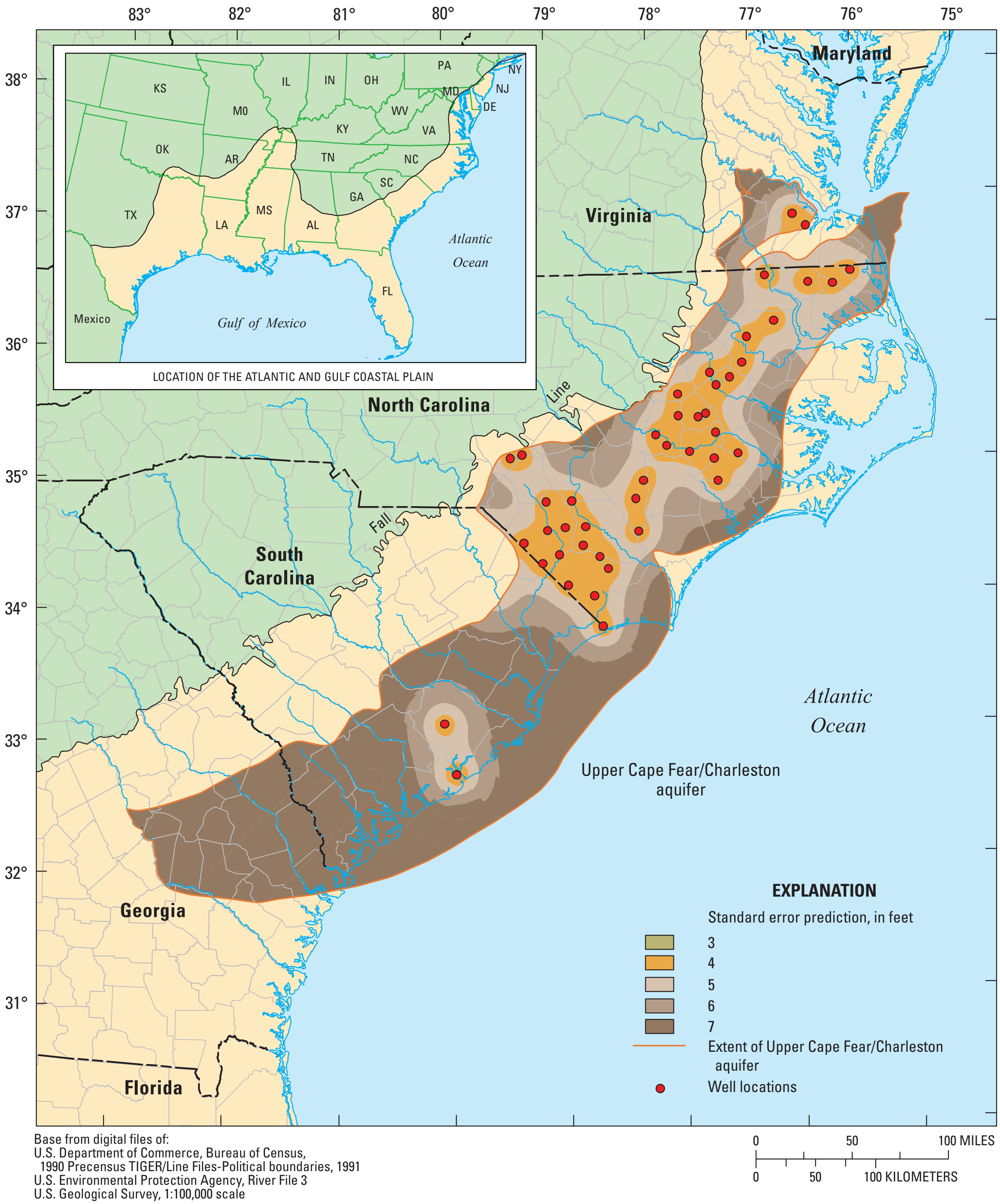



**Figure A28.** Prediction standard error of the groundwater level monitoring network in the Upper Cape Fear/Charleston aquifer in the Atlantic Coastal Plain of North and South Carolina.

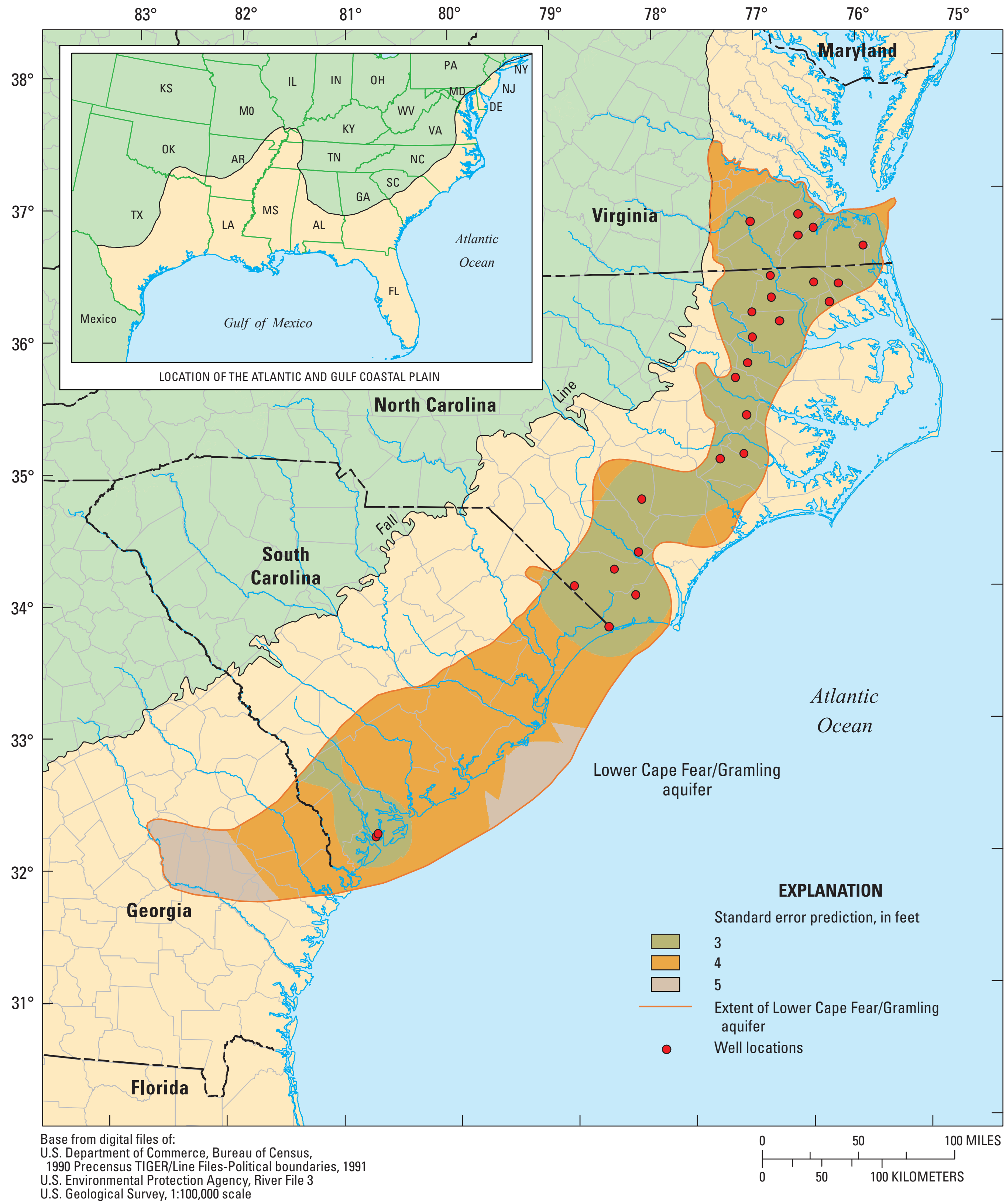



**Figure A29.** Prediction standard error of the groundwater level monitoring network in the Lower Cape Fear/Gramling aquifer in the Atlantic Coastal Plain of North and South Carolina.

prediction maps were created by using ordinary kriging with first-order trend removal (*figs. A23–A29*).

Prediction standard-error maps were produced from the predicted water-level surface maps to quantify the uncertainty of prediction across the aquifer extent (*figs. A23–A29*). The prediction standard-error maps show the spatial distribution of the range of error for the predicted surface (in this case, potentiometric surface) within each mapped contour interval. Note that the prediction standard-error maps tend to have high errors when they are generated from data with wide ranges of water-level altitudes and (or) data with clustered distributions of wells and (or) large areas void of wells.

The prediction standard-error maps, which show the relative accuracy and completeness of the water-level network, can be used to help identify areas with high uncertainties associated with water-level predictions (*figs. A23–A29*). The yellow areas shown on the maps have the smallest errors, and the networks in these areas represent the system well; the gray areas have the largest errors, and the networks in these areas do not represent the system well.

Overall, the predicted mean standard errors are lower in the shallow aquifers of the North and South Carolina ACP than in the deep aquifers. The predicted mean standard error for water levels was lowest for the Yorktown/Upper Floridan aquifers (layer 3, *fig. A23*) and the SC part of the Castle Hayne/Pungo River/Middle Floridan aquifers (layer 5, *fig. A24*) (mean standard error between 10 and 18 ft for layer 3, *table A2*). The predicted mean standard error for water levels was higher in the NC part of the Castle Hayne/Pungo River/Middle Floridan aquifers (layer 5, *fig. A24*) and the Beaufort/Gordon aquifers (layer 7, *fig. A25*), and in the NC part of the Peedee/Crouch Branch aquifer (layer 9, *fig. A26*) (mean standard error between 29 and 35 ft, *table A2*). The predicted mean standard error for water levels was highest in the Black Creek/McQueen Branch aquifer (layer 11, *fig. A27*) and the Upper Cape Fear/Charleston aquifer (layer 13, *fig. A28*) (mean standard errors of 48 and 55 ft, respectively, *table A2*). The predicted mean standard error for the Lower Cape Fear/Gramling aquifer (layer 15, *fig. A29*) is 31.07 ft, substantially less than those for the Black Creek/McQueen Branch aquifer (layer 11) and Upper Cape Fear/Charleston aquifer (layer 13, *table A2*). The difference in the predicted mean standard error is most likely because the range of water-level altitudes in the Lower Cape Fear/Gramling aquifer is less than the range of water-level altitudes in the Black Creek/McQueen Branch and Upper Cape Fear/Charleston aquifers. Water-level altitudes in the Lower Cape Fear/Gramling aquifer, therefore, have less uncertainty associated with them.

The groundwater level network in NC has a more comprehensive coverage than the groundwater level network in SC, especially in the deep aquifers—the Black Creek/McQueen Branch, Upper Cape Fear/Charleston, and Lower Cape Fear/Gramling aquifers. The predicted mean standard error for water levels in these deeper aquifer layers, therefore, generally is lower in NC than in SC. The groundwater level network has been a priority of the State of NC for decades; efforts have been made to acquire property, install observation wells, and collect either continuous or intermittent groundwater levels. By contrast, only a few sites in the western part of the SC ACP contain multiple wells for monitoring groundwater levels in all of the aquifers present at these locations. Most of the other groundwater level observation wells are single wells, some of which were installed for other purposes, such as water supply, and may be screened across several aquifers.

Overall, the groundwater level monitoring networks in North and South Carolina provide better coverage in the shallower aquifers—the Yorktown/Upper Floridan; Castle Hayne/Pungo River/Middle Floridan; Beaufort/Gordon; and Peedee/Crouch Branch aquifers—than in the deeper aquifers.

**Table A2.** Prediction standard-error statistics for the analysis of the groundwater level monitoring networks in the Atlantic Coastal Plain of North Carolina, South Carolina, and parts of eastern Georgia and southern Virginia.

[$mi^2$, square mile; ft, feet]

| Model layer | Area, in $mi^2$ | Minimum, in ft | Maximum, in ft | Range, in ft | Mean, in ft | Standard deviation, in ft |
|---|---|---|---|---|---|---|
| L3 East | 20,982 | 0.40 | 15.94 | 15.55 | 10.06 | 2.83 |
| L3 West | 20,812 | 0.45 | 31.41 | 30.96 | 18.38 | 7.25 |
| L5 East | 25,219 | 13.64 | 46.93 | 33.29 | 35.20 | 5.58 |
| L5 West | 16,891 | 8.66 | 14.75 | 6.09 | 12.69 | 1.10 |
| L7 East | 15,160 | 2.20 | 37.53 | 35.33 | 30.51 | 5.51 |
| L7 West | 25,245 | 19.14 | 41.57 | 22.43 | 29.42 | 6.47 |
| L9 | 49,916 | 22.94 | 43.17 | 20.23 | 31.59 | 5.09 |
| L11 | 51,079 | 36.67 | 59.35 | 22.68 | 48.51 | 3.95 |
| L13 | 41,889 | 22.47 | 80.71 | 58.24 | 55.35 | 12.78 |
| L15 | 32,024 | 20.36 | 46.36 | 26.00 | 31.07 | 6.05 |

Predicted groundwater levels in the shallower aquifers generally were accurate to within plus or minus 0 to 40 ft, while predicted groundwater levels in the Black Creek/McQueen Branch and Upper Cape Fear/Charleston aquifers generally were accurate to within plus or minus 30 to 80 ft. In addition, the groundwater level monitoring network in NC is more accurate for regional groundwater level coverage than the network in SC for the deeper aquifers—Black Creek/McQueen Branch; Upper Cape Fear/Charleston; and Lower Cape Fear/Gramling aquifers—because of the more comprehensive coverage. Regional potentiometric maps derived from the groundwater level data networks in North and South Carolina need to be used with the understanding of the strengths and weaknesses of the network. Continuous groundwater level networks are a key factor in determining trends in groundwater availability in the study area.

# Summary and Conclusions

The ACP aquifers and confining units are valuable natural resources that provide large quantities of high-quality groundwater for domestic and municipal supply, irrigation, and industrial uses. This chapter provides a regional analysis of groundwater availability for the area that will be useful for water-resource planning and management on a regional scale.

Overall, the ACP of North and South Carolina can be divided into the inner and outer Coastal Plain areas, which have different types of groundwater flow systems. Surface-water features, such as rivers and streams, control the groundwater flow patterns in the inner Coastal Plain. In this area, groundwater discharge from the aquifers provides large quantities of baseflow to the rivers and streams. Groundwater flow in the inner Coastal Plain typically is characterized by relatively steep gradients and short flow paths. Groundwater flow in the outer Coastal Plain typically is sluggish, with long, regional to subregional flow paths. Hydraulic conductivities in the outer Coastal Plain generally are good and result in most areas being able to produce large volumes of high-quality groundwater. Many areas of the outer Coastal Plain are underlain by several productive aquifers, which provide groundwater users with choices in production rates and water quality.

Overall, groundwater availability in the ACP aquifers and confining units of North and South Carolina is good in that supply generally exceeds demand. However, problems can occur locally when concentrated groundwater withdrawals lower groundwater levels to an extent that supply in specific locations is threatened.

A regionalized hydrologic simulation tool (a calibrated groundwater flow model) developed for this study (presented in *Chapter C* of this report) was used to assess groundwater availability with detailed groundwater budgets and also used to evaluate potential groundwater level responses to potential future climate variability. The regional model is able to assess how the system responds to the cumulative effects of human and environmental stresses at the aquifer-wide scale. For more detailed intermediate- and local-scale groundwater availability questions, the regional model provides a framework from which smaller-scaled issues can be examined.

The analysis of regional-scale groundwater budgets indicated that the largest component of the predevelopment and 2004 water budgets is vertical interlayer flow. The next largest budget component is the volume of water that flows into and out of the simulated specified-head boundaries. The total inflow through all specified-head boundaries is approximately equal to the outflow and is approximately 3,700 and 3,600 Mgal/d for the predevelopment and 2004 model budgets, respectively. Two other sources of water include a specified recharge rate of about 1,230 Mgal/d for predevelopment and 2004, and inflow from rivers at 13.5 Mgal/d for predevelopment and 16.4 Mgal/d for 2004. Water is removed from the model area by discharge to rivers at rates of 1,051 Mgal/d for predevelopment and 964 Mgal/d for 2004. Discharge of water through pumping wells is another component of flow for the model and accounts for 482 Mgal/d in the 2004 water budget. Additionally, during the time simulated by the model (1900–2004), water enters and is released from storage. For the 2004 water budget, rates of flow into and out of storage are 43 and 56 Mgal/d, respectively.

In addition to the regional-scale groundwater flow budget, the budgets of three sub-areas of the study area were analyzed in detail. The North Carolina Central Coastal Plain Capacity Use Area is a 15-county area in which groundwater levels have been declining since before 1960 in the Black Creek and Upper Cape Fear aquifers as a result of large-scale withdrawals.

In the Sumter, South Carolina, area, a large wellfield has withdrawn municipal drinking water from the Cretaceous aquifers underlying the town for more than 50 years. These withdrawals have only slightly modified the predevelopment groundwater flow system of the area with no substantial changes in groundwater storage. The aquifers underlying the Sumter area have relatively good groundwater transmission properties, and the area is adjacent to the inner Coastal Plain where direct recharge is available.

The Aiken, South Carolina, area, has received most of its potable water needs from the Cretaceous aquifers underlying the city. These withdrawals have produced a greater overall downward flow gradient in the system compared to predevelopment conditions and have decreased streamflow to a small extent.

The calibrated groundwater flow model (described in *Chapter C* of this report) was used to simulate potential effects on groundwater levels resulting from possible temporal variations in precipitation rates from 2010 to 2100. Temporal variations in precipitation rates from 2010 to 2100 were determined using an ensemble of global climate models. The predicted precipitation variability was converted to a specified net recharge rate for the groundwater flow model. Varying the recharge rates produces changes in groundwater levels in the higher altitudes of the model area where recharge is applied.

The recharge variations produce little changes in groundwater levels in the model areas downdip and away from the area of active recharge.

The groundwater level monitoring networks of the North and South Carolina ACP were evaluated by kriging the standard deviation of the network well locations as a measure of reliability in spatial estimation. The larger kriging standard deviations of the well locations were considered the less reliable estimates, while the smaller kriging standard deviations of the well locations are considered the more reliable estimates. Continuous groundwater level well location maps were generated for each aquifer using data from 609 current and historic wells. The predicted mean standard error was lower in the shallower aquifers of the North and South Carolina ACP than in the deeper aquifers. The groundwater level network in North Carolina has a more comprehensive coverage than the groundwater level network in South Carolina, especially in the deep aquifers—Black Creek/McQueen Branch, the Upper Cape Fear/Charleston, and Lower Cape Fear/Gramling aquifers. The predicted mean standard error for water levels in these deep aquifers, therefore, generally is lower in North Carolina than in South Carolina.

Many future challenges will face water-resource managers in the ACP of NC and SC with only a few primary ones discussed here. Demands for potable water from a rapidly growing population, especially in the coastal areas, are of primary concern. Also of concern are the potential effects on the ecosystem, especially on fragile wetlands and other habitats, from projected increasing groundwater withdrawals over the coming years. Lateral saltwater encroachment is occurring in at least one place within the study area—the northeastern end of Hilton Head Island, SC, in the Upper Floridan aquifer.

In order to quantify groundwater availability and to effectively evaluate the sustainability of the groundwater system, it is important to continually update the conceptual hydrologic model and maintain and enhance current tools used to understand the system response to a multitude of stresses. An iterative process that enables monitoring, analysis of basic data, and then implementation of selected management practices on a continual basis can provide insights to assist decision makers now and in the future. Awareness and integration of newly available geologic and hydrologic information, improvements to the existing groundwater monitoring networks, and technical advancements and capabilities associated with the simulation tools are examples of enhancements that could be made over time to assist water managers with decision making processes.

Examples of current (2009) activities that enhance the understanding of the regional hydrologic system include the following:

1. The South Carolina Water Plan (Badr and others, 2004) contains a detailed plan for a comprehensive groundwater quality and level monitoring network. Implementation of this plan would provide basic data for future hydrologic simulations.

2. The North Carolina Water Supply Plan (North Carolina Division of Water Resources, 2001) contains recommendations for management of the groundwater level declines in the North Carolina Central Coastal Plain Capacity Use Area. These recommendations could be implemented to improve the sustainability of the aquifers. Recent revisions to the plan call for approaches to analyze the cumulative effects of projected groundwater withdrawals. The plan calls for using hydrologic models as the primary tool to make these analyses.

3. The South Carolina Department of Health and Environmental Control has expanded the number of Capacity Use Areas within the South Carolina Coastal Plain to four. This program could be expanded to all of the SC Coastal Plain counties to better manage the groundwater resources of these areas.

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# Chapter B. Hydrogeologic Framework of the Atlantic Coastal Plain, North and South Carolina

By Joseph A. Gellici[1] and Jeff C. Lautier[2]

## Introduction

This chapter focuses on the hydrogeologic framework of the aquifers and confining units composing the Atlantic Coastal Plain (ACP) of North Carolina (NC) and South Carolina (SC). This is an area of approximately 47,500 square miles ($mi^2$), extending from the Fall Line to the present-day coastline, and from southern Virginia (VA) to eastern Georgia (GA) (*fig. B1*). The study area encompasses several formal aquifer systems contained within the sediments of the ACP. Aquifers and confining units located in the ACP of North Carolina and Virginia are part of the Northern ACP aquifer system (Trapp and Meisler, 1992). In South Carolina, aquifers and confining units in the ACP sediments are part of either the Southeastern Coastal Plain aquifer system (Miller, 1992) or the Floridan aquifer system (Miller, 1986). As the study area crosses the boundaries of these formal aquifer systems, no new regional-scale formal aquifer systems are designated, and the units under study will be referred to as the North and South Carolina ACP aquifers and confining units.

Included within this chapter is (1) a description of the hydrogeologic framework of the ACP aquifers and confining units of North and South Carolina in terms of its geometry (thickness, dip, and lateral extent), lithology and texture, hydrologic properties, and geophysical-log response; (2) an explanation of the connection of the newly defined SC hydrostratigraphic units, allostratigraphic formations, and biostratigraphic zones to the hydrostratigraphic units defined by Aucott and others (1987), Colquhoun and others (1983), and Miller and Renken (1988); (3) an extension of the SC hydrostratigraphic nomenclature and hierarchical classification scheme that was introduced at the U.S. Department of Energy Savannah River Site (SRS) (Aadland and others, 1995) to other regions of the SC ACP; and (4) a correlation of hydrostratigraphic units across the NC–SC border. Moreover, a generalized description of the NC framework is described along with a more detailed description of the SC framework. Because the SC framework presented in this report is new, more detail is being supplied for SC than for the NC framework discussion.

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Hydrostratigraphic correlations in North and South Carolina have historically been based on different types of data. In NC, over the past 40 years, the State has installed an extensive network of groundwater monitoring wells and has collected a database of continuous and synoptic groundwater level data (Robertson, 2007). The network contains 548 wells at 181 stations, most of which are in the ACP. These sites have wells screened in all of the major ACP aquifers present at the sites. These groundwater data have allowed for the delineation of aquifer boundaries by providing the means to determine where substantial differences in hydraulic head occur or by allowing a comparision of long-term groundwater level variations at various screen depths. South Carolina has no comparable long-term network of well clusters except in a small area of the western SC ACP (Agerton and others, 2007). However, the subsurface stratigraphic framework of SC is better understood than that of NC owing to an extensive coring program conducted by the U.S. Department of Energy and the South Carolina Water Resources Commission from 1984 to 1995 (Aadland and others, 1995), and to an extensive U.S. Geological Survey (USGS) coring program conducted from 1995 to 2000. Without a comprehensive network of groundwater observation wells, SC has relied on stratigraphic correlation to define the aquifers and confining units of the Coastal Plain. None of the previous studies of the NC–SC ACP area have attempted to establish the correlation of hydrogeologic units across the NC–SC State line.

Separate interpretations of the hydrogeologic frameworks for the North and South Carolina ACP have evolved during the past 100 years (Sloan, 1908; Clark and others, 1912). More recently, the NC regional hydrogeology has been described in several publications by Winner and Coble (1996) and Lautier (1998a, b, 2002, 2006). Winner and Coble (1996) used data that were available before 1989. Trapp and Horn (1997) included the NC ACP hydrogeology in a groundwater atlas. Lautier (1998a, b, 2002, 2006) sought to provide more detailed hydrogeologic framework interpretations covering three different multi-county areas, and used data collected before and after 1989. These recent efforts have included many NC monitoring network station observation wells (*fig. B2*) that have been installed since 1989 and corehole information from the USGS Coastal Carolina Project (U.S. Geological Survey, 2007). However, the entire NC Coastal Plain was not covered by these reports (Lautier, 1998a, b, 2002, 2006).

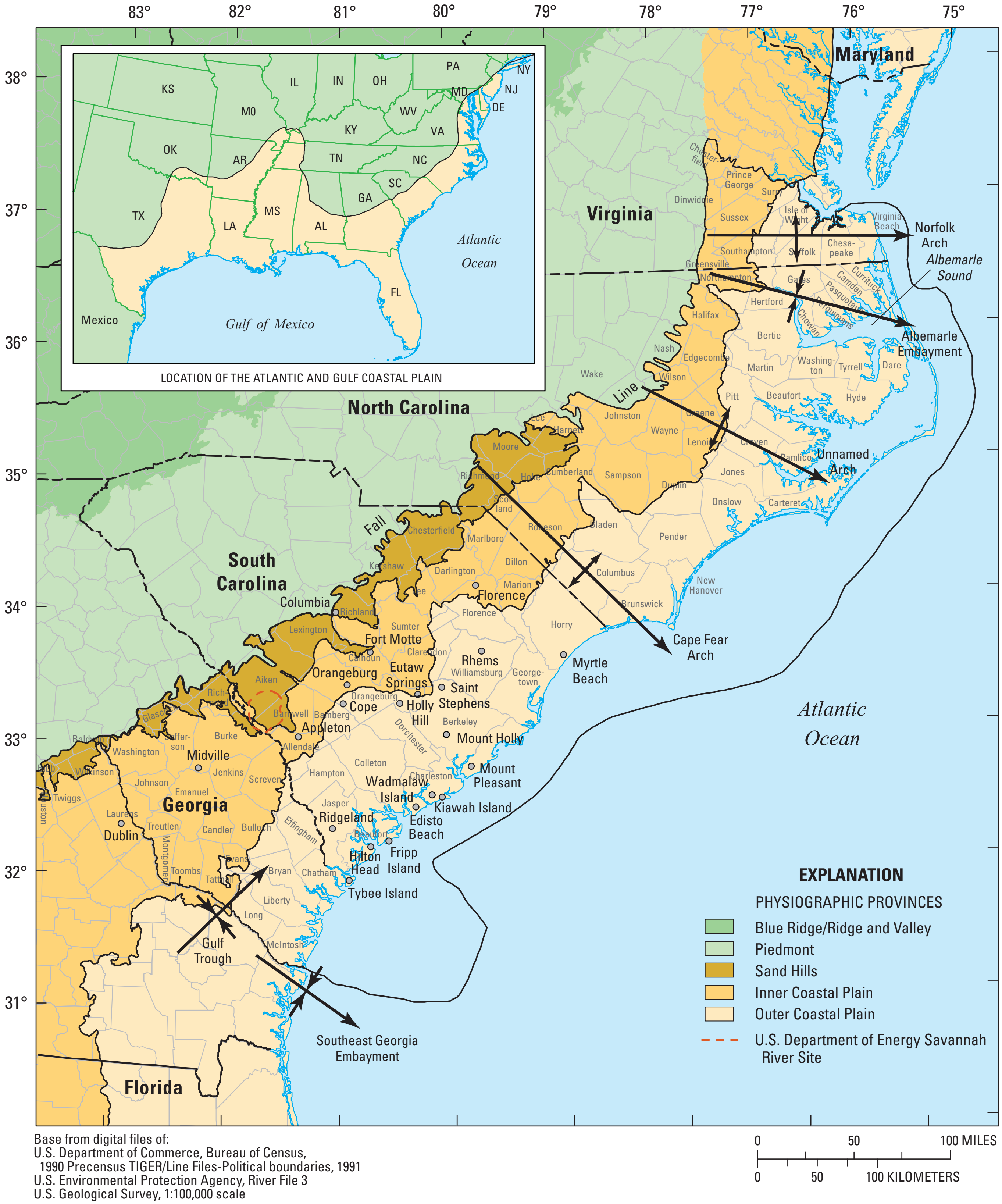



**Figure B1.** Location of the study area, major geological features, and the Atlantic Coastal Plain of North and South Carolina.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

0 50 100 MILES
0 50 100 KILOMETERS

**Figure B2.** Location of observation wells and boreholes in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia (see *Appendix B1* for more well information).

The two most commonly used statewide hydrogeologic-framework studies of the SC ACP are those of Colquhoun and others (1983) and Aucott and others (1987). The report by Colquhoun and others is, at its core, a delineation of the lithostratigraphic formations of the ACP. Aquifers were superimposed onto their lithostratigraphic cross sections and were named after prominent geologic formations composing the system; however, no structure contour or thickness maps of the aquifers and confining units were provided. Consequently, Colquhoun and others (1983) has been used primarily in geological studies rather than in hydrological studies. Aucott and others (1987), on the other hand, emphasizes hydrostratigraphic units and provides structure contour and thickness maps of the aquifers; therefore, that report has been used primarily in hydrological studies such as Campbell and van Heeswijk (1996). Both reports have been used and cited extensively (Logan and Euler, 1989; Newcome, 1989; Rodriguez and others, 1994; Castro and others, 1995; Hockensmith and Waters, 1997, 1998; Hockensmith, 2001).

The work described in this report is a cooperative effort among the NC Division of Water Resources, the SC Department of Natural Resources, and the USGS to describe the current (2007) state of knowledge of the hydrostratigraphy and groundwater conditions of the NC and SC ACP. Another major objective of the study is the attempt to link the NC and SC hydrostratigraphic units across the State border. *Chapter C* of this report describes a calibrated groundwater flow model of the NC and SC ACP aquifers and confining units that was constructed from the hydrostratigraphic framework described in this chapter. Uses of the model to simulate detailed groundwater flow budgets and potential future recharge variations from climate change are described in *Chapter A*.

The NC hydrostratigraphic framework is based on previous publications by Lautier (1998a, b, 2002, 2006) and Winner and Coble (1996). However, major revisions were made to the Aucott and others (1987) SC hydrogeologic framework. These revisions were primarily based on recent data collected during the drilling of 38 continuous coreholes within the SC ACP (*fig. B2*) along with geophysical logs and drill cutting descriptions from 68 water wells. Revisions to the SC hydrostratigraphic framework also are based on work done by Aadland and others (1995) at the SRS in western SC (*fig. B1*). This work introduced the concept of hydrostratigraphic units as provinces, systems, units, and zones to the SC ACP.

Since Aucott and others (1987) was published, much additional groundwater and stratigraphic data have become available for the SC ACP, mainly from coreholes, well-cluster sites, and water wells. A series of coreholes and well clusters were drilled at the SRS in Aiken and Barnwell Counties (*fig. B1*) during the mid- to late-1980s (Bledsoe, 1984, 1987, 1988; Bledsoe and others, 1990). Coreholes and well clusters also were drilled just outside the borders of the SRS in Aiken, Barnwell, and Allendale Counties during the late 1980s and early 1990s (Logan, 1987; Kuntz and Griffin, 1988; Gellici and others, 1995). Sidewall cores were collected from a 2,900-ft test hole (JAS-426) in Jasper County (Self-Trail and Bybell, 1997) and from a 3,833-ft test hole in Beaufort County (Temples and Englehardt, 1997). Five cores were drilled in Sumter County to characterize a landfill in the county (Prowell, 1993; Vroblesky, 1994). A core was drilled for an aquifer storage-and-recovery study in Horry County (Castro and others, 1995). Two coreholes were drilled in Darlington and Florence Counties that were used for developing a groundwater flow model (Falls, 1994; Rodriguez and others, 1994). Two coreholes were drilled in Aiken County for a water-supply study (Krambis, 2000; Harrelson and others, 2002; Gellici, 2007b), and two were drilled in Charleston County for an aquifer storage-and-recovery study (Campbell and others, 1997; Petkewich and others, 2004). A 1,000-ft corehole was drilled in Charleston County for a stratigraphic study (Bybell and others, 1998). Other deep cores were drilled as part of the Coastal Carolina Project, which was a collaboration between the South Carolina Department of Natural Resources (SCDNR) and the USGS, including two coreholes in Orangeburg County (Gellici, 2007a), two in Richland County, and a single core in each of the following counties: Berkeley, Charleston, Chesterfield, Colleton, Darlington, Dillon, Horry, Lee, Lexington, and Sumter (*fig. B2*).

Also of importance are original cores used by Aucott and others (1987) that have since been re-sampled for paleontological analyses and stratigraphically revised. These re-sampled cores include the revised Cretaceous stratigraphy of the USGS-Clubhouse Crossroads #1 (DOR-0052) core in Dorchester County (Gohn, 1992), the revised Cretaceous stratigraphy of the USGS-St. George No. 1 (DOR-211) core in Dorchester County (Self-Trail and Gohn, 1996), the revised Tertiary stratigraphy of the USGS-Pregnall No. 1 (DOR-208) core in Dorchester County (Edwards and others, 1997), and additional samples and revisions of the USGS-Brittons Neck (MN-0078) core in Marion County (D.C. Prowell, U.S. Geological Survey, written commun., 2002).

Hydrogeologic frameworks of the ACP in VA and GA were used in the study, primarily for selection of appropriate groundwater flow model boundaries for the model presented in *Chapter C* of this report. Inclusion of these boundaries requires that areas of southern VA and eastern GA be included in this study. In VA, the hydrogeologic frameworks of Meng and Harsh (1988) and McFarland and Bruce (2006) were correlated with the hydrogeologic framework of the NC Coastal Plain. In GA, the hydrogeologic frameworks of Brooks and others (1985), Clark and others (1985), and Faye and Mayer (1997) were used to extend the new SC hydrostratigraphy into the study area.

## Previous Investigations

Of the numerous published reports involving the mapping and characterization of the NC Coastal Plain hydrogeologic framework, only studies of regional importance are mentioned here. Stephenson and Johnson (1912) conducted the first comprehensive survey of the groundwater resources of the NC Coastal Plain. LeGrand (1964) presented a broad review of the hydrogeology of the Gulf and ACP, and outlined a hydrogeologic classification based on concepts of groundwater recharge and discharge conditions. Brown and others (1972) divided the ACP sediments from New York to NC into 17 chronostratigraphic units and mapped lithofacies and intrinsic permeability based on interpretations of geophysical logs and well cuttings. Nelson (1964) presented a multi-county study of the Swanquarter area of the NC Coastal Plain, which mapped the major aquifers and confining units and defined the contemporaneous potentiometric surfaces. Narkunas (1980) presented a multi-county groundwater study and hydrogeologic framework of the central part of the NC Coastal Plain that used data from NC monitoring network wells installed up to that time. Winner and Lyke (1989) presented a hydrogeologic framework study of the Cretaceous aquifers of the central part of the NC Coastal Plain. Winner and Coble (1996) provided a hydrogeologic framework study of the entire NC Coastal Plain, using data that were available up to 1989. Lautier (1998a, b, 2002, 2006) provided a hydrogeologic framework and assessment of the groundwater resources and conditions in three areas of the NC Coastal Plain. The following recent studies, although more localized, are important in delineating the hydrostratigraphy of the NC Coastal Plain: (1) Self-Trail and others (2004a) provide descriptions of the physical stratigraphy and geophysical logs from a corehole in Bladen County, NC (*figs. B1, B2*); (2) Weems and others (2007) provide descriptions of the physical stratigraphy and geophysical logs from a corehole in Bertie County, NC.

Geologic and hydrologic investigations of the SC ACP date back to at least 1843 when Ruffin (1843) published an agricultural survey of the State that included geological interpretations. Sloan (1907a, b) summarized the geology and mineral resources of SC. Darton (1896) investigated the artesian wells of North and South Carolina. Cooke (1936) published a geologic map and geological descriptions of the SC ACP. A report has been written about the groundwater resources of every County in the SC ACP including Orangeburg County (Siple, 1975); Georgetown and Horry Counties (Zack, 1977); Clarendon and Williamsburg Counties (Johnson, 1978); Beaufort, Colleton, Hampton, and Jasper Counties (Hayes, 1979); Sumter and Florence Counties (Park, 1980); Charleston, Berkeley, and Dorchester Counties (Park, 1985); Aiken, Allendale, Bamberg, and Barnwell Counties (Logan and Euler, 1989); Calhoun County (Greaney, 1993); Darlington, Dillon, Florence, Marion, and Marlboro Counties (Rodriguez and others, 1994); Kershaw County (Newcome, 2002); Richland County (Newcome, 2003); Lee County (Newcome, 2004a); Chesterfield County (Newcome, 2004b); Lexington County (Agerton and Baker, 2006); Hampton County (Newcome and Gellici, 2006); and Clarendon County (Newcome, 2006). Siple (1957) and Newcome (1989) provide overviews of the groundwater resources of the entire SC ACP (*fig. B1*).

Statewide potentiometric maps of the SC ACP aquifers are provided in the following reports: Aucott and Speiran (1985), Gawne (1990, 1994), Stringfield and Campbell (1993), Hockensmith and Waters (1997, 1998), and Hockensmith (2001, 2003a, b, 2008a, b, 2009). Aquifer-test results for the SC ACP are mainly found in Aucott and Newcome (1986), Newcome (1993, 2005), and Aadland and others (1995).

The following reports are considered to contain important stratigraphic information for the SC ACP: Siple (1967), Colquhoun and others (1983), Prowell and others (1985), Owens and Sohl (1989), Nystrom and others (1991), Sohl and Owens (1991), Gohn (1992), Gohn and Campbell (1992), Fallaw and Price (1995), Self-Trail and Gohn (1996), Edwards and others (1997), Falls and others (1997), Bybell and others (1998), Christopher and others (1999), Prowell and others (2000a), Christopher and Prowell (2002), Prowell and others (2003), and Self-Trail and others (2004). The following reports contain important hydrostratigraphic information for the SC ACP: Siple (1967), Colquhoun and others (1983), Aucott and others (1987), Miller and Renken (1988), Bledsoe and others (1990), Aadland and others (1995), and Falls and others (1997).

## Nomenclature and Classification of Hydrostratigraphic Units

Hydrostratigraphic nomenclature and the classification of hydrostratigraphic units as *provinces, systems, units,* and *zones* is adopted from Aadland and others (1995) and conforms to guidelines established by the USGS (Laney and Davidson, 1986) and the SC Hydrostratigraphic Subcommittee (Burt, 1987a, b). Topping the classification hierarchy (level 1) are hydrogeologic provinces, which define major regional rock or sediment packages that behave as a single unified hydrologic unit. The two hydrogeologic provinces in SC are the Southeastern Coastal Plain hydrogeologic province and the Piedmont hydrogeologic province (Aadland and others, 1995). Ranked at level 2 are aquifer and confining systems. Aquifer systems are composed of one or more aquifers that transmit water on a regional scale. Confining systems are composed of one or more confining units that impede regional groundwater flow.

The building blocks of the classification system are aquifer units and confining units (level 3). As defined by the SC Hydrostratigraphic Subcommittee, an aquifer is a mappable (greater than 400 $mi^2$) body of rock or sediments that is sufficiently permeable to conduct groundwater and yield significant quantities of water to wells and springs (Bates and Jackson, 1980). A confining unit is a mappable (greater than 400 $mi^2$) body of rock or sediments of significantly lower hydraulic conductivity than an adjacent aquifer, and is an impediment to groundwater flow into or out of an aquifer (Lohman, 1972).

Aquifers and confining units are formally named for a geographic or cultural feature that is located near a designated type-well locality where the system or unit is representative and well defined. In this report, confining units carry the name of the underlying aquifer.

In areas where a confining unit pinches out and two aquifers coalesce, a new name has been given to the aquifer. In areas where a confining system thins and no longer regionally separates the overlying and underlying aquifers, a single aquifer system is defined and named by combining the names of the two coalescing aquifer systems (Aadland and others, 1995). Where aquifer systems have combined, the individual aquifer and confining units can and commonly do extend into and form part of the combined system (Aadland and others, 1995).

Aquifers and confining units can be informally subdivided into zones (level 4) that are characterized by properties substantially different from the rest of the unit, such as hydraulic conductivity, water chemistry, lithology, or color. Names of aquifer and confining zones are informal and describe the unique property that differentiates the zone from the rest of the unit.

The aquifers and confining units of NC and SC are part of a much larger series of hydrogeologic units within the ACP. The correlations of ACP hydrostratigraphic units in the neighboring States of VA and GA are presented in *table B1*. Correlations with the Tertiary and Cretaceous aquifers are shown along with the corresponding groundwater flow model layers that are used in *Chapter C* of this report. The hydrostratigraphy of the VA Coastal Plain is derived from work by McFarland and Bruce (2006) and includes eight aquifers with their corresponding confining units. In eastern GA, the hydrostratigraphy of Clarke and others (1985) and Brooks and others (1985) includes five aquifers, along with their intervening confining units.

**Table B1.** Model layers and Atlantic Coastal Plain hydrogeologic units for southern Virginia, North Carolina, South Carolina, and eastern Georgia.

| Southern Virginia [1] | North Carolina [2] | Model layer | South Carolina [3] | Eastern Georgia [4, 5] |
|---|---|---|---|---|
| Surficial aquifer | Surficial aquifer | 1 | Surficial aquifer | Surficial aquifer |
| Yorktown confining zone | Yorktown confining unit | 2 | Upper Floridan confining unit | Upper Floridan–Jacksonian confining unit |
| Yorktown–Eastover aquifer | Yorktown aquifer | 3 | Upper Floridan aquifer | Upper Floridan–Jacksonian aquifer |
| Saint Marys confining unit | Castle Hayne–Pungo River confining unit | 4 | Middle Floridan confining unit | |
| Saint Marys aquifer | Castle Hayne–Pungo River aquifer | 5 | Middle Floridan aquifer | |
| Calvert confining unit | | | | |
| Piney Point aquifer | | | | |
| Nanjemoy–Marlboro confining unit | Beaufort confining unit | 6 | Gordon confining unit | Gordon confining unit |
| Aquia aquifer | Beaufort aquifer | 7 | Gordon aquifer | Gordon aquifer |
| Peedee confining zone | Peedee confining unit | 8 | Crouch Branch confining unit | Dublin confining unit |
| Peedee aquifer | Peedee aquifer | 9 | Crouch Branch aquifer | Dublin aquifer |
| Virginia Beach confining zone | Black Creek confining unit | 10 | McQueen Branch confining unit | Midville confining unit |
| Virginia Beach aquifer | Black Creek aquifer | 11 | McQueen Branch aquifer | Midville aquifer |
| Potomac confining zone | Upper Cape Fear confining unit | 12 | Charleston confining unit | Unnamed confining unit |
| Potomac aquifer | Upper Cape Fear aquifer | 13 | Charleston aquifer | |
| | Lower Cape Fear confining unit | 14 | Gramling confining unit | |
| | Lower Cape Fear aquifer | 15 | Gramling aquifer | |
| | Lower Cretaceous confining unit | 16 | Not Present | |
| | Lower Cretaceous aquifer | | | |
| Basement | Basement | | Basement | Basement |

[1] McFarland and Bruce, 2006.

[2] Winner and Coble, 1996.

[3] *Chapter C*, this volume.

[4] Clarke and others, 1985.

[5] Brooks and others, 1985.

## Methods of Investigation

Because of the depth of most of the sediments and the extensive surficial land cover, the majority of ACP sediments of North and South Carolina were not directly examined. Therefore, most of the interpretations of the deeper stratigraphy and hydrostratigraphy of the ACP come from data collected at boreholes of various kinds. The most valuable wells for hydrogeologic mapping purposes are properly constructed groundwater monitoring wells, which provide values of hydraulic head that are truly representative of the aquifer. Used in conjunction with borehole geophysical logs, well-to-well correlations were made in order to determine the three-dimensional hydrogeologic framework. Detailed stratigraphic data from coreholes and drill cuttings were collected to assist with correlations, although the primary concern was the continuity of hydraulically connected permeable and less permeable strata through the Coastal Plain. Quaternary through Cretaceous sedimentary sections were separated into component hydrogeologic units, mapped, and described across the study area using groundwater levels, borehole geophysical logs, paleontologic data, borehole lithologic logs, chloride concentrations, aquifer-test data, and surface resistivity measurements.

In previous framework studies in the NC and SC ACP, investigators had to rely mainly on geophysical logs, auger holes, and drill cuttings from water wells and from a few coreholes to delineate hydrogeologic units and to correlate them across the Coastal Plain. Cores were generally unavailable because of the costs associated with obtaining cores. With the advent of wireline coring, the costs and time requirements of coring have been reduced, and the number of coreholes in the study area has increased considerably (Shuter and Teasdale, 1989). Cores were visually examined, and samples from known depths were dated and analyzed. Coreholes drilled continuously to bedrock allow for an entire stratigraphic sequence of the ACP to be studied directly and related to other cores, drill cuttings, and outcrops. Cores were used to interpret geophysical logs, thereby improving hydrostratigraphic delineation and correlation with water wells that have geophysical logs but have not been cored.

Methods used to analyze the geologic, hydrogeologic, and geophysical data in NC and SC were combined to produce cross sections that correlate the ACP aquifers and confining units across the NC–SC border at two locations. One of these locations is in the inner Coastal Plain, and one is in the outer Coastal Plain.

## North Carolina Methods of Investigation

In NC, data from 149 wells, primarily groundwater monitoring wells drilled by the State of North Carolina, were used to build the hydrogeologic framework (*fig. B2*, *Appendix B1*). Geophysical logs obtained from these wells include, in most cases, the 16- and 64-inch short- and long-normal resistivity, spontaneous-potential, gamma-radiation, and single-point resistance. Continuous groundwater level data have been collected at many of these sites, and these data were used for regional correlations.

Borehole geophysical logs, including spontaneous potential, gamma ray, single-point resistance, and resistivity logs from boreholes in the study area were interpreted and correlated in order to identify and map hydrogeologic units. The spontaneous potential (SP) log is a recording over depth of the difference between the potential of a movable electrode in the borehole and the fixed potential of a surface electrode (Keys, 1990). The SP is the resulting effect of several electromotive forces, including clay potential, liquid junction potential, and electrokinetic potential. The right-hand boundary of the curve generally indicates impermeable formations such as clay. The left-hand boundary generally indicates formations of higher permeability such as those made up of sand or porous limestone. The SP log was used in this study to determine permeable bed boundaries and to estimate thickness and percentage of permeable materials. In addition, the SP log permitted correlation of beds from well to well, in conjunction with gamma-ray, resistivity, and lithologic logs. Natural gamma-ray logs measure the natural gamma radiation emitted by a geologic formation (Keys, 1990). High natural gamma curve values are typically indicative of high amounts of clay and phosphate minerals in the area of study, whereas lower curve values are indicative of the presence of limestone and sand in the geologic section. Gamma-ray curves in many cases were valuable for correlation, by virtue of having produced distinctive signatures across zones of phosphate mineralization. Single-point resistance logs measure the electrical resistance, in ohms, between an electrode in a well and an electrode at the land surface, or between two electrodes in a well. The measurement does not take into account the length or cross-sectional area of the current travel path, and thus cannot be used for quantitative interpretation (Keys, 1990). However, the single-point resistance curve was used for interpreting lithology and for thin bed detection. Normal-resistivity logs measure formation resistivity, which takes into account the length and cross-sectional area of the current travel path. Thus, short- and long-normal measurements take into account the intrinsic properties of the material and were used for quantitative interpretation of formation fluids. The long-normal curve provides a reading beyond the flushed zone of the borehole where formation fluids are generally undisturbed by drilling fluid (Keys, 1990).

Resistivity curves were used in combination with SP and gamma ray curves to help distinguish between freshwater- and saltwater-bearing strata, and between permeable and non-permeable strata. This combination of log types was used to identify and correlate aquifer and confining unit tops and bases, and to calculate the percentage of permeable material and the net thickness, in feet, of permeable material in each aquifer. Differences in chloride concentrations across confining units and similarities in chloride concentrations within the same aquifer were taken into account in order to accurately subdivide the hydrogeologic section.

Lithologic logs were used in combination with borehole geophysical logs to define vertical and lateral stratigraphic variations in the subsurface. Four coreholes were constructed in the NC Coastal Plain by the USGS between 2001 and 2005. These included the Fort Fisher corehole in New Hanover County, the Elizabethtown corehole in Bladen County, the Cove City corehole in Craven County, and the Hope Plantation corehole in Bertie County. Formation tops from lithostratigraphic logs and USGS coreholes were used in accordance with well log correlations to determine the relation between stratigraphic and hydrogeologic units.

The drawdown effects and lateral transmission of drawdown effects observed from regional pumping and from aquifer tests were used to identify the lateral continuity of an aquifer. Aquifer-test data were used to determine transmissivity, specific capacity, horizontal hydraulic conductivity, storativity, and specific storage of aquifers and confining beds.

## South Carolina Methods of Investigation

In SC, data from 38 coreholes and 68 water wells were used to build the hydrogeologic framework (*fig. B2*, *Appendix 1*). Some of the cores were drilled specifically for this study, whereas others were drilled for previous investigations dating back to 1975 (Gohn, 1992). Cores were described in terms of their lithology, grain size, sorting, induration, mineralogy, fossils, structures, and color. Geophysical logs obtained from each corehole and water well included, in most cases, the 16- and 64-inch short- and long-normal resistivity, spontaneous-potential, gamma-radiation, and single-point resistance.

Several types of paleontology samples were collected from the SC ACP cores and were microscopically analyzed for palynomorphs (pollen and spores from terrestrial plants and cysts of dinoflagellates) and calcareous nannofossils (remains of golden-brown, single-celled algae that live only in the oceans) in order to determine the age of the sediments (Self-Trail and Gohn, 1996; Self-Trail and Bybell, 1997; and Christopher and others, 1999). Approximately 700 paleontological age dates were collected in this manner during the course of the study. These analyses were essential in delineating the allostratigraphic units and, subsequently, in correlating the aquifers and confining units across the SC ACP. Samples that contained age-diagnostic fossil assemblages were assigned a fossil zonation. Fossil zonations for calcareous nannofossils are from Perch-Nielson (1985a, b), and zonations for pollen are from Christopher and others (1999) for the Turonian through Santonian Stages, from Christopher and Prowell (2002) for the Maastrichtian Stage, and from D.C. Prowell and R.A. Christopher (U.S. Geological Survey and Clemson University (retired), respectively, written commun., 2002) for the Campanian Stage.

Allostratigraphic formations, which are unconformity-bounded formations, were determined using core, fossil, and borehole geophysical data (Gellici, 2007a, b). Unconformities were identified in the cores by noting distinct changes in lithology and texture, rooting structures, hardpans, erosional surfaces, irregular contacts, burrowing, and transgressive lag deposits. Lag deposits in updip regions of the SC ACP typically consist of beds of poorly sorted quartz sand and gravel; downdip, they typically consist of beds of glauconite, phosphate, quartz sand and pebbles, and phosphatized bone, teeth, and shell fragments. Fossil data were examined to determine if assemblages changed vertically across lag deposits, signifying paleontological evidence of an unconformity. Radiation spikes on the gamma-ray log were used as further evidence of unconformities, especially in downdip sections consisting of marine deposits. Final determinations were made on allostratigraphic formation boundaries by using a combination of these data (core, fossil, and geophysical) and by correlation with nearby cores and outcrops that had biostratigraphic control.

Sedimentary layers were differentiated on the basis of relative permeability, primarily by visual inspections of the cores and by interpretations of geophysical logs. Particle-size analyses (available for about half of the cores and usually only from sandy intervals) and permeameter tests (available for about a quarter of the cores and in small numbers) also were used to help differentiate layers. Adjacent permeable layers were combined as potential aquifers and adjacent impermeable layers as potential confining units.

Borehole geophysical data were combined with groundwater level data (where available), and were used to delineate the major hydrostratigraphic units in specific coreholes in SC. A lack of groundwater level head differences across potential confining beds would indicate vertical hydraulic continuity and, therefore, the absence of a confining unit and a single aquifer. The presence of groundwater level differences across potential confining beds would indicate hydraulic separation and, therefore, the occurrence of a confining unit and two separate aquifers. With a few exceptions, hydrostatic head data obtained from well-cluster sites were available only in the west-central region of the SC ACP. This region was, therefore, the starting point for aquifer delineation and for correlation of hydrostratigraphic units across the rest of the Coastal Plain.

After delineation of aquifers and confining units, the hydrostratigraphic units were identified and correlated by using the allostratigraphic and biostratigraphic data collected from the project and with borehole geophysical logs. Several of the cores used by Aadland and others (1995) in their development of the west-central SC framework were age-dated, providing the ages of formations composing the aquifers and confining units defined in west-central SC. For example, the Crouch Branch confining unit consists mainly of strata of early Paleocene age. Clay beds of early Paleocene age in other cores were mapped as a continuation of the Crouch Branch confining unit. The same process was used for the aquifers.

Lateral hydraulic continuity of the aquifers and confining units was never directly measured and can only be assumed. Breaches in the confining unit caused by structural features such as faulting, or by changes in lithology caused by changing depositional settings, can exist between wells. Generally, aquifers and confining units in SC were more difficult to delineate and map on the eastern side of the SC ACP. Confining units are not as well defined as they are on the western side. This is probably due to the different depositional settings of the SC ACP whereby deltaic environments predominated on the western side and continental shelf environments predominated on the eastern side.

All available data from each corehole or water well used in the study were analyzed to select the top and bottom altitudes of each hydrostratigraphic unit present at that location. Selected wells were used to develop detailed cross sections, which are described in detail below. The top and bottom altitudes, along with the unit's geographic extent, were used to create structure contour and thickness maps of each aquifer and confining unit.

## Hydrogeologic Cross Sections

A series of cross sections was constructed within the study area (two regional strike sections, five regional dip sections, *Plates 1–7*, *table B2*) in order to illustrate the lateral distribution and thickness of the each hydrogeologic unit. Lines representing the altitude of land surface were superimposed on each cross section to indicate potential recharge–discharge relations. Land surface altitude data were obtained from a USGS digital elevation model by plotting the lines of section on the model surface. The vertical scale on the sections is 1 inch (in.) to 200 ft, and the horizontal scale is 1 in. to 10 miles (mi) in SC. In NC, the vertical scale is 1 in. to 178 ft vertically, and 1 in. is equal to 17,700 ft horizontally. The different scales were used to allow the cross sections to be presented in the maximum size feasible to fit on the plates. All latitude and longitude coordinates of well locations are referenced to the North American Datum of 1983 (NAD 83). The depths of the SC coreholes and water wells that did not reach the underlying consolidated basement rocks were projected to the basement contact, and the top altitudes of the contacts were estimated.

Section A–A′ (*Plate 1*; *table B2*), a dip section located in southwestern SC, illustrates the correlation of hydrogeologic units among coreholes AIK-817 (Logan, 1987), ALL-348 (Kuntz and others, 1989), JAS-426 (Self-Trail and Bybell, 1997), and BFT-2055 (Temples and Englehardt, 1997). Total depths are 561, 1,734, 2,900, and 3,833 ft, respectively. Sidewall cores were obtained from JAS-426 and BFT-2055 to basement; the other two boreholes were continuously cored to basement.

Section B–B′ (*Plate 2*; *table B2*), a dip section located in the central part of the SC ACP, illustrates the correlation of hydrogeologic units among coreholes RIC-585 (unpublished), RIC-543 (unpublished), SUM-296 (Prowell, 1993; Vroblesky, 1994), BRK-644 (unpublished), and CHN-820 (Self-Trail and others, 2004b). Total depths are 469, 557, 725, 1,826, and 1,536 ft, respectively. RIC-585, RIC-543, and BRK-644 were continuously cored to basement. SUM-296 and CHN-820 were continuously cored but did not reach basement.

Section C–C′ (*Plate 2*; *table B2*), a dip section located in northeastern SC, illustrates the correlation of hydrogeologic units among coreholes CTF-81 (unpublished), DAR-228 (Falls, 1994; Rodriguez and others, 1994), and FLO-268 (Curley, 1990), water well FLO-317, and coreholes MRN-78 (Reid and others, 1986) and HOR-973/1165 (Castro and others, 1995). Total depths are 245, 447, 716, 464, 1,230, and 1,427 ft, respectively. All of the coreholes were continuously cored to basement; however, the water well, FLO-317, did not reach basement.

Section D–D′ (*Plate 3*; *table B2*), located just inside NC and parallel to the NC–SC border, shows the dip-oriented correlations of hydrogeologic units among wells SC-A-3-83 (W 51A), Carver School (W 50G), Town of Laurinburg (X 49D), Division of Water Resources (DWR) Rowland (Z 47R), DWR Marietta (BB 45M), DWR Clarendon (DD 42N), Town of Tabor City (EE 42B), and DWR Calabash (HH 39J). Total depths are 104, 105, 349, 548, 552, 879, 330, and 1,335 ft, respectively. Only the DWR Rowland (Z 47R) and DWR Clarendon (DD 42N) sites are drilled to basement.

Section E–E′ (*Plate 3*; *table B2*), located in the central part of the NC Coastal Plain, shows the dip-oriented correlations of hydrogeologic units among wells Town of Farmville (M 27M), Town of Farmville (M 26Q), Bell Arthur (M 26U), Bell Arthur (N 25G), Town of Winterville (N 24P2), DWR Conley Station (N 23P), DWR Blackjack Station (N 22Y), DWR Chocowinity Station (N 21M), DWR Bath Station (O 17I), DWR Winsteadville Station (O 15N), DWR Sladesville Station (O 13F), DWR Swanquarter (P 11E), and DWR Hydeland Station (O 10W). Total depths are 396, 496, 497, 408, 400, 802, 210, 456, 702, 710, 472, 302, and 1,503 ft, respectively. Only the Town of Farmville (M 26Q) hole is drilled to basement.

Section F–F′ (*Plate 4*; *table B2*), located in the northern part of the NC Coastal Plain, shows the dip-oriented correlation of hydrogeologic units among wells DWR Cremo Station (G 19B), USGS Valhalla (G 15F), DWR Three Mile Desert Station (E 13M), USGS PA-T2-62 (F 10Q), DWR Big Flatty Station (G 9C), and Rapp Oil Kellogg No. 1 (G 6L). Total depths are 1,192, 528, 1210, 704, 731, and 5,140 ft, respectively. The only bore hole that is drilled to basement is DWR Cremo Station (G 19B).

Section G–G′ (*Plate 5*; *table B2*), oriented southwest-northeast within the central part of the NC Coastal Plain, illustrates the strike-oriented correlation of hydrogeologic units among wells DWR Marietta Station (BB 45M), DWR Boardman Station (AA 43Q), DWR Bladenboro Station (Z 41M), DWR Elizabethtown Station (Y 39M), DWR White Lake Prison Station (Y 38B), DWR White Lake Farm Well No. 5 (Y 37E), DWR Black Lake (X 36P), DWR Six Runs Station (V 35T), Town of Warsaw (T 32Y), Carolina Turkeys (S 31A), North Lenoir Water Corporation (P 28W), Environment and Natural Resources (ENR) Maury Research Station (O 27J), DWR West Research Campus (M 25F2), DWR Gold Point Station (J 22P), DWR Cremo Station (G 19B), and DWR Gates County Prison (C 16Q). Total depths are 552, 497, 575, 501, 497, 258, 440, 433, 360, 320, 408, 568, 574, 644, 1,192, and 1,080 ft, respectively. The boreholes that are drilled to

**Table B2.** Wells used in cross sections on *Plates 1–7*.

[GR, Gamma Ray; SPR, Single Point Resistance; SN, Short Normal; LN, Long Normal; SP, Spontaneous Potential]

| Cross-section well number on *Plates 1–7* | Cross section | Plate number | Local name of well | NC quadrangle number/ SC county number | Station identification | Well depth, in feet | Geophysical logs used on Plate |
|---|---|---|---|---|---|---|---|
| | | | North Carolina | | | | |
| 1 | D–D′ | 3 | SC-A-3-83 | W 51A | 344958079351501 | 104 | GR |
| 2 | D–D′ | 3 | Carver School | W 50G | 344844079324201 | 105 | GR |
| 3 | D–D′ | 3 | Town of Laurinburg | X 49D | 344418079284701 | 349 | GR, SPR |
| 4 | D–D′ | 3 | DWR Rowland | Z 47R | 343156079174701 | 548 | SP, GR, SPR |
| 5 | D–D′, G–G′ | 3, 5 | DWR Marietta | BB 45M | 342224079073901 | 552 | SP, GR, SPR |
| 6 | D–D′ | 3 | DWR Clarendon | DD 42N | 341200078530001 | 879 | SP, GR, SPR |
| 7 | D–D′ | 3 | Town of Tabor City | EE 42B | 340914078521601 | 330 | SP, GR, SPR |
| 8 | D–D′, D′–H | 3, 6 | DWR Calabash | HH 39J | 335334078352101 | 1,335 | SP, GR, SPR |
| 9 | E–E′ | 3 | Town of Farmville | M 27M | 353529077344701 | 396 | SP, SPR |
| 10 | E–E′ | 3 | Town of Farmville | M 26Q | 353518077353901 | 496 | SP, GR, SPR |
| 11 | E–E′ | 3 | Bell Arthur | M 26U | 353542077305902 | 497 | SP, SPR |
| 12 | E–E′ | 3 | Bell Arthur | N 25G | 353352077281203 | 408 | SP, SPR |
| 13 | E–E′ | 3 | Town of Winterville | N 24P2 | 353132077240401 | 400 | SP, SPR |
| 14 | E–E′ | 3 | DWR Conley Station | N 23P | 353146077193402 | 802 | SP, GR, SPR |
| 15 | E–E′ | 3 | DWR Blackjack Station | N 22Y | 353043077146001 | 210 | SP, GR, SPR |
| 16 | E–E′ | 3 | DWR Chocowinity Station | N 21M | 353038077060101 | 456 | SP, SPR |
| 17 | E–E′ | 3 | DWR Bath Station | O 17I | 352832076470101 | 702 | SP, GR, SPR |
| 18 | E–E′ | 3 | DWR Winsteadville Station | O 15N | 352749076380903 | 710 | SP, GR, SPR |
| 19 | E–E′, D′–H | 3, 6 | DWR Sladesville Station | O 13F | 352854076290901 | 472 | SP, GR, SPR |
| 20 | E–E′ | 3 | DWR Swanquarter | P 11E | 352440076194501 | 302 | SP, SPR |
| 21 | E–E′ | 3 | DWR Hydeland Station | O 10W | 352527076123103 | 1,503 | SP, GR, SPR |
| 22 | F–F′, G–G′ | 4, 5 | DWR Cremo Station | G 19B | 360900076560002 | 1,192 | SP, GR, SPR |
| 23 | F–F′ | 4 | USGS Valhalla | G 15F | 360828076391801 | 528 | SP, GR, SPR |
| 24 | F–F′ | 4 | DWR Three Mile Desert Station | E 13M | 361744076274401 | 1,210 | SP, GR, SPR, SN, LN |
| 25 | F–F′ | 4 | USGS PA-T2-62 | F 10Q | 361130076140001 | 704 | SP, SPR |
| 26 | F–F′, D′–H | 4, 6 | DWR Big Flatty Creek Station | G 9C | 360859076075801 | 731 | SP, GR, SPR |
| 27 | F–F′ | 4 | Rapp Oil Kellog No. 1 | G 6L | 360702075511001 | 5,140 | SP, SN |
| 28 | G–G′ | 5 | DWR Boardman Station | AA 43Q | 342620078581801 | 497 | SP, GR, SPR |
| 29 | G–G′ | 5 | DWR Bladenboro Station | Z 41M | 343027078451901 | 575 | SP, GR, SPR |
| 30 | G–G′ | 5 | DWR Elizabethtown Station | Y 39M | 343739078364601 | 501 | SP, GR, SPR |
| 31 | G–G′ | 5 | DWR White Lake Prison Station | Y 38B | 343917078311207 | 497 | SP, GR, SPR |
| 32 | G–G′ | 5 | DWR White Lake Farm Well No. 5 | Y 37E | 343950078295001 | 258 | SP, GR, SPR |
| 33 | G–G′ | 5 | DWR Black Lake | X 36P | 344122078245001 | 440 | SP, GR, SPR |
| 34 | G–G′ | 5 | DWR Six Runs Station | V 35T | 345113078154504 | 433 | SP, GR, SPR |
| 35 | G–G′ | 5 | Town of Warsaw | T 32Y | 350040078053401 | 360 | GR, SPR |
| 36 | G–G′ | 5 | Carolina Turkeys | S 31A | 350914077555601 | 320 | SP, GR, SPR |
| 37 | G–G′ | 5 | North Lenoir Water Corporation | P 28W | 352115077332301 | 408 | SP, GR, SPR |

**Table B2.** Wells used in cross sections on *Plates 1–7*.—Continued

[GR, Gamma Ray; SPR, Single Point Resistance; SN, Short Normal; LN, Long Normal; SP, Spontaneous Potential]

| Cross-section well number on *Plates 1–7* | Cross section | Plate number | Local name of well | NC quadrangle number/ SC county number | Station identification | Well depth, in feet | Geophysical logs used on Plate |
|---|---|---|---|---|---|---|---|
| | | | North Carolina—Continued | | | | |
| 38 | G–G′ | 5 | ENR Maury Research Station | O 27J | 352840077355508 | 568 | SP, GR, SPR |
| 39 | G–G′ | 5 | DWR West Research Campus | M 25F2 | 353641077241402 | 574 | SP, GR, SPR |
| 40 | G–G′ | 5 | DWR Gold Point Station | J 22P | 355124077145306 | 644 | SP, GR, SPR, SN |
| 41 | G–G′ | 5 | DWR Gates County Prision | C 16Q | 362604076434401 | 1,080 | SP, GR, SPR, SN |
| 42 | D′–H | 6 | Brunswick County Hospital | FF 35W | 340029078173001 | 263 | SP, GR, SPR |
| 43 | D′–H | 6 | Brunswick Tech | FF 34N | 340224078134501 | 212 | SP, SPR |
| 44 | D′–H | 6 | DWR Bolivia Station | FF 33D | 340416078084201 | 300 | SP, GR, SPR |
| 45 | D′–H | 6 | Colonial Trask 3 | EE 31H | 340825077573801 | 1,254 | SP, GR, SPR |
| 46 | D′–H | 6 | Coastal States Foy | CC 29L | 341700077465001 | 1,304 | GR |
| 47 | D′–H | 6 | DWR Topsail Beach Station | BB 28J | 342357077404201 | 1,348 | SP, GR, SPR |
| 48 | D′–H | 6 | DWR Deppe Station | V 23X | 345013077181301 | 1,001 | SP, GR, SPR |
| 49 | D′–H | 6 | DWR Godley Station | Q 16G | 351856076434103 | 1,012 | SP, GR, SPR, SN |
| 50 | D′–H | 6 | DWR Grassy Point Station | O 15U | 352542076353201 | 391 | SP, SPR |
| 51 | D′–H | 6 | DWR New Lake Station | M 12L | 353720076211801 | 1,011 | SP, GR, SPR |
| 52 | D′–H | 6 | DWR Newlands Station | J 11V | 355050076160705 | 1,449 | SP, GR, SPR |
| | | | South Carolina | | | | |
| 53 | A–A′ | 1 | New Ellenton (DNR/SRS corehole) | AIK-817 | 332616081462001 | 561 | SP, GR, SPR, LN |
| 54 | A–A′, I–I′ | 1, 7 | Appleton | ALL-348 | 330130081230401 | 1,734 | SP, GR, SPR, LN |
| 55 | A–A′ | 1 | Gillisonville | JAS-426 | 323704080594508 | 2,900 | SP, GR, SPR, LN |
| 56 | A–A′, A′–C′ | 1, 2 | Hilton Head | BFT-2055 | 321128080421500 | 3,833 | SP, GR, SPR, LN |
| 57 | B–B′ | 2 | Horrell Hill | RIC-585 | 335656080502709 | 469 | SP, GR, SPR, LN |
| 58 | B–B′ | 2 | Eastover | RIC-543 | 335229080421009 | 557 | SP, GR, SPR, LN |
| 59 | B–B′, I–I′ | 2, 7 | Manchester | SUM-296 | 334238080315600 | 725 | SP, GR, SPR, LN |
| 60 | B–B′ | 2 | Saint Stephen | BRK-644 | 332415079560209 | 1,826 | SP, GR, SPR, LN |
| 61 | B–B′, A′–C′ | 2, 7 | Santee Coastal Reserve | CHN-820 | 330921079215009 | 1,536 | SP, GR, SPR, LN |
| 62 | C–C′ | 2 | Cheraw State Park | CTF-81 | 343835079544209 | 245 | SP, GR, SN, LN |
| 63 | C–C′ | 2 | Lake Darpo | DAR-228 | 342731079524809 | 447 | SP, GR, SPR, LN |
| 64 | C–C′ | 2 | Florence | FLO-268 | 341013079472109 | 716 | SP, GR, SN, LN |
| 65 | C–C′ | 2 | Pamplico | FLO-317 | 335940079360509 | 464 | SP, GR, SPR, LN |
| 66 | C–C′ | 2 | Brittons Neck | MRN-78 | 335143079195008 | 1,230 | SP, GR, SPR, LN |
| 67 | C–C′, A′–C′ | 2, 7 | Myrtle Beach | HOR-973/1165 | 334321078541208 | 1,427 | SP, GR, SPR, LN |
| 68 | I–I′ | 7 | Clark Middle School | ORG-393 | 333029080515409 | 1,138 | SP, GR, SPR, LN |
| 69 | I–I′ | 7 | Lake City | FLO-274 | 335120079460200 | 1,090 | SP, GR, SPR, LN |
| 70 | I–I′ | 7 | Little Peedee State Park | DIL-121 | 341943079170209 | 647 | SP, GR, SPR, LN |
| 71 | A′–C′ | 7 | Edisto Island | COL-364 | 323013080174609 | 977 | SP, GR, SPR, LN |
| 72 | A′–C′ | 7 | Sullivans Island | CHN-635 | 324552079495809 | 2,540 | SP, GR, SPR, LN |

basement are: DWR White Lake Prison Station (Y 38B), DWR Bladenboro Station (Z 41M), ENR Maury Research Station (O 27J), and DWR Cremo Station (G 19B).

Section D′–H (*Plate 6*; *table B2*), oriented southwest-northeast in the outer Coastal Plain of NC, illustrates the strike-oriented correlation of hydrogeologic units among wells DWR Calabash Station (HH 39J), Brunswick County Hospital (FF 35W), Brunswick Tech (FF 34N), DWR Bolivia Station (FF 33D), Colonial Trask 3 (EE31H), Coastal States Foy (CC 29L), DWR Topsail Beach Station (BB 28J), DWR Deppe Station (V 23X), DWR Godley Station (Q 16G), DWR Grassy Point Station (O 15U), DWR Sladesville Station (O 13F), DWR New Lake Station (M 12L), DWR Newlands Station (J 11V), and DWR Big Flatty Creek Station (G 9C). Total depths are 1,335, 263, 212, 300, 1,254, 1,304, 1,348, 1,001, 1,012, 391, 472, 1,011, 1,449, and 731 ft, respectively. The bore holes that are drilled to basement are Colonial Trask 3 (EE31H) and DWR Topsail Beach Station (BB 28J).

Section I–I′ (*Plate 7*; *table B2*), oriented southwest-northeast in the inner Coastal Plain of SC, illustrates the strike-oriented correlation of hydrogeologic units among coreholes ALL-348 (Kuntz and others, 1989), ORG-393 (Gellici, 2007a), SUM-296 (Prowell, 1993; Vroblesky, 1994), FLO-274 (Falls, 1994; Rodriguez and others, 1994), and DIL-121 (unpublished). Total depths are 1,734, 1,138, 725, 1,090, and 647 ft, respectively. All of the coreholes were continuously cored to basement with the exception of SUM-296.

Section A′–C′ (*Plate 7*; *table B2*), oriented southwest-northeast in the outer Coastal Plain of SC, illustrates the strike-oriented correlation of hydrogeologic units among coreholes BFT-2055 (Temples and Englehardt, 1997) and COL-364, water well CHN-635, and coreholes CHN-820 (Self-Trail and others, 2004) and HOR-973/1165 (Castro and others, 1995). Total depths are 3,833, 977, 2,540, 1,536, and 1,427 ft, respectively. Sidewall cores to basement were obtained from BFT-2055. COL-364 and CHN-820 were continuously cored, but did not reach basement. HOR-973/1165 was continuously cored to basement, and water well CHN-635 did not reach basement.

The NC cross sections show three geophysical log traces: gamma, spontaneous potential, and single-point resistance. A generalized lithologic log shows the position and thickness of sand units, units of mostly clay and silt, and basement rocks. Plots of groundwater levels over time are presented on the NC plates for selected wells. The position of the saltwater-freshwater transition zone in NC also is indicated by the presence of groundwater containing 250 milligrams per liter (mg/L) of chloride. Results of laboratory analyses of chloride concentrations in groundwater samples collected at discrete depths in selected wells are presented along with the date of sample collection.

Eight columns of information are provided on *Plates 1, 2,* and *7* for each corehole for the SC sections. Beginning at the left, column 1 shows geologic formations, which are allostratigraphic units. Most formation contacts were determined using core data, geophysical logs, and paleontological data (D.C. Prowell, U.S. Geological Survey, written commun., 2002). Column 2 shows the estimated calcareous nannofossil zones based on diagnostic fossil assemblages (Column 3) recovered from core samples, contacts identified in cores, and geophysical-log response. New formation names may be needed where a single formation contains several calcareous nannofossil zones. For example, the Williamsburg Formation contains NP 6, NP 8, and NP 9 fossil zones, each of which probably represents an unconformity. The formation may need to be raised to group rank and defined by three new formations. The same applies to the Santee Formation; however, introducing and formalizing new geologic names was beyond the scope of this study.

Column 3 shows the paleontological age determination at specific depths. Sample depth and pollen and calcareous nannofossil zonations are shown on this column. Depths are in feet below land surface. Formation boundaries determined from intervals that have age-diagnostic fossils are more reliable than intervals that did not yield age-diagnostic fossils or that were barren of fossils. Formations in intervals that were barren of fossils were picked on the basis of core data, geophysical logs, and by dip and strike projections with other coreholes that have biostratigraphic control, or with outcrop data.

Column 4 is an overlay of the spontaneous-potential log in units of millivolts and the natural gamma-radiation log with units in counts per second. Column 5 is altitude, in feet, relative to the National Geodetic Vertical Datum of 1929 (NGVD 29). Column 6 is depth, in feet, below land surface. Column 7 is a lithologic log of the cores. At the water wells, lithology was estimated from drill cuttings and geophysical logs because no cores were available from these wells. An explanation of the lithology symbols is provided on each Plate. Column 8 is an overlay of the single-point resistance log (units are electrical resistance, in ohms) and the 64-in., long-normal resistivity log (units are electrical resistivity, in ohm-meters). Where the coreholes did not reach basement rock, depth to basement was estimated from the map of Prowell and others (2000a). No single-point resistance log was available for several of the coreholes, so the 16-in. short-normal electric log was used in its place.

Data collected from the coreholes and water wells presented on the cross sections were used to construct the hydrostratigraphic correlations from hole to hole across the ACP of NC and SC. Correlations at the NC–SC border were made using the available data at two locations—updip and downdip.

## Pre-Cretaceous Basement Rocks and Structural Geology of the Coastal Plain

The basement complex in SC consists of Paleozoic metamorphic and igneous rocks and consolidated to semi-consolidated Triassic sedimentary rocks (Aadland and others, 1995). Origins of these rocks are different, but their hydraulic properties are similar. The rocks are generally massive, dense, and practically impermeable, except where fracture openings are encountered. Few water wells tap the basement complex in the ACP of NC and SC except in updip regions near the Fall Line where groundwater in ACP sediments is limited.

The following is a general description of basement rocks underlying the ACP and is based on cores used in this report: "…a narrow early Mesozoic basin crosses the upper third of the Coastal Plain from Barnwell County to Dillon County and another large basin underlies the southernmost part of the Coastal Plain. Both of these basins are characterized by continental redbeds locally overlain by flood basalts. Of the remaining basement-rock types, slates and phyllites characterize the northern Coastal Plain areas and high-grade gneisses characterize the western and eastern Coastal Plain areas. Locally, intrusive granites were encountered in the western part of the Coastal Plain" (D.C. Prowell, U.S. Geological Survey, written commun., 2000).

The most prominent structural feature is the Cape Fear Arch (*fig. B1*), which has had a major effect on the distribution and thickness of sediments in the NC and SC ACP. The arch is a southeastward plunging anticline that intersects the NC coastline near Cape Fear. Along the axis of the arch, from the Fall Line to the coast, basement rocks dip 13 feet per mile (ft/mi) (Maher, 1971). The arch is asymmetrical in cross section, with the northeast limb steeper than the southwest limb. Tertiary sediments are absent along the crest and generally absent along the flanks of the arch. Some Late Cretaceous sediments are also missing from the crest of the arch. Owens and Gohn (1985) postulated that the arch was a depocenter during the early part of the Late Cretaceous, which is supported in this study by the increasing thickness of the Cape Fear Formation toward the arch.

Locations of Cretaceous and Cenozoic faults in the southeastern ACP were compiled by Prowell (1983). Most of the faults are northeast-trending, reactivated, high-angle reverse faults that are associated with early Mesozoic rift basins (Snipes and others, 1993). The most studied fault in the SC ACP is the Pen Branch Fault, located near the center of the SRS (Snipes and others, 1993). The Pen Branch is the northern boundary fault of the Dunbarton Basin, a Triassic rift basin that underlies the southeastern half of SRS. Offsets are about 100 ft at the base of the Late Cretaceous section and decrease to about 30 ft at the top of the Late Eocene Dry Branch Formation. These offsets are large enough to breach confining units, especially in updip regions where confining units are thin.

The slopes of basement rocks differ across the Coastal Plain, largely due to the effects of the Cape Fear Arch. Basement rocks dip to the southeast about 35 ft/mi on the western side of the SC ACP from Aiken County (AIK-817) to Hilton Head Island (BFT-2055) (*Plate 1*). On the eastern side, from Chesterfield County (CTF-81) to Myrtle Beach (HOR-973/1165), basement rocks dip 15 ft/mi. From Myrtle Beach to Hilton Head Island (along the coast), basement rocks have a slope of 17 ft/mi. In SC, the top of the crystalline basement rock ranges in altitude from 300 ft near the Fall Line to –4,000 ft in southernmost SC (*fig. B3*; *Appendix B1*). The thickness of the crystalline basement rocks is unknown.

Basement rocks at the Orangeburg corehole (ORG-393) are redbeds that consist of mudstone, pebbly mudstone, sandstone, and conglomeritic sandstone of probable Triassic age (*Appendix B2*). The rocks are poorly sorted and dense from compaction and iron cementation. Pebbles consist of quartz, feldspar, and a variety of metamorphic rock fragments. The unit is massive to crudely bedded. Primary intergranular porosity is low; however, common slickensided surfaces indicate the occurrence of secondary-fracture porosity that could increase flow through the rocks.

## North Carolina Coastal Plain Stratigraphy and Hydrostratigraphy

Stratigraphic units of the NC Coastal Plain are both marine and non-marine in origin and range in age from early Cretaceous to Quaternary (Sohl and Owens, 1991). *Figure B4* presents the stratigraphy and hydrogeologic units of the North and South Carolina Coastal Plain. For NC, recent geological and hydrogeological reports, including data from 147 wells drilled primarily by the State of NC, were used to develop the hydrogeological framework. No new stratigraphic interpretations of the NC Coastal Plain are presented in this report; therefore, the geologic units shown on the stratigraphic correlation chart (*fig. B4*) will not be described, and the reader is referred to the following references for details: Brown and others (1972), Gohn (1988), and Lautier (1998a, b, 2002, 2006). Many of these NC Coastal Plain units extend into southern Virginia (McFarland and Bruce, 2006).

The hydrostratigraphic interpretation of the NC Coastal Plain has evolved from early work by Stephenson (1907, 1923) to the more recent work of Winner and Coble (1996) and Lautier (1998a, b, 2002, 2006). The aquifers and confining units are discussed in descending order. Although the NC Tertiary units are in similar positions stratigraphically to units in SC, they are not continuous or hydraulically connected between the two States because there is a structural high along the NC–SC border and the younger (Tertiary) units have been eroded away there (see sections A–C′, *Plate 7*; D′–H, *Plate 6*; and I–I′, *Plate 7*).


**Figure B3.** Altitude of the top of the crystalline basement rocks underlying the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

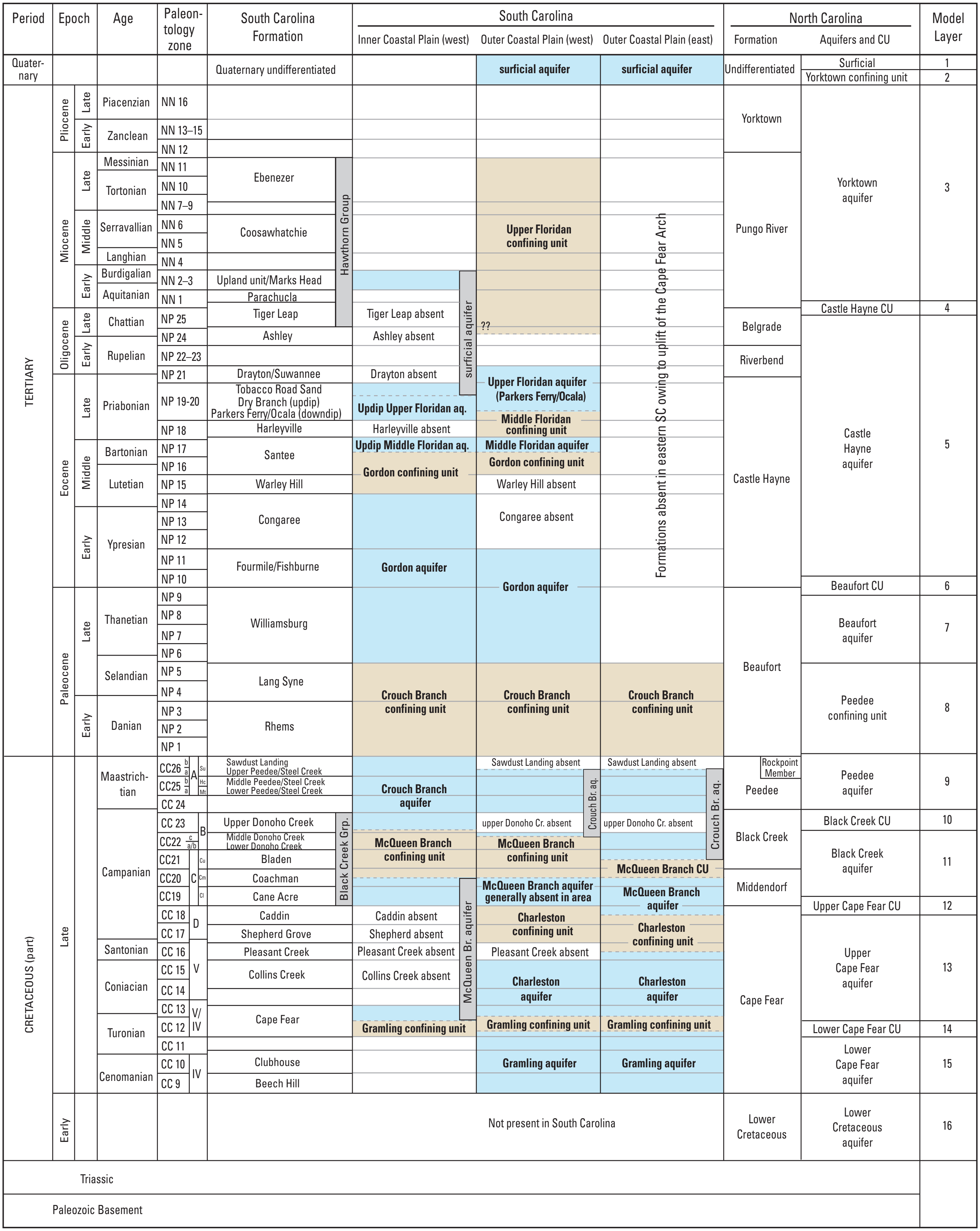



**Figure B4.** Stratigraphic correlations of hydrogeologic units of the North and South Carolina Coastal Plain. (aq., aquifer; cu, confining unit)

## Surficial Aquifer

The surficial aquifer (model layer 1, *Chapter C*) is the uppermost aquifer in the system of aquifers and confining units that compose the hydrogeologic framework of the NC Coastal Plain (*fig. B4*, *Appendix B1*). The surficial aquifer is unconfined; thus the water table fluctuates in response to changes in groundwater storage. The surficial aquifer is the first aquifer to receive recharge, storing water as it moves laterally to rivers, lakes, and other discharge areas, and downward in smaller quantities to deeper, confined aquifers. The surficial aquifer is uniformly present across the NC Coastal Plain, except where it is fully incised by rivers or streams. The top is equivalent to land surface, which generally slopes toward the coast and ranges in altitude from about 0 to 600 ft (*fig. B5*, *Appendix B1*). The thickness of the surficial aquifer in NC ranges from less than 10 ft in the central, northern, and southern parts of the NC Coastal Plain to more than 100 ft in parts of the Sand Hills and coastal areas (*figs. B1, B6*; *Appendix B1*).

The surficial aquifer is primarily composed of permeable sediments of Quaternary age, but it also contains older sediments in some areas because of the varying stratigraphic position of the first underlying confining layer. Included are the overlying soils, which vary in infiltration capacity across the region, thus affecting the rates at which recharge occurs. In terms of lithology, the surficial aquifer is generally composed of layers of sand and shell beds that vary highly in hydraulic conductivity due to variations in clay content and degree of cementation. In the outer Coastal Plain of NC (*fig. B1*), shallow sediments were deposited in a marginal marine environment (Brown and others, 1972), consisting of fine-grained sand, silt, clay, shell material, peat, and combinations thereof. Within the inner Coastal Plain of NC (*fig. B1*), shallow sediments become increasingly fluvial in character, become coarser and more poorly sorted, and consist of sand, sandy clay, clay, and scattered gravel units.


**Figure B5.** Areal extent and altitude of the top of the surficial aquifer (layer 1) in the Atlantic Coastal Plain of North and South Carolina Coastal Plain and parts of Virginia and Georgia, 2007.


**Figure B6.** Thickness of the surficial aquifer in the Atlantic Coastal Plain of North and South Carolina (layer 1) and parts of Virginia and Georgia, 2007.

## Yorktown Confining Unit and Aquifer

The Yorktown confining unit (model layer 2, *Chapter C*) consists of a series of clay and silt beds that do not compose a single unit because they vary greatly in stratigraphic position. The top of the Yorktown confining unit ranges in altitude from less than –100 ft to over 100 ft (*fig. B7*, *Appendix B1*). The confining unit thickness ranges from less than 10 to more than 50 ft in the NC Coastal Plain (*fig. B8*). Where Yorktown aquifer sands are present and the confining unit pinches out, these sands are included in the surficial (or unconfined) aquifer.

The Yorktown aquifer (model layer 3, *Chapter C*) is present only in the northern half of the NC Coastal Plain and is bounded to the west by the Fall Line (*fig. B1*). The aquifer is made up primarily of the Yorktown Formation of Pliocene age, but also contains part of the Miocene Pungo River Formation in the NC East Central Coastal Plain. It contains Quaternary-age sands in areas where the confining unit is in a higher stratigraphic position. The lithology of the aquifer consists of lenticular quartz sands that are fine to medium grained, shelly and clayey, and interbedded with blue to gray colored clay. Layers of shell material and gray colored shell marls are typically present. The unit generally contains numerous phosphatic zones. The aquifer is shallow enough in the western part of the NC Coastal Plain to be incised by streams and rivers, allowing direct discharge to surface water. The Yorktown aquifer is recharged by water moving downward from the overlying surficial aquifer.

Although outliers of the Yorktown Formation are present in Robeson, Bladen, Columbus, and Duplin Counties (*fig. B1*), they are not separated from the surficial aquifer by a recognizable confining unit. These outliers, are therefore not considered to be a distinct aquifer in these areas. The Yorktown aquifer is thus absent over the entire southern part of the NC Coastal Plain.

The Yorktown aquifer ranges in observed altitudes from –100 ft near the NC coast to 100 ft along the Fall line in NC (*fig. B9*). The aquifer thickens eastward from where it directly overlies basement rock at the Fall Line to a maximum of more than 300 ft in easternmost NC (*fig. B10*). Beds which compose the Yorktown confining unit and aquifer are equivalent in terms of their stratigraphic relation to Miocene, Pliocene, and younger formations in SC that are not grouped into a separate aquifer, and are considered to be part of the surficial aquifer. Therefore, there is no counterpart to the Yorktown confining unit and aquifer in SC.

Reported transmissivities by Lautier (1998a) for the Yorktown aquifer in the northeastern NC Coastal Plain ranged from 1 to 2,350 feet squared per day ($ft^2/d$), and horizontal hydraulic conductivities were in the range of 0.2 to 98 feet per day (ft/d), based on five aquifer tests. Winner and Coble (1996) used geophysical and lithologic data from 52 wells to estimate an average horizontal hydraulic conductivity of 22 ft/d.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure B7.** Areal extents and the top altitudes of the Yorktown confining unit (North Carolina) and Upper Floridan confining unit (South Carolina) (layer 2), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B8.** Thickness of the Yorktown confining unit (North Carolina) and Upper Floridan confining unit (South Carolina) (layer 2) in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census, 1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure B9.** Areal extents and the top altitudes of the Yorktown aquifer (North Carolina) and Upper Floridan aquifer (South Carolina) (layer 3), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure B10.** Thickness of the Yorktown aquifer (North Carolina) and Upper Floridan aquifer (South Carolina) (layer 3) in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

## Castle Hayne Confining Unit and Aquifer

The Castle Hayne confining unit (model layer 4, *Chapter C*) consists of clay and silt beds that vary in stratigraphic position between the upper part of the Castle Hayne Formation and younger units of variable age that overlie this formation across the NC Coastal Plain (*fig. B4*). The Castle Hayne confining unit is absent at a number of wells in the central and southern NC Coastal Plain, leaving the Castle Hayne aquifer in direct hydraulic connection with the shallower Yorktown or surficial aquifers. In many areas where the Castle Hayne aquifer is close to the surface, the Castle Hayne confining unit is thin or absent, and water-level differences are slight between the surficial and Castle Hayne aquifers. The top of the Castle Hayne confining unit ranges in altitude from –600 to over 61 ft (*fig. B11*, *Appendix B1*), and the thickness ranges from less than 1 to more than 300 ft in Currituck County (*fig. B12*). The Middle Floridan confining unit and aquifer in SC are equivalent to the Castle Hayne confining unit and aquifer in NC. However, the units are not continuous or hydraulically connected between the two States.

The Castle Hayne aquifer (model layer 5, *Chapter C*) is the most productive aquifer in the NC Coastal Plain. Transmissivity exceeds 35,000 $ft^2/d$, and the aquifer can yield up to 1,000 gallons per minute (gal/min) where it is best developed in the east-central part of the NC Coastal Plain. The aquifer is made up primarily of the Castle Hayne Formation of Eocene age, but also includes the Oligocene Belgrade and Riverbend Formations, where present above the Castle Hayne Formation (*fig. B4*). In areas where the underlying Beaufort confining unit is missing or deeper in the stratigraphic section, the aquifer may also include part or all of the Beaufort Formation of Paleocene age. The Castle Hayne aquifer contains the uppermost part of the Peedee Formation in localized areas where the Beaufort Formation is missing. In the northeastern NC Coastal Plain, the aquifer commonly contains sands of the Pungo River Formation in its upper part. The equivalent units to the Castle Hayne aquifer in SC are the Upper and Middle Floridan aquifers, although these are not contiguous or hydraulically connected.

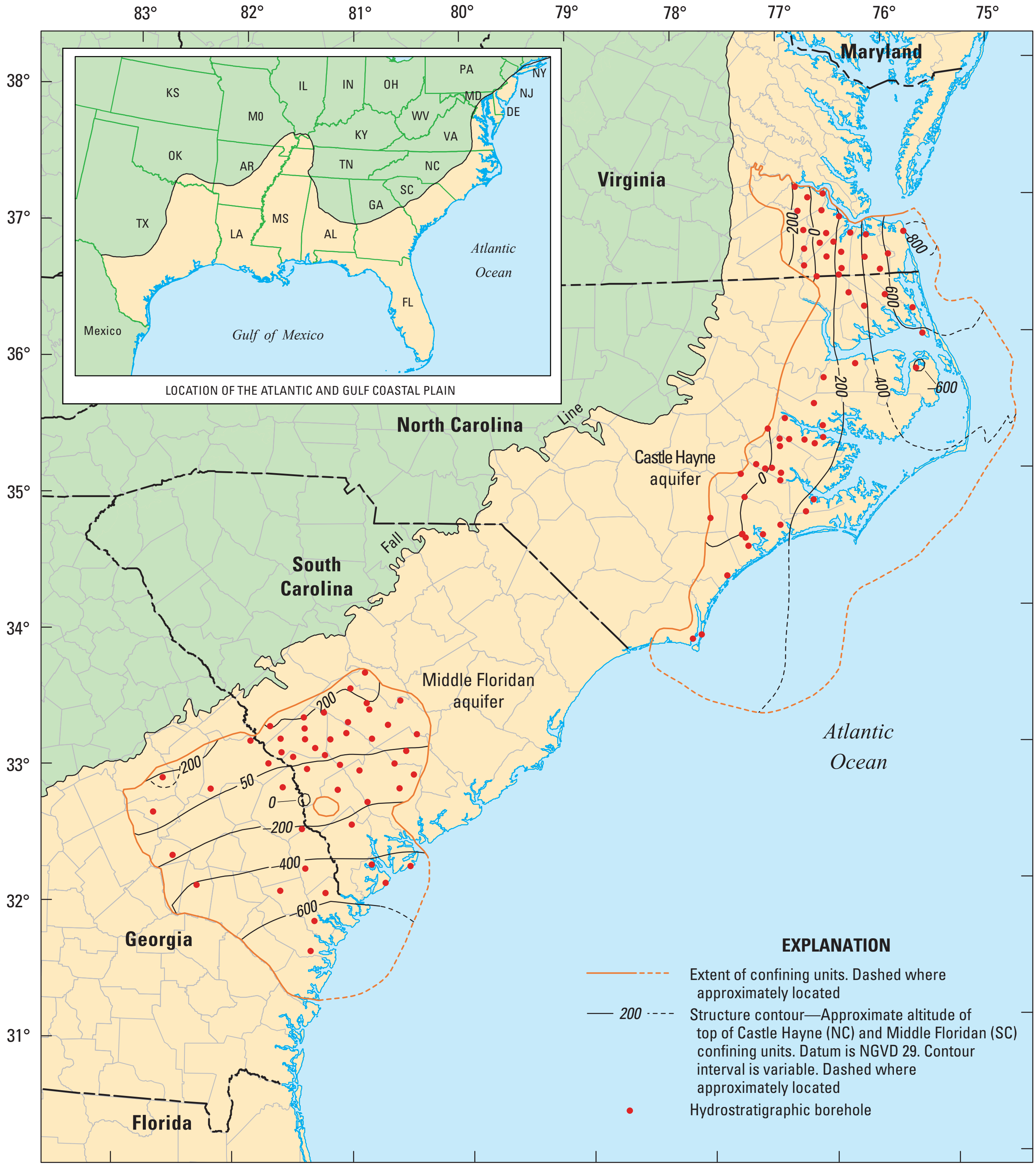
In terms of lithology, the Castle Hayne aquifer in the central and southern NC Coastal Plain may be generally described as a sandy, molluscan-mold limestone (Spring Garden Member) and a bryozoan-echinoid skeletal limestone (Comfort Member). The aquifer lithology grades downward into a calcareous, fine-grained sandstone. Where the Belgrade and River Bend Formations make up the upper part of the aquifer in Pender, Onslow, Jones, and Cartaret Counties (*fig. B1*), lithologies include oyster shells in a tan to orange sand matrix, fossiliferous, clayey sand, calcarenite, and sandy, molluscan-mold limestone. In the northeastern Coastal Plain, the aquifer is thin and composed primarily of sandy, glauconitic biomicrite, interbedded with pale green dolomite. The usefulness of the Castle Hayne aquifer as a water source greatly diminishes in the counties north of the Albemarle Sound (*fig. B1*) due to a reduction in transmissivity and hydraulic conductivity.

The Castle Hayne aquifer thickens from west to east, to a maximum of 530 ft, and becomes more deeply buried toward the east (*fig. B13*; *Plates 3, 4,* and *5*). The top of the Castle Hayne aquifer ranges in observed altitudes of –759 ft in the easternmost parts of the NC Outer Banks to 61 ft in Lenoir County (*fig. B14, Appendix B1*).

The Castle Hayne aquifer is recharged by water that leaks through its confining layer from the shallower Yorktown and surficial aquifers. In the outcrop area of the Castle Hayne Formation in northern Craven, eastern Jones, Onslow, Pender, New Hanover, and Brunswick Counties (*fig. B1*), the aquifer is overlain only by a thin veneer of sediments of post-Yorktown age, which allows for greater recharge rates, especially where substantial clay layers are absent in the shallow subsurface. Hydrograph data from groundwater monitoring sites (*Plates 3, 4,* and *5*) indicate that where the Castle Hayne aquifer is present in the shallow subsurface, nearly identical seasonal water-level fluctuations occur in the surficial and Castle Hayne aquifers, indicating a similar rate of recharge to both aquifers.


**Figure B11.** Areal extents and the top altitudes of the Castle Hayne confining unit (North Carolina) and the Middle Floridan confining unit (South Carolina) (layer 5), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B12.** Thickness of the Castle Hayne confining unit (North Carolina) and the Middle Floridan confining unit (South Carolina) (layer 4) in the Atlantic Coastal Plain of North Carolina and South Carolina and parts of Virginia and Georgia, 2007.




Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure B13.** Thickness of the Castle Hayne aquifer (North Carolina) and the Middle Floridan aquifer (South Carolina) (layer 5) in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

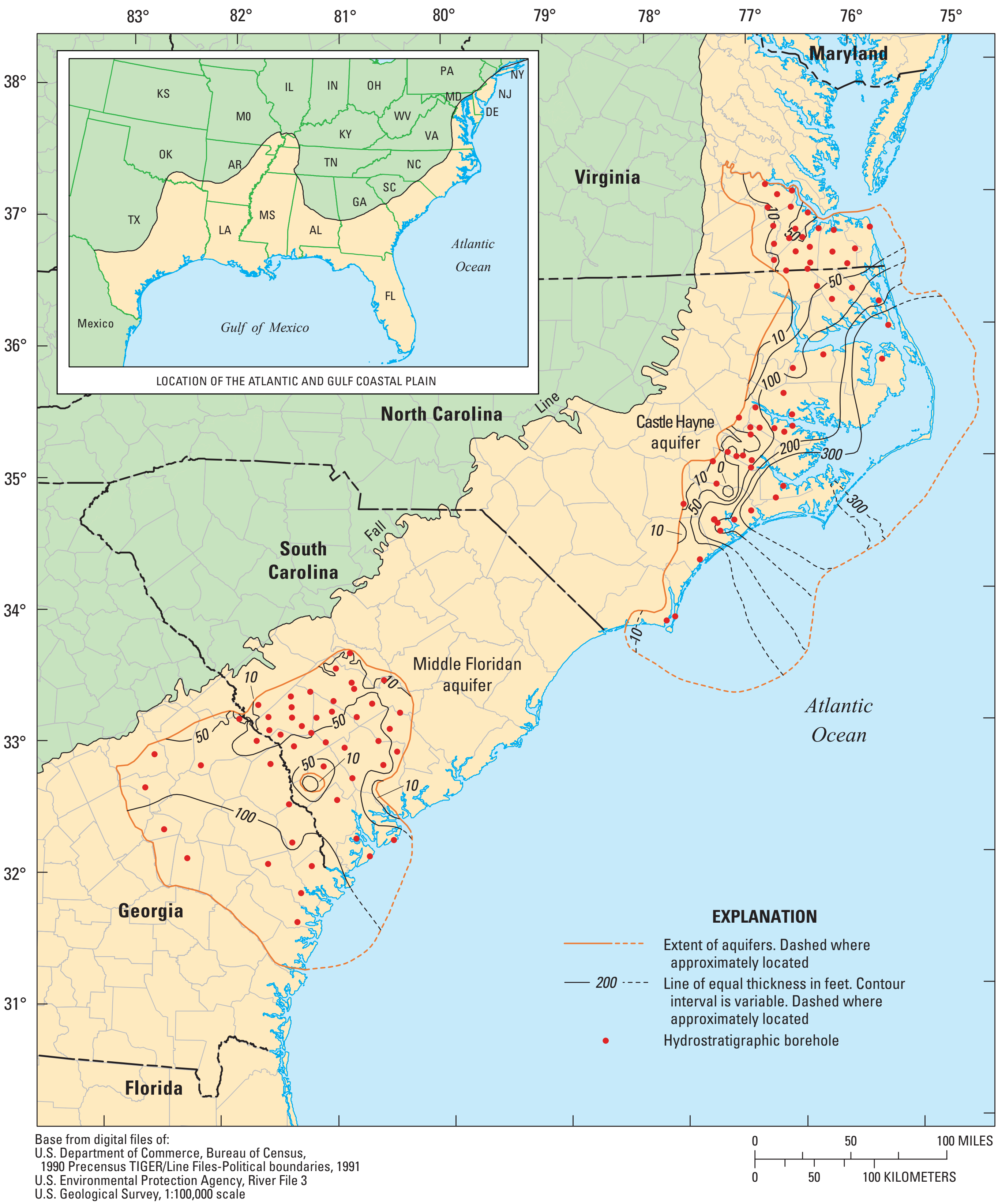



**Figure B14.** Areal extents and top altitudes of the Castle Hayne aquifer (North Carolina) and the Middle Floridan aquifer (South Carolina) (layer 5) in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

## Beaufort Confining Unit and Aquifer

The Beaufort confining unit (model layer 6, *Chapter C*) is composed of clays and silts in the upper part of the Beaufort Formation and the lower part of the Castle Hayne Formation (*fig. B4*). West of the updip limit of the Castle Hayne Formation, the confining unit can include clay and silt beds in the lower part of the Yorktown Formation, or where the Yorktown is missing clay and silt beds of Quaternary age. The top altitude of the Beaufort confining unit ranges from 0 ft parallel to the Fall Line to as deep as –1,127 ft in the northeastern part of the NC Coastal Plain (*fig. B15*, *Appendix B1*). The thickness of the Beaufort confining unit ranges from zero, in areas where it is eroded or pinches out, to a maximum of about 50 ft, where it is best developed in northeastern NC (*fig. B16*). The Gordon confining unit and aquifer in SC are equivalent to the Beaufort confining unit and aquifer in NC; however, the units are not continuous or hydraulically connected between the two States.

The Beaufort aquifer (model layer 7, *Chapter C*) extends through the eastern section of the northern half of the NC Coastal Plain. The aquifer is made up primarily of glauconitic, fossiliferous, and some clayey sands and intermittent thin limestone beds of the Paleocene Beaufort Formation. The aquifer also may include sandy limestone and sands of the lowermost Castle Hayne Formation (*fig. B4*). At some locations, the Beaufort aquifer includes sands and clays of the uppermost part of the Peedee Formation. Geophysical logs and water-level data indicate that the Beaufort aquifer is hydraulically connected to the Castle Hayne aquifer in many areas of the eastern NC Coastal Plain because of discontinuous confining beds. In these areas, the Beaufort is part of the Castle Hayne aquifer (*Plate 6*). Lloyd (1968) reported an average transmissivity of 1,600 $ft^2/d$ in Chowan County, based on an average of 22 aquifer-test calculations. Winner and Coble (1996) reported an average horizontal hydraulic conductivity of 35 ft/d.

The top of the Beaufort aquifer ranges in observed altitude from over –1,000 ft in northeastern NC to –5 ft in Jones County (*fig. B17*, *Appendix B1*). The maximum observed thickness of the aquifer is about 300 ft in northeastern NC (*fig. B18*).


Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure B15.** Areal extents and the top altitudes of the Beaufort confining unit (North Carolina) and the Gordon confining unit (South Carolina) (layer 6), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B16.** Thickness of the Beaufort confining unit (North Carolina) and the Gordon confining unit (South Carolina) (layer 6), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B17.** Areal extents and the top altitudes of the Beaufort aquifer (North Carolina) and the Gordon aquifer (South Carolina) (layer 7), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B18.** Thickness of the Beaufort aquifer (North Carolina) and the Gordon aquifer (South Carolina) (layer 7), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

## Peedee Confining Unit and Aquifer

The Peedee confining unit (model layer 8, *Chapter C*) comprises beds of clay and silt with varying amounts of sand, and is positioned stratigraphically near the contact of the Paleocene Beaufort and Late Cretaceous Peedee Formations in the eastern NC Coastal Plain (*fig. B4*). West of the updip limit of the Beaufort Formation, the Peedee confining unit is composed of the uppermost Peedee or in the lower part of the Yorktown Formations, or in beds of early Quaternary age (where the Yorktown is absent). The top of the Peedee confining unit varies from about 0 ft in the southeastern part of the NC Coastal Plain to more than –1,324 ft in the eastern NC Coastal Plain (*fig. B19, Appendix B1*). The thickness of the Peedee confining unit varies between 0 ft, where it pinches out, to a maximum observed value of about 50 ft in Craven County (*fig. B20*). In areas where the Peedee aquifer is directly overlain by the surficial aquifer, the Peedee aquifer acts as a semi-confined aquifer, and water levels are affected by seasonal recharge variations. In SC, the Peedee confining unit and aquifer are equivalent to the Crouch Branch confining unit and aquifer.

The Peedee aquifer (model layer 9, *Chapter C*) is present over most of the eastern NC Coastal Plain except for the northeastern counties. The aquifer pinches out to the north, just north of Warsaw, NC (well 35, *Plate 5*).

The Peedee aquifer is composed mainly of the Late Cretaceous Peedee Formation, but also may include part of the Late Cretaceous Black Creek Formation, and the lower part of the Beaufort Formation, where present (*fig. B4*). Updip from the western limit of the Beaufort Formation, the Peedee aquifer also may include sediments of Quaternary age. In areas where the Peedee Formation is directly overlain by the Yorktown Formation, sands in the upper part of the Yorktown Formation can be included in the Peedee aquifer. Due to the number of formations included, the lithology of the aquifer is variable. In general terms, the lithology is characterized as greenish gray to light brown, silty to clayey, fine- to very fine-grained quartz sand with trace quantities of glauconite, phosphorite, oyster shells, and pyrite. In southeastern Brunswick and north central New Hanover Counties (*fig. B1*), the Rocky Point Member makes up the uppermost part of the Peedee Formation, consisting of gray, sandy, moldic limestone, grading downward to calcareous sandstone. In some areas, the updip limit of the Peedee aquifer extends a few miles further to the west than the limit of the Peedee Formation, as delineated on the NC geologic map (Brown and others, 1985) because the Peedee aquifer contains older and younger beds below and above the Peedee Formation.

Various investigators have reported transmissivity values for the Peedee aquifer, including Lautier (2002), who calculated a range of 240 to 1,170 $ft^2/d$ for the central part of the NC Coastal Plain. In the southern part of the NC Coastal Plain, Lautier (2006) reported a range of 40 to 340 $ft^2/d$ for the Peedee aquifer. Harden and others (2003) estimated transmissivity values in Brunswick County between 3,000 and 6,000 $ft^2/d$.

The top altitudes of the Peedee aquifer range from 86 ft in Lenoir County to about –1,355 in Dare County (*fig. B21, Appendix B1*). The maximum thickness of the Peedee aquifer is about 300 ft in Brunswick County (*fig. B22*).

The Peedee aquifer primarily receives recharge by vertical leakage from overlying aquifers. Recharge also occurs in interstream areas where heads are lower in the Peedee aquifer than in shallower aquifers. Where the head is higher in the Peedee than in overlying aquifers, discharge occurs to streams and rivers. The rate of recharge is directly proportional to the vertical hydraulic conductivity and head difference across the confining bed, and inversely proportional to the thickness of the confining bed. Regional differences in these factors, as well as variations in the transmissivity of the aquifer, can cause recharge rates to vary across the study region.


**Figure B19.** Areal extents and the top altitudes of the Peedee confining unit (North Carolina) and the Crouch Branch confining unit (South Carolina) (layer 8), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B20.** Thickness of the Peedee confining unit (North Carolina) and the Crouch Branch confining unit (South Carolina) (layer 8), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B21.** Areal extents and the top altitudes of the Peedee aquifer (North Carolina) and the Crouch Branch aquifer (South Carolina) (layer 9), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B22.** Thickness of the Peedee aquifer (North Carolina) and the Crouch Branch aquifer (South Carolina) (layer 9), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

## Black Creek Confining Unit and Aquifer

The Black Creek confining unit (model layer 10, *Chapter C*) separates the Peedee aquifer from the Black Creek aquifer. Over most of the eastern NC Coastal Plain, the Black Creek confining unit is a thick, massive section of clay and silt with variable amounts of sand. This unit is primarily within the Black Creek Formation, but also contains lower clay and silt beds of the Peedee Formation (*fig. B4*). In the western NC Coastal Plain, the Black Creek confining unit may also include the lower part of the Yorktown Formation. Where the Yorktown is absent, the Black Creek confining unit includes clay and silt beds in the lower part of the Quaternary formations. The confining unit has been incised in major stream valleys in many parts of the western Coastal Plain and is well developed only in the interfluvial areas. The top of the Black Creek confining unit ranges in altitude from a high of over 200 ft to a low of –1,511 ft (*fig. B23, Appendix B1*). Over the entirety of the NC Coastal Plain, the Black Creek confining unit ranges in thickness from less than 10 ft along the updip limit to more than 200 ft in southeastern NC (*fig. B24*). The Black Creek confining unit and aquifer are equivalent to the McQueen Branch confining unit and aquifer in SC. The units are hydraulically connected between NC and SC.

The Black Creek aquifer (model layer 11, *Chapter C*) is made up primarily of the Late Cretaceous Black Creek Formation, but also includes permeable beds from older and younger formations in the NC Coastal Plain; in localized areas, it includes sands in the lower part of the Peedee Formation (*fig. B4*). In some places in northern Wayne and Greene, western Pitt, and Martin Counties, the Black Creek aquifer includes sands or shell beds in the lower part of the Yorktown Formation. Where the Yorktown and Peedee aquifers are absent in the southern part of the Coastal Plain, sands in the lower part of the Quaternary units make up part of the Black Creek aquifer. In the southwestern Coastal Plain, the Late Cretaceous Middendorf Formation interfingers with the Black Creek aquifer and appears to be connected hydraulically. Due to variations in the stratigraphic position of the Upper Cape Fear confining unit, the top of which defines the base of the Black Creek aquifer, sands in the Cape Fear Formation are included in the Black Creek aquifer over localized areas.

The Black Creek aquifer is made up of alternating beds of sand and clay. The sands are generally gray to olive gray in color, fine to medium grained, poorly sorted, and contain variable amounts of glauconite, phosphorite, shell fragments, and lignite, and traces of mica, pyrite, and marcasite. The lignite is of primary origin from organic material deposited along with the inorganic part of the sediments. Clays are generally gray to black and organic-rich. Individual sands appear to be laterally discontinuous based on electric log correlation (*Plates 3, 4, 5,* and *6*). However, it is evident that sands in the aquifer are well connected hydraulically over long distances, due to the widespread lateral transmission of drawdown effects from concentrated pumping centers in the central part of the NC Coastal Plain. The Black Creek aquifer is heavily used in the central and southern Coastal Plains due to its high-quality water and negligible treatment costs. Due to overuse of the Black Creek aquifer in the central part of the NC Coastal Plain, the State of NC has implemented mandatory withdrawal reduction rules in conjunction with capacity-use law in order to manage drawdown effects (North Carolina Division of Water Resources, 2001). Reduction rules were applied in this part of the NC Coastal Plain to the Upper and Lower Cape Fear aquifers as well. Reported transmissivities of the Black Creek aquifer range from 290 to 1,700 $ft^2/d$ from an analysis of 15 aquifer tests (Lautier, 2002, 2006).

The Black Creek aquifer pinches out along the Fall Line at the updip limit of the sediments. The approximate updip limit extends eastward through Wayne, Wilson, Edgecombe, and Martin Counties (*fig. B1*) to the NC coast, south of Albemarle Sound. The Black Creek Formation is present to the north of Albemarle Sound, but consists primarily of clay and is therefore mapped as part of the Upper Cape Fear confining unit. The altitude of the top of the Black Creek aquifer ranges from 317 ft above NGVD 29 in Richmond County to –1,612 ft in Dare County (*fig. B25, Appendix B1*). The Black Creek aquifer reaches a minimum thickness of less than 10 ft along the updip limit and a maximum thickness of 442 ft in Onslow County (*fig. B26*). The Black Creek aquifer is poorly defined in counties further east of Craven County.


**Figure B23.** Areal extents and the top altitudes of the Black Creek confining unit (North Carolina) and the McQueen Branch confining unit (South Carolina) (layer 10), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B24.** Thickness of the Black Creek confining unit (North Carolina) and the McQueen Branch confining unit (South Carolina) (layer 10), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.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U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

0 50 100 MILES
0 50 100 KILOMETERS

**Figure B25.** Areal extents and the top altitudes of the Black Creek aquifer (North Carolina) and the McQueen Branch aquifer (South Carolina) (layer 11), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B26.** Thickness of the Black Creek aquifer (North Carolina) and the McQueen Branch aquifer (South Carolina) (layer 11), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

## Upper Cape Fear Confining Unit and Aquifer

The Upper Cape Fear confining unit (model layer 12, *Chapter C*) consists of beds of clay and silt and variable but lesser amounts of sand that are in the upper part of the Cape Fear Formation and the lower part of the Black Creek Formation in some places (*fig. B4*). Where the Yorktown Formation directly overlies the Cape Fear Formation in the northern Coastal Plain, beds of low permeability in the lower part of the Yorktown Formation make up part of the Upper Cape Fear confining unit in some areas. In places where the Cape Fear Formation is directly overlain by sediments of Quaternary age, clays and silts in the lower part of the Quaternary are considered to be part of the confining unit. The altitude of the top of the Upper Cape Fear confining unit ranges from 200 ft along the updip limit to about –1,200 ft in southeastern NC (*fig. B27*, *Appendix B1*). The thickness of the Cape Fear confining unit ranges from about 50 ft over most of the NC Coastal Plain to about 100 ft along the NC–SC border (*fig. B28*). In SC, the Upper Cape Fear confining unit and aquifer are correlative and hydraulically connected to the Charleston confining unit and aquifer in SC.

The Upper Cape Fear aquifer (model layer 13, *Chapter C*) is made up primarily of the upper part of the Cape Fear Formation of Upper Cretaceous age. In some places, the Cape Fear aquifer can also include the Middendorf Formation or lowermost sands of the Black Creek Formation (*fig. B4*). The Black Creek aquifer is present over most of the NC Coastal Plain, pinching out either at the Fall Line or a few miles to the east of the Fall Line. Over the majority of the NC Coastal Plain, the lithology of the aquifer consists of alternating layers of clay and gray to red, poorly sorted, fine- to coarse-grained sand. Conglomerates and gravel beds are also common and increase the permeability of the aquifer. Also present throughout are accessory iron oxide minerals such as pyrite, marcasite, and siderite. Sediments of the Cape Fear Formation are interpreted to be nonmarine in origin, and were deposited in a fluvial-deltaic environment. In the easternmost counties of the NC Coastal Plain, thin limestone beds are present in the Cape Fear Formation, indicating the juxtaposition of marine and nonmarine sediments downdip. Although individual sand beds in the Cape Fear aquifer appear to be laterally discontinuous based on electric logs, drawdown effects are easily transmitted laterally through the aquifer over widespread areas.

Large cones of depression have formed around pumping centers in the central part of the NC Coastal Plain, in Bladen County and surrounding counties in the southern NC Coastal Plain, and in the northeastern NC Coastal Plain due to large-volume pumping from the southern Virginia area. Reported transmissivities in the Upper Cape Fear aquifer range from 25 to 440 $ft^2/d$ in the central NC Coastal Plain (Lautier, 2002) based on analyses of three aquifer tests. In the northeastern NC Coastal Plain, transmissivity from one aquifer test produced a result of 920 $ft^2/d$ (Lautier, 1998a).

The top of the Upper Cape Fear aquifer ranges in observed altitudes from about –1,400 ft in Dare County to over 200 ft in Moore County, near the Fall Line (*fig. B29, Appendix B1*). The Upper Cape Fear aquifer ranges in thickness from less than 10 ft along the updip limit of the aquifer to 665 ft in northeastern NC (*fig. B30*).

In NC, both the Upper and Lower Cape Fear aquifers are composed of sediments that are considered to be Upper Cretaceous in age, although inadequate data exist to determine with much confidence where the top of the Early Cretaceous is present. In SC, the equivalent to the Upper Cape Fear aquifer is the Charleston aquifer and confining unit. The Charleston and Upper Cape Fear aquifers are connected hydraulically as evidenced by water-level declines in Columbus and Robeson Counties, NC, due to pumping from the Charleston aquifer in SC.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure B27.** Areal extents and the top altitudes of the Upper Cape Fear confining unit (North Carolina) and the Charleston confining unit (South Carolina) (layer 12), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B28.** Thickness of the Upper Cape Fear confining unit (North Carolina) and the Charleston confining unit (South Carolina) (layer 12), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B29.** Areal extents and the top altitudes of the Upper Cape Fear aquifer (North Carolina) and the Charleston aquifer (South Carolina) (layer 13), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B30.** Thickness of the Upper Cape Fear aquifer (North Carolina) and the Charleston aquifer (South Carolina) (layer 13), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007

## Lower Cape Fear Confining Unit and Aquifer

The Lower Cape Fear confining unit (model layer 14, *Chapter C*) separates the upper and lower parts of the Cape Fear Formation into two distinct aquifers. Substantial differences in hydraulic head are measured in observation wells screened in the Upper and Lower Cape Fear aquifers across the NC Coastal Plain. This confining unit consists of regionally correlative clay and silt beds in the approximate middle of the Cape Fear Formation (*fig. B4*). The top altitude of the Lower Cape Fear confining unit varies from about –200 ft in the updip limit to about –1,200 ft in the downdip limit (*fig. B31, Appendix B1*). The thickness of the Lower Cape Fear confining unit is about 50 ft across most of the NC Coastal Plain, and about 100 ft near the NC–VA border (*fig. B32, Appendix B1*). At the NC–SC border, the Lower Cape Fear confining unit and aquifer are correlative and hydraulically connected to the Gramling confining unit and aquifer in SC.

The Lower Cape Fear aquifer (model layer 15, *Chapter C*) primarily comprises the lower part of the Cape Fear Formation of Upper Cretaceous age (*fig. B4*) and may also include sediments of early Cretaceous age. The Lower Cape Fear aquifer consists of alternating beds of nonmarine sand, gravel, and clay of similar color and character as the Upper Cape Fear aquifer. The basal portion of the Lower Cape Fear aquifer contains reworked materials from the underlying Paleozoic basement crystalline rocks in areas where the Lower Cretaceous aquifer is missing. This unit is overlain by the Upper Cape Fear aquifer throughout the study area, and is present mostly in the eastern half of the NC Coastal Plain. However, the updip limit is close to the Fall Line in the northernmost counties. The Lower Cape Fear aquifer pinches out at the basement surface, and does not crop out or subcrop elsewhere in the Coastal Plain. The aquifer is underlain by the Lower Cretaceous aquifer in the northeastern part of the NC Coastal Plain; elsewhere, the Lower Cape Fear is the deepest aquifer in the region. In the northwestern NC Coastal Plain, the aquifer is overlain only by the Upper Cape Fear, Yorktown, and surficial aquifers, and recharge rates in this area may be higher than in other areas.

The updip limit of the Lower Cape Fear aquifer is along a line starting from southern Robeson County, through Bladen, Sampson, Duplin, Lenoir, Greene, Wilson, Edgecombe, Halifax, and Northampton Counties (*fig. B1*). The top of the Lower Cape Fear aquifer ranges from an altitude of about –200 ft along the updip limit to about –1,200 ft along the downdip limit (*fig. B33, Appendix B1*). The thickness of the Lower Cape Fear aquifer ranges from about 10 ft in places along the updip limit to as much as 500 ft at the downdip limit (*fig. B34*). The Lower Cape Fear aquifer probably achieves greater thickness in the Albemarle Embayment; however, the base of the aquifer is poorly defined by existing data in that area.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure B31.** Areal extents and the top altitudes of the Lower Cape Fear confining unit (North Carolina) and the Gramling confining unit (South Carolina) (layer 14), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B32.** Thickness of the Lower Cape Fear confining unit (North Carolina) and the Gramling confining unit (South Carolina) (layer 14), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure B33.** Areal extents and the top altitudes of the Lower Cape Fear aquifer (North Carolina) and Gramling aquifer (South Carolina) (layer 15), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure B34.** Thickness of the Lower Cape Fear aquifer (North Carolina) and Gramling aquifer (South Carolina) (layer 15), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007

## Lower Cretaceous Confining Unit and Aquifer

The Lower Cretaceous aquifer (model layer 16, *Chapter C*) was first defined in NC by Winner and Coble (1996) to classify permeable sediments of Early Cretaceous age beneath the Lower Cape Fear aquifer in the Albemarle Embayment and extending south into Cartaret County, NC. In this area, beds thicken greatly eastward so that they make up approximately one-third to one-half of the total thickness of NC Coastal Plain sediments along the northern NC coastline. Based on available information, it is unclear where the boundary is between the Lower Cape Fear and Lower Cretaceous aquifers. It is also not possible to determine the position and extent of an intervening confining unit between the Lower Cape Fear and Lower Cretaceous aquifers. The Lower Cape Fear aquifer may include a substantial thickness of sediments of Early Cretaceous age. Because of a lack of water-level information, it is also uncertain whether the Lower Cretaceous aquifer constitutes a single aquifer, or could be divided by confining units into more than one aquifer. The Lower Cretaceous aquifer contains saltwater over most of its extent in the NC Coastal Plain, except in its updip fringes, as defined by Winner and Coble (1996).

The freshwater portion of the Lower Cretaceous aquifer varies in altitude from –200 ft to –1,200 ft (*fig. B35, Appendix B1*), and its thickness ranges from about 50 ft to as much as 800 ft in NC (*fig. B36*). There is no SC equivalent to the Lower Cretaceous aquifer. The underlying basement rocks and structural elements are discussed in a previous section of this report.


**Figure B35.** Areal extents and the top altitudes of the Lower Cretaceous confining unit and Lower Cretaceous aquifer in North Carolina (layer 16), in the Atlantic Coastal Plain of North Carolina and part of Virginia, 2007.


**Figure B36.** Thickness of the Lower Cretaceous confining unit and Lower Cretaceous aquifer in North Carolina (layer 16), in the Atlantic Coastal Plain of North Carolina and part of Virginia, 2007.

# South Carolina Coastal Plain Allostratigraphy and Biostratigraphy

Correlation of hydrostratigraphic units across the SC ACP was made possible in large part by the biostratigraphic and allostratigraphic frameworks developed during the past 10 years as part of the USGS Coastal Carolina project (U.S. Geological Survey, 2007). Although hydrostratigraphic boundaries do not directly coincide with biostratigraphic or allostratigraphic boundaries, strong relations exist that are useful in correlating hydrostratigraphic units from well to well over long distances. The following is a summary of the allostratigraphic formations and biostratigraphic zones, from oldest to youngest, that were used in the development of the new hydrogeologic framework for the SC ACP. Although not a comprehensive description, this summary provides an overview of the allostratigraphic formations, their age and fossil zonations, and their distributions across the SC ACP (*fig. B4*; *Plates 1, 2,* and *7*).

## Late Cretaceous Formations

The Cretaceous section of the SC ACP consists of late Cretaceous Cenomanian to Maastrichtian sediments that were deposited between 98 and 65 million years ago. These sediments reach a maximum thickness of about 2,200 ft in Beaufort County. Thirteen formations of Cretaceous age were identified in the cores, several of which may warrant being raised to group rank and divided into additional formations.

Formations constituting the lower part of the section generally alternate between oxidized, red to brown, coarse-grained clastic sediments deposited in fluvial-deltaic environments (Beech Hill and Cape Fear Formations), and gray to black, fine-grained clastic sediments deposited in marginal-marine environments (Clubhouse, Collins Creek, and Pleasant Creek Formations; *fig. B4*) (Gohn, 1992; Self-Trail and others, 2004b). Formations constituting the middle part of the Cretaceous section are dominated by gray to black, laminated, fine- to coarse-grained clastic sediments that were deposited in deltaic and shallow marine environments (Shepherd Grove, Caddin, Cane Acre, Coachman, Bladen, and Donoho Creek Formations). Formations constituting the upper part generally consist of light-colored, calcareous and clastic sediments that were deposited in deltaic to deep marine environments (Sawdust Landing and Peedee/Steel Creek Formations).

Formation tops were determined from the cores used in this study and are expressed in feet relative to NGVD 29. The lithic character of most formations changes geographically across the SC ACP in response to changing depositional environments. As such, the lithologic descriptions provided are generalized and may not be an accurate description of the various formations in all areas of the SC ACP.

### Beech Hill Formation

The Beech Hill Formation is the basal formation of the SC ACP and was defined at corehole DOR-37 (Gohn and others, 1977 and Gohn, 1992) in southern Dorchester County where it was provisionally assigned a Cenomanian age (corresponding to calcareous nannofossil zone CC 9; Gohn, 1992). At its type section, the Beech Hill Formation consists of yellow, green, and brown to red, noncalcareous clayey sand and clay. Beds typically are indurated but in some places are unconsolidated. In the Berkeley County corehole (BRK-644), permeable unconsolidated clayey sand layers are interbedded with hard, nodular clay beds. The Beech Hill Formation is present only in the outer SC ACP from Horry to Beaufort Counties and as far inland as northern Dorchester County where it constitutes the lower 25 ft of corehole in northern Dorchester County (DOR-211). The altitude at the top of the formation ranges from –1,164 ft in Berkeley County (BRK-644) to –1,317 ft at Myrtle Beach (HOR-973/1165), and from –2,530 ft in Jasper County (JAS-426) to –3,350 ft at Hilton Head Island (BFT-2055) (*Plate 7*). The Beech Hill Formation reaches a maximum thickness of 470 ft thick at Hilton Head Island (BFT-2055) (*Plate 1*).

### Clubhouse Formation

The Clubhouse Formation was defined at the corehole DOR-37 in southern Dorchester County (Gohn, 1992) and was assigned a late Cenomanian(?) and early Turonian age (calcareous nannofossil zones CC 10–11). At its type section, the Clubhouse Formation consists of gray and grayish-green laminated silty sand and silty clay and is slightly calcareous. Thin sand beds of the formation at Hilton Head Island are screened in a supply well for the town. The formation is present only in the outer Coastal Plain from Myrtle Beach to Hilton Head Island and as far inland as northern Jasper County (*Plates 1* and *7*). The Clubhouse Formation overlies the Beech Hill Formation. The altitude of the top of the Clubhouse Formation ranges from –1,264 ft at Myrtle Beach (HOR-973/1165) to –2,830 ft at Hilton Head Island (BFT-2055). The formation reaches a maximum thickness of 520 ft at Hilton Head Island (BFT-2055) (*Plate 1*).

### Cape Fear Formation

The Cape Fear Formation was named by Stephenson (1907) for crops out along the Cape Fear River in NC (*fig. A1*). A late Turonian to early Coniacian age was assigned to the formation (calcareous nannofossil zones CC 12–13) (Gohn, 1992; Christopher and others, 1999). Sediments of the formation are highly oxidized and generally noncalcareous, making them difficult to date. The Cape Fear Formation consists of fining-upward beds (5 to 30 ft thick) of poorly sorted clay, sand, and gravel. Beds are commonly weakly cemented with silica, which reduces porosity and permeability. Common colors include gray, green, yellow, orange, and red. Feldspar is widespread and is partially weathered to kaolinite. The formation is present throughout the Coastal Plain, except in the northern parts of Aiken and Lexington Counties. The Cape Fear Formation overlies pre-Cretaceous bedrock in the inner Coastal Plain and primarily the Clubhouse and Beech Hill Formations in the outer Coastal Plain. Altitudes range from +155 ft in Chesterfield County (CTF-81) to –954 ft at Myrtle Beach (HOR-973/1165), and from –369 ft in Aiken County (AIK-817) to –2,758 ft at Hilton Head Island (BFT-2055) (*Plates 1, 2* and *7*). The formation reaches a maximum thickness of 615 ft in northern Dorchester County (DOR-211).

## Collins Creek Formation

The Collins Creek Formation was defined at the CHN-820 corehole (*Plates 2* and *7*) in northeastern Charleston County (Self-Trail and others, 2004) and was assigned a middle to late Coniacian age (calcareous nannofossil zones CC 14–15). At its type section, the Collins Creek Formation consists predominantly of olive-gray, poorly sorted, fine to coarse organic-rich sand. Beds of sandy clay, clayey sand, and cemented zones of sand and shell fragments also are present (Self-Trail and others, 2004). The formation is slightly calcareous in the lower half and noncalcareous in the upper half. Sand beds of the Collins Creek Formation form part of a deep aquifer in coastal counties. The formation is absent in the inner Coastal Plain. A line drawn from northern Allendale County to northern Horry County approximates the updip limit of the formation (*fig. B1*). The Collins Creek Formation overlies the Cape Fear Formation throughout its extent. The altitude of the top of the formation ranges from –700 ft in Marion County (MRN-78) to –1,412 ft in Charleston County (CHN-820), and from –1,154 ft in Allendale County (ALL-348) to –2,510 ft at Hilton Head Island (BFT-2055) (*Plate 7*). The formation reaches a maximum thickness of 248 ft at Hilton Head Island (BFT-2055) (*Plate 1*).

## Pleasant Creek Formation

The Pleasant Creek Formation was defined at the CHN-820 corehole (*Plates 2* and *7*) in northeastern Charleston County (Self-Trail and others, 2004b) and was assigned a Santonian age (calcareous nannofossil zone CC 16). At its type section, the lower part of the formation consists of olive-gray, poorly sorted, fine to coarse glauconitic sand with scattered 0.5- to 1.5-ft-thick silica-cemented sand and shell zones. Most of the formation (more than 200 ft at the type section) consists of dark greenish-gray, dry and tight sandy clay that breaks with a conchoidal fracture. The formation locally contains beds consisting of up to 30-percent shell fragments and beds of sand and shell up to 3 ft thick that are cemented with calcium carbonate (Self-Trail and others, 2004b). The Pleasant Creek Formation has been found only in downdip cores. The formation overlies the Collins Creek Formation except at the Myrtle Beach corehole (HOR-973/1165) where the Pleasant Creek Formation overlies the Cape Fear Formation. The altitude of the top of the formation ranges from –568 ft in Marion County (MRN-78) to –1,703 ft in southern Dorchester County (DOR-37). The formation is absent at the south end of the SC ACP in Jasper County (JAS-426; *Plate 1*) and at Hilton Head Island (BFT-2055). The Pleasant Creek Formation reaches a maximum thickness of 259 ft at Myrtle Beach (HOR-973/1165) (*Plate 7*).

## Shepherd Grove Formation

The Shepherd Grove Formation was defined at corehole DOR-37 in southern Dorchester County (Gohn, 1992) and was assigned a late Santonian to early Campanian age (calcareous nannofossil zone CC 17). At its type section, the Shepherd Grove Formation is generally a fine-grained unit that consists of gray to olive-gray calcareous, silty clay, clayey silt, and clayey fine sand. Shell fragments are common. On the western side of the SC ACP, the formation extends inland only to about northern Jasper County. The formation reaches farther inland on the eastern side of the Coastal Plain, extending updip to about northern Florence County where it is present as a clayey sand unit at the FLO-268 corehole (*Plate 2*). The Shepherd Grove Formation overlies the Cape Fear Formation in the east-central parts of the Coastal Plain, the Pleasant Creek Formation in most of the outer SC ACP cores (*Plate 7*), and the Collins Creek Formation in Beaufort and Jasper Counties (*Plate 1*). The altitude of the top of the formation ranges from –201 ft in Dillon County (DIL-121) to –547 ft at Myrtle Beach (HOR-973/1165), and from –1,932 ft in Jasper County (JAS-426) to –2,466 ft at Hilton Head Island (BFT-2055) (*Plates 1, 2,* and *7*). The formation reaches a maximum thickness of 183 ft in northern Charleston County (CHN-820).

## Caddin Formation

The Caddin Formation was defined at corehole DOR-37 in southern Dorchester County (Gohn, 1992) and was assigned an early Campanian age (calcareous nannofossil zones CC 17–18). At its type section, the Caddin Formation consists of light olive-gray to greenish-gray, clayey, calcareous, fine-grained glauconitic sand. Glauconite locally constitutes up to 20 percent of the formation. In northern Berkeley County (BRK-644), the formation consists of a dark-greenish gray to greenish-black glauconitic sandy marl. A line drawn from northern Jasper County to northern Horry County approximates the updip limit of the formation (*fig. B1*). The Caddin Formation overlies the Shepherd Grove Formation. The altitude of the top of the formation ranges from –380 ft in Marion County (MRN-78) to –463 ft at Myrtle Beach (HOR-973/1165), and from –1,875 ft in Jasper County (JAS-426) to –2,329 ft at Hilton Head Island (BFT-2055) (*Plates 1* and *2*). The Caddin Formation reaches a maximum thickness of 137 ft at Hilton Head (BFT-2055).

## Cane Acre Formation

The Cane Acre Formation is the lowermost formation of the Black Creek Group. The formation was defined at corehole DOR-37 in southern Dorchester County (Gohn, 1992) and was assigned a middle Campanian age (calcareous nannofossil zone CC 19). At its type section, the formation consists of light-gray to light-olive-gray calcareous fine-grained sandy clay, calcareous silty clay, and calcareous fine- to medium-grained clayey sand. Updip, at the ORG-393 corehole in Orangeburg (and elsewhere updip) the formation consists of light-gray medium- to coarse-grained sand and clayey sand and forms part of an aquifer (*Plate 7; Appendix B2*). The Cane Acre Formation is present over most of the SC ACP except in extreme updip areas along the Fall Line and in the northeastern part of the SC ACP in Chesterfield and Marlboro Counties. The formation overlies the Cape Fear Formation in the inner Coastal Plain (*Plate 2*), the Shepherd Grove Formation in the east-central part of the SC ACP (*Plate 2*), and the Caddin Formation in the outer Coastal Plain (*Plate 2*). The altitude of the top of the formation ranges from –188 ft in Dillon County (DIL-121) to –394 ft at Myrtle Beach (HOR-973/1165), and from +233 ft in Aiken County (AIK-2448) to –2,222 ft at Hilton Head Island (BFT-2055). The Cane Acre Formation reaches a maximum thickness of 210 ft at the southern part of the SRS in Barnwell County (BRN-335) (*fig. B1*).

## Coachman Formation

The Coachman Formation is part of the Black Creek Group. The formation was defined at corehole DOR-37 in southern Dorchester County (Gohn, 1992) where it was assigned a middle and late Campanian age. Data collected for this study indicate that the age of the Coachman Formation is middle Campanian (calcareous nannofossil zone CC 20) (D.C. Prowell, U.S. Geological Survey, written commun., 2005). At its type section, the formation consists of gray and gray-green, calcareous, silty clay, clayey silt, and fine sand. An unconformity, identified in downdip cores and from paleontological evidence, suggests that the Coachman Formation can be divided into two formations in the eastern and southeastern parts of the SC ACP (D.C. Prowell, U.S. Geological Survey, written commun., 2005). This unconformity is identified on the cross sections with a dashed line. Because a formal division of the formation is beyond the scope of this report, the units were combined and named Coachman. The Coachman Formation is present over most of the SC ACP except in extreme updip areas along the Fall Line. The Coachman Formation overlies the Cane Acre Formation everywhere except in Darlington County (DAR-228) where it overlies Cape Fear sediments (*Plate 2*). Altitudes range from +120 ft in Darlington County (DAR-228) to –282 ft at Myrtle Beach (HOR-973/1165), and from –562 ft in Barnwell County (BRN-335) to –2,130 ft at Hilton Head Island (BFT-2055). The formation has a maximum thickness of 181 ft in northern Dorchester County (DOR-211).

## Bladen Formation

The Bladen Formation is the second youngest formation of the Black Creek Group. The Bladen Formation was named by Owens (1989) for exposures along the Cape Fear River in NC. The formation was described at corehole DOR-37 in southern Dorchester County (Gohn, 1992), where it was assigned a late Campanian age. Paleontological data collected for this study indicate that the age of the formation is late middle Campanian (calcareous nannofossil zone CC 21) (D.C. Prowell, U.S. Geological Survey, written commun., 2005). At the DOR-37 corehole in southern Dorchester County, the formation consists of olive-gray to gray, calcareous, silty clay, clayey silt, and fine sand. Sand content increases toward the upper part of the formation. Thin cemented beds are common, and mollusks (especially oysters) are locally common. The Bladen Formation is present over most of the Coastal Plain, except in far updip areas near the Fall Line. The formation thickens considerably from west to east, and overlies the Coachman Formation everywhere except in some updip areas in the northwest (for example, AIK-817) where the formation overlies Cane Acre sediments. The altitude of the top of the Bladen Formation ranges from +193 ft in Chesterfield County (CTF-81) to –260 ft at Myrtle Beach (HOR-973/1165), and from +246 ft in Aiken County (AIK-2249) to –1,940 ft at Hilton Head Island (BFT-2055, *Plates 1, 2,* and *7*). The formation has a maximum thickness of 224 ft in southern Dorchester County (DOR-37).

## Donoho Creek Formation

The Donoho Creek Formation is the uppermost formation of the Black Creek Group. The formation was named by Owens (1989) for exposures along the Cape Fear River in NC. The Donoho Creek Formation was described at corehole DOR-37 in southern Dorchester County (Gohn, 1992), where it was assigned an early Maastrichtian age. Recent paleontological data, however, indicate that the age of the formation is late Campanian (calcareous nannofossil zones CC 22–23) (Self-Trail and others, 2002; D.C. Prowell, U.S. Geological Survey, written commun., 2005). At DOR-37, the undivided Donoho Creek Formation is described as consisting of olive-gray to gray calcareous, clayey silt and fine sand, and calcareous silty clay. A basal, megafossiliferous clayey sand is 10 ft thick. The Donoho Creek Formation is present throughout the Coastal Plain, except in the northeastern counties of Kershaw, Chesterfield, Marlboro, and Darlington. The formation overlies the Bladen Formation everywhere except in the northern parts of Aiken and Lexington Counties, where it probably forms the basal Cretaceous Formation. The altitude of the top of the Donoho Creek Formation ranges from +401 ft in Aiken County (AIK-2448) to –1,856 ft at Hilton Head Island (BFT-2055), and from +129 ft in Lee County (LEE-75) to –229 ft at Myrtle Beach (HOR-973/1165). The formation reaches a maximum thickness of 292 ft in Allendale County (ALL-348) (*Plates 1, 2,* and *7*).

Paleontological evidence and physical evidence of unconformities in coreholes indicate that the Donoho Creek Formation can be subdivided. A biostratigraphic subdivision of the formation has been proposed, but has not been formalized (D.C. Prowell, U.S. Geological Survey, oral commun., 2002). For the purposes of this report, the Donoho Creek Formation is divided into three informal units—the lower, middle, and upper Donoho Creek units corresponding to calcareous nannofossil subzones CC 22a/b, CC 22c, and zone CC 23, respectively (*Plates 1, 2,* and *7*).

## Peedee Formation

The "Peedee beds" were first described by Ruffin (1843), and the Peedee Formation was formally named by Stephenson (1923) who designated an exposure on the Great Pee Dee River at Burches Ferry in Florence County as the type locality. The formation was described at corehole DOR-37 in southern Dorchester County (Gohn, 1992), where it was assigned a Maastrichtian age (calcareous nannofossil zones CC 25–26). At the DOR-37 corehole, the formation consists of a basal gray to olive-gray calcareous, clayey sand unit that grades upward into similarly colored calcareous, silty clay. The undivided Peedee is present across most of the SC ACP except in the eastern and northeastern parts, where uplift along the Cape Fear Arch caused erosion. The Peedee Formation overlies the Donoho Creek Formation everywhere. The altitude of the top of the Peedee Formation ranges from +176 ft in Lee County (LEE-75) to –5 ft at Myrtle Beach (HOR-973/1165), and from +348 ft in Aiken County (AIK-2449) to –1,672 ft at Hilton Head Island (BFT-2055). The formation reaches a maximum thickness of 233 ft in northern Dorchester County (DOR-211).

At its type locality in Florence County, the Peedee Formation consists of dark-green to gray, fossiliferous, glauconitic clayey sand and silt. In west-central SC, a fluvial, coarse-grained, age-equivalent unit of the Peedee Formation was named the Steel Creek Formation (Fallaw and Price, 1995) because of substantial differences in Peedee Formation lithology at its type locality compared to that observed at the SRS (*fig. B1*). At the SRS, the Peedee Formation consists of light-colored fine- to coarse-grained quartz sand and oxidized kaolinitic clay (Fallaw and Price, 1995), and constitutes a productive aquifer.

Christopher and Prowell (2002) recognized unconformities in the Peedee section in cores drilled throughout the Coastal Plain, and proposed a subdivision of the formation into three unconformity-bounded palynological zones. These zones were informally called the lower, middle, and upper Peedee units where Peedee-type lithologies were observed, and the lower, middle, and upper Steel Creek units where Steel Creek–type lithologies were observed (calcareous nannofossil zones CC 25a, CC 25b, and CC 26a, respectively). This same informal subdivision and terminology is used in this report (*Plates 1, 2,* and *7*).

## Sawdust Landing Formation

The Sawdust Landing Formation was named for exposures at Sawdust Landing on the Santee River in Calhoun County, SC (Muthig and Colquhoun, 1988). Until recently, fossils were unavailable from the formation, and most geologists considered it to be of early Paleocene age (Colquhoun and Muthig, 1991; Nystrom and others, 1991; Aadland and others, 1995; Fallaw and Price, 1995). Frederiksen and others (2000), however, recovered a late Cretaceous palynomorph from the Sawdust Landing Formation at a depth of 320.7 ft, in one of the Orangeburg County coreholes, ORG-393 (*Appendix B2*). The pollen assemblage contained the palynomorph *Rugubivesiculities*, which placed the Sawdust Landing Formation in the late Cretaceous (Frederiksen and others, 2000), corresponding to calcareous nannofossil subzone CC 26b. The Sawdust Landing Formation is now considered Maastrichtian in age and is thought to represent the uppermost Cretaceous Formation in the SC ACP (Christopher and Prowell, 2002).

At the ORG-393 corehole, the Sawdust Landing Formation consists of poorly sorted, fine to very coarse sand in a 5 to 20 percent dense clay matrix (*Appendix B2*). Feldspar is common, and sparse quartz gravel and lignite clasts are locally present. The formation is present only in the central and west-central parts of the Coastal Plain, and is absent downdip and on the eastern side of the Coastal Plain. The altitude of the top of the Sawdust Landing Formation ranges from +320 ft in Richland County (RIC-585) to –420 ft in Allendale County (ALL-348). The formation has a maximum thickness of 49 ft in Sumter County (SUM-296).

## Tertiary Formations

The Tertiary section of the SC ACP consists of early Paleocene to Miocene (65 to 5 million years (Ma)) sediments that reach a maximum thickness of about 1,600 ft at Hilton Head Island in Beaufort County (*Plate 1*). Thirteen formations and the undifferentiated Hawthorn Group were identified in the cores. Several of the formations may warrant being raised to group rank and further divided into additional formations.

Formations constituting the Paleocene section (Rhems, Lang Syne, and Williamsburg) generally consist of gray to black carbonaceous clay interbedded with light-colored quartz sand. Early Paleocene sediments are particularly fine grained across most of the SC ACP, whereas late Paleocene sediments are coarser and become increasingly fossiliferous downdip. These sediments were probably deposited in back-barrier, estuarine, and marginal-marine environments. Formations constituting the early and middle Eocene section (Fishburne, Congaree, and Warley Hill) consist of light-gray and green glauconitic quartz sand and kaolinitic clayey sand. The Fishburne and Warley Hill Formations become increasingly fossiliferous downdip, whereas sediments of the Congaree Formation are generally absent downdip. These sediments were probably deposited in deltaic and open-marine environments. The upper middle Eocene section (Santee Formation) is dominated by light-green and gray marl and cream-colored limestone, with the limestone deposited in an open-marine environment. The formation grades updip into calcareous and noncalcareous quartz sand. Formations constituting the late Eocene section (Harleyville, Dry Branch, and Tobacco Road Sand) generally consist of yellow, brown, purple, and red quartz sand and clayey sand in updip regions, and yellowish-gray, gray, and cream-colored limestone in downdip regions. The Dry Branch Formation grades to mixed carbonate/clastic sediments in the west-central part of the SC ACP and to pure carbonate sediments near the present-day coast, where it is called the Parkers Ferry Formation. The Harleyville Formation typically consists of clayey fine-grained limestone and calcareous clay in downdip regions. These formations were probably deposited in shallow to open-marine environments. The Oligocene section comprises the Tiger Leap, Drayton, and Ashley Formations, which consist of yellowish-gray, calcareous, silty and sandy clay. These sediments were probably deposited in open-marine environments. The Miocene section consists of the informal Upland unit. The Upland unit consists of yellow, brown, purple, and red poorly sorted clayey sand and gravel in updip regions. The Hawthorn Group, which consists of a phosphatic limestone, clayey sand, and clay, is thought to be the downdip age-equivalent unit of the Upland unit.

## Rhems Formation

The type locality of the Rhems Formation is at Perkins Bluff on the Black River, about 5 mi from the town of Rhems in Williamsburg County, SC, where it was first described by Sloan (1908). The Rhems Formation was later abandoned by Cooke (1936) and then reinstated by Van Nieuwenhuise and Colquhoun (1982). The formation was assigned an early Paleocene age (calcareous nannofossil zones NP 1–3). At its type section, the Rhems Formation consists of light-gray to black shale interlaminated with thin seams of fine-grained sand and mica. At the Orangeburg County corehole ORG-393, the formation consists of thin layers of grayish-black silty, carbonaceous clay laminated with very thin layers of greenish-gray and light-gray well-sorted, very fine quartz sand (*Plate 7; Appendix B2*). Other unconformities in the early Paleocene are evident from cores and fossils, and the formation may be divided in the future. The Rhems is present in the western, central, and southern parts of the Coastal Plain, but absent in counties along the NC border and in counties that border the Fall Line. The Rhems Formation overlies the Sawdust Landing Formation in the west-central and central parts of the Coastal Plain, and the Peedee Formation in coastal counties. The altitude of the top of the Rhems Formation ranges from +297 ft in Lexington County (LEX-844) to –1,560 ft at Hilton Head Island (BFT-2055; *Plate 7*). The formation reaches a maximum thickness of +159 ft in southern Dorchester County (DOR-37) and in Berkeley County (BRK-644).

## Lang Syne Formation

The type locality of the Lang Syne Formation is at Tombs Field Gully on Lang Syne Plantation, near Fort Motte in Calhoun County, SC (Sloan, 1908). A reference section in Calhoun County (Muthig and Colquhoun, 1988) was described as consisting of red and yellow (where weathered) or white, gray, and black (where freshly exposed) interbedded sand, silt, and clay and thin beds of silicified shell debris. Opaline claystone is the most characteristic lithology. The formation was assigned an early to late Paleocene age (Fallaw and Price, 1992) and corresponds to calcareous nannofossil zones NP 4–5. At the Sumter County corehole SUM-296, the Lang Syne Formation consists of brown and gray low-density, opaline claystone (fuller's earth). The formation overlies the Rhems Formation. Several unconformities are noted in the formation (D.C. Prowell, U.S. Geological Survey, written commun., 2005), but for the purposes of this report, these units are combined and are called Lang Syne. The top of the undivided Lang Syne Formation has altitudes that range from +337 ft in Lexington County (LEX-844) to –1,475 ft at Hilton Head Island (BFT-2055). The Lang Syne Formation reaches a maximum thickness of 297 ft in Charleston County (CHN-800).

## Williamsburg Formation

The Williamsburg Formation was named for exposures in Williamsburg and Berkeley Counties, SC (Sloan, 1908). The name was abandoned by Cooke (1936) and reinstated by Van Nieuwenhuise and Colquhoun (1982) who assigned a late Paleocene age (calcareous nannofossil zones NP 5–9). At its type section, the Williamsburg Formation consists of sandy shale, fuller's earth, fossiliferous clayey sand (Lower Bridge Member), and fossiliferous clayey sand and mollusk-rich, bioclastic limestones (Chicora Member) (Van Nieuwenhuise and Colquhoun, 1982; Edwards and others, 1997). At the Allendale County corehole ALL-348, the Williamsburg Formation consists of gray to black interbedded clay and coarse quartz sand overlying shelly clay and calcareous clay (*Plates 1* and *7*). In west-central SC, at the SRS, age-equivalent sediments are called the Snapp Formation (Aadland and others, 1995; Fallaw and Price, 1995). Several unconformities were observed in the coreholes drilled for this study (D.C. Prowell, U.S. Geological Survey, written commun., 2005). The unconformities are noted on the cross sections, but are combined and called Williamsburg. The undivided Williamsburg Formation is present in the west-central and southern parts of the SC ACP from Barnwell County to Orangeburg County and in all counties to the southeast. The formation is absent on the eastern side of the SC ACP and in counties that border the Fall Line. The Williamsburg Formation overlies the Lang Syne Formation. The altitude of the top of the Williamsburg Formation ranges from +117 ft in Barnwell County (BRN-335) to –1,285 ft at Hilton Head Island (BFT-2055). The formation reaches a maximum thickness of 207 ft in Jasper County (JAS-426).

## Fishburne Formation

The Fishburne Formation was defined at corehole DOR-37 in southern Dorchester County (Gohn and others, 1983), and was assigned an early Eocene age (Ypresian, calcareous nannofossil zones NP 10–11). At its type section, the formation consists of greenish-gray to pale-olive finely crystalline, nodular, glauconitic, clayey microfossil-mollusk limestone. The formation is present mainly in coastal areas of Beaufort, Colleton, Dorchester, Jasper, and southern Charleston Counties. At the Allendale (ALL-348) and Berkeley (BRK-644) County coreholes, late Paleocene to early Eocene sediments were dated and assigned an NP 10 zone (*Plates 1* and *2*). These sediments are included with the Fishburne Formation but may constitute a separate formation (D.C. Prowell, U.S. Geological Survey, written commun., 2005). Palynological assemblages indicate that some sand beds that overlie the Williamsburg Formation in west-central SC are equivalent in age with the Fishburne Formation and were subsequently named the Fourmile Formation at the SRS (Aadland and others, 1995; Fallaw and Price, 1995). Where present, the Fishburne overlies the Williamsburg Formation. The altitude of the top of the Fishburne Formation ranges from –392 ft at the type section in Dorchester County (DOR-37) to –1,219 ft at Hilton Head Island (BFT-2055). The formation reaches a maximum thickness of 120 ft in southern Colleton County at Edisto Beach (COL-364).

## Congaree Formation

The type locality of the Congaree Formation is in Calhoun County, SC. Sloan (1908) described the “Congaree Phase” as shale and sand of early and middle Eocene age. The Congaree Formation has been assigned a probable early Eocene to early middle Eocene age (calcareous nannofossil zones NP 12–14) (Fallaw and Price, 1995). In Aiken County, at the AIK-817 corehole, the formation consists of pale yellow and gray moderately to poorly sorted, medium to coarse quartz sand with little to no interstitial clay. The term Huber Formation refers to an updip age-equivalent facies of the Congaree Formation that is characterized by commercial kaolin beds capping the formation and cross-bedded coarse sand with kaolin balls (Nystrom and others, 1991). Several unconformities in the section were observed in coreholes and in outcrops in Aiken County. The Congaree Formation was informally subdivided into three units corresponding to zones NP 12, 13, and 14 (D.C. Prowell, U.S. Geological Survey, written commun., 2005). The separate NP zones are shown on the cross sections (*Plates 1, 2,* and *7*) where core and fossil data indicate their presence, but they are combined here and called the Congaree Formation. The undivided Congaree Formation is present in the western part of the SC ACP from Aiken County south to Allendale County and east to Orangeburg County. Downdip, widespread erosion by the overlying Santee Formation has left only scattered remnants of the formation (*Plates 1* and *7*). The Congaree Formation directly overlies crystalline bedrock at the Fall Line and overlies Cretaceous and Paleocene sediments elsewhere. The altitude of the top of the Congaree Formation ranges from +460 ft in northern Aiken County (AIK-2448) to –264 ft at the Allendale corehole (ALL-348). The formation reaches a maximum thickness of 106 ft in central Aiken County (AIK-817; *Plate 1*).

## Warley Hill Formation

The type locality of the Warley Hill Formation is in eastern Calhoun County, SC (Sloan, 1907a, b) and is assigned a middle Eocene age (calcareous nannofossil zone NP 15) (Fallaw and Price, 1995). The formation consists of green or yellowish-green glauconitic quartz sand and silt with moderate interstitial clay (Nystrom and others, 1991). At the Orangeburg County corehole ORG-393, the formation consists of olive-gray glauconitic sandy clay and marl consisting of fine- to very coarse-grained quartz sand in a 60- to 70-percent clay matrix that is cemented with calcium carbonate (*Appendix B2*). A second unconformity in the NP 15 zone is recognized in cores drilled for this study (D.C. Prowell, U.S. Geological Survey, written commun., 2005). Because the Warley Hill Formation has not been formally subdivided, both units are noted on the cross sections but are combined in this report and called the Warley Hill Formation. The Formation is present in the central and west-central parts of the SC ACP from Barnwell and Allendale Counties east to Calhoun County. The Warley Hill Formation overlies the Congaree Formation. The altitude of the top of the Warley Hill Formation ranges from +76 ft in Orangeburg County (ORG-393) to –209 ft in Allendale County (ALL-348). The formation reaches a maximum thickness of 54 ft in Allendale County (ALL-348).

## Santee Formation

The Santee Formation was named after the Santee River for exposures at Eutaw Springs in Orangeburg County, about 4 mi east-northeast of Eutawville, SC (Sloan, 1908). The formation was assigned a middle to early late Eocene age by Cooke and MacNeil (1952) and a late middle Eocene age at the SRS (Fallaw and Price, 1995). Edwards and others (1997) dated the Santee section at corehole DOR-208 in Dorchester County as late middle Eocene (calcareous nannofossil zones NP 16–18). Updip, the formation consists of yellow, tan, and white calcareous and noncalcareous quartz sand and clay (Tinker Creek Formation of Fallaw and Price, 1995). The formation becomes calcareous downdip in central Barnwell County, where it consists largely of light-green and gray clayey calcilutite and calcareous silt and clay (marl), with the carbonate content generally greater than 75 percent (Blue Bluff marl unit of Huddlestun and Hetrick, 1986). Farther downdip, in the Allendale County corehole ALL-348, the Santee Formation consists of a lower sandy limestone and calcareous sand unit, a middle Blue Bluff marl unit, and an upper unit that consists of permeable, cream-colored, bioclastic shelly limestone dominated by bryozoans and pelecypods. The formation grades to pure carbonates between Allendale County and the SC coast.

Several geologic units in the study area have been dated as NP 16, including the Blue Bluff marl unit (Fallaw and Price, 1995), the Moultrie Member described by Edwards and others (1997) at the DOR-208 corehole in Dorchester County, and the type section of the Santee Formation (Ralph Willoughby, South Carolina Geological Survey, oral commun., 2007). During the course of the study, several unconformities were noted in the upper middle Eocene section that may warrant a subdivision of the Santee Formation into four units (D.C. Prowell, U.S. Geological Survey, written commun., 2005). These are noted on the cross sections (*Plates 1, 2,* and *7*), but the entire late middle Eocene section is referred to as the Santee Formation in this report, including the updip clastic facies.

The undivided Santee Formation is present in the western and southern parts of the SC ACP, from southern Aiken County south to Beaufort County and northeast to Charleston County. The formation is absent in the eastern half of the SC ACP and in updip counties. The Santee Formation overlies the Warley Hill and Congaree Formations in updip counties and the Fishburne Formation and Paleocene sediments in downdip counties. The altitude of the top of the Santee Formation ranges from +237 ft in southern Aiken County (AIK-892) to –498 ft at Hilton Head Island (BFT-2055). The formation reaches a maximum thickness of 721 ft at Hilton Head Island (BFT-2055).

## Harleyville Formation

The Harleyville Formation has its type locality in northern Dorchester County, SC. The formation was originally described by Ward and others (1979) and raised to formation status by Weems and Lemon (1984). Generally, the formation consists of clayey fine-grained limestone and calcareous clay (Ward and others, 1979). The Harleyville Formation was dated as early late Eocene at the corehole DOR-208 in Dorchester County (calcareous nannofossil zone NP 18) where it was described as a yellowish-gray fossiliferous limestone (packstone) with abundant pelecypods (Edwards and others, 1997). The formation is present only in the southern part of the SC ACP from Hampton County, east to Dorchester County, and in all counties to the southeast. The altitude of the top of the Harleyville Formation ranges from –8 ft in northern Dorchester County (DOR-37) to –360 ft at Hilton Head Island (BFT-2005). The formation reaches a maximum thickness of 138 ft at Hilton Head Island (BFT-2055).

## Dry Branch Formation

The Dry Branch and Parkers Ferry Formations are considered age-equivalent units in this report. The Dry Branch has its type locality in Richmond County, GA (Huddleston and Hetrick, 1979, 1986; see Nystrom and others, 1991, for a historic overview of the formation) and has been dated as late Eocene (calcareous nannofossil zone NP 19–20; Fallaw and Price, 1995). Updip, in northern Barnwell County, SC (BRN-358), the formation is noncalcareous and consists of yellow, tan, and orange moderately sorted fine to coarse quartz sand interbedded with tan clay. Farther downdip, in Allendale County (ALL-348), the formation transitions to a mixed clastic/carbonate unit and consists of moderately sorted, fine to medium calcareous sand and sandy calcarenite. A 20-ft thick moldic limestone is present near the top of the formation. The formation grades into pure carbonates at the coast, where it is called the Parkers Ferry Formation or, further south, the Ocala Limestone. In this report, the name Parkers Ferry Formation is used in reference to the formation south of the Orangeburg Scarp (*fig. B1*). The Dry Branch/Parkers Ferry Formation is present in the western part of the Coastal Plain, from Aiken County to Beaufort County and east to Charleston County. It overlies the Santee and Congaree Formations. The altitude of the top of the formation ranges from +478 ft in northern Aiken County (AIK-2448) to –170 ft at Hilton Head Island (BFT-2055). The Dry Branch Formation reaches a maximum thickness of 215 ft in southern Colleton County at Edisto Beach (COL-364).

## Tobacco Road Sand Formation

The Tobacco Road Sand Formation has its type locality in Richmond County, GA (Huddleston and Hetrick, 1978). In SC, the formation consists of red, brown, tan, purple, and orange medium- to very coarse-grained quartz sand and quartz granules with minor to moderate interstitial clay (Nystrom and others, 1991). The Tobacco Road Sand was assigned a late Eocene age by Huddlestun and Hetrick (1986), corresponding to calcareous nannofossil zone NP 19–20. Few fossils have been found in the formation, and its age is uncertain. Recent evidence from GA indicates that the Tobacco Road Sand Formation is Oligocene in age and may be an updip facies of the Tiger Leap Formation (D.C. Prowell, U.S. Geological Survey, written commun., 2007). In this report, the Tobacco Road Sand Formation is considered late Eocene. The Tobacco Road Sand is present on the western side of the SC ACP from Aiken County south to Allendale County and possibly east to Orangeburg County. The formation overlies the Dry Branch Formation. The altitude of the top of the Tobacco Road Sand Formation ranges from +473 ft in Aiken County (AIK-2449) to +184 ft in Allendale County (ALL-348). The formation reaches a maximum thickness of 60 ft in Allendale County (ALL-348).

## Ashley Formation

The name Ashley was applied to beds in marl pits along the Ashley River in Dorchester County, SC (*fig. B1*). Later the unit was called the Ashley member of the Cooper Formation (Ward and others, 1979) and raised to formation status by Weems and Lemon (1984). The Ashley Formation was assigned a late Oligocene age in the DOR-37 core in Dorchester County (Hazel and others, 1977), corresponding to calcareous nannofossil zone NP 24. At corehole DOR-208 in Dorchester County, the Ashley Formation consists of a homogenous section of yellowish-gray fine-grained clayey calcarenite (Edwards and others, 1997). Small amounts of fine-grained glauconite and phosphate sand are present throughout the formation. The formation is present only in the southern part of the SC ACP from Beaufort County to Charleston County and inland as far as northern Dorchester County. The Ashley Formation overlies the Harleyville, Dry Branch, and Santee Formations. The altitude of the top of the Ashley Formation ranges from +48 ft in Dorchester County (DOR-211) to –88 ft at Hilton Head Island (BFT-2055). The formation reaches a maximum thickness of 141 ft in southern Dorchester County (DOR-37).

### Hawthorn Group

The Hawthorn Formation consists mainly of phosphatic limestone (Dall and Harris, 1892; Matson and Clapp, 1909). The formation was raised to group status in Georgia by Huddlestun (1988) and was later revised by Weems and Edwards (2001), who included five formations in the group. According to Weems and Edwards (2001), the group consists of the late Oligocene Tiger Leap Formation, most likely corresponding to calcareous nannofossil zone NP 25, and the Miocene Parachucla, Marks Head, Coosawhatchie, and Ebenezer Formations, most likely corresponding to calcareous nannofossil zones NN 1–12. The Hawthorn Group is present in the southern part of the SC ACP, where it overlies the Parkers Ferry Formation and possibly the Ashley Formation. The altitude of the top of the Hawthorn Group ranges from +19 ft in Jasper County (JAS-426) to –53 ft at Hilton Head Island (BFT-2055). The Hawthorn Group reaches a maximum thickness of 101 ft in Jasper County (JAS-426).

### Upland Unit

The Upland unit is an informal term for deposits that are present at higher altitudes in the west-central SC ACP (Fallaw and Price, 1992). The unit consists of red, purple, gray, orange, yellow, and tan poorly sorted, clayey, fine to very coarse sand and gravel. Colquhoun (1992) assigned the “upland” to the Oligocene and/or Miocene. Fallaw and Price (1995) assigned the unit to the Miocene, and Nystrom and others (1991) suggested a middle Miocene age (possibly corresponding to calcareous nannofossil zones NN 2–3). The unit is probably age-equivalent to one or more of the Miocene formations of the Hawthorn Group. The Upland unit is present in the western SC ACP from Aiken County to Allendale County and east to Lexington and Orangeburg Counties. The Upland unit overlies the Tobacco Road Sand, with the altitude of the top ranging from +494 ft in northern Aiken County (AIK-2448) to +282 ft in Allendale County (ALL-348). The unit reaches a maximum thickness of 98 ft in Allendale County (ALL-348).

### Undifferentiated Quaternary Units

Undifferentiated sediments are present toward the top of most coreholes south of the Orangeburg Scarp. These sediments are mapped as “undifferentiated Quaternary units.” At the Orangeburg corehole ORG-393, the upper 22 ft of sediments consist of yellowish-brown and reddish-orange poorly sorted, very fine to very coarse, clayey sand and gravel. Accessory minerals include opaque heavy minerals, mica, and feldspar. Undifferentiated Quaternary units overlie Cretaceous sediments in the east and Tertiary sediments in the west. The altitude of the top of the Quaternary ranges from +253 ft in Orangeburg County (ORG-393) to +8 ft in Charleston County (CHN-802). The sediments reach a maximum thickness of 74 ft in Charleston County (CHN-800).

## South Carolina Coastal Plain Hydrostratigraphy

The Southeastern Coastal Plain hydrogeologic province (*fig. B1*) in SC encompasses an area of about 22,500 $mi^2$ (Aucott, 1996). About 95 percent of South Carolina’s groundwater resources are in the province (Newcome, 1989). The Southeastern Coastal Plain consists of a sequence of Mesozoic and Cenozoic sedimentary units that are composed of unconsolidated to semiconsolidated layers of sand, clay, limestone, and marl. The province thickens from the Fall Line to the coast, where it reaches a maximum thickness of about 4,000 ft at the southernmost part of the State. Hydrostratigraphic units are described in descending order in terms of their geometry, age and stratigraphic correlation, lithology and texture, hydrologic properties, and geophysical-log signature. A generalized dip and strike section illustrates the hydrostratigraphic units delineated for this report (*fig. B37*).

In this study, seven hydrostratigraphic systems of the Southeastern Coastal Plain hydrogeologic province are delineated in SC—four aquifer systems and three confining systems (*fig. B4*). Six of these systems correlate with those mapped at SRS (Aadland and others, 1995) (*fig. B38*). A new basal system, defined herein as the Ridgeland aquifer system (*fig. B38*), is not present at SRS and is found only in the outer Coastal Plain. A comparison chart relates the hydrostratigraphic units defined in this study to those delineated and defined by Colquhoun and others (1983), Miller (1986), Aucott and others (1987), and Miller and Renken (1988) (*fig. B39*).

In ascending order, the aquifer systems are the Ridgeland, Midville, Dublin, and Floridan. The Ridgeland is the lowermost system of the Coastal Plain (*figs. B4* and *B38*). It consists of a single aquifer informally named the Gramling. Additional aquifers may occur in the Ridgeland, but few wells fully penetrate the system, and hydrologic data are sparse. The Midville aquifer system consists of the newly defined Charleston aquifer and Charleston confining unit and the previously defined McQueen Branch aquifer (Aadland and others, 1995). The Charleston aquifer and confining unit occur only in the

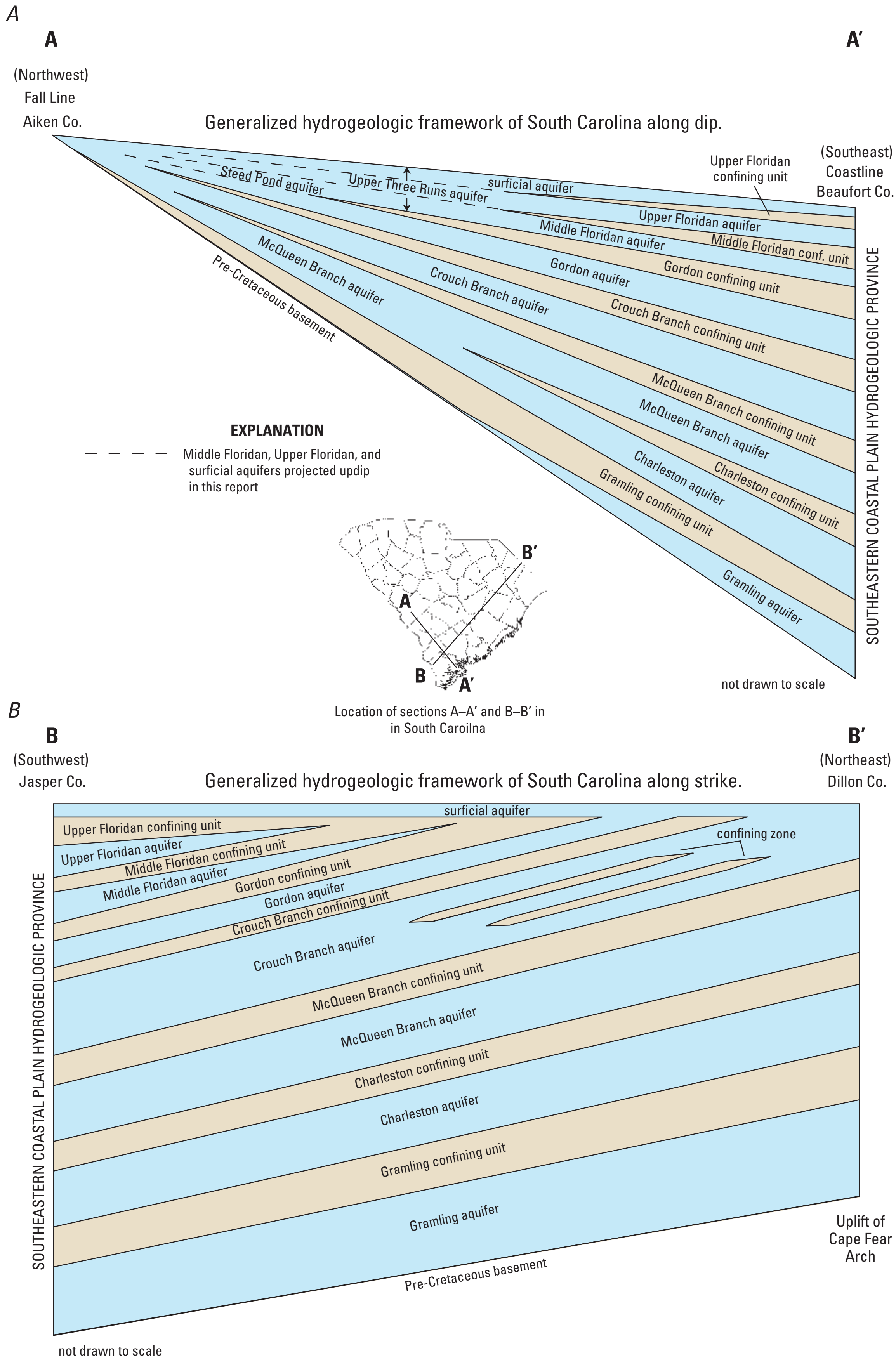


**Figure B37.** Generalized hydrogeologic framework of the South Carolina Coastal Plain along strike and dip.

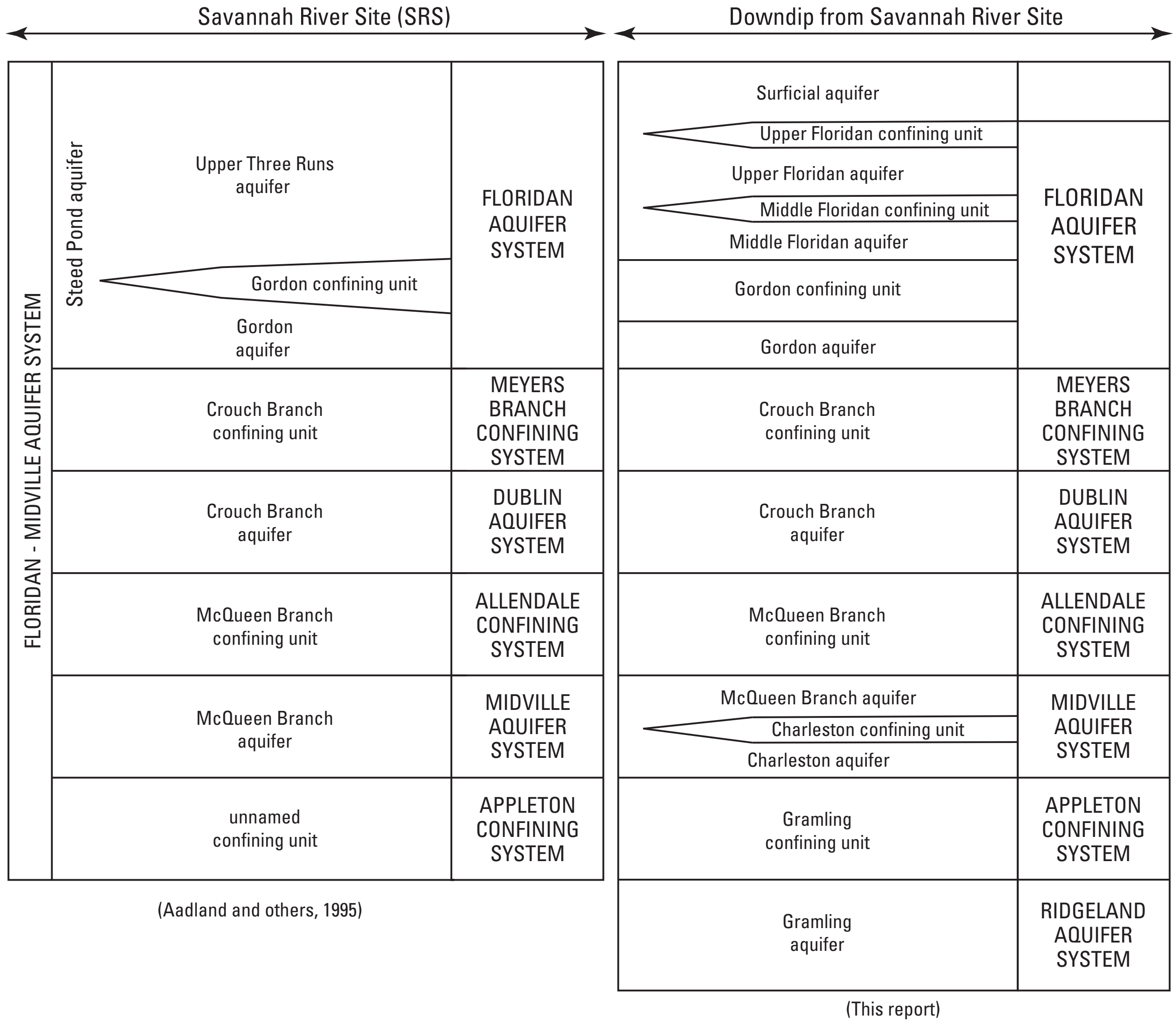


**Figure B38.** Hydrostratigraphy at the Savannah River Site as defined by Aadland and others (1995) compared to the hydrostratigraphy of the South Carolina Coastal Plain downdip of the Savannah River Site, as defined in this study.

middle and lower parts of the Coastal Plain and are not present at SRS. The McQueen Branch, which was defined at SRS, occurs over most of the Coastal Plain. The Dublin aquifer system contains a single aquifer—Crouch Branch—that was defined at SRS. It occurs over most of the Coastal Plain. East of the Congaree/Santee River basins, the Dublin contains several thick and continuous clay units that may divide the system into several aquifers (*fig. B37*).

The Floridan aquifer system occurs in the western part of the Coastal Plain, from the Fall Line to the coast. In the central and southern parts of SRS, the Floridan consists of the Gordon and Upper Three Runs aquifers separated by the Gordon confining unit (Aadland and others, 1995) (*fig. B38*). In northern SRS, the Gordon and Upper Three Runs aquifers coalesce to form the Steed Pond aquifer (Aadland and others, 1995) (*fig. B37*). Downdip from SRS, the Gordon aquifer and confining unit persist, but the Upper Three Runs aquifer splits into the Middle and Upper Floridan aquifers, which are separated by the Middle and Upper Floridan confining units, and the surficial aquifer. To accommodate the flow model described in *Chapter C* and to maintain the lateral continuity of the modeled layers, the Gordon, Middle and Upper Floridan, and surficial aquifers are all extended into updip regions where the Upper Three Runs and Steed Pond aquifers would normally occur (*fig. B37*). This was done by stratigraphic correlation.

In ascending order, the confining systems are the Appleton, Allendale, and Meyers Branch, all defined at the SRS (Aadland and others, 1995). Each system consists of a single confining unit: the Gramling, McQueen Branch, and Crouch Branch (*figs. B4* and *B38*). Several aquifers and confining units contain zones that have unique hydrogeologic properties.

Many of the hydrostratigraphic units described herein are present at one of the Orangeburg coreholes (ORG-393; *fig. B2*). This core, therefore, is used as a reference section in this report. A detailed description of the core is provided in *Appendix B2*. Although not a part of the groundwater flow model presented in *Chapter C*, a short description of the part of the Pre-Cretaceous basement buried beneath the SC ACP is provided in this report.

| | This report | Aucott and others (1987) | Miller (1986) Miller and Renken (1988) | Colquhoun and others (1983) |
|---|---|---|---|---|
| | surficial aquifer (layer 1) | surficial aquifer | surficial aquifer | unnamed |
| FLORIDAN AQUIFER SYSTEM | Upper Floridan confining unit (layer 2) | unnamed confining unit | Upper confining unit | unnamed confining beds |
| | Upper Floridan aquifer (layer 3) | Floridan aquifer system (Tertiary sand aquifer updip) | Upper Floridan aquifer (Pearl River aquifer updip) | Tertiary Limestone Aquifer System (Tertiary sand aquifer system updip) |
| | Middle Floridan confining unit (layer 4) | | | |
| | Middle Floridan aquifer (layer 5) | | | |
| | Gordon confining unit (layer 6) | Tertiary sand aquifer | middle confining unit/ Lower Floridan aquifer | unnamed confining beds |
| | Gordon aquifer (layer 7) | | Pearl River aquifer | Black Mingo Aquifer System |
| MEYERS BRANCH CONFINING SYSTEM | Crouch Branch confining unit (layer 8) | unnamed confining unit | Chattahoochee River confining unit | unnamed confining beds |
| DUBLIN AQUIFER SYSTEM | Crouch Branch aquifer (layer 9) | Black Creek aquifer | Chattahoochee River aquifer | Peedee and Black Creek aquifer systems |
| ALLENDALE CONFINING SYSTEM | McQueen Branch confining unit (layer 10) | unnamed confining unit | | unnamed confining beds |
| MIDVILLE AQUIFER SYSTEM | McQueen Branch aquifer (layer 11) | Middendorf aquifer | | Middendorf aquifer system |
| | Charleston confining unit (layer 12) | | | |
| | Charleston aquifer (layer 13) | | | |
| APPLETON CONFINING SYSTEM | Gramling confining unit (layer 14) | unnamed confining unit | Black Warrior River confining unit | |
| RIDGELAND AQUIFER SYSTEM | Gramling aquifer (layer 15) | Cape Fear aquifer | Black Warrior River aquifer | |

**Figure B39.** Current hydrostratigraphic correlations of the South Carolina Coastal Plain compared to past correlations.

## Surficial Aquifer

The surficial aquifer (model layer 1, *Chapter C*) is the water-table aquifer and consists mainly of terrace sediments that were deposited during transgressions and regressions of the sea since post-Miocene time. The surficial aquifer is present over most of the middle and outer parts of the SC ACP, ranges in altitude from about +600 ft in Aiken County to 0 ft along the coast, and reaches a maximum thickness of about 50 ft (*figs. B5* and *B6*; *Plates 1, 2,* and *7*; *Appendix B1*). Quaternary sediments are generally absent in coreholes in the west-central and updip parts of the SC ACP, and in this area, the surficial aquifer is of late Eocene through Miocene age. The surficial aquifers in NC and SC are equivalent and are hydraulically connected.

### Age and Stratigraphic Correlation

In most of SC, the surficial aquifer consists of strata of Quaternary age that probably correlate with Quaternary deposits described below the Orangeburg Scarp (Colquhoun, 1969), and with the surficial aquifer of Aucott and others (1987). Of the 38 coreholes used in SC, 18 penetrated undifferentiated Quaternary sediments. No dates, however, were obtained from core samples.

In the southern and central parts of the SRS, the water-table aquifer is called the Upper Three Runs aquifer, and in the northern part of the SRS, it is called the Steed Pond aquifer (*fig. B37*). The Upper Three Runs aquifer consists of the clastic phase of the Santee Formation, Dry Branch Formation, Tobacco Road Sand, and Upland unit. In this report, the clastic Santee is mapped as the updip extension of the Middle Floridan aquifer (*figs. B4* and *B37*), the Dry Branch is mapped as the updip extension of the Upper Floridan aquifer, and the Tobacco Road Sand and Upland unit are combined and mapped as the updip extension of the surficial aquifer. As such, the surficial aquifer at the SRS and surrounding areas consists of late Eocene(?) (Tobacco Road Sand) and early Miocene deposits (Upland unit).

### Lithology and Texture

The surficial aquifer is lithologically heterogeneous but generally consists of quartz gravel and sand, silt, clay, and shelly sand. The surficial aquifer in Beaufort, Jasper, and Colleton Counties was described by Hayes (1979) as follows: "Pleistocene deposits consist of brown, gray, and green clays interbedded with white to buff, subangular to angular, quartz sand. Shell beds composed of oyster shells embedded in a matrix of dark-green to gray clay are common along the coast. The Pliocene and Holocene deposits are not well known." Dale and Park (1999), in a study of the shallow aquifer at Hilton Head Island, described the Holocene deposits as clay, silty clay, and sand. They determined that the Pleistocene Wando Formation consists of three units: a sand unit, a silt and silty sand unit with shells, and a clay and silty clay unit with shells.

Park (1985) described surficial sediments in Charleston, Berkeley, and Dorchester Counties that were deposited as four Pleistocene formations: "The Wicomico generally is composed of fine sand, but it can contain some clay, coarse sand, and gravel locally." The Talbot Formation "generally consists of very fine gray to red or pink thin-bedded sand and clay." Cooke (1936, p. 151) described the Pamlico Formation at Johns Island as "…containing 5 ft of green glauconitic clay-sand, underlain by 3 ft of sand, in turn underlain by 2 ft of Pleistocene shell. The thickest sequence of Pamlico deposits occurs in the coastal section of Charleston County where 40 to 60 ft of sand, clay, and shell overlie the Cooper Formation." The Penholoway Formation (as described by Cooke, 1936, p. 147–148) consists of "dark grey pebbly sand…passing upward into fine black carbonaceous sand," overlain by 15 ft of "fine white crossbedded sand, weathering yellow (beach of river deposit)."

Pelletier (1985) described shallow deposits in Georgetown and Horry Counties and the southern part of Marion County as "undifferentiated near-surface clay, sand, limestone, and shell of Tertiary and Quaternary age." At the SRS, the aquifer consists of variably colored, moderately to poorly sorted, fine- to coarse-grained sand, pebbly sand, and minor clay beds of the Tobacco Road Sand, and poorly sorted, clayey sand, pebbly sand, and conglomerate of the Upland unit (Aadland and others, 1995). At the Orangeburg corehole ORG-393, the aquifer consists of moderately to poorly sorted, fine to very coarse clayey sand of Quaternary and possibly Oligocene age (*Appendix B2*).

### Hydrologic Properties

Transmissivity values calculated for five aquifer tests at Hilton Head Island range from 80 to 1,200 $ft^2$/d and average about 500 $ft^2$/d (Dale and Park, 1999). Horizontal hydraulic conductivity values calculated for these tests range from 4 to 65 ft/d and average 27 ft/d. Horizontal hydraulic conductivity values derived from minipermeameter tests of 231 core samples average 8 ft/d for the aquifer (Tobacco Road Sand) at the SRS (Aadland and others, 1995). At Wadmalaw Island, near Charleston, SC, transmissivity values calculated from two aquifer tests of the surficial aquifer are 190 and 270 $ft^2$/d, and hydraulic conductivity values are 20 ft/d (Hockensmith, 1997).

At the SRS, the surficial aquifer is generally connected with the underlying clastic phases of the Upper and Middle Floridan aquifers. In some areas of the SRS, however, confining beds located near the base of the Upper Floridan (Dry Branch Formation) impede the vertical movement of water and often support a hydraulic-head difference between the surficial aquifer and the underlying clastic phase of the Middle Floridan aquifer (Aadland and others, 1995). Farther downdip, in Beaufort, Colleton, Hampton, and Jasper Counties, the Upper Floridan confining unit supports a hydraulic-head difference between the surficial aquifer and the Upper Floridan aquifer (Dale and Park, 1999).

## Geophysical-Log Signature

During the construction of deep wells, the surficial aquifer typically is cased off to prevent caving; consequently, electric logs of these sediments generally are unavailable. Natural gamma counts vary depending on the lithology of the unit. At the SRS, the Tobacco Road Sand and the Upland unit have high interstitial clay and record elevated gamma counts. In areas where the Upper Floridan confining unit is present, the surficial aquifer is easily identified from the underlying confining unit by relatively low natural gamma counts (see Hayes, 1979).

## Floridan Aquifer System

The Floridan aquifer system overlies the Meyers Branch confining system, and is correlated with the Pearl River aquifer of Miller and Renken (1988) in updip regions and with the Floridan aquifer of Miller (1986) in downdip regions (*fig. B39*). In the western part of the SC coastal area, the Floridan aquifer system is commonly referred to as the principal artesian aquifer (Hayes, 1979); it consists of platform carbonates and is a highly productive aquifer system. Inland, the system transitions from pure carbonates to mixed carbonate/clastic deposits and, farther updip, to purely clastic deposits. The updip clastic equivalents are hydraulically connected to the downdip carbonate rocks and are thus considered part of the Floridan aquifer system. The system extends from the Fall Line to the coast and from the Savannah River to about the center of the SC ACP (*fig. B1*). In this study, the aquifer system consists of the Gordon, informally named Middle Floridan, and Upper Floridan aquifers, and the Gordon, informally named Middle Floridan, and Upper Floridan confining units (*figs. B37* and *B38*).

At the SRS, Aadland and others (1995) divided the Floridan aquifer system into two aquifers, the Upper Three Runs and Gordon aquifers, which are separated by the Gordon confining unit (*figs. B37* and *B38*). The Upper Three Runs aquifer consists of Eocene and Miocene sediments that include the clastic facies of the Santee Formation (called the Tinker Creek Formation at SRS; Fallaw and Price, 1995), Dry Branch Formation, Tobacco Road Sand, and Upland unit (*fig. B4*). Clay beds are thin, and, for the most part, these four formations are hydraulically connected at the SRS and were grouped as a single aquifer (Upper Three Runs) by Aadland and others (1995). The Gordon aquifer at the SRS (Aadland and others, 1995) consists of late Paleocene to early middle Eocene sediments that include the Williamsburg Formation (called the Snapp Formation at the SRS; Fallaw and Price, 1995), Fishburne Formation (called the Fourmile Formation at the SRS; Fallaw and Price, 1995), and the Congaree Formation (*fig. B4*). These three formations are hydraulically connected at the SRS and were grouped as a single aquifer (Gordon) by Aadland and others (1995) (*fig. B4*). The Gordon confining unit, which supports a head difference up to 40 ft at the SRS, consists of the middle Eocene Warley Hill Formation and the lower part of the Santee Formation (the Blue Bluff marl unit of Huddlestun and Hetrick, 1986). In the northern part of the SRS, the Gordon confining unit thins and no longer separates the Upper Three Runs and Gordon aquifers. The Upper Three Runs and Gordon aquifers coalesce and form the Steed Pond aquifer of Aadland and others (1995) (*fig. B37*).

Downdip from the SRS, in the vicinity of the Allendale County corehole (ALL-348), the Upper Three Runs aquifer splits into three aquifers (*fig. B37*)—the surficial aquifer and the Upper and Middle Floridan aquifers. The surficial aquifer consists mainly of Miocene and Quaternary sediments, the Upper Floridan aquifer consists of Oligocene and late Eocene carbonate sediments of the upper part of the Parkers Ferry Formation, and the Middle Floridan aquifer consists of middle Eocene carbonate sediments of the upper part of the Santee Formation (*fig. B4*). In order to maintain the lateral continuity of the groundwater flow model layers that are presented in *Chapter C* of this report, these three aquifers were extended updip into parts of the inner Coastal Plain. The surficial aquifer is extended updip by correlation of the Tobacco Road Sand and Upland unit, the Upper Floridan aquifer is extended updip by correlation of clastic age-equivalent sediments of the Parkers Ferry Formation (Dry Branch Formation), and the Middle Floridan aquifer is extended updip by correlation of clastic age-equivalent sediments of the Santee Formation (Tinker Creek Formation) (*fig. B4*). Although the clastic phases of the surficial, Upper Floridan, and Middle Floridan aquifers are hydraulically connected at the SRS, they are not combined as a single aquifer but instead are mapped as separate units from the Fall Line to the coast by stratigraphic correlation of the formations composing the aquifers. The Gordon aquifer also is mapped as a separate unit from the Fall Line to the coast. The Gordon aquifer persists to the coast, but generally contains only early Eocene (Fishburne Formation) and late Paleocene sediments (Williamsburg Formation) in downdip areas. For the most part, the Congaree Formation has been eroded by the overlying Santee Formation, and only thin (less than 20 ft) remnants of the formation remain in a few of the downdip coreholes. In contrast, the Santee section thickens substantially from about 175 ft at the Allendale corehole (ALL-348) to about 400 ft at the Jasper County corehole (JAS-426) (*Plate 1*). At JAS-426, Santee sediments overlie Williamsburg sediments, and the Congaree Formation is absent (*Plate 1*). The Williamsburg Formation forms the Gordon aquifer here and, together with the Fishburne Formation, forms most of the Gordon aquifer in downdip regions of the Coastal Plain.

The Floridan aquifer system of this report is correlated with the Tertiary sand aquifer and the Floridan aquifer system of Aucott and others (1987) (*fig. B39*). The Tertiary sand aquifer consists of an upper and a lower part. The upper part is the updip clastic equivalent of the Floridan aquifer system (Aucott and others, 1987). The upper part extends from about the Fall Line to the carbonate/clastic interface in Barnwell, Orangeburg, and Clarendon Counties (see fig. 2 in Aucott and others, 1987) where it then becomes the Floridan aquifer system. The upper part includes early to late Eocene sediments that consist of sand and clay of the Congaree Formation; marl, sand, and clay of the McBean Formation (an updip mixed carbonate/clastic facies of the Santee Formation); and sand and clay of the Barnwell Group (Dry Branch Formation and Tobacco Road Sand). The upper part correlates, to some extent, with the Upper Three Runs aquifer at the SRS (Aadland and others, 1995), which consists of middle to late Eocene and Miocene sediments that include the Santee and Dry Branch Formations, Tobacco Road Sand, and Upland unit. The Upper Three Runs aquifer, however, does not include the Congaree Formation, which forms part of the underlying Gordon aquifer.

The lower part of the Tertiary Sand aquifer of Aucott and others (1987) (*fig. B39*) extends south from its outcrop in the north-central part of the SC ACP to the SC coast. The lower part includes Paleocene to early Eocene sediments that consist of sand, clay, and limestone of the Black Mingo Group (see the report sections on the Williamsburg and Fishburne Formations). The lower part of the Tertiary Sand aquifer correlates, to some extent, with the Gordon aquifer at the SRS (Aadland and others, 1995), which consists of late Paleocene to early middle Eocene sediments and includes the Williamsburg Formation, the Fishburne Formation, and the Congaree Formation.

Sediments penetrated in reference well P-27 at the SRS are characteristic of the updip clastic phase of the Floridan aquifer system (Aadland and others, 1995). At well P-27, the system is 216 ft thick and consists of clay, sandy clay, and sand of the Snapp Formation (late Paleocene) and Fourmile Formation (early Eocene), all of the Orangeburg Group (middle Eocene) and Barnwell Group (late Eocene) sediments, and the overlying Upland unit (Miocene). The Floridan aquifer system includes all sediments from the top of the Meyers Branch confining system to the surficial aquifer. No reference well is known for the downdip Floridan aquifer system.

Miller (1986) considered late Paleocene strata to be part of the Floridan aquifer system in areas of Georgia and Florida. In South Carolina, however, Miller terminated the base of the Floridan aquifer system either in rocks of early Eocene age or in rocks of middle Eocene age (Miller, 1986). Aadland and others (1995) included the Gordon aquifer in the Floridan aquifer system in west-central SC. The Gordon aquifer includes not only early and middle Eocene strata, but it also includes late Paleocene strata. To maintain consistency with the mapping of Aadland and others, the Floridan aquifer system in this report also includes the Gordon aquifer.

## Upper Floridan Confining Unit

The Upper Floridan confining unit (model layer 2, *Chapter C*) overlies the Upper Floridan aquifer. The confining unit extends from the southernmost SC coast to southern Allendale County and from the Savannah River to western Colleton County (*figs. B1, B37*; *Plates 1, 2,* and *7*). The confining unit is absent from central Allendale County to the Fall Line, where the underlying Upper Floridan aquifer is essentially unconfined. The confining unit generally thickens from east to west in Beaufort and Jasper Counties and along the Ridgeland trough (see fig. 7 of Hughes and others, 1989), reaching a maximum thickness in SC of about 120 ft in the southern part of Beaufort County. In southeastern Georgia, the Upper Floridan confining unit is more than 300 ft thick (*Appendix B1*). The confining unit thins to 10–20 ft over the Beaufort arch in Beaufort County (Hayes, 1979; Waddell, 1989) (*fig. B1*). From Jasper County (JAS-426) to Hilton Head Island (BFT-2055), the confining unit dips about 2 ft/mi to the south-southeast (*fig. B8*; *Plate 1*).

### Age and Stratigraphic Correlation

The confining unit consists mainly of Miocene formations of the Hawthorn Group, which include the Parachucla, Marks Head, Coosawhatchie, and Ebenezer Formations (Weems and Edwards, 2001) (*fig. B4*). Sediments of the late Oligocene Tiger Leap Formation may compose lower parts of the confining unit. The confining unit is correlated with the "upper confining unit" of Ransom and others (2006), Falls and others (2005), and Miller (1986).

### Lithology and Texture

The lithology of the Upper Floridan confining unit is heterogeneous, generally consisting of phosphatic, clayey sand, sandy clay, sandy dolomitic limestone, and highly phosphatic dolomitic sandy and clayey limestone (Hayes, 1979). Duncan (1972) describes it as "olive green silt and sand interbedded with thin discontinuous lenses of marl and limestone." North and south of the Beaufort arch, the confining unit consists of an upper phosphatic clay unit, a middle sandy dolomitic limestone, and a lower silty clay unit (Waddell, 1989). At the Jasper County corehole (JAS-426), the unit is about 100 ft thick and consists of olive-gray and greenish-gray phosphatic sandy clay, clayey sand, and calcareous clayey sand. In a corehole at Tybee Island, GA, the confining unit consists of calcareous sand (Ebenezer Formation), phosphatic sand (Coosawhatchie Formation), and calcareous phosphatic sand (Marks Head Formation) (Foyle and others, 2001; Weems and Edwards, 2001). A hard phosphatic limestone is present in some places at the base of the confining unit, and is referred to as "cap rock." Colquhoun (1972) stated that the cap rock consists of "dense, hard, cherty limestone which is occasionally phosphatic." Parts of the confining unit, particularly in Jasper County, are permeable enough to be used for local domestic supplies (Hayes, 1979).

### Hydrologic Properties

Hydrographs (Dale and Park, 1999), water-level data (Siple, 1960), and isotopic data from the Beaufort County area (Burt, 1989) all indicate that the Upper Floridan confining unit is a leaky confining unit. Water from the overlying surficial aquifer seeps downward through the Upper Floridan confining unit and into the underlying Upper Floridan aquifer. Vertical hydraulic conductivities of $2.3 \times 10^{-4}$ and $2.5 \times 10^{-4}$ ft/d were measured for samples collected from the Upper Floridan confining unit at several offshore sites (Falls and others, 2005). An average vertical hydraulic conductivity of $5.4 \times 10^{-4}$ ft/d was reported for 11 samples of the Marks Head Formation that were collected from beneath the Savannah River near Tybee Island (U.S. Army Corps of Engineers, 1998; Falls and others, 2005; *fig. B1*).

### Geophysical-Log Signature

Phosphate is common in the Upper Floridan confining unit, resulting in high counts on the natural gamma-ray log. Zones of concentrated phosphate are present as natural gamma spikes, which are commonly found at formation contacts (lag beds) (see fig. 4 in Falls and others, 2005). In southern Jasper County, several natural gamma spikes are commonly present and mark formation contacts. The confining unit normally is cased off before drilling into the underlying limestone, so few electric logs are available through the unit. Where available, resistivity is generally lower in the confining unit than in the Upper Floridan aquifer. Electric logs are useful in identifying permeable zones in the Upper Floridan confining unit, which are commonly obscured on the natural gamma-ray log by phosphate.

## Upper Floridan Aquifer

The Upper Floridan aquifer (model layer 3, *Chapter C*) extends from the southern SC coast to Aiken County. The aquifer overlies the Middle Floridan confining unit in downdip areas and the Middle Floridan aquifer in updip areas. The Upper Floridan aquifer is overlain by the Upper Floridan confining unit downdip and the surficial aquifer updip (*fig. B4*; *Plates 1, 2,* and *7*). The carbonate phase of the aquifer is present from the SC coast to central Allendale County, and from the Coosawhatchie and Salkehatchie Rivers in Beaufort, Jasper, and Hampton Counties, west to the Savannah River (*fig. A1*). The aquifer thins in northwestern Colleton and southern Allendale Counties, where it transitions to the updip clastic phase. The clastic phase of the Upper Floridan aquifer persists inland to Aiken County, where it pinches out about 15 mi south of the Fall Line. Hydraulic continuity of the clastic and carbonate phases of the aquifer is thought to occur, so the two phases are considered a single aquifer (*fig. B9*).

Allendale County is an area that is transitional between the clastic and carbonate phases of the aquifer. A 20-ft sandy limestone toward the top of the late Eocene section at ALL-348 probably represents the updip limit of the carbonate phase of the Upper Floridan aquifer. The ALL-348 corehole is located above the Orangeburg Scarp, and erosion of the limestone has likely occurred south of the scarp in the southern part of the County, reemerging in northern Hampton County. In northern Allendale (ALL-357) and southern Barnwell Counties (BRN-335) the late Eocene Dry Branch Formation forms the clastic phase of the aquifer and consists predominantly of sand and interbedded sand and clay.

The carbonate phase of the Upper Floridan aquifer thickens from Colleton County toward the southwest in the direction of the Savannah River, reaching a maximum thickness of about 200 ft in southern Beaufort County (*fig. B10*, *Appendix B1*). The aquifer thins from southern Beaufort County towards Edisto Beach in southern Colleton County. At Edisto Beach, a thick (200+ ft) late Eocene sequence of marl and calcareous sand exists at corehole COL-364, but permeable limestone beds are absent. The updip clastic phase of the aquifer thickens from the Fall Line to Barnwell County, where it reaches a maximum thickness of about 130 ft (*fig. B10*, *Appendix B1*).

The Upper Floridan aquifer dips to the south-southeast about 5 ft/mi (*fig. B9*; *Plate 1*). Dips are shallow in the southern part of the SC ACP. From Jasper County (JAS-426) to Hilton Head Island (BFT-2055), the aquifer dips only about 1 ft/mi to the south-southeast. Shallow dips are the result of a post-Eocene localized structural event that warped the surface of the aquifer in these areas (Hughes and others, 1989), forming the Ridgeland trough in southern Jasper County (Heron and Johnson, 1966) and the Beaufort arch in Beaufort County (Siple, 1960). In southern Jasper County, for example, the Upper Floridan aquifer dips more steeply than it does in northern Beaufort County. In northern Beaufort County, the dip of the aquifer flattens out before reversing toward the north-northwest (landward). The aquifer then dips back to the southeast in southern Beaufort County. The structural event had the effect of “buckling” the aquifer across Beaufort County, forming a southwest- to northeast-trending arch from Port Royal Island to the southern part of Beaufort County, and forming a trough in the southern part of Jasper County (see fig. 5 of Hughes and others, 1989; see fig. 5 of Spigner and Ransom, 1979). The arch extends offshore from Hilton Head Island (Falls and others, 2005).

### Age and Stratigraphic Correlation

The carbonate phase of the Upper Floridan aquifer consists of the upper sections of the Parkers Ferry Formation (late Eocene; also known as the Ocala Limestone) (*fig. B4*; *Plates 1, 2,* and *7*). The aquifer may also include Oligocene sediments, which are thought to thin north of the Savannah River and pinch out to the north-northwest of Hilton Head Island (Foyle and others, 2001). The updip clastic phase of the Upper Floridan aquifer consists mainly of the Dry Branch Formation (late Eocene). The aquifer is correlated with the upper parts of the Upper Floridan aquifer of Miller (1986), with the upper parts of the Floridan aquifer system of Aucott and others (1987), with “Zone 1” and “Zone 2” of McCollum and Counts (1964), with the “upper hydrogeologic unit” of Spigner and Ransom (1979), and with the “upper permeable zone” of Hayes (1979).

### Lithology and Texture

The carbonate phase of the Upper Floridan aquifer consists of white to light-gray indurated and fossiliferous limestone (Hayes, 1979). Allochems consist largely of bryozoans and pelecypods. The clastic phase consists of yellow, tan, and orange moderately sorted fine to coarse quartz sand interbedded with tan clay. In Allendale County (ALL-348), the aquifer is a mix of clastic and carbonate sediments and consists of moderately sorted fine to medium calcareous sand, sandy calcarenite, and local sandy limestone.

### Hydrologic Properties

Transmissivity values of the carbonate phase of the Upper Floridan aquifer range from less than 500 $ft^2/d$ at Port Royal Island to about 70,000 $ft^2/d$ at Hilton Head Island (Hughes and others, 1989). Variations in transmissivity mainly reflect differences in aquifer thickness across the area. Transmissivity values generally increase to the southwest towards Georgia, where the aquifer is thickest. Hydraulic conductivity values range from 350 to 500 ft/d, except on northern Port Royal Island, where they range from 50 to 150 ft/d (Hughes and others, 1989). Transmissivity decreases substantially updip where the aquifer consists of quartz sand and clay. Few hydraulic data, however, are available in these areas. An aquifer test at the SRS indicated a transmissivity of 420 $ft^2/d$ and a hydraulic conductivity of 13 ft/d for the aquifer (D'Appolonia, Inc., 1981).

### Geophysical-Log Signature

The gamma ray is the most useful log for delineating the aquifer in downdip areas. Limestone composing the aquifer emits little radiation, and gamma counts are some of the lowest in SC. The lowest natural gamma counts were found in late Eocene limestone, and slightly higher counts occur in Oligocene limestone. Electric logs are strongly affected by groundwater salinity and can be useful in identifying the interface between fresh and brackish water in the aquifer.

## Middle Floridan Confining Unit

The informally named Middle Floridan confining unit (model layer 4, *Chapter C*) overlies the Middle Floridan aquifer and is overlain by the Upper Floridan aquifer (*fig. B37*; *Plates 1, 2,* and *7*). In areas where the Middle Floridan aquifer is absent, the Middle Floridan confining unit directly overlies the Gordon confining unit. In areas where the Upper Floridan aquifer is absent, the confining unit underlies the Upper Floridan confining unit or the surficial aquifer (*Plates 1, 2,* and *7*). The Middle Floridan confining unit is present only in the western and central parts of the SC ACP owing to uplift of the Cape Fear Arch (*fig. B1*) in the east. The confining unit reaches a maximum thickness of more than 300 ft in Beaufort County and dips to the south about 4 ft/mi (*figs. B11* and *B12*; *Plate 1*; *Appendix B1*). The Middle Floridan confining unit in SC is roughly equivalent in stratigraphic position to the Castle Hayne confining unit in NC; however, the units are not continuous or hydraulically connected between the two States.

### Age and Stratigraphic Correlation

The Middle Floridan confining unit consists of the Harleyville Formation (early late Eocene) and the lower parts of the Parkers Ferry Formation (late Eocene; also known as the Ocala Limestone) (*fig. B4*; *Plates 1, 2,* and *7*). In parts of Dorchester and Charleston Counties, the confining unit may also include the Ashley Formation (late Oligocene). The Middle Floridan confining unit is probably correlated with the lower to middle sections of the Upper Floridan aquifer of Miller (1986), with lower sections of the Floridan aquifer system of Aucott and others (1987), with the "semiconfining units" of Gawne and Park (1992), and with the "middle zone of low permeability" of Hayes (1979). The "middle confining unit" that separates the Upper and Lower Floridan aquifers is "... generally found in the middle part of rocks of middle Eocene age" (Miller, 1986). The Middle Floridan confining unit of this report is younger and is present in the lower part of rocks of late Eocene age.

### Lithology and Texture

Downdip, at Hilton Head Island**,** the Middle Floridan confining unit consists of fine calcarenites and calcilutites containing minor amounts of quartz sand and clay (Gawne and Park, 1992). Most of the confining unit is poorly consolidated and interbedded with thin layers of hard limestone. A sidewall core (382 ft) from the Hilton Head Island corehole (BFT-2055) consists of calcite (64 percent), quartz (14 percent), dolomite (14 percent), illite/smectite (5 percent), kaolinite (3 percent), and traces of feldspar (Core Laboratories, 1992). A laser particle-size analysis of the sample indicates that the core contains 10 percent fine sand, 18 percent very fine sand, 40 percent silt, and 32 percent clay.

Updip, at the Allendale County corehole (ALL-348), the confining unit consists of a relatively homogenous section of friable, moderately sorted, fine-grained calcareous quartz sand and, infrequently, calcareous quartz sand in a lime mud matrix. Allochems include pelecypods, bryozoans, and foraminifera. On the basis of visual estimations, the percentage of clastic and carbonate clasts is about equal. This mixed clastic/carbonate section grades upward to moldic sandy limestone (Upper Floridan aquifer).

### Hydrologic Properties

Static water-level differences among six well pairs in the Upper and Middle Floridan aquifers at Hilton Head Island did not exceed 0.7 ft (Gawne and Park, 1992). Water levels were slightly higher in the Upper Floridan aquifer at four of the six sites. During low-discharge, short-duration aquifer tests of the Middle Floridan aquifer, water levels in adjacent Upper Floridan aquifer wells did not lower substantially, confirming that "… the two aquifers are separated by a unit of low permeability" (Gawne and Park, 1992).

Water levels in an Upper Floridan aquifer observation well did not lower appreciably during a 96-hour aquifer test of the Middle Floridan well at Hilton Head Island (Groundwater Management Associates, Inc., 2006). During this test, the Middle Floridan aquifer well was pumped at a rate of 1,000 gal/min and had a drawdown of 70.3 ft after 96 hours. The Upper Floridan aquifer observation well, located 105 ft from the pumping well, had a drawdown of 0.5 ft. Nearby production wells in the Upper Floridan aquifer may have contributed to the 0.5-ft drawdown in the observation well. In addition, no appreciable water-level declines were observed in an Upper Floridan aquifer observation well during a 65-hour aquifer test of the underlying Middle Floridan aquifer at the Allendale County corehole (pumping 63 gal/min) (Karimjee and Hodges, 1996).

Horizontal hydraulic conductivity, measured from a sidewall core at Hilton Head Island (BFT-2055) is $4.1 \times 10^{-2}$ ft/d (Temples and Englehardt, 1997). Updip, at the Allendale County corehole (ALL-348), the confining unit supports a static hydraulic-head difference of about 40 ft.

### Geophysical-Log Signature

In general, natural gamma radiation levels in the Middle Floridan confining unit are slightly elevated on the natural gamma-ray log relative to the adjacent Upper and Middle Floridan aquifers, and resistivity values are slightly lower. Zones of low radiation and high resistivity, however, occur in the Middle Floridan confining unit and may indicate permeable zones (*Plate 1*). Negative potentials on the SP log also are associated with permeable zones in the confining unit.

## Middle Floridan Aquifer

The informally named Middle Floridan aquifer (model layer 5, *Chapter C*) overlies the Gordon confining unit and is overlain by the Middle Floridan confining unit where present in downdip areas (*fig. B37*; *Plates 1, 2,* and *7*). The Middle Floridan aquifer is present only in the western and central parts of the SC ACP owing to uplift of the Cape Fear Arch (*fig. B1*) in the east. The Middle Floridan aquifer reaches a maximum thickness of about 100 ft in Jasper County and dips to the south about 7 ft/mi (*figs. B13* and *B14*; *Plate 1*). The Middle Floridian aquifer in SC is roughly equivalent in stratigraphic position to the Castle Hayne aquifer in NC; however, the units are not continuous or hydraulically connected between the two States.

The Middle Floridan aquifer was informally named by Gawne and Park (1992) at Hilton Head Island, where it is now widely used for irrigation and drinking water. The aquifer is generally thin (less than 100 ft), and its lateral continuity is not well understood. In the west-central part of the Coastal Plain, the aquifer is known to be present in Allendale (ALL-348) and Bamberg (BAM-68) Counties, where it is used as a source of drinking water for small towns. Updip from these sites, however, from northern Allendale County (ALL-357) to central Barnwell County (BRN-349) and east to central Orangeburg County (ORG-393), the permeable limestone section of the Middle Floridan aquifer is at its updip limits, and the aquifer is only about 10 to 20 ft thick. In these areas, the Santee Formation is still relatively thick (100 ft), but most of the formation consists of marl (Blue Bluff marl unit) and forms the underlying Gordon confining unit (*fig. B4*). Only the upper part of the Santee Formation contains permeable limestone beds. In northern Barnwell County (BRN-358) and farther east in northern Orangeburg County (ORG-256), no limestone is present in the entire SC ACP sequence. At these coreholes, the Santee Formation consists of quartz sand and clay (called the Tinker Creek Formation in northern SRS and the McBean Formation elsewhere). The Middle Floridan aquifer continues updip in a clastic phase and pinches out about 20 mi south of the Fall Line.

South of the SRS, geophysical logs show some permeability in the Santee section at the Jasper County corehole (JAS-426); however, the Gulf Trough, a low-permeability feature of Tertiary age in the outer Georgia Coastal Plain, may extend into SC in this area and may reduce permeability of the Middle Floridan aquifer (Patterson and Herrick, 1971) (*fig. B1*). Well yields and hydraulic properties of the Middle Floridan aquifer are unknown in Jasper County. Farther south, in Beaufort County, local variations in permeability may limit the use of the aquifer in certain areas. At Hilton Head Island (BFT-2055), however, the aquifer is highly permeable (see discussion below). Northeast of Hilton Head, at Edisto Beach (COL-364), permeability is low, and the town uses a deeper local aquifer zone in the Eocene strata.

### Age and Stratigraphic Correlation

The Middle Floridan aquifer consists of the upper part of the Santee Formation (late middle Eocene) (*fig. B4*; *Plates 1, 2,* and *7*). The aquifer is correlated with the “middle Floridan aquifer” of Gawne and Park (1992) and, to some extent, with the lower part of the Upper Floridan aquifer of Miller (1986), with sections of the Floridan aquifer system of Aucott and others (1987), with “Zone 4” and (or) “Zone 3” of McCollum and Counts (1964), and possibly with the “lower permeable zone” of Spigner and Ransom (1979).

### Lithology and Texture

Downdip, at Hilton Head Island**,** the Middle Floridan aquifer consists of hard moldic limestone that is interbedded with poorly consolidated shelly limestone in a lime mud matrix (Gawne and Park, 1992). Allochems are mainly shell fragments of gastropods, bivalves, and bryozoans. Updip, at the Allendale County corehole (ALL-348), the aquifer consists of hard moldic limestone and shelly limestone in a lime mud matrix. The Middle Floridan aquifer contains minor amounts (less than 10 percent) of fine-grained quartz sand and terrigenous mud. Glauconite composes up to 3 percent of the unit. Pelecypod and bryozoan shell fragments are common. Wells completed in the Middle Floridan aquifer in Allendale County are commonly gravel-packed and screened to filter out the sand.

At the Bamberg County corehole (BAM-68), the Middle Floridan aquifer consists of a hard moldic limestone that grades downward to moderately hard permeable and shelly calcarenite in a lime mud matrix. Allochems consist mainly of pelecypod shell fragments with minor bryozoans. Minor quartz sand (less than 10 percent) is present. Calcarenite beds grade downward to shelly calcilutite and sandy marl to form the underlying Gordon confining unit.

### Hydrologic Properties

Transmissivity values from six Middle Floridan aquifer tests at Hilton Head Island range from 2,300 to 26,700 $ft^2$/d and average 10,500 $ft^2$/d (Gawne and Park, 1992). The wide range of values is attributed mainly to differences in aquifer thickness and to local variations in hydraulic conductivity. Horizontal hydraulic conductivity values, calculated from four of the tests, range from 220 to 290 ft/d and average 260 ft/d.

Transmissivity and hydraulic conductivity generally decrease updip in Allendale County. Four aquifer tests in the county have values that range from 3,300 to 6,300 $ft^2$/d and average 4,400 $ft^2$/d (Newcome, 2005). Horizontal hydraulic conductivity values range from 55 to 105 ft/d and average about 75 ft/d (Gellici and others, 1995).

### Geophysical-Log Signature

Resistivity of the Middle Floridan aquifer is moderately high [100 Ohm-meters (ohm-m)] in updip areas and decreases slightly in SC coastal counties (*Plate 1*). The aquifer is often difficult to identify on geophysical logs in downdip areas where it is marked by slight increases in resistivity together with decreases in natural gamma counts and negative potentials. Subtle decreases in gamma counts often indicate “clean” limestone intervals and corresponding increases in permeability.

## Gordon Confining Unit

The Gordon confining unit (model layer 6, *Chapter C*) overlies the Gordon aquifer and is overlain by the Middle Floridan aquifer (*fig. B37*; *Plates 1, 2,* and *7*). The confining unit is present only in the western and central parts of the SC ACP. In the eastern SC ACP, formations that compose the Gordon confining unit are absent due to uplift of the Cape Fear Arch (*Plate 7*). The confining unit reaches a maximum thickness greater than 300 ft in Beaufort County and dips to the south about 8 ft/mi (*figs. B15* and *B16*; *Plates 1* and *2*; *Appendix B1*). The Gordon confining unit in SC is roughly equivalent in stratigraphic position to the Beaufort confining unit in NC; however, the units are not continuous or hydraulically connected between the two States.

### Age and Stratigraphic Correlation

The Gordon confining unit consists of the Warley Hill Formation (middle middle Eocene) and the lower part of the Santee Formation (late middle Eocene) (*fig. B4*; *Plates 1, 2,* and *7*). The Gordon confining unit correlates with the Gordon confining unit of Aadland and others (1995) and is part of the Pearl River aquifer of Miller and Renken (1988). The confining unit also correlates with the Tertiary sand aquifer of Aucott and others (1987), and possibly with the “middle confining unit” of Miller (1986) (*fig. B39*).

### Lithology and Texture

In the central part of the SRS, the Gordon confining unit consists of fine-grained glauconitic clayey sand and clay of the Warley Hill Formation. The confining unit is generally thin (less than 20 ft) but supports static head difference of more than 40 ft at the SRS. In the southern part of the SRS, the confining unit consists of the Warley Hill interval and the overlying Blue Bluff marl unit of the Santee Limestone (*Plate 1*). The Blue Bluff unit consists of laminated clayey calcilutite, calcarenite, and calcareous silt and clay with indurated limestone nodules and lenses. Glauconite content can be as great as 30 percent. Thin-section analyses indicate that the dominant allochems are foraminifers, echinoderms, pelecypods, bryozoans, and broken skeletal debris (Aadland and others, 1995). The Blue Bluff lithology is known to extend as far east as the Orangeburg corehole (ORG-393) (Gellici, 2007a). At the ORG-393 corehole, the confining unit is a gray and olive-colored marl, which consists of very fine and fine quartz sand (40 percent), clay (30 percent), and shell fragments in a calcareous matrix (*Appendix B2*). Megafossils include bivalves, gastropods, and bryozoans.

### Hydrologic Properties

Permeameter tests of three calcareous clay samples from the “C-well” series of coreholes in Barnwell and Allendale Counties indicate that vertical hydraulic conductivity values of the Gordon confining unit range from $1.2 \times 10^{-4}$ to $2.0 \times 10^{-4}$ ft/d, and average $1.5 \times 10^{-4}$ ft/d (Aadland and others, 1995). The confining unit supports a head difference of about 40 ft at the Allendale corehole (ALL-348) and 50 ft at the Orangeburg corehole (ORG-393). The Gordon confining unit thickens downdip to about 300 ft at the Jasper County corehole (JAS-426) where it may contain permeable limestone as indicated by geophysical logs (*Plate 1*).

### Geophysical-Log Signature

Resistivity is generally low in the Gordon confining unit owing to the fine-grained character of the unit. Long-normal resistivity averages only 13 ohm-m at the Orangeburg corehole (ORG-393) (*Plate 7*). In downdip areas, slight increases in resistance on the single-point log, along with negative deflections on the spontaneous-potential log and low gamma counts, suggest permeability in the confining unit (see corehole BFT-2055, *Plate 1*). Gamma spikes from high concentrations of glauconite and phosphate commonly are present at the base of the Gordon confining unit and can be used as a marker for the Santee/Warley Hill contact.

## Gordon Aquifer

The Gordon aquifer (model layer 7, *Chapter C*) is the lowermost aquifer of the Floridan aquifer system. The Gordon aquifer overlies the Crouch Branch confining unit and is overlain by the Gordon confining unit (*fig. B37*; *Plates 1, 2,* and *7*). The aquifer is present in the western and central parts of the SC ACP. In the eastern SC ACP, formations that compose the Gordon aquifer are absent due to uplift of the Cape Fear Arch. The aquifer reaches a maximum thickness of more than 300 ft in Beaufort County and dips to the south about 14 ft/mi (*figs. B17* and *B18*; *Plate 1*; *Appendix B1*). The Gordon confining unit in SC is roughly equivalent in stratigraphic position to the Beaufort confining unit in NC; however, the units are not continuous or hydraulically connected between the two States.

### Age and Stratigraphic Correlation

The Gordon aquifer consists of several formations that are hydraulically connected. Updip, the aquifer consists mainly of the Congaree (early Eocene and early middle Eocene) and Williamsburg Formations (late Paleocene) (*fig. B4*; *Plates 1, 2,* and *7*). In some updip wells, the Gordon aquifer can also include beds of the Fishburne Formation (early Eocene; called the Fourmile Formation in updip areas), beds of the Warley Hill Formation (middle middle Eocene), and beds of the lower part of the Santee Formation (late middle Eocene). South of Allendale County, the Congaree Formation is eroded, and the Gordon aquifer consists of the Williamsburg Formation and (where present) the Fishburne Formation (*fig. B4*). In the northern part of the SRS and updip from the SRS, confining beds of the overlying Gordon confining unit thin, and the Gordon and Upper Three Runs aquifers coalesce to form the Steed Pond aquifer (*fig. B38*) (Aadland and others, 1995). In this report, the Steed Pond aquifer is not modeled. Instead, the Gordon aquifer is extended to updip areas by correlation with the Congaree Formation.

The Gordon aquifer is correlated with the Gordon aquifer of Aadland and others (1995), with the lower part of the Pearl River aquifer of Miller and Renken (1988), with the lower part of the Tertiary sand aquifer system of Colquhoun and others (1983), and with the lower part of the Tertiary sand aquifer of Aucott and others (1987) (*fig. B39*).

### Lithology and Texture

In updip regions, in and around the SRS, the Gordon aquifer is characterized by unconsolidated, poorly to moderately sorted fine- to coarse-grained sand and clayey sand with local gravel (*Plates 1, 2,* and *7*). The sand fraction consists of quartz with sparse lignite, muscovite, glauconite, feldspar, and monazite. Particle-size analyses of 661 samples of the aquifer from the SRS and surrounding areas indicate 2 percent gravel, 95 percent sand, and 3 percent mud (Aadland and others, 1995). Nearly 70 percent of the samples contain less than 2 percent mud. Grain size averages 1.6 $\Phi$ (lower medium sand). Phi ($\Phi$) is defined as the logarithmic transformation of the ratio of a grain diameter in millimeters to a standard grain diameter of 1 millimeter (Friedman and Sanders, 1978). Most of the samples were either moderately sorted (about 37 percent) or poorly sorted (about 30 percent). Downdip, in southern Barnwell and Allendale Counties, quartz sand grades into glauconitic, quartz-rich, fossiliferous grainstone, packstone, and wackestone (Aadland and others, 1995). Dominant allochems include foraminifers, pelecypods, and minor other mollusks, echinoderms, and bryozoans. Glauconite can be as high as 60 percent. Farther downdip, at the DOR-208 corehole in Dorchester County, the Congaree Formation is eroded, and the Gordon aquifer consists mainly of the Williamsburg Formation (Chicora Member), which consists of moldic quartz-bearing pelecypod limestone, calcareous laminated silty clay, and well-sorted silt and fine sand (Edwards and others, 1997). At the Orangeburg corehole ORG-393, the aquifer consists of gray and greenish-gray moderately sorted, fine- to coarse-grained clayey sand and interbedded sand and carbonaceous clay (*Appendix B2*).

### Hydrologic Properties

Generally, the Gordon aquifer is not as productive as the Crouch Branch or McQueen Branch aquifers. Transmissivity values calculated from 15 aquifer tests in the central part of the SRS average about 2,000 $ft^2$/d (Gellici and others, 1995). In central Barnwell County, the Gordon aquifer transmissivity averages about 4,900 $ft^2$/d owing to increases in aquifer thickness. Hydraulic conductivity values range from 24 to 41 ft/d and average 35 ft/d. Storage coefficients average $3.3 \times 10^{-4}$. South of the SRS, at the Allendale corehole (ALL-348), sieve analyses indicate that hydraulic conductivity decreases owing to a downdip increase in the percentage of mud, a decrease in grain size, and poorer sorting (Robertson and Thayer, 1990). Two aquifer tests of the Gordon aquifer in southern Charleston County produced transmissivity values of 750 and 900 $ft^2$/d.

### Geophysical-Log Signature

Resistivity decreases downdip due to increases in groundwater specific conductance and clay content of the Gordon aquifer. In northern Barnwell County, long-normal resistivity ranges from 200 to 300 ohm-m; in southern Barnwell County, from 100 to 150 ohm-m; and in Allendale County, from 40 to 80 ohm-m. Resistivity of the Gordon aquifer is consistently lower than that of the Cretaceous aquifers, possibly reflecting water chemistry differences (see corehole ORG-393 on *Plate 7*). Gamma radiation in the updip sections of the Congaree Formation is distinctly low and can be used, to some degree, to identify the Congaree interval (see corehole ORG-393 on *Plate 7*). Radiation increases downdip and is especially high in glauconite-rich beds of the aquifer. In downdip areas, negative deflections on the SP log, in conjunction with small increases in resistance on the single-point log, indicate permeability in the aquifer. This type of geophysical log response is particularly evident at the Hilton Head Island corehole (BFT-2055), in the interval from 1,230 to 1,480 ft (*Plate 1*). Strong negative SP signals and increases in resistance suggest permeability in this interval. No wells, however, have been completed in the Gordon aquifer in the Hilton Head area, and yields are unknown.

## Meyers Branch Confining System/ Crouch Branch Confining Unit

The Meyers Branch confining system was defined by Aadland and others (1995) at type well P-24 at the SRS in Barnwell County, where it was named for Meyers Branch. The confining system hydraulically separates the Dublin and Floridan aquifer systems and is present in the western and southern parts of the SC ACP. The Meyers Branch confining system is correlated with the Chattahoochee River confining unit of Miller and Renken (1988) (*fig. B39*). At P-24, the system is 134 ft thick and consists of clay and silty clay of the Peedee/Steel Creek Formation (Maastrichtian) and interbedded clay and clayey sand of the Sawdust Landing (Maastrichtian), Lang Syne (early Paleocene), and Snapp Formations (late Paleocene). The Meyers Branch confining system consists of a single confining unit—the Crouch Branch.

The Crouch Branch confining unit (model layer 8, *Chapter C*) overlies the Crouch Branch aquifer and underlies the Gordon aquifer in the western and southern parts of the SC ACP (*fig. B37*; *Plates 1, 2,* and *7*). The Crouch Branch confining unit is generally absent in the eastern part of the SC ACP owing to uplift of the Cape Fear Arch (*fig. B1*). Updip, in Aiken and Lexington Counties, clay beds composing the confining unit thin and are locally absent. In these areas, the Crouch Branch aquifer coalesces with the overlying Gordon aquifer. The Crouch Branch confining unit reaches a maximum thickness of more than 300 ft in Colleton and Charleston Counties, dipping to the south-southeast about 16 ft/mi in the western part of the Coastal Plain, and 8 ft/mi in the eastern part (*figs. B19* and *B20*; *Plates 1, 2,* and *7*; *Appendix B1*). The Crouch Branch confining unit in SC is roughly equivalent in stratigraphic position to the Peedee confining unit in NC. The units are continuous and hydraulically connected between the two States.

### Age and Stratigraphic Correlation

The Crouch Branch confining unit consists primarily of the Rhems (early Paleocene) and Lang Syne (early late Paleocene) Formations (*fig. B4*; *Plates 1, 2,* and *7*). In some areas, the Sawdust Landing Formation (latest Maastrichtian), the upper Peedee/Steel Creek units (late Maastrichtian), and the lower parts of the Williamsburg Formation (late Paleocene) are included in the confining unit. The Crouch Branch confining unit is correlated with the Crouch Branch confining unit mapped in west-central SC by Aadland and others (1995). The confining unit is also correlated with "confining beds" that separate the Black Creek and Tertiary Limestone/Tertiary Sand aquifer systems of Colquhoun and others (1983) and with the unnamed confining unit that separates the Black Creek and Tertiary sand aquifers of Aucott and others (1987) (*fig. B39*).

### Lithology and Texture

At the Orangeburg corehole (ORG-393), the Crouch Branch confining unit consists of carbonaceous silty-clay that is thinly laminated with well-sorted very fine to fine quartz sand and silt (Rhems Formation; *Appendix B2*). Sand laminations are several tenths of an inch thick. Very fine grained mica and lignite are common in the sand laminations. Downdip, at the Berkeley corehole (BRK-644), the Crouch Branch confining unit (Rhems Formation) consists of 50 to 70 percent very fine to fine-grained well-sorted quartz sand in a calcareous clay matrix with minor mica and traces of glauconite and lignite. Indurated layers (less than 1 ft thick) of shelly limestone are present at various places throughout the unit. At the Sumter corehole (SUM-296) the unit correlates with the Lang Syne Formation, which consists mainly of semiconsolidated opaline claystone (Vroblesky, 1994). Secondary opaline silicification characterizes much of the Crouch Branch confining unit and is commonly concentrated to the degree that the formation breaks with a conchoidal fracture.

### Hydrologic Properties

Permeameter tests of 18 clay and sandy clay samples from the Crouch Branch confining unit at the SRS indicate vertical hydraulic conductivity values ranging from $3.4 \times 10^{-6}$ to $1.7 \times 10^{-2}$ ft/d and averaging $1.3 \times 10^{-4}$ ft/d (Aadland and others, 1995). Horizontal hydraulic conductivity values from 13 clay and sandy clay samples range from $3.7 \times 10^{-5}$ to $3.2 \times 10^{-1}$ ft/d and average $4.9 \times 10^{-4}$ ft/d (Aadland and others, 1995). The confining unit supports a head difference of about 13 ft at the Allendale corehole (ALL-348) and 24 ft at the Orangeburg corehole (ORG-393).

### Geophysical-Log Signature

Resistivity is low and gamma radiation relatively high owing to the high clay content of the Crouch Branch confining unit. Long-normal resistivity averages 18 ohm-m at the Orangeburg corehole (ORG-393). Anomalously high resistivity of opaline claystones that form the confining unit may be due to unsaturated conditions at the site or to induration from silica cement.

## Dublin Aquifer System/Crouch Branch Aquifer

The Dublin aquifer system overlies the Allendale confining system and underlies the Meyers Branch confining system. The Dublin aquifer system is present across most of the Coastal Plain, although it coalesces with the Midville and Floridan systems updip and in the eastern part of the SC ACP (Aadland and others, 1995). The Dublin aquifer system is correlated with the upper part of the Chattahoochee River aquifer of Miller and Renken (1988) (*fig. B39*). Clarke and others (1985) defined the system at type well 21U4, near the town of Dublin, GA. In SC, sediments at reference well P-22 at the SRS in Barnwell County are characteristic of the aquifer system (Aadland and others, 1995). At this well, the Dublin aquifer system is 213 ft thick and consists of unconsolidated well-sorted sand and lignitic, micaceous, clayey sand of the Black Creek Group (Campanian), and moderately sorted medium to coarse sand and interbedded sand and clay of the Peedee/Steel Creek Formation (Maastrichtian). The system consists of a single aquifer—the Crouch Branch aquifer. Several confining beds in the eastern part of the SC ACP may warrant splitting the Dublin aquifer system into several aquifers.

The Crouch Branch aquifer (model layer 9, *Chapter C*) overlies the McQueen Branch confining unit and is overlain by the Crouch Branch confining unit (*fig. B37*; *Plates 1, 2,* and *7*). The Crouch Branch aquifer is present over most of the SC ACP but is absent or thins considerably in the northeastern part of SC in Chesterfield, Darlington, Dillon, and Marlboro Counties (*figs. B21* and *B22*). In the southern part of the Coastal Plain, the aquifer is fine grained. Production wells in Beaufort and Charleston Counties usually bypass the Crouch Branch aquifer and are completed in the deeper Charleston and Gramling aquifers. Sandy clay and calcareous clay beds divide the Crouch Branch aquifer in the eastern half of the Coastal Plain. The aquifer reaches a maximum thickness of more than 500 ft in Berkeley and Williamsburg Counties (*fig. B22*) and in southern SC, but much of the aquifer in these counties consists of low-permeability, fine-grained sediments. The Crouch Branch aquifer dips to the south-southeast about 18 ft/mi in the western part of the SC ACP and 2 ft/mi in the eastern part (*fig. B21*; *Plates 1, 2,* and *7*; *Appendix B1*). The shallow dip in the east is the result of erosion or nondeposition of the upper parts of the aquifer owing to uplift along the Cape Fear Arch. The Crouch Branch aquifer in SC is equivalent in stratigraphic position to the Peedee aquifer in NC (*fig. B4*). The units are continuous and hydraulically connected between the two States.

## Age and Stratigraphic Correlation

In the western part of the SC ACP, the aquifer consists of the upper part of the upper Donoho Creek unit (late Campanian), the Peedee/Steel Creek Formation (Maastrichtian) and, in some places, the Sawdust Landing Formation (late Maastrichtian) (*fig. B4*; *Plates 1, 2,* and *7*). In some areas, the Sawdust Landing Formation and the upper Peedee/Steel Creek unit consist of dense sandy clay and clayey sand, and are included in the overlying Crouch Branch confining unit. In the eastern and southern parts of the Coastal Plain, the Sawdust Landing Formation and the upper Donoho Creek unit (calcareous nannofossil zone CC 23) are absent. Also in the east, parts of the Bladen Formation are permeable and are included in the Crouch Branch aquifer (see report section "Allendale Confining System/McQueen Branch Confining Unit") (*fig. B4*).

Confining zones consisting of laminated sand and clay and beds of sandy marl are present in the eastern part of the inner and outer SC ACP (*Plates 2* and *7*) where they locally divide the Crouch Branch aquifer into three aquifer zones. The lower aquifer zone consists mainly of the Bladen Formation; the middle zone consists of the Donoho Creek Formation; and the upper zone consists of the Peedee Formation.

The Crouch Branch aquifer is correlated with the Crouch Branch aquifer mapped in west-central SC by Aadland and others (1995). The aquifer also is correlated with the Black Creek aquifer system of Colquhoun and others (1983) and with the Black Creek aquifer of Aucott and others (1987) (*fig. B39*).

## Lithology and Texture

In the west-central part of the Coastal Plain, from the SRS to Orangeburg, the Crouch Branch aquifer is characterized by unconsolidated, poorly sorted, fine- to coarse-grained sand and clayey sand in a kaolinite matrix and by interbedded fine sand and carbonaceous clay (*Plates 1, 2,* and *7*). Sediments are finer grained and more glauconitic and calcareous in the southern and eastern parts of the SC ACP than elsewhere. In Berkeley County (BRK-644), the aquifer consists of glauconitic and calcareous fine-grained clayey sand and limey clay (Peedee Formation), laminated clay and fine- to medium-grained sand with scattered shells (Donoho Creek Formation), and glauconitic and calcareous fine- to medium-grained clayey sand (Bladen Formation).

At the Orangeburg corehole (ORG-393), the lower part of the Crouch Branch aquifer (upper Donoho Creek unit) consists predominantly of quartz sand laminated with carbonaceous clay (*Appendix B2*). Mean grain size of five particle-size analyses ranges from 3.7 to 1.3 Φ (very fine to medium sand) and averages 2.8 Φ (fine sand). Most of the samples are very fine or fine grained, and most are poorly sorted. Sand averages 83 percent and mud 17 percent. The middle part of the Crouch Branch aquifer (Peedee/Steel Creek Formation) consists of unconsolidated, slightly clayey, fine- to very coarse-grained quartz sand (*Appendix B2*). Mean grain size of 12 particle-size analyses ranges from 2.9 to 0.2 Φ (fine to coarse grained) and averages 1.4 Φ (medium grained). Most of the samples are poorly sorted. Gravel averages 2 percent, sand 88 percent, and mud 10 percent. The upper part of the Crouch Branch aquifer (Sawdust Landing Formation) consists of fine- to very coarse-grained quartz sand in a kaolinite clay matrix (*Appendix B2*). The matrix constitutes up to 35 percent of the aquifer and is dense in places. Mean grain size of three particle-size analyses ranges from 2.2 to 0.4 Φ (fine to coarse grained) and averages 1.4 Φ (medium grained). All of the samples are poorly sorted. Gravel averages 4 percent, sand 78 percent, and mud 18 percent.

Particle-size analyses of 305 samples from the Crouch Branch aquifer in the SRS area indicate 3 percent gravel, 86 percent sand, and 11 percent mud (Aadland and others, 1995). Grain size of the samples averages 1.4 Φ (medium grained), and most (about 70 percent) are poorly sorted.

## Hydrologic Properties

The Crouch Branch is a highly productive aquifer, especially in the west-central and updip parts of the Coastal Plain, where it is thick and consists of unconsolidated medium- to coarse-grained sand. The Crouch Branch aquifer is, however, generally less permeable and transmissive than the underlying McQueen Branch aquifer.

Transmissivity calculated from a 7-day aquifer test at Cope (*fig. B1*) in western Orangeburg County is 11,000 $ft^2/d$ (Newcome, 2005). This transmissivity is essentially the same as that calculated for the aquifer in west-central SC in and around the SRS (Aadland and others, 1995). A storage coefficient of $2.6 \times 10^{-4}$ is calculated from the test, and the hydraulic conductivity is estimated at 85 ft/d. Downdip, at Holly Hill (*fig. B1*) in the southeast corner of Orangeburg County, transmissivity is only 2,100 $ft^2/d$ (Newcome, 2005), and hydraulic conductivity is 21 ft/d. The lower values reflect changing depositional environments from coarse-grained lithofacies in the northern part of the County to fine-grained lithofacies in the southeastern part of the County. Farther to the east, 21 aquifer tests of the Crouch Branch aquifer produce transmissivity values that range from about 1,000 to 6,200 $ft^2/d$ and average 2,400 $ft^2/d$ (median of 1,700 $ft^2/d$). These tests were in Dillon, Florence, Marion, and Marlboro Counties (Rodriguez and others, 1994).

## Geophysical-Log Signature

Resistivity signatures of the Crouch Branch aquifer on the long-normal log are similar to those of the McQueen Branch aquifer [see coreholes AIK-817 (*Plate 1*), ALL-348 (*Plate 1*), and ORG-393 (*Plate 7*)]. They are highest in the west and in updip areas where the aquifer consists of coarse-grained sediments and where groundwater is freshest. Downdip, mineralization of the Crouch Branch aquifer groundwater increases and resistivity decreases. To the east, Crouch Branch aquifer sediments are finer grained, clay content increases, and resistivity correspondingly decreases. The Sawdust Landing Formation typically has a lower resistivity than other formations that compose the Crouch Branch aquifer, primarily because of its high clay content. Some intervals of the Sawdust Landing consist of very poorly sorted quartz grains completely embedded in a dense kaolinite matrix.

In the western SC ACP, low radiation levels are a characteristic feature of the upper Donoho Creek unit of the Crouch Branch aquifer. Peedee/Steel Creek lithologies generally have higher radiation levels and typically contain gamma spikes. Gamma spikes are not always associated with lag beds in the Peedee/Steel Creek interval; some may be associated with concentrations of monazite or with coarse-grained sediments that are more likely to contain greater amounts of gamma-emitting feldspar.

# Allendale Confining System/ McQueen Branch Confining Unit

The Allendale confining system hydraulically separates the Midville and Dublin aquifer systems (*fig. B38*). The confining system is present across most of the Coastal Plain, but thins greatly in updip and eastern parts of the SC ACP (Aadland and others, 1995) where the Midville and Dublin systems coalesce. Miller and Renken (1988) treated the Midville and Dublin as a single system (their Chattahoochee River aquifer), and so the Allendale confining system has no correlative unit in their framework (*fig. B39*). Aadland and others (1995) defined the system at type well ALL-348 near the town of Appleton in Allendale County, SC, where it is 162 ft thick and consists mainly of clay, silty clay, and calcareous silt and clay of the Black Creek Group (Campanian). The Allendale confining system contains a single confining unit—the McQueen Branch confining unit.

The McQueen Branch confining unit (model layer 10, *Chapter C*) overlies the McQueen Branch aquifer and underlies the Crouch Branch aquifer over most of the SC ACP (*fig. B37*; *Plates 1, 2,* and *7*). In counties along the Fall Line, clay beds composing the confining unit thin and are locally absent. In these areas, the McQueen Branch and Crouch Branch aquifers coalesce. The confining unit reaches a maximum thickness of about 240 ft in southern Beaufort County, dipping to the south-southeast about 18 ft/mi in the western part of the Coastal Plain, and 8 ft/mi in the eastern part (*figs. B23* and *B24*; *Plates 1, 2,* and *7*; *Appendix B1*). The McQueen Branch confining unit in SC is equivalent in stratigraphic position to the Black Creek confining unit in NC. The units are continuous and hydraulically connected between the two States.

## Age and Stratigraphic Correlation

In the western and central parts of the SC ACP, the McQueen Branch confining unit consists of all or parts of three formations that, in ascending order, are the upper part of the Coachman (middle Campanian), the Bladen (late middle Campanian), and the Donoho Creek (late Campanian) (*fig. B4*; *Plates 1, 2,* and *7*). Typically, the lower and middle units of the Donoho Creek Formation (subzones CC 22a/b and CC 22c) and the lower half of the upper Donoho Creek unit (calcareous nannofossil zone CC 23) form part of the confining unit. A fine- to medium-grained sand facies in the upper half of the upper Donoho Creek unit forms part of the overlying Crouch Branch aquifer in the west-central area of the State.

The McQueen Branch confining unit is correlated with the McQueen Branch confining unit mapped in west-central SC by Aadland and others (1995). The confining unit also is correlated with the “confining beds” between the Middendorf and Black Creek aquifer systems of Colquhoun and others (1983) and with the unnamed confining unit between the Middendorf and Black Creek aquifers of Aucott and others (1987) in updip regions (*fig. B39*).

## Lithology and Texture

At the Orangeburg corehole (ORG-393), the confining unit consists of laminated sand and silty clay in a carbonaceous clay matrix (Coachman Formation); shelly calcareous clay (Bladen Formation); sandy marl, calcareous clay, and carbonaceous clay (lower and middle Donoho Creek units); and silty clay with fine-grained sand (lower part of upper Donoho Creek unit) (*Appendix B2*). Results of a detailed petrographic study of a sample from the middle Donoho Creek unit (1,028 ft) in the Allendale corehole (ALL-348) indicate that the sample contains fine quartz and clay minerals with minor to trace amounts of muscovite, collophane, heavy minerals, organic debris, pyrite, and skeletal fragments, including foraminifers, pelecypods, and bryozoans (Aadland and others, 1995).

In the eastern part of the SC ACP the thickness and permeability of the Bladen Formation increase. At the SRS, for example, the formation is 40 to 50 ft thick and consists of low-permeability, fine-grained calcareous silt and clay. In Florence County, the formation thickens to more than 100 ft and consists of permeable glauconitic sand and interbedded sand and clay. The permeable sand beds of the formation are considered part of the overlying Crouch Branch aquifer. As a result, the thickness of the confining unit decreases and that of the Crouch Branch aquifer increases (*fig. B22* and *Plate 7*). The thick McQueen Branch confining unit that effectively separates the McQueen Branch and Crouch Branch aquifers from the SRS to Orangeburg is essentially split by permeable sand beds of the Bladen Formation. These sand beds may well constitute a separate aquifer; however, no hydraulic-head data are available, and the sand is included in the overlying Crouch Branch aquifer. Clay beds of the upper Coachman and lower Bladen Formations form the McQueen Branch confining unit in the east.

At Florence (*fig. B1*), the McQueen Branch confining unit is anomalously thick (130 ft) (*Plate 7*) and effectively separates the Crouch Branch and McQueen Branch aquifers. The confining unit thins in all directions away from Florence. In areas from northern Charleston County to Horry County and inland to Berkeley County, the confining unit can be difficult to delineate and map owing to the absence of substantial clay beds in the Coachman and Bladen Formations. The section in the Berkeley County corehole (BRK-644, *Plate 2*) consists of fine-grained glauconitic sand and interbedded calcareous sand and clay.

## Hydrologic Properties

Permeameter tests of nine clay and sandy clay samples from the McQueen Branch confining unit at the SRS (*fig. B1*) indicate vertical hydraulic conductivity values that range from $6.8 \times 10^{-5}$ to $2.1 \times 10^{-2}$ ft/d and average $3.8 \times 10^{-4}$ ft/d (Bledsoe and others, 1990). Horizontal hydraulic conductivity values from five clay and sandy clay samples range from $4.7 \times 10^{-5}$ ft/d to $4.1 \times 10^{-3}$ ft/d and average $3.5 \times 10^{-4}$ ft/d. During a 7-day aquifer test (pumped at a rate of 2,200 gal/min) of the McQueen Branch aquifer at Cope, in Orangeburg County, water-level declines in the overlying Crouch Branch aquifer were negligible, indicating good separation in the area. The confining unit supports a static head difference of about 40 ft in Allendale County (ALL-348). Potentiometric maps of the McQueen Branch and Crouch Branch aquifers in Florence County (1992) show a head difference of 180 ft at the center of a cone of depression in the McQueen Branch aquifer (Rodriguez and others, 1994).

## Geophysical-Log Signature

Low resistivity values on the long-normal electric log and high radiation values on the gamma-ray log typically are recorded throughout the McQueen Branch confining unit owing to its high clay content (*Plate 1*). At the Orangeburg corehole (ORG-393), the resistivity averages only 5 ohm-m through the confining unit. Gamma-ray spikes commonly mark lag beds in the confining unit. At Orangeburg (*fig. B1*), a spike at 557 ft marks a lag bed at the base of the upper Donoho Creek unit (*Plate 7*) that consists of coarse-grained calcareous sand with phosphate, clay clasts, bivalve fragments, shark teeth, and rare pieces of bone. Hard, calcite-cemented beds in the Bladen Formation are commonly marked by spikes on the single-point resistance log.

# Midville Aquifer System

The Midville aquifer system overlies the Appleton confining system and underlies the Allendale confining system (*fig. B38*). The aquifer system is present over most of the Coastal Plain, although it coalesces with the Dublin and Floridan systems in updip regions (Aadland and others, 1995). The system is correlated with the lower part of the Chattahoochee River aquifer of Miller and Renken (1988) (*fig. B39*). Clarke and others (1985) defined the system at type well 28X1, near the town of Midville, GA (*fig. B1*). In SC, sediments at reference-well P-24 at the SRS in Barnwell County are characteristic of the aquifer system (Aadland and others, 1995). At this well, the Midville is 271 ft thick and consists of unconsolidated medium to very coarse sand of the Middendorf Formation (Late Cretaceous) and fine-grained clayey sand of the lower part of the Black Creek Group (Campanian). At the SRS, the system consists of a single aquifer—the McQueen Branch aquifer (*fig. B38*) (Aadland and others, 1995). In the downdip region of the Coastal Plain, this study has defined a system consisting of the McQueen Branch aquifer and the informally named “Charleston aquifer” and “Charleston confining unit” (*fig. B4*). The Charleston and McQueen Branch aquifers are hydraulically connected in the middle part of the Coastal Plain, but in the lower part, the Charleston underlies the McQueen Branch and is separated from it by thick clay beds that form the Charleston confining unit (*Plates 1, 2,* and *7*). The Charleston aquifer and confining unit are named after Charleston County where the aquifer is a major source of drinking water.

## McQueen Branch Aquifer

The McQueen Branch aquifer (model layer 11, *Chapter C*) overlies the Gramling confining unit in the inner Coastal Plain and the Charleston confining unit in the outer Coastal Plain, and is overlain throughout much of the SC ACP by the McQueen Branch confining unit (*fig. B38*; *Plates 1, 2,* and *7*). The aquifer is present over most of the Coastal Plain, but is fine grained in Beaufort, Colleton, and Jasper Counties and may not yield sufficient water in those counties to be considered a productive aquifer. The McQueen Branch aquifer reaches a maximum thickness of about 350 ft in Barnwell County (*fig. B26*). The aquifer dips to the south-southeast about 25 ft/mi in the western part of the SC ACP and 8 ft/mi in the eastern part (*fig. B25*; *Plates 1* and *2*; *Appendix B1*). The McQueen Branch aquifer in SC is equivalent in stratigraphic position to the Black Creek aquifer in NC (*fig. B4*). The units are continuous and hydraulically connected between the two States.

### Age and Stratigraphic Correlation

In updip regions of the SC ACP, the McQueen Branch aquifer consists of all or parts of three formations that, in ascending order, are the upper part of the Cape Fear (late Turonian to Coniacian), the Cane Acre (middle Campanian), and the lower part of the Coachman (middle Campanian) (*fig. B4*; *Plates 1, 2,* and *7*). In updip areas, the aquifer primarily consists of the Cane Acre Formation. In the eastern part of the Coastal Plain, the aquifer can also include strata of the upper part of the Shepherd Grove Formation (late Santonian to early Campanian) and the Caddin Formation (early Campanian) (*Plate 2*).

The McQueen Branch aquifer is correlated with the McQueen Branch aquifer mapped in west-central SC by Aadland and others (1995) (*fig. B38*), with the Middendorf aquifer of Aucott and others (1987) in updip regions, and with the Middendorf aquifer system of Colquhoun and others (1983) (*fig. B39*).

### Lithology and Texture

The McQueen Branch aquifer is characterized by unconsolidated, poorly sorted, fine- to coarse-grained sand and clayey sand with local gravel (*Plates 1, 2,* and *7*). The sand fraction consists of quartz with sparse carbonaceous material, mica, feldspar, and monazite. The amount of interstitial clay of 39 sand samples from the P-well series at the SRS ranges from 5 to 30 percent. Most of the clay matrix consists of kaolinite with minor to trace amounts of illite and smectite (Strom and Kaback, 1992). Gravel, feldspar, and interstitial clay are more abundant in the lower section of the aquifer (Cape Fear Formation). Clay and sandy clay beds as thick as 20 ft are present, especially towards the top of the aquifer in updip areas. Particle-size analyses of 285 samples of the aquifer from the SRS and surrounding areas indicate 4 percent gravel, 86 percent sand, and 10 percent mud (Aadland and others, 1995). Grain size of the samples averages 1.3 Φ (medium sand) and most, about 75 percent, are poorly sorted. (See *Appendix B2* for a detailed lithologic description of the McQueen Branch aquifer at the Orangeburg corehole.)

McQueen Branch aquifer sediments are fine grained, glauconitic, and slightly calcareous in the southern and eastern parts of the Coastal Plain. The Cane Acre Formation, which consists of medium-grained quartz sand in Allendale County, transitions to marl downdip in Jasper County (*Plate 1*). Permeable sediments of the aquifer generally are absent downdip in Jasper and Beaufort Counties and in the east in Colleton County. As such, the McQueen Branch aquifer is pinched out in these areas.

### Hydrologic Properties

The McQueen Branch aquifer is one of the most productive aquifers in the Coastal Plain of SC, especially in the west-central and updip parts of the SC ACP where it is thick and consists of unconsolidated coarse-grained sand. Generally, the aquifer thins to the east and south where it is less permeable. Results from a 7-day aquifer test made at Cope (*fig. B1*) in western Orangeburg County indicate a transmissivity of 27,000 $ft^2/d$ (Newcome, 2005). Horizontal hydraulic conductivity is 140 ft/d, and the storage coefficient is $2.7 \times 10^{-4}$. Transmissivity values of eight aquifer tests in the central part of the SRS (southern Aiken County) range from 14,000 to 50,000 $ft^2/d$ and average about 29,000 $ft^2/d$ (Aadland and others, 1995). To the east, results from 27 aquifer tests indicate that transmissivity values range from 300 to 9,100 $ft^2/d$ and average 3,800 $ft^2/d$ (median of 2,500 $ft^2/d$). These tests are from Darlington, Dillon, Florence, Marion, and Marlboro Counties (Rodriguez and others, 1994). At the coast, in Charleston County, where the aquifer is rarely used, transmissivity from a single test is 630 $ft^2/d$.

### Geophysical-Log Signature

Resistivity values from the McQueen Branch aquifer interval on the long-normal log strongly reflect the dissolved-solids concentrations of groundwater and clay content. In updip areas, resistivity values typically exceed 1,000 ohm-m; in the central part of the SC ACP, they typically exceed 100 ohm-m; and along the coast, values rarely exceed 10 ohm-m (*Plates 1, 2,* and *7*). The upper part of the aquifer commonly contains sandy clay and clayey sand beds that are marked by decreases in resistivity (see ORG-393 on *Plate 7*). Natural gamma radiation levels are relatively high in the lower part of the McQueen Branch aquifer, which consists of the Cape Fear Formation, and relatively low in the Cane Acre section. Gamma spikes are noted in the aquifer and are associated with concentrations of heavy minerals, mica, feldspar, and monazite.

## Charleston Confining Unit

The informally named Charleston confining unit (model layer 12, *Chapter C*) was identified in this study. The confining unit overlies the Charleston aquifer and underlies the McQueen Branch aquifer in the middle and lower parts of the SC ACP (*fig. B37*; *Plates 1, 2,* and *7*). Formations composing the unit are absent updip, and the confining unit pinches out (*fig. B37*). In these updip areas, the Charleston and McQueen

Branch aquifers coalesce and are connected (*fig. B37* and *Plate 1*). The confining unit reaches a maximum thickness of about 450 ft in Charleston County, dipping to the south-southeast about 18 ft/mi in the western part of the Coastal Plain, and 8 ft/mi in the eastern part (*figs. B27* and *B28*; *Plates 1, 2,* and *7*; *Appendix B1*). The Charleston confining unit in SC is equivalent in stratigraphic position to the Upper Cape Fear confining unit in NC. The units are continuous and hydraulically connected between the two States.

### Age and Stratigraphic Correlation

The Charleston confining unit consists primarily of the Late Cretaceous Shepherd Grove (late Santonian to early Campanian) and Caddin (early Campanian) Formations (*fig. B4*; *Plates 1, 2,* and *7*). On the eastern side of the SC ACP, the Caddin Formation is permeable, and the Charleston confining unit consists of the upper part of the Pleasant Creek Formation (Santonian) and the Shepherd Grove Formation (*fig. B4*). Generally, the confining unit is correlated with the unnamed confining unit that overlies the Middendorf aquifer of Aucott and others (1987) in downdip regions (*fig. B39*).

### Lithology and Texture

The Shepherd Grove Formation forms most of the Charleston confining unit and consists of noncalcareous to slightly calcareous clay, silty clay, clayey silt, and clayey fine sand. The formation typically is laminated with very fine to fine-grained quartz sand. Sparse lignite, pyrite, and mica are present, and shell fragments are common in downdip cores. The Caddin Formation at the Berkeley corehole (BRK-644, *Plate 2*) consists of indurated calcareous sandy clay with sparse shell fragments, lignite, and mica. The matrix has a slight conchoidal fracture and is described as “hard and dry.” The sand fraction is very fine to fine grained and commonly contains glauconite. Tight, calcite-cemented sand beds (less than 2 ft) are present in some places throughout the formation. In northern Charleston County, the Pleasant Creek Formation (CHN-820) consists of dark greenish-gray, dry and tight sandy clay that breaks with a conchoidal fracture. Locally, the formation contains beds consisting of up to 30 percent shell fragments, and beds of sand and shell up to 3 ft thick that are cemented with calcium carbonate.

### Hydrologic Properties

No hydrologic data are available for the Charleston confining unit. On the basis of its lithology, it is expected that the unit is an effective confining unit. Core samples that appeared to be dry were recovered from the Charleston confining unit interval at CHN-820, implying that little water is moving through the unit.

### Geophysical-Log Signature

Resistivity values on the long-normal electric log are generally less than 10 ohm-m, reflecting the high clay content in the Charleston confining unit. Resistivity remains very low, even in those cores described as being “dry.” Hard, cemented zones are noted on the single-point electric log as high-resistance spikes. Natural gamma radiation is consistently high and generally flat throughout the confining unit, reflecting the high clay content (*Plate 2*). No radiation spikes are observed in the unit. The SP trace is flat and essentially rides the shale baseline, indicating low permeability.

## Charleston Aquifer

The informally named Charleston aquifer (model layer 13, *Chapter C*) was defined in this study; it overlies the Gramling confining unit and underlies the Charleston confining unit in the middle and outer parts of the SC ACP (*fig. B37*; *Plates 1, 2,* and *7*). In the southernmost counties, sediments composing the aquifer are fine grained and may not yield sufficient water to wells. At Hilton Head Island (*fig. B1*), for example, production wells bypass the Charleston interval and are screened in the deeper Gramling aquifer. In the central part of the Coastal Plain, the aquifer thins and coalesces with the overlying McQueen Branch aquifer (*fig. B37*; *Plate 1*). Farther updip, at the SRS (*fig. B1*), formations that compose the Charleston are absent. The aquifer reaches a maximum thickness of more than 300 ft in Jasper County (*fig. B30*). The Charleston aquifer dips to the south-southeast about 20 ft/mi in the western part of the SC ACP and 15 ft/mi in the eastern part (*fig. B29*; *Plates 1* and *2*; *Appendix B1*). The Charleston aquifer in SC is equivalent in stratigraphic position to the Upper Cape Fear aquifer in NC. The units are continuous and hydraulically connected between the two States.

### Age and Stratigraphic Correlation

The Charleston aquifer consists primarily of the Late Cretaceous Collins Creek Formation (middle to late Coniacian). In places, the aquifer also contains the upper part of the Cape Fear Formation (late Turonian to Coniacian) and, in the eastern part of the Coastal Plain, the Pleasant Creek Formation (Santonian) (*fig. B4*; *Plates 1, 2,* and *7*). In general, the aquifer is correlated with the Middendorf aquifer of Aucott and others (1987) in downdip regions and with the Middendorf aquifer system of Colquhoun and others (1983) (*fig. B39*).

### Lithology and Texture

The Charleston aquifer consists of unconsolidated sand, clayey sand, and clay. The sand fraction consists of poorly sorted, fine- to very coarse-grained quartz with up to 10 percent mica, sparse glauconite, pyrite nodules, and lignite. Shell fragments are common in some beds. Calcite-cemented beds of sand and shells, up to 2 ft thick, are present in the aquifer. Lignitic sand beds, a characteristic lithology of the aquifer, are common in the upper part of the aquifer.

### Hydrologic Properties

Charleston aquifer transmissivity values calculated from aquifer tests at Mount Holly and Saint Stephens in Berkeley County are 3,100 and 4,100 $ft^2/d$, respectively (Newcome, 2005; *fig. B1*). The well at Mount Holly has a storage coefficient of $2 \times 10^{-4}$. Transmissivity values from six tests at Mount Pleasant in Charleston County range from 1,500 to 2,400 $ft^2/d$ and average 1,800 $ft^2/d$ (Newcome, 2005).

### Geophysical-Log Signature

Within the Charleston aquifer, resistivity values on the long-normal log are 30 to 40 ohm-m inland (in northern Berkeley County at corehole BRK-644), and generally less than 20 ohm-m in coastal counties (*Plates 1, 2,* and *7*). These differences reflect greater mineralization of groundwater in coastal counties [greater than 1,000 milligrams per liter (mg/L) of total dissolved solids in Charleston County and about 350 mg/L of total dissolved solids at Saint Stephen in Berkeley County]. In Charleston County, a group of three sand beds separated by clay beds forms the Charleston aquifer and is noted on electric logs as alternating zones of high and low resistivity (Gohn and Campbell, 1992) (see CHN-635 on *Plate 7*).

## Appleton Confining System/ Gramling Confining Unit

The Appleton is the lowermost confining system of the SC ACP. Aadland and others (1995) defined the system at type well ALL-348 near the town of Appleton (*fig. B1*) in Allendale County, SC, where it is 237 ft thick and consists of saprolite, which is derived from igneous rock, and interbedded sand, clayey sand, and clay of the Late Cretaceous Cape Fear Formation. In updip areas, the confining system hydraulically separates SC ACP sediments from underlying basement rocks; in downdip areas, the system separates the Ridgeland and Midville aquifer systems. The Appleton confining system underlies the entire Coastal Plain, although the unit thins considerably to the northwest (Aiken County) where it consists only of saprolite. The system is correlated with the Black Warrior River confining unit of Miller and Renken (1988) (*fig. B39*). The system contains a single confining unit, informally called the “Gramling confining unit,” after Gramling Creek, just east of Orangeburg, SC (*fig. B1*) (Gellici, 2007a).

The Gramling confining unit (model layer 14, *Chapter C*) is the lowermost confining unit in the Coastal Plain. The confining unit overlies basement crystalline rocks in the inner and middle parts of the SC ACP and the Gramling aquifer in the lower part. The unit is overlain by the Charleston aquifer across most of the SC ACP (*fig. B37*; *Plates 1, 2,* and *7*), reaching a maximum thickness of over 300 ft in Florence County (*fig. B32*; *Plate 7*; *Appendix B1*). The confining unit dips to the south-southeast about 24 ft/mi in the western part of the Coastal Plain, and 10 ft/mi in the eastern part (*fig. B31*; *Plates 1* and *2*; *Appendix B1*).

### Age and Stratigraphic Correlation

The Gramling confining unit consists of saprolite and the Late Cretaceous Cape Fear Formation (late Turonian to Coniacian) (*fig. B4*; *Plates 1, 2,* and *7*). The confining unit is correlated with the “unnamed” basal confining unit of Aadland and others (1995) (*fig. 38*) and with the lowermost unnamed confining unit that overlies the Cape Fear aquifer of Aucott and others (1987) (*fig. B39*). The Gramling confining unit is mapped as “crystalline rocks of the Piedmont” in the updip area of the SC ACP and as the Middendorf aquifer system by Colquhoun and others (1983).

### Lithology and Texture

The Gramling confining unit is characterized by unconsolidated to semiconsolidated beds of clay, clayey sand, sand, and gravel. The sand fraction consists of poorly sorted, fine- to very coarse-grained quartz with minor feldspar and sparse mica, lignite, and monazite. Friable coarse-grained feldspar grains that are partially weathered to kaolinite are common throughout the confining unit. Much of the Gramling confining unit is consolidated in varying degree by silica cement. Beds were deposited in a series of fining-upward sequences (5 to 30 ft thick). Interstitial clay can be high due to weathering of feldspar to kaolinite, but some sand beds lack clay and silica cement and are unconsolidated and permeable. A sidewall core (2,300 ft) from the Jasper County corehole (JAS-426, *Plate 1*) contains quartz (42 percent), illite/smectite/mica (23 percent), potassium feldspar (18 percent), kaolinite (12 percent), albite (3 percent), and plagioclase (2 percent) (Core Laboratories, 1997). (See *Appendix B2* for a detailed lithologic description of the Gramling confining unit at the Orangeburg corehole, ORG-393.)

### Hydrologic Properties

Permeability is generally low, and is controlled principally by post-depositional processes within the Gramling confining unit. Primary intergranular porosity is low owing to poor sorting and interstitial clay. Porosity and permeability are further reduced by alteration of feldspar to authigenic clay, by silica cementation, and by compaction. Silty-clay samples from the Allendale corehole (ALL-348) have vertical hydraulic conductivity values that range from $3.8 \times 10^{-3}$ to $1.6 \times 10^{-2}$ ft/d and average $1.1 \times 10^{-2}$ ft/d (Core Laboratories, 1992; Gellici and others, 1995).

Beds of permeable unconsolidated sand and gravel are present in the Gramling confining unit where little or no pore-filling cement or clay is present (*Plates 1, 2,* and *7*). The beds typically are thin (<20 ft), are of limited lateral extent, and are probably poorly connected with other permeable beds. An aquifer test of a well that is reported to be completed in the confining unit indicates a transmissivity of 1,200 $ft^2/d$ (Rodriguez and others, 1994).

In downdip areas, where the Gramling confining unit overlies the Gramling aquifer, delineating the boundary between the confining unit and underlying aquifer can be difficult (see *Plate 7*). Lithologies of the two units are similar, and the contact is indefinite. Some degree of hydraulic connection can be expected across the confining unit.

### Geophysical-Log Signature

Low resistivity values on the long-normal electric log are a characteristic feature of the Gramling confining unit (*Plates 1, 2,* and *7*). Even beds of loose sand and little clay have values that rarely exceed 20 ohm-m. This response is probably caused by mineralized formation water, which is the result of long residence times or of dissolution of labile framework grains. Interstitial clay in the confining unit also causes low resistivity values. Permeable sand beds in the confining units are identified as slight deflections to the left on the spontaneous-potential log together with slight increases in resistance on the single-point electric log.

## Ridgeland Aquifer System/Gramling Aquifer

The Ridgeland aquifer system was defined in this study based on the unique hydrogeologic properties of sediments penetrated at corehole JAS-426, in Jasper County, SC (*fig. B1*). The aquifer system is named after the town of Ridgeland, SC, located about 10 mi west of the corehole. The aquifer system overlies crystalline basement rocks and underlies the Appleton confining system. Ridgeland is the lowermost aquifer system of the SC ACP (*fig. B38*). A line drawn from northern Jasper County to northern Horry County approximates the updip limit of the aquifer system. North of this line, the system pinches out against crystalline basement rocks. The system thickens to more than 1,000 ft at Hilton Head Island (BFT-2055), and thins towards the northeast to about 300 ft at Myrtle Beach (HOR-973/1165) (*fig. 34*). The Ridgeland aquifer system correlates generally with the Black Warrior River aquifer of Miller and Renken (1988) and with the Cape Fear aquifer of Aucott and others (1987) (*fig. B39*).

The type section of the Ridgeland aquifer system is from 2,397 to 2,796 ft (399 ft) in the JAS-426 corehole in Jasper County, SC (*Plate 1*), and includes the Late Cretaceous Beech Hill and Clubhouse Formations and the lower part of the Cape Fear Formation (*fig. B4*). The Ridgeland aquifer system consists of interbedded silty clay, sandy silty clay, and silty clayey sand, with minor gravel and feldspar. Median grain size of 22 sidewall core samples ranges from 6 to 2 $\Phi$ (silt to medium-grained sand) and averages 3.25 $\Phi$ (very fine-grained sand) (Core Laboratories, 1997). Gravel, sand, silt, and clay average 1, 50, 42, and 7 percent, respectively. Empirically-derived hydraulic conductivity of these same samples ranges from less than 0.5 to 2 ft/d and averages about 1 ft/d (Core Laboratories, 1997).

Interbedded sand and clay characterize the Ridgeland aquifer system. Thick sand units are generally absent. As a result, delineating the boundaries of specific aquifers and confining units can be difficult. In addition, few wells fully penetrate the system, and hydrologic data are sparse. As such, the vertical and lateral hydraulic continuity of the system are unknown. More than one aquifer may be present. For the purposes of this report, however, the entire system is informally referred to as the “Gramling aquifer,” named after the overlying confining unit.

The Gramling aquifer (model layer 15, *Chapter C*) constitutes the entire Ridgeland aquifer system, and is present primarily in the southern part of the SC ACP (*fig. B33*). The aquifer overlies basement rocks and underlies the Gramling confining unit (*fig. B37*; *Plates 1–5*). The Gramling aquifer reaches a maximum thickness of more than 1,000 ft in Beaufort County, dipping to the south about 19 ft/mi in the western part of the Coastal Plain, and 14 ft/mi in the eastern part (*figs. B33* and *B34*; *Plates 1* and *3*; *Appendix B1*).

### Age and Stratigraphic Correlation

The Gramling aquifer is present at the base of the SC ACP sequence and includes the Late Cretaceous Beech Hill (Cenomanian) and Clubhouse Formations (late Cenomanian(?) to early Turonian) and the lower part of the Cape Fear Formation (late Turonian to Coniacian) (*fig. B4*; *Plates 1–5*). The aquifer is generally correlated with the Cape Fear aquifer of Aucott and others (1987) and with the Middendorf aquifer system of Colquhoun and others (1983) (*fig. B39*).

### Lithology and Texture

The Gramling aquifer is characterized by unconsolidated to semiconsolidated interbedded and laminated sand, clayey sand, silt, and clay. The sand fraction consists mainly of quartz but can contain moderate amounts of feldspar, particularly in the Beech Hill and Cape Fear Formations. Minor to sparse mica and lignite are present. Calcareous sediments are common in the Clubhouse Formation. Grain size is predominantly fine with minor coarse sand and gravel. Coarser sand is more common in the Beech Hill and Cape Fear Formations. Silica-cemented beds in the Cape Fear Formation are common and reduce permeability of the aquifer. A sidewall core (2,440 ft) from the Jasper County corehole (JAS-426, *Plate 1*) within the Gramling aquifer contains quartz (61 percent), potassium feldspar (15 percent), illite/smectite/mica (12 percent), kaolinite (10 percent), and albite (2 percent) (Core Laboratories, 1997).

### Hydrologic Properties

Few hydrologic data are available for the Gramling aquifer. Currently (2008), the Gramling aquifer is used only at Hilton Head and Fripp Islands in Beaufort County and may be partially screened in a supply well at Kiawah Island in Charleston County (*fig. B1*). Gramling aquifer transmissivity, calculated from an aquifer test of the well at Fripp Island, is 200 $ft^2/d$ (Newcome, 2005). In a supply well at Hilton Head Island (BFT-2055), 18 well screens were emplaced through the interval from 2,782 to 3,840 ft. The screens range in length from 8 to 18 ft and tap thin sand beds that compose the Gramling aquifer. Transmissivity calculated from an aquifer test of BFT-2055 is 1,200 $ft^2/d$ (Newcome, 2005).

### Geophysical-Log Signature

Low resistivity on the long-normal electric log (<20 ohm-m) and high radiation on the gamma-ray log characterize the Gramling aquifer. Spontaneous-potential (SP) logs are flat and smooth where clayey sediments predominate, and they have slight negative deflections adjacent to thin, permeable sand beds (*Plate 7*). Water in the aquifer is slightly brackish, causing the low resistivity and negative SP response. A fine-grained lithology and high interstitial-clay content cause elevated radiation levels on the gamma-ray log. Gamma-ray spikes are noted in the aquifer in some wells, indicating lag beds of glauconite and phosphate, concentrations of heavy minerals, or radioactive minerals such as monazite.

## Discussion

Several important differences exist between the framework developed in this study and that of Aucott and others (1987) (*fig. B39*). These differences include the following:

1. The Middendorf aquifer mapped in updip regions by Aucott is comparable to the McQueen Branch aquifer mapped in updip areas of this report. Fossil data, however, indicate that strata traditionally mapped as the Middendorf aquifer in downdip areas (Santonian) are older than strata mapped as the Middendorf aquifer in updip areas (Campanian). In this report, the older strata are mapped as the Charleston aquifer, and the younger strata are mapped as the McQueen Branch aquifer.
2. The Tertiary sand aquifer of Aucott is divided into the Gordon, Middle Floridan, and Upper Floridan aquifers and confining units for this report.
3. The Floridan aquifer system of Aucott is divided into the Middle and Upper Floridan aquifers and associated confining units for this report.
4. The Floridan aquifer system is extended down-section to include late Paleocene strata of the Gordon aquifer and laterally to include clastic sediments in updip regions for this report.
5. Confining units are named after the aquifer that they confine for this report.

Most of the McQueen Branch aquifer consists of the Cane Acre Formation (middle Campanian), which was previously mapped as the Middendorf Formation (Colquhoun and others, 1983; Fallaw and Price, 1995). Hazel and others (1977) originally assigned an early late Austinian age to the Middendorf, indicating a Santonian or early Campanian age. Gohn (1992), citing several supporting paleontological studies (Christopher, 1982; Valentine, 1984; Sohl and Owens, 1991), assigned strata of Santonian age to the Middendorf Formation at the USGS-Clubhouse Crossroads #1 corehole. Recent studies of cores and outcrops (Prowell and others, 2003) and paleontological data collected from the ORG-393 corehole and other updip coreholes indicate that much of these updip strata that were mapped as the Middendorf Formation are not Santonian but, instead, are Campanian (calcareous nannofossil zone CC 18–19). In this report, therefore, the name Cane Acre Formation is used in place of the Middendorf Formation.

The hydrogeologic framework developed for this study relies heavily on paleontological data to make delineations and correlations of the hydrostratigraphic units. Hydraulic-head data, available from well-cluster sites or from wireline formation tests, would be useful to verify vertical hydraulic continuity of the aquifers and to determine if head differences exist across confining units. Currently, these data are lacking in the eastern Coastal Plain, where cluster sites are scarce and hydrostratigraphic units are not well defined owing to the lithologic complexity of the SC ACP in these areas. Generally, static-head differences between adjacent aquifers in SC are small. Aquifers, therefore, are not clearly distinguished by groundwater levels that are obtained from wells spaced several miles apart. Well-cluster sites would help to resolve the relatively small static-head differences observed between aquifers.

Parts of the inner Coastal Plain are deeply incised by streams, which can break the lateral hydraulic continuity of aquifers. Groundwater in these areas discharges along the flanks of valley walls and into surrounding streams, creating hydraulically isolated "islands" of groundwater. As such, the lateral continuity of aquifers in these updip areas is obscure. Water levels measured for the same aquifer but on different ridges may have no relation to one other because the aquifer is not hydraulically connected across the valley. Although aquifers in this report were mapped well into the inner Coastal Plain, the hydraulic continuity of the aquifers in this region is uncertain.

# Correlation of Hydrostratigraphic Units Across the North Carolina–South Carolina Border

In order to determine the continuity of hydrostratigraphic units across the border between NC and SC, two cross sections were constructed from southwest to northeast along approximate structural strike using four wells. *Figure B40* includes data from USGS corehole DIL-121 and the NC DWR Marietta (BB 45M) monitoring station. *Figure B41* includes data from a cored well from Myrtle Beach, SC (HOR-973-1165), and the NC DWR Calabash (HOR-388/HH 39J) monitoring station.

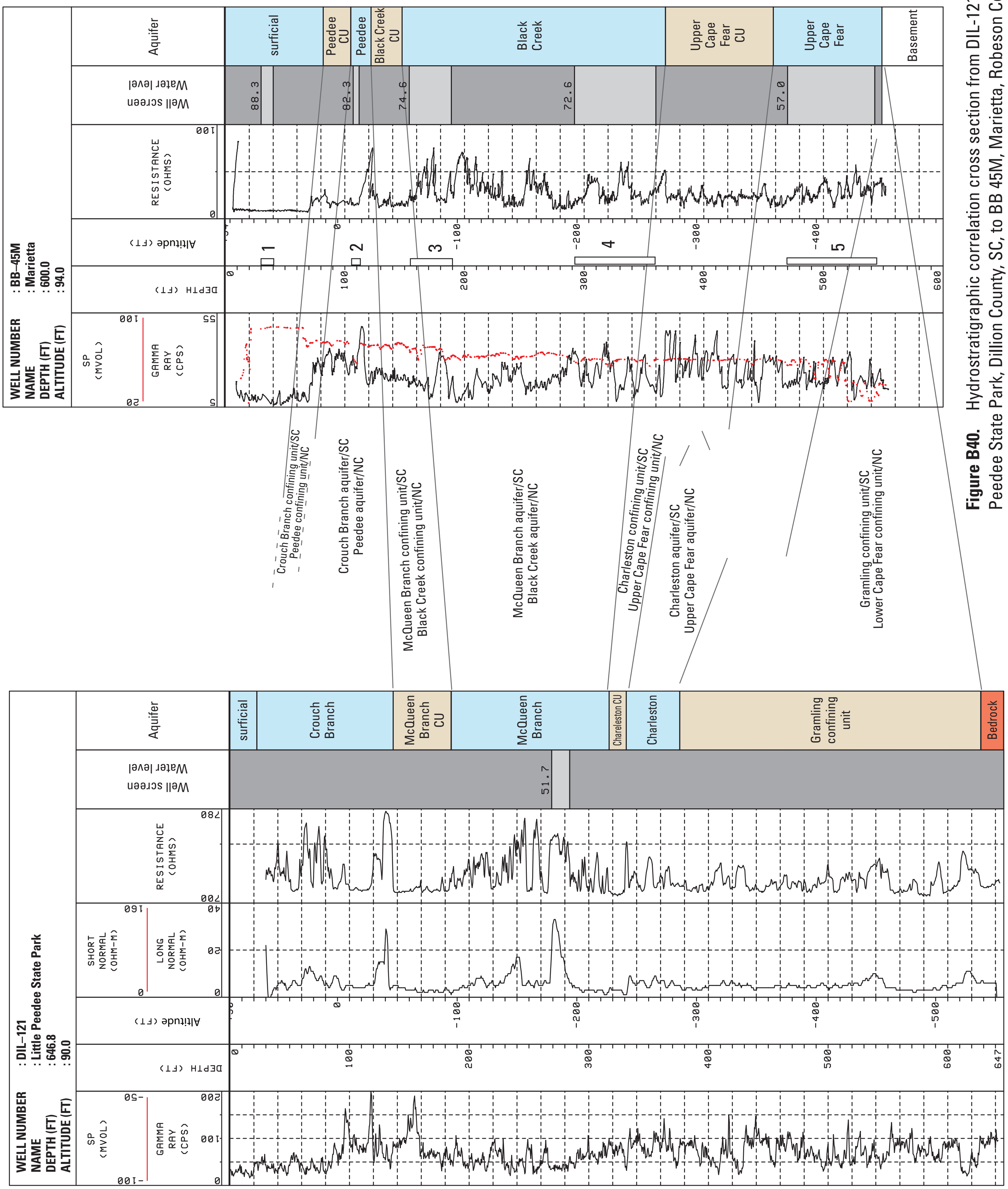


**Figure B40.** Hydrostratigraphic correlation cross section from DIL-121, Little Peedee State Park, Dillion County, SC, to BB 45M, Marietta, Robeson County, NC.

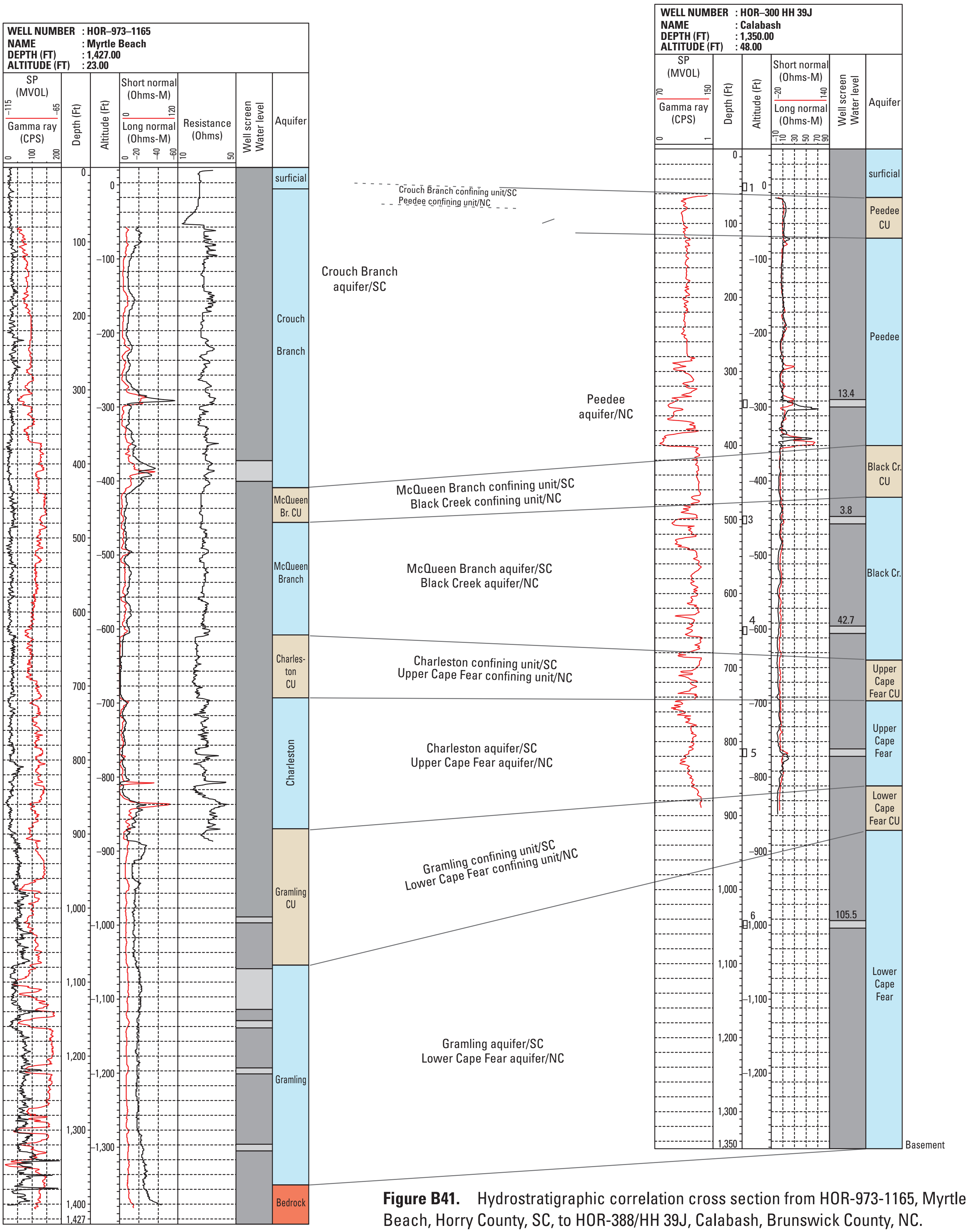


**Figure B41.** Hydrostratigraphic correlation cross section from HOR-973-1165, Myrtle Beach, Horry County, SC, to HOR-388/HH 39J, Calabash, Brunswick County, NC.

Correlations across the NC–SC border were limited by disparate strengths and weaknesses among the data available in each State. The NC Division of Water Resources maintains an extensive network of groundwater monitoring stations in the NC Coastal Plain; well nests screened in each of the major aquifers make it possible to delineate aquifer boundaries by determining where substantial differences in hydraulic head occur, or by the comparison of long-term water-level variations at various screen depths. South Carolina does not have the advantage of a network of nested groundwater level observation well stations. The subsurface stratigraphic framework of NC is not as clearly understood as in SC, where the USGS Coastal Carolina project has been completed and regional interpretations have been made. The mapping of hydrogeologic units in SC, then must rely almost exclusively on stratigraphic correlation from a corehole network rather than a monitoring station network.

The hydrostratigraphic correlations of the ACP sediments at the NC–SC border determined by this study are illustrated in *figures B40* and *B41*. At the updip location (*fig. B40*), between Marietta, NC, and Little Peedee State Park, the surficial aquifer is present at both locations. Underlying the surficial aquifer is the Peedee/Crouch Branch aquifer in SC and the Peedee/Crouch Branch confining unit in NC. The Peedee/Crouch Branch confining unit is not present in SC. The Black Creek/McQueen Branch confining unit along with the Black Creek/McQueen Branch aquifer are present in both locations. The Upper Cape Fear/Charleston aquifer and confining unit are present at both locations, but the correlations are questionable due to the relative thinness of the units in SC. The Upper Cape Fear aquifer is the lowermost unit present at the Marietta location, whereas the Gramling confining unit is the lowermost ACP unit present in SC.

At the downdip location (*fig. B41*) along the NC–SC coast, the ACP hydrostratigraphy is correlated between Myrtle Beach, SC, and Calabash, NC. The surficial aquifer is present at both locations and is underlain by the Crouch Branch aquifer in SC and the Peedee confining unit in NC. The Crouch Branch confining unit is not present at the Myrtle Beach location. The Peedee aquifer underlies the Crouch Branch confining unit at Calabash. The Black Creek/McQueen Branch aquifer and confining unit underlie the Peedee aquifer at both locations. Below these units are the Upper Cape Fear/Charleston aquifer and confining unit. The lowermost units present are the Lower Cape Fear/Gramling aquifer and confining unit.

Continuous groundwater levels collected at the Marietta and Calabash, NC, stations have been collected since the early 1970s (*fig. B42*; *Plates 5, 6,* and *7*). At the Marietta station, groundwater levels are collected within the four aquifers that underlie the site: the surficial aquifer, the Peedee aquifer, the Black Creek aquifer (three locations within the aquifer), and the Upper Cape Fear aquifer. Overall groundwater levels at the Marietta station have been declining over the period of record most likely because of withdrawals from the City of Florence, SC (*fig. B1*). The overall vertical groundwater gradient at the Marietta station is downward, indicating an area of

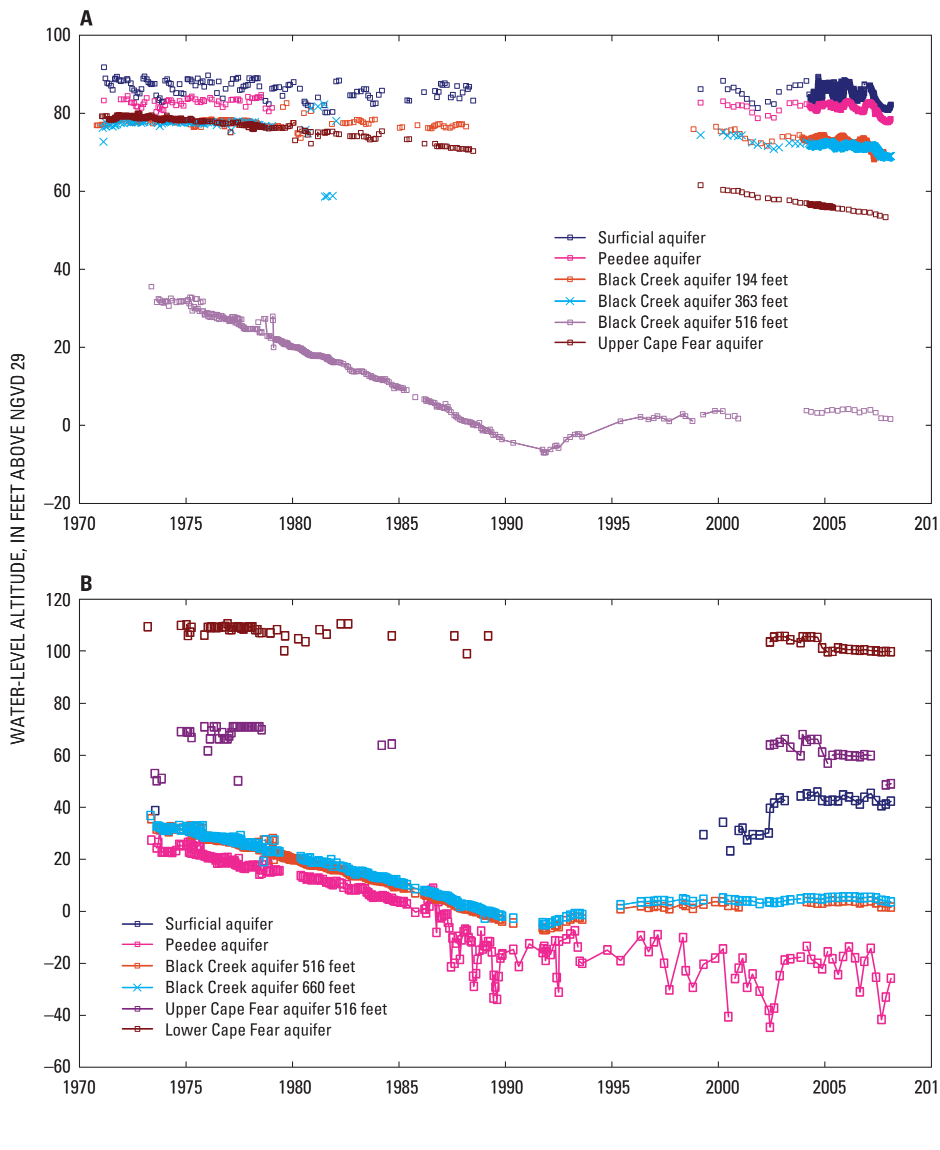


**Figure B42.** Continuous groundwater altitudes from the *A*, Marietta, North Carolina, monitoring station, Robeson County, North Carolina, and *B*, Calabash, North Carolina, monitoring station, Brunswick County, North Carolina.

groundwater recharge. Groundwater levels within the 516-ft level of the Black Creek aquifer have declined the most at the Marietta station in response to withdrawals from the Black Creek/McQueen Branch aquifers in Dillon, Florence, and Marlboro Counties in SC and in Robeson and Bladen Counties in NC (*fig. B1*). No comparable continuous groundwater levels were collected from the DIL-121 site in SC.

At the Calabash, NC, station, groundwater levels are collected within the five aquifers that underlie the site: the surficial, Peedee, Black Creek (two locations within the aquifer), Upper Cape Fear, and Lower Cape Fear aquifers. Groundwater levels in the Peedee and Black Creek aquifers at the Calabash station declined from the early 1970s until the early 1990s in response to withdrawals in Horry County, SC, and Brunswick County, NC. In about 1992, Myrtle Beach, SC (*fig. B1*) switched from a groundwater source to a surface-water source for raw potable water. From the early 1990s until the present (2008), groundwater levels in the Peedee and Black Creek aquifers have stabilized. The overall vertical groundwater gradient at the Calabash station is upward, indicating an area of groundwater discharge. No comparable continuous groundwater levels were collected from the HOR-973/1165 site in SC.

Overall, at the coastal site, hydrostratigraphic units correlate well in the coastal area along the NC–SC State line because most of the units are present (*fig. B41*). Correlations further updip, between Dillon County, SC, and Robeson County, NC, are more problematic, and will need further work.

## Summary

The North Carolina (NC) and South Carolina (SC) segment of the Atlantic Coastal Plain (ACP) consists of approximately 45,000 square miles and extends from the Fall Line to offshore under the present-day Atlantic Ocean. The hydrogeologic frameworks of the North and South Carolina Coastal Plain have evolved separately over the past 100 years, but are both described in this report. The hydrostratigraphic units present at the NC–SC border are correlated.

The hydrogeologic framework of the NC Coastal Plain aquifers and confining units consists of nine aquifers separated by eight confining units. From top to bottom, the aquifers are the surficial aquifer, Yorktown aquifer, Castle Hayne aquifer, Beaufort aquifer, Peedee aquifer, Black Creek aquifer, Upper Cape Fear aquifer, Lower Cape Fear aquifer, and Lower Cretaceous aquifer. The uppermost aquifer, the surficial aquifer in most places, is a water-table aquifer; the bottom of the system is underlain by various types of crystalline bedrock. The sedimentary deposits forming the aquifers are of Holocene to Cretaceous age and are composed mostly of sand, with lesser amounts of gravel and limestone. The confining units between the aquifers are composed primarily of clay and silt. The total thickness of the aquifers and confining units ranges from zero, along the Fall Line, to more than 5,000 feet (ft) in easternmost NC. Prominent structural features are the increasing easterly dip of the sediments along with the Cape Fear Arch, the axis of which trends in a southeast direction. The hydrostratigraphy was primarily determined from correlations of geophysical logs and drill cutting descriptions from 145 wells distributed across the NC Coastal Plain. Aquifers and confining units were defined by using the geophysical logs and drill cuttings, as well as water-level and water-quality data and evidence of the continuity of pumping effects. Structure contour and thickness maps delineate the aquifers and confining units. Hydrogeologic sections depict the correlation of these aquifers throughout the NC Coastal Plain.

The thickness of the surficial aquifer in NC ranges from less than 10 ft in the central, northern, and southern parts of the NC Coastal Plain to more than 100 ft in parts of the Sandhills and coastal areas. The surficial aquifer is primarily composed of permeable sediments of Quaternary age, but it also contains older sediments in various places due to the varying stratigraphic position of the first confining layer. Included are the overlying soils, which vary in infiltration capacity across the region, thus affecting the rates at which recharge occurs.

The Yorktown aquifer is present only in the northern half of the NC Coastal Plain and is bounded to the west by the Fall Line. Although outliers of the Yorktown Formation are present in Robeson, Bladen, Columbus, and Duplin Counties, they are not separated from the surficial aquifer by a recognizable confining unit, and therefore are not considered to be a distinct aquifer in these areas. The Yorktown aquifer is absent over the entire southern part of the Coastal Plain. The Yorktown aquifer ranges in observed altitudes from –100 ft in Dare County to 100 ft in Greene County. The aquifer thickens eastward from where it directly overlies basement rock at the Fall Line to a maximum of 300 ft in easternmost NC. Reported transmissivities for the Yorktown aquifer in the northeastern NC Coastal Plain ranged from 1.0 to 2,350 square feet per day ($ft^2$/d), and horizontal hydraulic conductivities ranged from 0.2 to 98 feet per day (ft/d), based on five aquifer tests. The Yorktown confining unit can be described as a series of clay and silt beds that do not compose a single unit because the beds vary substantially in stratigraphic position. The top of the Yorktown confining unit ranges in altitude from less than –100 ft to over 100 ft. The thickness of the confining unit ranges from less than 10 to more than 50 ft in the NC Coastal Plain.

The Castle Hayne aquifer typically is a sandy, molluscan-mold limestone and a bryozoan-echinoid skeletal limestone and is the highest yielding aquifer in the NC Coastal Plain. Aquifer transmissivity exceeds 35,000 $ft^2$/d, and aquifer yields can be up to 1,000 gallons per minute (gal/min). The Castle Hayne aquifer is roughly equivalent to the Middle Floridan aquifer in SC, although the two are not contiguous or hydraulically connected. The Castle Hayne aquifer thickens from west to east, to a maximum of 530 ft, and becomes more deeply buried toward the east. The top of the Castle Hayne aquifer ranges in observed altitudes from over –600 ft in the easternmost parts of NC to 65 ft in Lenoir County. The Castle Hayne aquifer is recharged by water that leaks through its confining layer from the overlying Yorktown and surficial aquifers. The

Castle Hayne confining unit consists of clay and silt beds that vary in stratigraphic position between the upper part of the Castle Hayne Formation and younger units of variable age, which overlie this formation across the Coastal Plain. The top of the Castle Hayne confining unit ranges in altitude from –600 to over 75 ft, while the thickness ranges from less than 1 to more than 200 ft on the Currituck County outer banks.

The Beaufort aquifer extends through the eastern section of the northern half of the NC Coastal Plain and is made up primarily of glauconitic, fossiliferous, clayey sands and intermittent thin limestone beds of the Paleocene Beaufort Formation. An average transmissivity of 1,600 $ft^2/d$ in Chowan County, based on the average of 22 aquifer-test calculations, is reported. The top of the Beaufort aquifer ranges in observed altitude from over –1,300 ft in the Outer Banks to 27 ft in Lenoir County. The maximum observed thickness of the aquifer is 132 ft in Dare County. In SC there is no Beaufort aquifer equivalent because the Beaufort Formation is primarily composed of clay or silt and is considered to be a part of the Crouch Branch confining unit. The Beaufort confining unit is composed of clays and silts in the upper part of the Beaufort Formation and the lower part of the Castle Hayne Formation. The top altitudes of the Beaufort confining unit range from 27 ft in Lenoir County to as much as –1,000 ft in the northeastern part of the NC Coastal Plain. The thickness of the Beaufort confining unit ranges between zero, in areas where it is eroded or pinches out, to a maximum of about 300 ft in northeastern NC.

The Peedee aquifer is present over most of the eastern NC Coastal Plain except for the northeastern counties. The Peedee aquifer is composed principally of the Late Cretaceous Peedee Formation. Reported transmissivity values for the Peedee aquifer range from 240 to 1,170 $ft^2/d$ for the central part of the NC Coastal Plain. In the southern part of the NC Coastal Plain, the values are reported to range from 40 to 340 $ft^2/d$ for the Peedee aquifer. The maximum thickness of the Peedee aquifer is 300 ft in Brunswick County. The top ranges in altitude between 88 ft in Lenoir County to –800 ft in Carteret County. In SC, the Peedee aquifer is equivalent to the Crouch Branch aquifer. Sediments of equivalent age are also referred to as the Peedee aquifer in Virginia.

The Peedee confining unit is composed of beds of clay and silt with varying amounts of sand that are positioned stratigraphically near the contact of the Paleocene Beaufort and Late Cretaceous Peedee Formations in the eastern NC Coastal Plain. The thickness of the Peedee confining unit varies between 0 ft to a maximum of 121 ft in Craven County. The top of the Peedee confining unit varies from about 0 ft in the southeastern part of the NC Coastal Plain to over –800 ft in the eastern Coastal Plain.

The Black Creek aquifer is made up primarily of the Late Cretaceous Black Creek Formation, but also includes permeable beds from older and younger formations in the NC Coastal Plain and, in localized areas, sands in the lower part of the Peedee Formation. Reported transmissivities from 15 aquifer tests in the Black Creek aquifer range from 290 to 1,700 $ft^2/d$. The Black Creek aquifer pinches out along the Fall Line at the updip limit of the sediments. The Black Creek aquifer reaches a minimum thickness of less than 10 ft along the updip limit and a maximum thickness of 442 ft in Onslow County. The altitude of the top of the Black Creek aquifer ranges from 317 ft in Richmond County to –1,207 ft in Craven County. The Black Creek aquifer is equivalent to the McQueen Branch aquifer and confining unit in SC. The Black Creek confining unit separates the Peedee aquifer from the Black Creek aquifer. The Black Creek confining unit ranges in thickness from less than 10 ft along the updip limit to more than 400 ft in southeastern NC. The top of the Black Creek confining unit ranges in altitude from a low of –800 ft to a high of over 200 ft.

The Upper Cape Fear aquifer is made up primarily of the upper part of the Cape Fear Formation of Late Cretaceous age. Reported transmissivities from three aquifer tests in the Upper Cape Fear aquifer range from 25 to 920 $ft^2/d$ in the NC Central Coastal Plain. The top of the Upper Cape Fear aquifer ranges in observed altitudes from –1,400 ft in Dare County to 200 ft in Moore County, near the Fall Line. The Upper Cape Fear aquifer ranges in thickness from 665 ft in northeastern NC to less than 10 ft along the updip limit of the aquifer. The Charleston and Upper Cape Fear aquifers are connected hydraulically as evidenced by water-level declines in Columbus and Robeson Counties, NC, that are due to pumping from the Charleston aquifer in SC. The Upper Cape Fear confining unit consists of beds of clay, silt, and variable but lesser amounts of sand that are in the upper part of the Cape Fear Formation and in the lower part of the Black Creek Formation in some places. The altitude of the top of the Upper Cape Fear confining unit ranges from –200 ft along the updip limit to about –1,200 ft in southeastern NC. The thickness of the Cape Fear confining unit ranges from about 50 ft over most of the NC Coastal Plain to about 500 ft in southern Virginia.

The Lower Cape Fear aquifer is composed primarily of the lower part of the Cape Fear Formation of Upper Cretaceous age. The top of the Lower Cape Fear aquifer ranges from about –200 ft along the updip limit to about –1,200 ft along the downdip limit. The thickness of the Lower Cape Fear aquifer ranges from about 10 ft in places along the updip limit to as much as 500 ft in the downdip limit. In SC, the Lower Cape Fear aquifer is correlated to the Gramling aquifer.

The Lower Cape Fear confining unit separates the upper and lower parts of the Cape Fear Formation into two distinct aquifers. The top altitude of the Lower Cape Fear confining unit varies from about –200 ft in the updip limit to about –1,200 ft in the downdip limit. The thickness of the Lower Cape Fear confining unit is about 50 ft over most of the NC Coastal Plain and about 100 ft thick near the North Carolina–Virginia border.

The Lower Cretaceous aquifer consists of permeable sediments of Lower Cretaceous age beneath the Lower Cape Fear aquifer in the Albemarle Embayment and extending south into Cartaret County, NC. The freshwater part of the Lower Cretaceous aquifer varies in altitude from –200 ft to –1,200 ft.

The freshwater part of the thickness of the Lower Cretaceous aquifer ranges from about 50 ft to as much as 800 ft in NC.

Fifteen hydrostratigraphic units were delineated in SC using core, fossil, borehole geophysical, and hydraulic-head data, and a new hydrostratigraphic nomenclature is applied. There are eight Tertiary/Quaternary units. The surficial aquifer blankets a variety of units from the Upper Floridan aquifer in the southern part of SC to the Crouch Branch aquifer in the eastern part of SC. The surficial aquifer described here is comparable to the surficial aquifer of Aucott and others (1987). The surficial aquifer is mainly Quaternary (undifferentiated), consists of sand, clayey sand, and shell beds, and is present throughout the SC ACP. The Upper Floridan confining unit overlies the Upper Floridan aquifer in downdip areas and has no comparable unit in the framework of Aucott and others (1987). The Upper Floridan confining unit is Miocene (Hawthorn Group), consists of phosphatic sandy clay and sandy limestone, and is present in the southern regions of the Coastal Plain. The Upper Floridan aquifer overlies the Middle Floridan confining unit and is comparable to the upper parts of the Floridan aquifer system of Aucott and others (1987). The Upper Floridan aquifer is late Eocene and possibly early Oligocene (includes Dry Branch/Parkers Ferry and Drayton(?) Formations), consists of limestone (downdip) and sand (updip), and is present in the western half of the Coastal Plain. The Middle Floridan confining unit overlies the Middle Floridan aquifer and has no comparable unit in the framework of Aucott and others (1987). The Middle Floridan confining unit is late Eocene (Harleyville and Dry Branch/Parkers Ferry Formations), consists of fine-grained calcarenites and calcilutites, and is present in the western half of the Coastal Plain. The Middle Floridan aquifer overlies the Gordon confining unit and is comparable to the lower parts of the Floridan aquifer system of Aucott and others (1987). The Middle Floridan aquifer is late middle Eocene (Santee Formation), consists of limestone (downdip) and sand (updip), and is present only in the western half of the Coastal Plain. The Gordon confining unit overlies the Gordon aquifer and has no comparable unit in the framework of Aucott and others (1987). The Gordon confining unit is middle Eocene (Santee and Warley Hill Formations), consists of marl, glauconitic clayey sand, and sandy clay, and is present in the western half of the Coastal Plain. The Gordon aquifer overlies the Crouch Branch confining unit and is comparable to the lower part of the Tertiary sand aquifer of Aucott and others (1987). The Gordon aquifer is predominantly late Paleocene through early middle Eocene (Williamsburg, Fishburne, and Congaree Formations), consists of sand, clayey sand, and limestone, and is present throughout the western half of the Coastal Plain. The Crouch Branch confining unit is early Paleocene and early late Paleocene (Rhems and Lang Syne Formations), consists of carbonaceous clay, fine sand, and opaline claystone, and is present mainly west of the Congaree/Santee Rivers. The Crouch Branch confining unit overlies the Crouch Branch aquifer and is comparable to the confining unit that separates the Black Creek and Tertiary sand aquifers of Aucott and others (1987).

There are seven Cretaceous units. The Crouch Branch aquifer overlies the McQueen Branch confining unit and is comparable to the Black Creek aquifer of Aucott and others (1987). The Crouch Branch aquifer is late Campanian through Maastrichtian (Donoho Creek, Peedee/Steel Creek, and Sawdust Landing Formations), consists of sand and clayey sand, and is present throughout the SC ACP except in the north-northeast regions. The McQueen Branch confining unit overlies the McQueen Branch aquifer and is comparable to the confining unit that separates the Middendorf and Black Creek aquifers of Aucott and others (1987). The McQueen Branch confining unit is middle to late Campanian (Coachman, Bladen, and Donoho Creek Formations), consists of carbonaceous clay and fine sand, and is present throughout the SC ACP except near the Fall Line. The McQueen Branch aquifer overlies the Gramling confining unit in the inner Coastal Plain and the Charleston confining unit in the outer Coastal Plain. The McQueen Branch aquifer is comparable to the Middendorf aquifer of Aucott and others (1987). The McQueen Branch aquifer is Turonian through middle Campanian (Cape Fear, Cane Acre, and Coachman Formations), consists of sand and clayey sand, and is present throughout most of the Coastal Plain. The Charleston confining unit is comparable to the confining unit separating the downdip Middendorf and Black Creek aquifers of Aucott and others (1987). The Charleston confining unit is Santonian through early Campanian (Pleasant Creek, Shepherd Grove, and Caddin Formations), consists of calcareous sandy clay and clayey sand, and is present in the lower half of the Coastal Plain. The Charleston aquifer, which was mapped as the Middendorf aquifer by Aucott and others (1987), overlies the Gramling confining unit. The Charleston aquifer is Coniacian through Santonian (Cape Fear, Collins Creek, and Pleasant Creek Formations), consists of lignitic sand and clayey sand, and is present in the lower half of the Coastal Plain. The Gramling confining unit overlies the Gramling aquifer and is comparable to the confining unit that separates the Cape Fear and Middendorf aquifers of Aucott and others (1987). The Gramling confining unit is Turonian through Coniacian (Cape Fear Formation), consists of silica-cemented gravel, sand, and clay, and is present throughout the Coastal Plain. The basal Gramling aquifer is comparable to the Cape Fear aquifer of Aucott and others (1987). The Gramling aquifer is Cenomanian through Coniacian (Beech Hill, Clubhouse, and Cape Fear Formations), consists of gravel, sand, and clay, and is present in the lower half of the Coastal Plain.

Several important differences exist between the current hydrogeologic framework in SC and previous frameworks. The Middendorf aquifer mapped in updip regions by Aucott is comparable to the McQueen Branch aquifer mapped in updip areas of this report. Fossil data, however, indicate that strata mapped as the Middendorf aquifer in downdip areas (Santonian) are older than strata mapped as the Middendorf aquifer in updip areas (Campanian). In this report, the older strata are mapped as the Charleston aquifer, and the younger strata are mapped as the McQueen Branch aquifer. The Tertiary sand aquifer of Aucott is divided into the Gordon, Middle Floridan, and Upper Floridan aquifers and confining units. The Floridan aquifer system of Aucott is divided into the Middle and Upper Floridan aquifers and associated confining units. The Floridan aquifer system is extended down-section to include late Paleocene strata of the Gordon aquifer and laterally to include clastic sediments in updip regions for this report. Confining units are named after the aquifer that they confine for this report.

In order to determine the continuity of hydrogeologic units across the border between NC and SC, two hydrogeologic cross sections were constructed from south to north along approximate structural strike, using four wells. The sections indicate that most of the late Cretaceous aquifers and confining units correlate across the border. The exceptions are the Peedee and Gramling confining units.

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**Appendix B1.** Aquifer and confining unit top surface altitudes interpreted from borehole geophysical logs, cores, and other data in the Coastal Plain of North Carolina, South Carolina, eastern Georgia, and southern Virginia.

[Borehole locations are on *figure B3*; borehole numbers in **bold** are coreholes; —, not present]

| Borehole location on *figure B3* | Borehole number | Latitude (decimal degrees) | Longitude (decimal degrees) | Top surface altitude, in feet: Land surface/top of surficial aquifer | Yorktown/Upper Floridan confining unit | Yorktown/Upper Floridan aquifer | Castle Hayne/Pungo River/Middle Floridan confining unit | Castle Hayne/Pungo River/Middle Floridan aquifer | Beaufort/Gordon confining unit | Beaufort/Gordon aquifer | Peedee/Crouch Branch confining unit | Peedee/Crouch Branch aquifer | Black Creek/McQueen Branch confining unit | Black Creek/McQueen Branch aquifer | Upper Cape Fear/Charleston confining unit | Upper Cape Fear/Charleston aquifer | Lower Cape Fear/Gramling confining unit | Lower Cape Fear/Gramling aquifer | Lower Cretaceous aquifer | Basement rock |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North Carolina | | | | | | | | | | | | | | | | | | | | |
| 1 | AA 26X | 34.660000 | –77.478889 | 10 | — | — | — | — | — | — | –221 | –246 | –533 | –607 | –1006 | –1092 | –1202 | –1267 | — | –1445 |
| 2 | AA 27W | 34.433333 | –77.563889 | 37 | — | — | — | — | — | — | –172 | –195 | –488 | –546 | –955 | –1035 | –1135 | –1206 | — | –1363 |
| 3 | AA 35N | 34.455982 | –78.307832 | 28 | — | — | — | — | — | — | –6 | –14 | –150 | –233 | –366 | –407 | –517 | –577 | — | –642 |
| 4 | AA 43Q | 34.438889 | –78.971667 | 80 | — | — | — | — | — | — | 48 | 31 | –12 | –28 | –180 | –309 | — | — | — | –416 |
| 5 | B 20U | 36.507222 | –77.005834 | 69 | — | — | — | — | 9 | –9 | — | — | — | — | –38 | –85 | –275 | –339 | –606 | –752 |
| 6 | BB 28J | 34.399976 | –77.678170 | 60 | — | — | 2 | –17 | — | — | –110 | –142 | –447 | –505 | –862 | –1000 | –1088 | –1154 | — | –1288 |
| 7 | BB 28N | 34.675000 | –77.708333 | 34 | — | — | — | — | — | — | –114 | –142 | –440 | –480 | –814 | –869 | –1076 | –1137 | — | –1213 |
| 8 | BB 45M | 34.373333 | –79.127222 | 94 | — | — | — | — | — | — | — | — | 34 | –11 | –266 | –368 | — | — | — | –455 |
| 9 | C 14T | 36.436111 | –76.501389 | 25 | –58 | –108 | –217 | –277 | –326 | –346 | — | — | — | — | –427 | –449 | –755 | –770 | –1221 | –2088 |
| 10 | C 22Q | 36.434167 | –77.227500 | 105 | 66 | 50 | — | — | — | — | — | — | — | — | –1 | –15 | –27 | –82 | — | –415 |
| 11 | D 10A | 36.411111 | –76.175000 | 8 | –64 | –106 | –410 | –547 | –624 | –646 | — | — | — | — | –817 | –862 | –1104 | –1327 | –1612 | –2814 |
| 12 | D 12V | 36.333333 | –76.366667 | 15 | –58 | –93 | –320 | –375 | –449 | –475 | — | — | — | — | –524 | –577 | –1209 | –1271 | –1450 | –2605 |
| 13 | D 18M | 36.380000 | –76.890833 | 38 | — | — | — | — | –50 | –62 | — | — | — | — | –114 | –170 | –270 | –302 | — | –902 |
| 14 | DD 37L | 34.208333 | –78.441667 | 48 | — | — | — | — | — | — | –8 | –30 | –222 | –266 | –448 | –476 | –597 | –714 | — | –884 |
| 15 | DD 42N | 34.210698 | –78.896111 | 108 | — | — | — | — | — | — | 15 | 6 | –187 | –204 | –333 | –432 | –542 | –586 | — | –771 |
| 16 | E 7J | 36.305834 | –75.929723 | 5 | –80 | –150 | –615 | –759 | –948 | –1000 | — | — | — | — | –1423 | –1469 | –1763 | –1910 | –2203 | –4516 |
| 17 | E 25J | 34.210278 | –78.896667 | 37 | — | — | — | — | — | — | — | — | — | — | 16 | –3 | –49 | –67 | — | –182 |
| 18 | EE 36K | 34.128756 | –78.338547 | 61 | — | — | — | — | — | — | 10 | 3 | –307 | –373 | –592 | –618 | –754 | –834 | — | –1054 |
| 19 | EE 39O | 34.125932 | –78.663792 | 60 | — | — | — | — | — | — | –5 | –20 | –272 | –290 | –433 | –506 | –647 | –742 | — | –901 |
| 20 | G 6L | 36.117222 | –75.852778 | 10 | –79 | –116 | –520 | –560 | –1060 | –1160 | — | — | — | — | –1310 | –1500 | –2165 | –2325 | –2700 | –5055 |
| 21 | G 19B | 36.164722 | –76.937778 | 65 | 37 | 1 | — | — | –55 | –71 | — | — | — | — | –109 | –145 | –363 | –451 | –991 | –1033 |
| 22 | G 24O | 36.126667 | –77.411667 | 93 | 65 | 53 | — | — | — | — | — | — | — | — | 17 | 11 | –89 | –150 | — | –245 |
| 23 | GG 31J | 33.973611 | –77.919444 | 9 | — | — | –95 | –113 | — | — | –171 | –219 | –461 | –539 | –835 | –905 | –1045 | –1125 | — | –1515 |
| 24 | GG 31P | 33.944444 | –77.997778 | 25 | — | — | –27 | –43 | — | — | –65 | –89 | –451 | –616 | –800 | –867 | –988 | –1094 | — | –1525 |
| 25 | H 24Q | 36.030000 | –77.397222 | 90 | 79 | 50 | — | — | — | — | — | — | — | — | –5 | –19 | –158 | –255 | — | –306 |
| 26 | HH 39J | 33.892777 | –78.589421 | — | — | — | — | — | — | — | — | 47 | –354 | –420 | –643 | –700 | –805 | –875 | — | –1286 |
| 27 | HH 39K | 36.301111 | –77.436667 | 50 | — | — | — | — | — | — | –12 | –50 | –349 | –416 | –638 | –694 | –802 | –868 | — | –1282 |
| 28 | I 13X | 35.916795 | –76.469963 | 11 | –25 | –53 | –261 | –292 | –417 | –496 | — | — | — | — | –594 | –767 | –990 | –1008 | –1750 | –2100 |
| 29 | J 7T | 35.863889 | –75.925000 | 3 | –143 | –189 | –532 | –617 | –1127 | –1207 | –1324 | –1355 | –1511 | –1612 | –1709 | –1852 | –2548 | –2682 | –2900 | –5119 |
| 30 | J 22P | 35.482494 | –77.597095 | 75 | 61 | 47 | — | — | — | — | — | — | 5 | –47 | –165 | –193 | –437 | –461 | — | –569 |
| 31 | J 26H | 35.892778 | –77.538333 | 50 | — | — | — | — | — | — | — | — | — | — | 21 | 10 | — | — | — | –299 |
| 32 | J 28J | 35.895277 | –77.678888 | 88 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | –85 |
| 33 | J 28S | 35.854167 | –77.687500 | 98 | — | — | — | — | — | — | — | — | — | — | 86 | 34 | –24 | –84 | — | –126 |
| 34 | K 17A | 35.823880 | –76.758325 | 33 | –20 | –44 | –115 | –123 | –211 | –238 | — | — | –322 | –395 | –500 | –632 | –900 | –950 | — | –1550 |
| 35 | K 26M | 35.790983 | –77.547998 | 33 | — | — | — | — | — | — | — | — | — | — | –23 | –29 | –195 | — | — | –290 |

**Appendix B1.** Aquifer and confining unit top surface altitudes interpreted from borehole geophysical logs, cores, and other data in the Coastal Plain of North Carolina, South Carolina, eastern Georgia, and southern Virginia.—Continued

[Borehole locations are on *figure B3*; borehole numbers in **bold** are coreholes; —, not present]

| Borehole location on *figure B3* | Borehole number | Latitude (decimal degrees) | Longitude (decimal degrees) | Top surface altitude, in feet: Land surface/ top of surficial aquifer | Yorktown/ Upper Floridan confining unit | Yorktown/ Upper Floridan aquifer | Castle Hayne/ Pungo River/ Middle Floridan confining unit | Castle Hayne/ Pungo River/ Middle Floridan aquifer | Beaufort/ Gordon confining unit | Beaufort/ Gordon aquifer | Peedee/ Crouch Branch confining unit | Peedee/ Crouch Branch aquifer | Black Creek/ McQueen Branch confining unit | Black Creek/ McQueen Branch aquifer | Upper Cape Fear/ Charleston confining unit | Upper Cape Fear/ Charleston aquifer | Lower Cape Fear/ Gramling confining unit | Lower Cape Fear/ Gramling aquifer | Lower Cretaceous aquifer | Basement rock |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North Carolina—Continued | | | | | | | | | | | | | | | | | | | | |
| 36 | K 27N | 35.790000 | –77.639444 | 104 | 70 | 44 | — | — | — | — | — | — | — | — | 37 | –2 | –66 | –152 | — | –200 |
| 37 | K 28V | 35.756389 | –77.689444 | 95 | — | — | — | — | — | — | — | — | — | — | 1 | –9 | –35 | –71 | — | –197 |
| 38 | K 30T | 35.771388 | –77.838055 | 120 | — | — | — | — | — | — | — | — | — | — | 74 | 60 | — | — | — | 1 |
| 39 | L 24B | 35.749580 | –77.364980 | 55 | 37 | 28 | — | — | — | — | 15 | 5 | –3 | –29 | –199 | –217 | –435 | –483 | — | –635 |
| 40 | L 25P | 35.856521 | –77.248202 | 13 | 3 | –7 | — | — | — | — | — | — | –38 | –47 | –88 | –122 | –344 | –412 | — | –442 |
| 41 | L 28F | 35.731111 | –77.740278 | 121 | 99 | 82 | — | — | — | — | — | — | — | — | 78 | 41 | — | — | — | –124 |
| 42 | M 17X | 35.637500 | –76.854167 | 40 | — | — | — | –63 | –222 | –245 | –348 | –367 | –453 | –570 | –647 | –692 | –1173 | –1243 | — | –1550 |
| 43 | M 24L | 35.626957 | –77.359692 | 20 | — | — | — | — | — | — | –10 | –26 | –50 | –84 | –252 | –267 | –475 | –520 | — | –636 |
| 44 | M 26Q | 35.607778 | –77.596111 | 80 | 72 | 50 | — | — | — | — | — | — | 27 | 16 | –96 | –156 | –393 | –400 | — | –423 |
| 45 | M 29P | 35.605555 | –77.821388 | 90 | — | — | — | — | — | — | — | — | — | — | 56 | –7 | — | — | — | –58 |
| 46 | M 29Q | 35.601388 | –77.810833 | 85 | 77 | 71 | — | — | — | — | — | — | — | — | 49 | –21 | — | — | — | –65 |
| 47 | M 29R | 35.600278 | –77.815833 | 75 | 69 | 63 | — | — | — | — | — | — | 57 | 49 | 37 | 27 | — | — | — | –87 |
| 48 | M 30L | 35.631433 | –77.852263 | 103 | 73 | 63 | — | — | — | — | — | — | — | — | 41 | 36 | — | — | — | –45 |
| 49 | M 31I | 35.640278 | –77.937222 | 122 | 103 | 97 | — | — | — | — | — | — | — | — | 81 | 72 | — | — | — | 64 |
| 50 | N 21M | 35.536399 | –77.119290 | 33 | — | — | 10 | –1 | –76 | –87 | –180 | –209 | –286 | –328 | –520 | –550 | –825 | –850 | — | –1400 |
| 51 | N 23P | 35.529964 | –77.326652 | 70 | 64 | 55 | — | — | — | — | 2 | –44 | –131 | –216 | –372 | –404 | –601 | –610 | — | –860 |
| 52 | N 31I | 35.311944 | –78.032500 | 135 | — | — | — | — | — | — | — | — | 100 | 91 | 37 | 17 | — | — | — | –66 |
| 53 | N 31M | 35.541666 | –77.971666 | 145 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 73 |
| 54 | O 17I | 35.473171 | –76.782610 | 8 | –2 | –16 | –103 | –119 | — | — | — | — | –620 | –650 | –690 | –720 | –1070 | –1100 | — | –2000 |
| 55 | O 23L | 35.463640 | –77.275232 | 42 | 32 | 24 | 4 | 1 | — | — | –94 | –112 | –212 | –262 | — | — | –634 | –728 | — | –1036 |
| 56 | O 27J | 35.477778 | –77.599722 | 77 | 69 | 47 | — | — | — | — | — | — | 15 | –7 | –123 | –199 | –339 | — | — | –449 |
| 57 | O 27J | 35.475000 | –77.591666 | 78 | 62 | 35 | — | — | — | — | — | — | 10 | –16 | –122 | –202 | –337 | –396 | — | –467 |
| 58 | O 28K | 35.455055 | –77.668767 | — | — | — | — | — | — | — | — | — | — | — | –89 | –153 | –269 | –297 | — | — |
| 59 | O 28K | 35.455055 | –77.668767 | 37 | — | — | — | — | — | — | — | — | 24 | 15 | –48 | –114 | –260 | –280 | — | –350 |
| 60 | O 30J | 35.469778 | –77.849778 | 97 | — | — | — | — | — | — | — | — | 70 | 65 | –4 | –23 | — | — | — | –115 |
| 61 | O 30Q | 35.438889 | –77.898611 | 128 | — | — | — | — | — | — | — | — | — | — | 22 | –12 | — | — | — | –96 |
| 62 | O 41L | 35.464444 | –78.778611 | 290 | — | — | — | — | — | — | — | — | 278 | 264 | — | — | — | — | — | 209 |
| 63 | P 17I | 35.386451 | –76.783141 | 9 | –26 | –34 | –42 | –75 | — | — | — | — | –611 | –678 | –780 | –800 | –1130 | –1150 | — | –2100 |
| 64 | P 18V | 35.343707 | –76.861047 | 36 | 6 | –14 | –50 | –108 | — | — | — | — | –560 | –640 | –780 | –800 | –1130 | –1150 | — | –2050 |
| 65 | P 19M | 35.373479 | –76.951008 | 27 | 23 | 3 | –39 | –45 | — | — | — | — | –443 | –540 | –700 | –720 | –1070 | –1100 | — | –1500 |
| 66 | P 22J | 35.381484 | –77.087762 | 41 | — | — | 9 | –15 | — | — | –219 | –237 | –411 | –519 | –610 | –630 | –990 | –1010 | — | –1350 |
| 67 | P 22J | 35.387222 | –77.173333 | 48 | 33 | 26 | –4 | –20 | –98 | –116 | –126 | –140 | –307 | –390 | –734 | –762 | –875 | –925 | — | –1210 |
| 68 | P 22U | 35.332429 | –77.172490 | 26 | — | — | 3 | –40 | — | — | –168 | –192 | –362 | –482 | –580 | –600 | –875 | –930 | — | –1260 |
| 69 | P 26U | 35.336736 | –77.511829 | 72 | — | — | — | — | — | — | 60 | 44 | –125 | –172 | –342 | –363 | –608 | –648 | — | –760 |
| 70 | P 27A | 35.416111 | –77.592222 | 78 | — | — | — | — | — | — | — | — | 14 | –24 | –150 | –192 | –342 | — | — | –362 |

**Appendix B1.** Aquifer and confining unit top surface altitudes interpreted from borehole geophysical logs, cores, and other data in the Coastal Plain of North Carolina, South Carolina, eastern Georgia, and southern Virginia.—Continued

[Borehole locations are on *figure B3*; borehole numbers in **bold** are coreholes; —, not present]

| Borehole location on *figure B3* | Borehole number | Latitude (decimal degrees) | Longitude (decimal degrees) | Top surface altitude, in feet | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Land surface/ top of surficial aquifer | York- town/ Upper Floridan confining unit | York- town/ Upper Floridan aquifer | Castle Hayne/ Pungo River/ Middle Floridan confining unit | Castle Hayne/ Pungo River/ Middle Floridan aquifer | Beau- fort/ Gordon confin- ing unit | Beau- fort/ Gordon aquifer | Peedee/ Crouch Branch confining unit | Peedee/ Crouch Branch aquifer | Black Creek/ McQueen Branch confining unit | Black Creek/ McQueen Branch aquifer | Upper Cape Fear/ Charles- ton confining unit | Upper Cape Fear/ Charles- ton aquifer | Lower Cape Fear/ Gramling confin- ing unit | Lower Cape Fear/ Gramling aquifer | Lower Creta- ceous aquifer | Base- ment rock |
| North Carolina—Continued | | | | | | | | | | | | | | | | | | | | |
| 71 | P 31M | 35.375556 | –77.957222 | 118 | — | — | — | — | — | — | — | — | — | — | 78 | 56 | — | — | — | –52 |
| 72 | P 31Y | 35.335556 | –77.985556 | 66 | — | — | — | — | — | — | — | — | — | — | 50 | 33 | — | — | — | –84 |
| 73 | P 35U | 35.343056 | –78.256944 | 125 | — | — | — | — | — | — | — | — | 117 | 108 | 86 | 70 | — | — | — | 10 |
| 74 | P 38O | 35.374444 | –78.567500 | 210 | — | — | — | — | — | — | — | — | 190 | 160 | 124 | 109 | — | — | — | 62 |
| 75 | P 41O | 35.382222 | –78.828333 | 239 | — | — | — | — | — | — | — | — | 229 | 220 | — | — | — | — | — | 183 |
| 76 | Q 25D | 35.327137 | –77.478071 | 65 | — | — | — | — | — | — | 11 | –15 | –135 | –185 | –341 | –381 | –559 | –595 | — | –735 |
| 77 | Q 27R | 35.269344 | –77.618238 | 44 | — | — | — | — | — | — | 36 | 9 | –57 | –138 | –330 | –380 | — | — | — | –586 |
| 78 | Q 30H | 35.551111 | –77.934722 | 130 | — | — | — | — | — | — | — | — | — | — | 97 | 54 | — | — | — | –42 |
| 79 | Q 30I | 35.301111 | –77.866389 | 105 | — | — | — | — | — | — | — | — | 93 | 72 | –50 | –108 | — | — | — | –244 |
| 80 | Q 31D | 35.322222 | –77.970000 | 63 | — | — | — | — | — | — | — | — | 60 | 53 | –22 | — | — | — | — | –105 |
| 81 | Q 32D | 35.319444 | –78.061944 | 164 | — | — | — | — | — | — | — | — | 150 | 128 | 93 | 57 | — | — | — | –40 |
| 82 | Q 32I | 35.553333 | –77.935555 | 133 | — | — | — | — | — | — | — | — | — | — | 123 | 116 | — | — | — | 55 |
| 83 | Q 32M | 35.329444 | –78.060555 | 138 | — | — | — | — | — | — | — | — | 128 | 121 | 44 | 31 | — | — | — | –37 |
| 84 | Q 32O | 35.299166 | –78.038611 | 175 | — | — | — | — | — | — | — | — | — | — | 75 | 51 | — | — | — | –88 |
| 85 | Q 32W | 35.261667 | –78.034167 | 185 | — | — | — | — | — | — | — | — | 157 | 151 | 31 | 11 | — | — | — | –77 |
| 86 | Q 36U | 35.250833 | –78.348056 | 180 | — | — | — | — | — | — | — | — | 130 | 108 | 10 | –1 | — | — | — | –119 |
| 87 | R 21O | 35.210833 | –77.156667 | 23 | — | — | — | — | — | — | –241 | –273 | –433 | –473 | –770 | –790 | –980 | –1000 | — | –1410 |
| 88 | R 23U | 35.175833 | –77.250556 | 47 | — | — | 22 | 12 | — | — | –223 | –323 | –395 | –740 | –760 | 10000 | –900 | –930 | — | –1300 |
| 89 | R 23W | 35.177222 | –77.297778 | 34 | — | — | — | — | –137 | –158 | –203 | –272 | –385 | –420 | –718 | –734 | –860 | –890 | — | –1200 |
| 90 | R 23X | 35.172305 | –77.311178 | 46 | — | — | 29 | 6 | –97 | –104 | –174 | –210 | –368 | –434 | –716 | –732 | –844 | –882 | — | –1190 |
| 91 | R 24N | 35.206666 | –77.390000 | 60 | — | — | 56 | 46 | –44 | –50 | –97 | –160 | –306 | –344 | –612 | –626 | –790 | –810 | — | –993 |
| 92 | R 25J | 35.221944 | –77.425833 | 55 | — | — | — | — | –27 | –44 | –69 | –136 | –263 | –297 | –539 | –571 | –677 | –795 | — | –925 |
| 93 | R 27A | 35.238611 | –77.595000 | 43 | — | — | — | — | — | — | 23 | –13 | –83 | –177 | –333 | –379 | –593 | –623 | — | –697 |
| 94 | R 29T | 35.196160 | –77.752000 | 110 | — | — | — | — | — | — | 68 | 60 | –6 | –54 | –262 | –288 | — | — | — | –490 |
| 95 | R 31C | 35.244508 | –77.963034 | 150 | — | — | — | — | — | — | — | — | 127 | 100 | 13 | –6 | — | — | — | –170 |
| 96 | R 32E | 35.241944 | –78.068055 | 120 | — | — | — | — | — | — | — | — | — | — | 66 | 52 | — | — | — | –91 |
| 97 | R 32O | 35.205556 | –78.075000 | 160 | — | — | — | — | — | — | — | — | 141 | 135 | 44 | 16 | — | — | — | –168 |
| 98 | R 39P | 35.191667 | –78.654167 | 143 | — | — | — | — | — | — | — | — | 95 | 86 | 29 | 9 | — | — | — | –60 |
| 99 | R 45N | 34.810394 | –77.487225 | 325 | — | — | — | — | — | — | — | — | — | — | 251 | 226 | — | — | — | 143 |
| 100 | R 49M | 35.205278 | –79.464167 | 505 | — | — | — | — | — | — | — | — | — | — | 349 | 295 | — | — | — | 281 |
| 101 | S 21I | 35.137500 | –77.105556 | 27 | — | — | — | — | –199 | –223 | — | — | –633 | –701 | –893 | –905 | –1135 | –1150 | — | –1600 |
| 102 | S 21Y | 35.095556 | –77.152222 | 21 | — | — | — | — | –294 | –307 | –339 | –355 | –558 | –660 | –900 | –920 | –1140 | –1160 | — | –1590 |
| 103 | S 22J | 35.137475 | –77.171389 | 28 | — | — | 10 | 1 | — | — | –319 | –346 | –502 | –594 | –830 | –860 | –1050 | –1072 | — | –1490 |
| 104 | S 26I | 35.139489 | –77.530205 | 55 | — | — | 45 | 39 | 7 | –5 | –65 | –91 | –230 | –275 | –439 | –483 | –683 | –701 | — | –875 |
| 105 | S 39T | 35.104444 | –78.589722 | 170 | — | — | — | — | — | — | — | — | 103 | 74 | 41 | –5 | –110 | –145 | — | –180 |

**Appendix B1.** Aquifer and confining unit top surface altitudes interpreted from borehole geophysical logs, cores, and other data in the Coastal Plain of North Carolina, South Carolina, eastern Georgia, and southern Virginia.—Continued

[Borehole locations are on *figure B3*; borehole numbers in **bold** are coreholes; —, not present]

| Borehole location on *figure B3* | Borehole number | Latitude (decimal degrees) | Longitude (decimal degrees) | Top surface altitude, in feet: Land surface/top of surficial aquifer | Yorktown/Upper Floridan confining unit | Yorktown/Upper Floridan aquifer | Castle Hayne/Pungo River/Middle Floridan confining unit | Castle Hayne/Pungo River/Middle Floridan aquifer | Beaufort/Gordon confining unit | Beaufort/Gordon aquifer | Peedee/Crouch Branch confining unit | Peedee/Crouch Branch aquifer | Black Creek/McQueen Branch confining unit | Black Creek/McQueen Branch aquifer | Upper Cape Fear/Charleston confining unit | Upper Cape Fear/Charleston aquifer | Lower Cape Fear/Gramling confining unit | Lower Cape Fear/Gramling aquifer | Lower Cretaceous aquifer | Basement rock |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North Carolina—Continued | | | | | | | | | | | | | | | | | | | | |
| 106 | S 41W | 35.090556 | –78.788056 | 125 | — | — | — | — | — | — | — | — | 96 | 90 | 49 | 9 | — | — | — | –75 |
| 107 | S 42O | 35.119167 | –78.911667 | 240 | — | — | — | — | — | — | — | — | — | — | 113 | 74 | — | — | — | –28 |
| 108 | S 48H | 35.144722 | –79.371667 | 475 | — | — | — | — | — | — | — | — | — | — | 299 | 229 | — | — | — | 206 |
| 109 | T 22A | 35.082778 | –77.180278 | 34 | — | — | –20 | –38 | –289 | –302 | –334 | –342 | –529 | –644 | –872 | –922 | –1110 | –1150 | — | –1550 |
| 110 | T 29G | 35.056327 | –77.807143 | 127 | — | — | — | — | — | — | 45 | 35 | –79 | –113 | –301 | –323 | –270 | –290 | — | –550 |
| 111 | T 48T | 35.033333 | –79.348889 | 350 | — | — | — | — | — | — | — | — | — | — | 198 | 144 | — | — | — | 102 |
| 112 | U 18Q | 34.933879 | –76.890064 | 26 | –21 | –34 | –74 | –84 | –489 | –516 | –674 | –747 | –1017 | –1064 | –1350 | –1400 | –1770 | –1800 | — | –2800 |
| 113 | U 26J | 34.969429 | –77.503222 | 71 | — | — | 61 | 47 | –11 | –25 | –123 | –153 | –289 | –323 | –685 | –715 | –850 | –890 | — | –1080 |
| 114 | U 34B | 34.988899 | –78.189350 | 145 | — | — | — | — | — | — | — | — | 99 | 71 | –58 | –93 | –190 | –208 | — | –310 |
| 115 | U 35D | 34.975278 | –78.306111 | 155 | — | — | — | — | — | — | — | — | 104 | 81 | –67 | –112 | –191 | –204 | — | –297 |
| 116 | U 38T | 34.944167 | –78.507778 | 134 | — | — | — | — | — | — | — | — | 95 | 59 | –30 | –86 | –166 | –176 | — | –219 |
| 117 | U 41A | 34.987500 | –78.754167 | 130 | — | — | — | — | — | — | — | — | 88 | 70 | 11 | –20 | — | — | — | –103 |
| 118 | U 46O | 34.975278 | –79.236667 | 253 | — | — | — | — | — | — | — | — | 231 | 218 | 126 | 51 | — | — | — | –4 |
| 119 | U 53M | 34.960556 | –79.791111 | 340 | — | — | — | — | — | — | — | — | 332 | 317 | — | — | — | — | — | 225 |
| 120 | V 19W | 34.848611 | –76.962500 | 41 | 16 | 1 | –187 | –245 | — | — | –759 | –796 | –915 | –1207 | –1429 | –1519 | –1874 | –1924 | — | –2365 |
| 121 | V 23X | 34.837042 | –77.303278 | 45 | — | — | — | — | –195 | –221 | –421 | –458 | –641 | –761 | –1025 | –1100 | –960 | –1010 | — | –1540 |
| 122 | V 24G | 34.900000 | –77.395833 | 52 | — | — | — | — | –168 | –186 | –298 | –328 | –448 | –598 | –888 | –928 | –1028 | –1068 | — | –1318 |
| 123 | V 42U | 34.843611 | –78.838333 | 147 | — | — | — | — | — | — | — | — | 125 | 113 | –86 | –119 | — | — | — | –237 |
| 124 | V 45U | 34.843151 | –79.087593 | 185 | — | — | — | — | — | — | — | — | 173 | 160 | 55 | –103 | — | — | — | –167 |
| 125 | V 52I | 34.891667 | –79.686111 | 325 | — | — | — | — | — | — | — | — | 303 | 283 | 147 | — | — | — | — | 117 |
| 126 | W 22V | 34.757222 | –77.193333 | 37 | 1 | –11 | –116 | –167 | — | — | –584 | –634 | –755 | –983 | –1220 | –1261 | –1410 | –1446 | — | –1769 |
| 127 | W 25F | 34.604530 | –78.241805 | 26 | — | — | — | — | — | — | –198 | –258 | –392 | –433 | –748 | –794 | –994 | –1020 | — | –1210 |
| 128 | W 29D | 34.824016 | –77.812048 | 45 | — | — | — | 9 | –1 | — | –95 | –125 | –213 | –245 | –544 | –579 | — | — | — | –743 |
| 129 | W 36N | 34.786111 | –78.396944 | 125 | — | — | — | — | — | — | 72 | 56 | 31 | 13 | –119 | –150 | –231 | –259 | — | –279 |
| 130 | W 43L | 34.801561 | –78.973485 | 151 | — | — | — | — | — | — | — | — | 138 | 126 | –51 | –127 | — | — | — | –209 |
| 131 | W 48V | 34.766389 | –79.366389 | 208 | — | — | — | — | — | — | — | — | 152 | 124 | –29 | –101 | — | — | — | –156 |
| 132 | W 51V | 34.759722 | –79.610556 | 250 | — | — | — | — | — | — | — | — | 186 | 177 | 68 | 16 | — | — | — | 5 |
| 133 | X 24S | 34.692198 | –77.351180 | 20 | — | — | –82 | –98 | — | — | –400 | –440 | –676 | –838 | –1063 | –1174 | –1270 | –1306 | — | –1550 |
| 134 | X 26R | 34.427778 | –77.619444 | 50 | — | — | — | — | –145 | –163 | –200 | –215 | –385 | –445 | –876 | –930 | –1040 | –1070 | — | –1223 |
| 135 | X 26U | 34.700000 | –77.533333 | 57 | — | — | –33 | –71 | — | — | –357 | –409 | –473 | –531 | –973 | –1003 | –1219 | –1241 | — | –1351 |
| 136 | X 45J | 34.726944 | –79.092778 | 166 | — | — | — | — | — | — | — | — | 154 | 132 | –32 | –184 | — | — | — | –296 |
| 137 | X 26S | 34.672222 | –77.505556 | 38 | — | — | 30 | 8 | — | — | –122 | –142 | –462 | –552 | –880 | –942 | –996 | –1046 | — | –1212 |
| 138 | Y 25D | 34.697222 | –77.537500 | 65 | — | — | –35 | –73 | — | — | –329 | –387 | –459 | –511 | –947 | –993 | –1204 | –1226 | — | –1330 |
| 139 | Y 25Q | 34.611365 | –77.482799 | 66 | — | — | –14 | –86 | — | — | –404 | –456 | –548 | –674 | –988 | –1044 | –1280 | –1300 | — | –1400 |
| 140 | Y 30S | 34.604749 | –77.856070 | 14 | — | — | — | — | — | — | –24 | –46 | –298 | –342 | –673 | –744 | — | — | — | –902 |

**Appendix B1.** Aquifer and confining unit top surface altitudes interpreted from borehole geophysical logs, cores, and other data in the Coastal Plain of North Carolina, South Carolina, eastern Georgia, and southern Virginia.—Continued

[Borehole locations are on *figure B3*; borehole numbers in **bold** are coreholes; —, not present]

| Borehole location on *figure B3* | Borehole number | Latitude (decimal degrees) | Longitude (decimal degrees) | Top surface altitude, in feet: Land surface/ top of surficial aquifer | York-town/ Upper Floridan confining unit | York-town/ Upper Floridan aquifer | Castle Hayne/ Pungo River/ Middle Floridan confining unit | Castle Hayne/ Pungo River/ Middle Floridan aquifer | Beau-fort/ Gordon confin-ing unit | Beau-fort/ Gordon aquifer | Peedee/ Crouch Branch confining unit | Peedee/ Crouch Branch aquifer | Black Creek/ McQueen Branch confining unit | Black Creek/ McQueen Branch aquifer | Upper Cape Fear/ Charles-ton confining unit | Upper Cape Fear/ Charles-ton aquifer | Lower Cape Fear/ Gramling confin-ing unit | Lower Cape Fear/ Gramling aquifer | Lower Creta-ceous aquifer | Base-ment rock |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | North Carolina—Continued | | | | | | | | | | | | |
| 141 | Y 34P | 35.215833 | –79.146111 | 34 | — | — | — | — | — | — | 1 | –30 | –107 | –123 | –255 | –294 | –451 | –474 | — | –544 |
| 142 | Y 38B | 34.655278 | –78.522500 | 65 | — | — | — | — | — | — | — | — | –38 | –49 | –168 | –203 | –318 | –365 | — | –425 |
| 143 | Y 39G | 34.632500 | –78.620833 | 130 | — | — | — | — | — | — | 100 | 86 | 10 | 1 | –135 | –177 | –311 | –330 | — | –384 |
| 144 | Y 42F | 34.644444 | –78.916667 | 140 | — | — | — | — | — | — | — | — | 114 | 67 | –185 | –242 | — | — | — | –327 |
| 145 | Z 41M | 34.507500 | –78.755278 | 116 | — | — | — | — | — | — | 68 | 50 | –14 | –33 | –151 | –196 | –367 | –408 | — | –459 |
| 146 | Z 45V | 34.501111 | –79.109444 | 108 | — | — | — | — | — | — | — | — | 40 | –10 | –258 | –438 | — | — | — | –504 |
| 147 | Z 47R | 34.532009 | –79.296151 | 145 | — | — | — | — | — | — | — | — | 61 | 33 | –170 | –288 | — | — | — | –357 |
| | | | | | | | | South Carolina | | | | | | | | | | | | |
| 148 | **AIK–0817** | 33.437778 | –81.770278 | 418 | — | 374 | — | — | — | 346 | 240 | 231 | 23 | 12 | — | — | — | — | — | –120 |
| 149 | **AIK–0826** | 33.542500 | –81.485833 | 296 | 295 | 294 | — | — | — | 266 | 241 | 220 | –0 | –21 | — | — | — | — | — | –210 |
| 150 | **AIK–0892** | 33.337500 | –81.708611 | 354 | — | 264 | — | 236 | — | 207 | — | 74 | –175 | –199 | — | — | –370 | — | — | –396 |
| 151 | **AIK–0902** | 33.353611 | –81.808889 | — | — | — | — | — | — | 231 | 139 | 68 | –86 | –119 | — | — | — | — | — | –317 |
| 152 | **AIK–2448** | 33.624444 | –81.849722 | 489 | — | 477 | — | — | — | 459 | — | 400 | — | — | — | — | — | — | — | 367 |
| 153 | **AIK–2449** | 33.539444 | –81.855000 | 493 | — | 464 | — | — | — | 429 | — | 347 | 239 | 232 | — | — | — | — | — | 180 |
| 154 | **ALL–0348** | 33.025000 | –81.384722 | 281 | 123 | 111 | 26 | –39 | –122 | –165 | –353 | –464 | –841 | –881 | — | –1155 | –1208 | — | — | –1441 |
| 155 | **ALL–0357** | 33.113333 | –81.506111 | 242 | — | 170 | 72 | 57 | 15 | –71 | –200 | –280 | –665 | –696 | — | — | –978 | — | — | –1154 |
| 156 | **BAM–0068** | 33.055833 | –81.098333 | 109 | 108 | 107 | 46 | –26 | –115 | –177 | –343 | –443 | –843 | –893 | –1123 | –1193 | –1243 | –1493 | — | –1593 |
| 157 | BAM–0076 | 33.242500 | –81.182500 | 214 | — | 154 | — | 24 | — | –16 | –176 | –236 | –626 | –686 | — | — | –986 | — | — | –1136 |
| 158 | BAM–0083 | 33.288333 | –81.043056 | 151 | 150 | 149 | — | 79 | 49 | –40 | –91 | –173 | –591 | –649 | — | — | –951 | — | — | –1136 |
| 159 | **BFT–2055** | 32.191111 | –80.704167 | 9 | –56 | –111 | –231 | –541 | –591 | –1221 | –1476 | –1673 | –2036 | — | –2223 | — | –2661 | –2761 | — | –3821 |
| 160 | BFT–2067 | 32.325556 | –80.823611 | 19 | –46 | –98 | –181 | –424 | –487 | –1031 | –1251 | –1431 | –1861 | — | –2031 | –2281 | –2531 | –2681 | — | –3481 |
| 161 | BFT–2092 | 32.313611 | –80.488889 | 9 | –66 | –98 | –138 | –461 | –546 | –936 | –1291 | –1541 | –1841 | — | –2071 | –2391 | –2521 | –2571 | — | –3591 |
| 162 | BRK–0430 | 33.078056 | –79.999444 | 17 | — | — | 8 | — | –133 | –178 | –283 | –523 | –983 | –1063 | –1223 | –1513 | –1643 | –1818 | — | –2233 |
| 163 | BRK–0437 | 33.366944 | –80.117222 | 81 | — | — | — | — | — | 54 | –34 | –199 | –739 | –779 | –879 | –1029 | –1194 | –1469 | — | –1719 |
| 164 | **BRK–0644** | 33.404167 | –79.933889 | 74 | — | — | — | — | — | 51 | –108 | –202 | –689 | –710 | –842 | –1010 | –1208 | –1475 | — | –1707 |
| 165 | **BRN–0240** | 33.438889 | –81.239167 | 206 | 205 | 204 | — | 164 | — | 122 | 63 | 14 | –228 | –241 | — | — | –576 | — | — | –647 |
| 166 | BRK–2689 | 33.291111 | –79.686944 | 34 | — | — | — | — | — | 8 | –153 | –296 | –749 | –816 | –1016 | –1216 | –1396 | –1616 | — | –1916 |
| 167 | BRN–0295 | 33.126944 | –81.229167 | 194 | — | 174 | 68 | 24 | –26 | –88 | –266 | –356 | –696 | –776 | — | — | –1136 | — | — | –1286 |
| 168 | **BRN–0303** | 33.245833 | –81.616111 | 294 | — | 190 | — | 134 | — | 95 | –56 | –126 | — | –316 | — | — | –633 | — | — | –776 |
| 169 | **BRN–0335** | 33.146667 | –81.607500 | 206 | — | 156 | — | 62 | 44 | –26 | –157 | –266 | –541 | –583 | — | — | –815 | — | — | –994 |
| 170 | **BRN–0349** | 33.178611 | –81.314444 | 208 | — | 184 | — | 54 | 28 | –33 | –218 | –297 | –627 | –710 | — | — | –1015 | — | — | –1118 |
| 171 | **BRN–0358** | 33.321389 | –81.407222 | 264 | — | 203 | — | 144 | 102 | 92 | –16 | –64 | –346 | –378 | — | — | –676 | — | — | –770 |
| 172 | BRN–0386 | 33.242778 | –81.403333 | — | — | 180 | — | 110 | 61 | 20 | –89 | –145 | –495 | –550 | — | — | –870 | — | — | –1000 |

**Appendix B1.** Aquifer and confining unit top surface altitudes interpreted from borehole geophysical logs, cores, and other data in the Coastal Plain of North Carolina, South Carolina, eastern Georgia, and southern Virginia.—Continued

[Borehole locations are on *figure B3*; borehole numbers in **bold** are coreholes; —, not present]

| Borehole location on *figure B3* | Borehole number | Latitude (decimal degrees) | Longitude (decimal degrees) | Top surface altitude, in feet | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Land surface/ top of surficial aquifer | Yorktown/ Upper Floridan confining unit | Yorktown/ Upper Floridan aquifer | Castle Hayne/ Pungo River/ Middle Floridan confining unit | Castle Hayne/ Pungo River/ Middle Floridan aquifer | Beaufort/ Gordon confining unit | Beaufort/ Gordon aquifer | Peedee/ Crouch Branch confining unit | Peedee/ Crouch Branch aquifer | Black Creek/ McQueen Branch confining unit | Black Creek/ McQueen Branch aquifer | Upper Cape Fear/ Charleston confining unit | Upper Cape Fear/ Charleston aquifer | Lower Cape Fear/ Gramling confining unit | Lower Cape Fear/ Gramling aquifer | Lower Cretaceous aquifer | Basement rock |
| South Carolina—Continued | | | | | | | | | | | | | | | | | | | | |
| 173 | BRN–0921 | 33.402778 | –81.414444 | 349 | — | 279 | — | 204 | 169 | 159 | — | 37 | — | –201 | — | — | –501 | — | — | –551 |
| 174 | CAL–0129 | 33.731667 | –80.879722 | 327 | — | — | — | 304 | — | 265 | 207 | 157 | –99 | –125 | — | — | –333 | — | — | –403 |
| 175 | CAL–0131 | 33.659167 | –80.663889 | 236 | — | — | — | — | 216 | 188 | 163 | 111 | –314 | –374 | — | — | –564 | — | — | –784 |
| 176 | CHN–0182 | 33.200556 | –79.435556 | 9 | — | — | — | — | — | –27 | –107 | –337 | –796 | –831 | –1041 | –1331 | –1491 | –1691 | — | –2141 |
| 177 | CHN–0635 | 32.764444 | –79.832778 | 6 | — | — | –66 | — | –281 | –324 | –409 | –684 | –944 | –1124 | –1364 | –1804 | –2018 | –2254 | — | –2794 |
| 178 | **CHN–0800** | 32.782500 | –79.945000 | 9 | — | — | –65 | — | –304 | –346 | –420 | –735 | –1038 | –1221 | –1376 | –1841 | –2041 | –2291 | — | –2841 |
| 179 | **CHN–0802** | 32.940833 | –79.657500 | 7 | — | — | –36 | — | — | –167 | –263 | –558 | –843 | –993 | –1223 | –1623 | –1803 | –2043 | — | –2593 |
| 180 | CHN–0814 | 32.602778 | –80.143611 | 4 | — | — | –96 | — | –321 | –566 | –656 | –1021 | –1296 | — | –1531 | –1978 | –2216 | –2476 | — | –3046 |
| 181 | **CHN–0820** | 33.155833 | –79.363889 | 9 | — | — | — | — | — | –33 | –112 | –358 | –776 | –826 | –1019 | –1377 | –1530 | –1691 | — | –2241 |
| 182 | CLA–0056 | 33.634167 | –80.360000 | 139 | — | — | — | — | — | 118 | 97 | 45 | –426 | –456 | –601 | –649 | –741 | — | — | –1001 |
| 183 | CLA–0064 | 33.694167 | –80.213611 | 124 | — | — | — | — | — | — | 104 | 74 | –341 | –391 | –544 | –598 | –676 | — | — | –1001 |
| 184 | COL–0053 | 32.983889 | –80.455833 | 49 | — | — | –9 | –104 | –149 | –221 | –436 | –636 | –1076 | –1151 | –1251 | –1481 | –1611 | –1851 | — | –2201 |
| 185 | COL–0241 | 33.015000 | –80.928889 | 79 | 69 | 11 | –21 | –109 | –201 | –291 | –440 | –541 | –941 | –991 | –1166 | –1336 | –1421 | –1671 | — | –1888 |
| 186 | COL–0336 | 32.723611 | –80.621111 | 24 | –24 | — | –56 | — | –216 | –436 | –556 | –786 | –1246 | –1336 | –1406 | –1696 | –1926 | –2176 | — | –2576 |
| 187 | COL–0348 | 32.883333 | –80.580833 | 21 | 6 | — | –29 | –141 | –209 | –269 | –466 | –639 | –1129 | –1189 | –1269 | –1489 | –1699 | –1944 | — | –2267 |
| 188 | COL–0349 | 33.065278 | –80.623889 | 74 | 48 | 20 | 2 | –57 | –126 | –181 | –358 | –516 | –946 | –1006 | –1126 | –1316 | –1416 | –1656 | — | –1926 |
| 189 | **COL–0364** | 32.503611 | –80.296111 | 9 | –41 | — | –71 | — | –359 | –661 | –827 | –1181 | –1511 | — | –1741 | –2141 | –2341 | –2461 | — | –3191 |
| 190 | COL–0374 | 32.558889 | –80.454722 | 4 | –46 | — | –106 | — | –276 | –526 | –661 | –976 | –1346 | — | –1546 | –1956 | –2196 | –2396 | — | –2946 |
| 191 | COL–0382 | 32.783889 | –80.859167 | 24 | 14 | –11 | –48 | –191 | –256 | –458 | –666 | –806 | –1356 | –1416 | –1466 | –1696 | –1976 | –2146 | — | –2476 |
| 192 | **CTF–0081** | 34.643056 | –79.911667 | 192 | — | — | — | — | — | — | — | 183 | — | 154 | — | — | –1 | — | — | –27 |
| 193 | CTF–0082 | 34.537222 | –79.908056 | 204 | — | — | — | — | — | — | — | 189 | — | 154 | — | — | –56 | — | — | –141 |
| 194 | CTF–0088 | 34.447778 | –80.216944 | 404 | — | — | — | — | — | — | — | 394 | 209 | 202 | — | — | 64 | — | — | –29 |
| 195 | DAR–0090 | 34.268611 | –79.807500 | 132 | — | — | — | — | — | — | — | 126 | –43 | –116 | — | — | –303 | — | — | –510 |
| 196 | DAR–0226 | 34.367778 | –80.189167 | 338 | 337 | 336 | 335 | 334 | 333 | 332 | 331 | 329 | 130 | 116 | — | — | –21 | — | — | –151 |
| 197 | **DAR–0228** | 34.458611 | –79.880000 | 179 | 178 | 177 | 176 | 175 | 174 | 173 | 172 | 171 | — | 119 | — | — | –97 | — | — | –268 |
| 198 | DIL–0114 | 34.451944 | –79.405556 | 142 | — | — | — | — | — | — | — | 124 | 4 | –20 | — | — | –228 | — | — | –405 |
| 199 | **DIL–0121** | 34.328611 | –79.283889 | 94 | — | — | — | — | — | — | — | 71 | –43 | –91 | –223 | –237 | –282 | –534 | — | –534 |
| 200 | **DOR–0037** | 32.888056 | –80.359167 | 17 | — | — | –3 | — | –215 | –350 | –528 | –779 | –1243 | –1327 | –1403 | –1733 | –1844 | –2043 | — | –2445 |
| 201 | DOR–0052 | 32.959444 | –80.202222 | 29 | — | — | 19 | — | –192 | –321 | –541 | –633 | –1131 | –1196 | –1291 | –1611 | –1731 | –1911 | — | –2341 |
| 202 | **DOR–0211** | 33.156944 | –80.521667 | 77 | — | — | 47 | –14 | –53 | –123 | –326 | –445 | –883 | –953 | –1114 | –1243 | –1324 | –1623 | — | –1885 |
| 203 | FLO–0264 | 34.101944 | –79.734167 | 105 | — | — | — | — | — | — | — | 67 | –213 | –255 | — | — | –405 | — | — | –675 |
| 204 | **FLO–0268** | 34.170278 | –79.789167 | 112 | — | — | — | — | — | — | — | 103 | –77 | –237 | — | — | –329 | — | — | –579 |
| 205 | **FLO–0274** | 33.855556 | –79.767222 | 74 | — | — | — | — | — | — | — | 44 | –328 | –359 | –516 | –596 | –654 | — | — | –1003 |
| 206 | FLO–0275 | 34.158333 | –79.794722 | 119 | — | — | — | — | — | — | — | 96 | –96 | –221 | — | — | –381 | — | — | –621 |
| 207 | FLO–0286 | 34.117778 | –79.767222 | 115 | — | — | — | — | — | — | — | 77 | –117 | –233 | — | — | –385 | — | — | –635 |

**Appendix B1.** Aquifer and confining unit top surface altitudes interpreted from borehole geophysical logs, cores, and other data in the Coastal Plain of North Carolina, South Carolina, eastern Georgia, and southern Virginia.—Continued

[Borehole locations are on *figure B3*; borehole numbers in **bold** are coreholes; —, not present]

| Borehole location on *figure B3* | Borehole number | Latitude (decimal degrees) | Longitude (decimal degrees) | Top surface altitude, in feet | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Land surface/ top of surficial aquifer | Yorktown/ Upper Floridan confining unit | Yorktown/ Upper Floridan aquifer | Castle Hayne/ Pungo River/ Middle Floridan confining unit | Castle Hayne/ Pungo River/ Middle Floridan aquifer | Beaufort/ Gordon confining unit | Beaufort/ Gordon aquifer | Peedee/ Crouch Branch confining unit | Peedee/ Crouch Branch aquifer | Black Creek/ McQueen Branch confining unit | Black Creek/ McQueen Branch aquifer | Upper Cape Fear/ Charleston confining unit | Upper Cape Fear/ Charleston aquifer | Lower Cape Fear/ Gramling confining unit | Lower Cape Fear/ Gramling aquifer | Lower Cretaceous aquifer | Basement rock |
| South Carolina—Continued | | | | | | | | | | | | | | | | | | | | |
| 208 | FLO–0310 | 34.243333 | –79.791667 | 129 | — | — | — | — | — | — | — | 117 | –61 | –151 | — | — | –321 | — | — | –531 |
| 209 | FLO–0313 | 34.033333 | –79.662222 | 107 | — | — | — | — | — | — | — | 80 | –283 | –333 | — | — | –493 | — | — | –793 |
| 210 | FLO–0317 | 33.994444 | –79.601389 | 86 | — | — | — | — | — | — | — | 56 | –278 | –349 | –489 | –534 | –594 | — | — | –914 |
| 211 | GEO–0088 | 33.251667 | –79.270833 | 4 | — | — | — | — | — | –16 | –46 | –301 | –701 | –746 | –966 | –1096 | –1348 | –1536 | — | –2046 |
| 212 | GEO–0090 | 33.443889 | –79.519722 | 25 | — | — | — | — | — | 10 | –10 | –145 | –605 | –655 | –845 | –1025 | –1195 | –1375 | — | –1675 |
| 213 | GEO–0185 | 33.356944 | –79.381944 | 19 | — | — | — | — | — | –21 | –111 | –221 | –686 | –731 | –921 | –1131 | –1301 | –1481 | — | –1831 |
| 214 | GEO–0234 | 33.561944 | –79.012222 | 4 | — | — | — | — | — | — | –46 | –96 | –516 | –541 | –746 | –876 | –1076 | –1246 | — | –1596 |
| 215 | GEO–0249 | 33.661944 | –79.246667 | 41 | — | — | — | — | — | — | 12 | –64 | –469 | –501 | –715 | –879 | –1019 | –1159 | — | –1459 |
| 216 | GEO–0277 | 33.518889 | –79.330556 | 18 | — | — | — | — | — | — | –10 | –94 | –580 | –627 | –802 | –982 | –1132 | –1272 | — | –1582 |
| 217 | GEO–0298 | 33.461111 | –79.103056 | 10 | — | — | — | — | — | — | –50 | –147 | –560 | –605 | –820 | –970 | –1190 | –1350 | — | –1740 |
| 218 | HAM–0092 | 32.746944 | –81.236111 | 111 | 25 | –1 | –44 | — | –189 | –561 | –681 | –789 | –1259 | –1349 | –1469 | –1539 | –1739 | –1939 | — | –2189 |
| 219 | HAM–0191 | 32.873056 | –81.117500 | 111 | 81 | 41 | –39 | –124 | –166 | –485 | –614 | –689 | –1159 | –1239 | –1389 | –1489 | –1639 | –1839 | — | –2059 |
| 220 | HOR–0287 | 33.853056 | –79.071667 | 26 | — | — | — | — | — | — | — | 13 | –324 | –344 | –524 | –642 | –774 | –904 | — | –1154 |
| 221 | HOR–0998 | 34.020000 | –79.223333 | 79 | — | — | — | — | — | — | — | 39 | –251 | –296 | –421 | –521 | –621 | –821 | — | –951 |
| 222 | **HOR–1165** | 33.723333 | –78.903889 | 22 | — | — | — | — | — | — | — | –6 | –410 | –457 | –609 | –694 | –871 | –1055 | — | –1352 |
| 223 | **JAS–0426** | 32.618333 | –80.995833 | 63 | 15 | –83 | –159 | –227 | –322 | –627 | –843 | –940 | –1547 | — | –1707 | –1877 | –2225 | –2334 | — | –2733 |
| 224 | LEE–0019 | 34.063889 | –80.064722 | 139 | — | — | — | — | — | — | — | 102 | –180 | –241 | — | — | –416 | — | — | –609 |
| 225 | LEE–0072 | 34.102778 | –80.163889 | 174 | — | — | — | — | — | — | — | 143 | –110 | –136 | — | — | –341 | — | — | –496 |
| 226 | **LEE–0075** | 34.202500 | –80.174444 | 198 | — | — | — | — | — | — | — | 175 | –12 | –26 | — | — | –229 | — | — | –339 |
| 227 | LEX–0154 | 33.877778 | –81.166667 | 347 | 346 | 346 | 344 | 343 | 342 | 341 | 340 | 339 | — | 219 | — | — | 59 | — | — | 51 |
| 228 | **LEX–0844** | 33.745556 | –81.107778 | 372 | 371 | 370 | 369 | 368 | 367 | 366 | 336 | 292 | — | 61 | — | — | –162 | — | — | –174 |
| 229 | MLB–0182 | 34.668889 | –79.730556 | 189 | 188 | 187 | 186 | 185 | 184 | 183 | 182 | 181 | 180 | 179 | — | — | –11 | — | — | –71 |
| 230 | MLB–0183 | 34.638055 | –79.593611 | 207 | 206 | 205 | 204 | 203 | 202 | 201 | 200 | 199 | 149 | 99 | — | — | –36 | — | — | –163 |
| 231 | **MRN–0078** | 33.861944 | –79.330556 | 29 | — | — | — | — | — | — | — | –6 | –326 | –341 | –521 | –636 | –751 | –951 | — | –1129 |
| 232 | MRN–0089 | 34.195278 | –79.240833 | 79 | — | — | — | — | — | — | — | 62 | –179 | –236 | –336 | — | –421 | — | — | –701 |
| 233 | MRN–0125 | 34.151389 | –79.378611 | 79 | — | — | — | — | — | — | — | 44 | –159 | –238 | –371 | –406 | –446 | — | — | –721 |
| 234 | ORG–0108 | 33.348611 | –80.679722 | 141 | — | — | — | 121 | 31 | –94 | –139 | –189 | –609 | –659 | –809 | –909 | –979 | –1159 | — | –1259 |
| 235 | **ORG–0256** | 33.615278 | –81.007500 | 284 | — | — | — | 259 | 214 | 202 | 142 | 72 | –146 | –176 | — | — | –446 | — | — | –516 |
| 236 | ORG–0262 | 33.526389 | –80.571389 | 164 | — | — | — | 129 | 114 | 60 | 14 | –31 | –456 | –501 | –646 | –706 | –793 | — | — | –1031 |
| 237 | ORG–0368 | 33.461111 | –80.842500 | 192 | — | — | — | 163 | 122 | –1 | –58 | –108 | –458 | –528 | — | — | –793 | — | — | –1008 |
| 238 | ORG–0380 | 33.368611 | –81.028889 | 176 | — | 166 | — | 136 | 96 | –29 | –74 | –124 | –484 | –536 | — | — | –824 | — | — | –1001 |
| 239 | **ORG–0393** | 33.508056 | –80.865000 | 252 | — | — | — | 203 | 161 | 58 | –21 | –46 | –386 | –441 | — | — | –725 | — | — | –864 |
| 240 | ORG–0429 | 33.279167 | –80.428056 | 74 | — | — | — | 58 | 29 | –26 | –176 | –311 | –851 | –896 | –986 | –1110 | –1206 | –1476 | — | –1726 |
| 241 | ORG–0461 | 33.247222 | –80.819444 | 114 | — | — | 64 | 15 | –66 | –166 | –226 | –306 | –696 | –776 | –926 | –1036 | –1066 | –1276 | — | –1366 |
| 242 | RIC–0062 | 33.830556 | –80.630556 | 146 | 145 | 144 | 143 | 142 | 141 | 140 | 139 | 64 | –209 | –229 | — | — | –441 | — | — | –511 |

**Appendix B1.** Aquifer and confining unit top surface altitudes interpreted from borehole geophysical logs, cores, and other data in the Coastal Plain of North Carolina, South Carolina, eastern Georgia, and southern Virginia.—Continued

[Borehole locations are on *figure B3*; borehole numbers in **bold** are coreholes; —, not present]

| Borehole location on *figure B3* | Borehole number | Latitude (decimal degrees) | Longitude (decimal degrees) | Top surface altitude, in feet: Land surface/ top of surficial aquifer | Yorktown/ Upper Floridan confining unit | Yorktown/ Upper Floridan aquifer | Castle Hayne/ Pungo River/ Middle Floridan confining unit | Castle Hayne/ Pungo River/ Middle Floridan aquifer | Beaufort/ Gordon confining unit | Beaufort/ Gordon aquifer | Peedee/ Crouch Branch confining unit | Peedee/ Crouch Branch aquifer | Black Creek/ McQueen Branch confining unit | Black Creek/ McQueen Branch aquifer | Upper Cape Fear/ Charleston confining unit | Upper Cape Fear/ Charleston aquifer | Lower Cape Fear/ Gramling confining unit | Lower Cape Fear/ Gramling aquifer | Lower Cretaceous aquifer | Basement rock |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | South Carolina—Continued | | | | | | | | | | | |
| 243 | **RIC–0543** | 33.874722 | –80.702778 | 188 | 188 | 186 | 186 | 184 | 184 | 182 | 181 | 163 | –104 | –128 | — | — | –323 | — | — | –369 |
| 244 | **RIC–0585** | 33.948889 | –80.840833 | 329 | — | — | — | — | — | — | — | 319 | 42 | 9 | — | — | –110 | — | — | –136 |
| 245 | RIC–0613 | 34.111944 | –80.884722 | 424 | 422 | 421 | 420 | 419 | 417 | 417 | 415 | 414 | 278 | 256 | — | — | 188 | — | — | 179 |
| 246 | **SUM–0296** | 33.710556 | –80.532222 | 170 | — | — | — | — | — | — | 144 | 87 | –355 | –391 | — | — | –600 | — | — | –810 |
| 247 | SUM–0328 | 34.033611 | –80.456667 | 375 | 374 | 373 | 372 | 371 | 370 | 369 | 307 | 261 | –6 | –33 | — | — | –216 | — | — | –321 |
| 248 | **SUM–0340** | 33.990278 | –80.358889 | 142 | 141 | 140 | 139 | 138 | 137 | 136 | 135 | 134 | –122 | –130 | — | — | –366 | — | — | –462 |
| 249 | SUM–0347 | 33.841389 | –80.264722 | 145 | — | — | — | — | — | — | — | 102 | –315 | –365 | — | — | –548 | — | — | –745 |
| 250 | WIL–0176 | 33.731111 | –79.462222 | 39 | — | — | — | — | — | — | — | –11 | –461 | –496 | –661 | –796 | –881 | –1111 | — | –1321 |
| 251 | WIL–0208 | 33.583611 | –79.870833 | 74 | — | — | — | — | — | — | 63 | –31 | –556 | –594 | –826 | –941 | –1066 | –1276 | — | –1456 |
| 252 | WIL–0211 | 33.681667 | –79.557222 | 49 | — | — | — | — | — | — | — | 14 | –521 | –561 | –756 | –853 | –946 | –1201 | — | –1401 |
| 253 | WIL–0213 | 33.772778 | –79.448056 | 51 | — | — | — | — | — | — | — | 26 | –399 | –414 | –569 | –739 | –844 | –1049 | — | –1249 |
| | | | | | | | | | Eastern Georgia | | | | | | | | | | | |
| 254 | 24V001 | 32.702500 | –82.717222 | 355 | — | 255 | 180 | 100 | 20 | –70 | –180 | –220 | –685 | –730 | — | — | –1050 | — | — | –1450 |
| 255 | 24X005 | 32.955000 | –82.638888 | 374 | — | 244 | — | 174 | 104 | 69 | –101 | –126 | — | –326 | — | — | –521 | — | — | –721 |
| 256 | 25T002 | 32.386944 | –82.542778 | 350 | 300 | 100 | –50 | –170 | –350 | –400 | –580 | –790 | –1341 | –1481 | –1800 | –1850 | –1961 | –2021 | — | –2681 |
| 257 | 28X001 | 32.875555 | –82.220833 | 268 | 208 | 148 | 98 | 43 | –22 | –62 | — | –261 | –582 | –601 | — | — | –961 | — | — | –1231 |
| 258 | GA-LI-OT-1 | 31.691944 | –81.348333 | 25 | –25 | –375 | –625 | –725 | –875 | — | –1725 | –2125 | –2675 | — | –2975 | — | –3295 | –3455 | — | –4239 |
| 259 | 34U001 | 32.585000 | –81.427222 | 129 | 79 | –21 | –131 | –231 | –331 | –521 | –676 | –811 | –1321 | –1351 | –1651 | –1821 | –2101 | –2291 | — | –2545 |
| 260 | **32Y019** | 33.064722 | –81.720833 | 249 | — | 145 | 56 | 39 | 5 | –76 | –232 | –283 | –601 | –635 | — | — | –941 | — | — | –1126 |
| 261 | **30Z017** | 33.230000 | –81.878889 | 244 | — | 197 | — | 162 | — | 88 | –3 | –50 | –246 | –256 | — | — | –508 | — | — | –608 |
| 262 | **33X048** | 32.890278 | –81.595278 | 109 | 89 | 75 | –91 | –119 | –223 | –256 | –461 | –540 | –941 | –983 | — | –1231 | –1303 | — | — | –1591 |
| 263 | 33R045 | 32.131944 | –81.611660 | 84 | –27 | –243 | –393 | –516 | –637 | –966 | –1191 | –1416 | –2066 | — | –2216 | –2366 | –2666 | –2766 | — | –3416 |
| 264 | 34S011 | 32.295277 | –81.396666 | 79 | –7 | –198 | –321 | –446 | –542 | –871 | –1121 | –1321 | –1971 | — | –2121 | –2271 | –2571 | –2721 | — | –3251 |
| 265 | Pooler Well | 32.116944 | –81.221944 | 19 | –81 | –281 | –481 | –581 | –731 | –1381 | –1561 | –1721 | –2131 | — | –2381 | — | –2661 | –2861 | — | –3781 |
| 266 | Renken well | 32.170277 | –82.332500 | 219 | 169 | –81 | –281 | –431 | –631 | –781 | –1091 | –1241 | –1931 | –2141 | –2381 | –2431 | –2601 | –2711 | — | –3444 |
| 267 | 35P109 | 31.911944 | –81.316389 | 9 | –91 | –320 | –551 | –626 | –795 | — | –1641 | –1991 | –2341 | — | –2591 | — | –2891 | –3091 | — | –3941 |
| | | | | | | | | | Southern Virginia | | | | | | | | | | | |
| 268 | 50F 1 | 37.165278 | –77.510000 | 189 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 134 |
| 269 | 51B 3 | 36.685830 | –77.385280 | 123 | 110 | 56 | — | — | — | — | — | — | — | — | — | 22 | — | — | 10 | –130 |
| 270 | 51D 1 | 36.943330 | –77.399170 | 75 | — | 65 | — | — | — | — | — | — | — | — | — | — | — | — | 21 | –33 |
| 271 | 51F 7 | 37.169720 | –77.396110 | 170 | 140 | 110 | — | — | — | — | — | — | — | — | — | 88 | — | — | 52 | 6 |
| 272 | 51G 1 | 37.279167 | –77.410000 | 56 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 6 |
| 273 | 51G 3 | 37.345560 | –77.377780 | 180 | — | — | 83 | — | 33 | — | — | — | — | — | — | 12 | — | — | 2 | –155 |
| 274 | 52E 2 | 37.083610 | –77.362220 | 140 | — | — | — | — | 130 | — | — | — | — | — | — | — | — | — | 95 | –250 |
| 275 | 52F 1 | 37.221111 | –77.290000 | 131 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | –39 |

**Appendix B1.** Aquifer and confining unit top surface altitudes interpreted from borehole geophysical logs, cores, and other data in the Coastal Plain of North Carolina, South Carolina, eastern Georgia, and southern Virginia.—Continued

[Borehole locations are on *figure B3*; borehole numbers in **bold** are coreholes; —, not present]

| Borehole location on *figure B3* | Borehole number | Latitude (decimal degrees) | Longitude (decimal degrees) | Top surface altitude, in feet: Land surface/top of surficial aquifer | Yorktown/Upper Floridan confining unit | Yorktown/Upper Floridan aquifer | Castle Hayne/Pungo River/Middle Floridan confining unit | Castle Hayne/Pungo River/Middle Floridan aquifer | Beaufort/Gordon confining unit | Beaufort/Gordon aquifer | Peedee/Crouch Branch confining unit | Peedee/Crouch Branch aquifer | Black Creek/McQueen Branch confining unit | Black Creek/McQueen Branch aquifer | Upper Cape Fear/Charleston confining unit | Upper Cape Fear/Charleston aquifer | Lower Cape Fear/Gramling confining unit | Lower Cape Fear/Gramling aquifer | Lower Cretaceous aquifer | Basement rock |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Southern Virginia—Continued | | | | | | | | | | | |
| 276 | 52F 7 | 37.192500 | –77.351110 | 142 | — | 112 | — | — | — | — | — | — | — | — | — | 68 | — | — | 22 | –110 |
| 277 | 53A 6 | 36.516670 | –77.240560 | 120 | 59 | 34 | — | — | — | — | — | — | — | — | — | 6 | — | — | –64 | –400 |
| 278 | 53A 4 | 36.584720 | –77.204170 | 39 | 26 | 18 | 1 | — | — | — | — | — | — | — | — | — | –34 | — | –74 | –411 |
| 279 | 53C 1 | 36.772780 | –77.174440 | 105 | — | 45 | 15 | — | — | –20 | — | — | — | — | — | –49 | — | — | –57 | –500 |
| 280 | 53D 3 | 36.978610 | –77.150560 | 100 | 85 | 66 | 30 | — | 16 | 3 | — | — | — | — | — | –6 | — | — | –20 | –444 |
| 281 | 53D 4 | 36.925000 | –77.177780 | 90 | — | 52 | 20 | — | — | 2 | — | — | — | — | — | –5 | — | — | –38 | –426 |
| 282 | 53G 15 | 37.334170 | –77.190000 | 17 | — | — | — | — | –20 | –36 | — | — | — | — | — | –91 | — | — | –133 | –300 |
| 283 | 54A 3 | 36.589170 | –77.110000 | 100 | — | 26 | 6 | — | — | –2 | — | — | — | — | –12 | –20 | –31 | — | –48 | –500 |
| 284 | 54C 2 | 36.819720 | –77.066940 | 115 | 85 | 39 | –7 | — | –25 | –32 | — | — | — | — | — | –38 | — | — | –59 | –750 |
| 285 | 54D 1 | 36.979170 | –77.005830 | 110 | 78 | 58 | –5 | — | –31 | –50 | — | — | — | — | — | –98 | — | — | –112 | –620 |
| 286 | 54G 10 | 37.332220 | –77.097780 | 35 | — | — | 15 | –23 | –49 | –95 | — | — | — | — | — | –135 | — | — | –142 | –565 |
| 287 | 55B 59 | 36.646111 | –76.894444 | 20 | — | — | — | –70 | –78 | –88 | — | — | — | — | –112 | –116 | –168 | — | –284 | –1000 |
| 288 | 55C 12 | 36.768056 | –76.888333 | 15 | — | — | — | –69 | –83 | –109 | — | — | — | — | — | — | –121 | — | –210 | –1000 |
| 289 | 55D 5 | 36.904167 | –76.888889 | 90 | 69 | 32 | 9 | –69 | –79 | –125 | — | — | — | — | — | –142 | — | — | –158 | –1000 |
| 290 | 55E 1 | 37.045833 | –76.935000 | 108 | 80 | 46 | –2 | –66 | –73 | –95 | — | — | — | — | — | –149 | — | — | –202 | –1250 |
| 291 | 55F 20 | 37.222500 | –76.951667 | 90 | 70 | 55 | –24 | –58 | –80 | –113 | — | — | — | — | — | –178 | — | — | –205 | –800 |
| 292 | 56A 10 SOW | 36.562500 | –76.783889 | 45 | — | — | –93 | –104 | –120 | –136 | — | — | — | — | –152 | –229 | –250 | — | –407 | –1000 |
| 293 | 56F 42 | 37.142222 | –76.840833 | 110 | 75 | 60 | 14 | –82 | –123 | –202 | — | — | — | — | — | –241 | — | — | –256 | –1000 |
| 294 | 57B 2 | 36.704444 | –76.687778 | 73 | — | –19 | –41 | –147 | –201 | –232 | — | — | — | — | — | — | –252 | — | –384 | –1000 |
| 295 | 57C 32 | 36.806297 | –76.743878 | 81 | 33 | –45 | –66 | –135 | –155 | –203 | — | — | — | — | — | — | –226 | — | –277 | –1000 |
| 296 | 57D 20 | 36.875556 | –76.682222 | 50 | 40 | –59 | –100 | –141 | –203 | –239 | — | — | — | — | — | –260 | — | — | –290 | –1250 |
| 297 | 57E 10 SOW | 37.043333 | –76.716389 | 85 | — | 14 | –37 | –152 | –175 | –215 | — | — | — | — | — | –261 | — | — | –268 | –1250 |
| 298 | 57F 4 VEP | 37.165556 | –76.699167 | 36 | — | — | –29 | –159 | –194 | –265 | — | — | — | — | — | –290 | — | — | –339 | –1300 |
| 299 | 58A 2 SOW | 36.568889 | –76.583333 | 56 | 38 | 24 | –103 | –217 | –249 | –273 | — | — | — | — | –286 | –414 | –440 | — | –576 | –1874 |
| 300 | 58A 76 SOW | 36.615278 | –76.555556 | 33 | 15 | 7 | –133 | –253 | –275 | –292 | — | — | — | — | –305 | –389 | –417 | — | –580 | –1750 |
| 301 | 58B 12 | 36.734167 | –76.553056 | 20 | — | — | –92 | –248 | –274 | –323 | — | — | — | — | — | — | –335 | — | –461 | –1750 |
| 302 | 58C 7 | 36.810556 | –76.619167 | 40 | — | –47 | –86 | –180 | –236 | –291 | — | — | — | — | — | — | –310 | — | –356 | –1500 |
| 303 | 58D 6 | 36.994167 | –76.558333 | 22 | — | –45 | –121 | –191 | –269 | –322 | — | — | — | — | — | –346 | — | — | –361 | –1500 |
| 304 | 59C 13 | 36.871667 | –76.463056 | 16 | –1 | –42 | –194 | –330 | –344 | –360 | — | — | — | — | — | — | –383 | — | –492 | –1750 |
| 305 | 60B 20 | 36.690833 | –76.342778 | 16 | –24 | –34 | –150 | –421 | –435 | –458 | — | — | — | — | –476 | –505 | –569 | — | –734 | –2250 |
| 306 | 60C 7 | 36.854167 | –76.321389 | 10 | — | — | –127 | –430 | –448 | –453 | — | — | — | — | — | — | –472 | — | –649 | –2250 |
| 307 | 61A 12 | 36.598144 | –76.208575 | 13 | 3 | –28 | –119 | –531 | –549 | –587 | –603 | –696 | — | — | –783 | –791 | –840 | — | –1012 | –2750 |
| 308 | 61B 11 | 36.707500 | –76.129722 | 15 | –59 | –73 | –177 | –612 | –638 | –651 | –673 | –740 | — | — | –776 | –793 | –848 | — | –1053 | –2750 |
| 309 | 63C 1 | 36.866667 | –75.980833 | 20 | –26 | –36 | –106 | –837 | –862 | –866 | — | — | — | — | –888 | –897 | –932 | — | –1096 | –3000 |

# Appendix B2. Core description of ORG-393 (#68, section I–I′, *Plate 7*).

Core was described by David C. Prowell of the U.S. Geological Survey. Depths are reported in feet below land surface.

See *Plate 7* for a graphic lithology column. Colors are from the Rock-Color Chart, which uses the Munsell color system. Charts are distributed by the Geological Society of America, P.O. Box 9140, Boulder, CO 80301.

ORG-393 Depth (ft)

## Surficial Aquifer

(Unnamed Quaternary unit)

Clayey sand, moderate yellowish brown (10-YR-5/4) (Schoeneberger and others, 2002) and moderate reddish brown (10R4/6) to moderate reddish orange (10-R-6/6), fine to very coarse quartz sand in a 20 to 40 percent clay matrix, poorly sorted; trace gravel (up to 20 mm); trace feldspar; local iron staining; poorly bedded with some evidence of cross beds (15 to 20 degrees) in clay- and silt-rich beds; poorly consolidated ................................................ 0–21.6

(Unnamed Oligocene unit)

Clayey sand, dark yellowish orange (10-YR-6/8), very fine to medium quartz sand and beds of fine to very coarse quartz sand in a 5 to 25 percent clay matrix, moderately to poorly sorted; 2 to 3 percent mica; trace feldspar; mottled texture; crudely bedded in fining-upwards sequence; poorly consolidated ........................................ 21.6–40.5

Silty clay, dark gray (N-3) with common dark yellowish orange staining (10-YR-6/6), very fine to fine quartz sand and silt in a 50 to 70 percent clay matrix, well sorted; 1 to 2 percent mica; trace pyrite as concretions and trace lignite/carbon clasts; thinly laminated beds; poorly consolidated ..................................................................................... 40.5–49.4

## Middle Floridan Aquifer

(Santee Formation, clastic phase)

Clayey sand, dark yellowish orange (10-YR-6/6), fine to coarse quartz sand near top of interval and very fine to fine sand near base, 5 to 25 percent clay matrix, moderately to well sorted; 1 to 2 percent mica; local blebs of carbon/manganese; local very thin clay stringers; crudely bedded with hint of cross bedding; poorly consolidated ...... 49.4–65.0

(Santee Formation, carbonate phase)

Marl, pale olive (10-Y-6/2), very fine to fine quartz sand and clay in a calcium carbonate matrix, well sorted; 1 to 2 percent glauconite and phosphate(?); sparse silicified shells ................................................................................ 65.0–66.3

Limestone, yellowish gray (5-Y-7/2); impure limestone with 5 to 10 percent quartz sand, 5 to 10 percent shell fragments, and 5 percent clay, poorly to moderately sorted; sparse mollusk(?) shells extend across core diameter; local iron oxidation; weakly indurated except for local 0.5 ft beds of purer calcium carbonate .................................... 66.3–76.0

Marl, greenish gray (5-G-6/1) and yellowish gray (5-Y-7/2), very fine to fine quartz sand and silt (10 to 20 percent) in a calcareous clay matrix (80 to 90 percent); 1 to 2 percent mica; sparse phosphate and shell fragments; trace glauconite; well-bedded ........................................................................................................................ 76.0–82.5

Limestone, yellowish gray (5-Y-8/1) to white (N-9), impure limestone with 5 to 10 percent quartz sand and 20 to 30 percent shell fragments, poorly sorted; local calcium carbonate cemented beds (0.3 to 0.5 ft), otherwise sediment is broken into coarse granules; shells consist of mollusks, pelecypods, bryozoans, and unidentified microfossils; fragmented texture ........................................................................................................................ 82.5–91.5

### Gordon Confining Unit

(Santee Formation, carbonate phase)

Marl, grayish olive green (5-GY-3/2), light olive gray (5-Y-5/2) and greenish gray (5GY-6/1), very fine to fine quartz sand (40 percent), clay (35 percent), and shell fragments (20 percent) in a calcareous matrix; megafossils are bivalves, gastropods, and bryozoans; sparse bone fragments and shark teeth; trace lignite, glauconite, and phosphate; phosphate especially abundant from 146 to 153 ft; large brown bivalves common from 153 to 158 ft; generally moderately to well-cemented with calcium carbonate; local hard layers (0.3 to 0.4 ft) of calcium carbonate; common burrows; well-bedded with thin laminations in clayey zones ........................................................................................ 91.5–158.0

Phosphatic marl, marl as described above but with a significant increase in phosphate and glauconite; phosphate and glauconite increase with depth composing 50 to 60 percent of the core towards the base of the interval ............ 158.0–177.4

(Warley Hill Formation)

Marl, olive gray (5-Y-3/2), fine to very coarse quartz sand and silt in a 60 to 70 percent clay matrix; weak reaction with hydrochloric acid; 5 to 30 percent glauconite; common very fine carbonaceous matter; sparse shell fragments; well laminated; well compacted ........................................................................................ 177.4–186.5

Clayey sand, olive gray (5-Y-3/2), fine to very coarse quartz sand in a 20 to 30 percent clay matrix, poorly sorted; 5 to 10 percent glauconite; sparse gravel (3 to 4 mm); trace blue quartz and carbonaceous matter; massive ............. 186.5–189.5

(Congaree Formation)

Silty clay, grayish green (10-GY-5/2), very fine to fine quartz sand and silt in a 60 percent clay matrix, well sorted; 2 to 4 percent mica; 1 to 2 percent glauconite; well laminated ........................................................................... 189.5–194.3

## Gordon Aquifer

(Congaree Formation)

Clayey sand, olive gray (5-Y-3/2), fine to coarse quartz sand in a 10 to 20 percent clay matrix, moderately sorted; sparse gravel (2 to 3 mm); trace glauconite; weak reaction with hydrochloric acid; massive .................................... 194.3–208.0

Laminated sand and clay, dark greenish gray (5-GY-4/1) to light olive gray (5-Y-5/2), fine to very coarse quartz sand and gravel in a 5 percent clay matrix, poorly sorted; trace garnet, blue quartz, monazite and rutilated quartz; trace lignite and carbonaceous clay; thinly laminated cross-bedded clay and fine sand beds; loose to moderately compact .......... 208.0–212.5

Interbedded sand and clay, same as described above but thickly bedded .......................................................... 212.5–228.0

Laminated sand and clay, same as described above but thinly bedded ............................................................ 228.0–229.8

Clayey sand, light olive gray (5-Y-5/2), fine to very coarse quartz sand and gravel in 5 percent clay matrix (grain size coarsens with depth), poorly sorted; trace garnet, blue quartz, monazite, rutilated quartz, and glauconite; common lignite/carbonaceous clay; thinly laminated cross-bedded clay and fine sand beds; loose to moderately compact ..... 229.8–272.7

## Crouch Branch Confining Unit

(Rhems Formation)

Laminated sand and clay, grayish black (N-2), very carbonaceous clay with 10 percent silt, locally interbedded with 1 to 4 mm thick, fine to very fine quartz sand, well sorted; common lignite and mica; low-angle cross beds locally coated with fine lignite; local pyritized roots/tubes and pyrite-cemented sand clasts; well laminated ............ 272.7–298.2

## Crouch Branch Aquifer

(Sawdust Landing Formation)

Clayey sand, light blue (5-B-7/6) to greenish gray (5-G-6/1), fine to very coarse quartz sand in a 10 to 20 percent dense clay matrix, poorly sorted; 1 to 2 percent mica; trace feldspar, rutilated quartz, garnet, and monazite; common granular pyrite; very dense and massive ........................................................................................... 298.2–308.0

Clayey sand, same as described above except occurring as fining-upwards sequences of very coarse to fine sand and lacking the dense clay matrix ........................................................................................................ 308.0–323.3

(upper Steel Creek unit)

Sandy clay, light gray (N-8), fine to coarse quartz sand (20 to 50 percent) in a dense clay matrix (50 to 80 percent); 2 to 4 percent mica; trace rutilated quartz; slightly carbonaceous; evidence of carbonized roots and desiccation cracks; dense and indurated ........................................................................................................ 323.3–330.0

Clayey sand, very light gray (N-8) with grayish orange (10-YR-7/4) staining, similar to that described above except with 70 to 80 percent sand in a stiff clay matrix, very poorly sorted; 5 to 7 percent mica; local gravel (up to 3 mm); grain size coarsens with depth; dense and indurated ............................................................................ 330.0–348.0

Sand, very light gray (N-8), fine to coarse quartz sand in a 0 to 5 percent clay matrix, poorly sorted; grain size coarsens with depth; 2 to 4 percent mica and locally very micaceous with some grains up to 3 mm; lower 7 feet of interval contains common gravel (up to 5 mm) and white clay balls (up to 8 mm); trace monazite and lignite; low-angle cross beds in thin layers; poorly consolidated ............ 348.0–365.2

Interbedded sand and clay, similar to that described above except with alternating beds of sand and carbonaceous clay; sand beds are light gray (N-7) and are 0.2 to 5 feet thick, and clay beds are medium dark gray (N-4) and are 0.1 to 0.5 feet thick; the interval is predominately sand; poorly consolidated ............ 365.2–398.0

(middle Steel Creek unit)

Interbedded sand and clay, similar to that described above except that sand beds are thinner (0.2 to 3 feet thick) and carbonaceous clay seams are increasingly present in the sand beds; lignite and pyrite also increase in this interval; poorly consolidated ............ 398.0–423.0

Clayey sand, light olive gray (5-Y-6/1), fine to very coarse quartz sand in a 5 to 10 percent clay matrix, poorly sorted; trace pyrite and lignite clasts; trace gravel; poorly consolidated ............ 423.0–433.5

Sand, olive gray (5-Y-4/1), fine to medium quartz sand in a 5 to 10 percent clay matrix, moderately to well sorted; local gravel (up to 2 mm); trace lignite and pyritized lignite; possible burrows; massive; poorly consolidated ............ 433.5–444.7

Clayey sand, dark gray (N-3), very fine to fine quartz sand with many 20 mm flattened clay clasts; 5 percent mica; very unique; possible lag bed ............ 444.7–446.0

(lower Peedee unit)

Laminated sand and clay, sand layers are grayish green (5 GY-6/1) and clay layers are dark gray (N-3), very fine to fine quartz sand laminated with thin (2 to 10 mm) beds of micaceous carbonaceous clay (up to 20 percent); 5 to 8 percent mica; trace lignite; well laminated ............ 446.0–449.5

Sand, light gray (N-7), fine to very coarse quartz sand in a 0 to 5 percent clay matrix, poorly sorted; 1 to 3 percent mica; trace lignite and pyritized lignite; trace rutilated quartz; massive texture ............ 449.5–455.0

Laminated sand and clay, light olive gray (5-Y-6/1), very fine to fine quartz sand laminated with micaceous and carbonaceous clay, well sorted; 4 to 5 percent mica; trace glauconite and pyrite; sparse lignite fragments (up to 15 mm); well laminated with 3 to 8 mm clay layers separated by 20 to 50 mm sand layers ............ 455.0–457.5

Glauconitic sand, light olive gray (5-Y-6/1), fine to very coarse quartz sand in a 0 to 5 percent clay matrix, poorly sorted; 1 to 3 percent mica; trace glauconite; local lignitic fragments (up to 3 mm) and pyritized lignite; possible in-situ weathered feldspars and/or white clay blebs; massive texture; poorly consolidated ............ 457.5–468.0

(upper Donoho Creek unit)

Interbedded sand and clay, sand layers are light olive gray (5-Y-6/1) and clay layers are dark gray (N-3), very fine to fine quartz sand laminated with thin layers of carbonaceous clay, well sorted; some sand beds consist of fine to very coarse sand; 5 to 8 percent mica; trace pyrite; well laminated with 3 to 5 mm clay layers and 10 to 30 mm sand layers ............ 468.0–513.8

## McQueen Branch Confining Unit

(upper Donoho Creek unit)

Silty clay, dark greenish gray (5-GY-4/1), very fine to fine quartz sand and silt in a 30 to 40 percent clay matrix, well sorted; 2 to 5 percent mica; trace glauconite, pyrite, lignite, and phosphate; common burrows; locally numerous bivalve molds/casts; well laminated ............ 513.8–553.3

Lag bed, light olive gray (5-Y-5/2), calcareous sand lag bed, fine to coarse quartz sand in a 10 to 30 percent clay matrix, poorly sorted; weakly cemented with calcium carbonate; 1 to 2 percent mica; 1 percent granular phosphate (up to 6 mm); 1 percent very coarse sand; sparse carbonaceous clay clasts (up to 30 mm); common bivalve fragments; sparse shark teeth and bone fragments; massive texture; well indurated ............ 553.3–557.2

(middle Donoho Creek unit)

Marl, olive gray (5-Y-3/2) to olive black (5-Y-2/1), plastic carbonaceous clay to marl with 5 percent silt, well sorted; 2 to 4 percent mica; weak reaction with hydrochloric acid; common bivalve shells (some preserved in mother-of-pearl); unidentified fossil fragments; very fossiliferous in lower part of interval; well laminated; well compacted ............ 557.2–568.0

Sandy marl, olive gray (5-Y-3/2), very fine to fine quartz sand and silt in a 20 to 30 percent calcareous clay matrix, well sorted; 4 to 5 percent mica; trace glauconite/chlorite; common bivalve fragments and complete shells; evidence of local heavy bioturbation, otherwise, alternating 10–20 mm beds of calcareous sand and calcareous silty clay below 572.5 feet .......... 568.0–587.5

Marl, sand beds are dark grayish green (5-GY-4/1) and clayey marl beds are dark gray (N-3), very fine to fine calcareous sand interbedded with beds of clayey marl, well sorted; individual beds are 0.5 to 2.0 feet thick; 2 to 4 percent mica; 1 percent glauconite; abundant megafossil shells (mostly bivalves); sand beds are massive and bioturbated; clayey marl beds are well laminated .......... 587.5–599.2

Lag bed, olive gray (5-Y-4/1), calcareous lag bed, fine to coarse quartz sand in a 10 to 30 percent clay matrix cemented with calcium carbonate, poorly sorted; 2 to 3 percent mica; 1 percent phosphate grains (up to 7 mm); trace glauconite; cemented sand clasts (up to 20 mm); common shell fragments (mostly bivalves); chaotic texture, especially in lower 4 feet .......... 599.2–606.0

(Bladen Formation)

Sand, olive gray (5-Y-3/2), fine to medium quartz sand, well to moderately sorted; 2 to 4 percent mica; trace glauconite and rutilated quartz; extremely lignitic from 610 to 611 feet; local thin carbonaceous clayey layers (1 to 2 mm); well bedded with low-angle cross beds .......... 606.0–611.0

Marl, olive gray (5-Y-3/2), very fine to fine quartz sand (10 percent) in a sticky calcareous clay/marl, well sorted; 5 to 10 percent mica; 5 percent pyritized leaves/wood; common bivalve shells and shell fragments; possible bone fragments; increasing calcium carbonate cementation with depth; poorly laminated with shell fragments; well indurated towards bottom of interval .......... 611.0–623.0

Shelly limestone, light olive gray (5-Y-5/2), bivalve-rich bed cemented with calcium carbonate, well indurated .......... 623.0–625.4

Marl, olive gray (5-Y-3/2), very fine to fine quartz sand (10 percent) in a sticky calcareous clay/marl, well sorted; 5 to 10 percent mica; 5 percent pyritized leaves/wood; common bivalve shells and shell fragments; possible bone fragments; poorly laminated with shell fragments; well indurated .......... 625.4–632.5

Shelly limestone, olive gray (5-Y-4/1), bivalve-rich bed cemented with calcium carbonate, well indurated .......... 632.5–639.1

Marl, same as marl described above .......... 639.1–642.0

Shelly limestone, same as shelly limestone described above .......... 642.0–645.8

Marl, same as marl described above .......... 645.8–651.0

Shelly limestone, same as shelly limestone described above .......... 651.0–659.2

Marl, same as marl described above .......... 659.2–669.8

(Coachman Formation)

Laminated sand and clay, light gray (N-7) to dark gray (N-3), very fine to fine sand in a 10 to 15 percent carbonaceous clay matrix, well sorted; 3 to 4 percent mica; trace glauconite/chlorite; trace very fine lignite; numerous lignite fragments (up to 60 mm) replaced by pyrite; abundant pyritized wood; no calcareous sediments or fossils (as seen in overlying section of core); thinly laminated with carbonaceous clay .......... 669.8–692.9

### McQueen Branch Aquifer

(Coachman Formation)

Clayey sand, very light gray (N-8) to light gray (N-7), fine to very coarse quartz sand in a 10 to 15 percent clay matrix, poorly sorted; 2 to 3 percent mica; trace monazite and rutilated quartz; local lignite fragments (up to 70 mm) that are partially replaced by pyrite; 1 percent gravel (up to 8 mm) in thin (0.3 to 0.5 ft) beds; evidence of cross beds; poorly consolidated .......... 692.9–711.2

(Cane Acre Formation)

Sandy clay, medium light gray (N-6), fine to coarse quartz sand (10 to 20 percent) in a dense waxy clay (70 to 80 percent); 2 to 4 percent mica; 1 percent lignite fragments (up to 50 mm); well bedded .......... 711.2–716.0

Clayey sand, medium gray (N-5), fine to very coarse quartz sand in a 5 to 10 percent clay matrix, moderately to poorly sorted; 5 percent very fine lignite; 2 percent mica; 1 percent gravel (up to 4 mm); 1 percent pyritized wood; large (up to 40 mm) lignite fragments; low-angle cross beds ........ 716.0–724.2

Clay, light gray (N-7) to light olive gray (5-Y-6/1) with pale red (5-R-6/2) staining, dense, waxy clay containing 5 to 10 percent fine to very coarse quartz sand; 2 to 5 percent mica; trace rutilated quartz and monazite; evidence of backfilled roots/mud cracks; evidence of slickensides and desiccation cracks ........ 724.2–741.0

Clayey sand, light gray (N-7) to medium gray (N-5) and olive gray (5-Y-4/1), fine to very coarse quartz sand in 2 to 25 percent clay matrix, poorly sorted; 1 to 2 percent gravel; 2 percent mica; 1 percent rutilated quartz and monazite; trace feldspar and lignite; massive to well bedded; poorly consolidated near top of interval but dense and well indurated below 748 feet ........ 741.0–764.7

Sandy clay, olive gray (5-Y-4/1), very fine to fine quartz sand (20 percent) in a dense clay matrix (80 percent), well sorted; 2 to 3 percent mica; crudely bedded with evidence of roots/fractures; common carbonaceous matter .... 764.7–774.2

Sand, light olive gray (5-Y-6/1), fine to very coarse quartz sand in a 1 to 5 percent clay matrix, poorly sorted; 1 percent gravel; 1 percent rutilated quartz; trace lignite; local thin (30 mm) carbonaceous clay layers; massive, poorly consolidated ........ 774.2–808.0

Sandy clay, brownish black (5-YR-2/1), fine to coarse quartz sand (20 percent) in a clay matrix (70 percent), poorly sorted; 8 percent lignite fragments (up to 20 mm); 2 percent mica; weak bedding; compact ........ 808.0–809.5

Sand, sand is light olive gray (5-Y-6/1) to medium gray (N-5) and clay is grayish black (N-2), fine to very coarse quartz sand in a 5-percent clay matrix, poorly sorted; trace rutilated quartz and monazite; local lignite fragments (up to 20 mm); thick (0.5 ft) carbonaceous clay beds; hint of cross bedding; poorly consolidated ........ 809.5–851.3

Silty clay, dark gray (N-3), very fine to fine quartz sand and silt (15 percent) in carbonaceous clay matrix (85 percent), well sorted; sand occurs in thin (1 to 3 mm) layers; 3 to 4 percent mica; 2 to 3 percent lignite; 1 percent pyritized wood and granular pyrite; well laminated with slightly inclined bedding; compact ........ 851.3–859.5

Sand, light olive gray (5-Y-6/1) to medium gray (N-5), fine to very coarse quartz sand in a 5 percent clay matrix, poorly sorted; 1 to 2 percent mica; trace rutilated and yellow quartz; abundant lignite and pyritized lignite from 865 to 867 feet; lignite fragments up to 50 mm; weakly bedded ........ 859.5–894.5

(Cape Fear Formation)

Sandy clay, very light gray (N-8), medium to very coarse quartz sand (20 to 30 percent) in a dense clay matrix (65 to 70 percent), poorly sorted; trace gravel (up to 2 mm); 1 to 2 percent mica; trace rutilated quartz and feldspar; evidence of backfilled roots/fractures; very compact ........ 894.5–900.0

Sand, olive gray (5-Y-4/1), fine to very coarse quartz sand in a 5 to 15 percent clay matrix, poorly sorted; trace rutilated quartz and lignite; trace gravel (up to 3 mm); moderately to poorly consolidated ........ 900.0–908.0

Sandy gravel, olive gray (5-Y-4/1), same as described above but with 10 to 15 percent gravel (up to 5 mm) ........ 908.0–910.0

Sand, light olive gray (5-Y-6/1), fine to very coarse quartz sand in a 5 percent clay matrix, poorly sorted; 1 percent mica; trace rutilated quartz and lignite; sparse gravel; massive texture with only faint signs of cross bedding; sand gets coarser with depth; poorly consolidated ........ 910.0–922.0

Clayey sand, light olive gray (5-Y-6/1), fine to very coarse quartz sand in a 5 to 10 percent clay matrix, poorly sorted; 2 to 4 percent mica; trace feldspar, rutilated quartz, and lignite; local pyritized nodules (up to 15 mm); grain size increases with depth; very dense and indurated ........ 922.0–933.0

Sandy gravel, light olive gray (5-Y-6/1), same as described above except with 10 to 15 percent gravel (up to 15 mm) and an increase in feldspar (2 percent) ........ 933.0–936.2

Clayey sand, light olive gray (5-Y-6/1) to olive gray (5-Y-4/1), fine to very coarse quartz sand in a dense clay matrix, poorly sorted; interval is a clayey sand grading downwards to sand and gravel (fining-upwards sequence); 2 to 3 percent mica; 2 percent gravel (10 mm quartz and 6 mm feldspar) in basal 0.5 feet; 1 percent feldspar; trace rutilated quartz; very poorly bedded; very dense and indurated ........ 936.2–939.5

Sandy gravel, very light gray (N-8) to medium gray (N-5), same as describe above except basal gravel is 6 mm quartz and 3 mm feldspar ........ 939.5–943.2

Clayey sand, very light gray (N-8), fine to very coarse quartz sand in a dense clay matrix, poorly sorted; interval is a clayey sand grading downwards to very coarse sand and gravel (fining-upwards sequence); evidence of rooting or filled fractures at top of interval; 2 to 3 percent mica; 2 percent gravel; 1 percent feldspar; trace rutilated quartz; very poorly bedded; dense and indurated ................................................ 943.2–955.8

Sandy gravel, light olive gray (5-Y-6/1) with local dark yellowish orange (10-YR-6/6) iron staining, fine to very coarse quartz sand in a 5 to 10 percent clay matrix, poorly sorted; 5 to 10 percent gravel (quartz grains up to 15 mm and feldspar grains up to 14 mm); 2 to 5 percent mica; 1 percent feldspar; massive texture; dense and well indurated .... 955.8–968.5

Clayey sand, light olive gray (5-Y-6/1), fine to medium quartz sand, moderately sorted; 2 to 4 percent mica; 1 percent feldspar; trace rutilated quartz; massive texture; dense and well indurated................................................ 968.5–970.5

Sandy gravel, medium light gray (N-6), fine to very coarse quartz sand and gravel, poorly sorted; gravel 10 to 15 percent; 2 to 4 percent mica; 1 percent feldspar; trace rutilated quartz; faint evidence of cross bedding; dense and well indurated ..........................................................................................................................................970.5–977.0

## Gramling Confining Unit

(Cape Fear Formation)

Sandy gravel, greenish gray (5-GY-6/1), fine to coarse quartz sand and gravel in a 5 to 10 percent clay matrix, moderately sorted; 3 to 4 percent mica; 1 percent feldspar (up to 8 mm); trace rutilated quartz; well indurated by silica(?) cement ........................................................................................................................................ 977.0–998.5

Silty clay, greenish gray (5-GY-6/1) with moderate red (5-R-5/4) and dark yellowish orange (10-YR-6/6) staining, silt (10 percent) in a crumbly, dry clay matrix, well sorted; 4 to 10 percent mica; extensive iron staining; well laminated; slickensided fractures; root structures; dense and compact ............................................................ 998.5–1000.0

Clayey sand, olive gray (5-Y-4/1), fine to very coarse quartz sand in a 5 to 10 percent clay matrix, poorly sorted; 5 to 10 percent mica (local 0.1 ft beds are 40 to 50 percent mica); 1 percent gravel (up to 12 mm); 1 percent feldspar; well indurated and dense ............................................................................................ 1000.0–1003.0

Sandy clay, grayish green (10-GY-5/2) with dark yellowish orange (10-YR-6/6) staining, fine to medium quartz sand in a 5 to 10 percent clay matrix, moderately sorted; grading downwards to fine to very coarse sand and gravel; 5 to 10 percent mica (local 0.1 ft beds are 40 to 50 percent mica); gravel up to 12 mm (quartz) and 4 mm (feldspar); local iron staining; massive and well indurated ................................................................... 1003.0–1006.0

Sandy gravel, olive gray (5-Y-4/1), fine to very coarse quartz sand in a 5 to 10 percent clay matrix, poorly sorted; 1 percent gravel (up to 12 mm); 5 to 10 percent mica (local thin beds contain 20 to 25 percent very coarse mica); trace rutilated and yellow quartz; massive texture; well indurated ......................................................................... 1006.0–1011.5

Sandy clay, brownish black (5-YR-2/1) to brownish gray (5-YR-4/1), fine to medium quartz sand (40 percent) in a waxy, carbonaceous clay matrix (60 percent), moderately sorted; 4 to 6 percent mica; 1 percent feldspar; trace rutilated quartz; evidence of clay-filled roots/fractures; well laminated ......................................................... 1011.5–1013.5

Sandy gravel, medium gray (N-5) to olive gray (5-Y-4/1) with moderate yellowish brown (10-YR-5/4) staining, fine to very coarse quartz sand and gravel, poorly sorted; 1 percent feldspar; trace rutilated quartz; gravel up to 15 mm as rutilated quartz, 8 mm as smoky quartz, and 5 mm as feldspar; local iron staining; crude bedding ........ 1013.5–1023.4

Sandy clay, grayish green (10-GY-5/2), fine to medium quartz sand (35 percent) in a clay matrix (60 percent), well sorted; 1 to 2 percent mica; 1 percent feldspar; trace rutilated quartz; well laminated .................................. 1023.4–1025.0

Sandy gravel, grayish green (10-GY-5/2), fine to very coarse quartz sand and gravel in a clay matrix 5 to 15 percent clay matrix, poorly sorted; gravel up to 25 mm as quartz and 6 mm as feldspar; 1 to 2 percent mica; 1 percent feldspar; trace rutilated quartz; massive to crudely bedded ..................................................................... 1025.0–1031.8

Clayey sand, light olive gray (5-Y-6/1), fine to very coarse quartz sand in a 5 to 10 percent clay matrix, poorly sorted; 5 to 10 percent mica (up to 8 mm); 1 percent gravel (up to 7 mm as rutilated quartz and up to 25 mm as smoky quartz); massive to poorly bedded; indurated .................................................................... 1031.8–1034.0

Sandy gravel, light olive gray (5-Y-6/1) to grayish green (10-GY-5/2), fine to very coarse quartz sand and gravel, poorly sorted; 10 percent gravel (up to 30 mm as smoky quartz, 19 mm as rutilated quartz, 16 mm as white quartz, and 3 mm as feldspar); sparse slate-belt foliated quartz/rock pebbles; 1 to 2 percent mica; 1 percent feldspar; common clay clasts in lower 5 feet; trace garnet and lignite (up to 30 mm); weakly bedded; compact/cemented ................ 1034.0–1055.5

Clayey sand, greenish gray (5-G-5/2), fine to coarse quartz sand in a clay matrix, poorly sorted; 2 to 3 percent mica; trace blue quartz, rutilated quartz, garnet, and feldspar; massive; semi-consolidated to well indurated ........ 1055.5–1058.0

Sandy gravel, greenish gray (5-G-5/2), fine to very coarse quartz sand and gravel, poorly sorted; gravel up to 8 mm as smoky quartz, 10 mm as slate belt quartz/rock pebbles, and 3 mm as feldspar; 2 to 3 percent mica; trace blue quartz, rutilated quartz, garnet, and feldspar; massive; semi-consolidated to well indurated ................................. 1058.0–1064.7

Clayey sand, grayish green (10-GY-5/2), fine to coarse quartz sand in a 25 to 30 percent clay matrix, poorly sorted; 3 to 4 percent mica; 1 percent feldspar; well indurated .................................................................... 1064.7–1067.0

Sandy gravel, grayish green (10-GY-5/2), fine to very coarse quartz sand and gravel, poorly sorted; gravel up to 30 mm as smoky quartz, 20 mm as rutilated quartz, and 6 mm as feldspar; 3 to 4 percent mica; 1 percent feldspar; massive texture; well indurated ........................................................................................................ 1067.0–1073.0

Sandy clay, light olive gray (5-Y-6/1) with local dark yellowish orange (10-YR-6/6) iron staining, fine to medium quartz sand in a 10 to 20 percent clay matrix, well sorted; 2 to 3 percent mica; 1 percent feldspar; trace garnet; faint bedding disrupted by backfilled burrows/roots; bedding appears undulatory and local iron staining is present; well indurated ............................................................................................... 1073.0–1074.9

Sandy gravel, grayish green (5-G-5/2) with local dark yellowish orange (10-YR-6/6) iron staining, fine to very coarse quartz sand and gravel, poorly sorted; gravel up to 7 mm as smoky quartz and 5 mm as feldspar; 2 to 3 percent mica; 1 percent feldspar; trace garnet; massive texture; well indurated .......................................... 1074.9–1078.0

Sandy clay, light olive gray (5-Y-6/1) with local dark yellowish orange (10-YR-6/6) iron staining, fine to medium quartz sand in a 10 to 20 percent clay matrix, well sorted; faint bedding disrupted by backfilled burrow/roots; well indurated ......................................................................................................... 1078.0–1080.5

Sandy gravel, grayish green (5-G-5/2), fine to very coarse quartz sand and gravel, poorly sorted; common feldspar; local metamorphic rock fragments and clay clasts; mottled; massive to crudely bedded; poorly consolidated to indurated ........................................................................................................ 1080.5-1116.5

## Piedmont Hydrogeologic Province

(Redbeds)

Sandstone, moderate reddish brown (10-R-4/6) mottled with light greenish gray (5-G-8/1), mudstone to pebbly mudstone to conglomeratic sandstone, very poorly sorted; highly fractured; slickensided surfaces; pebbles are quartz, feldspar, and a variety of metamorphic rock fragments; conglomeratic in lower 6 feet; massive to crudely bedded; indurated ..........................................................................................................1116.5–1138.0

# Chapter C. Simulation of Groundwater Flow in the Atlantic Coastal Plain, North and South Carolina and Parts of Georgia and Virginia, Predevelopment to 2004

By Alissa L. Coes, Bruce G. Campbell, Matthew D. Petkewich, and Jason M. Fine

## Introduction

A three-dimensional, groundwater flow model of the Atlantic Coastal Plain (ACP) aquifers and confining units was developed, calibrated and is documented in this chapter. The hydrologic system of the Coastal Plain of North Carolina (NC) and South Carolina (SC) and parts of Georgia (GA) and Virginia (VA) was evaluated in order to update and combine two existing groundwater models that simulate groundwater flow and water use in the aquifers of the study area. Revision of the models was deemed necessary because additional hydraulic, geologic, water-level, and water-use data are available for use in model calibration, and hydrogeologic inconsistencies at the NC–SC border have been reconciled since the development of the previous models.

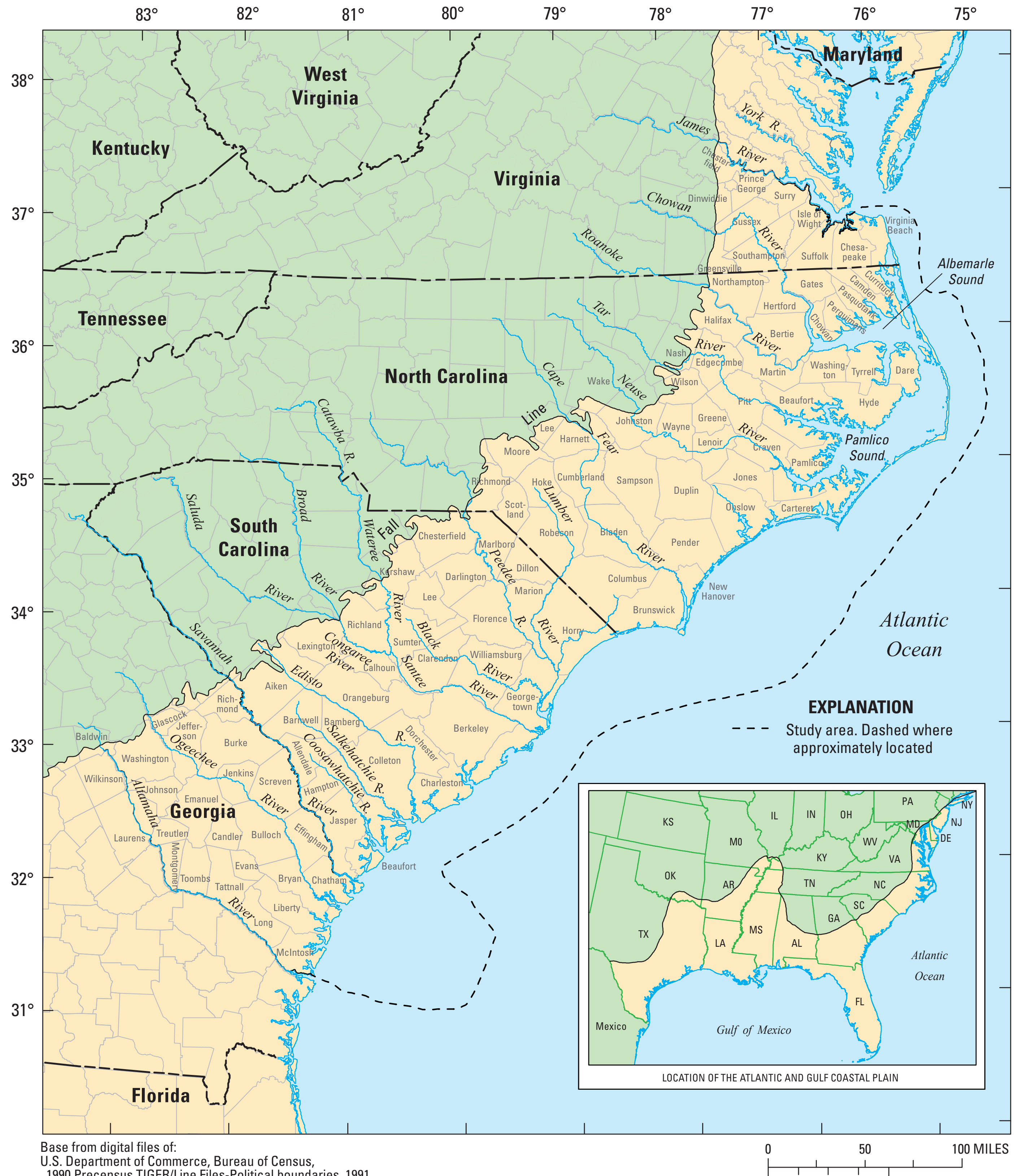
The new model simulates groundwater flow at regional and intermediate spatial scales superimposed on a transient time scale from 1900 to 2004. Documented herein are the (1) development of a transient, three-dimensional groundwater flow model; (2) model calibration process and results; and (3) model limitations and future challenges. The modeling tool developed as part of this study can be used to evaluate groundwater availability within the study area by examining the effects of both human and climatic temporal changes on the groundwater budget components. An additional benefit of the transient, calibrated, three-dimensional numerical model is the ability to use the model to forecast system response to these same effects, thus providing insights into the longer-term sustainability of the system.

## Model Development

The groundwater flow model of the ACP aquifers and confining units was constructed in several phases (*fig. C1*). The first phase required the preparation of a revised and updated hydrostratigraphic framework that combined separate frameworks from NC and SC. This effort is documented in *Chapter B* of this report. The study area has a relatively complex geologic structure that is dominated by arches and embayments and required the use of numerous hydrostratigraphic data (*figs. C2, C3*; *table C1*). The study area was subdivided into model cells of 4 square miles ($mi^2$) with 16 layers, and the simulation time from 1900 to 2004 was discretized into 29 stress periods. After the initial model was constructed, it was calibrated primarily by using automated parameter estimation techniques (Doherty, 2005). The following sections describe the model, the calibration process, and the simulation results in detail.

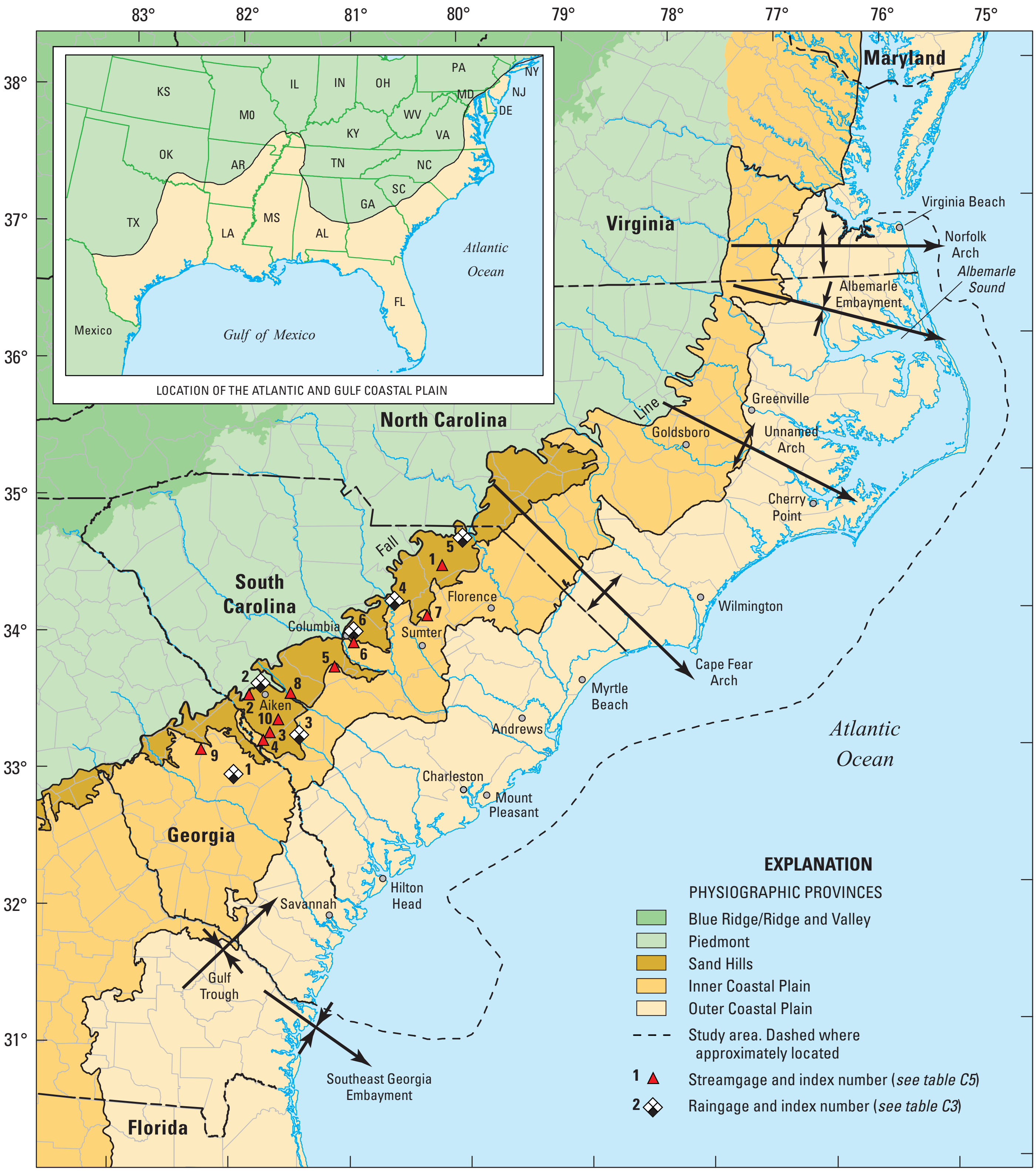
## Simulation of Groundwater Flow

The USGS groundwater flow model, MODFLOW-2000 (Harbaugh and others, 2000), was used to simulate the groundwater flow within the NC and SC Coastal Plain. The MODFLOW-2000 model simulates single-density groundwater flow in three dimensions by using a block-centered, finite-difference method. Groundwater sources and sinks were represented using the RIV package for rivers (McDonald and Harbaugh, 1983), the WEL package for wells (McDonald and Harbaugh, 1983), the RCH package for recharge (McDonald and Harbaugh, 1983), and the CHD package for specified heads (McDonald and Harbaugh, 1988). Groundwater flow was represented by using the LPF package, and the flow equations were solved by using the GMG package (Harbaugh and others, 2000). The NC–SC Coastal Plain model was calibrated using PEST (Doherty, 2005) from predevelopment to recent (2004) conditions using automated-parameter estimation of aquifer and confining unit hydraulic conductivity, specific storage, and anisotropy. Recharge and riverbed conductance were calibrated only during the initial steady-state stress period. The model was calibrated to reported groundwater levels and stream baseflows. Sensitivity analysis was performed on the parameters of hydraulic conductivity, specific storage, and anisotropy and the boundary conditions of recharge and head-dependent boundaries.




Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure C1.** Location of the Atlantic Coastal Plain in North and South Carolina and parts of Virginia and Georgia.




Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure C2.** Locations of natural characteristics within distinct areas of the Atlantic Coastal Plain Physiographic Province, with a focus on the study area in North and South Carolina, southeastern Virginia, and eastern Georgia.

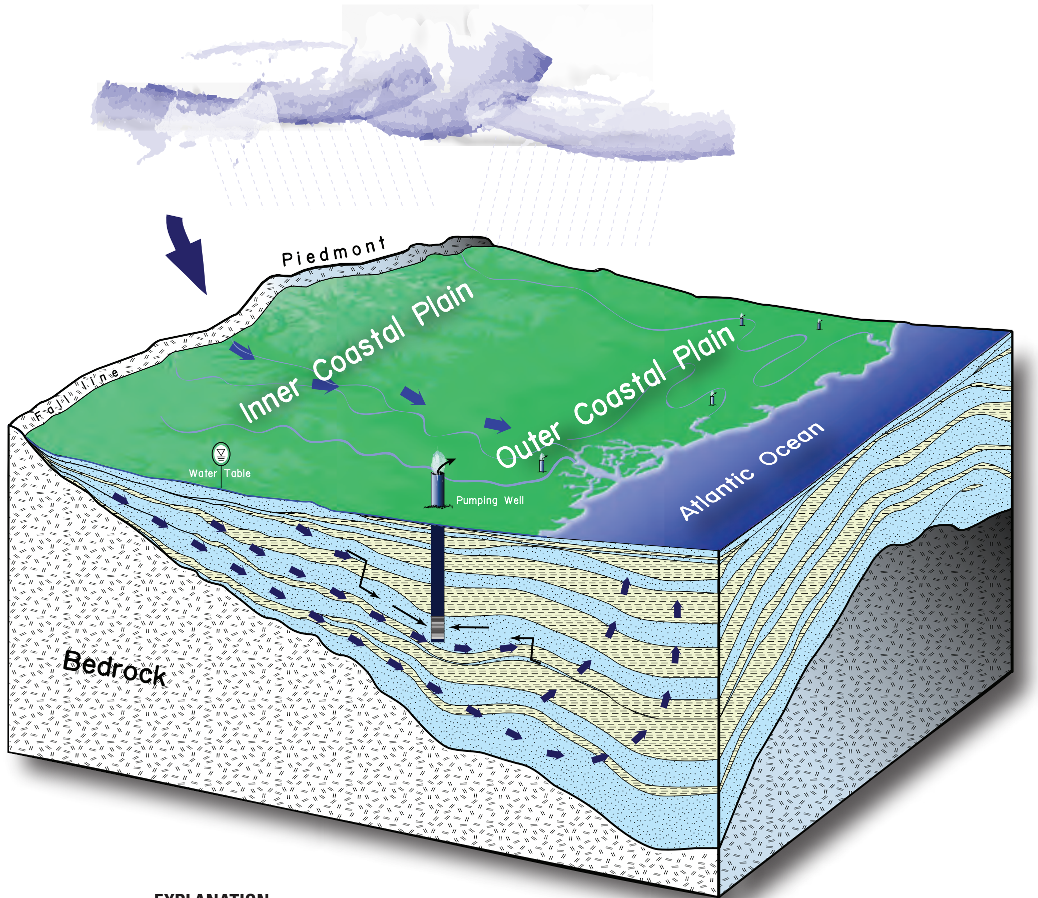



**Figure C3.** Generalized cross section of the aquifers and confining units of the Atlantic Coastal Plain of North and South Carolina, 2007.

## Spatial Discretization

The model boundary encompasses 143,000 mi$^2$, of which about 56 percent is actively simulated. The regular grid consists of 130 rows and 275 columns of 4-mi$^2$ cells; a maximum of 20,106 cells are active per model layer (*fig. C4*). The longest axis is oriented 43 degrees north of east.

The tops and extents of all aquifers and confining units, except for the surficial aquifer, were determined by using hydrostratigraphic data from 309 boreholes (*figs. B2, B5–B36*; Harrelson and Fine, 2006). The top of the surficial aquifer was created by using the mean altitude of the 30-meter (m) National Elevation Dataset (NED; U.S. Geological Survey, 1999) within each model cell. The land-surface altitude at each borehole also was determined from 30-m NEDs. The hydrologic-unit tops were interpolated between the boreholes and extrapolated to the unit extents and offshore where data do not exist. Each hydrologic unit was defined as a single model layer, producing 16 layers (*table C1*). Each model layer was defined to have a nominal thickness of at least 2 feet (ft). In areas where aquifers or confining units are in reality absent, the cells in that nominal thickness were assigned the same hydraulic properties as the underlying hydrologic unit. Most model layers, therefore, actually contain the majority of a single hydrologic unit plus thin layers of overlying hydrologic units. Model layers had maximum thicknesses that ranged from 116 to 5,004 ft (*table C2*).

## Temporal Discretization

The model simulates groundwater flow from predevelopment (before 1900) to 2004 using 29 stress periods. The first stress period represents conditions before 1900 using the steady-state approximation. Pumping for each of the following stress periods was as follows: eight 10-year stress periods representing 1900–1979; five 2-year stress periods representing 1980–1989; and fifteen 1-year stress periods representing 1990–2004. Two time steps were used in each stress period.

**Table C1.** Model layers in relation to Atlantic Coastal Plain hydrogeologic units in North Carolina, South Carolina, eastern Georgia, and southern Virginia.

[N/A , not applicable]

| Model layer | Virginia[1] | North Carolina[2] | South Carolina[3] | Georgia[4] |
|---|---|---|---|---|
| 1 | Surficial | Surficial | Surficial | Surficial |
| 2 | Yorktown confining unit | Yorktown confining unit | Upper Floridan confining unit | Upper Three Runs aquifer |
| 3 | Yorktown aquifer | Yorktown aquifer | Upper Floridan aquifer | |
| 4 | Saint Marys confining unit | Pungo River confining unit<br>Pungo River aquifer<br>Castle Hayne confining unit | Middle Floridan confining unit | |
| 5 | Saint Marys aquifer<br>Calvert confining unit<br>Piney Point aquifer | Castle Hayne aquifer | Middle Floridan aquifer | |
| 6 | Nanjemoy–Marlboro confining unit | Beaufort confining unit | Gordon confining unit | Gordon confining unit |
| 7 | Aquia aquifer | Beaufort aquifer | Gordon aquifer | Gordon aquifer<br>Millers Pond confining unit<br>Millers Pond aquifer |
| 8 | Peedee confining unit | Peedee confining unit | Crouch Branch confining unit | Upper Dublin confining unit |
| 9 | Peedee aquifer | Peedee aquifer | Crouch Branch aquifer | Upper Dublin aquifer<br>Lower Dublin confining unit<br>Lower Dublin aquifer |
| 10 | N/A | Black Creek confining unit | McQueen Branch confining unit | Upper Midville confining unit |
| 11 | N/A | Black Creek aquifer | McQueen Branch aquifer | Upper Midville aquifer<br>Lower Midville confining unit<br>Lower Midville aquifer |
| 12 | Virginia Beach confining unit | Upper Cape Fear confining unit | Charleston confining unit | N/A |
| 13 | Virginia Beach aquifer | Upper Cape Fear aquifer | Charleston aquifer | N/A |
| 14 | Potomac confining unit | Lower Cape Fear confining unit | Gramling confining unit | Basal confining unit |
| 15 | N/A | Lower Cape Fear aquifer | Gramling aquifer | N/A |
| 16 | N/A | Lower Cretaceous confining unit<br>Lower Cretaceous aquifer | N/A | N/A |

[1] McFarland and Bruce, 2006.

[2] Winner and Coble, 1996.

[3] *Chapter B*, this report.

[4] Cherry, 2006.

**Table C2.** Median and maximum model-layer thicknesses in the Atlantic Coastal Plain model simulating groundwater flow, predevelopment to 2004, in North and South Carolina and parts of Virginia and Georgia.

| Model layer | Median thickness, in feet | Maximum thickness, in feet |
|---|---|---|
| 1 | 35 | 213 |
| 2 | 9 | 255 |
| 3 | 10 | 311 |
| 4 | 14 | 726 |
| 5 | 18 | 257 |
| 6 | 15 | 116 |
| 7 | 35 | 353 |
| 8 | 43 | 364 |
| 9 | 309 | 690 |
| 10 | 49 | 249 |
| 11 | 130 | 432 |
| 12 | 88 | 463 |
| 13 | 142 | 624 |
| 14 | 130 | 815 |
| 15 | 281 | 1,058 |
| 16 | 2,736 | 5,004 |


**Figure C4.** Atlantic Coastal Plain groundwater model grid showing boundary conditions in layer 1, which represents the surficial aquifer.

## Boundary Conditions

Most of model layer 1 is a specified-head boundary in areas where the surficial aquifer is underlain by confining units (*fig. C4*). For regional models, the shallow water-table surface is often used as a source/sink boundary condition because the model grid scale precludes simulation of the water-table aquifer. This approach is appropriate when the water-table surface is relatively stationary. Because water-table surface maps are not readily available, the altitude of the water table used in model cells is estimated by a two-step process. First, a regression equation is developed using existing land and water-table altitudes from wells in the area. This equation is then used to predict the water-table surface for each model cell using mean land-surface altitudes available from Digital Elevation Models (DEM) (Kuniansky and others, 2009). For this study, 81 wells in NC with water-level measurements collected from 1942 to 1980 were used to develop a regression for estimation of the water table prior to groundwater development. Error in the data used for the regression results from data collected at different times and the inability to use long-term average water levels during predevelopment. However, the temporal error is probably less than 7 ft for any given measurement based on the variations in water levels of the long-term monitoring wells. Additionally, these data are historical, and the locations of many of the wells were obtained by hand plotting the well on a 1:24,000-scale topographic map. The error in the land-surface altitude of these wells is generally considered to be less than 5 ft (half of the contour interval of the topographic map). The best-fit linear regression was achieved by estimating the water-table altitude from the land-surface altitude, with a coefficient of determination ($R^2$) of 0.996, indicating that the linear regression explains 99.6 percent of the variation in water-table altitude. The linear regression equation is:

$$WT_{alt} = 0.9365(L_{alt}) - 2.403, \quad (1)$$

where $WT_{alt}$ is the predicted water-table altitude and $L_{alt}$ is the land-surface altitude at the well (units are in feet). All altitudes are referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). The root mean square error (standard error of the estimate) is 7.4 ft. Attempts to develop regressions for estimation of the water-table depth using depth to water from land-surface altitudes or log transforms of these data were abandoned after obtaining $R^2$ values of 0.5 and less, which indicated a poor relation. Land-surface altitudes of the 81 wells ranged from 3 to 600 ft NGVD 29. The majority of the data points represent land-surface altitudes less than 210 ft, with only five values greater than 210 ft. The regression equation is best used for estimating the water-table altitude over the lower ACP where land-surface altitude is less than 300 ft and greater than 3 ft. Additionally, once the mean land-surface altitude for a cell was less than 2.44 ft, the water-table altitude was set to 0 ft rather than using the regression equation, so that no water-table altitudes were set to negative values.

In an area of the inner Coastal Plain (*fig. A1*), model layer 1 contains active model cells, and recharge was defined for layer 1 in this area where the hydrogeologic units crop out near the Fall Line (*fig. C2*). The bottom altitude of model layer 16 was set at the top of bedrock and was simulated as a no-flow boundary. The depth to the top of bedrock was based on lithologic data from boreholes (Harrelson and Fine, 2006).

The northwest (updip) boundaries of all layers were simulated as no-flow boundaries and are located along the Fall Line (*fig. C4*). The southeast (downdip) termini of all model layers also were simulated with no-flow boundaries. These no-flow boundaries are located near the approximate location of the freshwater-saltwater divide. The onshore divide was defined where the chloride concentration of the groundwater reached 10,000 milligrams per liter (mg/L; Lee and others, 1986; Aucott, 1996; Giese and others, 1997; Lautier, 1998, 2001, 2006). The location of the offshore divide was not known and was defined to be at such a distance from the coast line as to not introduce boundary effects. The northeast and southwest boundaries were simulated as specified-head boundaries in layer 1 at the James River in Virginia to the northeast and the Altamaha River in Georgia to the southwest (*fig. C1*), and along groundwater flow paths in layers 2 through 16.

### Recharge

Recharge was specified in the area east of where the hydrogeologic units crop out along the Fall Line (*fig. C4*) and where the land-surface altitudes are the highest in the study area. Recharge was considered spatially uniform across the area where recharge was applied. The recharge rate has a high degree of uncertainty associated with it; recharge was, therefore, adjusted during calibration within acceptable bounds during the initial steady-state stress period, producing a steady-state calibrated value of 0.0004 foot per day (ft/d) or 1.75 inches per year (in/yr). In the transient stress periods, recharge was varied temporally based on historical precipitation data from six stations in the inner Coastal Plain (*table C3*; *figs. C2, C5*). The percentage difference between the precipitation for each time step and the calibrated steady-state recharge value of 0.0004 ft/d was used to determine whether recharge during the time step should increase or decrease and by how much. Recharge was varied from a minimum of 0.000249 ft/d (1.09 in/yr) in time step 26 (2001) to a maximum of 0.000541 ft/d (2.37 in/yr) in time step 23 (1998, *fig. C6*).

### Groundwater Use

Water-use data from 1900 to 2004 for 3,957 wells as reported by State regulatory agencies (N.C. Wilson, North Carolina Department of Water Resources, oral commun., 2005; South Carolina Department of Health and Environmental Control, written commun., 2007) and in previous model investigations (Aucott, 1988, 1996; Giese and others, 1997),

**Table C3.** Descriptions of precipitation stations in part of the Atlantic Coastal Plain in South Carolina and Georgia.

[NOAA, National Oceanic and Atmospheric Administration; ft NAVD 88, in feet relative to North American Vertical Datum of 1988]

| NOAA station number | Station location | Map index number (see *fig. C2*) | Altitude, in ft NAVD 88 | Period of record | Annual mean precipitation, in inches | Annual maximum precipitation, in inches | Annual minimum precipitation, in inches |
|---|---|---|---|---|---|---|---|
| 095882 | Millen, GA | 1 | 195 | 1882–2004 | 46.21 | 74.67 | 28.92 |
| 380074 | Aiken, SC | 2 | 400 | 1854–2004 | 47.11 | 71.36 | 22.38 |
| 380764 | Blackville, SC | 3 | 324 | 1884–2004 | 47.32 | 75.1 | 27.85 |
| 381310 | Camden, SC | 4 | 140 | 1849–2004 | 47.27 | 83.41 | 27.16 |
| 381588 | Cheraw, SC | 5 | 140 | 1882–2004 | 47.30 | 67.93 | 29.72 |
| 381944 | Columbia, SC | 6 | 242 | 1872–2004 | 43.92 | 74.49 | 27.11 |

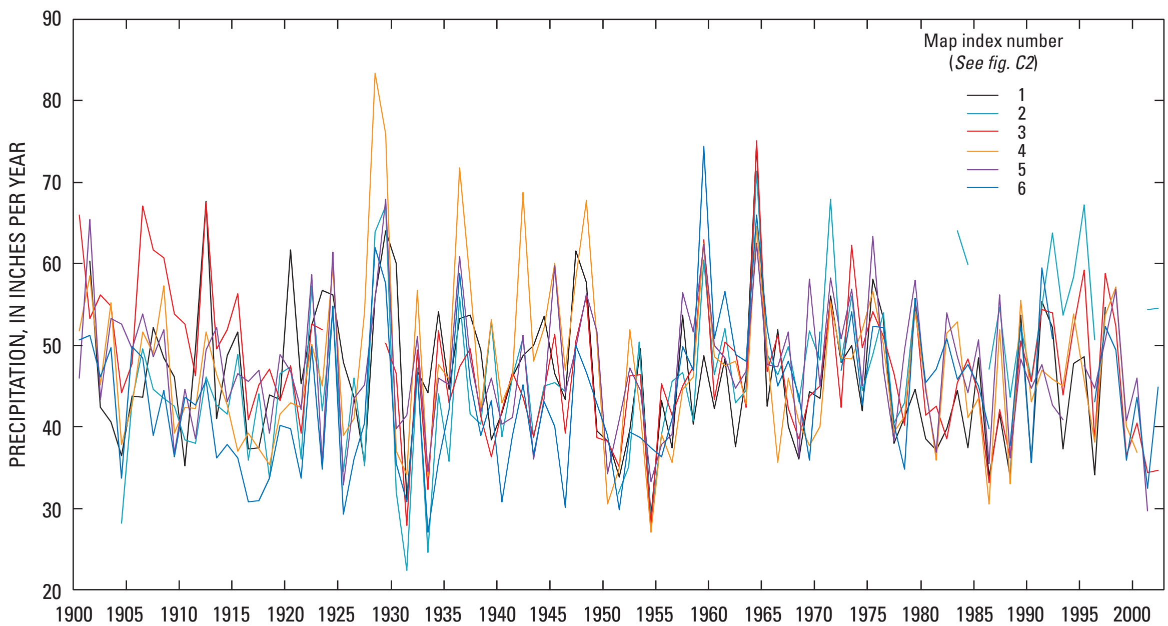



**Figure C5.** Continuous precipitation data from precipitation stations in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

were used in this investigation (*figs. C7, C8A–G*). Only withdrawals greater than 3 million gallons per month were included in the model because smaller withdrawals are not required to be reported to the State agencies and, therefore, generally are unknown. Pumpage from domestic wells is not reported to the State agencies and was not included in the withdrawal volumes. Pumpage from domestic wells in the NC–SC Coastal Plain, however, is primarily from the surficial aquifer and is not applicable because layer 1 mostly has a specified head as the upper boundary. In some cases, pumpage for multiple wells was reported by agencies as a single rate; in these instances, the reported rate was subdivided over several wells. Most well records did not have an aquifer designated as the specific one from which pumping occurred. For all wells, the pumpage was attributed to the model layer or layers within which the tops and bottoms of the screened intervals were located. Wells screened in more than one layer had the pumpage divided equally between the multiple aquifer layers. Overall, recent water-use data are considered to be more accurate than historical water-use data.

Prior to 1900, no major pumping occurred from the NC–SC ACP aquifers. Withdrawals from the deep, confined aquifers began in 1879 in Charleston, SC, but the volumes were relatively small. Increased groundwater withdrawals from the ACP aquifers began in the 1940s from the Yorktown and Upper Floridan aquifers (model layer 3, *table C1*). Withdrawals from all of the aquifers generally have increased from 1900 to 2004.

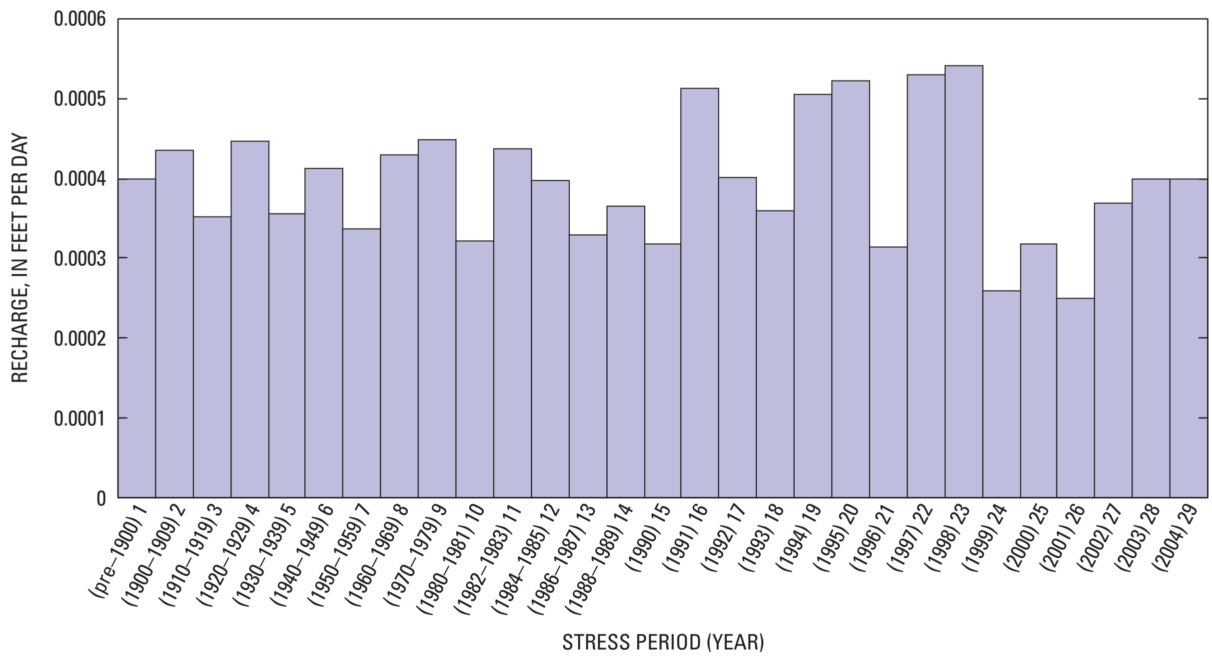



**Figure C6.** Simulated recharge by model stress period for hydrogeologic units in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

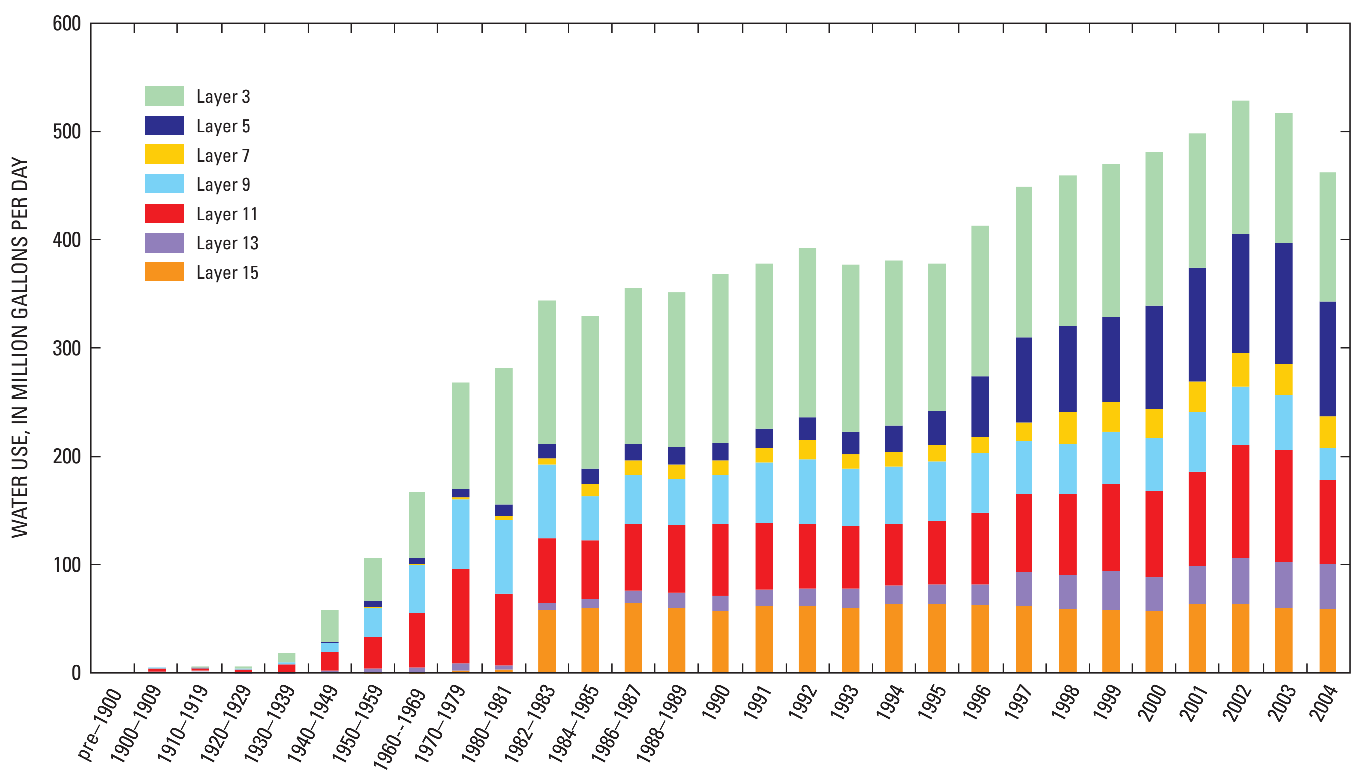
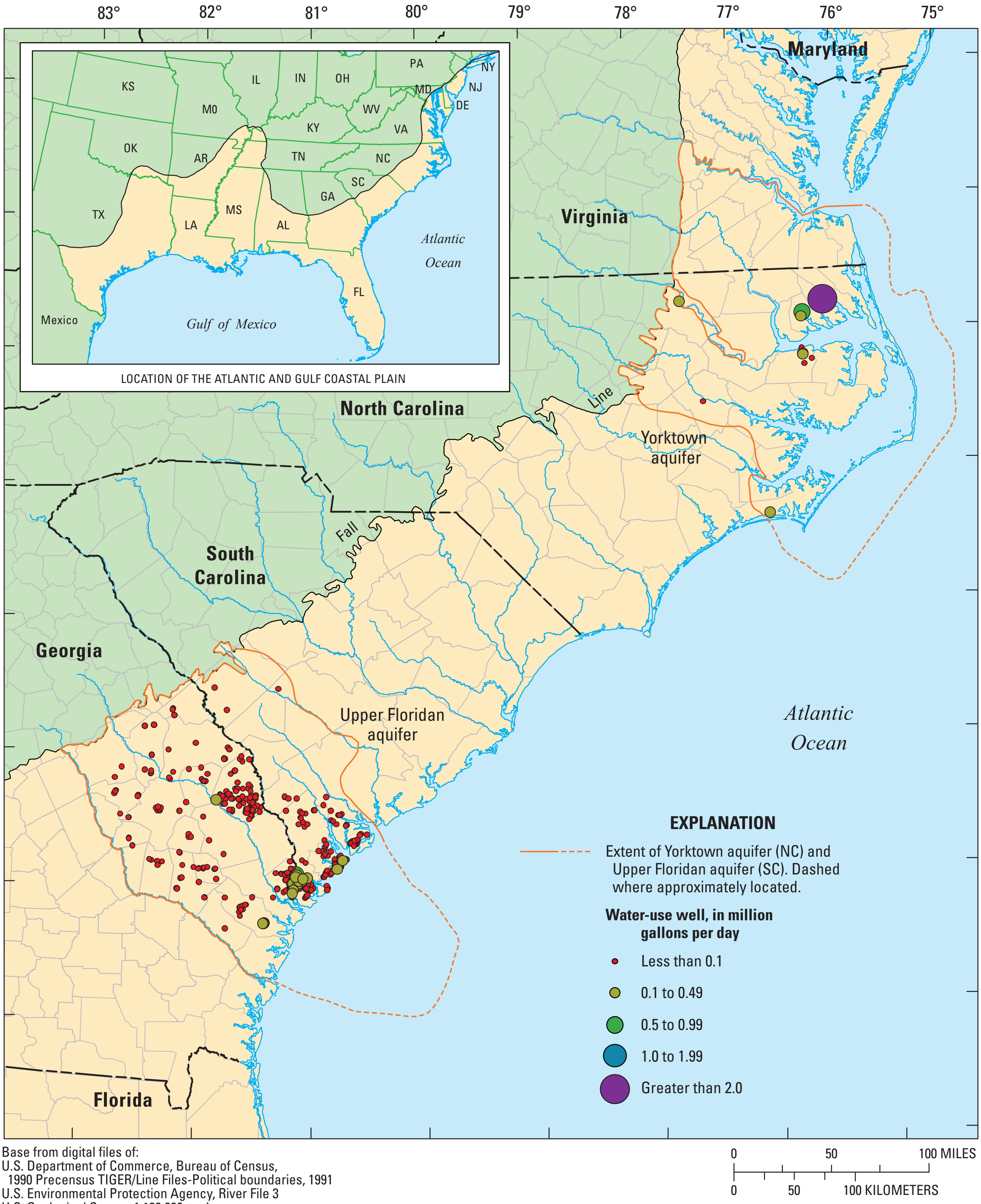



**Figure C7.** Groundwater use by model layer for wells in in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.




Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure C8A.** Locations of water-use wells and 2004 withdrawal amounts from the Yorktown aquifer (North Carolina) and the Upper Floridan aquifer (South Carolina) (layer 3), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

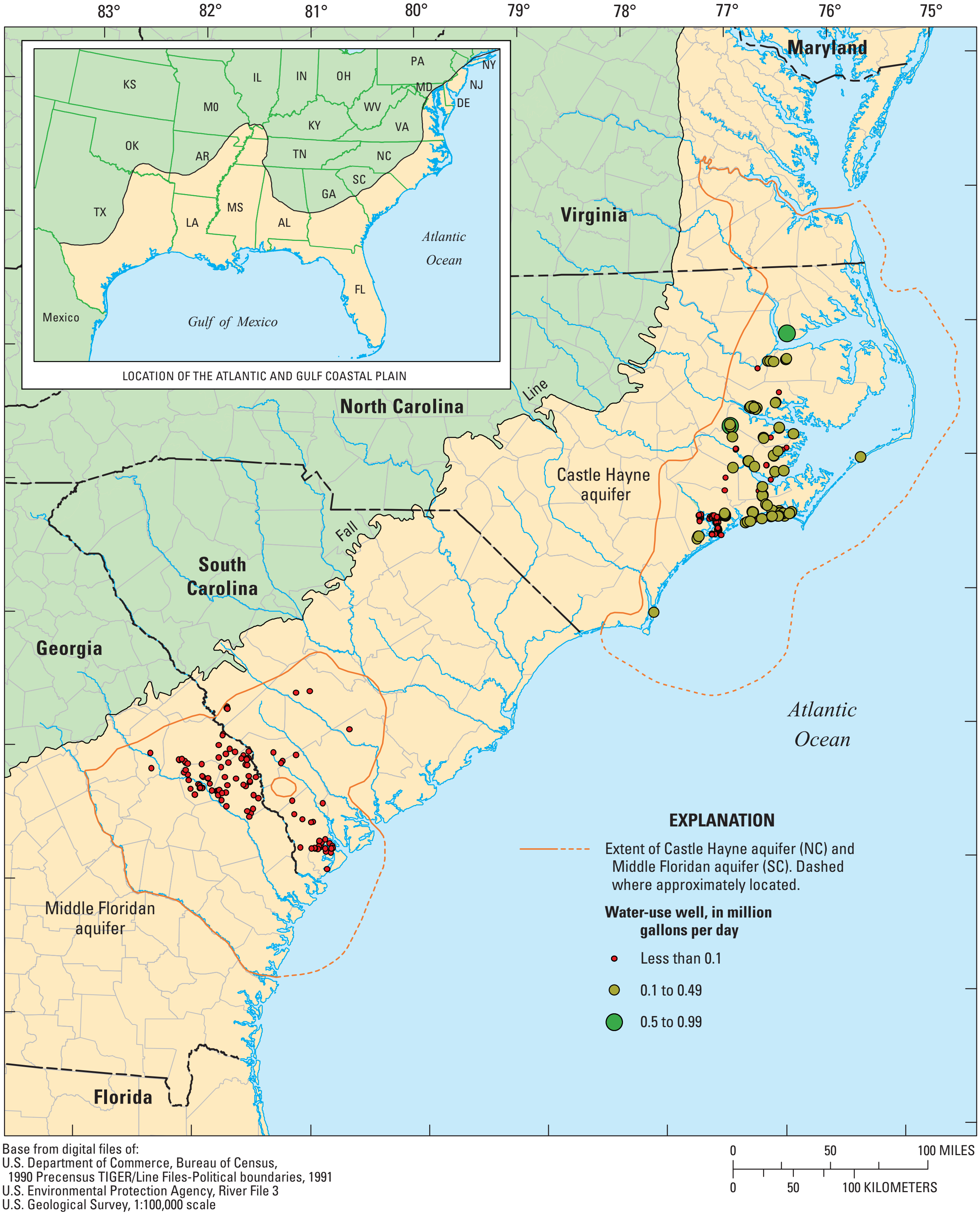



**Figure C8B.** Locations of water-use wells and 2004 withdrawal amounts from the Castle Hayne aquifer (North Carolina) and the Middle Floridan aquifer (South Carolina) (layer 5), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

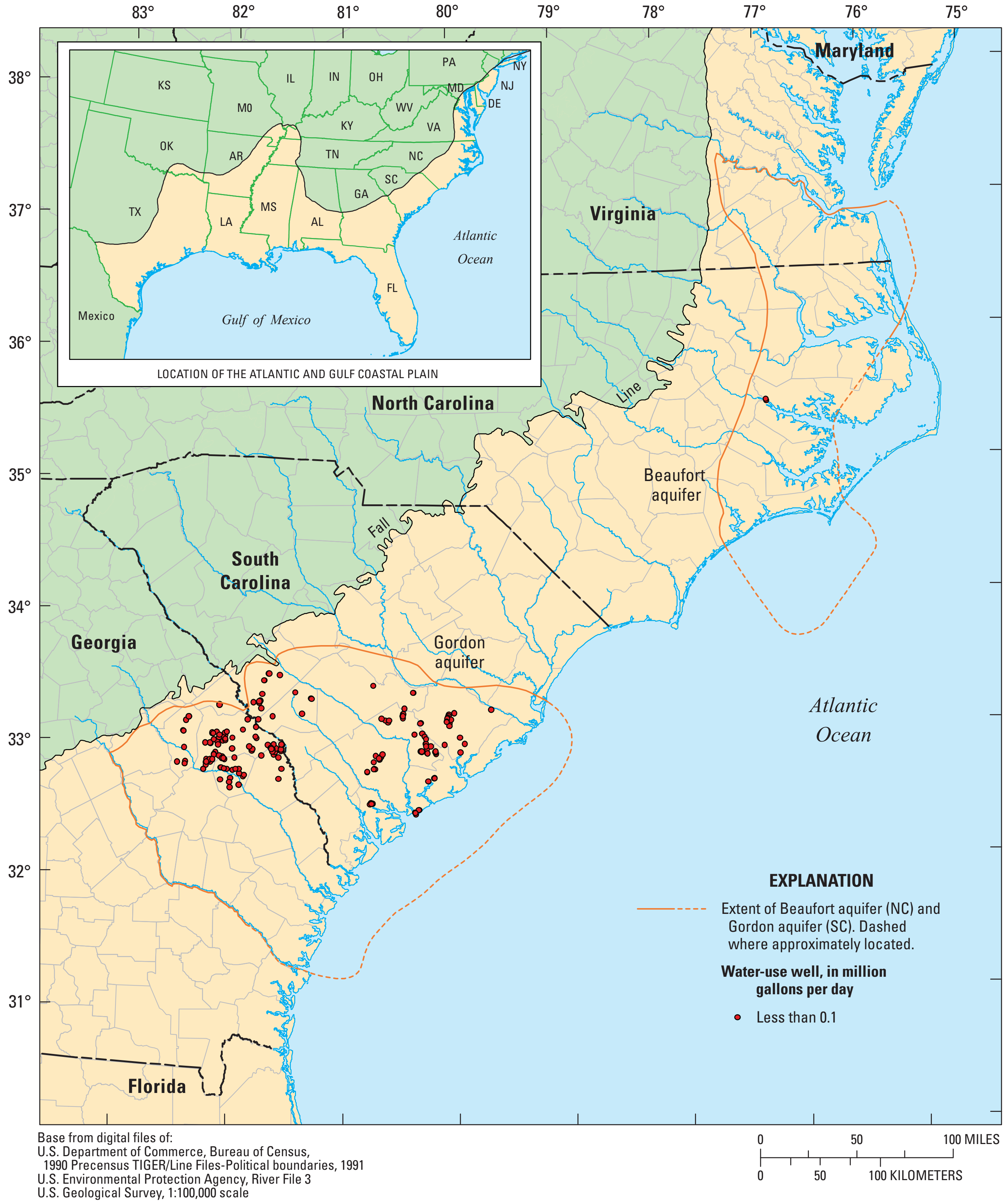



**Figure C8C.** Locations of water-use wells and 2004 withdrawal amounts from the Beaufort aquifer (North Carolina) and the Gordon aquifer (South Carolina) (layer 7), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

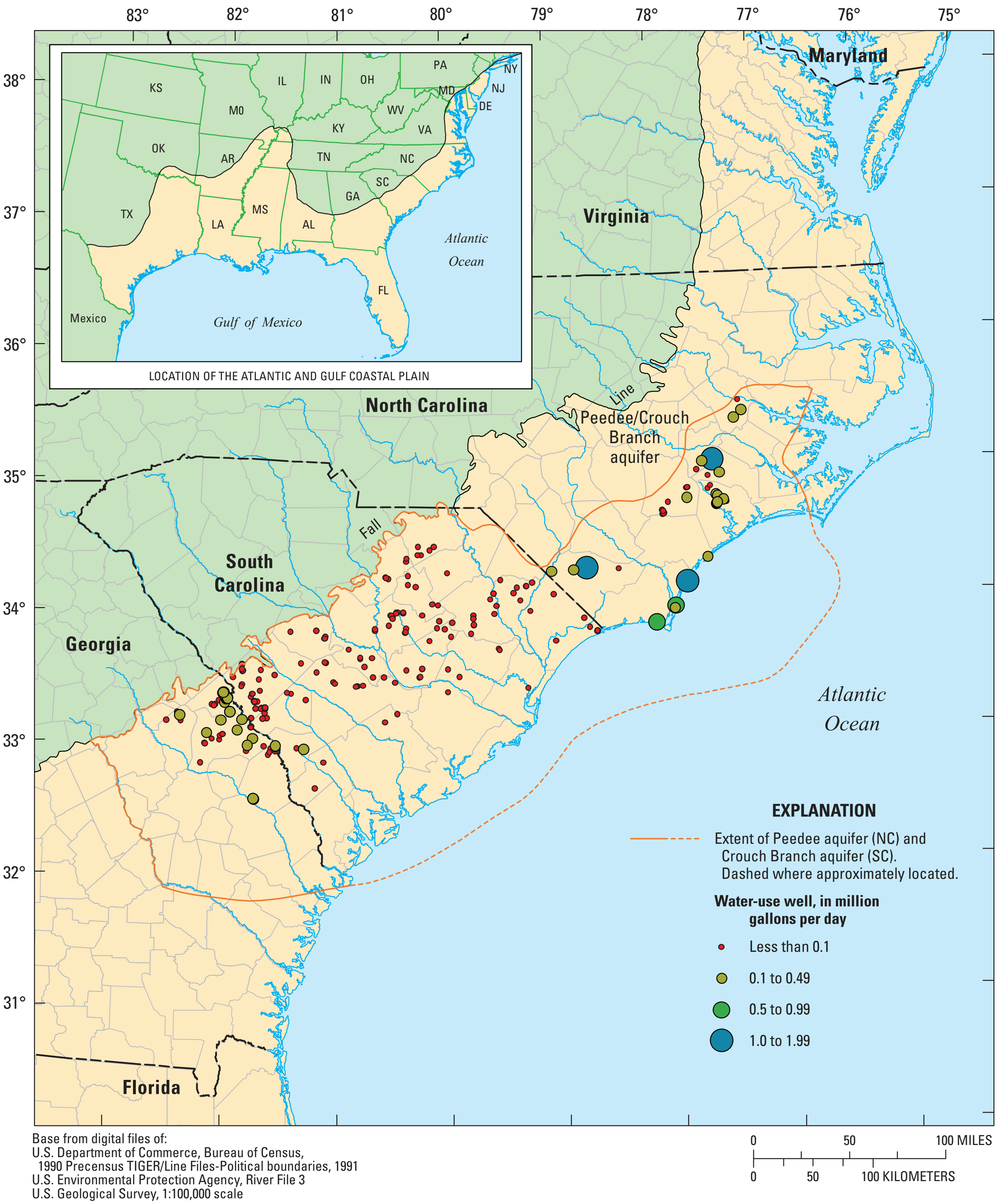



**Figure C8D.** Locations of water-use wells and 2004 withdrawal amounts from the Peedee aquifer (North Carolina) and Crouch Branch aquifer (South Carolina) (layer 9), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

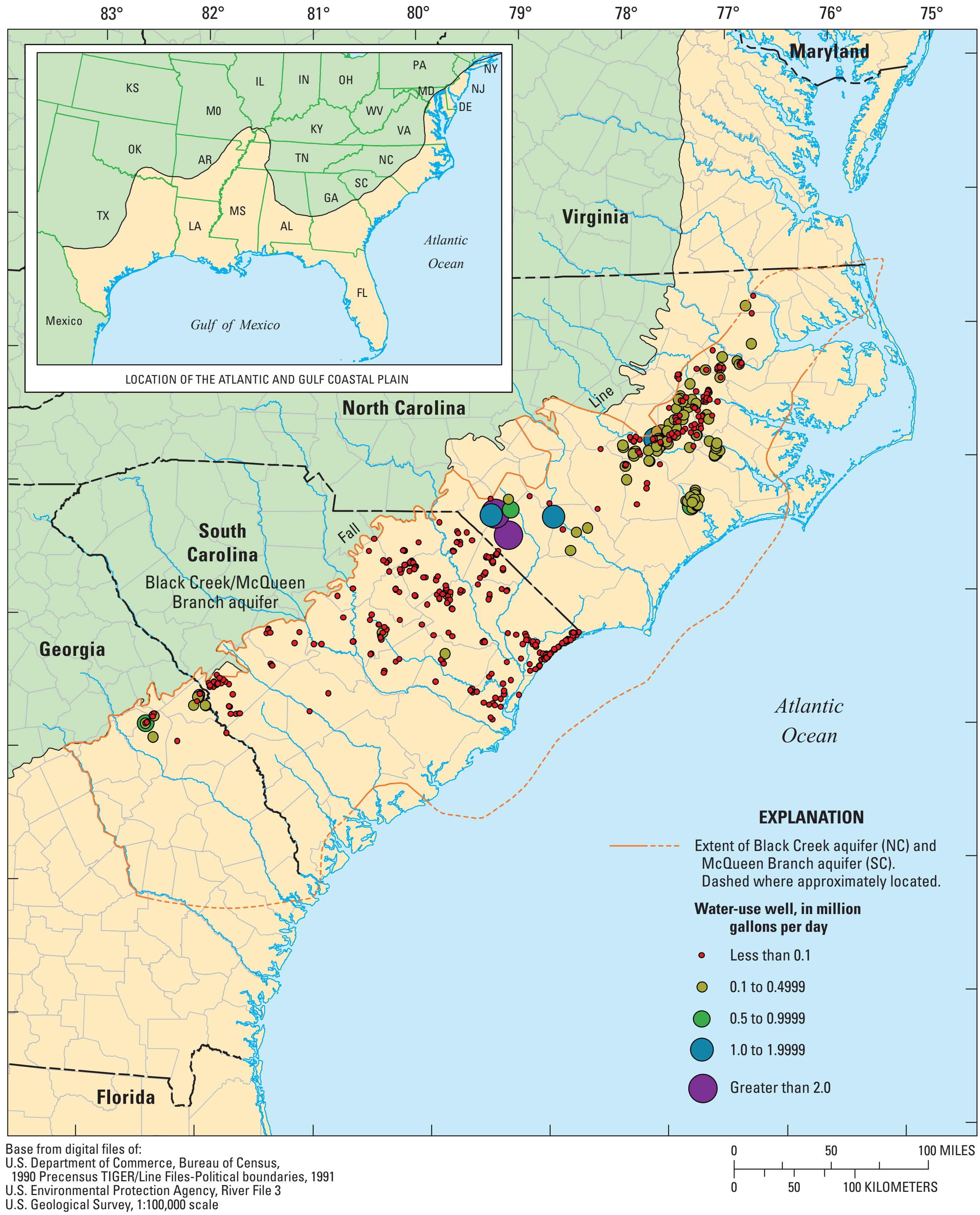
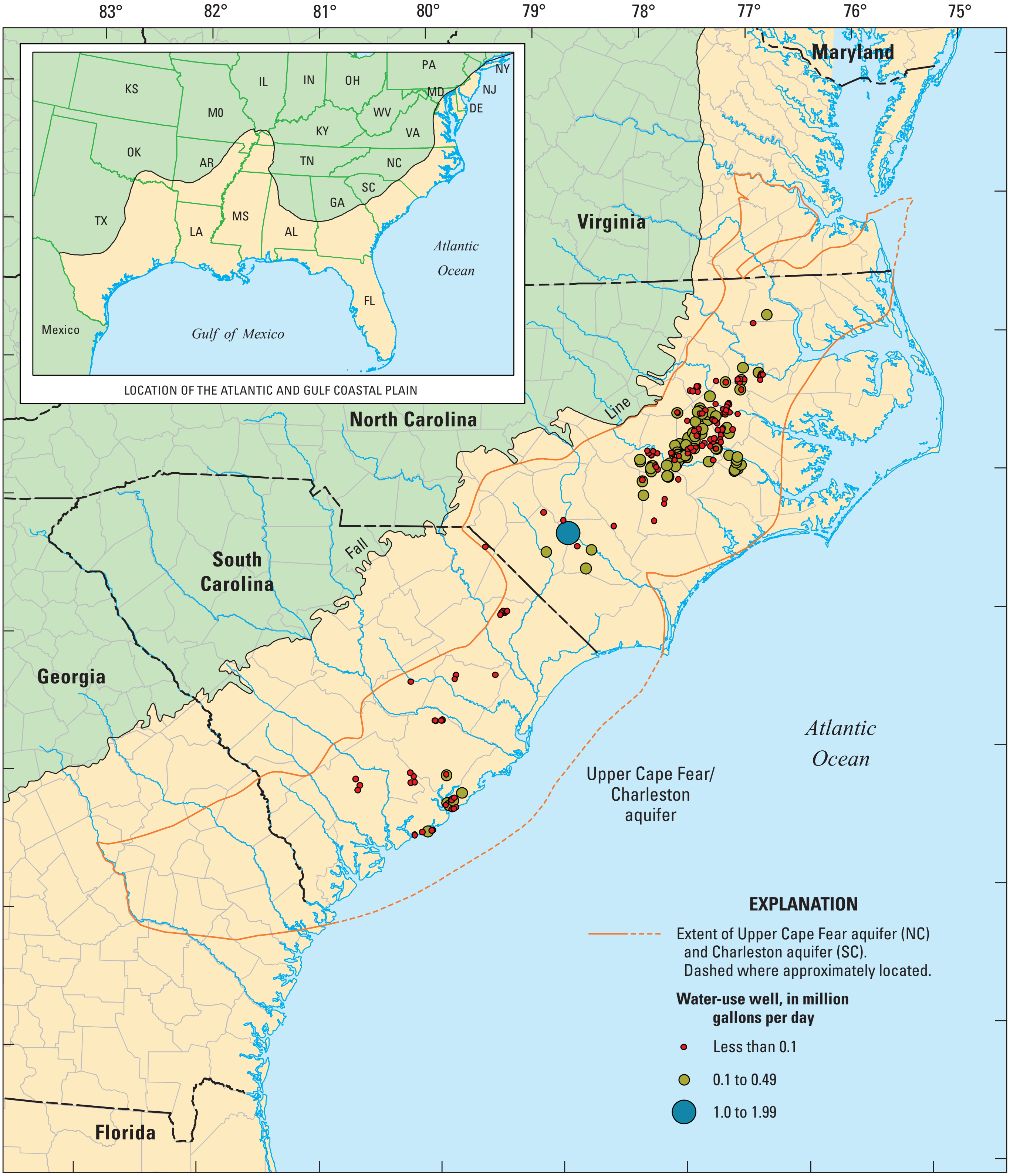



**Figure C8E.** Locations of water-use wells and 2004 withdrawal amounts from the Black Creek aquifer (North Carolina) and McQueen Branch aquifer (South Carolina) (layer 11), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

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1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
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**Figure C8F.** Locations of water-use wells and 2004 withdrawal amounts from the Upper Cape Fear aquifer (North Carolina) and the Charleston aquifer (South Carolina) (layer 13), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

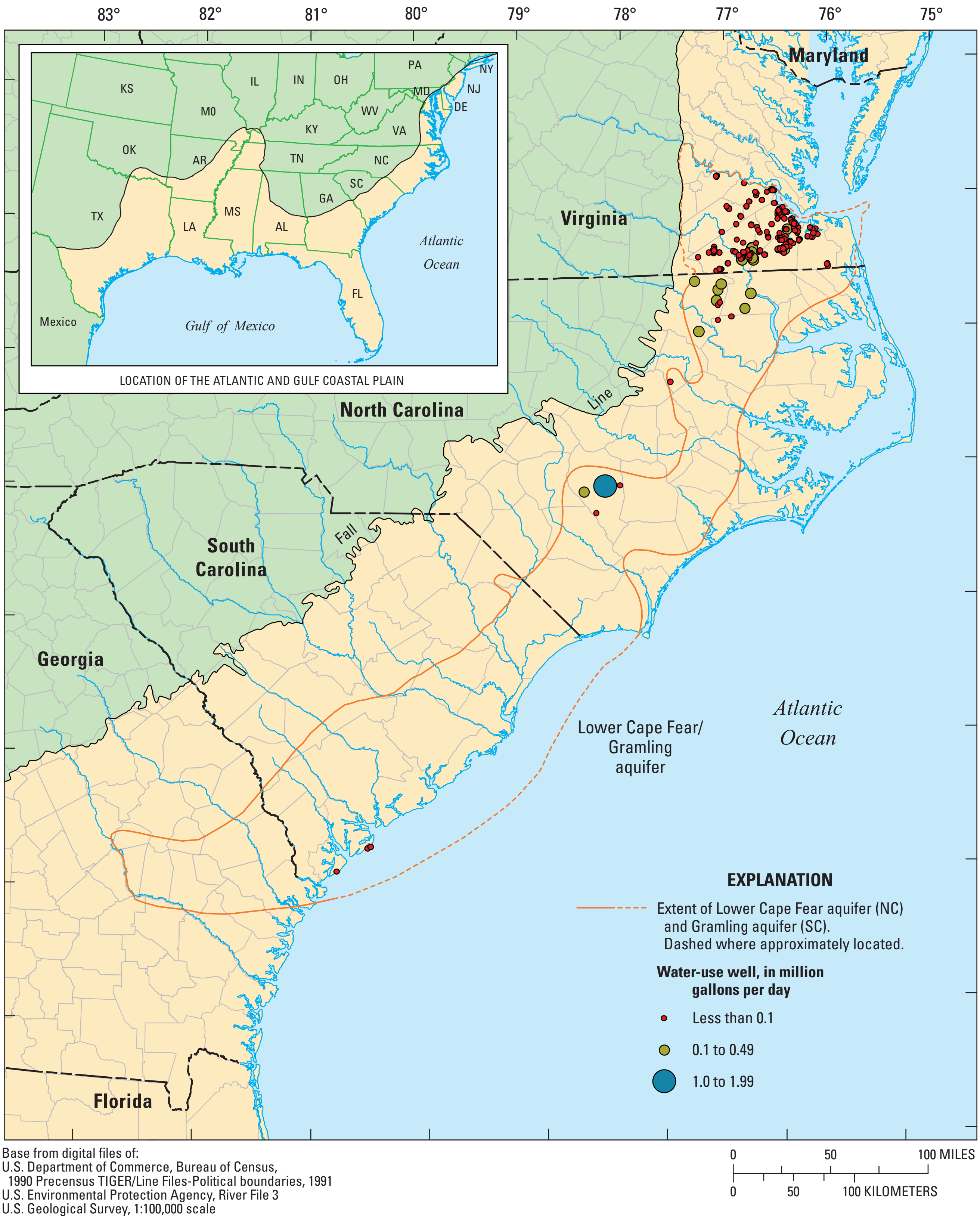


**Figure C8G.** Locations of water-use wells and 2004 withdrawal amounts from the Lower Cape Fear aquifer (North Carolina) and the Gramling aquifer (South Carolina) (layer 15) , in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

## Hydraulic Properties Used in Model Calibration

Initial horizontal hydraulic conductivity values for all aquifers were derived from published transmissivity data (*table C4*; Aucott and Newcome, 1986; Newcome, 1993, 2000; Harrelson and Fine, 2006; Dorothy Payne, U.S. Geological Survey, written commun., December 2006; Michael Peck, U.S. Geological Survey, written commun., December 2006). Horizontal hydraulic conductivities for all aquifers, except the surficial aquifer, were adjusted during model calibration. Horizontal hydraulic conductivities were calculated by dividing the published transmissivity value at a well by either the thickness of the aquifer, if known, or the total length of the well screen if aquifer thickness was not known. Calculated hydraulic conductivities were not used if the resultant value was not representative of the typical hydraulic conductivity range for the type of aquifer being simulated. Horizontal hydraulic conductivity of the aquifer units is the best defined property in the model, and aquifer-test results used in this model are estimated to have an uncertainty factor of approximately one order of magnitude (Eve Kuniansky, U.S. Geological Survey, oral commun., December 2006). In general, more aquifer-test data are available for the shallow aquifers; therefore, they are better characterized than the deeper aquifers.

Specific storage values for the confined aquifers initially were derived from published storage coefficient data (Aucott and Newcome, 1986; Newcome, 1993, 2000) and adjusted during model calibration. Specific storage values were calculated in a similar manner to the hydraulic conductivity values using the reported storage coefficient and aquifer thickness, or screen length if thickness was unknown. Calculated specific storage values were not used if the resultant value was not representative of the typical storativity range for the type of aquifer being simulated. Uncertainty associated with the values of specific storage comes from several sources, including the aquifer test data-collection techniques, the data-analysis methodology, and the aquifer thickness at the aquifer test wells. Fetter (1988) indicates that values of specific storage are generally very small, 0.0001 $ft^{-1}$ or less.

No hydraulic property data were available for horizontal hydraulic conductivity of the confining units, specific storage of the confining units, specific yield of the surficial aquifer, and vertical anisotropy (defined as the ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity) of the aquifers or confining units. Therefore, these inputs were calibrated during the simulation process. The initial values for these properties were set within the range of reasonable values for the aquifers and confining units. Fetter (1988) indicates that clay units typically will have a hydraulic conductivity ranging between 0.000003 and 0.003 ft/d.

## Observations Used in Model Calibration

Groundwater level and river baseflow observations were compiled for use in the model calibration and are available in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2005). Groundwater levels from prior to 1980 were used to develop the predevelopment steady-state hydraulic-head observations, and groundwater levels from 1980 and 2004 were used to develop the transient hydraulic-head observations. Historical river baseflow data from streamgages were used to develop groundwater discharge observations.

**Table C4.** Ranges of reported aquifer transmissivity, and calculated and simulated hydraulic conductivities for the aquifers in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

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

| Aquifer | Model layer | Reported transmissivity[1], in $ft^2/d$ | | | Horizontal hydraulic conductivity, in ft/d | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Calculated | | Simulated | |
| | | Minimum | Maximum | Mean | Minimum | Maximum | Minimum | Maximum |
| Surficial and Upper Three Runs | 1 | 20 | 15,000 | 1,300 | 11.8 | — | 216 | 216 |
| Yorktown and Upper Floridan | 3 | 2.0 | 530,000 | 20,000 | 4.00 | 1,340 | 2.0 | 1,150 |
| Pungo River, Castle Hayne, and Middle Floridan | 5 | 190 | 530,000 | 18,000 | 1.00 | 169 | 2.0 | 262 |
| Beaufort and Gordon | 7 | 10 | 21,000 | 3,200 | 2.10 | 1,340 | 0.8 | 169 |
| Peedee and Crouch Branch | 9 | 49 | 27,000 | 2,400 | 3.00 | 223 | 0.8 | 177 |
| Black Creek and McQueen Branch | 11 | 49 | 34,000 | 2,800 | 2.00 | 303 | 0.8 | 175 |
| Upper Cape Fear and Charleston | 13 | 130 | 31,000 | 5,300 | 1.00 | 102 | 0.5 | 129 |
| Lower Cape Fear and Gramling | 15 | 10 | 6,000 | 1,600 | 1.00 | 45.8 | 1.4 | 64.0 |

[1] Aucott and Newcome, 1986; Newcome, 1993; Newcome, 2000; Dorothy Payne and Michael Peck, U.S. Geological Survey, written commun., 2006; Harrelson and Fine, 2006.

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.

## Groundwater Levels

Observed groundwater level data for the NC and SC Coastal Plain were used for calibration of the flow model (*fig. C9A–G*). Minimal water-level data were available for the predevelopment period prior to 1900; therefore, water-level data collected prior to 1980 were used to develop hydraulic-head observations for the steady-state calibration. Previous investigators considered groundwater pumping to have minimally affected pre-1980 regional water levels in the ACP (Aucott and Speiran, 1985). Predevelopment, steady-state head observations were derived at 1,073 wells. Head observations were obtained from 453 wells for the 1980 calibration and 738 wells for the 2004 calibration. Overall, the hydraulic-head observations in each layer cover the known extent of each unit and generally are distributed evenly, with the exceptions of the southern portion of NC in the Beaufort/Gordon aquifers (layer 7, *fig. C9C*), the southern portion of SC in the Black Creek/McQueen Branch aquifer (layer 11, *fig. C9E*), and most of the Lower Cape Fear/Gramling aquifer (layer 15, *fig. C9G*). No head data were available for the Lower Cretaceous aquifer (layer 16). Continuous groundwater level observations over multiple years from individual wells were used to depict changes in groundwater levels over time.

The largest source of error associated with the groundwater level data is the location of the well and land-surface altitude at the well site. The locations for most of the wells (70 percent) that were used for calibration purposes were interpolated from topographic maps and therefore may have substantial error. Approximately 14 percent of the well site locations were determined by global positioning system equipment. It was unknown how 10 percent of the locations of the well sites were determined, and the remainder of the well locations were determined by using other means such as surveying techniques. To normalize all of the water-level observations, all of the well locations were used in an interpolation process using USGS DEMs to determine the land-surface altitude. The vertical accuracy of the DEM used was 49.21 ft (15 m) or less (M.A. Lowery, U.S. Geological Survey, written commun., 2008) and was generally derived from USGS topographic maps with 10- or 20-ft contour intervals. Therefore, because of the uncertainty associated with the source of most of the land-surface data for the wells, the largest contour interval in the mapped study area, or 20 ft, was selected as one of the water-level calibration targets. That is, one of the primary goals of the calibration process was to match the observed groundwater levels within plus or minus 20 ft. Also, another calibration target was employed that uses the standard deviation of the water-level residuals (the observed subtracted from the calculated value) divided by the range in data (Kuniansky and others, 2004). This value is dimensionless and ideally should be less than 1.0. This statistic takes into account the range of water-level data. A good fit to the observed water levels would be approximately 0.1 (dimensionless), which was also a calibration target.

## River Baseflow

River baseflows calculated for 10 USGS streamgaging sites on 8 rivers in the inner Coastal Plain and Sand Hills were used as observations of groundwater discharge for model calibration (*fig. C2*; *table C5*). Daily streamflow data from selected sites were used with the USGS computer program PART (Rutledge, 1998) to estimate the groundwater discharge component of the overall streamflow. The program PART uses linear interpolation to estimate groundwater discharge during periods of surface-water runoff based on antecedent streamflow recession. Streamgaging sites in the Sand Hills and southern part of the inner ACP were exclusively used in the baseflow analysis because streams in this area are well connected to the aquifers that are present. Streamgaging sites in the northern part of the inner Coastal Plain were not used in the baseflow analysis because streams in this area are not well connected to the underlying confined aquifers.

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 of the daily streamflow data is determined and is included in the USGS records for each station. These ratings are “excellent,” which means that 95 percent of the daily streamflow data are within 5 percent of the true streamflow; “good” ratings are within 10 percent; “fair” ratings are within 15 percent; and “poor” ratings categorize daily streamflow data that have less than “fair” accuracy. Data from streamgages selected for inclusion in the model calibration are all from relatively small basins (generally less than 200 $mi^2$) in the inner Coastal Plain. These inner Coastal Plain streams have unstable sandbeds that tend to shift over time or from high-flow events and, therefore, result in “poor” ratings. Thus, it is assumed that all of the streamflow data used in the model calibration are rated “poor,” and the accuracy of the groundwater discharge data is essentially unknown. A calibration target of 15 percent of observed streamflow was set for the discharge data.

Streambed conductance was calibrated during the initial steady-state stress period. The mean streambed conductance values ranged from a low of 1.9 square feet per day per foot [($ft^2$/d)/ft] to a high of 80 ($ft^2$/d)/ft (*table C5*).

# Model Calibration

The NC–SC Coastal Plain model was calibrated to groundwater level and stream baseflow conditions from 1900 to 2004 using 29 stress periods. The first stress period represents conditions before 1900 and assumes steady-state conditions (no pumping from the ACP aquifers). The first eight transient stress periods are each a decade in length and represent the time period from 1900 to 1980 when the accuracy in terms of location and volume of the withdrawal data

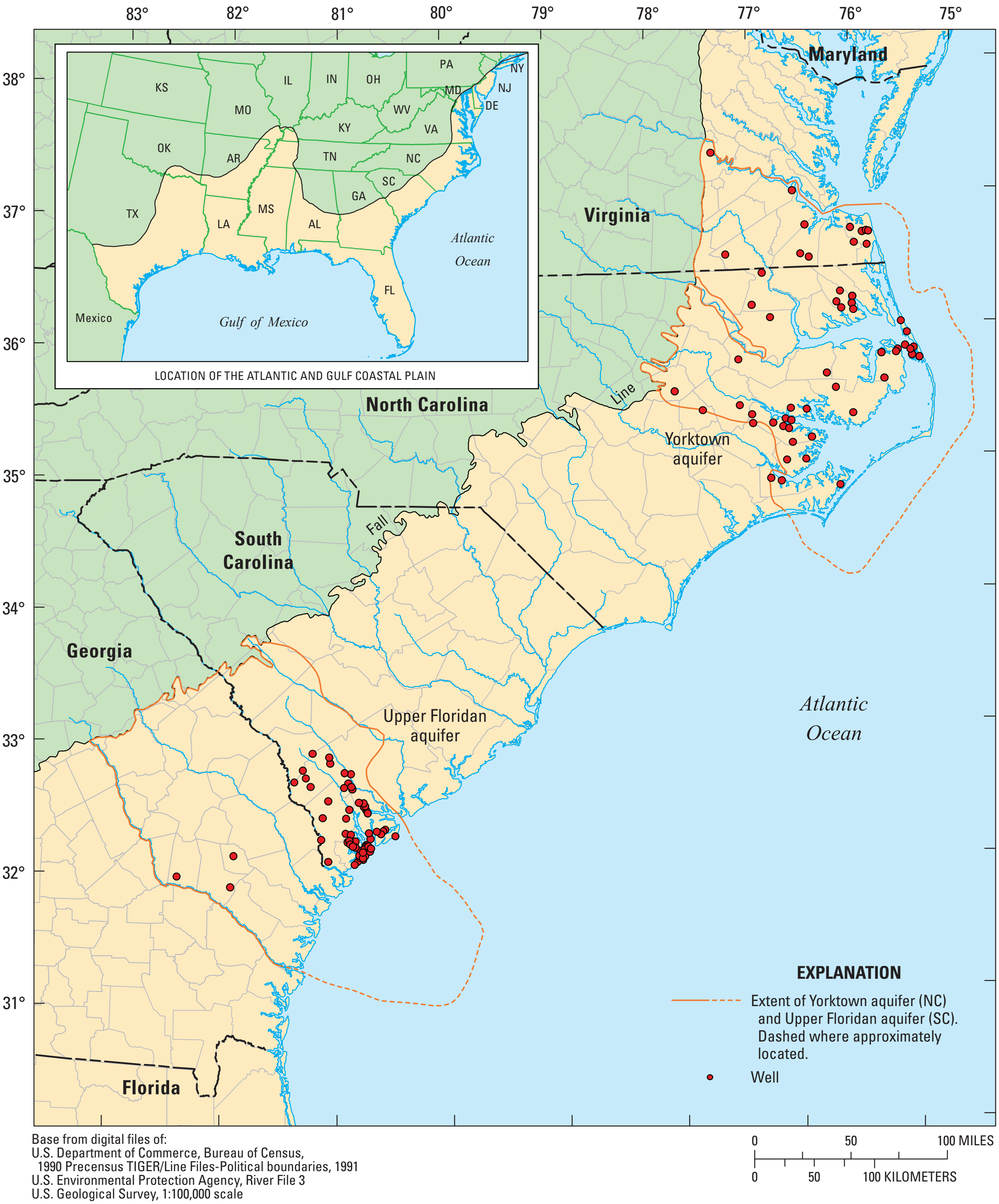


**Figure C9A.** Location of water-level wells completed in the Yorktown aquifer (North Carolina) and Upper Floridan aquifer (South Carolina) (layer 3) in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C9B.** Locations of water-level wells completed in the Castle Hayne aquifer (North Carolina) and Middle Floridan aquifer (South Carolina) (layer 5), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C9C.** Locations of water-level wells completed in the Beaufort aquifer (North Carolina) and the Gordon aquifer (South Carolina) (layer 7), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C9D.** Locations of water-level wells completed in the Peedee aquifer (North Carolina) and the Crouch Branch aquifer (South Carolina) (layer 9), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C9E.** Locations of water-level wells completed in the Black Creek aquifer (North Carolina) and the McQueen Branch aquifer (South Carolina) (layer 11), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


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U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

0 50 100 MILES
0 50 100 KILOMETERS

**Figure C9F.** Locations of water-level wells completed in the Upper Cape Fear aquifer (North Carolina) and the Charleston aquifer (South Carolina) (layer 13), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C9G.** Locations of water-level wells completed in the Lower Cape Fear aquifer (North Carolina) and the Gramling aquifer (South Carolina) (layer 15), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

**Table C5.** Streamflow and baseflow data used in model calibration and calibrated streambed conductance for selected sites in South Carolina and Georgia.

[USGS, U.S. Geological Survey; mi$^2$, square mile; ft$^3$/s, cubic feet per second; in/yr, inches per year; (ft$^2$/d)/ft, square feet per day per foot; SRS, Savannah River Site]

| USGS station number | Station name | Map index number (See *fig. C2*) | Drainage area, in mi$^2$ | Period of record, in years | Mean streamflow | | Mean baseflow | | Baseflow index, in percent of total flow | Calibrated streambed conductance [(ft$^2$/d)/ft] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | ft$^3$/s | in/yr | ft$^3$/s | in/yr | | Mean | Maxi-mum | Mini-mum |
| 02130900 | Black Creek near McBee, SC | 1 | 108 | 1960–2002 | 152 | 19.2 | 122 | 15.3 | 80 | 2.0 | 2.0 | 2.0 |
| 02196689 | Little Horse Creek near Graniteville, SC | 2 | 26.6 | 1990–1998 | 34.2 | 17.5 | 29.9 | 15.3 | 87 | 16 | 40 | 4 |
| 02197310 | Upper Three Runs above Road C (SRS), SC | 3 | 176 | 1975–1997 | 212 | 16.4 | 179 | 13.8 | 85 | 1.9 | 1.9 | 1.9 |
| 02197315 | Upper Three Runs at Road A (SRS), SC | 4 | 203 | 1980–2001 | 231 | 15.4 | 196 | 13.1 | 85 | 1.9 | 1.9 | 1.9 |
| 02173351 | Bull Swamp Creek near Swansea, SC | 5 | 34.4 | 2002–2002 | 6.47 | 2.6 | 5.26 | 2.08 | 81 | 33 | 40 | 30 |
| 02169570 | Gills Creek near Columbia, SC | 6 | 59.6 | 1967–2002 | 74.4 | 17.0 | 47.4 | 10.8 | 64 | 40 | 40 | 40 |
| 02135300 | Scape Ore Swamp near Bishopville, SC | 7 | 96.0 | 1969–2002 | 98.0 | 13.9 | 74.7 | 10.6 | 76 | 2.0 | 2.0 | 2.0 |
| 02172500 | South Edisto near Montmorenci, SC | 8 | 198 | 1941–1965 | 244 | 16.7 | 196 | 13.5 | 80 | 58 | 58 | 58 |
| 02197600 | Brushy Creek near Wrens, GA | 9 | 28.0 | 1959–1993 | 27.0 | 13.0 | 19.0 | 9.00 | 70 | 80 | 80 | 80 |
| 02197300 | Upper Three Runs near Ellenton, SC | 10 | 87.0 | 1967–2001 | 103 | 16.2 | 95.4 | 14.9 | 92 | 1.9 | 1.9 | 1.9 |

is least well known. The next five transient stress periods are each 2 years in length and represent the time period from 1980 to 1990 when more accurate groundwater withdrawal data were available. The final 15 transient stress periods are each 1 year in length and represent the period from 1990 to 2004, a period when relatively accurate water-use data were available for all of the ACP aquifers. The model was calibrated to conditions during predevelopment, 1980, and 2004.

The model was calibrated with an automated parameter-estimation approach using the computer program PEST (Doherty, 2005), and the model used regularized inversion and pilot points (de Marsily and others, 1984; LaVenue and Pickens, 1992; Doherty, 2003; Hunt and others, 2007). Using this method, hydraulic conductivity values were estimated at pilot points distributed throughout the model; the estimated values then were interpolated to each active model grid cell (*fig. C10A–G*). The pilot points were spatially distributed to match well locations where hydraulic conductivity data were available; in areas where no hydraulic conductivity data were available, the pilot points were distributed in an approximate regularly spaced distribution. The estimation of hydraulic conductivities at the pilot points was conducted so that the weighted sum-of-squares differences between model-generated water-level values and stream baseflows and between field water-level measurements and stream baseflows were minimized.

The use of pilot points for parameterization resulted in many more parameters than would have resulted by using zones of uniform parameter values. Regularized inversion was used through PEST to numerically stabilize the overparameterized inverse problem (Doherty, 2003). In addition, by using regularization in the parameter-estimation process, a large number of parameters could be estimated, allowing for locations where heterogeneity likely exists to be identified through the calibration process (Doherty, 2003).

Parameters selected for estimation during model calibration were hydraulic conductivity, specific storage, and anisotropy of the aquifers and confining units. Riverbed conductance and recharge were estimated for steady-state conditions. Published horizontal hydraulic conductivity values from the NC and SC Coastal Plain aquifers were used as initial values for the hydraulic conductivity pilot points (Aucott and Newcome, 1986; Newcome, 1993, 2000; Harrelson and Fine, 2006; Dorothy Payne, U.S. Geological Survey, written commun., December 2006; Michael Peck, U.S. Geological Survey, written commun., December 2006). These values

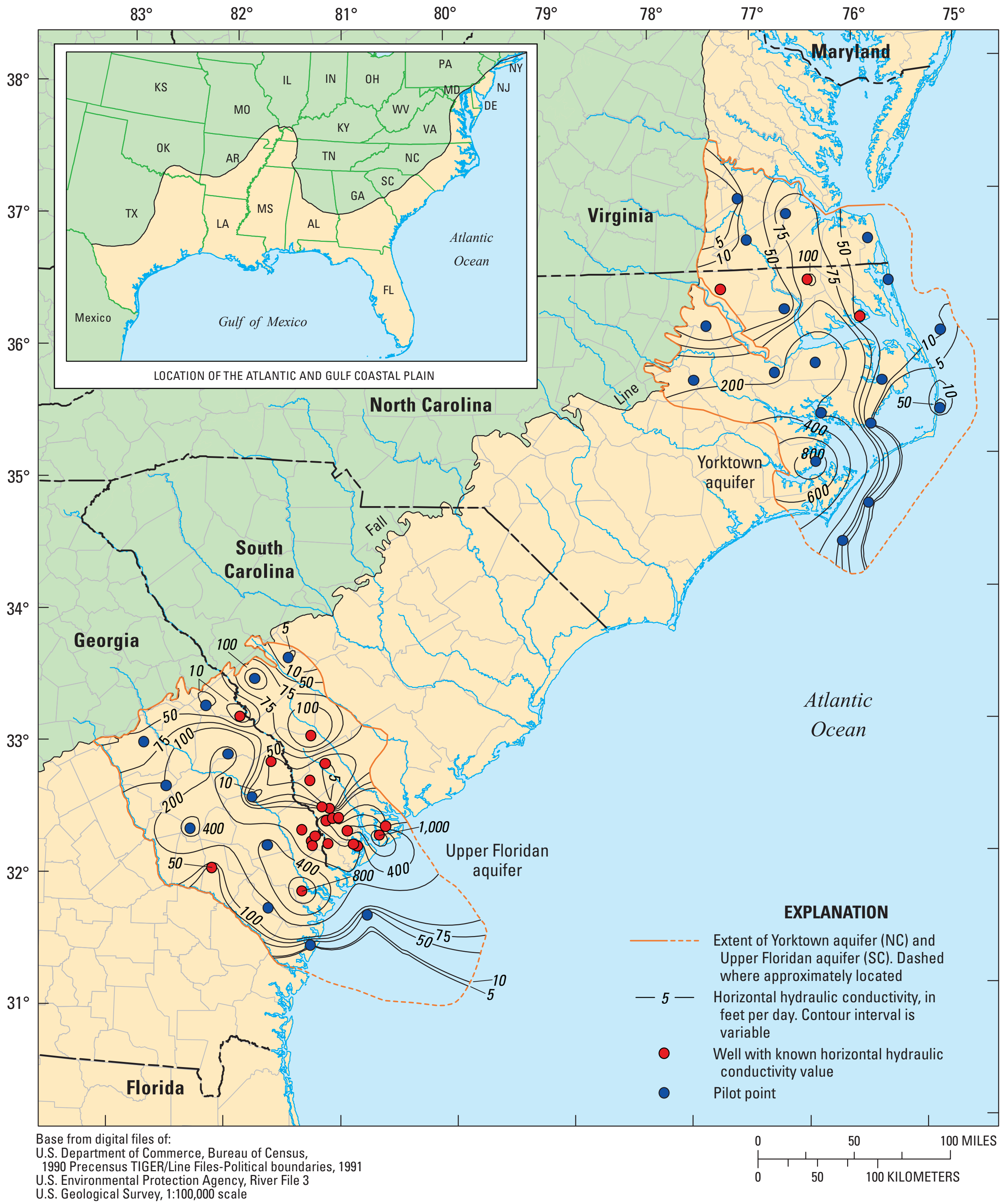



**Figure C10A.** Calibrated horizontal hydraulic conductivities for the Yorktown aquifer (North Carolina) and the Upper Floridan aquifer (South Carolina) (layer 3), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

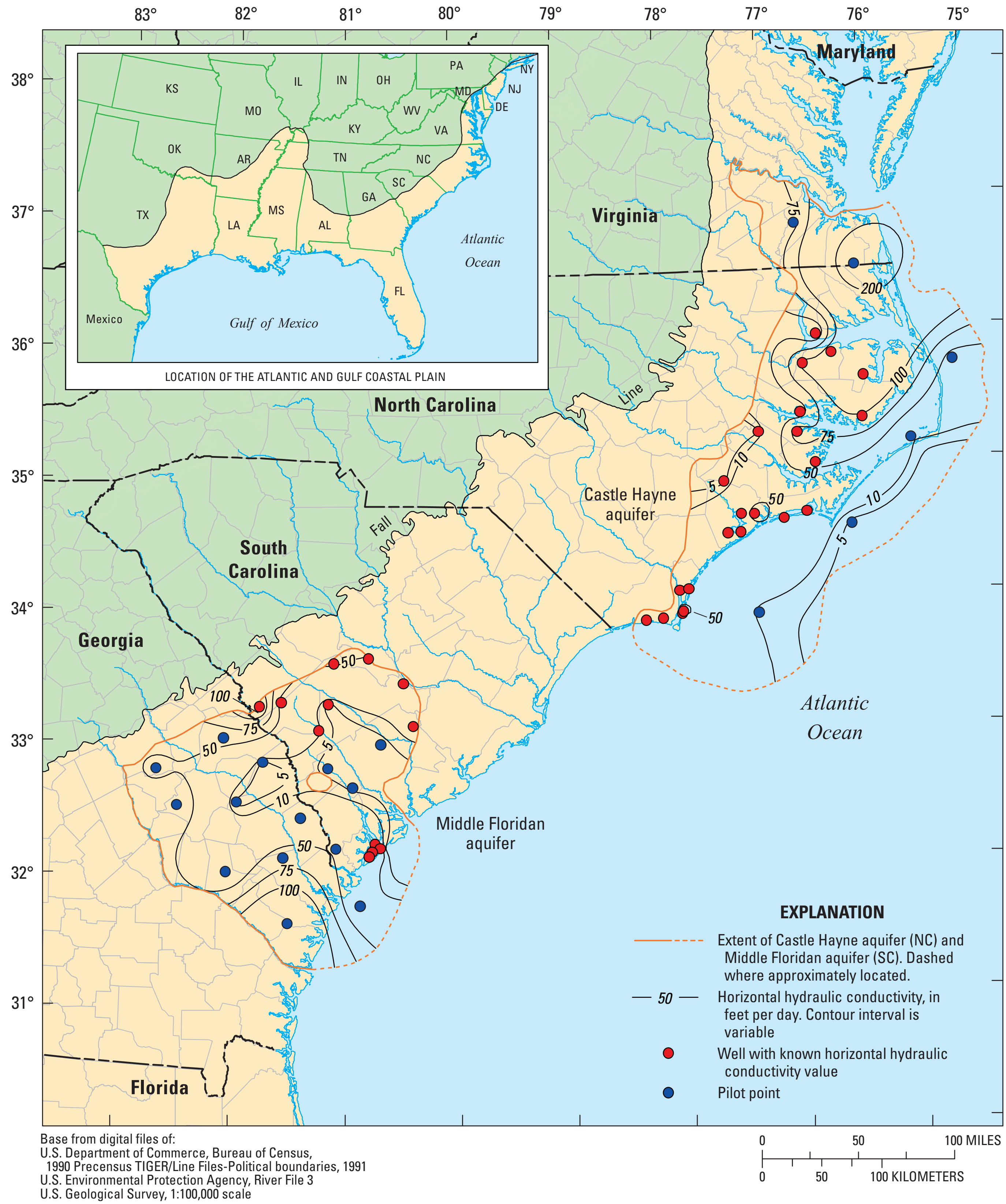
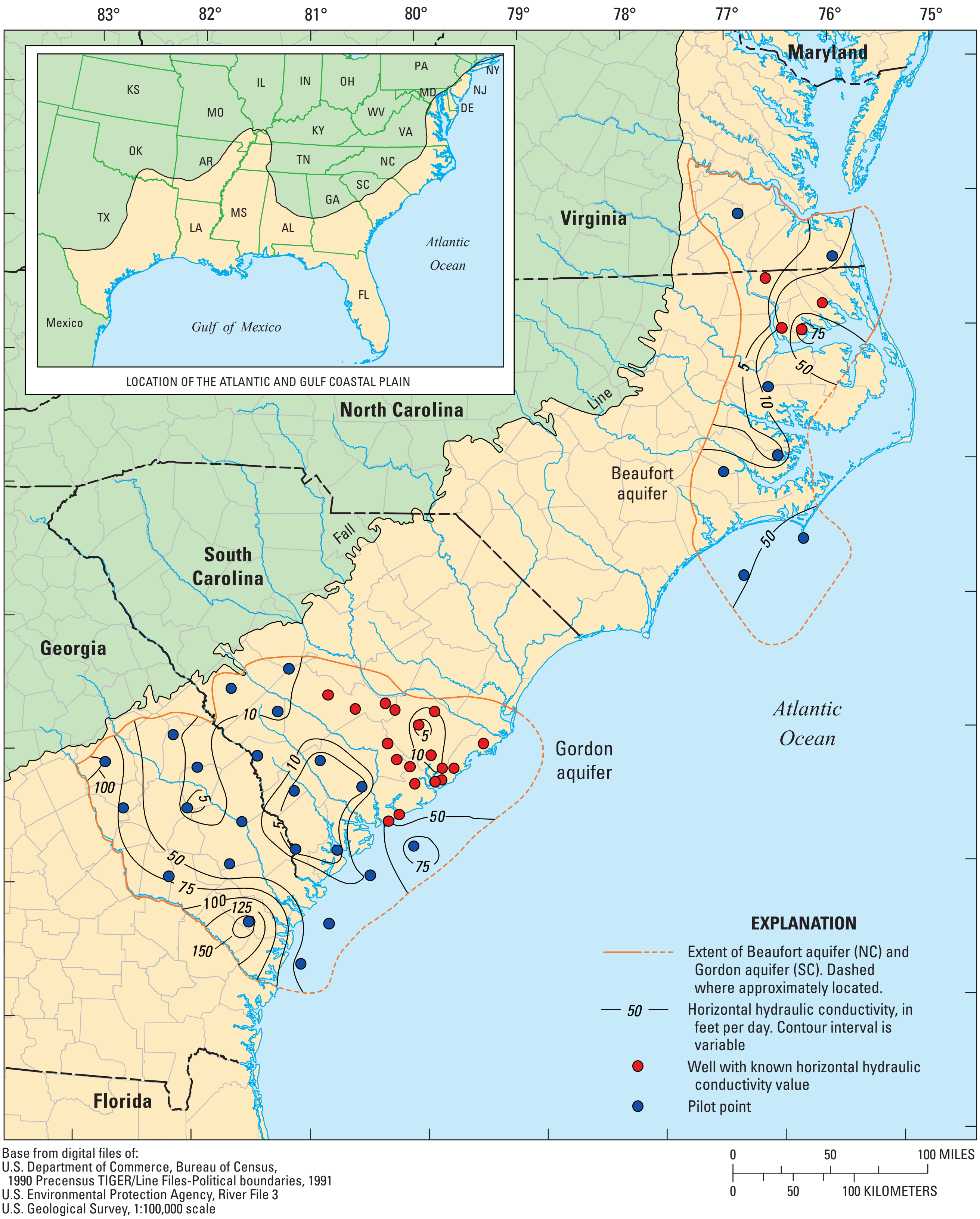



**Figure C10B.** Calibrated horizontal hydraulic conductivities for the Castle Hayne aquifer (North Carolina) and the Middle Floridan aquifer (South Carolina) (layer 5), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

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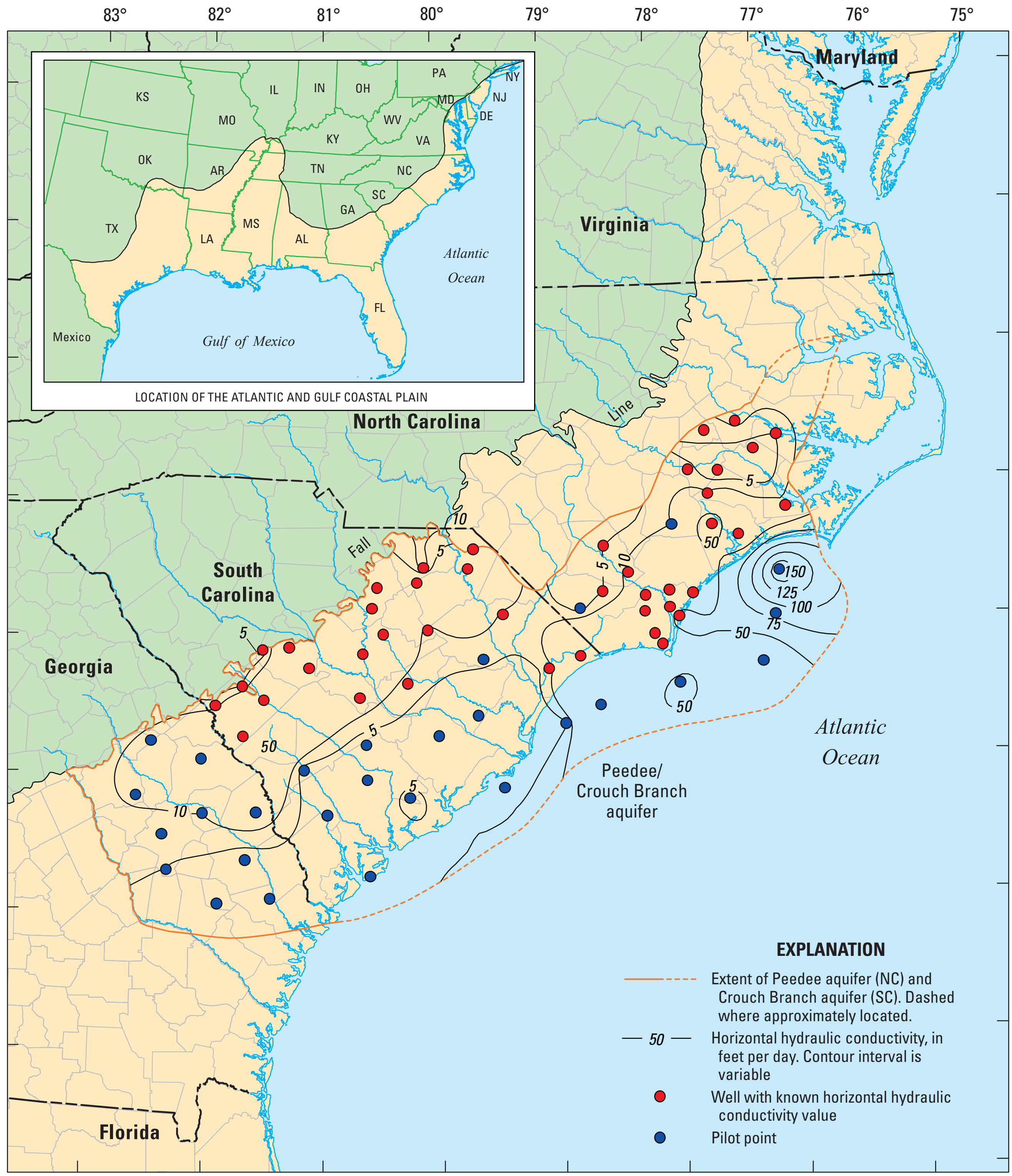
U.S. Geological Survey, 1:100,000 scale

**Figure C10C.** Calibrated horizontal hydraulic conductivities for the Beaufort aquifer (North Carolina) and the Gordon aquifer (South Carolina) (layer 7), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

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U.S. Geological Survey, 1:100,000 scale

**Figure C10D.** Calibrated horizontal hydraulic conductivities for the Peedee aquifer (North Carolina) and the Crouch Branch aquifer (South Carolina) (layer 9), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

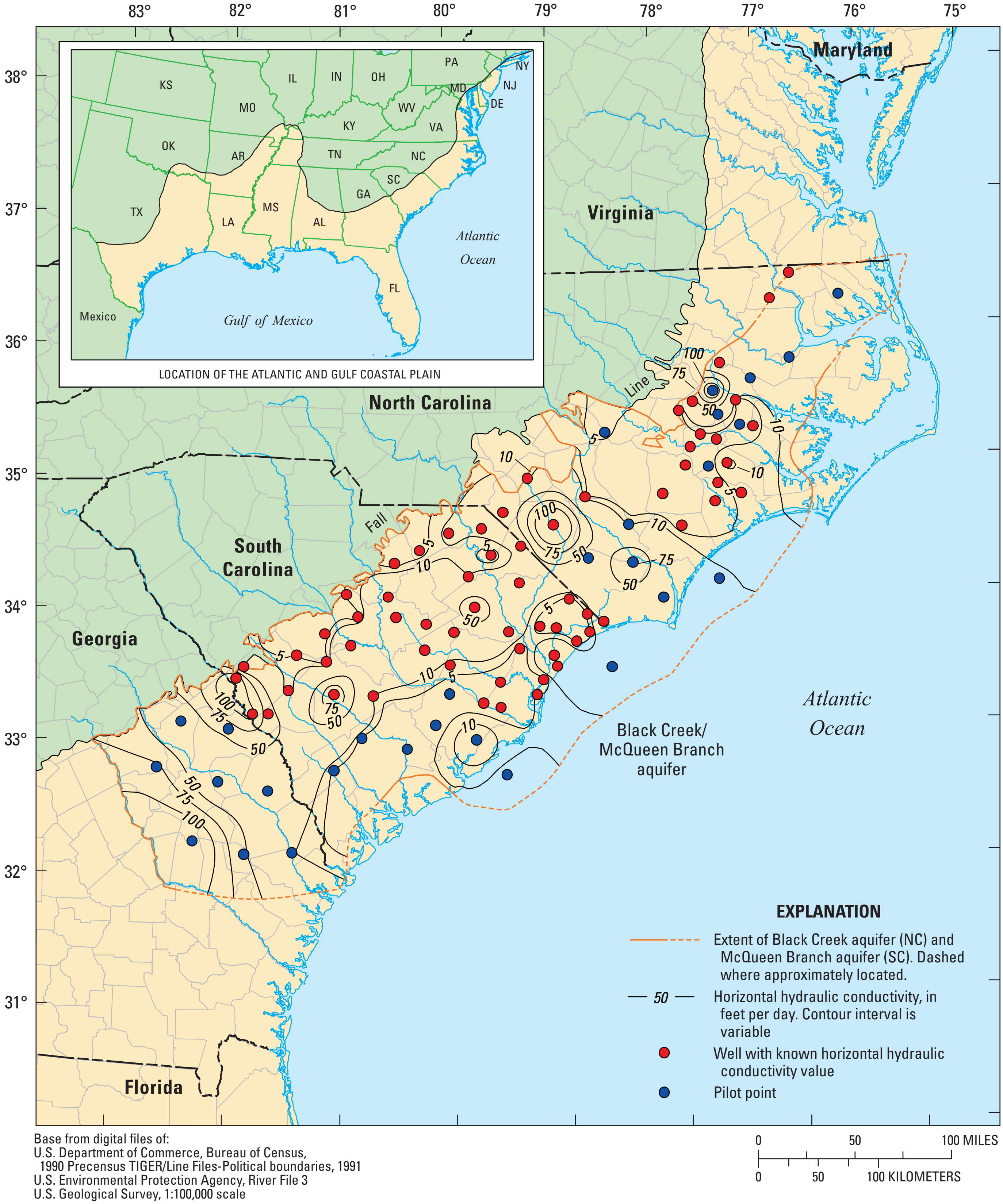



**Figure C10E.** Calibrated horizontal hydraulic conductivities for the Black Creek aquifer (North Carolina) and the McQueen Branch aquifer (South Carolina) (layer 11), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

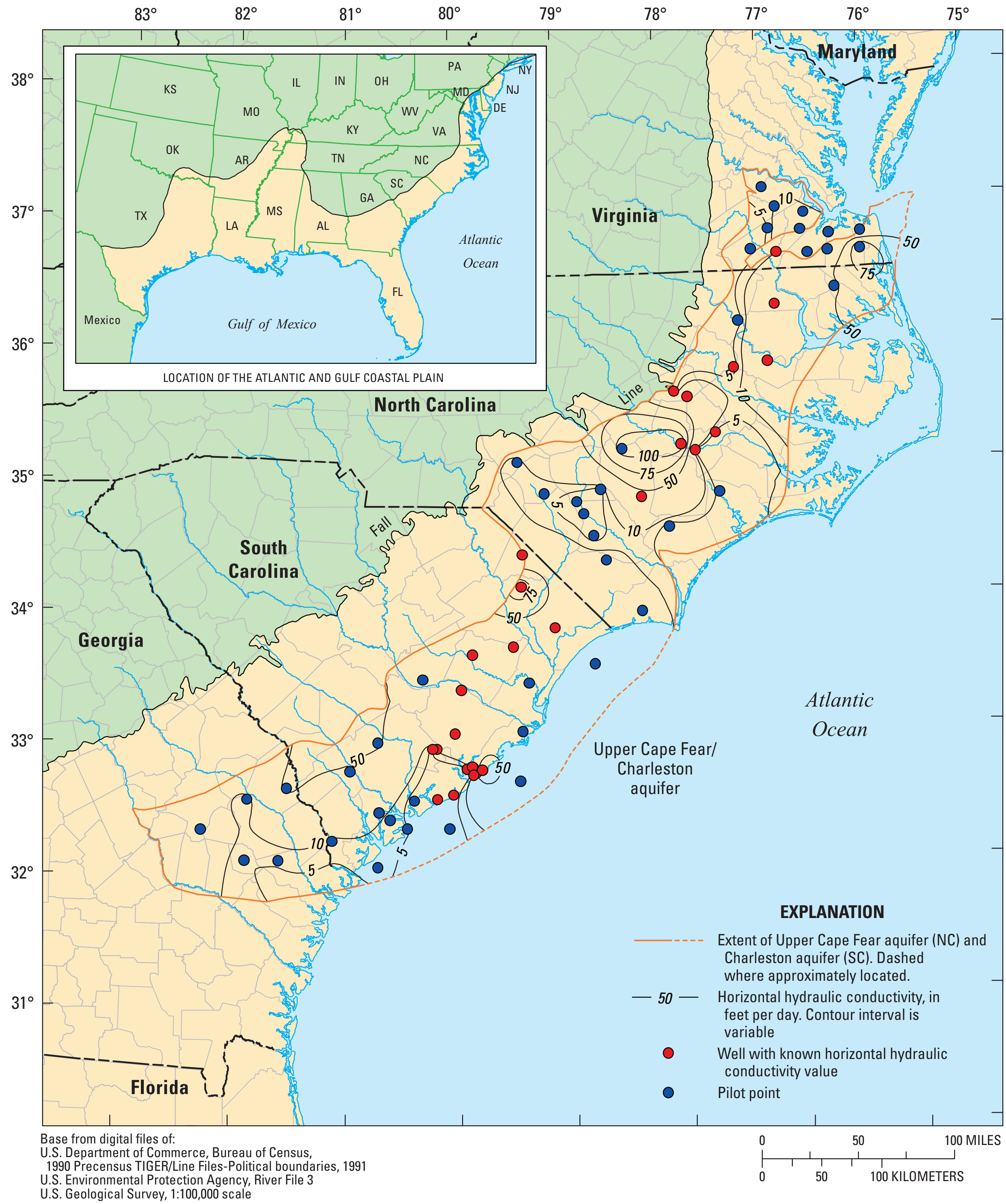



**Figure C10F.** Calibrated horizontal hydraulic conductivities for the Upper Cape Fear aquifer (North Carolina) and the Charleston aquifer (South Carolina) (layer 13), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

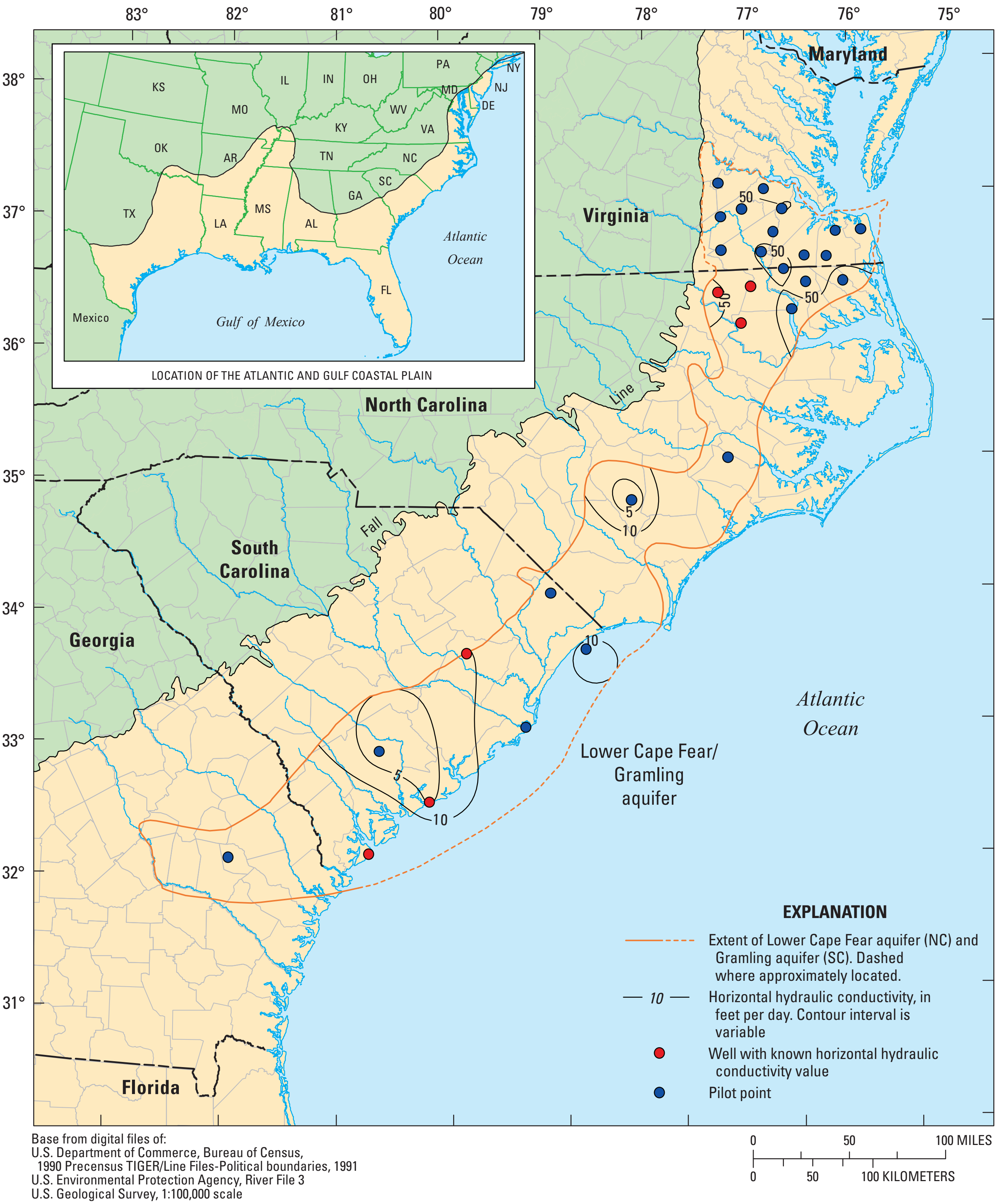



**Figure C10G.** Calibrated horizontal hydraulic conductivities for the Lower Cape Fear aquifer (North Carolina) and the Gramling aquifer (South Carolina) (layer 15), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

were allowed to vary within reasonable limits during model calibration to obtain the best fit to the observation data. Few measurements of hydraulic conductivity were available for the confining units within the NC and SC ACP. The hydraulic conductivity within confining unit layers 4, 6, 8, 10, 12, and 14 (*table C1*) was assumed to be spatially uniform. A reasonable value was assigned as the hydraulic conductivity of each confining unit layer; the values were allowed to vary within reasonable limits during model calibration.

Calibrated hydraulic conductivity values for the aquifers ranged from 0.5 to 1,150 ft/d; the highest mean value occurred in layer 3, and the lowest occurred in layer 9 (*table C6*; *figs. C10A* and *D*). Calibrated hydraulic conductivity values for the confining units ranged from 2.18E–05 ft/d in layer 10 to 9.10E–02 ft/d in layer 2. Calibrated specific storage values were 1.50E–06 $ft^{-1}$ for all confined aquifers and confining units except for layer 1, which had a calibrated specific yield of 0.1 $ft^{-1}$. Calibrated vertical anisotropies for the aquifers ranged from 1.0 to 3.0 and from 1.3 to 3.0 for the confining units (*table C6*).

## Model Fit—Groundwater Levels

Predevelopment groundwater flow was simulated by assuming steady-state conditions. The calibration included a total of 1,070 water-level measurements from 1900 to 1979—276 in layer 3; 132 in layer 5; 99 in layer 7; 231 in layer 9; 233 in layer 11; 86 in layer 13; and 13 in layer 15. The residuals, computed as the measured groundwater levels minus the simulated water levels, are normally distributed for layers 3, 5, 7, 9, 11, and 13 and slightly skewed to the positive side for layer 15, which had only 13 observations (*table C7*; *figs. C11, C12*). Calculated residuals range from –58 to 85 ft with mean residuals of 4.0, –2.6, –2.0, –2.7, –4.0, –1.2, and 14 ft for layers 3, 5, 7, 9, 11, 13, and 15, respectively (*fig. C13*). The root mean square error of the residuals for the layers ranged from 10 to 27 ft. The percentage of simulated residuals within the 20-ft calibration target varied between 52 and 87 percent for layers 3, 5, 7, 9, 11, and 13; the percentage of simulated values within the 20-ft calibration target was 8 percent for layer 15. Residuals for the predevelopment water levels from all of the layers combined produced an overall $R^2$ of 0.96, and the percentage of predevelopment simulated water levels within the 20-ft calibration target for all layers combined was 64 percent.

Another method for 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 layer. A ratio of less than 0.1 indicates that residuals are generally less than 10 percent of the altitude range of the observations (Kuniansky and others, 2004). The fit of calibration for predevelopment conditions ranged from 0.04 to 0.09 for layers 3, 5, 7, 9, 11, and 13; the fit of calibration was 0.16 for layer 15, most likely because the residuals were not normally distributed and because of the low number of observations available for this aquifer (*table C7*). The fit of calibration for the predevelopment water levels from all of the layers combined was 0.05.

Groundwater conditions for 1980 were simulated assuming transient conditions. The calibration included a total of 451 water-level measurements from 1980—163 in layer 3; 52 in layer 5; 44 in layer 7; 99 in layer 9; 48 in layer 11; 35 in layer 13; and 10 in layer 15. The 1980 water-level residuals are distributed normally for layers 3, 5, 7, 9, 11, and 13 and slightly skewed to the positive side for layer 15 (*table C8*; *figs. C14, C15*). Calculated residuals range from –62 to 57 ft with mean residuals of 3.6, –1.0, –8.8, –10, 1.1, 6.3, and 4.8 ft for layers 3, 5, 7, 9, 11, 13, and 15, respectively (*fig. C16*). The percentage of simulated values within the 20-ft calibration

**Table C6.** Calibrated hydraulic conductivity values, and calibrated values of specific yield, specific storage, and vertical anisotropy in the model layers representing the aquifers and confining units in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

[ft/d, feet per day; ft, feet; —, no data; note: single horizontal hydraulic conductivity values were used for layers 1, 4, 6, 8, 10, 12, 14, and 16]

| | Layer | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydraulic property | Statistic | | | | | | | | | | | | | | | | |
| Horizontal hydraulic conductivity (ft/d) | Minimum | 216 | 9.90E–6 | 2.0 | 1.73E–3 | 2.0 | 2.13E–4 | 0.8 | 1.93E–4 | 0.8 | 2.18E–5 | 0.8 | 7.95E–5 | 0.5 | 2.81E–4 | 1.4 | 25.0 |
| | Maximum | | 9.10E–2 | 1,150 | | 262 | | 169 | | 177 | | 175 | | 129 | | 64.0 | |
| | Mean | | 2.29E–2 | 176 | | 46.1 | | 26.3 | | 18.3 | | 22.9 | | 22.4 | | 26.3 | |
| | Standard deviation | | 3.90E–2 | 253 | | 49.5 | | 32.8 | | 26.4 | | 35.1 | | 28.5 | | 18.3 | |
| Specific yield ($ft^{-1}$) | Calibrated | 0.1 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Specific storage ($ft^{-1}$) | Calibrated | — | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 | 1.50E–6 |
| Vertical anisotropy | Calibrated | 1.8 | 3.0 | 2.3 | 3.0 | 1.9 | 1.3 | 3.0 | 3.0 | 1.1 | 1.6 | 1.3 | 3.0 | 1.5 | 2.4 | 1.0 | 3.0 |

**Table C7.** Statistics for model calibration based on predevelopment conditions for aquifers in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

[ft, feet]

| | Layer 3 | Layer 5 | Layer 7 | Layer 9 | Layer 11 | Layer 13 | Layer 15 | Model |
|---|---|---|---|---|---|---|---|---|
| **Number of observations** | 276 | 132 | 99 | 231 | 233 | 86 | 13 | 1,070 |
| **Range of observations (ft)** | 389 | 236 | 324 | 359 | 351 | 266 | 152 | 389 |
| **Minimum residual (ft)** | –50 | –36 | –33 | –49 | –54 | –58 | –35 | –58 |
| **Maximum residual (ft)** | 85 | 30 | 31 | 51 | 48 | 69 | 43 | 85 |
| **Mean residual (ft)** | 4.0 | –2.6 | –2.0 | –2.7 | –4.0 | –1.2 | 14 | –0.9 |
| **Standard deviation of residuals (ft)** | 19 | 10 | 14 | 16 | 21 | 23 | 24 | 18 |
| **Root mean square error of residuals (ft)** | 19 | 10 | 14 | 16 | 21 | 23 | 27 | 18 |
| **Percentage of values within 20-foot error criteria** | 63 | 87 | 70 | 68 | 52 | 52 | 8.0 | 64 |
| **Calibration fit[1]** | 0.05 | 0.04 | 0.04 | 0.04 | 0.06 | 0.09 | 0.16 | 0.05 |

[1]Calibration fit, standard deviation of residuals divided by the range of observations (Kuniansky and others, 2004).

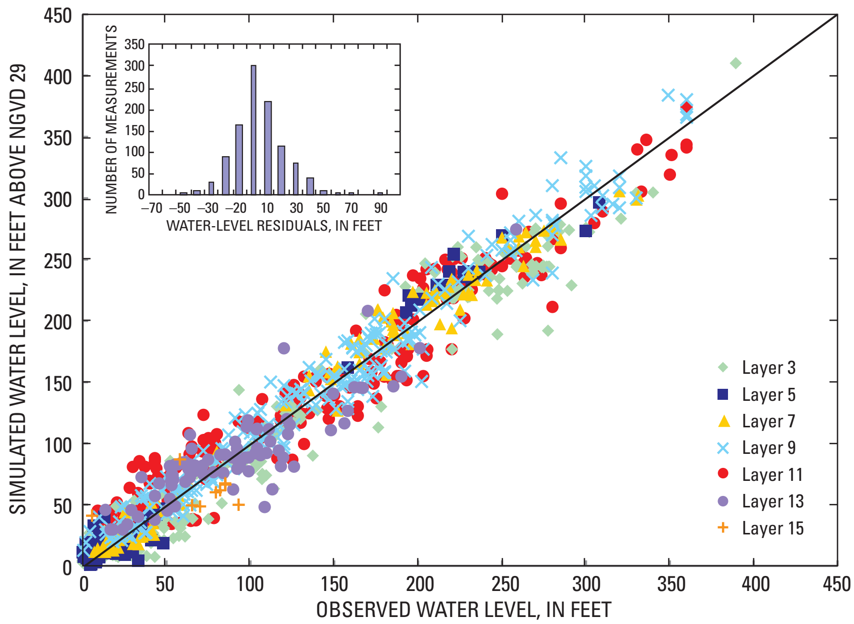



**Figure C11.** Observed and simulated water levels for predevelopment calibration, in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

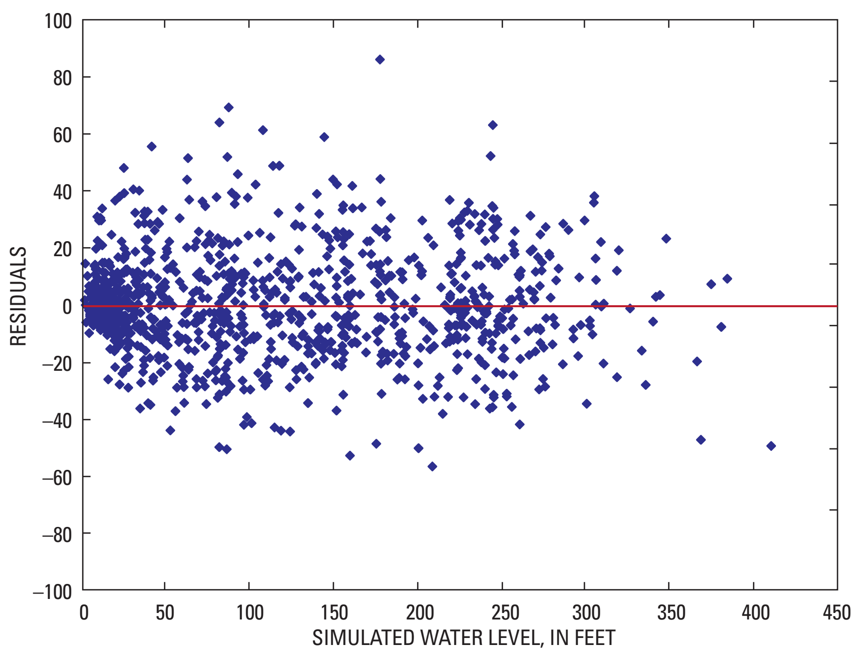
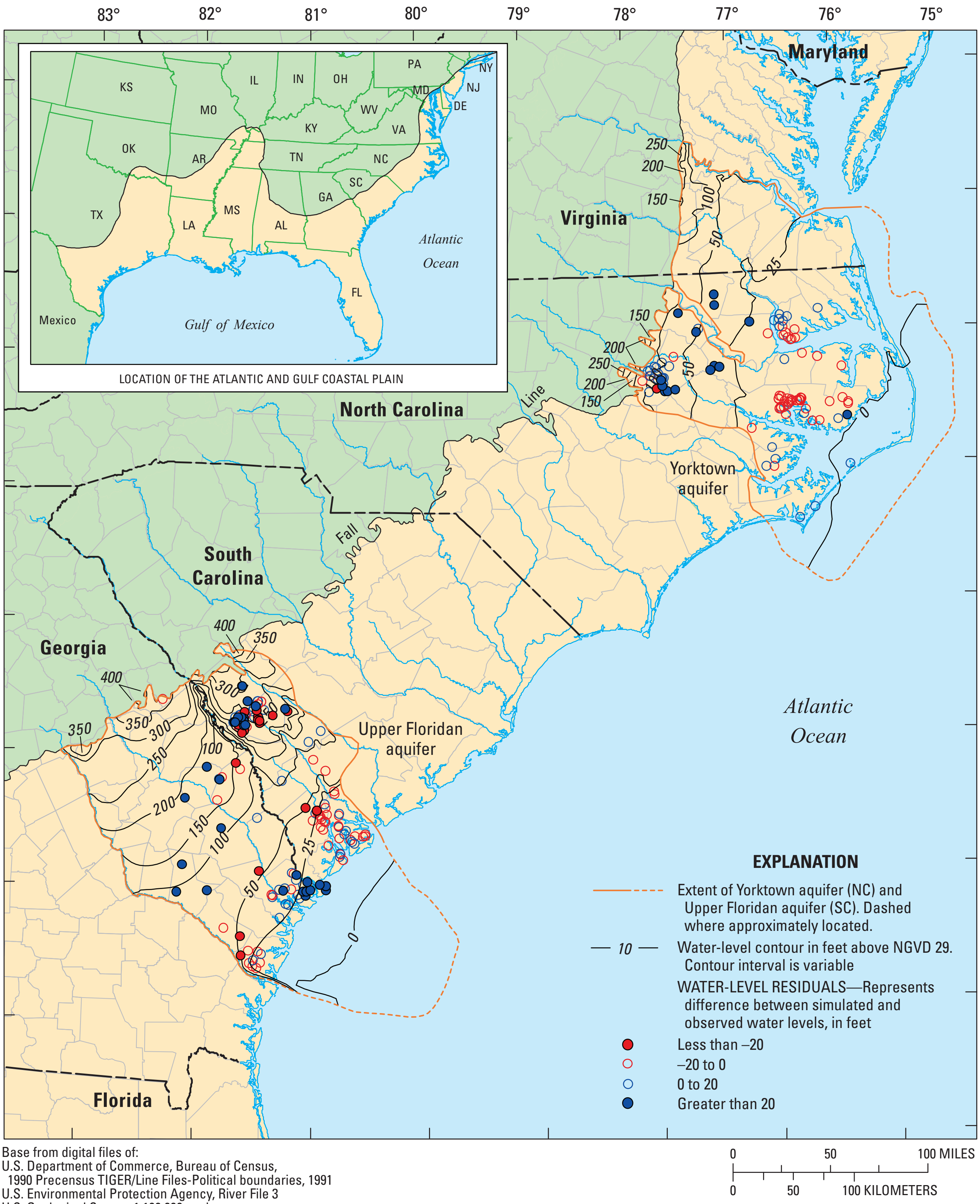



**Figure C12.** Water-level residuals and simulated water levels for predevelopment calibration in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.




Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure C13A.** Simulated water levels and water-level residuals for steady-state calibration for the Yorktown aquifer (North Carolina) and the Upper Floridan aquifer (South Carolina) (layer 3), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C13B.** Simulated water levels and water-level residuals for steady-state calibration for the Castle Hayne aquifer (North Carolina) and the Middle Floridan aquifer (South Carolina) (layer 5), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C13C.** Simulated water levels and water-level residuals for steady-state calibration for the Beaufort aquifer (North Carolina) and the Gordon aquifer (South Carolina), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

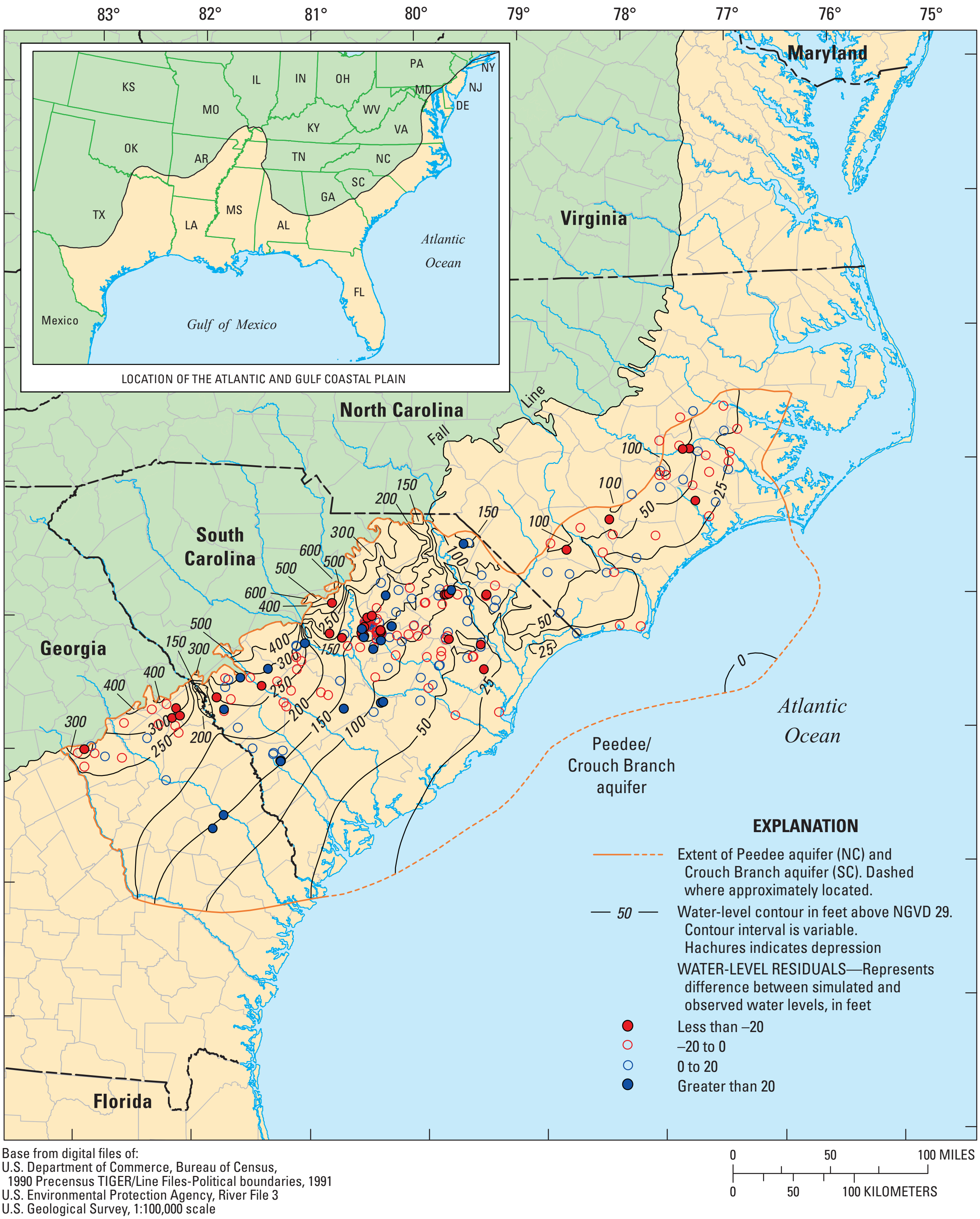



**Figure C13D.** Simulated water levels and water-level residuals for steady-state calibration for the Peedee aquifer (North Carolina) and the Crouch Branch aquifer (South Carolina) (layer 9), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

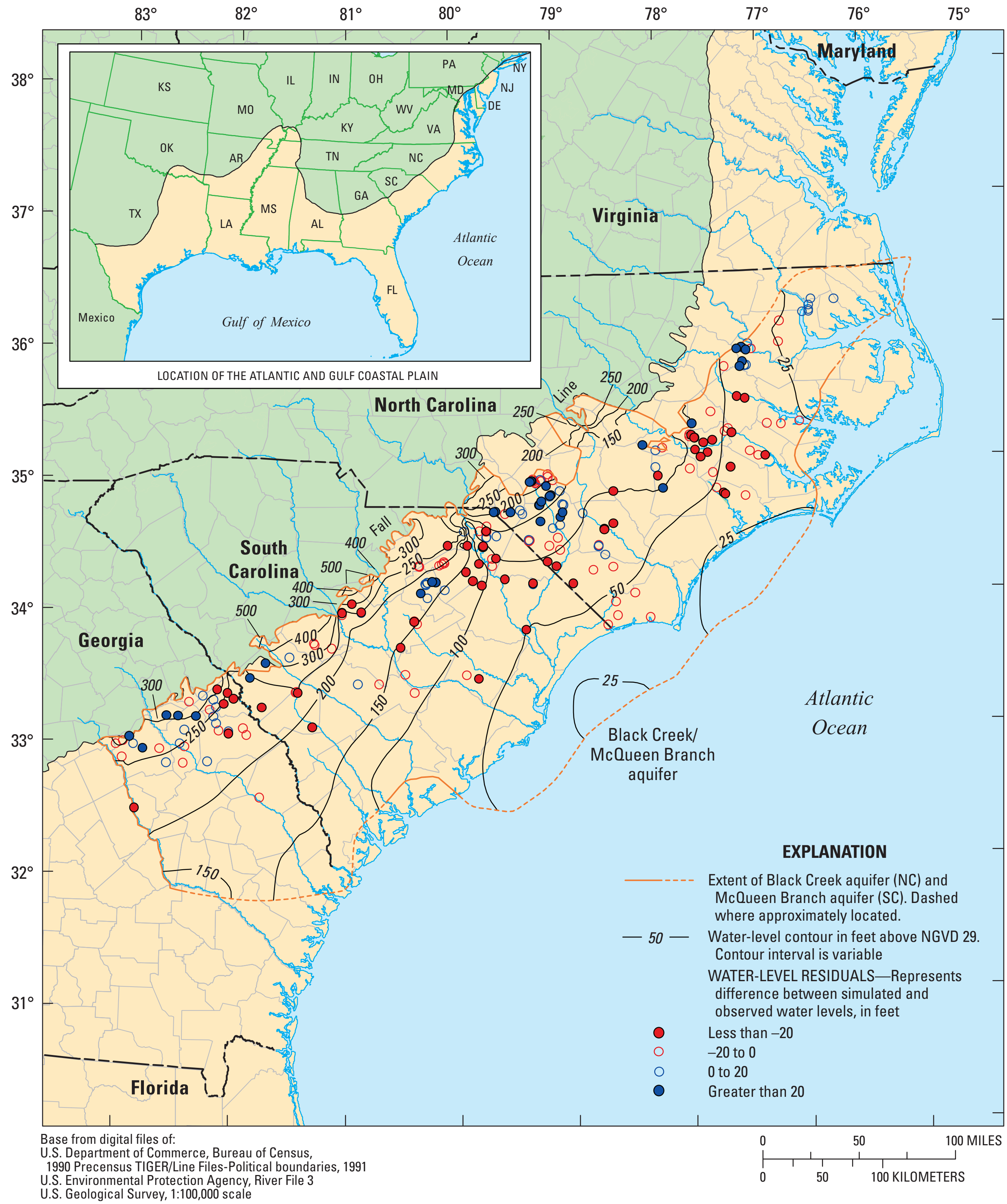



**Figure C13E.** Simulated water levels and water-level residuals for steady-state calibration for the Black Creek aquifer (North Carolina) and the McQueen Branch aquifer (South Carolina) (layer 11), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C13F.** Simulated water levels and water-level residuals for steady-state calibration for the Upper Cape Fear aquifer (North Carolina) and the Charleston aquifer (South Carolina) (layer 13), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C13G.** Simulated water levels and water-level residuals for steady-state calibration for the Lower Cape Fear aquifer (North Carolina) and the Gramling aquifer (South Carolina) (layer 15), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C13H.** Simulated water levels and water-level residuals for steady-state calibration for the Lower Cretaceous confining unit and Lower Cretaceous aquifer (North Carolina) (layer 16), in the Atlantic Coastal Plain of North Carolina and parts of Virginia, 2007.

**Table C8.** Statistics for model calibration based on 1980 conditions for aquifers in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

[ft, feet]

| | Layer 3 | Layer 5 | Layer 7 | Layer 9 | Layer 11 | Layer 13 | Layer 15 | Model |
|---|---|---|---|---|---|---|---|---|
| **Number of observations** | 163 | 52 | 44 | 99 | 48 | 35 | 10 | 451 |
| **Range of observations (ft)** | 392 | 205 | 325 | 343 | 438 | 233 | 80 | 438 |
| **Minimum residual (ft)** | –25 | –29 | –28 | –53 | –49 | –62 | –34 | –62 |
| **Maximum residual (ft)** | 39 | 25 | 19 | 24 | 57 | 50 | 38 | 57 |
| **Mean residual (ft)** | 3.6 | –1 | –8.8 | –10 | 1.1 | 6.3 | 4.8 | –1.0 |
| **Standard deviation of residuals (ft)** | 11 | 10 | 12 | 17 | 20 | 24 | 26 | 17 |
| **Root mean square error of residuals (ft)** | 12 | 11 | 15 | 20 | 20 | 24 | 25 | 17 |
| **Percentage of values within 20-foot error criteria** | 74 | 84 | 72 | 63 | 54 | 45 | 30 | 70 |
| **Calibration fit**[1] | 0.03 | 0.05 | 0.04 | 0.05 | 0.05 | 0.10 | 0.32 | 0.04 |

[1]Calibration fit, standard deviation of residuals divided by the range of observations (Kuniansky and others, 2004).

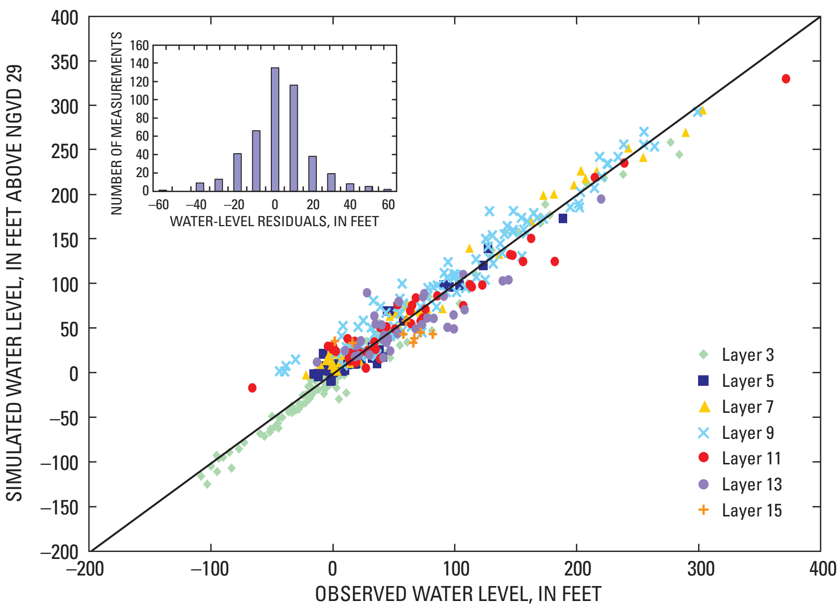



**Figure C14.** Observed and simulated water levels for 1980 calibration in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

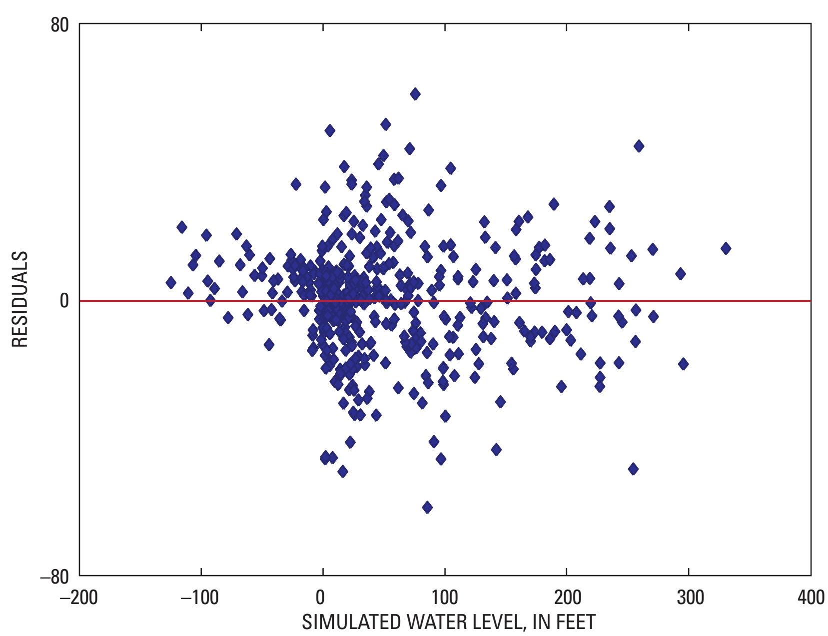



**Figure C15.** Water-level residuals and simulated water levels for 1980 calibration in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.


**Figure C16A.** Simulated water levels and water-level residuals for 1980 calibration for the Yorktown aquifer (North Carolina) and the Upper Floridan aquifer (South Carolina) (layer 3), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C16B.** Simulated water levels and water-level residuals for 1980 calibration for the Castle Hayne aquifer (North Carolina) and the Middle Floridan aquifer (South Carolina) (layer 5), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C16C.** Simulated water levels and water-level residuals for 1980 calibration for the Beaufort aquifer (North Carolina) and the Gordon aquifer (South Carolina) (layer 7), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C16D.** Simulated water levels and water-level residuals for 1980 calibration for the Peedee aquifer (North Carolina) and the Crouch Branch aquifer (South Carolina) (layer 9), in the Atlantic Coastal Plain of North and South Carolina and parts of Georgia, 2007.


**Figure C16E.** Simulated water levels and water-level residuals for 1980 calibration for the Black Creek aquifer (North Carolina) and the McQueen Branch aquifer (South Carolina) (layer 11), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C16F.** Simulated water levels and water-level residuals for 1980 calibration for the Upper Cape Fear aquifer (North Carolina) and the Charleston aquifer (South Carolina) (layer 13), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C16G.** Simulated water levels and water-level residuals for 1980 calibration for the Lower Cape Fear aquifer (North Carolina) and the Gramling aquifer (South Carolina) (layer 15), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C16H.** Simulated water levels for 1980 calibration for the Lower Cretaceous confining unit and the Lower Cretaceous aquifer in North Carolina (layer 16), in the Atlantic Coastal Plain of North Carolina and parts of Virginia, 2007.

target varied between 30 and 84 percent, and the root mean square error for the layers ranged from 11 to 25 ft. Residuals for the 1980 water levels from all of the layers combined produce an overall $R^2$ of 0.95, and the percentage of 1980 simulated water levels within the 20-ft calibration target for all layers combined was 70 percent. The fit of calibration for the 1980 water-level data ranged from 0.03 to 0.10 for layers 3, 5, 7, 9, 11, and 13; the fit of calibration was 0.32 for layer 15, most likely because the residuals were not distributed normally and because of the low number of observations available for this layer. The fit of calibration for the 1980 water levels from all layers combined was 0.04.

Groundwater conditions for 2004 were simulated assuming transient conditions. The calibration included a total of 767 water-level measurements—139 in layer 3; 125 in layer 5; 80 in layer 7; 162 in layer 9; 130 in layer 11; 94 in layer 13; and 37 in layer 15. The 2004 water-level residuals are distributed normally for all layers (*table C9*; *figs. C17, C18*). Calculated residuals range from –112 to 139 ft with mean residuals of 0.9, 0.8, –16, –7.1, 16, –5.0, and –5.5 ft for layers 3, 5, 7, 9, 11, 13, and 15, respectively (*fig. C19*). The percentage of simulated values within the 20-ft calibration target varied between 27 and 82 percent, and the root mean square error for the layers ranged from 10 to 42 ft. Residuals for the 2004 water levels from the layers combined produce an overall $R^2$ of 0.89, and the percentage of 2004 simulated water levels within the 20-ft calibration target for all layers combined was 55 percent. The fit of calibration for the 2004 water-level data ranged from 0.03 to 0.14. The fit of calibration for the 2004 water levels from all layers combined was 0.05.

Overall, simulated water-level trends followed observed continuous groundwater levels (*figs. C20, C21*). The model does not accurately represent observed groundwater levels in areas where heads have been obviously affected by pumping, but water-use data are not available, such as in well SU-50 in layer 9 (*fig. C21E*), where pumping was not reported prior to 1983. Similarly, the model somewhat underestimates drawdown from pumping in some areas of layers 13 and 15 in NC, such as in wells O30J3 (*fig. C21H*) and G19B4 (*fig. C21J*), where water-use data are also missing.

## Model Fit—Stream Baseflow

Calculated and simulated mean annual baseflows were compared at 10 streamgaging locations in the inner Coastal Plain of NC and SC (*fig. C2; table C10*). Mean baseflows were underestimated at 9 of the 10 locations. In general, the smaller streams with lower baseflows had better fits than the larger streams with higher baseflows. Bull Swamp Creek near Swansea, SC, is the smallest stream and had the best fit, and Little Horse Creek near Graniteville, SC, had the poorest fit. Only three of the streams had a percentage of simulated annual baseflows within the 15-percent calibration criteria—Bull Swamp Creek near Swansea, SC, had 50 percent of simulated annual baseflows within the calibration criteria; Gills Creek at Columbia, SC, had 13 percent; and Scape Ore Swamp near Bishopville, SC, had 11 percent.

The low simulated mean annual baseflows relative to the calculated mean annual baseflows are a result of the scale of the model. The stream widths that the model simulated are all less than 100 ft during baseflow conditions (U.S. Geological Survey, 2005). An entire 2-mi by 2-mi model cell, however, is defined as a stream cell if any part of the stream is located within the cell boundaries. This scale issue produces an overall underestimation of baseflows by the model.

## Simulated Regional Water Budget

Simulated water budget components for the model include inflow from recharge, inflow and outflow through specified-head boundaries and rivers, outflow to wells, and net changes in storage (*fig. C22*). The primary source of water to the model is inflow from specified-head boundaries, with the inflow ranging from a total of 2,570 to 3,310 million gallons per day (Mgal/d). The majority of this inflow is through the upper specified-head boundary in layer 1 and the lateral specified-head boundaries in layers 11, 13, 15, and 16. Inflow from recharge ranges from 766 to 1,660 Mgal/d; river inflow ranges from 12.3 to 20.0 Mgal/d. A minimum of 1.78 Mgal/d is released from storage in stress period 4 (1920–29), and a maximum of 456 Mgal/d is released from storage in stress period 24 (1999).

The primary water loss is through specified-head boundaries, which lose 2,620 to 3,510 Mgal/d. The majority of this loss is through the upper specified-head boundary in layer 1 and the lateral specified-head boundaries in layers 13 and 15. Rivers discharge 879 to 1,110 Mgal/d of water from layer 1 over all stress periods, and well withdrawals range from a minimum of 5 Mgal/d [in stress period 2 (1900–09)] to a maximum of 563 Mgal/d [in stress period 27 (2002)]. A minimum of 0 Mgal/d [in stress period 7 (1950–59)] and a maximum of 286 Mgal/d [in stress period 16 (1991)] of water is added to storage over all stress periods.

There are 16 specified-head cells in layer 1 that have anomalously high or low water budgets due to uneven altitude changes from the DEM averaging process described earlier. These cells are all located along the inner and outer Coastal Plain boundary (*fig. C2*) in southern Barnwell County, SC (*fig. C1*). Adjacent cells have a high or low water budget related to the specified head simulated in the surficial aquifer and tend to cancel each other so the overall water budget is unaffected. This problem is described in detail in Kuniansky and Danskin (2003). The model simulates historical groundwater levels reasonably well in the aquifers below this area (*figs. C13C, C13D, C13E, C16C, C16D, C16E, C19C, C19D,* and *C19E*). The mean of the flow from layer 1 to layer 2 of all of the specified-head cells for predevelopment is –54 cubic feet per day ($ft^3/d$). The mean of the flow from layer 1 to layer 2 of all of the specified-head cells for 2004 is 1,641 $ft^3/d$. This difference indicates that the specified-head cells in layer 1 are a small sink during predevelopment but change to a small source of water by 2004.

**Table C9.** Statistics for model calibration based on 2004 conditions for aquifers in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

[ft, feet]

| | Layer 3 | Layer 5 | Layer 7 | Layer 9 | Layer 11 | Layer 13 | Layer 15 | Model |
|---|---|---|---|---|---|---|---|---|
| **Number of observations** | 139 | 125 | 80 | 162 | 130 | 94 | 37 | 767 |
| **Range of observations (ft)** | 184 | 336 | 327 | 549 | 595 | 436 | 231 | 595 |
| **Minimum residual (ft)** | –40 | –28 | –68 | –94 | –112 | –112 | –62 | –112 |
| **Maximum residual (ft)** | 72 | 28 | 39 | 45 | 139 | 139 | 66 | 139 |
| **Mean residual (ft)** | 0.9 | 0.8 | –16 | –7.1 | 16 | –5.0 | –5.5 | |
| **Standard deviation of residuals (ft)** | 18 | 10 | 19 | 24 | 39 | 40 | 31 | 28 |
| **Root mean square error of residuals (ft)** | 18 | 10 | 25 | 25 | 42 | 37 | 31 | 28 |
| **Percentage of values within 20-foot error criteria** | 78 | 82 | 50 | 56 | 34 | 28 | 27 | 55 |
| **Calibration fit[1]** | 0.10 | 0.03 | 0.06 | 0.04 | 0.07 | 0.09 | 0.14 | 0.05 |

[1]Calibration fit, standard deviation of residuals divided by the range of observations (Kuniansky and others, 2004).

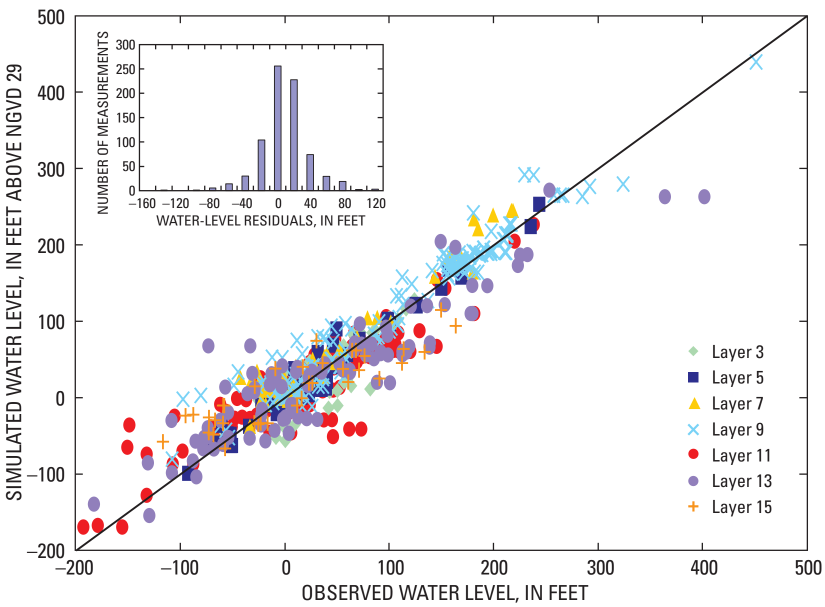



**Figure C17.** Observed and simulated water levels for 2004 calibration in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

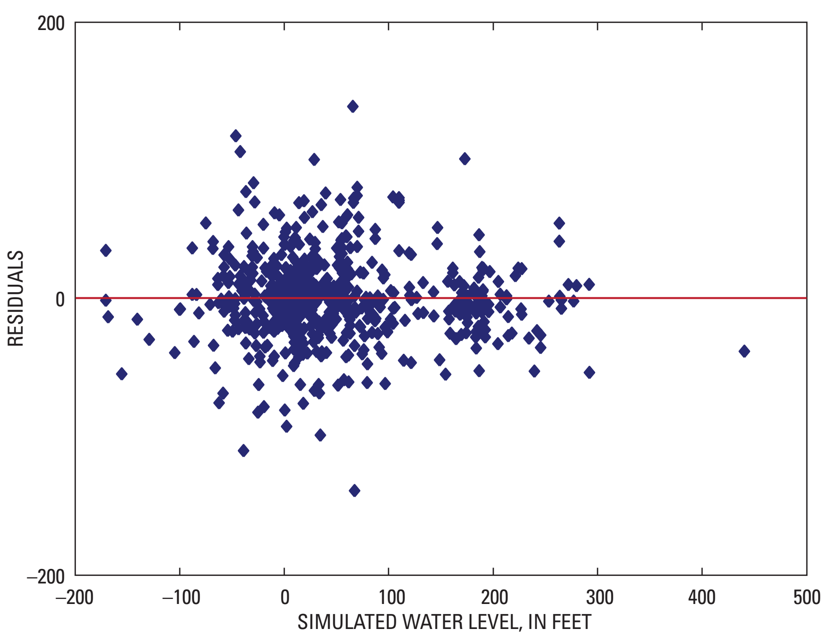



**Figure C18.** Water-level residuals and simulated water levels for 2004 calibration in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia.

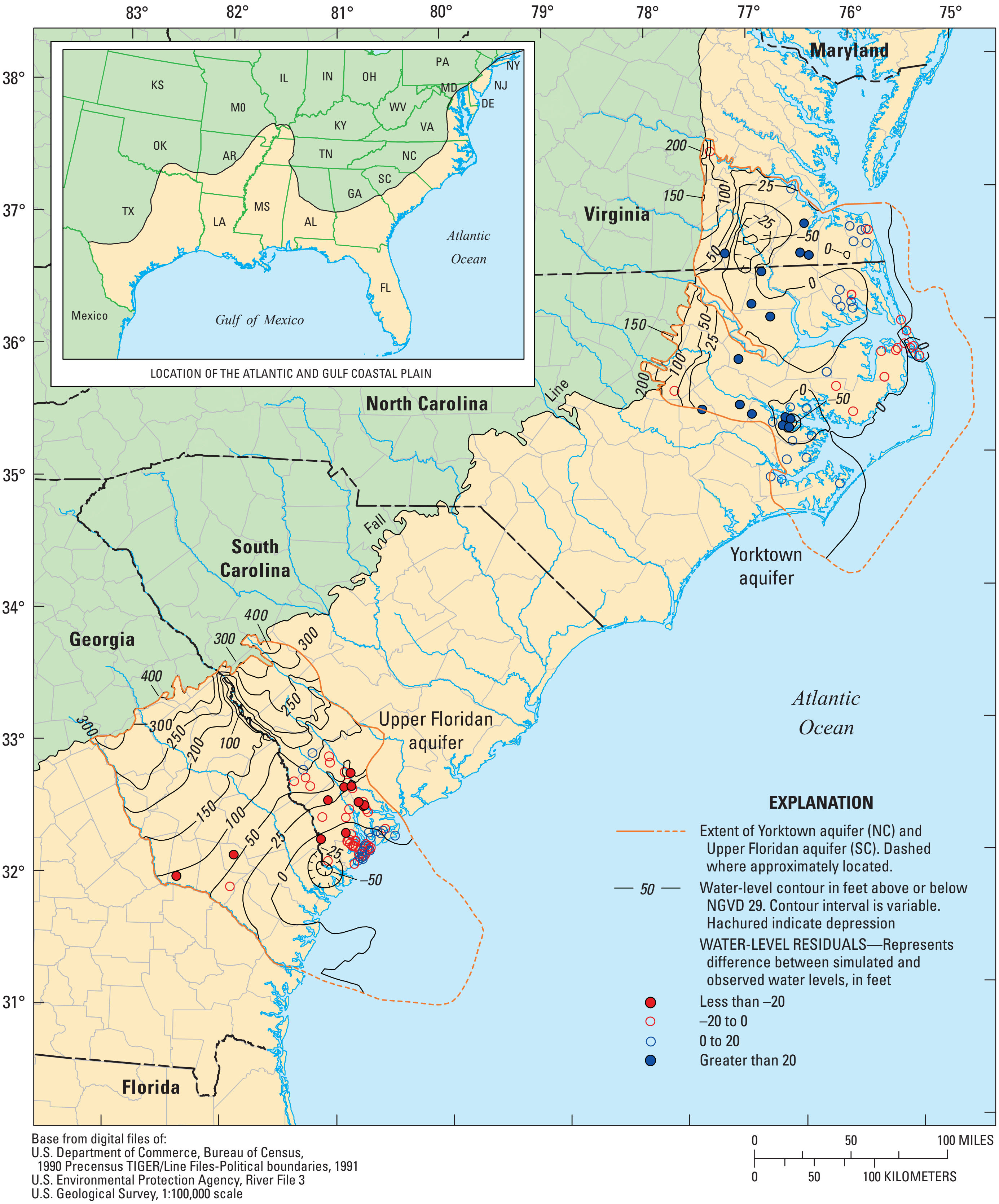



**Figure C19A.** Simulated water levels and water-level residuals for 2004 calibration for the Yorktown aquifer (North Carolina) and the Upper Floridan aquifer (South Carolina) (layer 3), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

0 50 100 MILES
0 50 100 KILOMETERS

**Figure C19B.** Simulated water levels and water-level residuals for 2004 calibration for the Castle Hayne aquifer (North Carolina) and the Middle Floridan aquifer (South Carolina) (layer 5), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C19C.** Simulated water levels and water-level residuals for 2004 calibration for the Beaufort aquifer (North Carolina) and the Gordon aquifer (South Carolina) (layer 7), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census, 1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure C19D.** Simulated water levels and water-level residuals for 2004 calibration for the Peedee aquifer (North Carolina) and the Crouch Branch aquifer (South Carolina) (layer 9), in the Atlantic Coastal Plain of North and South Carolina and parts of Georgia, 2007.

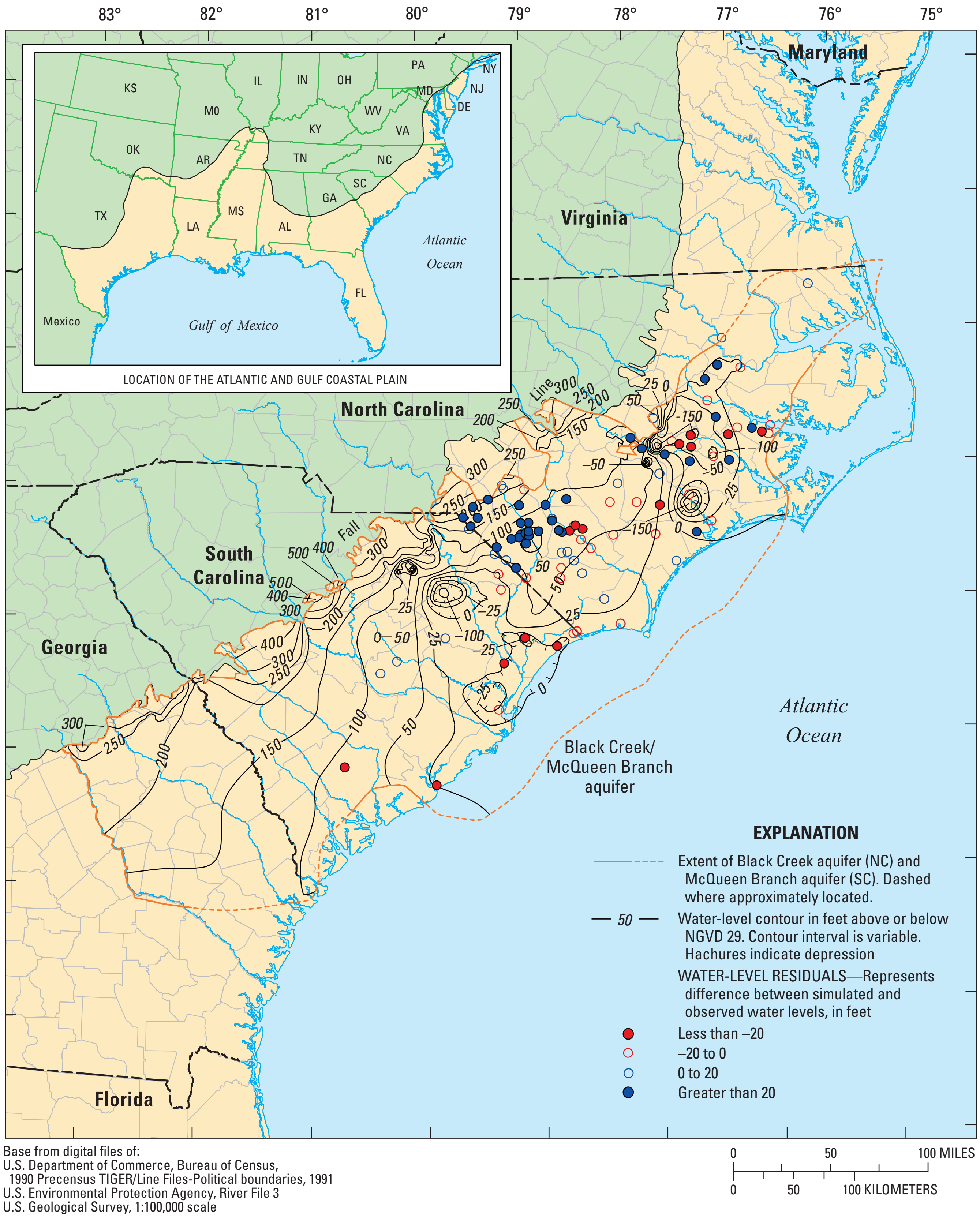



**Figure C19E.** Simulated water levels and water-level residuals for 2004 calibration for the Black Creek aquifer (North Carolina) and the McQueen Branch aquifer (South Carolina) (layer 11), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.

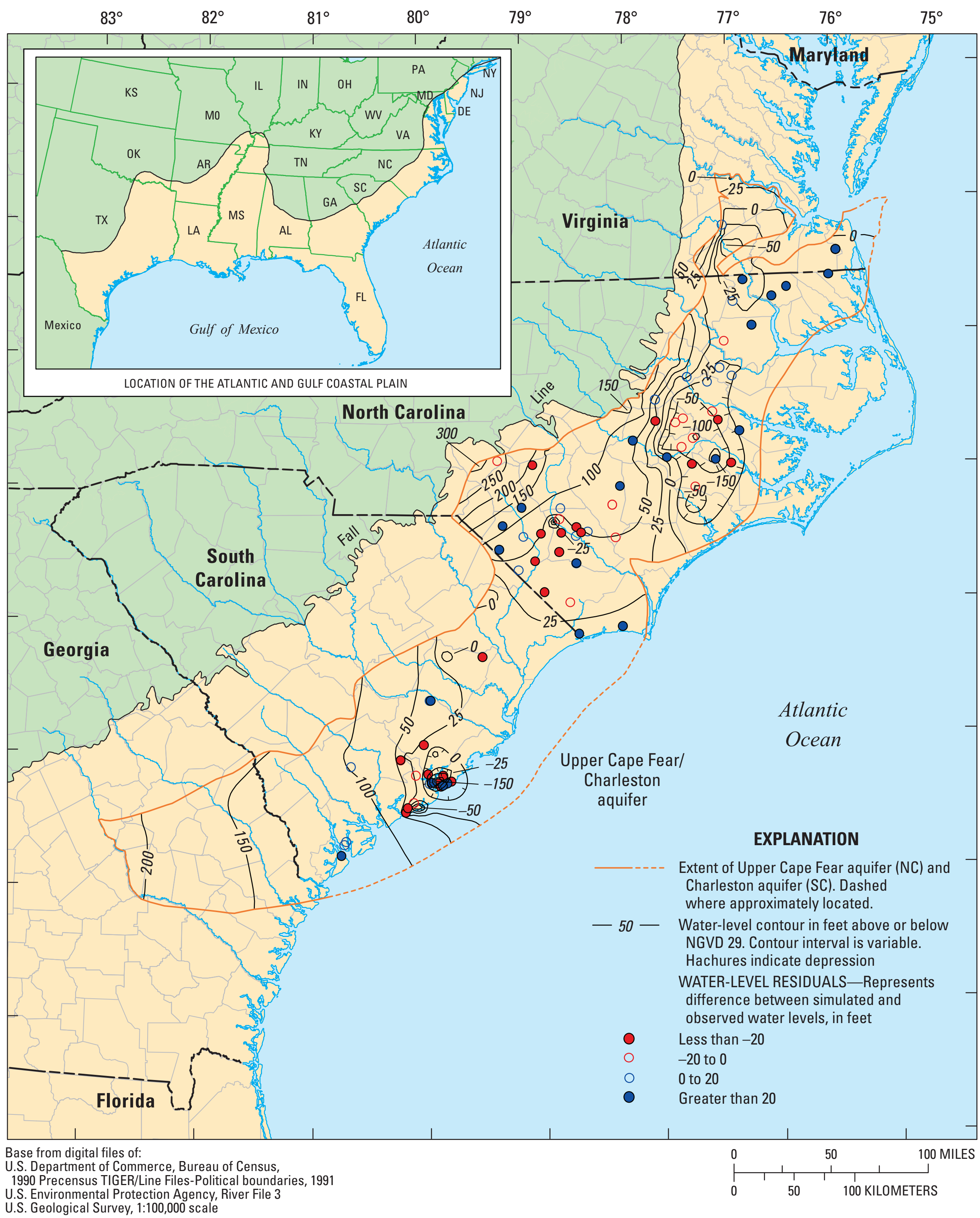



**Figure C19F.** Simulated water levels and water-level residuals for 2004 calibration for the Upper Cape Fear aquifer (North Carolina) and the Charleston aquifer (South Carolina) (layer 13), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


**Figure C19G.** Simulated water levels and water-level residuals for 2004 calibration for the Lower Cape Fear aquifer (North Carolina) and the Gramling aquifer (South Carolina) (layer 15), in the Atlantic Coastal Plain of North and South Carolina and parts of Virginia and Georgia, 2007.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census, 1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure C19H.** Simulated water levels for 2004 calibration for the Lower Cretaceous confining unit and the Lower Cretaceous aquifer (North Carolina) (layer 16), in the Atlantic Coastal Plain of North Carolina and parts of Virginia, 2007.


Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

**Figure C20.** Locations of wells in the Atlantic Coastal Plain of North and South Carolina and southeastern Georgia with continuous observed groundwater levels, 2007.

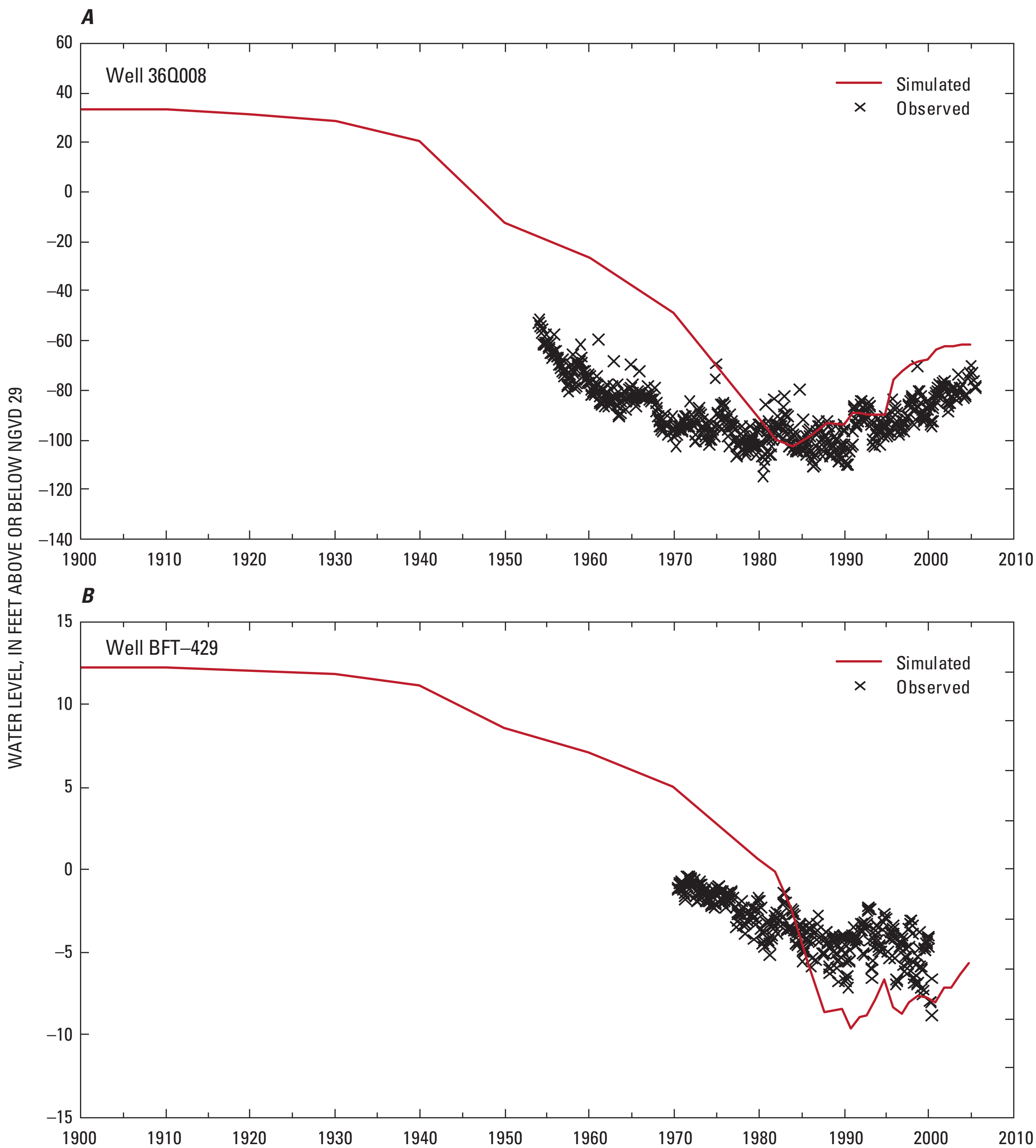



**Figure C21A.** Hydrographs of simulated and observed water levels for the *A*, Yorktown aquifer (North Carolina) and *B*, Upper Floridan aquifer (South Carolina) (see *fig. C20* for well locations).

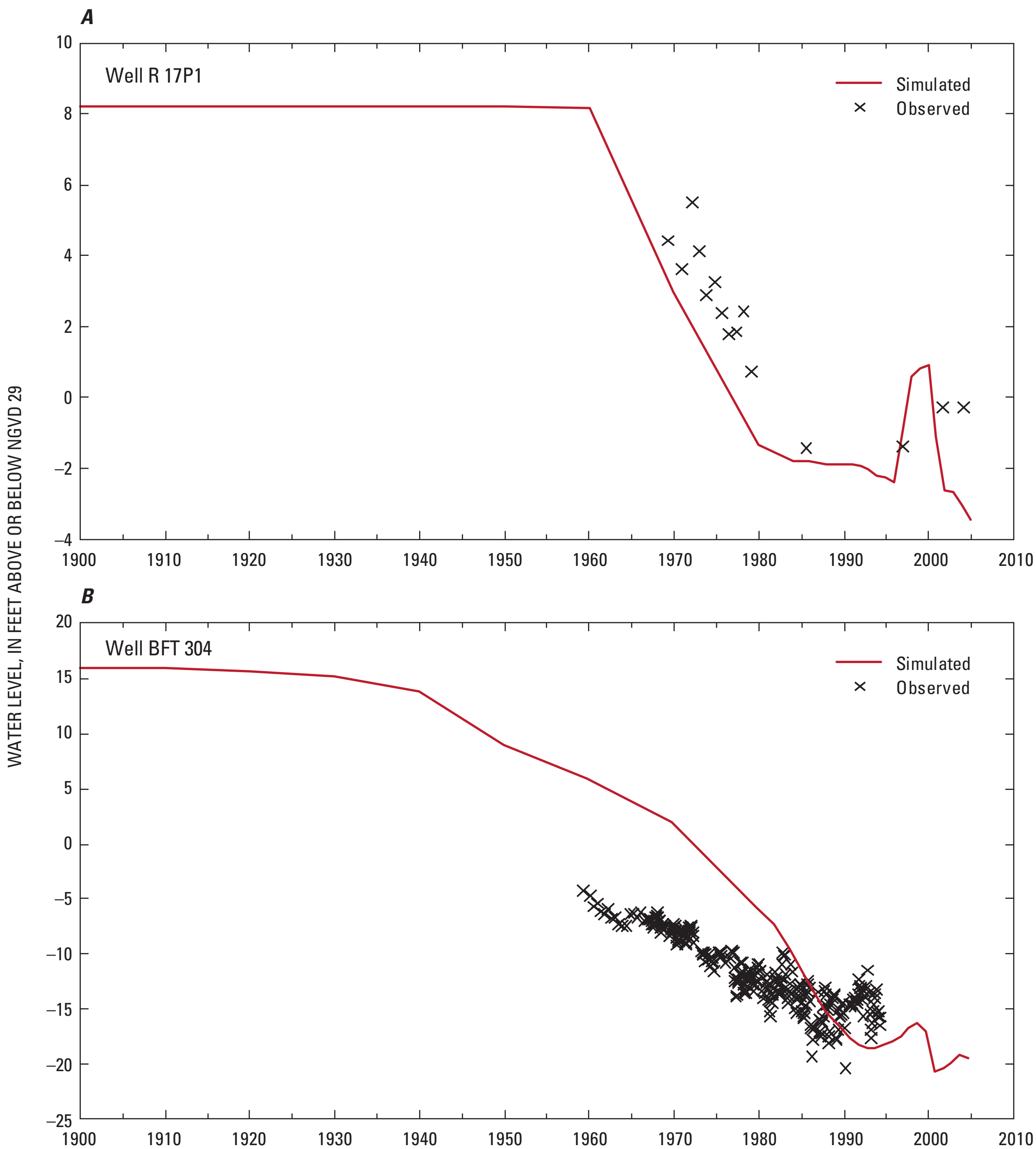



**Figure C21B.** Hydrographs of simulated and observed water levels for *A*, the Castle Hayne aquifer (North Carolina) and *B*, Middle Floridan aquifer (South Carolina) (see *fig. C20* for well locations).

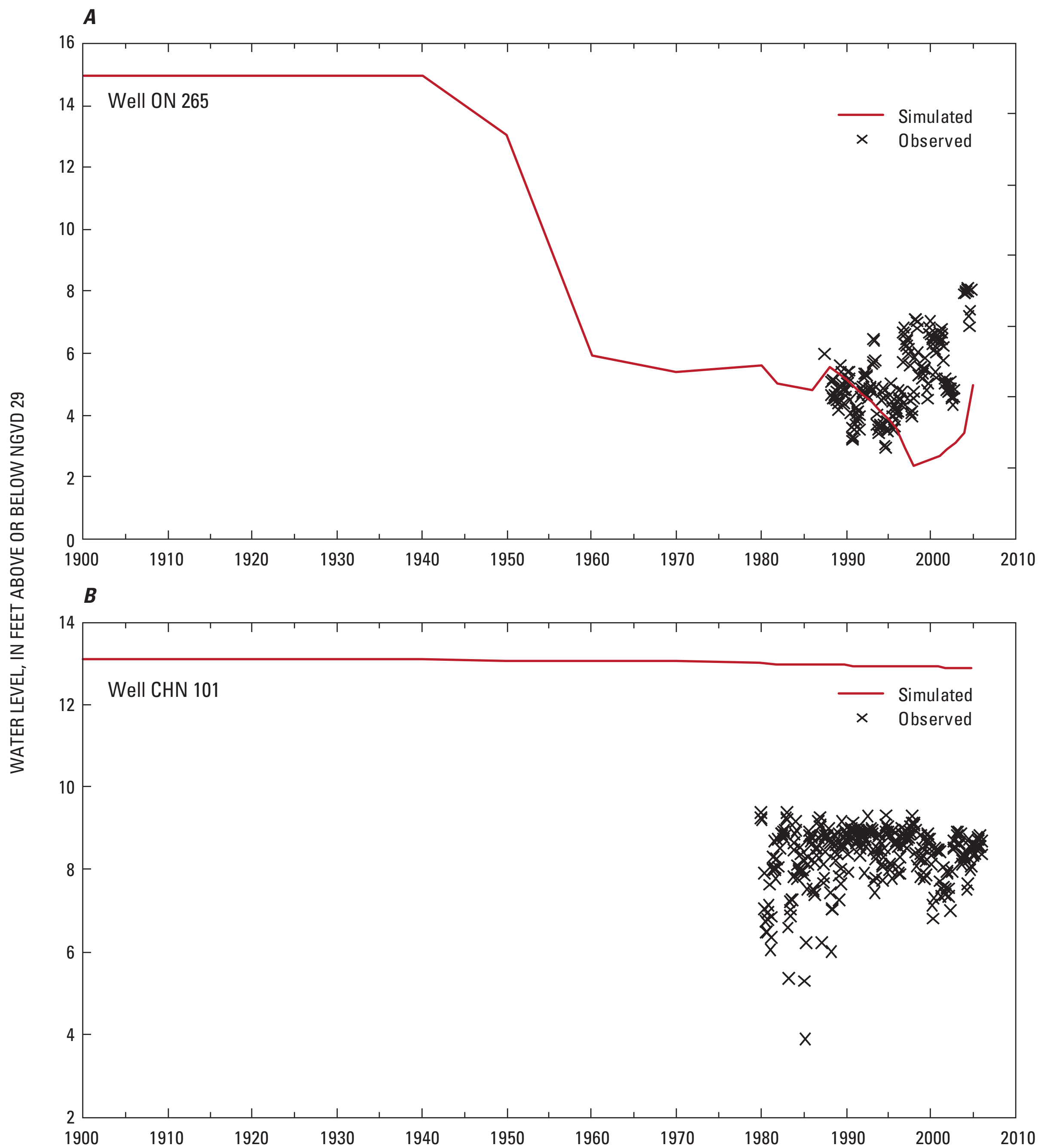



**Figure C21C.** Hydrographs of simulated and observed water levels for the *A*, Beaufort aquifer (North Carolina) and *B*, Gordon aquifer (South Carolina) (see *fig. C20* for well locations).

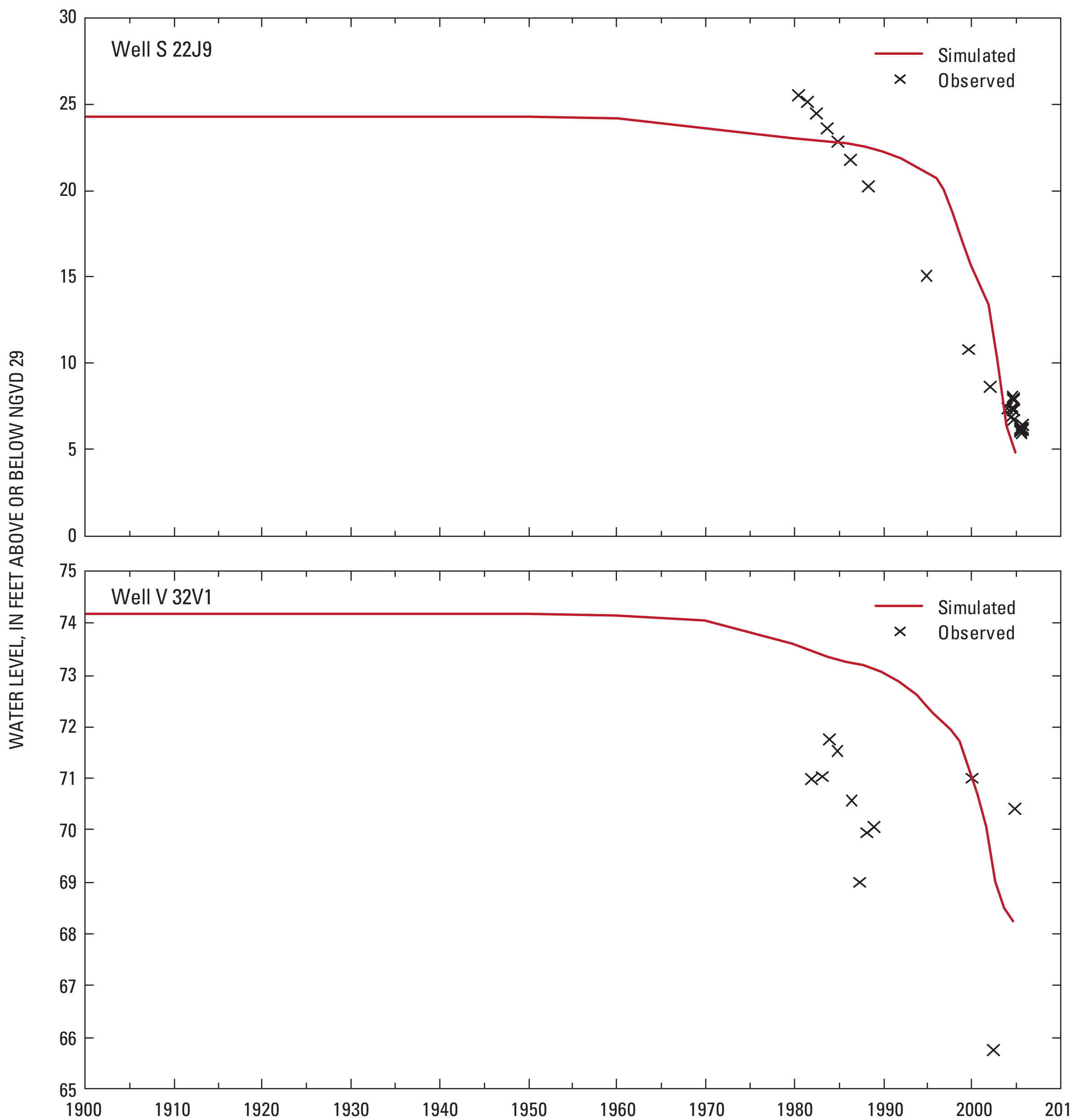



**Figure C21D.** Hydrographs of simulated and observed water levels for the Peedee aquifer in North Carolina (see *fig. C20* for well locations).

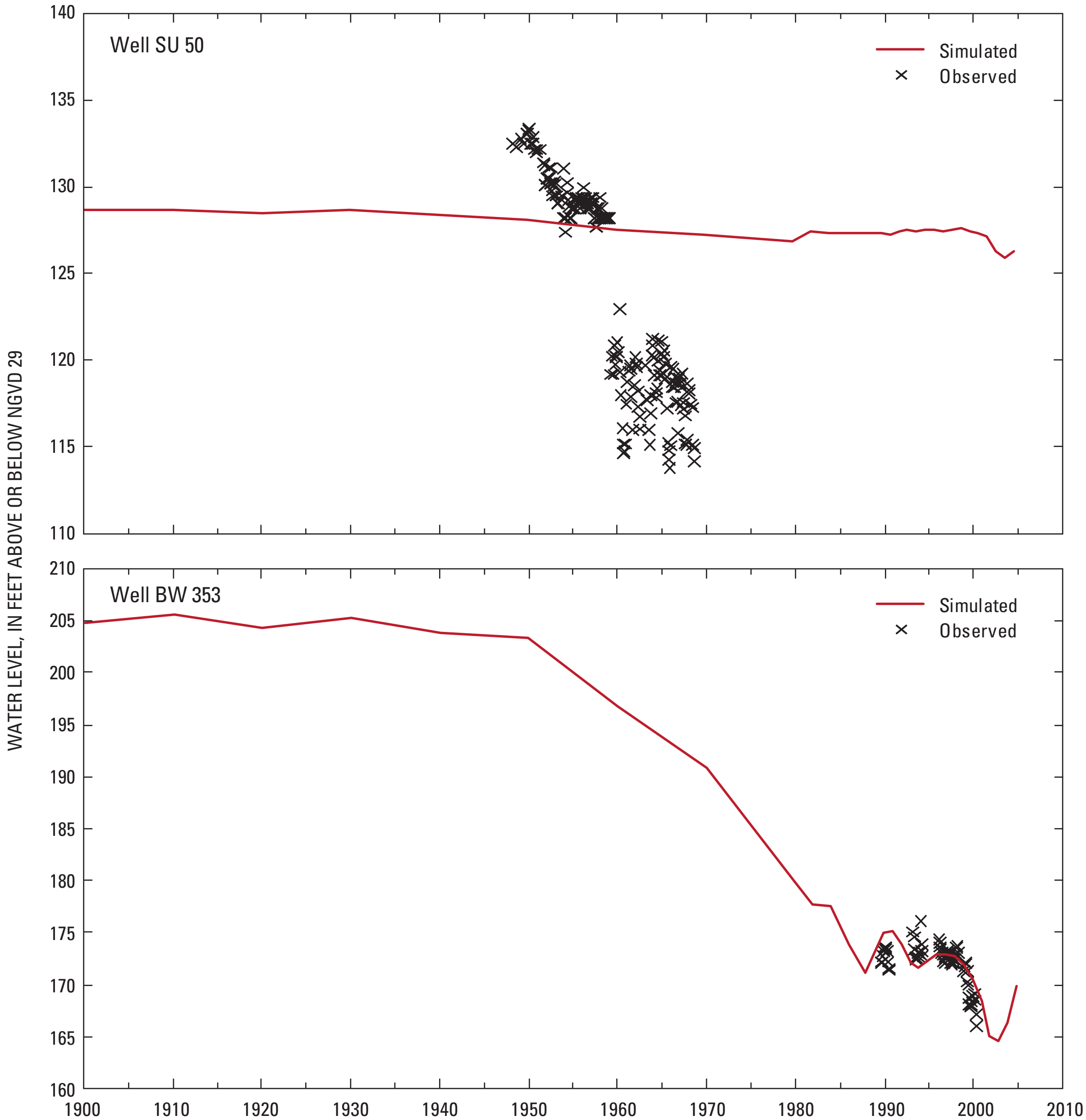



**Figure C21E.** Hydrographs of simulated and observed water levels for the Crouch Branch aquifer in South Carolina (see *fig. C20* for well locations).

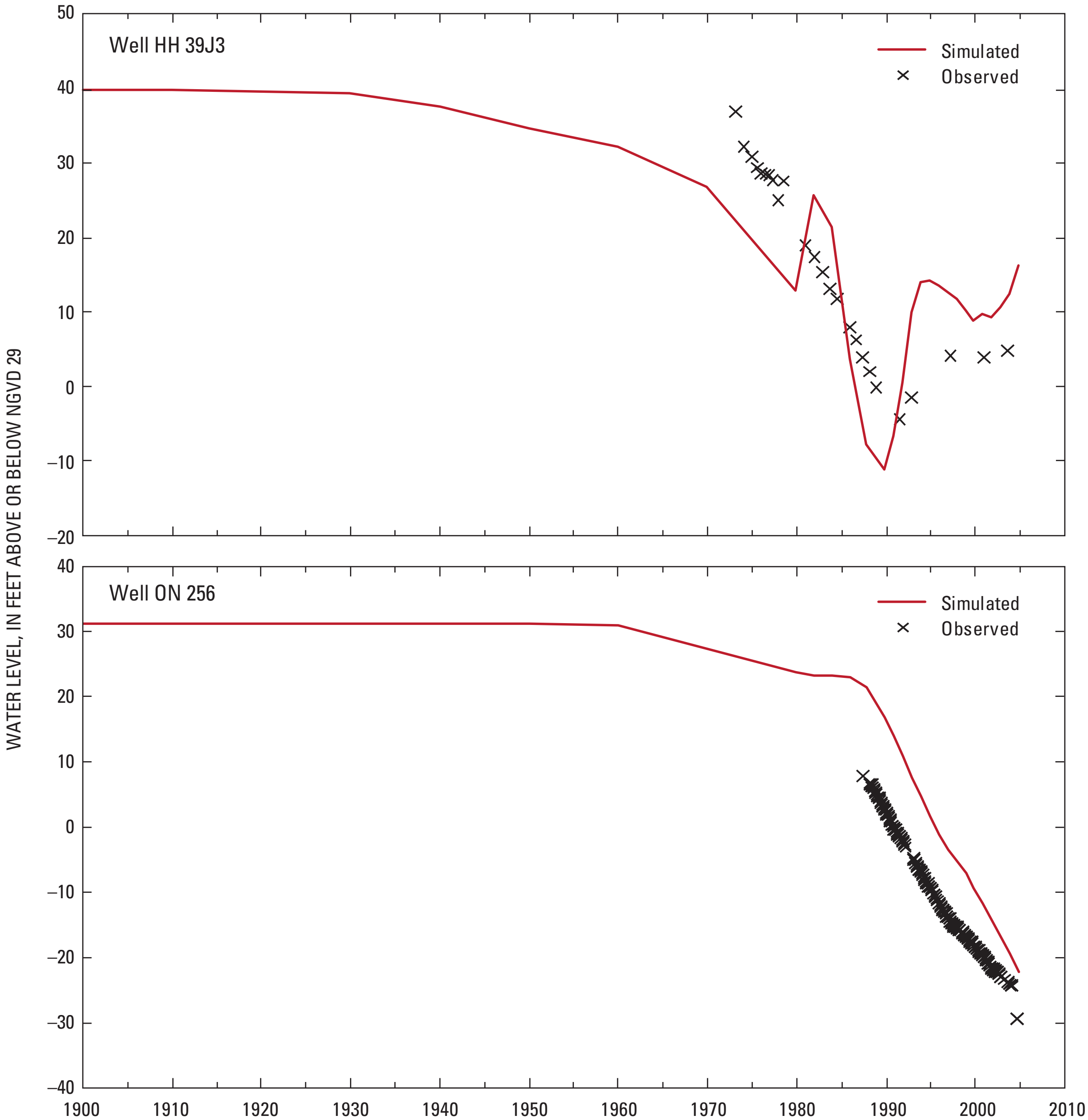



**Figure C21F.** Hydrographs of simulated and observed water levels for the Black Creek aquifer in North Carolina (see *fig. C20* for well locations).

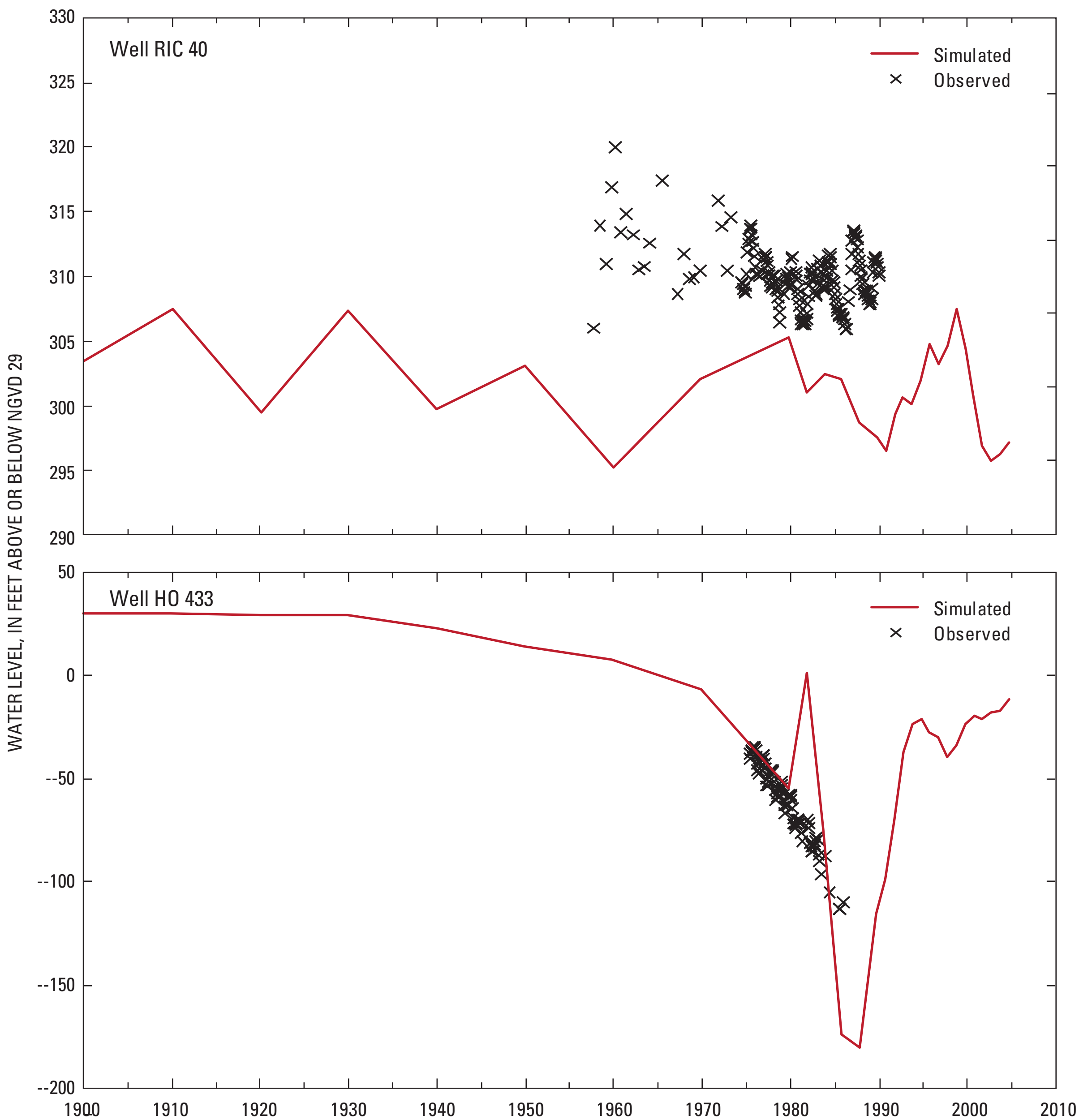



**Figure C21G.** Hydrographs of simulated and observed water levels for the McQueen Branch aquifer in South Carolina (see *fig. C20* for well locations).

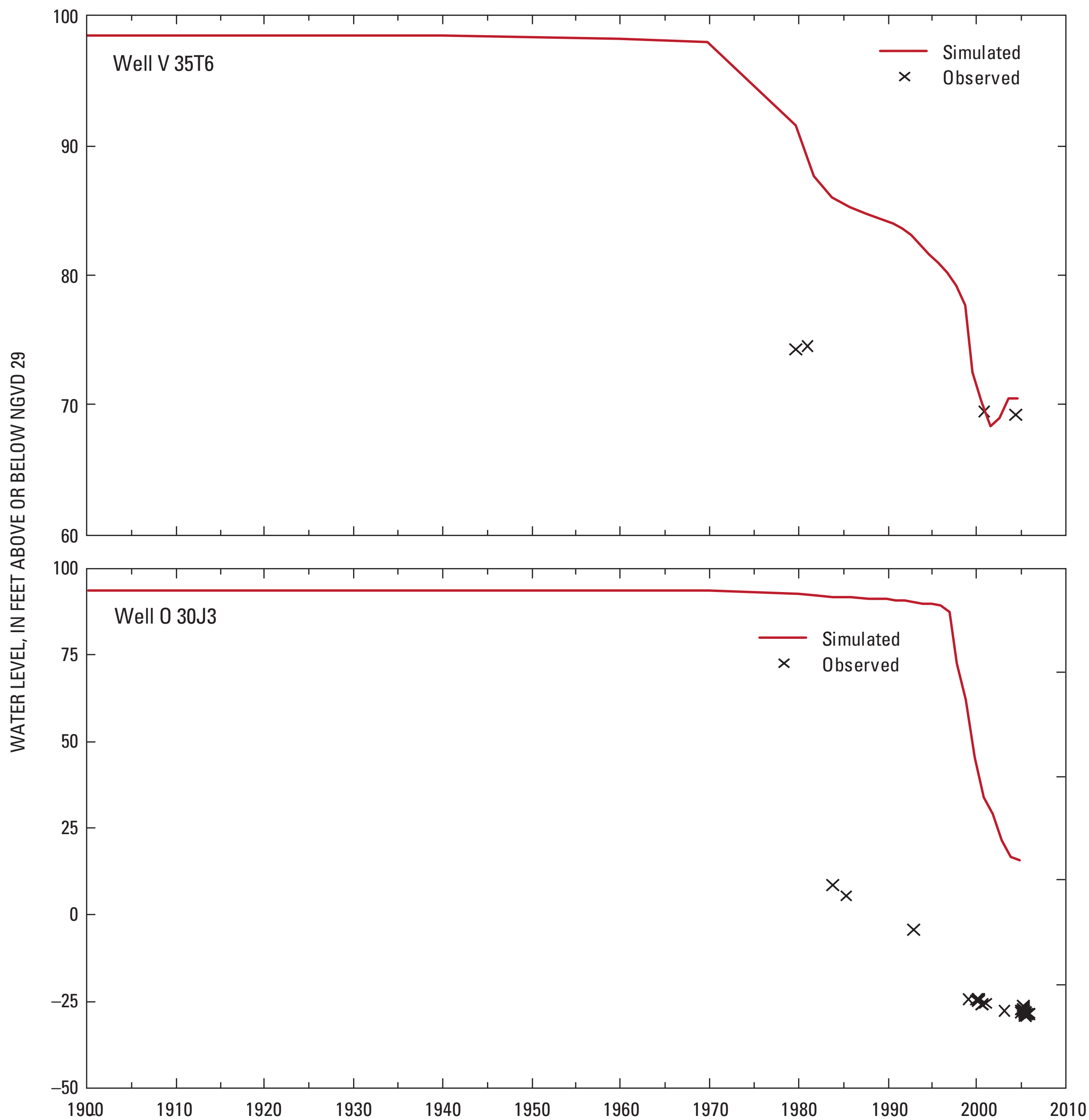



**Figure C21H.** Hydrographs of simulated and observed water levels for the Upper Cape Fear aquifer in North Carolina (see *fig. C20* for well locations).

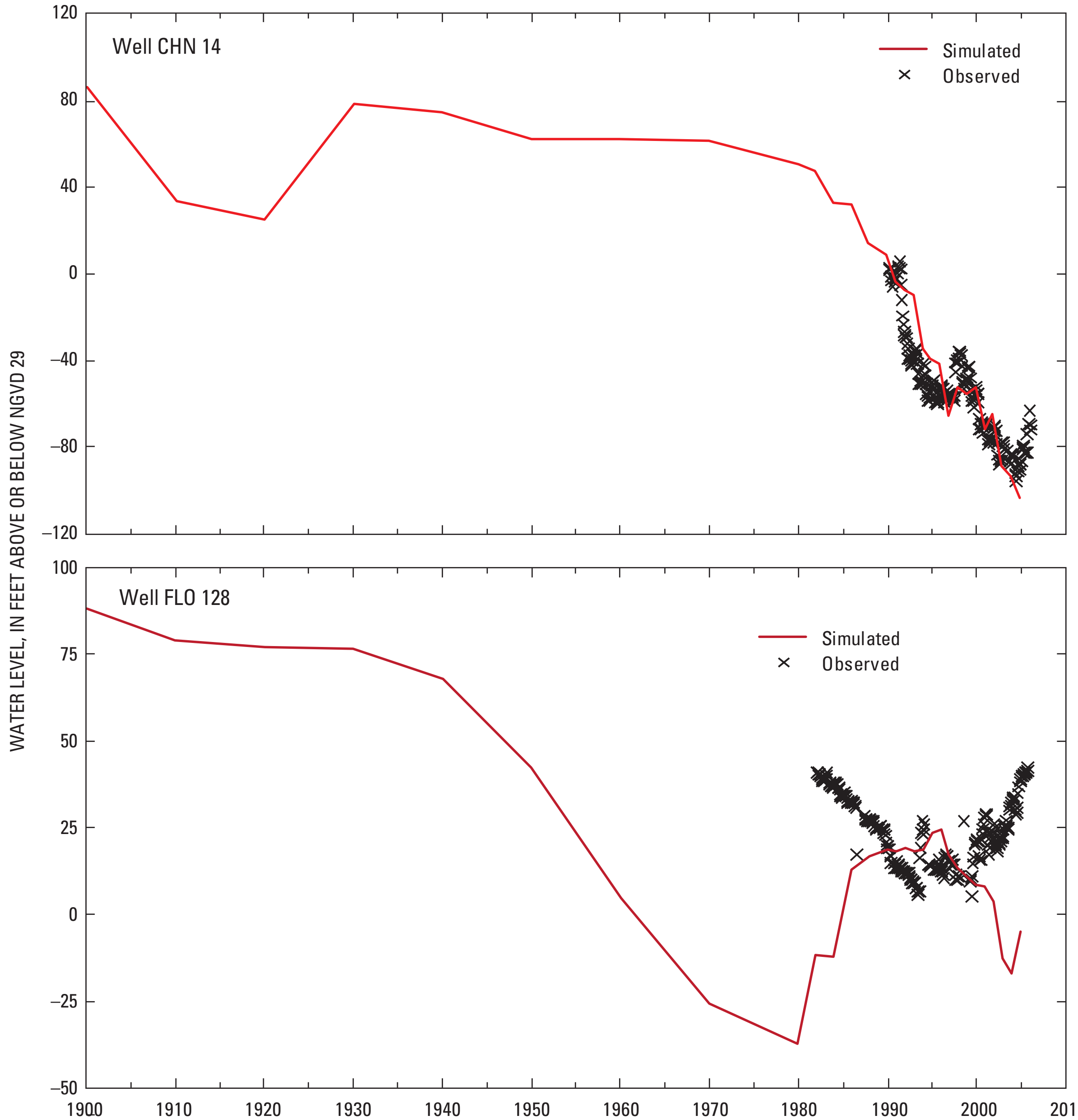



**Figure C21I.** Hydrographs of simulated and observed water levels for the Charleston aquifer in South Carolina (see *fig. C20* for well locations).

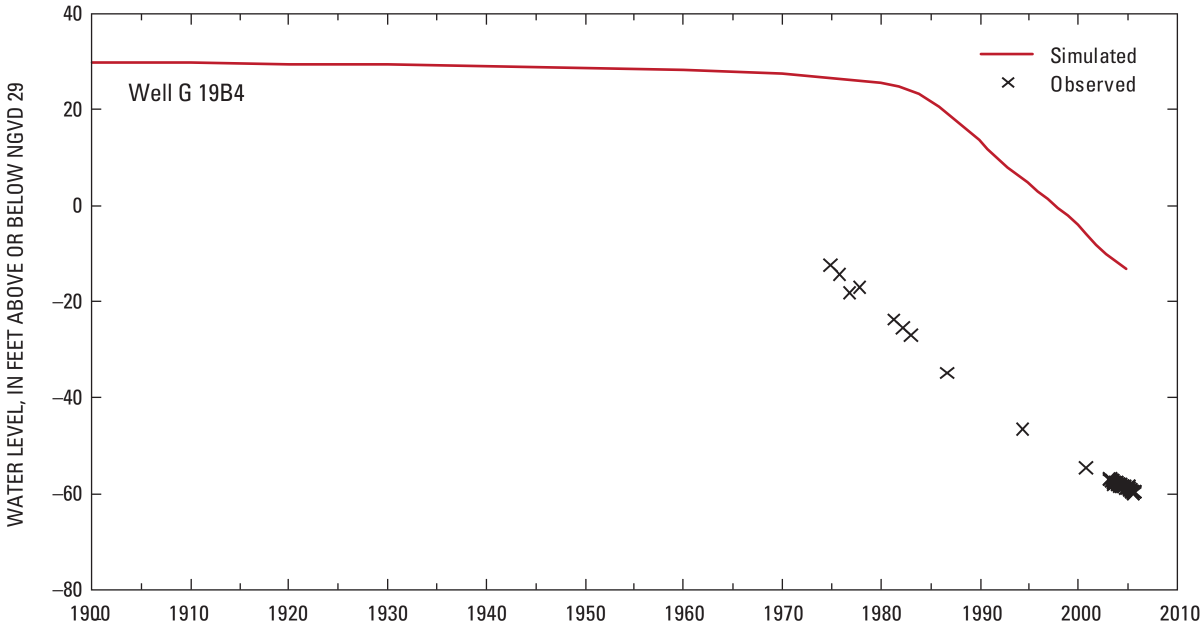



**Figure C21J.** Hydrographs of simulated and observed water levels for the Lower Cape Fear aquifer in North Carolina (see *fig. C20* for well locations).

**Table C10.** Observed and simulated mean annual baseflows for selected streamgages in the Atlantic Coastal Plain of South Carolina and parts of Georgia.

[USGS, U.S. Geological Survey; $ft^3/s$, cubic feet per second; $ft^3/d$, cubic feet per day; SRS, Savannah River Site]

| USGS station number | Station name | Map index number (See *fig. C2*) | Mean calculated annual baseflow, in $ft^3/s$ | Mean simulated annual baseflow, in $ft^3/s$ | Percentage of simulated annual baseflows within the 15-percent error criteria | Mean observed annual baseflow, in $ft^3/d$ | Mean simulated annual baseflow, in $ft^3/d$ |
|---|---|---|---|---|---|---|---|
| 02173351 | Bull Swamp Creek near Swansea, SC | 5 | 5.26 | 5.75 | 50 | 454,464 | 496,546 |
| 02169570 | Gills Creek at Columbia, SC | 6 | 47.4 | 29.7 | 13 | 4,096,225 | 2,562,899 |
| 02135300 | Scape Ore Swamp near Bishopville, SC | 7 | 74.7 | 41.9 | 11 | 6,453,856 | 3,622,829 |
| 02130900 | Black Creek near McBee, SC | 1 | 121 | 18.6 | 0 | 10,456,940 | 1,603,179 |
| 02197600 | Brushy Creek near Wrens, GA | 9 | 14.0 | 2.16 | 0 | 1,209,600 | 186,666 |
| 02196689 | Little Horse Creek near Graniteville, SC | 2 | 30.5 | 0.801 | 0 | 2,633,035 | 69,205 |
| 02197300 | Upper Three Runs near New Ellenton, SC | 10 | 95.4 | 7.08 | 0 | 8,242,208 | 611,828 |
| 02197310 | Upper Three Runs above Road C (SRS), SC | 3 | 95.4 | 8.17 | 0 | 8,242,208 | 705,796 |
| 02197315 | Upper Three Runs at Road A (SRS), SC | 4 | 41.9 | 4.14 | 0 | 3,622,666 | 358,110 |
| 02172500 | South Fork Edisto near Montmorenci, SC | 8 | 197 | 21.6 | 0 | 16,997,084 | 1,868,484 |

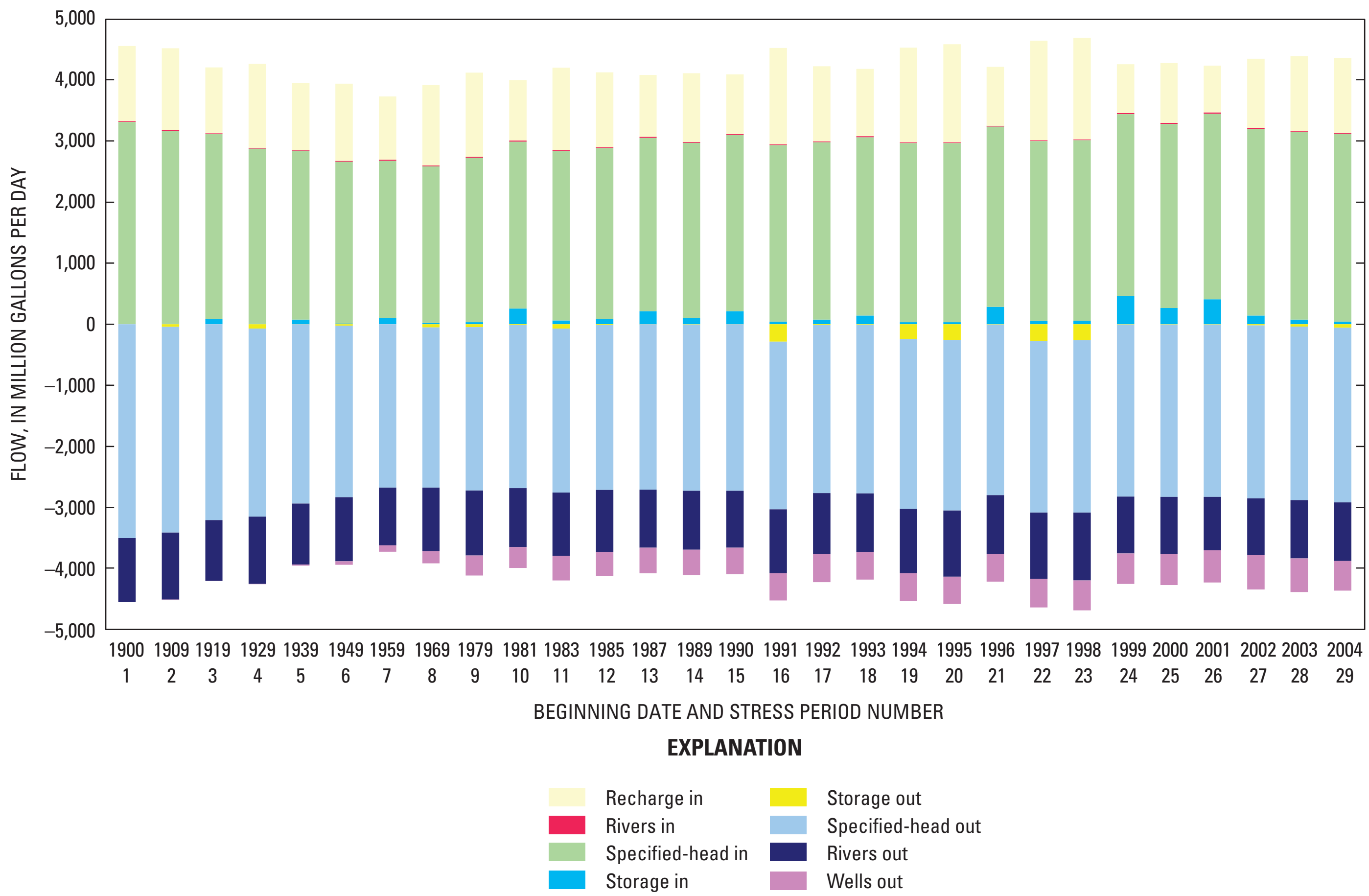



**Figure C22.** Simulated groundwater budget per model stress period from predevelopment to 2004 in the Atlantic Coastal Plain aquifers of North and South Carolina and parts of Virginia and Georgia.

## Sensitivity Testing and Analysis

The sensitivity of the calibrated model to the model inputs was evaluated to determine the relative importance of model parameters and boundary conditions on simulated groundwater levels and flows. Variations in parameters to which the calibrated model is most sensitive will result in larger differences in simulated groundwater levels than differences produced by variations in parameters to which the model is less sensitive. Sensitive parameters, therefore, are more likely to be accurately estimated during model calibration than less sensitive parameters. The sensitivity of the NC–SC Coastal Plain model to the calibrated aquifer parameters of horizontal hydraulic conductivity, vertical anisotropy, specific storage, and specific yield was evaluated with composite sensitivity analysis. The sensitivity of the model to the specified head and recharge boundary conditions, streambed conductance, and well withdrawals was evaluated using the perturbation method.

Relative composite sensitivities were calculated for 432 aquifer parameters used in model calibration (*fig. C23*). The parameters include 391 horizontal hydraulic conductivity values associated with pilot points in the aquifers and one confining unit, 8 horizontal hydraulic conductivity values in the confining units and one aquifer, 16 specific storage values, 1 specific yield value, and 16 vertical anisotropy values. 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 model parameter, a larger value of the associated relative composite sensitivity indicates more sensitivity of simulated conditions to the given parameter.

The model is relatively more sensitive to the horizontal hydraulic conductivity of the confining units in layers 10, 12, and 14 and of the aquifer in layer 1 and to the specific storage of the aquifers and confining units in layers 11, 12, 13, 14, and 15. The model is relatively less sensitive to the horizontal hydraulic conductivity of the confining units in layers 4 and 6 and of the aquifer in layer 16, to the specific storage of the confining unit in layer 10 and the aquifer in layer 16, and to the vertical anisotropy of the confining units in layers 2, 10, 12, and 14. The model has relatively little sensitivity to the remaining hydraulic parameters. The model has a low sensitivity to the horizontal hydraulic conductivity pilot points for the aquifer in layers 3, 5, 7, 9, 11, 13, and 15 and for the confining unit in layer 2 relative to other hydraulic parameters.

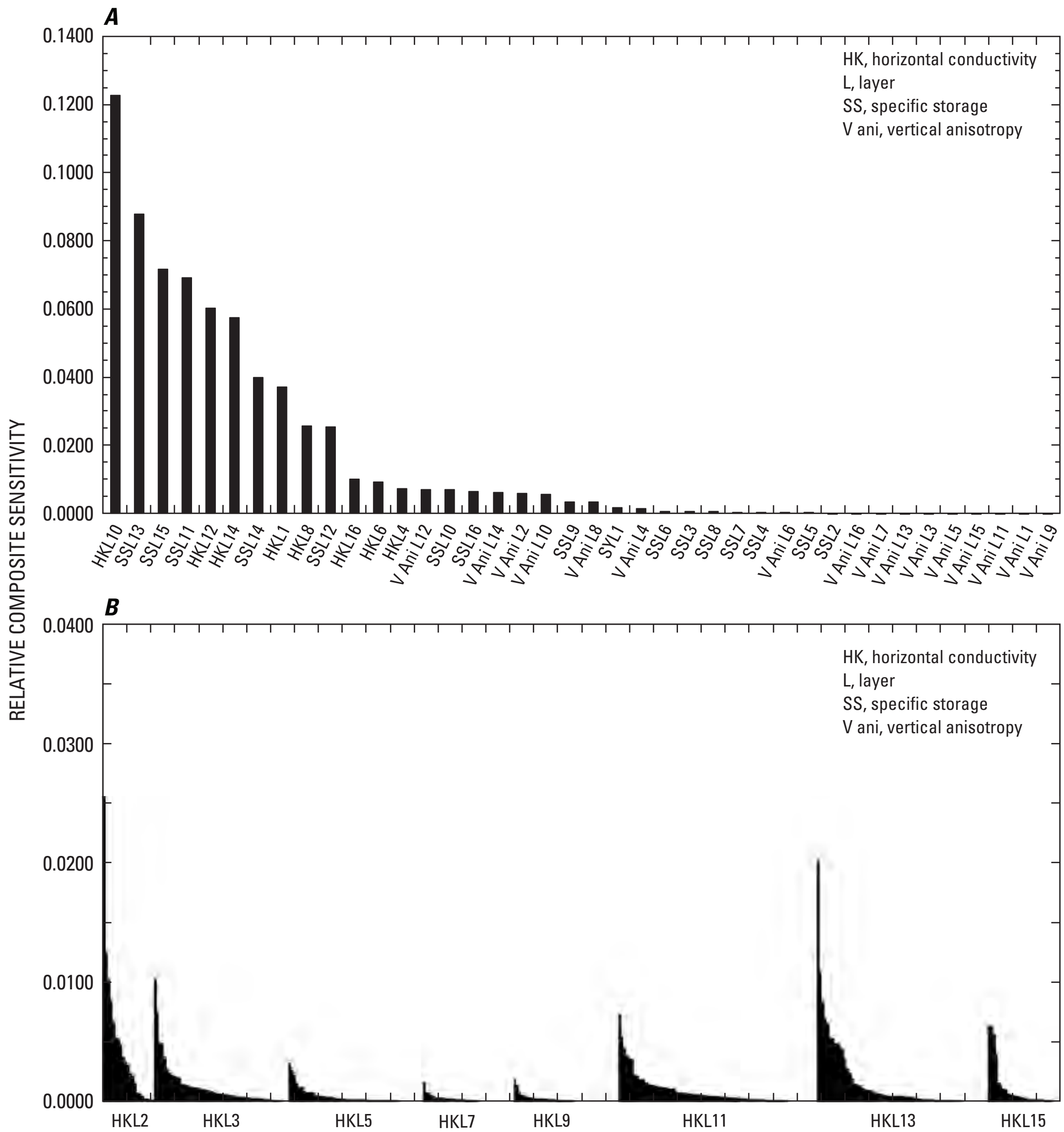



**Figure C23.** Relative composite sensitivities for *A*, aquifer parameters and *B*, aquifer–parameter pilot points.

The perturbation method was used to examine model sensitivity to the lateral specified heads on the northeast and southwest boundaries, the specified-head boundary defined for the top of layer 1, and the recharge boundary defined for layer 1. The perturbation method also was used to examine model sensitivity to streambed conductance and changes in groundwater withdrawals. Model sensitivity to these boundary conditions was examined by simulating a change in one boundary at a time and comparing the sum-of-squares error of the new simulation with that of the calibrated simulation.

To evaluate model sensitivity to the specified heads defined at the northeast and southwest boundaries for layers 2 through 16, 15 simulations were conducted where the northeast and southwest boundaries for layers 2 through 16 were converted individually to no-flow boundaries. The sum-of-squares error of all 15 simulations was greater than the sum-of-squares error of the calibrated model. The smallest increase in error was 1.0 percent for the conversion of boundaries for layer 11 to no flow; the largest increase in error was 1.1 percent for the conversion of boundaries for layer 15 to no flow.

To evaluate the sensitivity of the upper boundary of layer 1, four simulations were conducted in which the specified-head boundary was increased by 1 ft and decreased by 1 ft and in which the recharge rate was increased by 10 percent and decreased by 10 percent. Increasing the upper specified-head boundary by 1 ft increased the sum-of-squares error by 2.5 percent; decreasing the specified-head boundary by 1 ft decreased the sum-of-squares error by 2.3 percent. Considering that the specified heads of the upper boundary were set equal to the mean altitude in each 4-$mi^2$ cell, the sensitivity of the specified-head boundary is relatively small. Increasing the recharge rate by 10 percent decreased the sum-of-squares error by only 0.2 percent; decreasing the recharge rate by 10 percent increased the sum-of-squares error by only 0.6 percent, indicating little sensitivity of the model to the recharge rate.

To evaluate the sensitivity of the model to streambed conductance, two simulations were conducted in which conductance values were decreased by half and increased by 100 percent. Neither decreasing nor increasing the streambed conductance values changed the sum-of-squares error of the model. The model is not sensitive to streambed conductance, and the calibrated values may not be accurate estimates of true streambed conductance values.

To evaluate the sensitivity of the model to changes in groundwater withdrawals, three simulations were conducted in which pumping was decreased by 10 percent and increased by 10 and 20 percent. Decreasing pumping by 10 percent increased the sum-of-squares error by 30.2 percent; increasing pumpage by 10 percent decreased the sum-of-squares error by 20.4 percent. Increasing pumpage by 20 percent decreased the sum-of-squares error by 31.0 percent; increasing pumpage further did not further decrease the sum-of-squares error. The decrease in model error with the increase in groundwater withdrawals corresponds to the known underrepresentation of pumping in the model. Withdrawals less than 3 million gallons per month are not required to be reported to the State agencies and are, therefore, unknown.

## Model Limitations

Numerical models are based on limited data and are simplifications of actual groundwater flow systems. The simplifications incorporated into the development of a groundwater model can limit the ability of the model to predict actual hydraulic conditions over time. Accuracy and prediction capabilities of this model are affected by the finite-difference discretization, boundary conditions, hydraulic properties, and observations used in the model calibration.

The model was spatially discretized into a grid of 4-mi$^2$ cells and was temporally discretized into 1 steady-state stress period and 28 transient stress periods. The relatively large size of the grid cells is adequate to represent regional groundwater flow conditions but limits the ability of the model to accurately simulate local flow conditions, such as discharge to wells or rivers. The 28 transient stress periods range in length from 10 years (in the earlier periods of the model) to 1 year (in the more recent time periods of the model). The variable-length stress periods are appropriate for the accuracy of the water-use data and temporally sparse observations but cannot represent seasonal variation within the groundwater flow system.

Boundary choices can affect model uncertainty, run times, and stability. The lateral boundaries defined for the model are artificial and are not true boundaries of the natural hydrologic system. The northeastern and southwestern specified-head boundaries in the upper layer of the model were placed at two major rivers that act as natural hydraulic boundaries only for the directly incised upper hydrogeologic units. The northeastern and southwestern lateral specified-head boundaries in layers 2 through 16 were placed along groundwater flow paths. The model is not sensitive to the lateral specified-head boundaries; model error did not substantially change with the conversion of these boundaries from specified head to no flow. The northwestern no-flow boundary of the model was placed along the Fall Line, and the southeastern no-flow boundary of the model was placed at the freshwater/saltwater divide, both of which can be considered natural hydraulic boundaries in the groundwater system. The locations of the freshwater/saltwater divides of the various aquifers are only approximately known and can be expected to change over time in response to transient pumping stresses. Care should be taken, however, when interpreting simulated water levels near all model boundaries.

The upper boundary of layer 1 has two zones: (1) in the outer Coastal Plain, the upper boundary of layer 1 is set as specified heads equal to the values calculated by equation 1; and (2) in an area along the Fall Line where confined hydrogeologic units crop out, net recharge was applied. Increasing and decreasing the specified heads in layer 1 did not substantially change model error. The recharge rate specified in the model is uncertain and was calibrated within reasonable limits during the steady-state stress period. The calibrated recharge rate was varied temporally during the transient stress periods based on historical precipitation data from six stations located in the inner Coastal Plain. These six stations represent a small fraction of the large area covered in the model where recharge is simulated, and precipitation data at these stations were collected over a 104-year period; therefore, the precipitation data most likely are subject to a degree of uncertainty. Increasing and decreasing the recharge rate by 10 percent, however, did not substantially change model error.

Groundwater withdrawals simulated in the model underrepresent actual historical water use because pumping rates less than 3 million gallons per month are not required to be reported to the State agencies and, therefore, are unknown. In addition, approximately 10 percent of the total volume of reported water use in SC was not simulated in the model because either the pumped aquifer was unknown or the well location was unknown. The calibrated model was very sensitive to groundwater withdrawals; model error improved by 31 percent when the amount of simulated groundwater withdrawals was increased by 20 percent. The sensitivity of the model to withdrawals and the known underrepresentation of pumping emphasize the importance and need for improved monitoring of groundwater use in both NC and SC.

Hydraulic properties of horizontal hydraulic conductivity, vertical anisotropy, specific storage, and specific yield were all calibrated to some degree during the simulation process. Initial values of hydraulic conductivity and specific storage for the aquifer were derived from published transmissivity and storage coefficient data and are the best-defined hydraulic properties in the model. In some cases, however, aquifer thicknesses at the wells had to be assumed from screen length. The model was most sensitive to the hydraulic conductivity of the aquifer in layer 1 and of the confining units in layers 10, 12, and 14, and to the specific storage of the aquifers and confining units in layers 11, 12, 13, 14, and 15. The model was less sensitive to hydraulic conductivity, vertical anisotropy, specific storage, and specific yield in other layers; these calibrated values may be less accurate than the values that are more sensitive. All of the calibrated hydraulic-property distributions are large-scale approximations of measured and estimated values.

The hydraulic heads used as steady-state and transient calibration targets have uncertainty associated with the accuracy of the land-surface altitudes of each well; the calibration target was to match simulated and observed water levels within 20 ft. In addition, the clustering of head data in one area and the lack of head data in other areas can lead to areas being overemphasized or underemphasized during model calibration, respectively. Care was taken during this study to limit the clustering of head data, but the lack of head data in some areas is a limitation that cannot be corrected. Finally, because of minimal predevelopment water-level data, hydraulic-head observations used in the steady-state calibration were derived from water levels collected prior to 1980. Major groundwater pumping began in the NC–SC Coastal Plain in the 1940s; some of the groundwater levels used to develop the steady-state hydraulic-head observations may not reflect true steady-state conditions.

Stream baseflows simulated by the model do not accurately represent calculated baseflows. A scale issue occurs between the 2-mi by 2-mi model cells and the stream widths that the model simulates, which are less than 100 ft during baseflow conditions. Because of this scale issue, the model is not capable of accurately simulating baseflow for most streams. In addition, the model is insensitive to streambed conductance, and the calibrated values may not be accurate representations of true conductances.

# Future Opportunities for Improvements

As with all numerical models of complex natural systems, there are many ways that the model can be improved. Moreover, taking advantage of opportunities to increase knowledge of the quantity and movement of groundwater in the aquifers and confining units also would benefit the short- and long-term use of the newly developed forecasting tool. The limitations discussed below also can be viewed as opportunities for further enhancement of the hydrogeologic framework, along with integration of any newly available hydrologic information. Future enhancements to the simulation codes could lead to opportunities to improve the numerical model. The cumulative effect of these enhancements could be to improve understanding of how groundwater flow within the aquifer and confining units occurs, thus enabling a better approximation of groundwater flow through the use of more realistic numerical models.

The first recognized limitation is that the revised hydrostratigraphy presented in this report and used in the model is based on limited data. Additional continuous coreholes distributed throughout the study area could provide supplemental information regarding lithologic descriptions, paleontologic ages, and aquifer and confining unit hydrologic properties that could be used to update the hydrostratigraphic interpretations, resulting in more accurate top and bottom altitudes. Many of the more deeply buried units have few, if any, available aquifer-test results. Additional test wells drilled into these more deeply buried units could provide opportunities for additional aquifer tests to be conducted to determine properties such as horizontal and vertical hydraulic conductivities and storage coefficients.

As better simulation tools become available, the spatial discretization of the study area could be reduced, allowing for the more accurate simulation of groundwater–surface-water interactions. Refining the discretizaton of the study area could allow the surficial aquifer to be simulated as an active layer rather than as a specified-head boundary. Groundwater–surface-water interactions could be better quantified through detailed field studies and the classification of streambed sediments. Streamgages are sparse in the inner Coastal Plain of the study area; additional streamgages on small tributaries could provide additional baseflow data and additional model calibration points.

Recharge was applied to the water table without simulating the flow processes in the unsaturated zone. The unsaturated zone is known to vary from a few inches to as much as 200 ft in the study area. Transient storage in the unsaturated zone is not simulated in the model and most likely represents a substantial volume of groundwater in the inner Coastal Plain of the study area. A MODFLOW package, UZF1 (Niswonger and others, 2006), could be used to simulate this unsaturated flow.

The model does not simulate variable-density groundwater flow, which is an important element of groundwater flow in the coastal part of the study area. Future versions of the model could use the SEAWAT package (Langevin and others, 2007). The addition of a variable-density flow capability to the model would allow for the simulation of regional saltwater encroachment processes and the potential effects of climate change related to sea-level changes.

The water-use data included in the model are known to contain errors and omissions. Data prior to about 1980 are generally estimated from population figures. Current data are not always complete, and many wells cannot be accurately placed in the model as a result of missing construction information. A more complete and accurate water-use database would reduce the uncertainty associated with transient model simulations. Use of the Multinode-Well Package for MODFLOW (Halford and Hanson, 2002) could result in more accurate simulation of groundwater-use data for wells that are open to more than one aquifer.

As new climate models are developed, updated versions of the groundwater model could be coupled directly to climate models to deliver efficient and less uncertain results. Coupling the model to optimization techniques such as the GWM package (Ahlfeld and others, 2005) also could provide a powerful management tool for groundwater users and State regulatory agencies.

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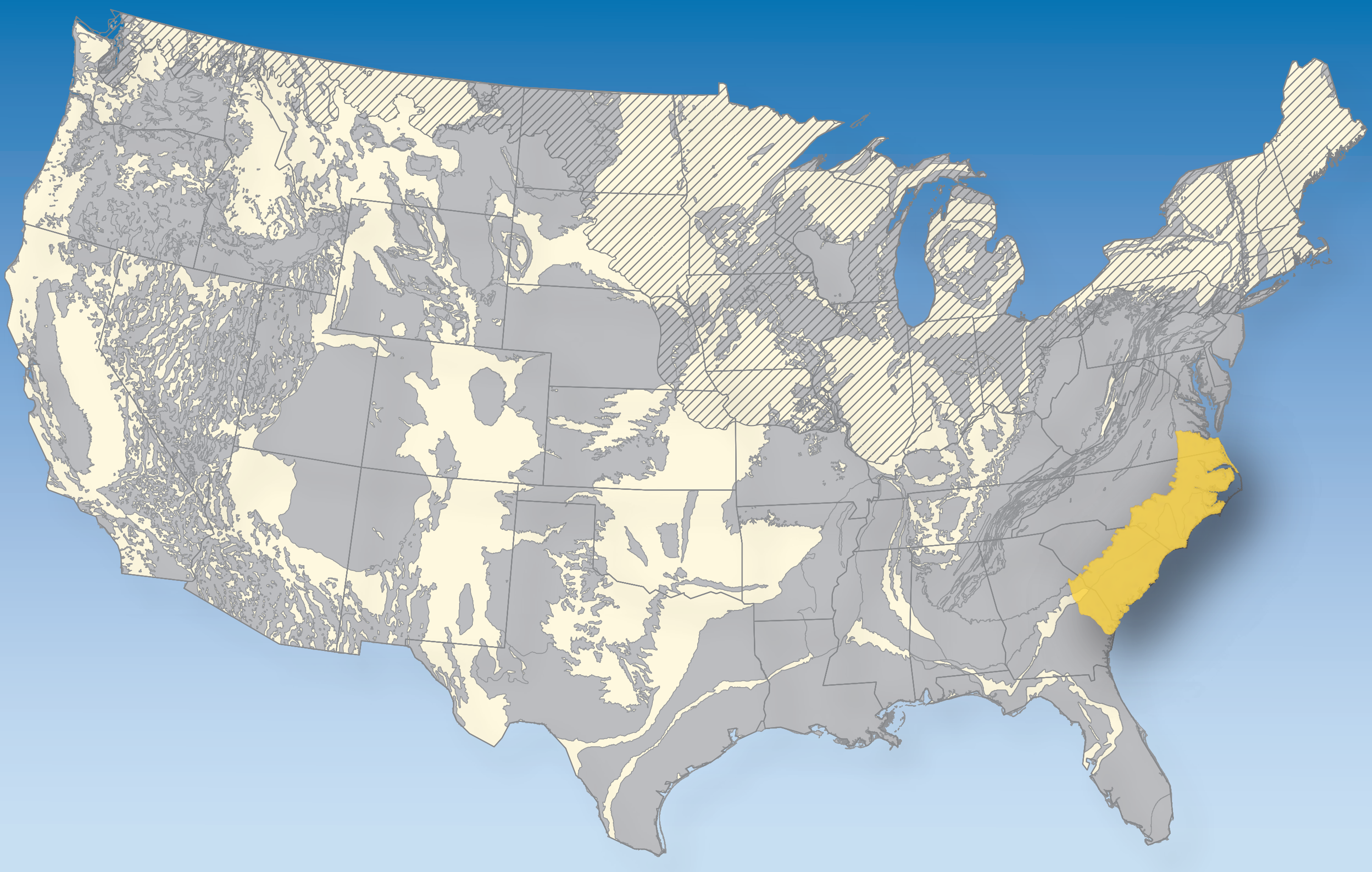
# Groundwater Availability in the Atlantic Coastal Plain of North and South Carolina



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