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Simulation of Ground-Water Flow in Coastal Georgia, and Adjacent Parts of South Carolina and Florida—Predevelopment, 1980, and 2000

Scientific Investigations Report 2005-5089

Prepared in cooperation with the
Georgia Department of Natural Resources
Environmental Protection Division

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

Cover photograph: Great Egret, Clam Creek, Jekyll Island, Georgia
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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia: 2005
This report is a Web-only publication: *pubs.water.usgs.gov/sir2005-5089*

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Suggested citation:
Payne, D.F., Malek Abu Rumman, and J.S. Clarke, 2005, Simulation of ground-water flow in coastal Georgia and adjacent parts of South Carolina and Florida—Predevelopment, 1980, and 2000: U.S. Geological Survey, Scientific Investigations Report 2005-5089, 91 p.

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
inch per year per foot [(in/yr)/ft]	83.33	millimeter per year per meter [(mm/yr)/m]

*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.

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

$$°F = (1.8 \times °C) + 32$$

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

$$°C = (°F - 32) / 1.8$$

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

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

Historical data collected and stored as North American Datum 1927 have been converted to NAD 83 for this publication.

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

Simulation of Ground-Water Flow in Coastal Georgia and Adjacent Parts of South Carolina and Florida—Predevelopment, 1980, and 2000

By Dorothy F. Payne, Malek Abu Rumman, and John S. Clarke

Abstract

A digital model was developed to simulate steady-state ground-water flow in a 42,155-square-mile area of coastal Georgia and adjacent parts of South Carolina and Florida. The model was developed to (1) understand and refine the conceptual model of regional ground-water flow, (2) serve as a framework for the development of digital subregional ground-water flow and solute-transport models, and (3) serve as a tool for future evaluations of hypothetical pumping scenarios used to facilitate water management in the coastal area.

Single-density ground-water flow was simulated using the U.S. Geological Survey finite-difference code MODFLOW-2000 for mean-annual conditions during predevelopment (pre–1900) and the years 1980 and 2000. The model comprises seven layers: the surficial aquifer system, the Brunswick aquifer system, the Upper Floridan aquifer, the Lower Floridan aquifer, and the intervening confining units. A combination of boundary conditions was applied, including a general-head boundary condition on the top active cells of the model and a time-variable fixed-head boundary condition along part of the southern lateral boundary.

Simulated heads for 1980 and 2000 conditions indicate a good match to observed values, based on a plus-or-minus 10-foot (ft) calibration target and calibration statistics. The root-mean square of residual water levels for the Upper Floridan aquifer was 13.0 ft for the 1980 calibration and 9.94 ft for the 2000 calibration. Some spatial patterns of residuals were indicated for the 1980 and 2000 simulations, and are likely a result of model-grid cell size and insufficiently detailed hydraulic-property and pumpage data in some areas. Simulated potentiometric surfaces for predevelopment, 1980, and 2000 conditions all show major flow system features that are indicated by estimated potentiometric maps.

During 1980–2000, simulated water levels at the centers of pumping at Savannah and Brunswick rose more than 20 ft and 8 ft, respectively, in response to decreased pumping. Simulated drawdown exceeded 10 ft in the Upper Floridan aquifer across much of the western half of the model area, with drawdown exceeding 20 ft along parts of the western, northern, and southern boundaries where irrigation pumping increased during this period.

From predevelopment to 2000 conditions, the simulated water budget showed an increase in inflow from, and decrease in outflow to, the general-head boundaries, and a reversal from net seaward flow to net landward flow across the coastline. Simulated changes in recharge and discharge distribution from predevelopment to 2000 conditions showed an increase in extent and magnitude of net recharge cells in the northern part of the model area, and a decrease in discharge or change to recharge in cells containing major streams and beneath major pumping centers.

The model is relatively sensitive to pumping and the controlling head at the fixed-head boundary and less sensitive to the distribution of aquifer properties in general. Model limitations include: (1) its spatial scale and discretization, (2) the extent to which data are available to physically define the flow system, (3) the type of boundary conditions and controlling parameters used, (4) uncertainty in the distribution of pumping, and (5) uncertainty in field-scale hydraulic properties. The model could be improved with more accurate estimates of ground-water pumpage and better characterization of recharge and discharge.

Introduction

During the last several decades, population growth in the coastal area of Georgia, increased tourism, and sustained industrial activity have resulted in an increase in ground-water pumpage. Recent periods of severe drought also have increased stresses on the coastal ground-water system. Projected increase in coastal population during the next several decades is expected to result in increased, competing ground-water demands. The principal source of water in the coastal area is the Upper Floridan aquifer, an extremely permeable, high-yielding aquifer that was first developed in the late 1800s and has been used extensively in the area since then. Pumping from the Upper Floridan aquifer has resulted in substantial water-level decline near Savannah, Georgia, and saltwater intrusion at the northern end of Hilton Head Island, South Carolina, and at Brunswick, Georgia. This saltwater contamination has constrained further development of the Upper Floridan aquifer in the coastal area and created competing demands for the limited supply of water. The Georgia Environmental Protection Division (GaEPD) has capped permitted withdrawal from the Upper Floridan aquifer at 1997 rates in parts of the coastal area to limit further saltwater intrusion, prompting interest in the development of alternative sources of water supply, primarily from the shallower surficial and Brunswick aquifer systems.

In order to develop a strategy to address these problems and projected future coastal water resource needs, the GaEPD has implemented the Georgia Coastal Sound Science Initiative (CSSI), a series of scientific and feasibility investigations designed to assess coastal area ground-water resources and address issues of saltwater intrusion and resource sustainability. The role of the U.S. Geological Survey (USGS) in the CSSI is to collect and analyze hydrogeologic data in order to refine the conceptual models of ground-water flow and saltwater transport, expand the conceptual model of the ground-water flow system to include potential ground-water resources other than the Upper Floridan aquifer, and synthesize this information into digital models that describe the ground-water flow system. The GaEPD will use these digital models to help design a coastal area ground-water management strategy.

The digital models developed by the USGS as part of the CSSI must satisfy multiple objectives at varying scales. Objectives include simulation of (1) the regional flow system, including the Brunswick aquifer system and the Lower Floridan aquifer, in addition to the Upper Floridan aquifer; (2) subregional flow and localized saltwater intrusion in the Savannah, Ga.–Hilton Head Island, S.C., area; and (3) localized saltwater intrusion at Brunswick, Ga. To satisfy these objectives, the USGS has developed a consistent set of ground-water flow and solute-transport models. These models update and expand on earlier digital models for the area.

Purpose and Scope

This report documents the USGS digital ground-water flow model developed to simulate the coastal Georgia regional ground-water flow system, including the Floridan aquifer system and the Brunswick aquifer system. This model is used to (1) understand and refine the conceptual model of regional ground-water flow, (2) serve as a framework for the development of digital subregional ground-water flow and solute-transport models, and (3) serve as a tool for future evaluations of hypothetical pumping-distribution scenarios used to facilitate water management in the coastal area. Discussions in this report include modeling procedures; boundary condition construction, testing and rationale; rationale for the steady-state approximation; calibration approach; sensitivity analyses; estimated volumetric flow budgets for predevelopment, 1980, and 2000 conditions; and water-level changes from predevelopment to 2000 and from 1980 to 2000. Data acquired as part of the CSSI were integrated with available data from USGS databases, publications, and a variety of other sources, to create model input and calibration sets that are as current and self-consistent as practicable.

Description of Study Area

The GaEPD defines the coastal area of Georgia to include the 6 coastal counties and adjacent 18 counties, an area of about 12,240 square miles (mi^2) (fig. 1). To account for natural hydrologic boundaries used for model simulation, the study area has been expanded to 42,155 mi^2 extending inland in Georgia and into northeastern Florida and southwestern South Carolina, and the adjacent offshore area (see fig. 1).

The 24-county coastal area has been subdivided by GaEPD into three subareas—the northern, southern, and central subareas—to facilitate implementation of the State's water-management practices (fig. 1). The northern subarea is northwest of the Gulf Trough, a prominent geologic feature that represents a zone of low permeability in the Floridan aquifer system. The southern subarea lies south of what GaEPD has called the "Satilla Line," a postulated hydrologic boundary based on a change in the configuration of the potentiometric surface of the Upper Floridan aquifer, and by linear changes depicted on aeromagnetic, aeroradioactivity, gravity, and isopach maps (William H. McLemore, Georgia Environmental Protection Division, oral commun., January 6, 2000). The central subarea lies between the northern and southern subareas, and includes the largest concentration of pumping in the coastal area—the Savannah, Brunswick, and Jesup pumping centers (fig. 1).

The study area is in the Coastal Plain physiographic province. Topographic relief ranges from low in the central and southern subareas to steep in the northern subarea. Altitudes are as high as 100 ft (above NAVD 88) in the central and southern subareas, and 300 ft in the northern subarea. Land use is largely urban in industrial areas and cities such as Savannah and Brunswick; outside of these areas, land use is a mix of forest, grazed woodland, cropland with pasture, marsh, and swampland.

The study area has a mild climate with warm, humid summers and mild winters. Mean-annual temperature ranges from about 63 degrees Fahrenheit (ºF) in Burke County, Ga., to about 70°F in Glynn County, Ga., for the period 1971–2000 (National Oceanic and Atmospheric Administration, 2002). Mean-annual precipitation, based on the period 1971–2000, ranges from about 47 inches per year (in/yr) at Waynesboro, Ga., to about 53 in/yr at Folkston, Ga. (Priest, 2004). Rainfall is not evenly distributed throughout the year. Maximum rainfall generally occurs during the summer months of June, July, and August. Estimated evapotranspiration ranges from 31 in/yr in the northern part of the study area to more than 40 in/yr in Charlton and Ware Counties, Ga., near the Okefenokee Swamp (Krause and Randolph, 1989). Rainfall as a source of recharge to aquifers is most important during the nongrowing season, generally October through March, when evapotranspiration is lowest.

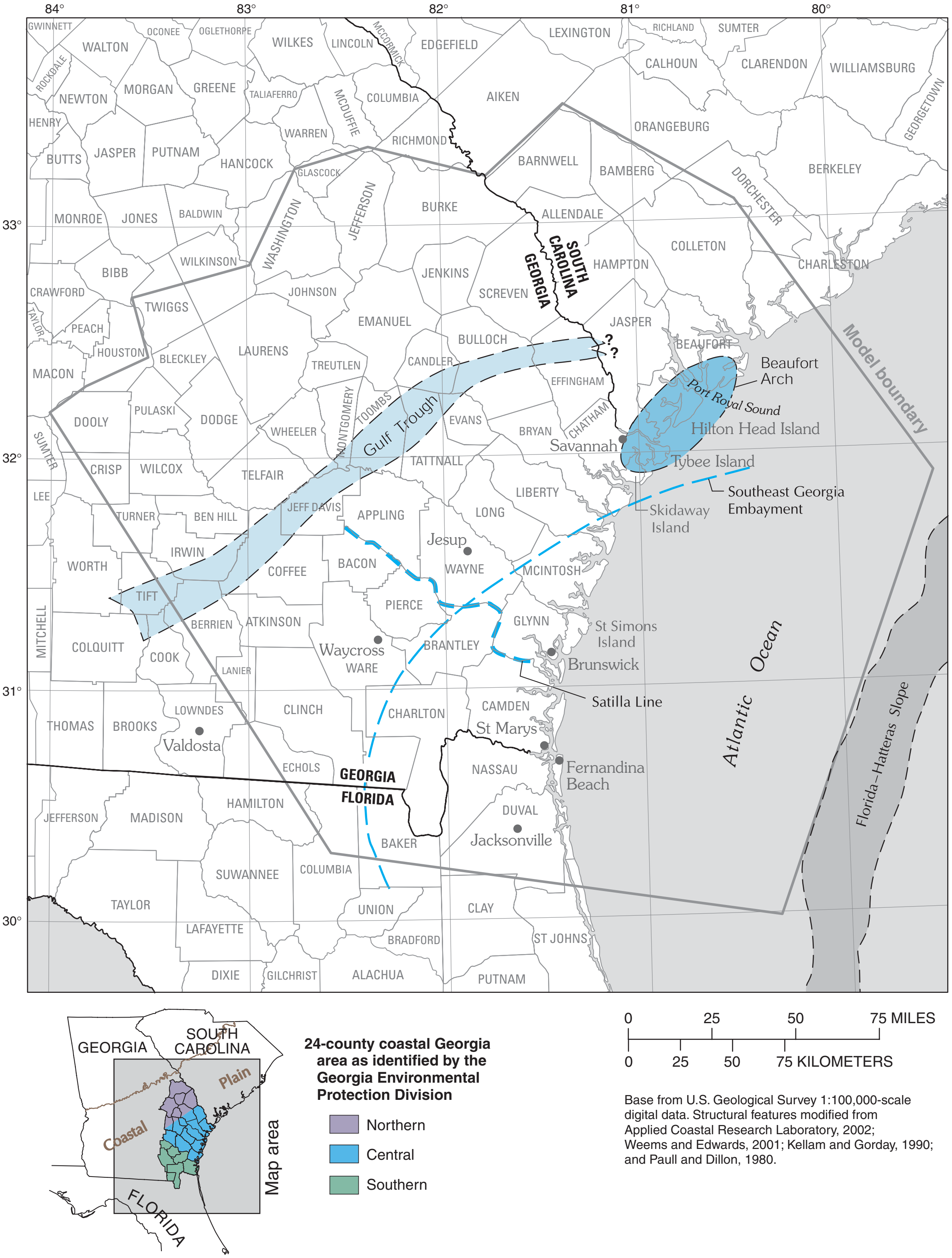


Figure 1. Location of 24-county coastal Georgia area, model area, and major structural features.

Previous Investigations

Several ground-water flow investigations of the Floridan aquifer system have been conducted in the study area, some of which incorporate digital modeling. As part of the USGS Regional Aquifer System Analysis (RASA) program, steady-state ground-water flow models of the Floridan aquifer system underlying Florida, southern Georgia, and parts of Alabama and South Carolina were developed for predevelopment conditions (Bush, 1982) and for 1980 conditions (Bush and Johnston, 1988). In these models, the Upper and Lower Floridan aquifers were simulated as active layers. In the Bush (1982) model, the top boundary was simulated as a specified flux and the bottom boundary as no-flow. In the Bush and Johnson (1988) model, the top boundary (surficial aquifer) and bottom boundary (Fernandina permeable zone) were simulated as specified-head layers.

Also as part of the RASA program, a subregional model comprising the area from coastal Georgia to the updip extent of the Floridan aquifer system and adjacent parts of Florida and South Carolina was developed for predevelopment conditions (Krause, 1982), then recalibrated and refined for steady-state 1980 conditions (Krause and Randolph, 1989). In both models, the surficial aquifer was simulated as a source-sink boundary, but only in the latter model was a source-sink boundary applied to the area of the Fernandina permeable zone. The subregional model was updated and recalibrated to 1985 conditions (Randolph and others, 1991) and refined for consistency with subsequently developed, smaller-scale models (Clarke and Krause, 2000). A smaller subregional model, comprising primarily the coastal counties of the RASA subregional model, was developed as part of a multiscale, multimodel ground-water management tool (Randolph and others, 1991). This model is "telescoped" at a finer grid resolution within the area of the RASA model. Vertical boundaries are identical to those of the RASA model, and lateral boundaries are derived from the RASA model.

Several smaller-scale models have been developed, focusing on the Savannah–Chatham County, Ga., area. Counts and Krause (1976) developed a model that simulated the "principal artesian aquifer" (which incorporates both the Upper and Lower Floridan aquifers) as a single layer calibrated for steady-state predevelopment conditions, then for transient conditions during 1956, 1960, and 1970, using time steps of variable length. A combination of source-sink and no-flow boundary conditions was used for both lateral and the top boundaries, with a no-flow boundary condition at the bottom. This model was subsequently expanded and refined (with modifications to the boundary conditions) and calibrated to 1980 conditions, using a steady-state approximation (Randolph and Krause, 1984). These two models were used to simulate hypothetical changes in ground-water levels responding to possible changes in pumping distribution. Another model for this area was developed to simulate the water-supply potential of both the Upper and Lower Floridan aquifers (Garza and Krause, 1996). This model was "telescoped" within the area of the larger RASA model of Krause and Randolph (1989). Vertical boundaries are identical to those of the RASA model, and lateral boundaries are derived from the RASA model.

Smaller-scale models have been developed for the Brunswick–Glynn County, Ga., area. Krause and Counts (1975) developed a model for the principal artesian aquifer (incorporating both Upper and Lower Floridan aquifers) that simulated steady-state predevelopment conditions and transient conditions for 1960 and 1970 using time steps of variable length. A model based on the subregional RASA model (Krause and Randolph, 1989) was developed to simulate ground-water flow in both the Upper and Lower Floridan aquifers and to evaluate the possible effects of hypothetical changes in local pumping (Randolph and Krause, 1990). This model was telescoped within the area of the larger RASA model of Krause and Randolph (1989), and used boundary conditions in a similar manner as the previously described smaller-scaled models. The Randolph and Krause (1990) model was calibrated for steady-state conditions during predevelopment and May 1980, and included an independent check using May 1985 pumping input and water-level observations.

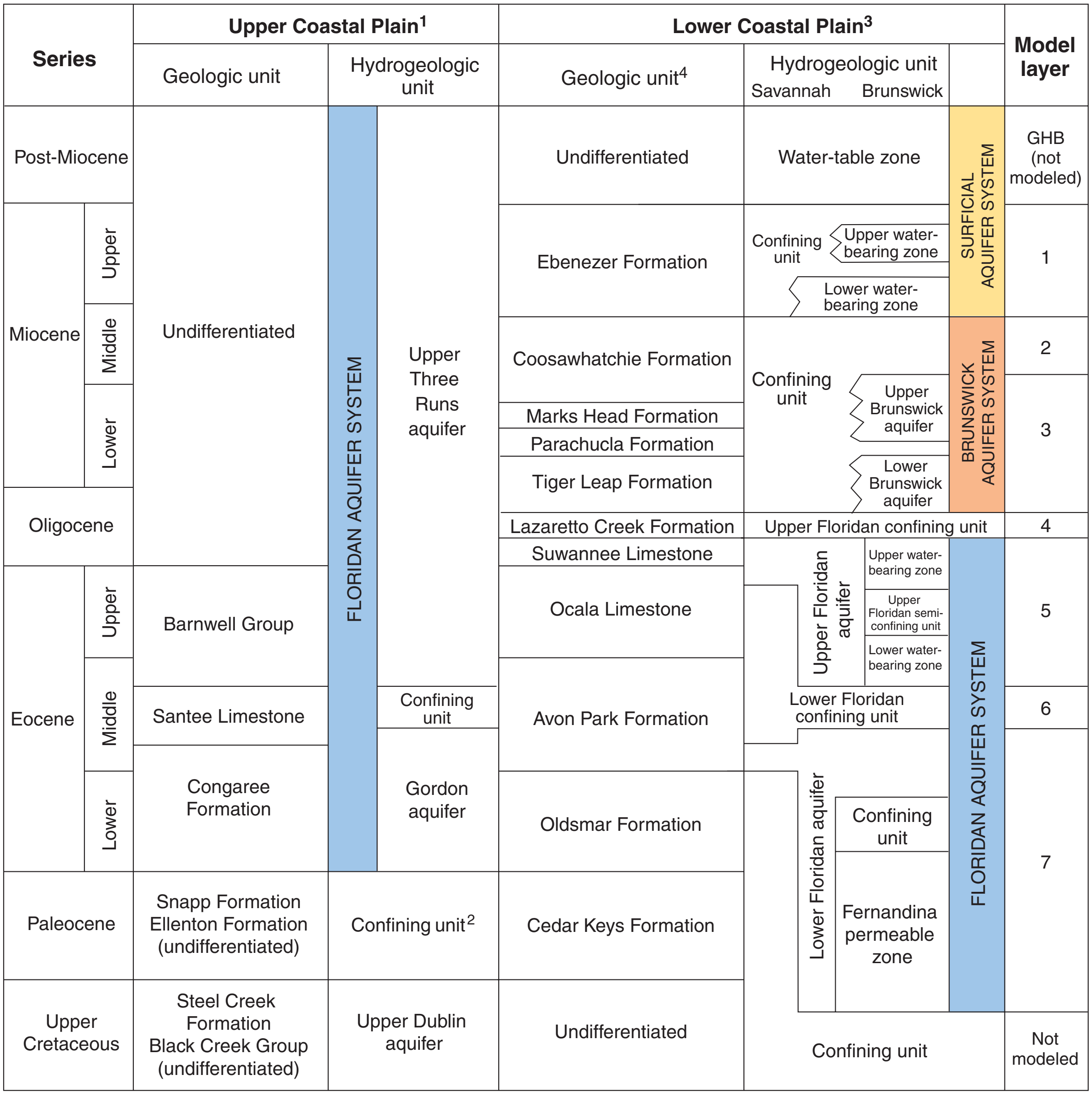
Clarke and Krause (2000) compared hydraulic-property data from the Savannah–Chatham County area (Garza and Krause, 1996) and Brunswick–Glynn County area (Randolph and Krause, 1990) models for consistency with the RASA model (Krause and Randolph, 1989), revised hydraulic-property data where required, and reported revised calibration statistics for the three models. The updated models were then used to simulate a variety of water-management scenarios for coastal Georgia.

Hydrogeology

Coastal Plain sediments of varying permeability comprise the aquifer and confining units in the study area. These sediments have been divided into geologic formations on the basis of their geologic characteristics and into aquifers and confining units on the basis of their water-bearing characteristics.

Geologic Setting

Coastal Plain strata consist of consolidated to unconsolidated layers of sand and clay, and semiconsolidated to very dense layers of limestone and dolomite. These sediments range in age from Late Cretaceous to Holocene, and unconformably overlie igneous, metamorphic, and sedimentary rocks of Paleozoic to Mesozoic age. The sedimentary units generally strike southwest-northeast, and dip and thicken to the southeast, where they reach a maximum thickness of 5,500 ft in Camden County (Wait and Davis, 1986). A generalized correlation of geologic and hydrogeologic units and corresponding model layers is shown in figure 2. Prominent structural features in the area (figs. 1 and 3), such as the Southeast Georgia Embayment, Beaufort Arch, and Gulf Trough, influence the thickness of sediments. Figure 3 is a schematic block diagram showing hydrogeologic units and the influence of structural features on their occurrence and relative thickness.



[1]Modified from Falls and others, 1997.
[2]In local areas includes Millers Pond aquifer.
[3]Modified from Randolph and others, 1991; Clarke and Krause, 2000.
[4]Modified from Randolph and others, 1991; Weems and Edwards, 2001.

Figure 2. Generalized correlation of geologic and hydrogeologic units and model layers (GHB, general-head boundary).

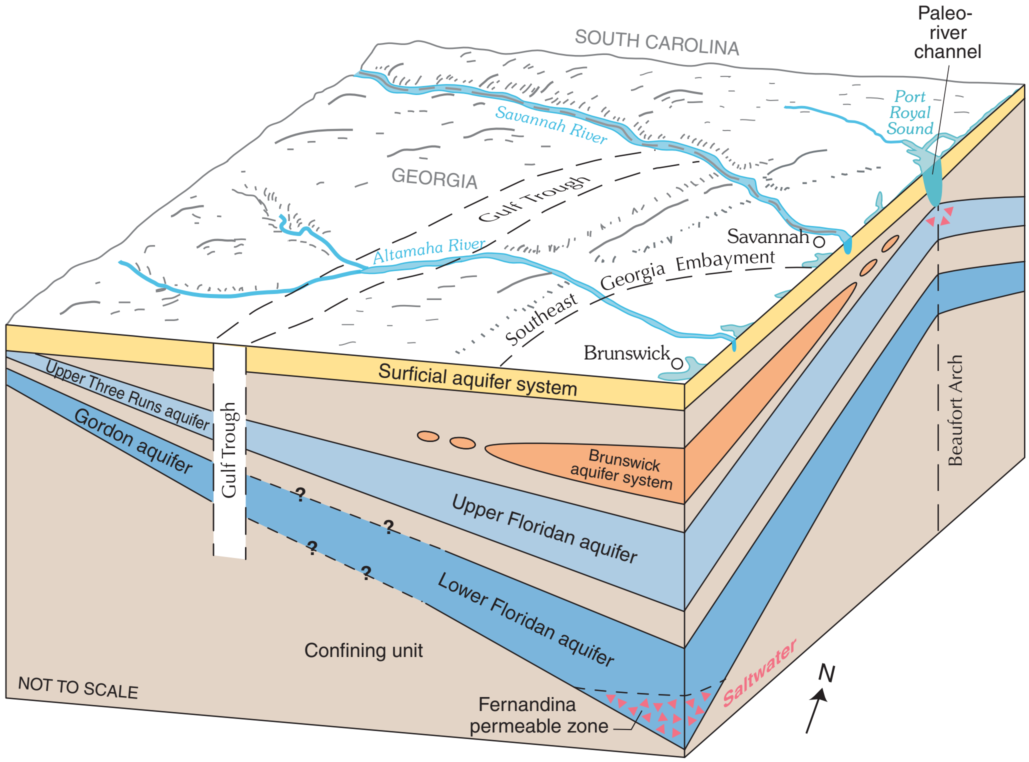


Figure 3. Schematic block diagram showing hydrogeologic units and influence of structural features on their occurrence.

The Southeast Georgia Embayment is a shallow east-to-northeast plunging syncline that subsided at a moderate rate from the Late Cretaceous until the late Cenozoic (Miller, 1986). Thickness of Coastal Plain deposits is greatest near the embayment (fig. 3).

The Beaufort Arch is centered near Hilton Head Island, S.C., and trends parallel to the coast. The arch interrupts the regional southward dip of the sediments in that area. Within the area influenced by the Beaufort Arch, Coastal Plain deposits thin and are at shallower depths than near the Southeast Georgia Embayment.

The Gulf Trough is a zone of relatively thick accumulations of fine-grained clastic sediments and clay-bearing carbonates, in which the permeability of Coastal Plain deposits decrease. In this area, ground-water flow is partially impeded by the juxtaposition of rocks of higher permeability updip and downdip of the trough, with those of lower permeability within the trough (Krause and Randolph, 1989).

In addition to the aforementioned geologic features, the Satilla Line (fig. 1) is a postulated hydrologic boundary identified by GaEPD based on a change in the configuration of the potentiometric surface of the Upper Floridan aquifer, and by linear changes depicted on aeromagnetic, aeroradioactivity, gravity, and isopach maps (William H. McLemore, Georgia Environmental Protection Division, oral commun., January 6, 2000). This feature may affect ground-water flow in the area; however, its geologic origin and nature are unknown.

Hydrogeologic Units

The principal source of water for all uses in the coastal area is the Floridan aquifer system, consisting of the Upper and Lower Floridan aquifers (Miller, 1986; Krause and Randolph, 1989). Secondary sources of water include the surficial and Brunswick aquifer systems (Clarke, 2003), consisting of sand of Miocene to Holocene age. These water-bearing units are separated by confining units of relatively low permeability.

Surficial and Brunswick Aquifer Systems

The surficial aquifer system (model layer 1; fig. 2) consists of interlayered sand, clay, and thin limestone beds of Miocene to Holocene age (Clarke, 2003). The aquifer system includes a water-table zone and two confined zones; however, the areal extent of the confined zones is unknown. Leeth (1999) reported two confined zones in Camden County; and Clarke and others (1990) reported one confined zone at Brunswick, Glynn County, and at Skidaway Island, Chatham County. Multiple confined zones are believed to be present mostly in areas where deposits are thick, such as in the Southeast Georgia Embayment (figs. 1 and 3). Reported transmissivity of the water-table zone ranges from 14 to 6,700 feet squared per day (ft^2/d), and for the confined zones ranges from 150 to 6,000 ft^2/d (Clarke, 2003). In this study, undifferentiated sediments comprising the confined zones of the surficial aquifer system are grouped into the upper model layer (layer 1).

The surficial aquifer system is separated from the underlying Brunswick aquifer system by a confining unit (model layer 2; fig. 2) consisting of silty clay and dense, phosphatic limestone of Miocene age. Wait and Gregg (1973) reported vertical hydraulic conductivity of this unit (determined from laboratory analysis of core) at Brunswick, Glynn County, ranges from 5.3×10^{-5} to 1.3×10^{-4} feet per day (ft/d).

The Brunswick aquifer system (model layer 3: fig. 2) consists of two water-bearing zones—the upper Brunswick aquifer and the lower Brunswick aquifer (Clarke, 2003). The upper Brunswick aquifer consists of poorly sorted, fine to coarse, slightly phosphatic and dolomitic quartz sand and dense phosphatic limestone (Clarke and others, 1990; Leeth, 1999). The lower Brunswick aquifer consists of poorly sorted, fine to coarse, phosphatic, dolomitic sand (Clarke and others, 1990). In general, the upper Brunswick aquifer has lower transmissivity than the lower Brunswick aquifer. Reported transmissivity of the upper Brunswick aquifer ranges from 15 to 3,500 ft^2/d, and that of the lower Brunswick ranges from 25 to 4,700 ft^2/d, with highest values for both aquifers within the area of the Southeast Georgia Embayment in Glynn County (Clarke, 2003). Outside and along the margins of the Southeast Georgia Embayment (figs. 1 and 3), permeable sediments comprising the Brunswick aquifer system are discontinuous, and the aquifer system has a higher percentage of low permeability, clayey deposits (Clarke, 2003). In this study, sediments comprising the upper and lower Brunswick aquifers are considered as a single unit, with combined thickness and composite hydraulic properties used for model simulations.

Floridan Aquifer System

The Floridan aquifer system, consisting of the Upper and Lower Floridan aquifers (Miller, 1986; Krause and Randolph, 1989), is composed of carbonate rocks of mostly Paleocene to Oligocene age that locally include Upper Cretaceous rocks (fig. 2). The Floridan aquifer system extends from the southern coastal plain of South Carolina, west across the coastal plain of Georgia and Alabama, and south across Florida. Thickness of the Floridan aquifer system in the study area ranges from less than 100 ft where the aquifer system crops out in South Carolina to about 2,800 ft in Brunswick, Ga. (Miller, 1986).

The Upper Floridan aquifer is overlain by a confining unit (model layer 4; fig. 2) consisting of layers of silty clay and dense phosphatic dolomite of Oligocene age that separate the aquifer from overlying permeable units of the Brunswick aquifer system (Clarke, 2003). Reported vertical hydraulic conductivity of this confining unit, based on laboratory analysis of core, ranges from 2.3×10^{-4} to 3.0 ft/d (Clarke and others, 2004).

The Upper Floridan aquifer (model layer 5; fig. 2) is highly productive and consists of Eocene to Oligocene limestone and dolomite. The aquifer crops out or is near land surface in the northwestern part of the study area and near Valdosta in Lowndes County, Ga. (fig. 1), where it is unconfined or semiconfined. To the southeast, the aquifer becomes progressively more deeply buried and confined. In this report, clastic sediments of the Upper Three Runs aquifer (Falls and others, 1997) in the upper Coastal Plain that are hydraulically connected to carbonate deposits of the lower Coastal Plain are included as part of the Upper Floridan aquifer (figs. 2 and 3). The transition from carbonate to clastic deposits generally occurs north of the Gulf Trough (figs. 1 and 3). Reported transmissivity of the Upper Floridan aquifer ranges from 530 ft^2/d in Beaufort County, S.C., to 600,000 ft^2/d in Coffee County, Ga. (Clarke and others, 2004). Hydraulic properties of the Upper Floridan aquifer vary greatly in the study area, because of the heterogeneity (and locally because of anisotropy) of the aquifer and the confinement (or lack of confinement) by confining units (Krause and Randolph, 1989). A characteristic of the Floridan aquifer system, especially the Upper Floridan aquifer, is that in many places, zones of very high hydraulic conductivity exist within relatively small vertical intervals of the aquifer (Clarke and others, 2004).

In some areas, several distinct water-bearing zones have been identified within the Upper Floridan aquifer. McCollum and Counts (1964) identified five water-bearing zones near the Savannah–Hilton Head Island area in strata that would later be defined as part of the Floridan aquifer system, the upper two of which are part of the Upper Floridan aquifer (Krause and Randolph, 1989). In the Brunswick–Glynn County, Ga., area, Wait and Gregg (1973) identified two distinct water-bearing zones (fig. 2) in the Upper Floridan aquifer (their "principal artesian aquifer"), and estimated that about 70 percent of the total flow from wells open to both zones was coming from the upper zone. In Beaufort County, S.C., the term *middle Floridan aquifer* is used by the State of South Carolina (Ransom and White, 1999) for a water-bearing zone approximately 250–550 ft below land surface.

The Upper Floridan aquifer is underlain by a confining unit (model layer 6; fig. 2) of dense, recrystallized limestone and dolomite of middle to late Eocene that hydraulically separates to varying degrees the Upper Floridan aquifer from the Lower Floridan aquifer (fig. 2). Locally in the Brunswick, Ga., area, the confining unit is breached by fractures or solution openings, which enhance the vertical exchange of water between the Upper and Lower Floridan aquifers (Krause and Randolph, 1989).

The Lower Floridan aquifer (model layer 7; fig. 2) is composed mainly of dolomitic limestone of early and middle Eocene age; at Brunswick, Ga., however, it includes highly permeable limestone of Paleocene and Late Cretaceous age (Krause and Randolph, 1989). In the northwestern part of the study area, the clastic Gordon aquifer (Brooks and others, 1985; Falls and others, 1997) is an updip unit that is hydraulically connected to the Lower Floridan aquifer (figs. 2 and 3). Reported transmissivity of the Lower Floridan aquifer ranges from 170 ft^2/d in Barnwell County, S.C., to 43,000 ft^2/d in Camden County, Ga. (Clarke and others, 2004). Although no aquifer tests were conducted in wells completed solely in the Lower Floridan aquifer in northeastern Florida, it is likely that transmissivity of the aquifer is high—possibly exceeding 100,000 ft^2/d (Clarke and others, 2004).

The Lower Floridan aquifer includes several water-bearing zones in parts of the study area. In the Savannah–Hilton Head area, the lowermost water-bearing zone of McCollum and Counts (1964) is included in the Lower Floridan aquifer (W.F. Falls, U.S. Geological Survey, written commun., August 28, 2003). In southeastern South Carolina, units of Paleocene and early Eocene age can contain permeable beds, and production wells are commonly screened in these zones and in the overlying Santee Limestone (Newcome, 2000). In this report, these productive zones, and the Santee Limestone, are considered part of the Lower Floridan aquifer. In southeastern Georgia and northeastern Florida, the Lower Floridan includes a deeply buried, cavernous and highly permeable, saline water-bearing unit known as the Fernandina permeable zone (Krause and Randolph, 1989). This unit is the probable source of saltwater contamination in the Upper and Lower Floridan aquifers at Brunswick, Ga., and Jacksonville, Fla. (Krause and Randolph, 1989). The lateral continuity of this zone is unknown; however, test drilling conducted as part of the CSSI indicates that the unit is present in downtown Brunswick and is absent in northern McIntosh County and at St. Simons Island in eastern Glynn County (W.F. Falls, U.S. Geological Survey, written commun., 2003).

Ground-Water Flow System

Ground-water flow is controlled mainly by rates and distribution of recharge to and discharge from the system, the extent and effects of confinement, the ability of the aquifers to transmit and store water, ground-water withdrawal, and the dips of the aquifer and confining units. A schematic diagram of the conceptualized ground-water flow system in the coastal area is shown in figure 4.

Recharge to the water-table zone of the surficial aquifer system occurs directly from precipitation throughout the study area; recharge to confined aquifers from precipitation occurs at outcrop areas (mostly north of the Gulf Trough; figs. 1 and 3), or from downward leakage through adjacent semiconfining units. Natural discharge occurs directly into some stream reaches or indirectly through upward leakage into adjacent units.

The extent and subsurface geometry of the Brunswick aquifer system is poorly understood—the aquifer system is not known to crop out—thus, recharge is believed to be restricted to leakage from the overlying surficial aquifer system or underlying Upper Floridan aquifer. Natural discharge from the Brunswick aquifer system is through upward leakage into the surficial aquifer system and streams.

Ground-water flow in the Upper Floridan aquifer is illustrated on a potentiometric-surface map for May 1998 (Peck and others, 1999) shown in figure 5. In the updip, northern part of the study area (north of the Gulf Trough; fig. 1) where the aquifers are exposed at or near land surface, the Floridan aquifer system receives recharge. Because the units are relatively shallow and that area is characterized by greater topographic relief, some aquifer discharge is directly to streams, as indicated by contours that bend upstream. From these northern areas, ground water flows mostly southeastward toward the coast and discharges into overlying units and surface-water bodies—major streams, estuaries, and the Atlantic Ocean. As ground water flows coastward, low-permeability sediments near the Gulf Trough impede ground-water flow and cause a steep potentiometric gradient, as indicated by contours on the potentiometric map (fig. 5).

South of the Gulf Trough, in the downdip part of the study area (fig. 4), the Upper Floridan aquifer is deeper and overlain by thick confining units and the Brunswick aquifer system. Here, water may enter or discharge from the aquifer through leaky confining units.

Localized areas of natural recharge to the Upper Floridan aquifer are present in Beaufort County, S.C. This recharge results from the shallow depth of the aquifer near the Beaufort Arch and localized areas of little or no confinement above the Upper Floridan aquifer (fig. 1).

Because little is known about regional ground-water flow in the Lower Floridan aquifer, the regional flow characteristics of the Lower Floridan aquifer are assumed to be similar to those of the Upper Floridan aquifer.

Predevelopment

Prior to development during the 1880s, recharge to the Floridan aquifer system was roughly offset by natural discharge to springs (both on land and offshore), rivers and other surface-water bodies, diffuse upward leakage, and other discharge areas (fig. 4A). The hydraulic head in the Upper Floridan aquifer was sufficiently high that earliest wells flowed at land surface throughout much of the coastal area, with water levels about 65 ft above NAVD 88 at Brunswick, and 30–40 ft above NAVD 88 at Savannah (Krause and Clarke, 2001). Recharge occurred in the northwestern part of the area, and water flowed downgradient toward the coast.

During predevelopment, the Floridan aquifer system likely contained freshwater throughout most of the coastal area. Saltwater was present near the aquifer system's northeastern extent on Parris Island (north of Hilton Head Island; fig. 1), S.C., in wells drilled during 1899 (Landmeyer and Belval, 1996), likely along the freshwater-saltwater interface offshore (Krause and Clarke, 2001), and in parts of north-central Florida (Stringfield, 1966). The aquifer system also probably contained saltwater at depth that is not derived from seawater, underlying freshwater in the system in the lower part of the Lower Floridan aquifer, for example, in Brunswick, Ga. (Wait and Gregg, 1973).

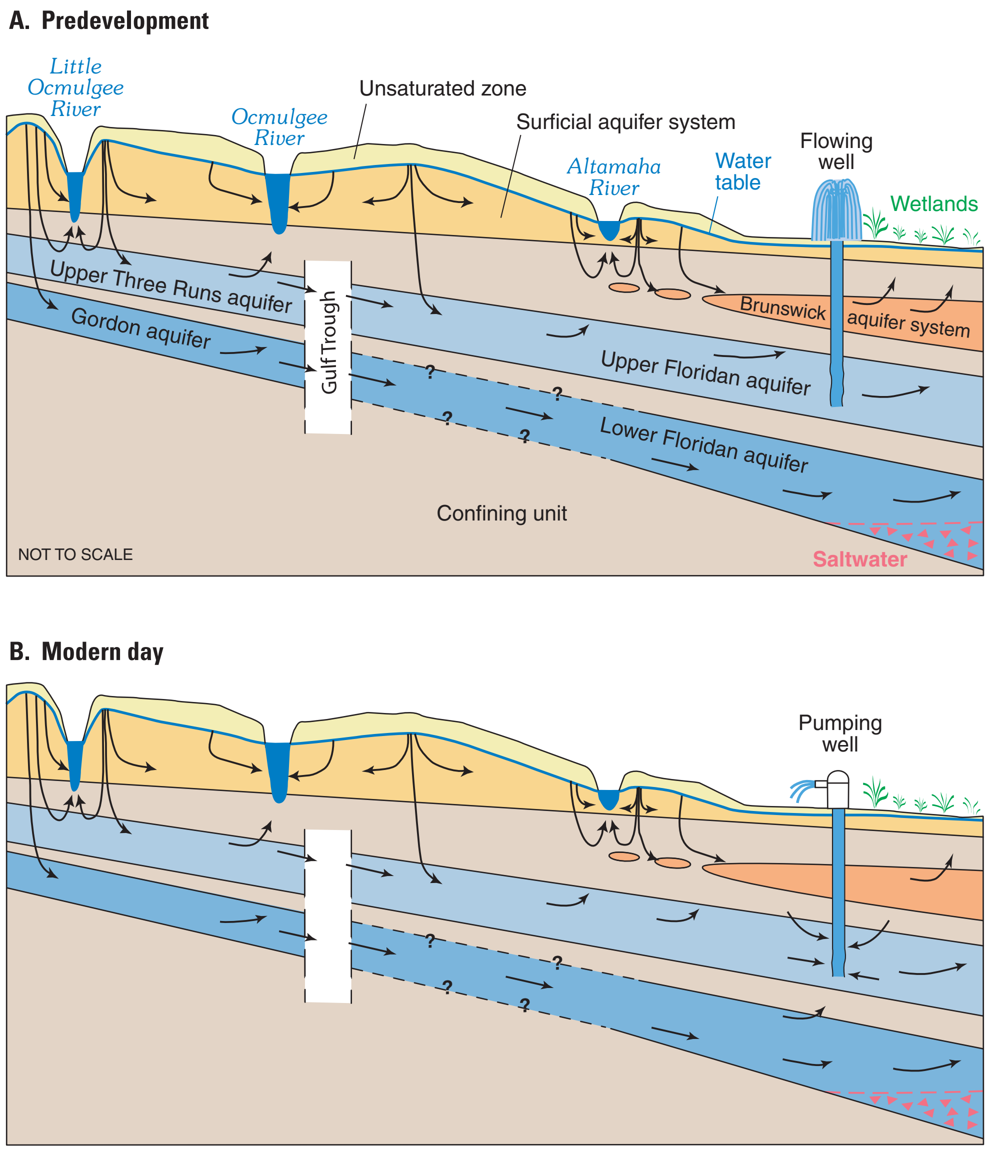
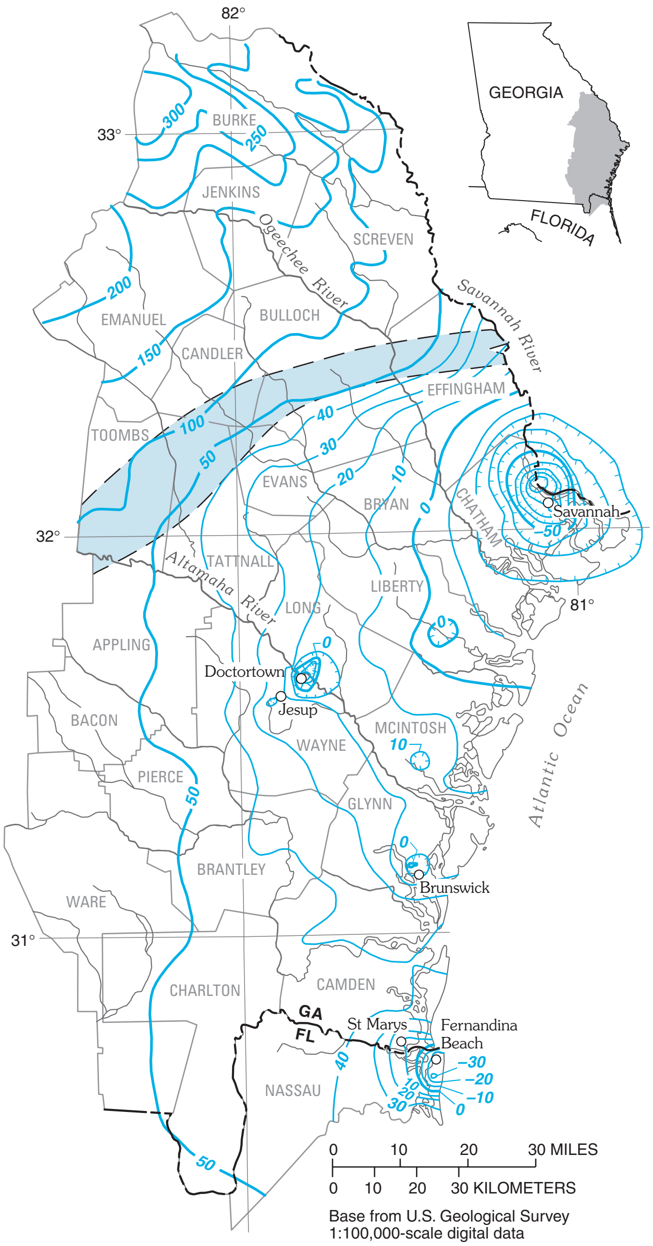


Figure 4. Schematic diagram showing conceptual model of (*A*) predevelopment and (*B*) modern-day (2000) flow system (modified from Priest, 2004). Arrows indicate general direction of ground-water flow.

Modern Day: 1980 and 2000

The modern-day flow system (figs. 4B and 5) reflects changes that have occurred as a result of ground-water development (withdrawal). Ground-water withdrawal has lowered water levels, induced additional recharge, reduced natural discharge, and increased chloride concentration of ground water along the coast. Cones of depression have developed in the potentiometric surface of the Upper Floridan aquifer in the Savannah, Brunswick, Jesup, and St. Marys, Ga.–Fernandina Beach, Fla., areas (fig. 5). The most extensive cone of depression is centered in the Savannah, Ga., area, and is likely the result of large pumping rates and low transmissivity of the thinning aquifer toward the Beaufort Arch area.

The hydraulic gradient has steepened near these cones of depression and from the recharge area downgradient toward the coast. These steeper gradients have resulted in high ground-water flow velocities and large quantities of water infiltrating into the Upper Floridan aquifer, both vertically and laterally. The cones of depression have "captured" ground-water flow, which prior to development, may have discharged offshore. In addition, diffuse upward leakage of water from the Upper Floridan aquifer into overlying units, streams, and wetlands may have decreased or ceased, and wells no longer flow at land surface (fig. 4B).



EXPLANATION

Gulf Trough—Approximately located (Applied Coastal Research Laboratory, 2002)

100 **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells during May 1–26, 1998. Hachures indicate depression. Contour interval 10 and 50 feet. Datum is NAVD 88

Figure 5. Potentiometric surface of the Upper Floridan aquifer, May 1998 (modified from Peck and others, 1999).

Data from offshore test wells drilled during the early 1980s at Port Royal Sound, off Hilton Head Island, indicated that saltwater having a chloride concentration exceeding 250 milligrams per liter (mg/L) was present within a few thousand feet of the shoreline, with some onshore wells containing water of elevated chloride concentration near the coastline in the Hilton Head Island area. This saltwater appears to enter the aquifer through breaches in the overlying Upper Floridan aquifer confining unit and probably does not represent the steady-state freshwater-saltwater interface wedge. Test wells drilled during the late 1970s in the Upper Floridan aquifer 60–70 miles (mi) offshore of Jacksonville, Fla., indicate that the freshwater-saltwater interface occurs far offshore in the southern part of the coastal area (Johnston and others, 1982).

Recharge and Discharge

Recharge to the hydrologic system is from rainfall, which varies spatially from an average of about 47 to 53 in/yr based on mean-annual precipitation for the 30-year period 1971–2000 (Priest, 2004). Rainfall is greatest in the southern part of the area and least in the northern part of the area (fig. 6). Most of the recharge is discharged from shallow, local flow systems into small streams or is lost as evapotranspiration. A small percentage of recharge infiltrates through clayey confining units and enters the deep, confined regional flow system. In the regional flow system, some water discharges to major streams and wetlands and some flows southward, discharging to the Atlantic Ocean.

Estimates of mean-annual ground-water discharge to streams (baseflow) determined using hydrograph-separation methods are considered to approximate a large percentage of the long-term average recharge to the ground-water flow system (Clarke and West, 1998). Priest (2004) used hydrograph-separation techniques to estimate average annual baseflow during 1971–2001 for 14 streamgaging sites in coastal Georgia (fig. 6). Estimated baseflow at the 14 sites ranged from 4.4 in/yr along the Little Satilla River to 10 in/yr along the Altamaha River.

A portion of estimated long-term average recharge, based on hydrograph separation, flows into and out of the shallow, unconfined aquifer system, allowing only a fraction to recharge the regional flow system. Thus, the estimated baseflow values are likely substantially larger than recharge to the regional flow system and may be considered to be an upper limit to regional recharge simulated by the model. Drought estimates of baseflow reported by Priest (2004) range from 0 to 2.4 in/yr and may represent a more reasonable estimate of recharge to the regional aquifer system.

Williamson and others (1990) estimated recharge to the regional ground-water flow system to be generally less than 3 in/yr for 1980 conditions in the easternmost Gulf Coast Coastal Plain region. This area overlaps the westernmost part of the southeastern Atlantic Coastal Plain in Alabama. Although this area does not coincide with the study area for this report, it is proximal to it and has similar topographic, climatic, and hydrogeologic characteristics that would suggest that regional recharge rates in the coastal Georgia study area may be similar to those estimated by Williamson and others (1990).

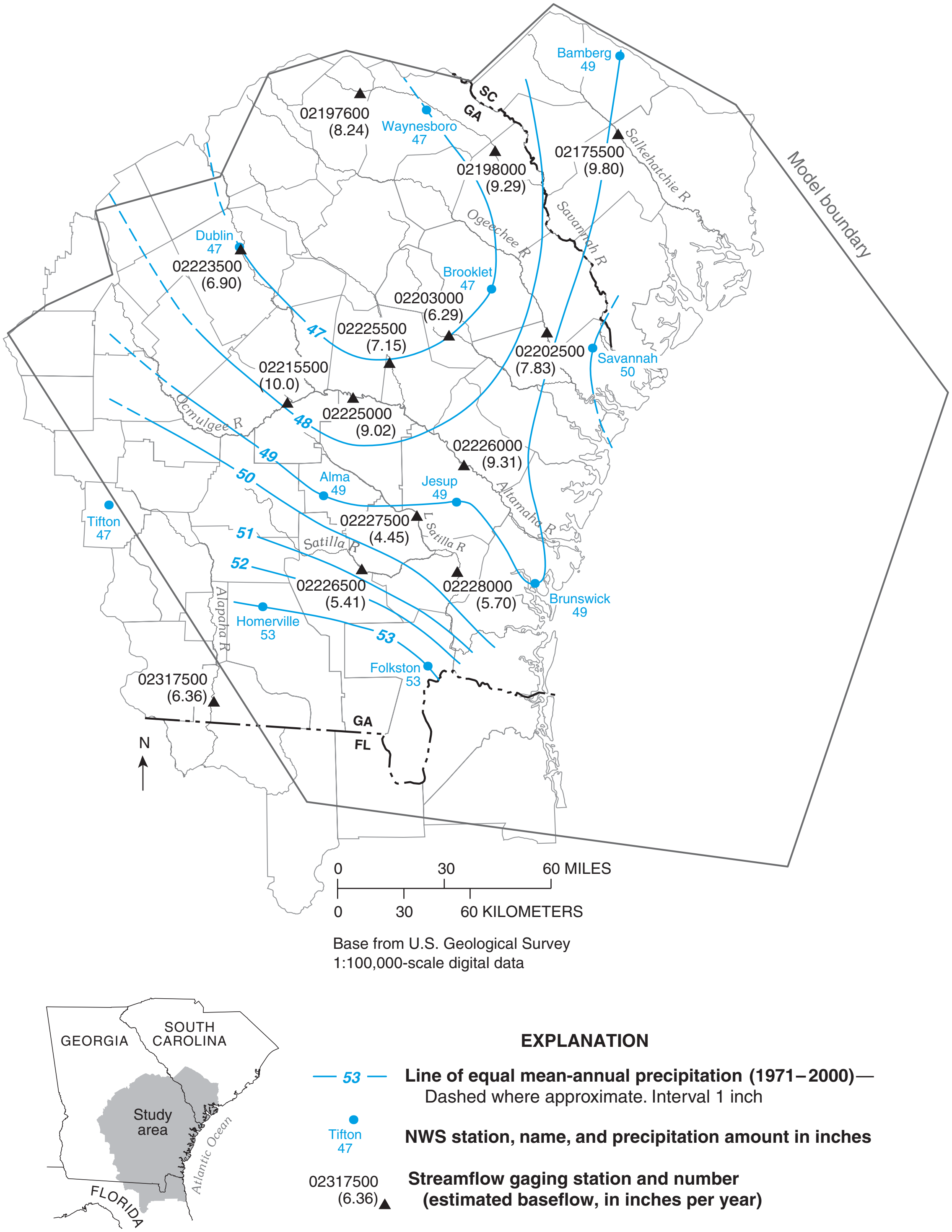


Figure 6. Mean-annual precipitation for selected National Weather Service (NWS) stations and mean-annual baseflow computed using hydrograph-separation analysis in the model area, 1971–2000 (modified from Priest, 2004).

Ground-Water Pumpage

The locations of ground-water pumping centers and quantities of water withdrawn from these centers may affect substantially ground-water levels in the study area. Changes in pumping rates and the addition of new pumping centers may alter the configuration of potentiometric surfaces, reverse ground-water flow directions, and increase seasonal and long-term water-level fluctuations in the aquifers.

County aggregate and site-specific data were used to estimate average annual pumpage for 1980 and 2000 using procedures described by Taylor and others (2003). County aggregate pumping data for Florida are from Marella (2004), and for Georgia are from Fanning (2003) and Pierce and others (1982). W.J. Stringfield provided South Carolina county aggregate data (U.S. Geological Survey, written commun., 2002). J.L. Fanning provided site-specific data for Georgia (U.S. Geological Survey, written commun., 2002). P. Bristol provided site-specific data for South Carolina (South Carolina Department of Health and Environmental Control, written commun., 2003). Site-specific pumping estimates for Florida are from Sepúlveda (2002).

Pumping distribution along the Georgia coastal area has varied with time. Prior to the 1950s, ground-water withdrawal was limited to scattered pumping centers near major towns such as Savannah, Ga. As major industries developed and local populations increased in coastal Georgia cities, pumpage in the study area increased substantially.

The Upper and Lower Floridan aquifers provide the largest amount of ground water in the study area, with an average total withdrawal during 2000 of 682 and 133 million gallons per day (Mgal/d), respectively. Pumping from the Upper and Lower Floridan aquifers during 1980–2000 is summarized in tables 1 and 2, respectively, and shown in figure 7. Water use from the Brunswick aquifer system is considerably less than from the Upper and Lower Floridan aquifers (probably less than 1 Mgal/d); specific data for this unit, however, are not available during this period.

Average daily pumpage from the Upper Floridan aquifer and its updip equivalents during 2000 exceeded 10 Mgal/d in Duval and Nassau Counties, Fla.; in Beaufort County, S.C.; and in Burke, Camden, Chatham, Coffee, Dooly, Glynn, Jefferson, Liberty, Pulaski, Screven, Washington, Wayne, and Wilcox Counties, Ga. (table 1). The largest withdrawals from the Upper Floridan aquifer were in Chatham (68 Mgal/d), Glynn (61 Mgal/d), and Wayne (63 Mgal/d) Counties, Ga. In the Lower Floridan aquifer and its updip equivalents, average daily pumpage during 2000 exceeded 1 Mgal/d in Duval County, Fla.; and in Burke, Chatham, Coffee, Crisp, Dooly, Jefferson, Laurens, Pulaski, Screven, Washington, and Wilcox Counties, Ga. (table 2). The largest withdrawal from the Lower Floridan aquifer was in Duval County, Fla., where pumpage exceeded 95 Mgal/d during 2000 (table 2).

During 1980–2000, total pumpage from the Upper Floridan aquifer increased by 17 percent, from 583 Mgal/d during 1980 to a peak of 682 Mgal/d during 2000 (table 1, fig. 7). In the Lower Floridan aquifer, withdrawal increased by 14 percent from a low of 117 Mgal/d during 1980 to a high of 133 Mgal/d during 2000 (table 2; fig. 7).

Table 1. Estimated ground-water pumpage from the Upper Floridan aquifer in the coastal area of Georgia and adjacent parts of South Carolina and Florida, 1980–2000.
[do., ditto]

State	County	Pumpage, in million gallons per day					
		1980	1985	1990	1995	1997	2000
Florida	Baker	1.72	2.88	3.68	2.11	2.11	2.11
do.	Columbia	3.05	4.79	5.07	6.92	6.57	6.04
do.	Duval	53.96	47.44	41.91	43.91	44.83	44.40
do.	Hamilton	0.10	0.30	0.44	0.44	0.46	0.49
do.	Nassau	44.09	46.76	49.72	46.66	50.19	49.38
Georgia	Appling	5.71	2.60	2.10	2.38	2.47	4.17
do.	Atkinson	1.89	1.50	0.58	1.58	1.58	2.91
do.	Bacon	2.63	2.28	2.11	2.47	2.21	4.04
do.	Ben Hill	3.71	4.92	3.34	10.97	10.98	7.57
do.	Berrien	2.43	3.26	2.80	4.65	4.66	5.33
do.	Bleckley	5.59	4.28	3.29	2.35	2.35	6.66
do.	Brantley	1.46	1.63	1.83	1.90	1.94	1.30
do.	Bryan	0.67	0.87	1.03	1.06	1.70	1.60
do.	Bulloch	3.75	2.71	5.87	7.83	5.05	5.70
do.	Burke	10.30	6.34	5.82	8.16	8.22	22.34
do.	Camden	37.12	42.98	45.74	47.15	45.83	50.55
do.	Candler	1.83	2.57	1.64	1.67	1.70	2.79
do.	Charlton	6.50	1.22	1.38	1.45	0.95	1.25
do.	Chatham	79.75	78.98	85.54	75.84	70.66	68.15
do.	Clinch	0.85	0.72	0.65	1.03	1.04	1.44

Table 1. Estimated ground-water pumpage from the Upper Floridan aquifer in the coastal area of Georgia and adjacent parts of South Carolina and Florida, 1980–2000.—Continued

[do., ditto]

State	County	Pumpage, in million gallons per day					
		1980	1985	1990	1995	1997	2000
Georgia	Coffee	12.59	7.98	5.60	7.59	7.52	15.23
do.	Crisp	3.16	3.45	5.31	10.28	10.24	8.56
do.	Dodge	7.02	3.95	2.40	4.28	4.28	3.96
do.	Dooly	6.30	9.45	3.18	9.25	9.25	18.68
do.	Echols	0.17	0.18	0.25	1.04	1.77	2.88
do.	Effingham	2.26	2.06	4.98	5.98	4.42	4.62
do.	Emanuel	7.34	5.30	4.18	4.51	4.53	4.22
do.	Evans	0.38	0.31	0.38	0.49	0.46	0.70
do.	Glascock	0.73	0.72	0.99	1.34	1.35	1.36
do.	Glynn	95.40	77.84	82.02	63.68	61.61	61.14
do.	Irwin	1.96	1.86	2.15	5.75	5.75	6.25
do.	Jeff Davis	5.11	5.80	4.77	3.09	3.09	3.84
do.	Jefferson	4.97	9.90	8.85	7.76	7.62	12.06
do.	Jenkins	2.74	2.65	2.45	3.19	3.13	4.03
do.	Johnson	1.37	1.81	0.92	1.83	1.83	2.12
do.	Lanier	3.07	2.92	1.69	2.02	2.02	1.97
do.	Laurens	4.32	4.15	4.23	5.78	5.81	7.94
do.	Liberty	13.62	14.58	17.97	15.91	16.10	15.69
do.	Long	0.29	0.24	0.23	0.27	0.27	0.69
do.	McIntosh	0.70	1.03	0.76	1.07	1.09	0.85
do.	Montgomery	0.89	1.51	0.94	2.40	2.40	1.61
do.	Pierce	2.64	2.03	1.80	3.24	3.42	6.22
do.	Pulaski	6.94	8.27	6.87	8.59	8.53	11.46
do.	Screven	7.90	7.19	7.87	6.36	6.93	16.24
do.	Tattnall	1.56	1.89	1.77	3.53	3.59	3.66
do.	Telfair	3.28	4.62	3.30	6.33	6.33	4.00
do.	Tift	1.89	2.19	2.61	3.95	3.80	3.57
do.	Toombs	2.87	3.91	3.61	3.65	4.17	6.30
do.	Treutlen	0.49	0.54	0.79	1.31	1.31	1.10
do.	Turner	1.02	1.00	0.93	2.91	2.92	2.57
do.	Ware	6.25	7.25	6.20	5.51	5.97	8.45
do.	Washington	10.01	12.24	13.02	14.39	14.88	16.01
do.	Wayne	74.54	69.80	69.27	64.89	63.59	63.47
do.	Wheeler	1.60	0.83	0.61	2.22	2.22	1.07
do.	Wilcox	4.06	9.84	5.40	8.43	8.43	14.74
South Carolina	Allendale	7.84	7.84	8.31	9.44	9.85	9.59
do.	Bamberg	1.99	1.99	2.09	2.52	4.04	6.32
do.	Barnwell	1.15	1.15	3.32	2.91	4.90	7.50
do.	Beaufort	0.85	20.80	17.48	19.56	33.58	21.44
do.	Colleton	0.00	0.00	0.00	0.00	0.00	0.00
do.	Hampton	3.21	3.21	3.95	4.32	5.99	8.63
do.	Jasper	1.25	1.16	1.97	1.31	2.13	3.34
	Total	**582.81**	**584.49**	**579.96**	**603.42**	**616.62**	**682.31**

Data sources: County aggregate and site-specific data were used to estimate average annual pumpage for 1980 and 2000 using procedures described by Taylor and others (2003). County aggregate pumping data for Florida are from Marella (2004), and for Georgia are from Fanning (2003) and Pierce and others (1982). W.J. Stringfield (U.S. Geological Survey, written commun., 2002) provided South Carolina county aggregate data. J.L. Fanning (U.S. Geological Survey, written commun., 2002) provided site-specific data for Georgia. Paul Bristol (South Carolina Department of Health and Environmental Control, written commun., 2003) provided site-specific data for South Carolina. Site-specific pumping for Florida is estimated from Sepúlveda (2002).

Table 2. Estimated ground-water pumpage from the Lower Floridan aquifer in the coastal area of Georgia and adjacent parts of South Carolina and Florida, 1980–2000.
[do., ditto]

State	County	Pumpage, in million gallons per day					
		1980	1985	1990	1995	1997	2000
Florida	Baker	0.26	0.43	0.55	0.32	0.32	0.32
do.	Columbia	0.00	0.00	0.00	0.00	0.00	0.00
do.	Duval	92.52	99.13	100.46	95.01	99.48	95.98
do.	Hamilton	0.00	0.00	0.00	0.00	0.00	0.00
do.	Nassau	2.51	2.16	2.00	2.09	2.18	2.21
Georgia	Appling	0.00	0.00	0.00	0.00	0.00	0.00
do.	Atkinson	0.00	0.00	0.00	0.00	0.00	0.00
do.	Bacon	0.00	0.00	0.00	0.00	0.00	0.00
do.	Ben Hill	0.21	0.39	0.38	1.30	1.30	0.59
do.	Berrien	0.41	0.53	0.45	0.67	0.67	0.77
do.	Bleckley	0.87	0.63	0.41	0.40	0.40	1.00
do.	Brantley	0.00	0.00	0.00	0.00	0.00	0.00
do.	Bryan	0.00	0.00	0.00	0.00	0.00	0.00
do.	Bulloch	0.23	0.20	0.16	0.31	0.32	0.32
do.	Burke	1.60	0.92	0.83	1.26	1.27	3.24
do.	Camden	0.00	0.00	0.00	0.00	0.00	0.00
do.	Candler	0.26	0.34	0.17	0.19	0.19	0.37
do.	Charlton	0.00	0.00	0.00	0.00	0.00	0.00
do.	Chatham	3.58	3.20	4.13	3.76	3.78	3.23
do.	Clinch	0.00	0.00	0.00	0.00	0.00	0.00
do.	Coffee	1.49	0.78	0.25	0.47	0.53	1.73
do.	Crisp	0.32	0.28	0.78	1.58	1.59	1.30
do.	Dodge	1.01	0.52	0.22	0.46	0.46	0.41
do.	Dooly	0.96	1.46	0.41	1.29	1.29	2.93
do.	Echols	0.00	0.00	0.00	0.00	0.00	0.00
do.	Effingham	0.02	0.01	0.03	0.04	0.03	0.03
do.	Emanuel	0.85	0.68	0.36	0.52	0.52	0.48
do.	Evans	0.05	0.04	0.05	0.06	0.06	0.09
do.	Glascock	0.04	0.02	0.02	0.02	0.02	0.02
do.	Glynn	0.00	0.00	0.00	0.00	0.00	0.00
do.	Irwin	0.25	0.21	0.26	0.87	0.87	0.96
do.	Jeff Davis	0.81	0.89	0.66	0.40	0.40	0.47
do.	Jefferson	0.69	1.44	1.03	0.76	0.97	1.68
do.	Jenkins	0.41	0.37	0.33	0.47	0.46	0.61
do.	Johnson	0.17	0.26	0.12	0.27	0.27	0.32
do.	Lanier	0.00	0.00	0.00	0.00	0.00	0.00
do.	Laurens	0.74	0.62	0.60	0.97	0.95	1.31
do.	Liberty	0.00	0.00	0.00	0.00	0.00	0.00
do.	Long	0.01	0.01	0.01	0.02	0.02	0.07
do.	McIntosh	0.00	0.00	0.00	0.00	0.00	0.00
do.	Montgomery	0.11	0.20	0.10	0.33	0.33	0.19
do.	Pierce	0.00	0.00	0.00	0.00	0.00	0.00
do.	Pulaski	1.11	1.31	1.09	1.31	1.35	1.81
do.	Screven	1.18	1.03	0.40	0.66	0.69	2.32
do.	Tattnall	0.06	0.09	0.08	0.28	0.28	0.15
do.	Telfair	0.48	0.55	0.32	0.83	0.82	0.42
do.	Tift	0.33	0.38	0.46	0.69	0.66	0.62
do.	Toombs	0.24	0.31	0.20	0.27	0.27	0.69

Table 2. Estimated ground-water pumpage from the Lower Floridan aquifer in the coastal area of Georgia and adjacent parts of South Carolina and Florida, 1980–2000.—Continued
[do., ditto]

State	County	Pumpage, in million gallons per day					
		1980	1985	1990	1995	1997	2000
Georgia	Treutlen	0.06	0.05	0.06	0.12	0.12	0.11
do.	Turner	0.17	0.17	0.16	0.50	0.50	0.44
do.	Ware	0.00	0.00	0.00	0.00	0.00	0.00
do.	Washington	1.52	1.89	1.96	2.16	2.04	2.07
do.	Wayne	0.00	0.00	0.00	0.00	0.00	0.00
do.	Wheeler	0.21	0.10	0.06	0.34	0.34	0.14
do.	Wilcox	0.68	1.69	0.90	1.43	1.43	2.53
South Carolina	Allendale	0.00	0.00	0.00	0.00	0.00	0.00
do.	Bamberg	0.00	0.00	0.00	0.00	0.00	0.00
do.	Barnwell	0.00	0.00	0.00	0.00	0.00	0.00
do.	Beaufort	0.00	0.05	0.01	0.01	0.09	0.26
do.	Colleton	0.35	0.55	0.56	0.58	0.47	0.51
do.	Hampton	0.00	0.00	0.00	0.00	0.00	0.00
do.	Jasper	0.01	0.00	0.00	0.00	0.01	0.01
	Total	**116.77**	**123.88**	**121.00**	**123.00**	**127.74**	**132.69**

Data sources: County aggregate and site-specific data were used to estimate average annual pumpage for 1980 and 2000 using procedures described by Taylor and others (2003). County aggregate pumping data for Florida are from Marella (2004), and for Georgia are from Fanning (2003) and Pierce and others (1982). W.J. Stringfield (U.S. Geological Survey, written commun., 2002) provided South Carolina county aggregate data. J.L. Fanning (U.S. Geological Survey, written commun., 2002) provided site-specific data for Georgia. Paul Bristol (South Carolina Department of Health and Environmental Control, written commun., 2003) provided site-specific data for South Carolina. Site-specific pumping for Florida is estimated from Sepúlveda (2002).

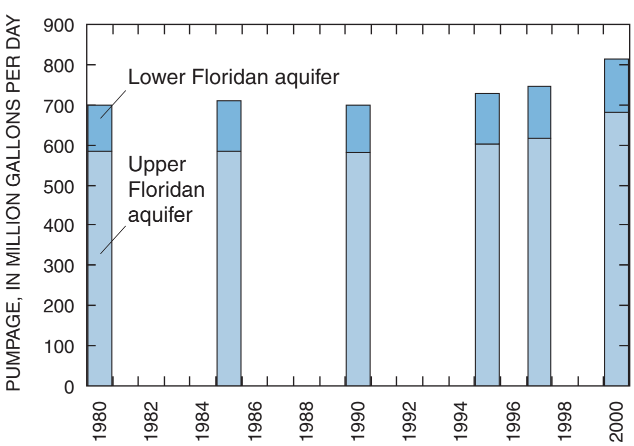


Figure 7. Estimated ground-water pumpage from the Upper and Lower Floridan aquifers, 1980–2000 (see tables 1 and 2 for county totals and data sources).

Ground-Water-Level Trends

Ground-water levels are affected by precipitation, evapotranspiration, and pumpage. Water levels generally are highest in the winter-early spring when precipitation is greatest, evapotranspiration is lowest, and irrigation withdrawals are minimal; water levels are lowest during summer and fall when evapotranspiration and pumpage are greatest. In parts of the study area, water levels may respond to pumpage from an adjacent aquifer. This response is most pronounced in the northern part of the study area and results from greater aquifer interconnection as a result of discontinuous or leaky confining units.

During 1980–2000, water levels showed a combination of rises and declines in response to changing pumping patterns. During this period, total ground-water use increased; however, the distribution of withdrawal changed—decreases exceeding 10 Mgal/d occurred in Chatham and Glynn Counties, and increases exceeding 10 Mgal/d occurred in Burke, Camden, Dooly, and Wilcox Counties, Ga.; and in Beaufort County, S.C. (tables 1 and 2; fig. 7).

To determine water-level trends during 1980–2000, water levels in the Brunswick aquifer system and Upper and Lower Floridan aquifers were compared and differences computed (appendix A; fig. 8). Water-level data for the Brunswick aquifer system are sparse; water levels in one well in Charlton County (30E002) declined 9 ft during 1980–2000 (appendix A, fig. 1A, table A1). In the Upper Floridan aquifer, water levels rose almost 10 ft near the Savannah and from 10 to 20 ft near the Brunswick pumping center, and declined in most of the rest of the study area (fig. 8, appendix A). Water levels also rose near Jesup in Wayne County by more than 10 ft. The largest declines, greater than 20 ft, were in the western part of the area and near the Gulf Trough. These declines correspond to a general increase in pumpage from the Upper Floridan aquifer in these areas. In the Lower Floridan aquifer, water levels in five wells at Brunswick were about the same to 5.2 ft lower during 2000 than during 1980 (appendix A).

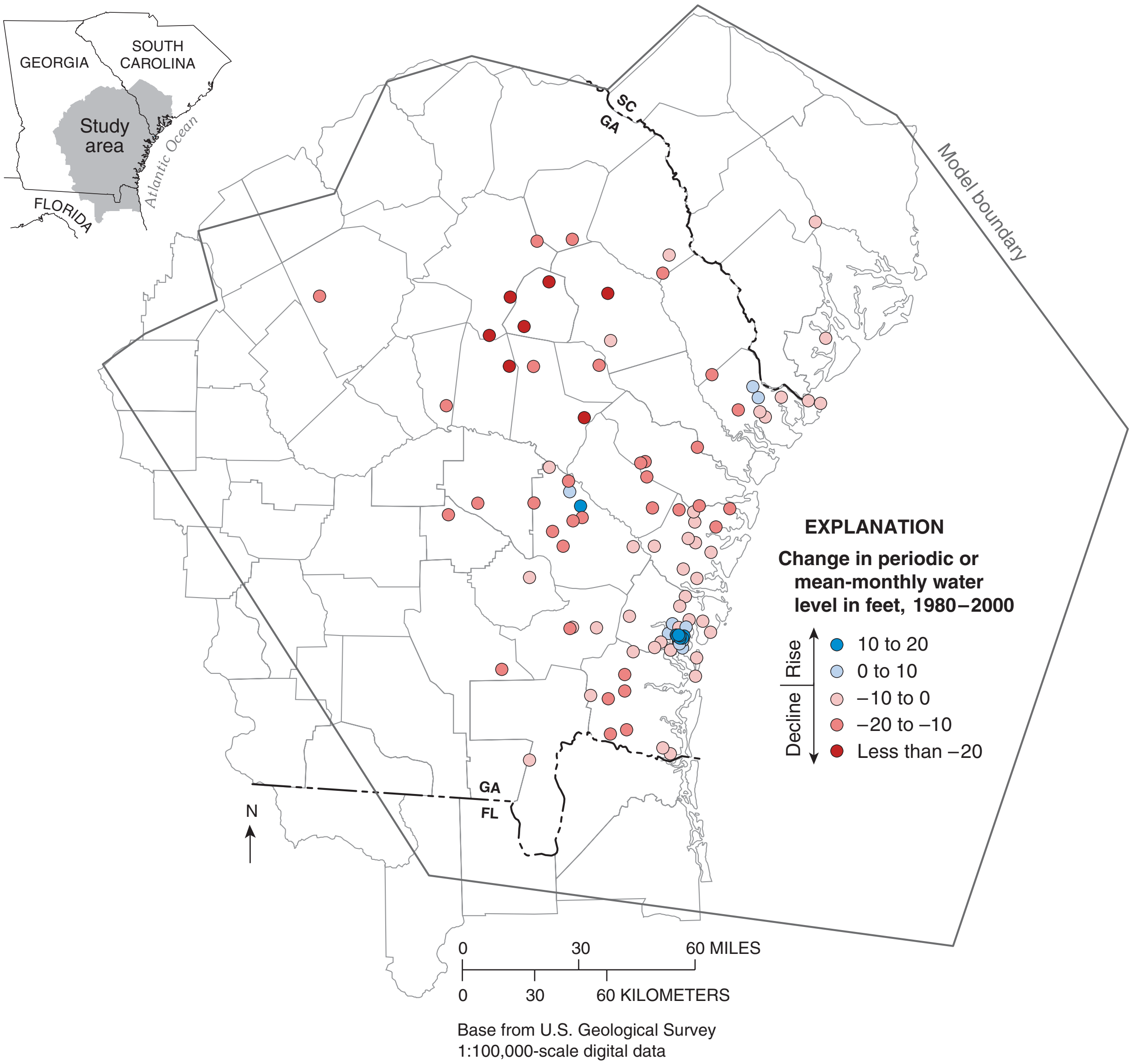


Figure 8. Change in water levels in wells completed in the Upper Floridan aquifer, May 1980–September 2000.

Saltwater Contamination

Saltwater contamination has been documented at Hilton Head Island, S.C., and Brunswick, Ga. (Counts and Donsky, 1963; Gregg and Zimmerman, 1974; Hayes, 1979; Hughes and others, 1989; Krause and Randolph, 1989; Landmeyer and Belval, 1996; Wait, 1965). Sources of chloride contamination are different in the two areas.

Offshore of the Savannah–Hilton Head Island area, the position of the saltwater wedge is uncertain, as is the degree to which the wedge contributes to saltwater intrusion. Near Hilton Head Island, possible sources of saltwater contamination include modern seawater encroachment or remnant ancient seawater as a result of incomplete flushing of the aquifer. The most likely source of contamination is seawater entering the Upper Floridan aquifer in areas where the overlying confining unit is thin or absent, and where hydraulic gradients are favorable for the migration of seawater into the aquifer. Erosion has partially or completely removed the confining unit overlying the Upper Floridan aquifer in the area offshore of Hilton Head Island, in Calibogue Sound, on Pinckney Island, and in the Colleton River (Foyle and others, 2001) exposing the aquifer to seawater or brackish water. Withdrawal of water from the Upper Floridan aquifer in the Savannah area since the late 1800s has resulted in the development of a regional cone of depression on the potentiometric surface that extends from

Savannah northeastward across Hilton Head Island. This situation, combined with pumping on Hilton Head Island, has resulted in reversal of the normally seaward hydraulic gradients. These conditions may allow seawater to enter the aquifer and flow laterally downgradient toward pumping centers. Specific-conductance data for the Upper Floridan aquifer in this area indicate that saltwater is moving southward from points on the northern end of Hilton Head Island, Pinckney Island, and the Colleton River (Camille Ransom III, South Carolina Department of Health and Environmental Control, oral commun., 2004).

Beneath downtown Brunswick, the occurrence of saltwater in the Upper Floridan aquifer has been known for several decades (Wait, 1965). Water at about 2,400 ft below land surface in the lower part of the Lower Floridan aquifer (Fernandina permeable zone) has chloride concentrations greater than 30,000 mg/L, indicating that this is connate water and a likely source of saltwater in the Upper Floridan aquifer at Brunswick (Krause and Randolph, 1989). The presence of steeply-dipping fractures and zones of abundant solution features in the Floridan aquifer system in one of these wells (Maslia and Prowell, 1990) suggests that saltwater is transported vertically upward into the Upper Floridan aquifer from depth. Isochlor maps indicate that there may be as many as four points of saltwater intrusion in the Brunswick area (Jones, 2001); the geometry and distribution of possible conduits, however, are poorly defined in the area.

In previous conceptual models of regional offshore ground-water chemistry, an offshore saltwater wedge has been inferred to extend from the coastline near Port Royal Sound, S.C., to 85 mi offshore of the Georgia–Florida border (Krause and Clarke, 2001). The configuration of this feature is based on sparse offshore water-chemistry data, an inferred extension of the onshore chloride distribution (Sprinkle, 1982), and application of the Ghyben-Herzberg principle (Reilly and Goodman, 1985). Data collected offshore of the Georgia-Florida border indicate that if such a feature exists, then it is relatively far offshore (Johnston and others, 1982), and likely does not contribute to saltwater intrusion in the southernmost coastal counties of Georgia or in northeastern Florida.

Simulation of Ground-Water Flow

A single-density, digital ground-water flow model was developed for the coastal area of Georgia, Florida, South Carolina, and adjacent offshore area using the USGS finite-difference code MODFLOW-2000 (Harbaugh and others, 2000). The model was used to characterize the confined ground-water flow system, simulate ground-water management scenarios, and create a framework for local-scale solute-transport models. A three-dimensional approach was used that allows for simulation of flow in both aquifers and confining units and incorporates vertical and horizontal hydraulic properties of hydrogeologic units. This approach allows the model to be more directly and consistently translated into related variable-density solute-transport models, or amended for other purposes. Available data are limited to horizontal properties in aquifers and vertical properties in confining units, and no conclusions regarding the anisotropy of units can be made. Thus, for this study, hydraulic properties within each layer are assumed to be isotropic.

The model was designed to simulate major components of the confined and regional ground-water flow system, as depicted on the schematic diagram shown in figure 4, specifically to characterize flow in the Brunswick and Floridan aquifer systems. Recharge to, and discharge from, the confined portion of the surficial aquifer system is applied using a general-head boundary throughout the study area; recharge to regional confined aquifers is applied using a general-head boundary at outcrop areas (mostly north of the Gulf Trough; figs. 1 and 3), or from downward leakage through overlying semiconfining units. Because the extent and subsurface geometry of the Brunswick aquifer system is poorly understood—the aquifer system is not known to crop out—simulated recharge is restricted to leakage from the overlying surficial aquifer system or underlying Upper Floridan aquifer. Natural discharge from the Brunswick aquifer system is through upward leakage into the surficial aquifer system and streams. Because little is known about regional ground-water flow in the Lower Floridan aquifer, it is assumed that the regional flow characteristics of the Lower Floridan aquifer are similar to those of the Upper Floridan aquifer. Thus, simulated lateral boundary conditions for the Upper and Lower Floridan aquifers are identical. Regional discharge is simulated as diffuse leakage through confining units in downdip areas and offshore, and along a southern specified-head boundary. Model design, including layering, hydraulic properties, and boundary conditions are described in greater detail in subsequent sections of this report.

The model was calibrated to simulate steady-state flow and mean-annual conditions for predevelopment (pre–1900) and the years 1980 and 2000. The years 1980 and 2000 were chosen because of the relative abundance and distribution of ground-water-level and pumpage data for simulated aquifers. Pumping data are less reliable for the year 1980 than 2000, but water-level measurement coverage is better, particularly in the updip (north of Gulf Trough) area. Because predevelopment data are lacking, the model was not calibrated to match heads at a specific well. Instead, simulated water levels were qualitatively compared to a map showing the estimated potentiometric surface of the Upper Floridan aquifer during predevelopment (Johnston and others, 1980).

Steady-state simulation was performed because the purpose of the model is to simulate the ultimate effect on the flow system resulting from changes in mean-annual pumping, and not to determine how quickly the system responds to these changes. To determine whether time-dependent processes would affect overall changes in water levels due to pumping within the temporal scope of the model (mean-annual conditions), the model’s transient response was tested (appendix B). Results showed that relatively extreme changes in stress are required to affect a transient response; and for the purpose of this model, the steady-state approximation is appropriate.

Spatial Discretization

The finite-difference technique used by MODFLOW-2000 (Harbaugh and others, 2000) requires that the simulated area be divided into discrete blocks or cells. The model encompasses 42,155 mi^2 and is constructed with 119 rows and 108 columns, of which a maximum of 10,417 cells are active per layer (fig. 9). The flow system is horizontally discretized using irregular grid spacing, with cell sizes ranging from approximately 4,000 x 5,000 ft (0.7 mi^2) to 16,500 x 16,500 ft (9.8 mi^2). A greater grid density at Savannah and Brunswick was chosen to enable simulation of steeper head gradients near cones of depression and to facilitate linkage with smaller-scale solute-transport models being developed in those areas. Graphical grid-generation tools from the graphical user interface ARGUS™ enabled visual adjustment of grid position and density. The model is oriented such that columns covering Savannah and Brunswick are aligned to enable greater grid density in those areas. Columns are oriented approximately parallel to the shoreline and the continental shelf escarpment to facilitate application of the southeastern (offshore) boundary.

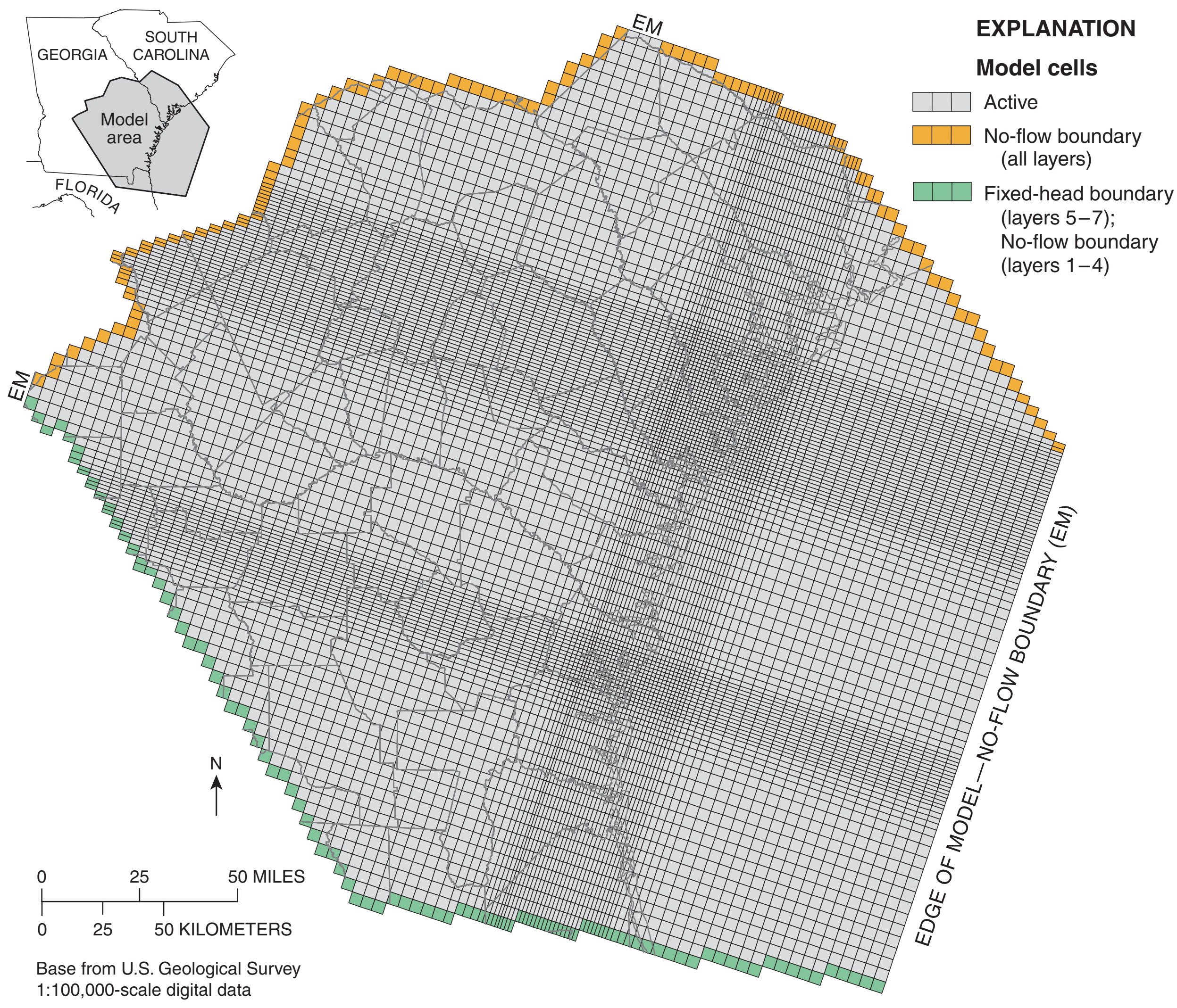


Figure 9. Model grid and lateral boundary conditions.

Model Layering

The model was vertically discretized with one layer of model cells per hydrogeologic layer, and variable thickness depending on the thickness of the layer. There are seven actively simulated aquifer and confining unit layers in the model (figs. 2 and 10). The aquifers include:

- the confined upper and lower water-bearing zones of the surficial aquifer system grouped together as layer 1,
- the upper and lower Brunswick aquifers grouped together to form the Brunswick aquifer system (layer 3),
- the Upper Floridan aquifer (layer 5), and
- the Lower Floridan aquifer (layer 7).

In addition, confining units between these units are actively simulated (layers 2, 4, and 6). The Fernandina permeable zone of the Lower Floridan aquifer (layer 7) is not simulated as a distinct zone in the model, because of uncertainty about its extent, hydraulic properties, and lack of data with which to calibrate those properties.

The surficial aquifer system is divided into two zones—a water-table zone, which serves as general-head boundary; and the underlying confined upper and lower water-bearing zones, which are grouped together to form layer 1 of the model. Although the surficial aquifer system is actively simulated, the spatial discretization of the model is insufficient to simulate accurately unconfined flow-system characteristics. Simulated flow in the confined surficial aquifer system is used primarily as a means to move water into and out of the deeper confined aquifers, and not to provide detailed characterization of flow in the unit.

Maps showing the altitude of the top of each layer were contoured and digitized based on published literature (Brooks and others, 1985; Charm and others, 1969; Clarke and others, 1990; Hathaway and others, 1981; Kellam and Gorday, 1990; Miller, 1986; Scholle, 1979; Steele and McDowell, 1998) and unpublished data (A. Foyle, Georgia Southern University, Applied Coastal Research Laboratory, written commun., 2002; J. Gellici, South Carolina Department of Natural Resources, written commun., 2002; H. Gill, Jordan Jones and Goulding, written commun., 2001), and modified using new well information collected as part of the CSSI (Falls and others, 2001; Foyle and others, 2001). The altitude of the top of each layer was adjusted where necessary and justifiable in order to ensure that the surfaces did not intersect one another.

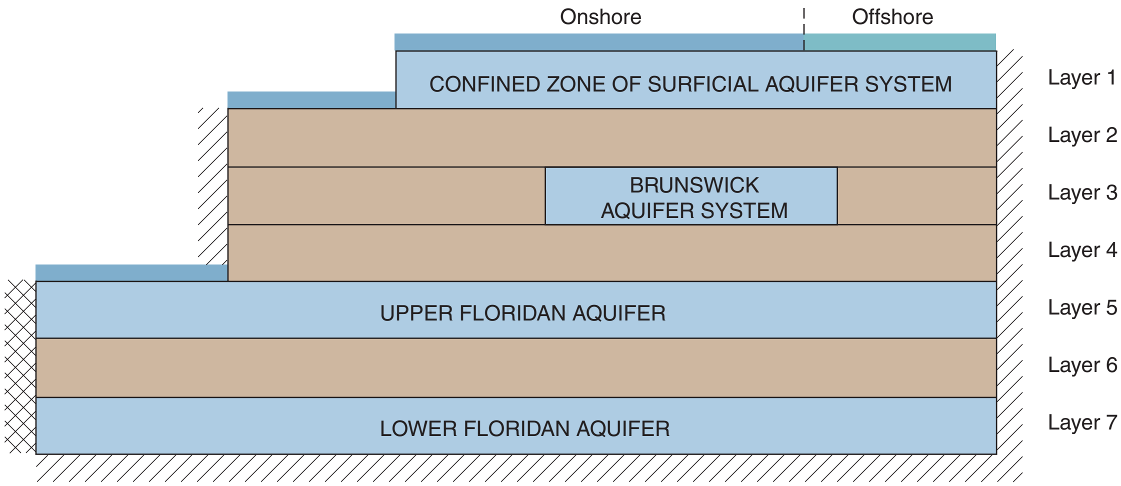
The MODFLOW-2000 (Harbaugh and others, 2000) code requires that model layers are continuous across the entire model area. A schematic diagram (fig. 10) and hydrogeologic sections (fig. 11) along the approximate strike and dip of geologic formations illustrate how model layers are discretized. To simulate the "pinchout" or absence of the Brunswick aquifer system (layer 3) in parts of the study area, layer 3 was assigned a nominal thickness and hydraulic properties representative of the average of adjacent layers 2 and 4 (figs. 10 and 11). In areas where layer 3 is absent, the Upper Floridan aquifer (layer 5) is separated from the surficial aquifer system by a composite confining unit consisting of layers 2, 3, and 4.

Hydraulic Properties

Hydraulic-property input into the model consists of vertical and horizontal hydraulic conductivity for all layers. Initial hydraulic conductivities were assigned on the basis of available field data including aquifer test, specific-capacity, and laboratory permeability data (Clarke and others, 2004; Golder Associates, Inc., 2003). In addition, information on potentiometric-head gradients and geologic setting (lithologic descriptions, depositional environment, and structural features) was used to estimate an approximate distribution of hydraulic conductivity (fig. 12). Available data are limited to horizontal properties in aquifers and vertical properties in confining units, and no relation can be established regarding the anisotropy of units. Thus, for this study, hydraulic properties within each layer are assumed isotropic.

For aquifer layers (1, 3, 5, and 7) data used as initial hydraulic conductivities were derived mostly from aquifer-test transmissivity values (Clarke and others, 2004) and then divided by aquifer thickness to determine hydraulic conductivity. For confining units (layers 2, 3, 4, and 6), initial hydraulic conductivities were derived largely from laboratory permeability data. In layers 1, 6, and 7, the conductivity of each was assumed to be homogenous because of limited data for the surficial aquifer system, the Lower Floridan confining unit, and the Lower Floridan aquifer, respectively. The hydraulic conductivity for layers 2, 3, 4 and 5 were distributed into zones, as shown in figure 12. During calibration, values were modified where appropriate and supported by hydrogeologic information to improve model results. Final calibrated hydraulic conductivity values for each layer are shown in figure 12; ranges of reported and calibrated transmissivity for aquifers and vertical hydraulic conductivity for confining units are shown in table 3. Reported transmissivity values vary by several orders of magnitude even across small areas (Clarke and others, 2004), allowing some flexibility in calibrated values.

The range of calibrated transmissivity of aquifer units varies generally within one order of magnitude of reported ranges of values. For confining units, reported vertical hydraulic conductivity is limited to core permeameter data that are sparse and poorly distributed in the study area. In addition, these data are representative of local conditions where the core was recovered, and do not represent a large portion of the unit, and typically represent matrix permeability (not secondary). For these reasons, adjustments to the vertical hydraulic conductivity arrays during calibration were allowed a considerably greater degree of variation than the reported ranges and may be several orders of magnitude different that reported ranges.



EXPLANATION

Aquifer

Confining unit

General-head boundary—Represents water table or equivalent freshwater head that provides flow to underlying confined aquifers. Flow is restricted by a conductance term, which is equivalent to hydraulic conductivity

Onshore area—Water-table head

Offshore area—Equivalent freshwater head of overlying saltwater column

No-flow boundary

No-flow or fixed-head boundary

Figure 10. Schematic diagram showing model layers and boundary conditions.

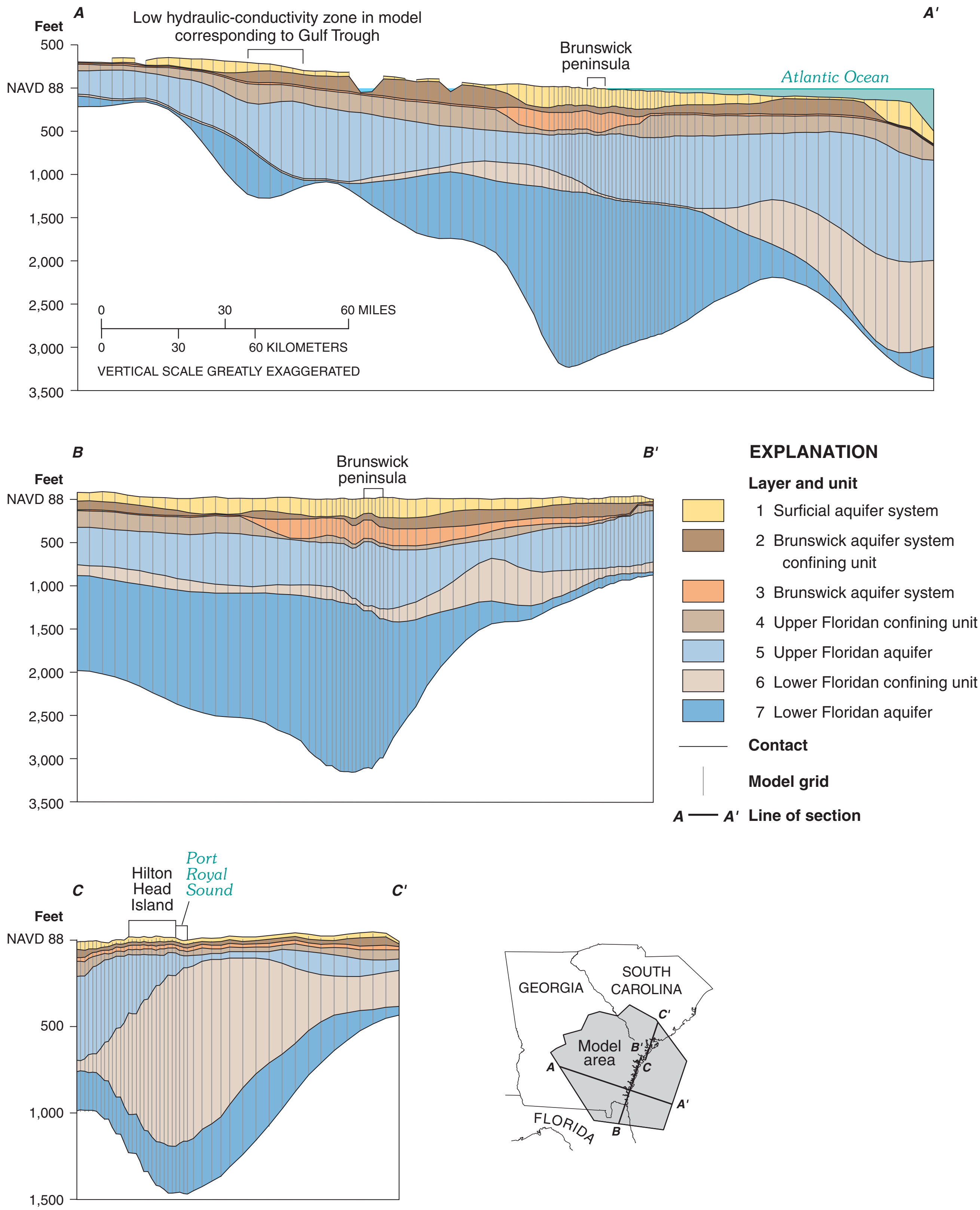
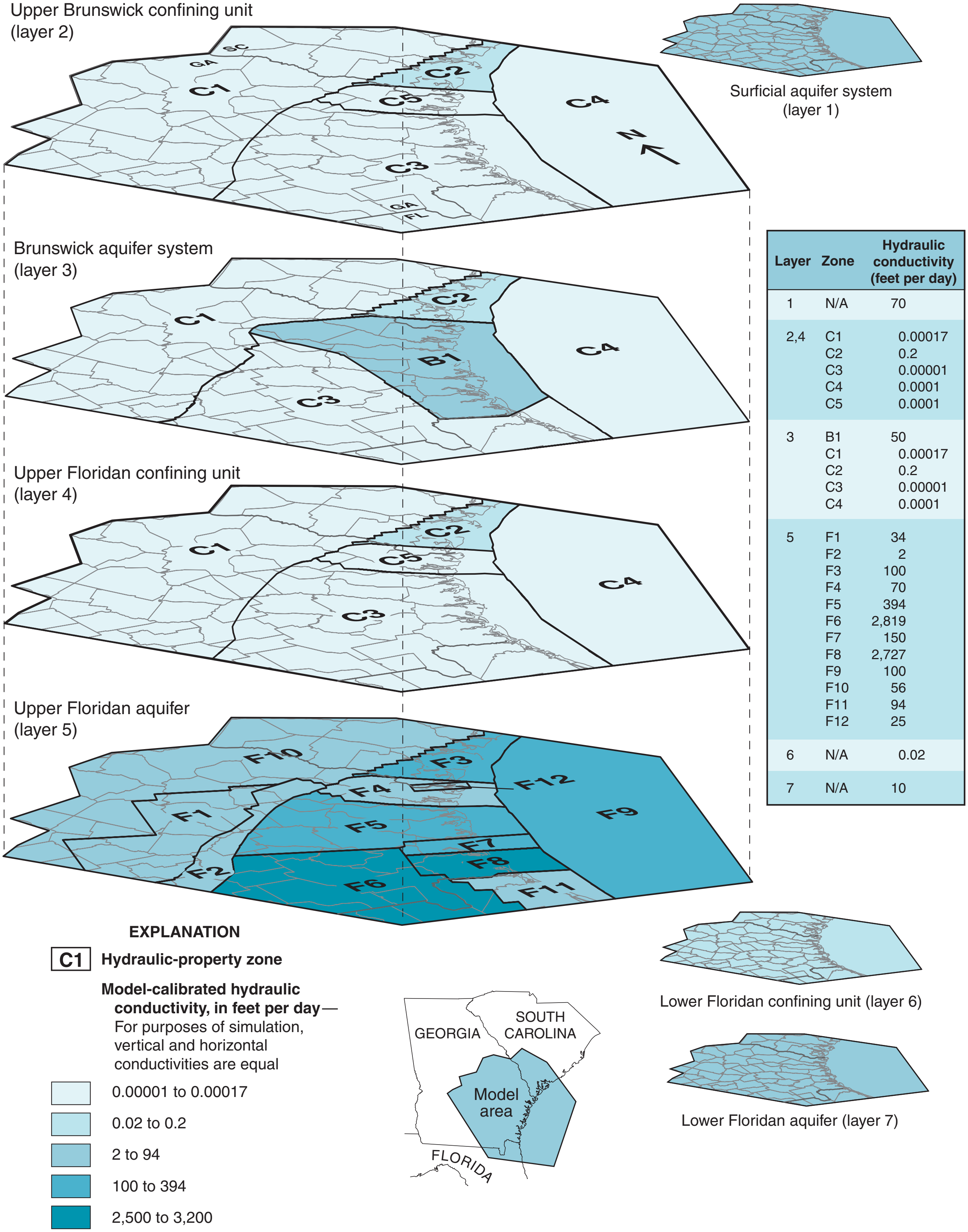


Figure 11. Hydrogeologic sections showing vertical discretization of hydrogeologic units simulated by the model.



Layer	Zone	Hydraulic conductivity (feet per day)
1	N/A	70
2,4	C1	0.00017
	C2	0.2
	C3	0.00001
	C4	0.0001
	C5	0.0001
3	B1	50
	C1	0.00017
	C2	0.2
	C3	0.00001
	C4	0.0001
5	F1	34
	F2	2
	F3	100
	F4	70
	F5	394
	F6	2,819
	F7	150
	F8	2,727
	F9	100
	F10	56
	F11	94
	F12	25
6	N/A	0.02
7	N/A	10

Figure 12. Schematic diagram showing simulated hydraulic-property zones by model layer.

Table 3. Reported and simulated ranges of aquifer transmissivity and confining unit vertical hydraulic conductivity.

[Yellow, Golder Associates, Inc., 2003; Clarke, 2003; blue, Clarke and others, 2004; brown, Clarke and others, 1990]

Unit	Layer	Transmissivity, in feet squared per day			
		Reported		Simulated	
		Minimum	Maximum	Minimum	Maximum
Surficial aquifer system	1	540	14,000	350	19,100
Brunswick aquifer system	3	10	4,700	250	13,350
Upper Floridan aquifer	5	530	600,000	60	3,020,000
Lower Floridan aquifer	7	170	43,000	50	28,900
		Vertical hydraulic conductivity, in feet per day			
Unit	**Layer**	**Report**		**Simulated**	
		Minimum	**Maximum**	**Minimum**	**Maximum**
Upper Brunswick confining unit	2	0.000053	0.00013	0.00017	0.2
Upper Floridan confining unit	4	0.000232	3.01896	0.00017	0.2
Lower Floridan confining unit	6	0.000004	0.16	0.02	0.02

Layer 2 is the confining unit overlying the Brunswick aquifer system and is represented by five zones. The Brunswick aquifer system comprises one of five zones in layer 3, zone B1; and zones C1 through C4 represent the lower permeability confining units beyond the aquifer system extent. With the exception of zone B1 in layer 3, layers 2, 3, and 4 are zoned identically such that the three layers represent and function as a single confining unit separating the surficial aquifer system (layer 1) from the Upper Floridan aquifer (layer 5). Although there are few data to define zones or calibrate these confining unit zones specifically, model results indicate that heads in the Upper Floridan aquifer (layer 5) were sensitive to the spatial distribution of hydraulic conductivity in the overlying confining units. Zones in these layers were used to regulate distribution of recharge to the Upper Floridan aquifer (layer 5), which resulted in a better calibration of simulated head. In zone C2, in the coastal zone of South Carolina, higher hydraulic conductivity was assigned to layer 2 to enable recharge of water into the Upper Floridan aquifer near mounds or highs on the potentiometric-surface map of the Upper Floridan aquifer (Ransom and White, 1999).

Hydraulic properties for the Upper Floridan aquifer (layer 5) were designated based on an abundance of published data (Clarke and others, 2004) and are divided into 12 zones (fig. 12). Zones F1 and F10 represent updip clastic equivalent units of the Upper Floridan aquifer in the northern Coastal Plain (north of Gulf Trough), and generally are assigned lower hydraulic conductivity than coastal zones (zones F3–F9, F11), which represent more carbonate lithologies. Zone F2 represents the low-permeability Gulf Trough feature, as indicated by published data (Clarke and others, 2004) and by a steepening of contours on the Upper Floridan aquifer potentiometric surface (Peck and others, 1999).

Zones F5 through F8 and F11 represent highly transmissive parts of the Upper Floridan aquifer either in or adjacent to the Southeast Georgia Embayment. Data in the area of zone F6 are sparse; a low hydraulic gradient, however, is indicated on the Upper Floridan aquifer potentiometric surface (Peck and others, 1999), indicating a high permeability. Zone F7 has a relatively lower permeability than the adjacent zone F8 and corresponds to an observed change in the configuration of the Upper Floridan potentiometric surface referred to as the Satilla Line. Hydraulic conductivity in zone F11 was assigned a lower value than surrounding areas to account for a pronounced hydraulic gradient and cone of depression caused by years of heavy pumping in the St. Marys–Fernandina Beach area (Peck and others, 1999). Zone F5 represents a transitional area between the Southeast Georgia Embayment and the Beaufort Arch, where the potentiometric gradient increases, but is still outside of the area of the cone of depression centered at Savannah. Zone F5 was assigned a hydraulic conductivity between those of adjacent zones F6 and F4.

Zone F3 represents a part of the Upper Floridan aquifer that is in or around the Beaufort Arch where the aquifer thins and becomes relatively shallow. In zone F3, the hydraulic gradient is lower than in adjacent areas, and there are some highs on the potentiometric surface that are considered to be recharge zones for the Upper Floridan aquifer (Ransom and White, 1999). The hydraulic conductivity of this zone was assigned a relatively higher value than that assigned to adjacent zones.

Zones F4 and F12 include the large cone of depression centered in the Savannah area. During initial model development, zone F4 comprised the entire area of the cone of depression; however, simulations indicated a distinct and consistent spatial bias in the residuals between observed and simulated heads for this area. Consequently, zone F12 was added to the model and assigned a lower hydraulic conductivity to improve the spatial bias in residuals.

Zone F9 represents the offshore area, where there are few available data. The model, however, is relatively insensitive to the hydraulic conductivity of this zone; consequently, values assigned here had little effect on the calibration.

Boundary Conditions

Boundary conditions generally are based on natural hydrologic boundaries where available; where unavailable, artificial boundaries were constructed. A schematic diagram of model layers and vertical boundary conditions is shown in figure 10.

Vertical Boundaries

The lowermost model boundary represents no-flow conditions. Throughout the model area, this boundary corresponds to the contact between the Lower Floridan aquifer and underlying low-permeability sediments of Paleocene age and older (figs. 2 and 10).

The uppermost boundary simulates a general-head boundary condition, with different controlling heads and conductance terms (equivalent to hydraulic conductivity) for onshore and offshore areas (fig. 10). In the onshore area, this boundary condition was applied to the top active aquifer cell in the model, which may be in layer 1, 2, or 5, depending on which unit crops out at land surface (figs. 10 and 11). This type of boundary condition was chosen because a reliable spatial distribution of recharge could not be calculated within the scope of the study.

Initially, a fixed-head boundary was applied at the top of the model; however, this resulted in unreasonable simulated values of recharge to the regional flow system per model cell. A reasonable calculated per-cell recharge is estimated from baseflow calculations (Priest, 2004) and recharge rates determined for similar hydrologic settings (Williamson and others, 1990). By using a general-head boundary with resistance in the form of a conductance term, the recharge may be effectively limited to reasonable amounts. For the onshore area, the controlling head is the estimated water table (Peck and Payne, 2003), which is set at land-surface altitude at major streams, assuming that streams represent the intersection of the water table with land surface. The conductance term is a function of variable cell thickness, an assumed spatially constant hydraulic conductivity (which is indirectly estimated during model calibration), and the hydraulic conductivity of the active cell to which the boundary condition is applied. Conceptually, this boundary condition represents a source-sink boundary in the unconfined portion of the surficial aquifer that recharges to and discharges from the confined, regional ground-water system.

For the offshore area, a general-head boundary condition was applied to the top active cells, all of which are in layer 1. The controlling head for the offshore part of the model area is the freshwater equivalent of the saltwater head, and the conductance is assumed to be constant everywhere for simplicity. For the offshore area, conductance is not made a function of thickness because control of the thickness of the top layer is limited, and the estimated thickness of this layer in the offshore cells generally is only a few feet. These simplifications should not have a large affect on simulated results because flow from the confined system in the offshore area is assumed to be controlled predominantly by the hydraulic properties of layers 2 through 4, which primarily are confining units. Conceptually, this boundary condition represents a source-sink boundary in the ocean that recharges to and discharges from the confined, regional ground-water system.

Lateral Boundaries

Lateral boundary conditions for the ground-water flow model (figs. 9 and 10) were selected to coincide as closely as possible with assumed no-flow boundaries or ground-water divides. With the exception of the Floridan aquifer system (layers 5, 6, and 7), lateral boundaries for all layers are designated as no-flow.

Simulated flow in the Floridan aquifer system is bounded laterally by a combination of no-flow and fixed-head boundaries. The northwestern boundary approximately follows the updip extent of the Floridan aquifer system or its equivalent, as defined by Miller (1986), and is defined in the model as a no-flow boundary. The onshore part of the northeastern boundary was assigned a no-flow boundary because it is approximately parallel to estimated flow lines as shown on the potentiometric surface of the Upper Floridan aquifer (Ransom and White, 1999). This boundary was projected offshore and connected to the southeastern (seaward) no-flow boundary by the easternmost offshore boundary. To the southwest and south of the model area, there are no proximal natural hydrologic boundaries for the Floridan aquifer system, as it extends west beneath Alabama and south beneath Florida. Additionally, a no-flow boundary parallel to estimated flow lines is not an appropriate boundary condition because potentiometric-surface maps of the Upper Floridan aquifer indicate that water levels and estimated flowpaths change with time (Bradner, 1999; Clarke, 1987; Johnston and others, 1980 and 1981; Peck and others, 1999). In these areas, a time-variable, fixed-head boundary condition was applied from the top of the Upper Floridan aquifer to the bottom of the Lower Floridan aquifer (layers 5, 6, and 7) to enable simulation of changing ground-water levels. The controlling head varies spatially along the boundary according to potentiometric-head distributions derived from published maps for May 1980 (Johnston and others, 1981), May 1998 (Peck and others, 1999), and September 2000 (Peck and McFadden, 2004).

Offshore Boundary

In single-density models, a regional-scale freshwater-saltwater interface usually is represented as a no-flow boundary, assuming that the system is at steady state and the interface is sufficiently far from stressed areas to function as if at steady state. In reality, the aquifers in this study area are highly stressed near the coast, and the location of the regional freshwater-saltwater interface is unknown. Thus, the type and location of boundary condition chosen for the offshore area must be considered. If the location and type of boundary condition affect the calculated heads within the time frame of interest, then it must be constructed carefully; if instead, the model is relatively insensitive to variation in reasonable boundary conditions, then the simplest approach can be used.

To determine the appropriate type of lateral boundary for the offshore area, a series of tests was conducted, whereby the position of and type of boundary were varied and changes in simulated head determined at selected onshore locations. Two types of boundaries were tested: (1) a fixed-head boundary for which the controlling head was set to the freshwater equivalent of NAVD 88, and (2) a no-flow boundary representing the freshwater-saltwater interface. Both types of boundaries were applied along a vertical plane and positioned at several locations relative to the continental shelf margin: (1) at the shelf margin (the shelf-margin test boundary), (2) about 30 mi inland from the shelf margin (the intermediate test boundary), and (3) about 60 mi inland from the shelf margin (the near-shore test boundary). Locations of the tested boundaries and results of the evaluation are shown in figure 13.

The shelf-margin test boundary is approximately at the Florida–Hatteras slope (fig. 1), which represents the farthest location of a natural freshwater-saltwater interface. The near-shore test boundary is the closest boundary to the coast and includes a small onshore area where it intersects the northern and southern boundaries. This boundary represents an unlikely location of the regional freshwater-saltwater interface, because offshore drilling indicates that freshwater is present in the Upper Floridan aquifer 60–70 mi offshore of Fernandina Beach, Fla. (JOIDES J-1 site, Johnston and others, 1982). In addition, although saltwater contamination of the Upper Floridan aquifer has occurred near Hilton Head Island, S.C., freshwater is present in deeper parts of the aquifer, and saltwater appears to be entering through breaches in the Upper Floridan aquifer confining unit, rather than horizontal movement of the regional interface.

The difference in simulated head using the two types of boundary conditions at the three locations is shown in figure 13B. The tests indicate that the type of boundary had less effect on simulated head when positioned closer to the shelf margin. Using the shelf-margin test boundary and the intermediate test boundary, the difference in simulated head using the two types of boundaries was about 2 ft or less. The largest difference in simulated head between no-flow and fixed-head boundary conditions results from using the near-shore test boundary, with a maximum difference of about 3.5 ft in the Upper and Lower Floridan aquifers at Brunswick. Although the different types of boundaries affect onshore simulated head, these variations are within an acceptable error margin for the model when positioned near the intermediate or shelf-margin test-boundary locations, which are more likely locations for an offshore freshwater-saltwater interface. Following these tests, the decision was made to position the offshore boundary along the shelf margin and to utilize the simpler, no-flow boundary condition.

Pumpage

County aggregate and site-specific data were used to estimate average annual pumpage for 1980 and 2000 using procedures described by Taylor and others (2003). For layers 3, 5, and 7, the sum of site-specific and nonsite-specific pumping rates for 1980 and 2000 were assigned to the model grid cells. Pumpage was not assigned to layer 1, the surficial aquifer system, because there is too much uncertainty whether the pumping would be in the unconfined portion, which is not actively simulated, or the confined portion, which is actively simulated. In addition, there is not sufficient data to calibrate properly the confined surficial aquifer.

Site-specific data generally include permitted industrial and public-supply systems, and consist of withdrawal data, permit information, and well locations. These data typically include information on the aquifer utilized or well-construction information that may be used to help determine the aquifer utilized. For some multiwell permits, well-specific pumping data were acquired or estimated from data provided by the permittee. Nonsite-specific data consist of the remainder of county aggregate pumping after the sum of site-specific pumping for that county had been subtracted; these data may comprise agricultural, domestic, commercial, or other categories of water use for unpermitted wells. Because nonsite-specific data do not include specific withdrawal locations or aquifer being utilized, it is important to evaluate how best to assign this pumpage to the model.

A series of tests was conducted using a preliminary version of the model to determine the best way to distribute estimated nonsite-specific pumpage for the model. The tests evaluated the response of simulated head in the Upper Floridan aquifer at selected locations in the study area to a variety of pumping distributions for the year 2000. Sites selected for evaluation were located in areas representative of the variable hydrogeology, topography, and land use of the study area. Each simulation utilized site-specific data for 2000, and the following nonsite-specific pumping distributions:

- Distribution A: nonsite-specific data are not utilized.
- Distribution B: all nonsite-specific data are assigned to the Upper Floridan aquifer.
- Distribution C: nonsite-specific data are equally distributed among the surficial aquifer system, the Brunswick aquifer system, the Upper Floridan aquifer, and the Lower Floridan aquifer.
- Distribution D: nonsite-specific data are divided among the surficial aquifer system, the Brunswick aquifer system, and the Upper Floridan and Lower Floridan aquifers based on an estimated percentage distribution of wells with assigned aquifer designations in the USGS National Water Information System database using procedures described by Taylor and others (2003).

The simulated head in the Upper Floridan aquifer resulting from the test simulations at seven locations is shown in figure 14. Results indicate that simulated head was higher (on average 32 ft) for simulations conducted without nonsite-specific pumping data (distribution A) than for simulations in which it is included (distributions B–D). When the nonsite-specific pumping was attributed entirely to the Upper Floridan aquifer (distribution B), simulated heads generally were lower than for test distributions C and D, on average by 4 ft.

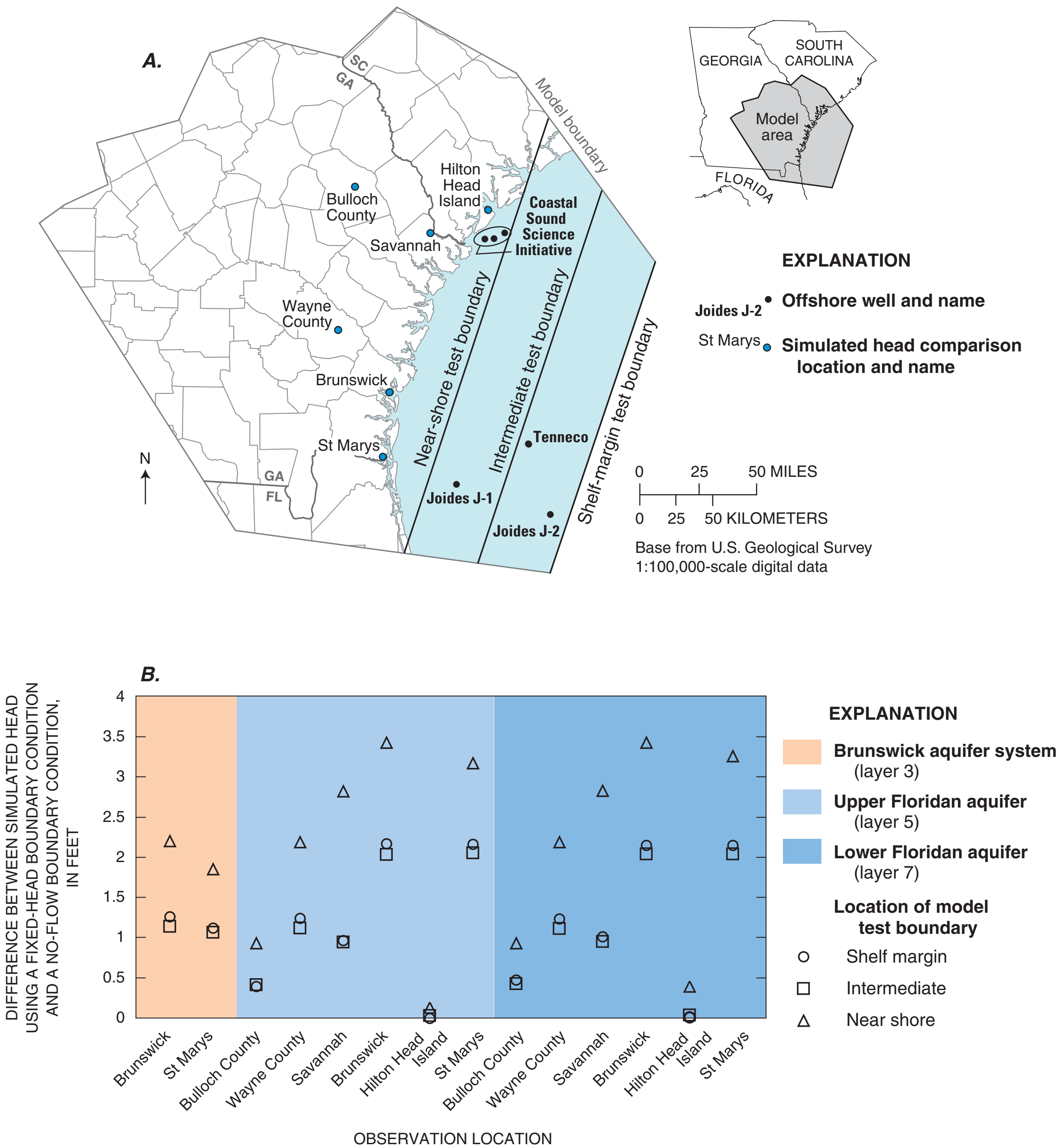


Figure 13. (*A*) Location of tested model boundaries, selected onshore wells, and offshore drilling sites; and (*B*) difference between simulated head using fixed-head and no-flow boundary conditions in layers 3, 5, and 7 at various locations in the study area. Positive values indicate that simulated head using a fixed-head boundary is consistently higher than that using a nonfixed-head boundary. Higher values simulated for the near-shore test boundary indicate the model is more sensitive to the type of boundary condition used when the boundary is located closer to shore (and thus closer to onshore simulated-head comparison locations).

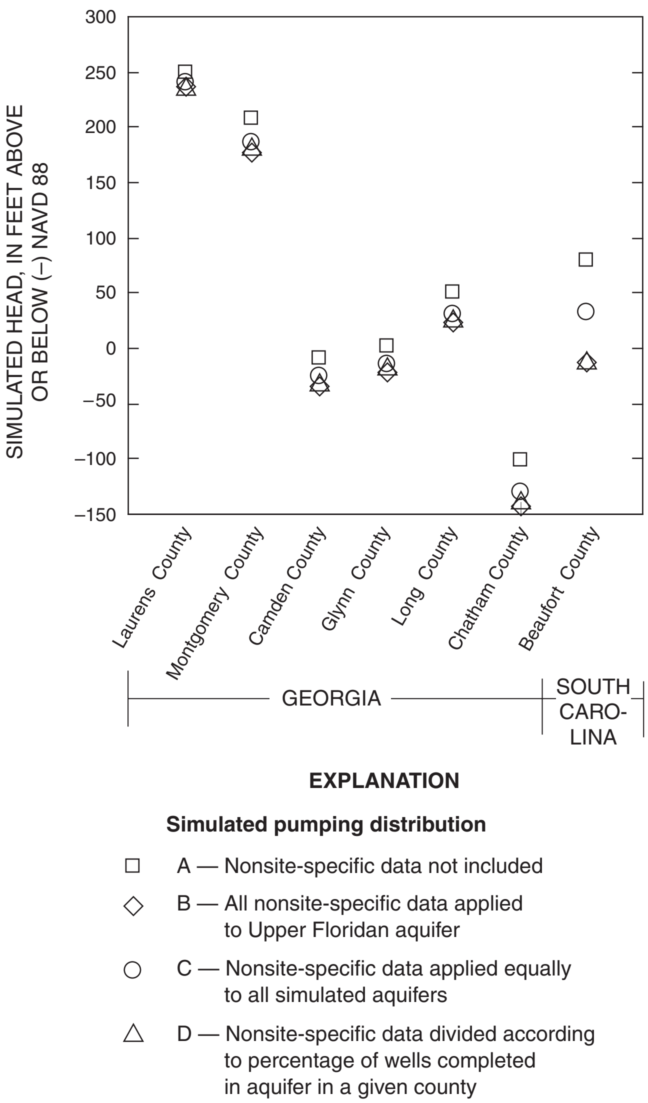


Figure 14. Effects of various pumping distributions on simulated head in the Upper Floridan aquifer.

Simulated head for pumping distributions C and D are intermediate relative to those for distributions A and B. When pumping was equally divided among the aquifers (distribution C), simulated heads generally were higher than when distribution D was applied by an average of 10 ft. This difference results because distribution C assigns a greater percentage of pumping to the shallow surficial and Brunswick aquifer systems than distribution D, which is based on the proportion of wells completed in the various aquifers in a given county. This distribution reduces the amount of pumpage designated for the Upper Floridan, resulting in higher simulated head.

Nonsite-specific pumping is an important consideration for model simulations because it comprises a substantial portion of total pumpage applied to some model layers; without these data, no pumping would be attributed to the Brunswick aquifer system. Although there are no permitted wells in the Brunswick aquifer system for 1980–2000, it is highly likely that some pumpage occurred during this period. Intuitively, the distribution among aquifers based on the percentage of wells completed in an aquifer in a given county would be more reasonable than an equivalent distribution among aquifers, because the former is based on existing well information, and the latter may apply too much pumpage to units that generally are used less, such as the surficial aquifer system and Lower Floridan aquifer. For these reasons, distribution D was chosen as the means to assign nonsite-specific pumping data to the model.

Because the nonsite-specific pumping comprises an estimated remainder of total pumping in a county and is at an unknown location, this pumping was assumed to be distributed equally across each county, based on a preliminary model-grid cell size of 15.54 mi^2. Other, more complex distributions were tested—for example, distributing agricultural pumping according to land use determined using a geographic information system—but the results indicated that there was little effect on overall distribution of stresses in the ground-water model (Taylor and others, 2003).

Simulated ground-water pumpages for the Brunswick aquifer system and the Upper and Lower Floridan aquifers are shown in figure 15 for the 1980 simulation and in figure 16 for the 2000 simulation. There is an apparent decrease in pumping in the Brunswick aquifer system between 1980 and 2000. Because of improved water-use reporting, a greater fraction of estimated total pumpage is attributed to site-specific, and a lesser fraction to nonsite-specific, pumping for 2000 than for 1980. This results in an apparent decline in nonsite-specific pumpage and results in an apparent decline in pumpage for the Brunswick aquifer system in some counties during this period—for example, Glynn County and Liberty County. It is more likely that pumpage increased during this time period, but there are no data to substantiate this. Ultimately, the total amount of pumping is small, there are few observations with which to calibrate and many other sources of uncertainty, so the effect on the model results is insignificant. Note that county totals, described earlier, may be larger than pumpage applied to the model in some counties that are split along model boundaries.

Model Calibration

The model was calibrated by adjusting hydraulic properties and boundary conditions to match observed water levels. Other factors considered during calibration include: (1) matching simulation results to the conceptual model of the ground-water flow system, including distributions of recharge and discharge areas, and directions of flow among aquifers; (2) adhering to the geologic and hydrogeologic framework; (3) maintaining reasonable values of hydraulic properties as defined by field data (Clarke and others, 2004); and (4) maintaining reasonable values of aquifer recharge in cells supplied by the general-head boundary when compared to baseflow estimates reported by Priest (2004) and other estimates of regional recharge (Williamson and others, 1990).

The model was calibrated using the following procedure:

1. The model initially was calibrated to 2000 stress conditions using head data.
2. Hydraulic-characteristics arrays derived from calibration of the 2000 period were used as initial conditions for simulation of 1980 conditions.
3. The additional observations for 1980 allowed additional refinement of the aquifer characteristics, particularly in the updip area.
4. These modified characteristics then were used to refine calibration of 2000 conditions.

This iterative process continued until the model was calibrated for both 1980 and 2000 conditions. Upon completion of calibration to 1980 and 2000 conditions, a simulation of predevelopment conditions was performed by removing all pumping from the model and comparing these results to an estimated predevelopment potentiometric surface for the Upper Floridan aquifer (Krause and Randolph, 1989).

Improvement in the quality of the 1980 and 2000 steady-state simulations between successive model runs was evaluated by comparisons of the following:

- residuals (differences) between observed head and simulated head; and the mean, root-mean square, and standard deviation of the residuals; and
- percentage of wells whose residual met established calibration criteria (see discussion below).

The mean of the residuals indicates whether the mean difference between computed and observed water levels is skewed positive or negative in magnitude. The root-mean square is the square root of the average deviation of the residuals from zero.

Aquifer and confining-unit properties were initially based on available data and were adjusted using trial-and-error parameter estimation during calibration. Automated parameter estimation techniques were attempted, but there are not enough different types of observation data for these techniques to be successful (Hill, 1998).

Calibration Targets

In calibrating the model, two types of water-level observations (appendix A) were used: (1) synoptic water-level measurements from the Upper Floridan aquifer during May 1980 and September 2000, and (2) mean-monthly water levels for sites with continuous recorder data.

An accuracy analysis of water-level data provides a calibration target of acceptable margin of error (table 4). Most observations for both 1980 and 2000 are for the Upper Floridan aquifer (layer 5). Because too few observations exist for either the Brunswick aquifer system (layer 3) or Lower Floridan aquifer (layer 7) to be analyzed separately, observations from all layers (3, 5, and 7) are analyzed as a single set. Because observation data differ by site and season for the two calibration years, a separate accuracy analysis is provided for each year.

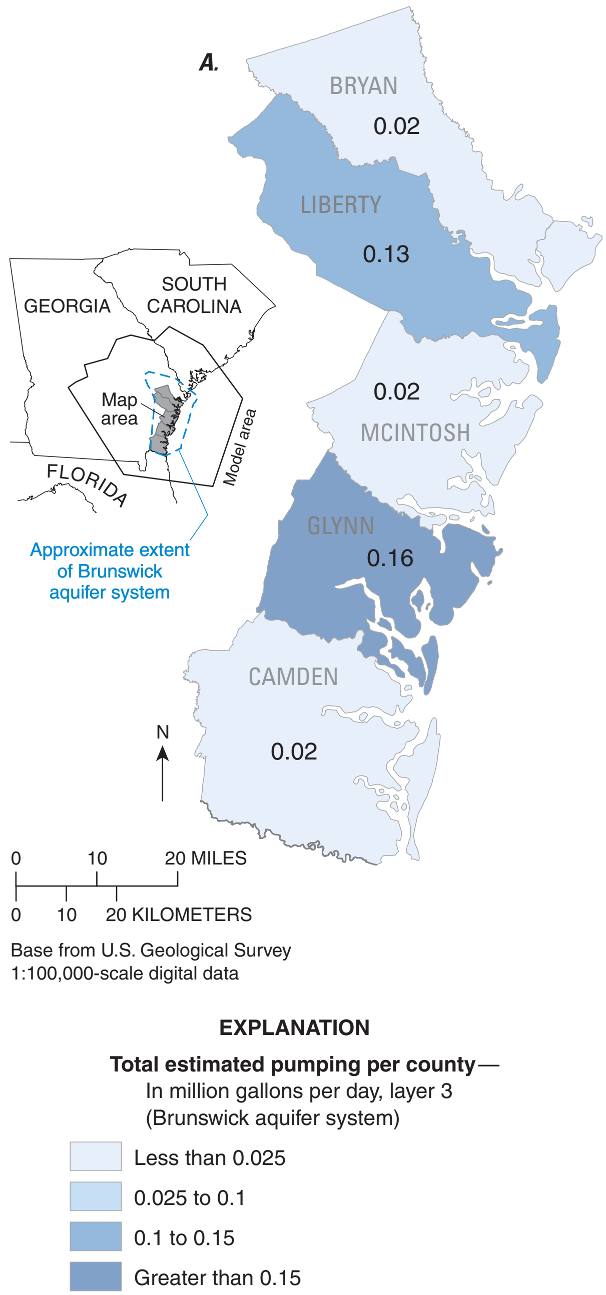


Figure 15. Distribution of ground-water pumpage by model layer, 1980, (*A*) layer 3, Brunswick aquifer system (values rounded to 0.01 million gallons per day [10,000 gallons per day], values do not agree with values shown in table 8 and figures 28A and 29 because of rounding; (*B*) layer 5, Upper Floridan aquifer; (*C*) layer 5, Upper Floridan aquifer (enlarged view); (*D*) layer 7, Lower Floridan aquifer.

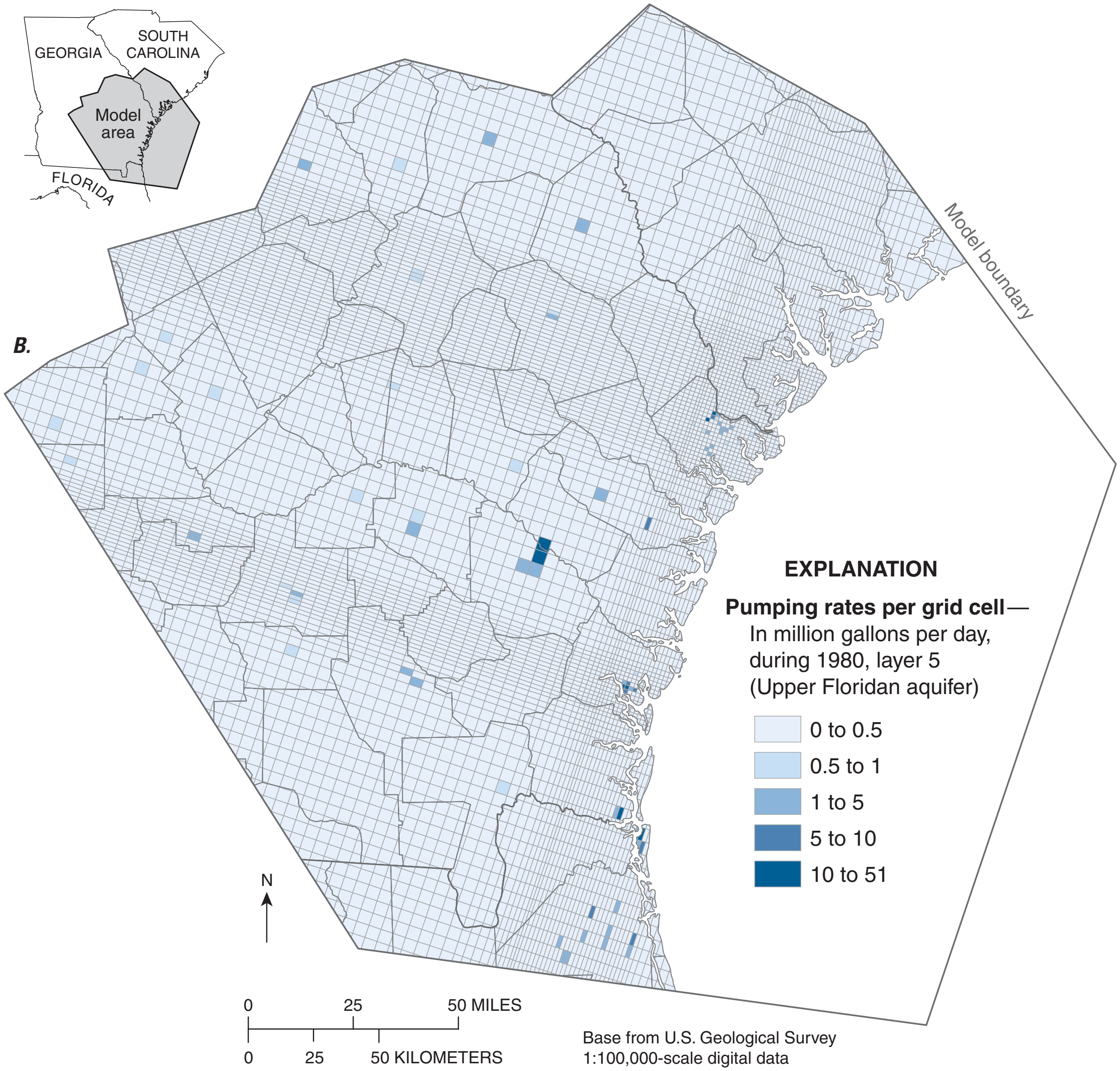


Figure 15. Distribution of ground-water pumpage by model layer, 1980, (*A*) layer 3, Brunswick aquifer system; (*B*) layer 5, Upper Floridan aquifer; (*C*) layer 5, Upper Floridan aquifer (enlarged view); (*D*) layer 7, Lower Floridan aquifer—continued.

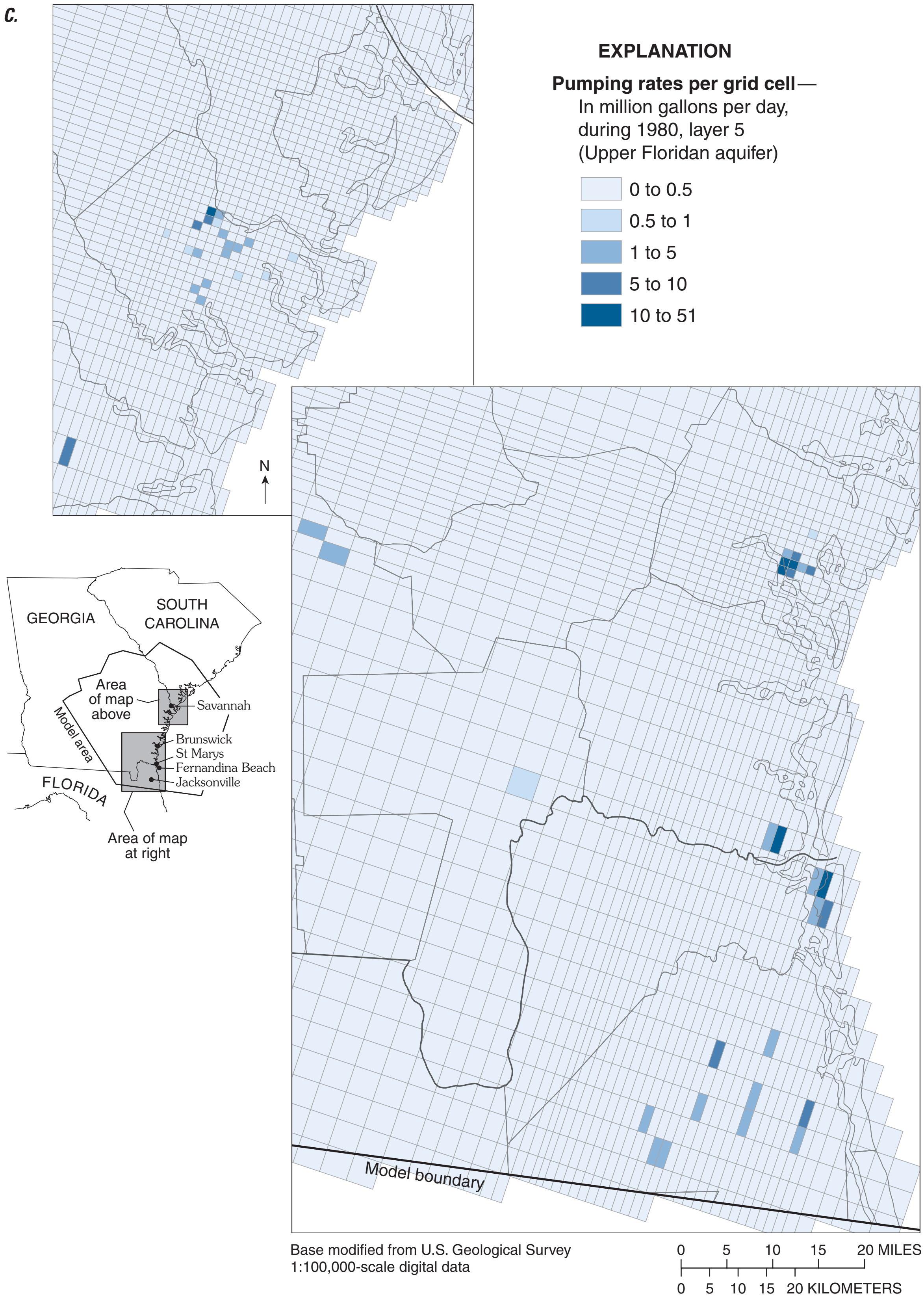


Figure 15. Distribution of ground-water pumpage by model layer, 1980, (*A*) layer 3, Brunswick aquifer system; (*B*) layer 5, Upper Floridan aquifer; (*C*) layer 5, Upper Floridan aquifer (enlarged view); (*D*) layer 7, Lower Floridan aquifer—continued.

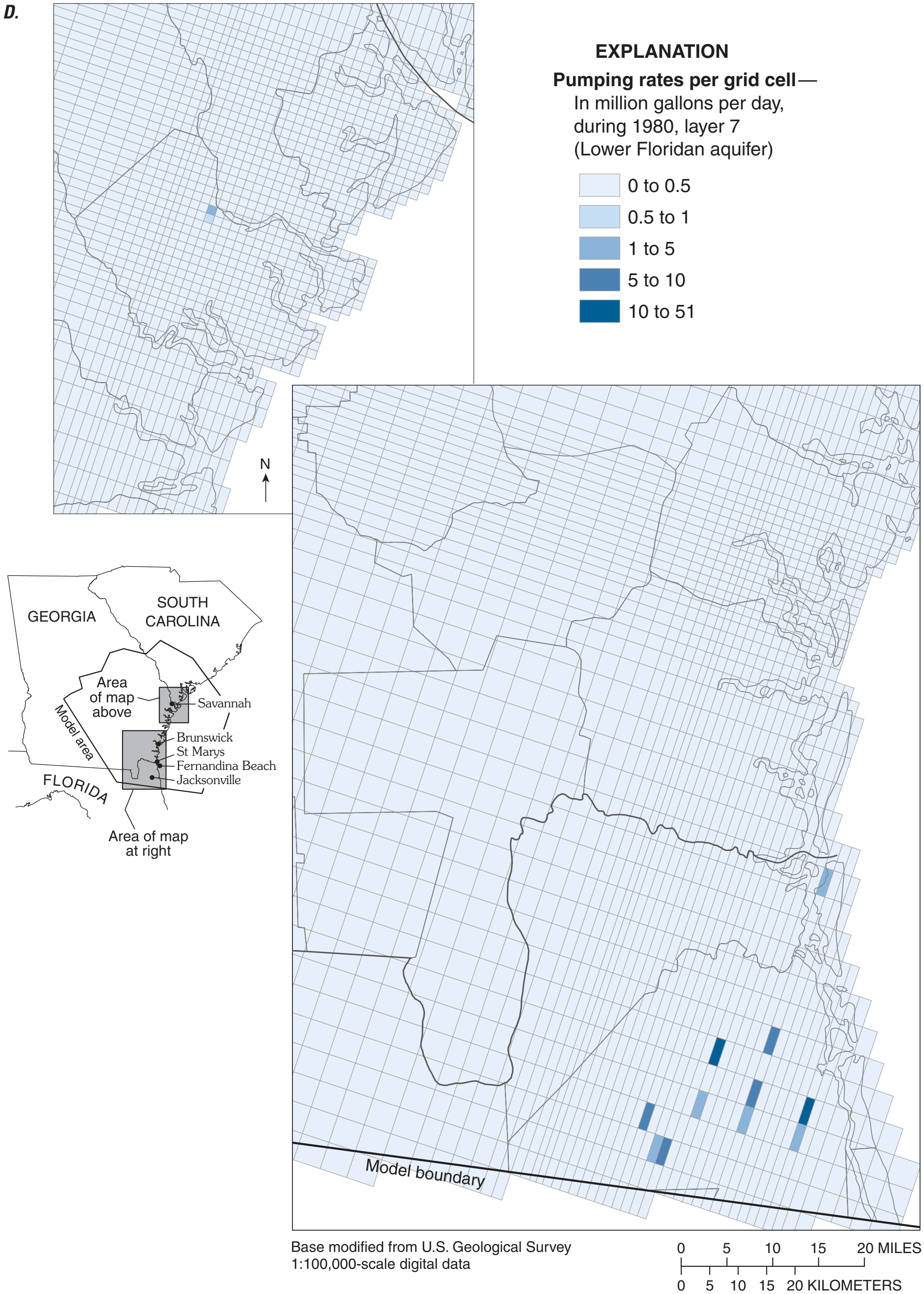


Figure 15. Distribution of ground-water pumpage by model layer, 1980, (*A*) layer 3, Brunswick aquifer system; (*B*) layer 5, Upper Floridan aquifer; (*C*) layer 5, Upper Floridan aquifer (enlarged view); (*D*) layer 7, Lower Floridan aquifer—continued.

Table 4. Statistics for quantifiable components of observation accuracy.

Factor	Year 1980	Year 2000
Altitude accuracy		
Number of observations	297	176
Range (feet)	0.1 to 10	0.1 to 10
Average (feet)	4.5	4.1
Standard deviation (feet)	3.5	3.3
Percent of observations without accuracy data	29	18
	Period of record	
Seasonal variation		
Number of observations	67	
Range (feet)	0.4 to 7.1	
Average (feet)	2.2	
Standard deviation (feet)	1.3	
Sum of standard deviations for altitude accuracy and seasonal variation	**4.8**	**4.6**

Quantifiable components of water-level observation accuracy analysis include the accuracy of the land-surface altitude, annual variation in water levels, and accuracy of the water-level measurement. Water-level measurement error is considered to be insignificant. Land-surface altitude accuracy differs depending on the method used for determination. For values determined from topographic maps, one-half of the contour interval (generally 10 ft) is considered to be the altitude accuracy. For values determined using global-positioning instrumentation or surveying, the accuracy generally is within 1 ft; however, these data are sparse in the study area. Annual water-level variability was determined using data from wells equipped with continuous recorders. The data used for this analysis include all years from the period of record through 2002 for which 10 or more months of mean-monthly data exist.

Observation accuracy consists of the sum of the standard deviations of land-surface altitude accuracy and annual variability of water-level accuracy, and is 4.8 ft for 1980 and 4.6 ft for 2000 (table 4). Because of other potential errors in the observation data, as well as errors in data used for model input or in development of the conceptual model, Kuniansky and others (2003) suggested that a good calibration target for fit of simulated-to-observed water levels would be two times the standard deviation of observation accuracy. Thus, the final calibration targets for simulated ground-water levels are 9.6 ft for 1980 and 9.2 ft for 2000. For the purpose of simplicity, these values are rounded to 10 ft for both the 1980 and 2000 simulations. An additional statistic used to evaluate model calibration is computed by dividing the standard deviation of the residuals by the range of water-level variation. Generally, if the range of water-level data is large, the standard deviation of residual errors also is large. This dimensionless statistic generally should be less than one; a good fit of the data would be reflected if the ratio was approximately 0.1 or less indicating that the residuals are generally less than 10 percent of the range in altitude of the observations (Kuniansky and others, 2003).

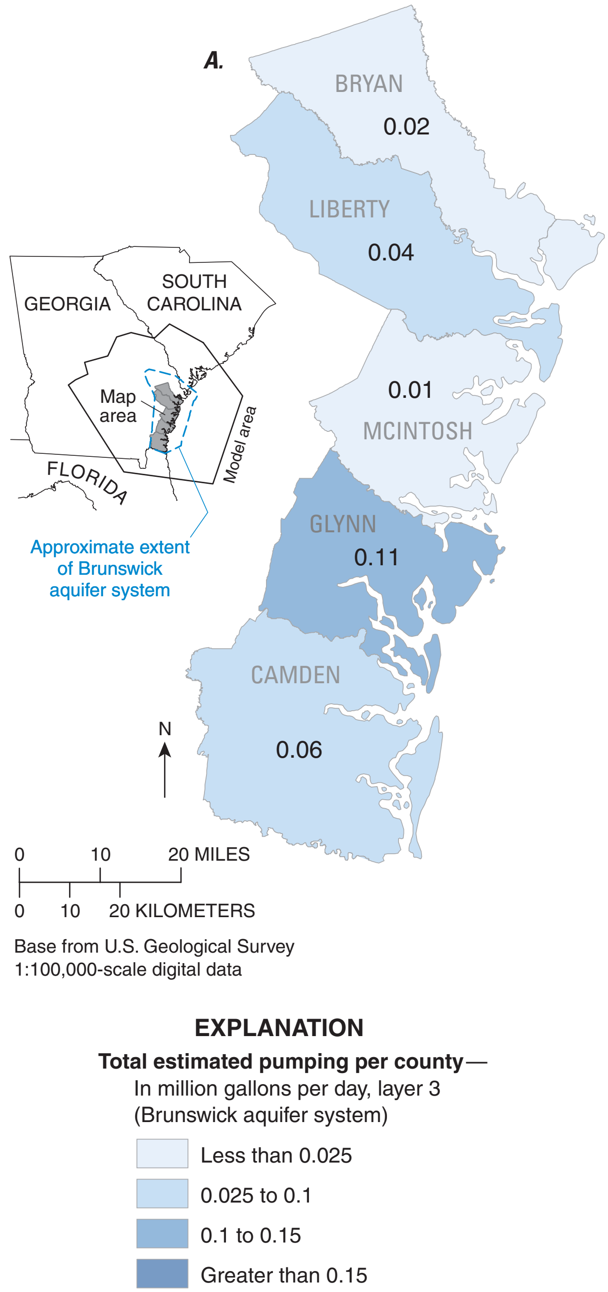


Figure 16. Distribution of ground-water pumpage by model layer, 2000, (*A*) layer 3, Brunswick aquifer system (values rounded to 0.01 million gallons per day [10,000 gallons per day], values do not agree with values shown in table 9 and figures 28B and 29 because of rounding; (*B*) layer 5, Upper Floridan aquifer; (*C*) layer 5, Upper Floridan aquifer (enlarged view); (*D*) layer 7, Lower Floridan aquifer.

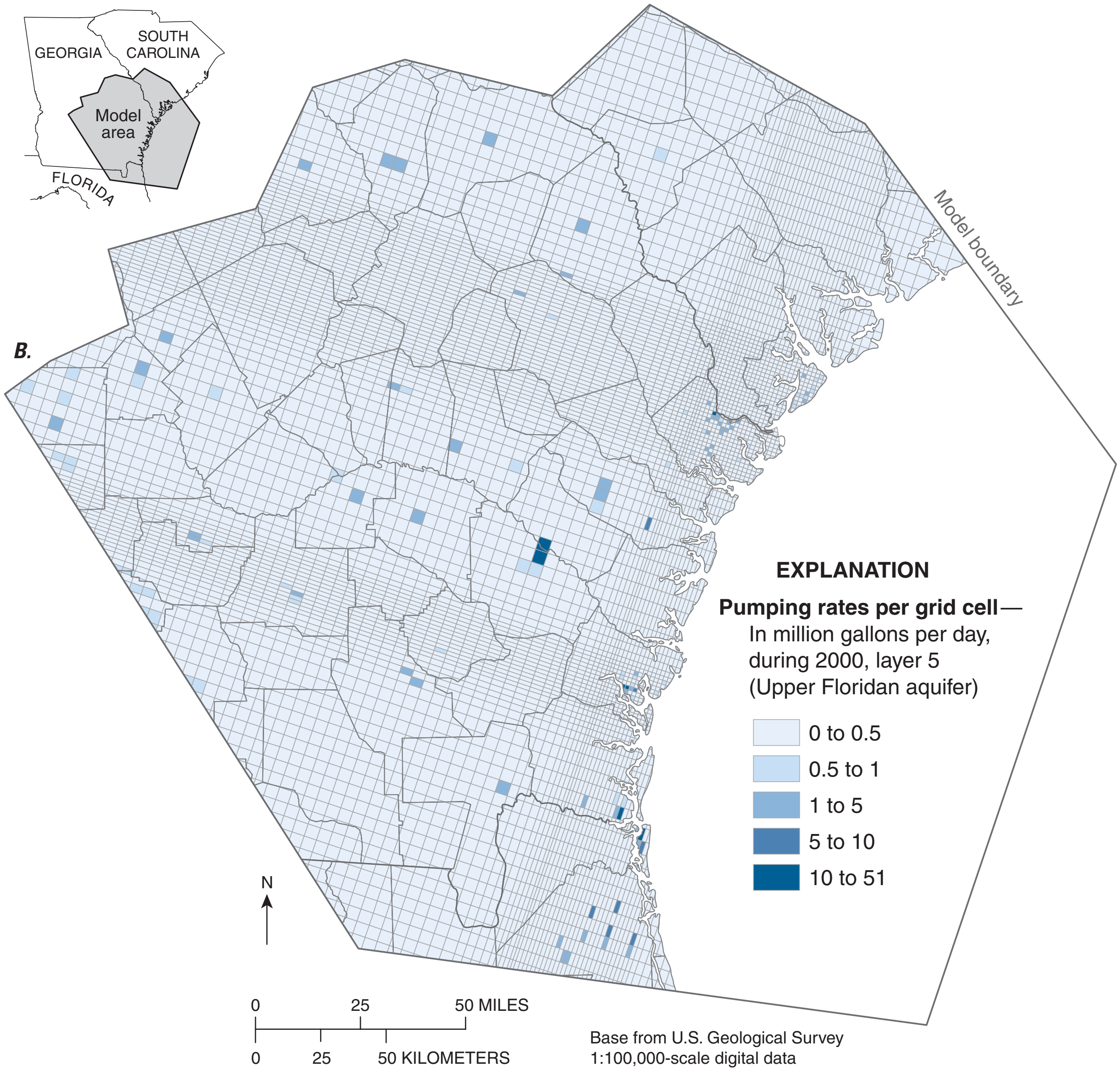


Figure 16. Distribution of ground-water pumpage by model layer, 2000, (*A*) layer 3, Brunswick aquifer system; (*B*) layer 5, Upper Floridan aquifer; (*C*) layer 5, Upper Floridan aquifer (enlarged view); (*D*) layer 7, Lower Floridan aquifer—continued.

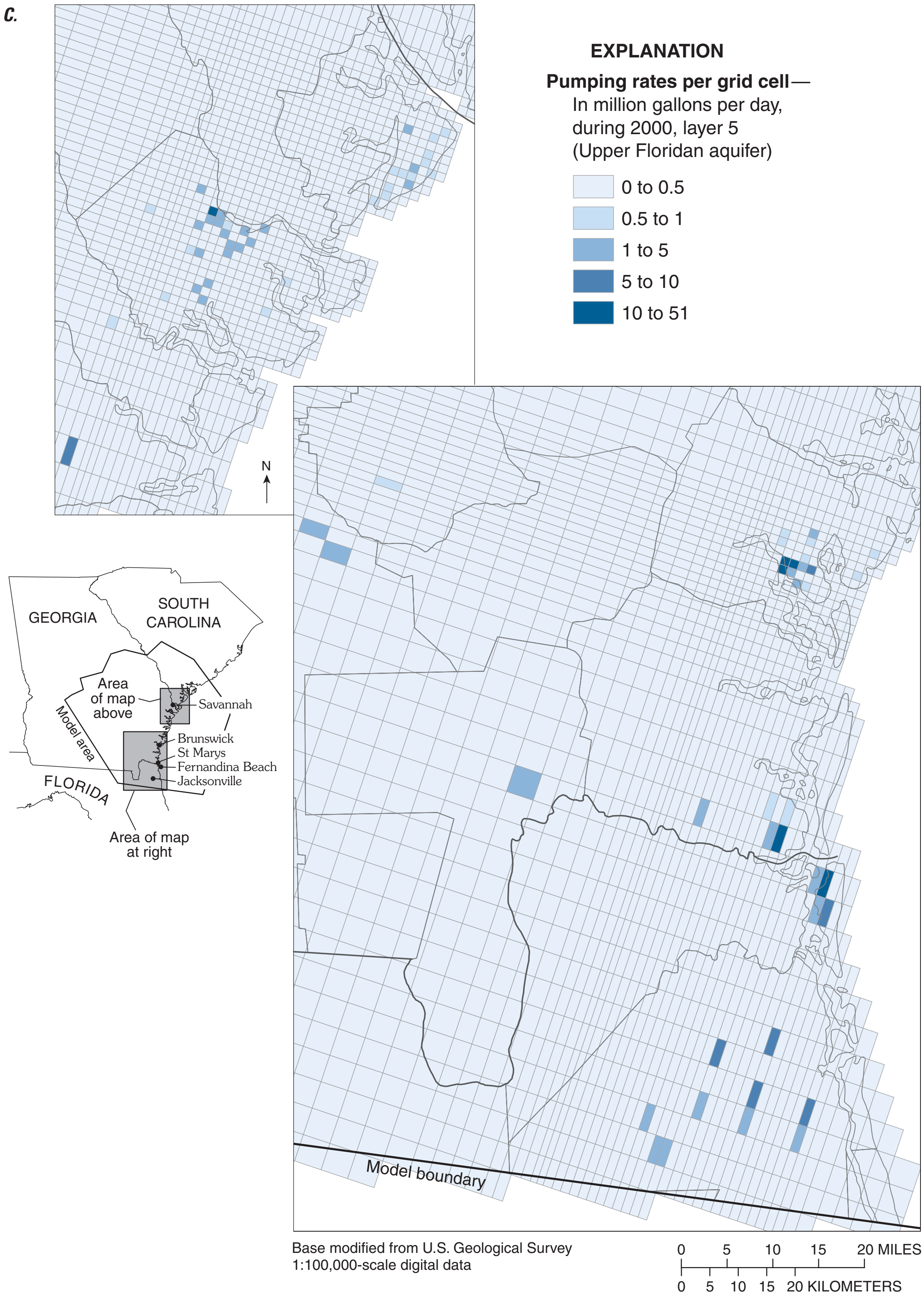


Figure 16. Distribution of ground-water pumpage by model layer, 2000, (*A*) layer 3, Brunswick aquifer system; (*B*) layer 5, Upper Floridan aquifer; (*C*) layer 5, Upper Floridan aquifer (enlarged view); (*D*) layer 7, Lower Floridan aquifer—continued.

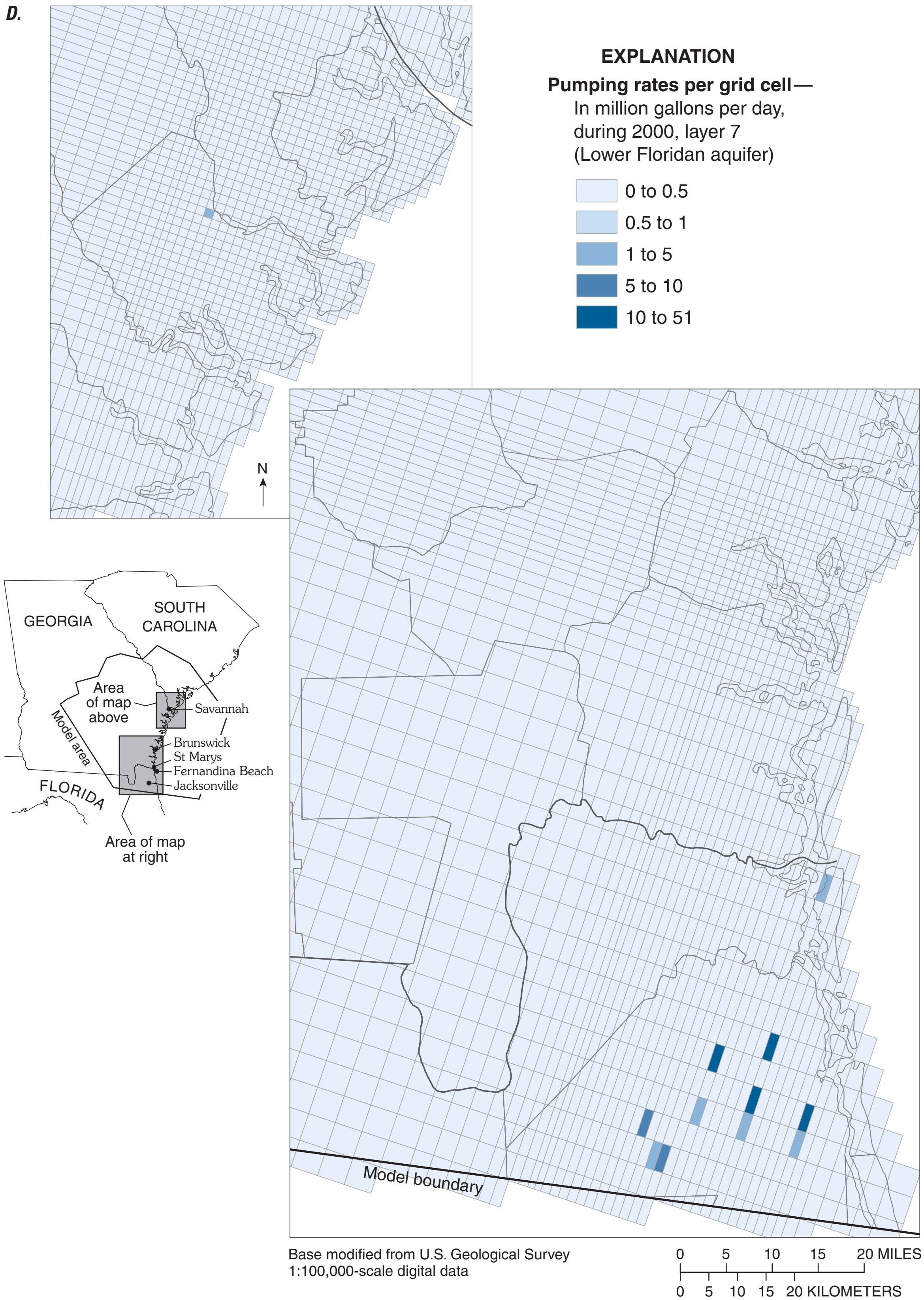


Figure 16. Distribution of ground-water pumpage by model layer, 2000, (*A*) layer 3, Brunswick aquifer system; (*B*) layer 5, Upper Floridan aquifer; (*C*) layer 5, Upper Floridan aquifer (enlarged view); (*D*) layer 7, Lower Floridan aquifer—continued.

Recharge

During model calibration, the amount of recharge allowed into the regional system was constrained by stream baseflow data (Priest, 2004) and estimates of regional recharge in a proximal and hydrologically similar area (Williamson and others, 1990). The model simulates the regional flow system and does not attempt to simulate specifically the shallow unconfined flow system. Estimated recharge to the regional system is not likely to exceed long-term average stream baseflow estimates from hydrograph separation, and is more likely to be on the order of drought baseflow estimates. The maximum allowable recharge into any model cell was limited to 1–10 inches. Stream baseflow data (Priest, 2004) were used indirectly in model calibration as a control on recharge into the system. Because the scope of the study does not include a detailed evaluation of stream-aquifer interaction, the model was not designed to simulate ground-water discharge to streams. Instead, the baseflow estimates are interpreted as a maximum amount of recharge that could occur in any grid cell, as calculated from the flux of the general-head boundary condition into the active area of the model. Long-term average stream baseflow estimates for 14 basins in the model area range from 4 to 10 in/yr (fig. 6) (Priest, 2004). Assuming that stream discharge approximately equals recharge in an unstressed steady-state system, the maximum allowable recharge into any model cell is limited to approximately 10 in/yr.

Recharge/discharge rate in inches per year is calculated as:

$$\frac{Q}{A} = \frac{K(h_2 - h_1)}{L} \times \textit{conversion factor}$$

where

Q is the discharge rate in cubic feet per day,
A is area of the cell in square feet,
K is the hydraulic conductivity of the general-head boundary cell in feet per day,
h_2 is the controlling head (water-table altitude) in feet,
h_1 is the calculate head in the topmost active cell in feet,
L is one-half the active cell thickness (the distance between the grid-cell centroid where head is calculated and the imposed boundary condition at the top of the cell), and
conversion factor converts units of feet per day to inches per year.

When the controlling head altitude (h_2) is greater than that of the adjacent active model cell, the calculated rate is positive, recharge occurs, and water enters the modeled system from the general-head boundary. When h_2 is lower than that of the adjacent active model cell, discharge occurs, and water exits the system to the general-head boundary.

Steady-State Simulation of Predevelopment Flow System

The predevelopment flow system was simulated by eliminating all pumping from the calibrated 1980–2000 model. Although a quantitative evaluation using calibration statistics is not possible because of sparse water-level observations, the simulation can be evaluated qualitatively by comparing to an estimated predevelopment potentiometric-surface map for the Upper Floridan aquifer (Krause and Randolph, 1989).

Ground-Water Flow

Although the simulated and estimated predevelopment potentiometric-surface maps for the Upper Floridan aquifer do not match exactly, they do show similar features, including an upstream deflection of potentiometric contours along major streams in the northwestern part of the area, a steepening of the potentiometric gradient in the area of the Gulf Trough, a flattening of the potentiometric gradient in the southwestern part of the model area, and flow toward a potentiometric low in coastal South Carolina near Hilton Head Island and Port Royal Sound (fig. 17) (see locations, fig. 1). Simulated predevelopment flow in the Lower Floridan aquifer (layer 7) is similar to flow in the Upper Floridan (layer 5), with nearly identical ground-water levels.

In the Brunswick aquifer system, simulated predevelopment flow generally is to the southeast, with part of the flow northeastward toward a potentiometric low in eastern Chatham County (fig. 17). A more gentle hydraulic gradient in the southeastern model area reflects the greater thickness and transmissivity of the aquifer system near the Southeast Georgia Embayment. Simulated water levels in the Brunswick aquifer system, where present, generally were higher than in the Upper Floridan aquifer in the northwestern part of the area, indicating a potential for downward flow into the Upper Floridan. In the southeastern part of the area, simulated water levels in the Brunswick aquifer system were lower than in the Upper Floridan aquifer, indicating a potential for upward flow into the Brunswick aquifer system.

Water Budget

The simulated predevelopment water budget includes the following components of inflow and outflow to the ground-water flow system: (1) recharge from the general-head boundary, (2) inflow across lateral specified-head boundaries, (3) discharge to the general-head boundary, and (4) outflow across lateral specified-head boundaries (fig. 18; table 5). Predevelopment flow was characterized using the MODFLOW postprocessor ZONEBUDGET (Harbaugh, 1990). Flow was summarized by model layer (table 5) and by dividing the model into several zones and computing discharge into and out of the zone. Zones were designated to summarize discharge to and from fixed-head and general-head boundaries, between adjacent layers, and along the coastline (fig. 18).

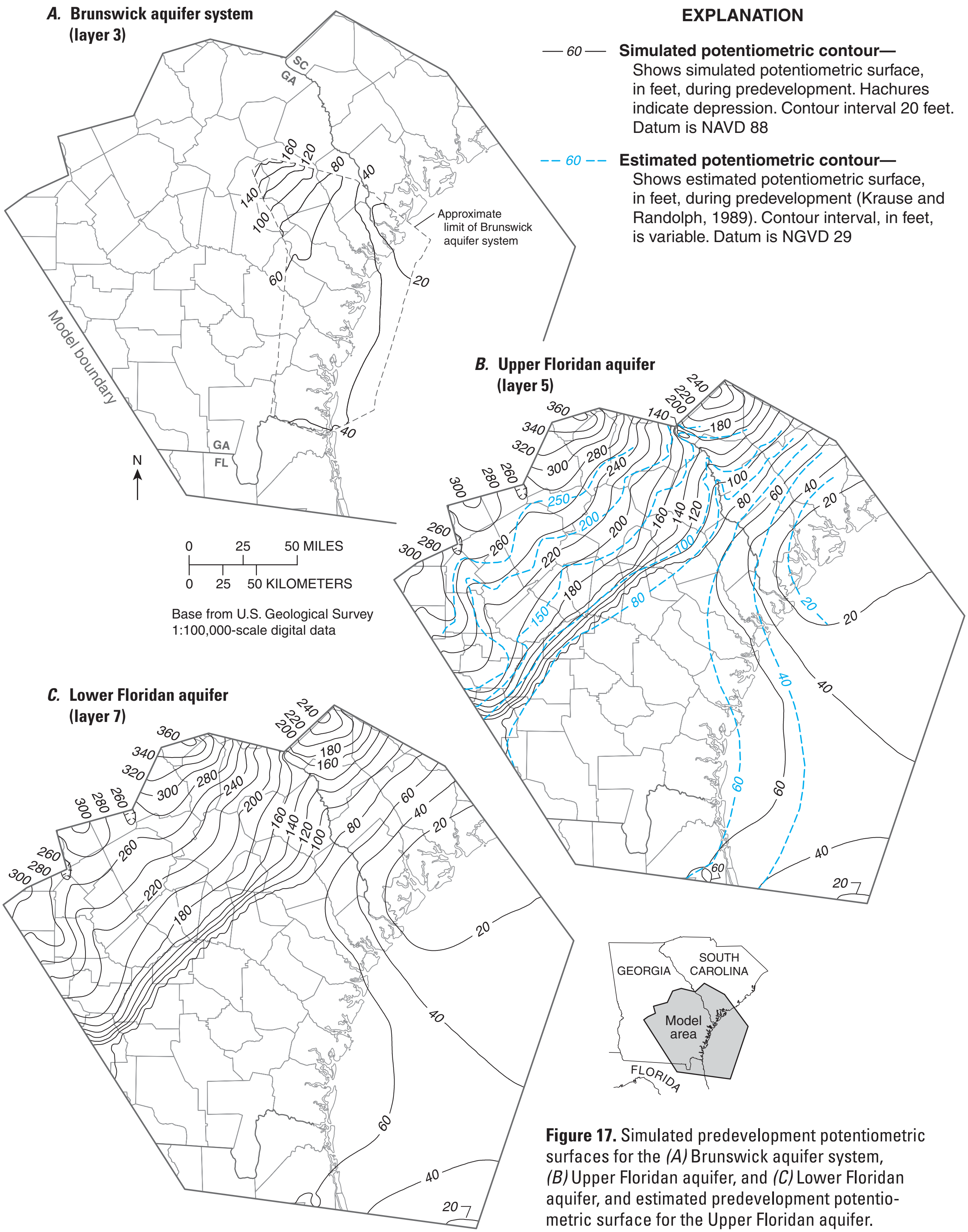


Figure 17. Simulated predevelopment potentiometric surfaces for the *(A)* Brunswick aquifer system, *(B)* Upper Floridan aquifer, and *(C)* Lower Floridan aquifer, and estimated predevelopment potentiometric surface for the Upper Floridan aquifer.

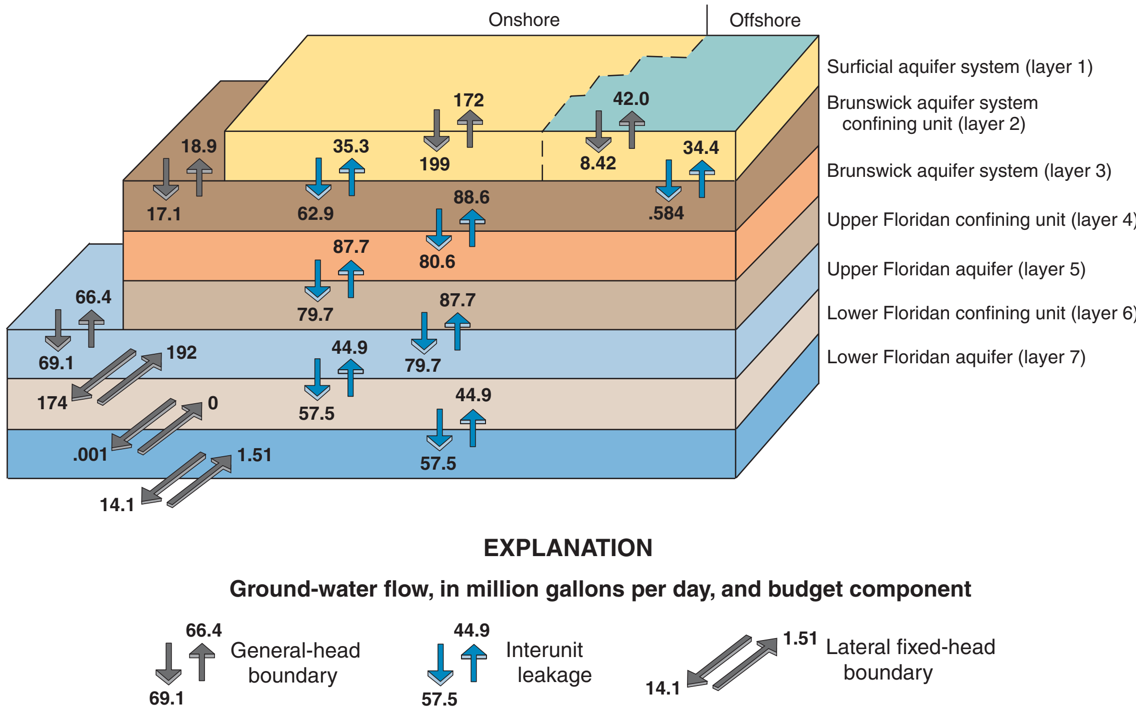


Figure 18. Schematic diagram showing simulated predevelopment water budget.

Table 5. Simulated predevelopment water budget by model layer.

[Values reported to three significant digits and may not sum to totals because of independent rounding; —, not applicable.]

Model layer	Hydrogeologic unit	Inflow, in million gallons per day			Outflow, in million gallons per day		
		Inflow from general-head boundary	Inflow across lateral boundaries	Total	Outflow to general-head boundary	Outflow across lateral boundaries	Total
1	Surficial aquifer system	208.0	—	208.0	214.0	—	214.0
2	Confining unit	17.1	—	17.1		—	18.9
3	Brunswick aquifer system	—	—	—	—	—	—
4	Confining unit	—	—	—		—	—
5	Upper Floridan aquifer	69.1	192	261	66.4	174	240
6	Confining unit	—	0.000	0.000		0.001	0.001
7	Lower Floridan aquifer	—	1.51	1.51	—	14.1	14.1
	Total all layers	**294**	**193**	**487**		**188**	**487**
	Percentage of flow	**60.3**	**39.7**	**100**		**38.6**	**100**

Based on the total simulated inflow of 487 Mgal/d, 60.3 percent (294 Mgal/d) is contributed by leakage from the general-head boundary, and 39.7 percent (193 Mgal/d) is contributed as inflow from lateral specified-head boundaries in layers 5 and 7 (table 5). Based on the total 487 Mgal/d outflow, ground-water discharge to the general-head boundary accounts for 61.4 percent of the outflow, with 38.6 percent attributed to outflow at lateral specified-head boundaries. Along the lateral specified-head boundary, the net flow is about 18 Mgal/d into the model area in the Upper Floridan aquifer and 12.6 Mgal/d out of the model area in the Lower Floridan aquifer.

Flow from the general-head boundary represents recharge from the water table to deeper confined aquifers. A map showing the areal distribution of recharge and discharge in the onshore area is shown in figure 19. The total simulated recharge to the ground-water system in the onshore area is 285 Mgal/d (fig. 18), which is equivalent to an average of about 0.21 in/yr across the entire onshore area. Simulated recharge per model cell was 4 inches or less throughout the area, which was within the 10-in/yr limit based on stream baseflow (Priest, 2004) and other estimates of regional recharge (Williamson and others 1990). The simulated recharge-discharge map (fig. 19) indicates that recharge generally occurs in interstream areas and discharge occurs in stream valleys and lowland areas near the coast. Areas with the highest recharge rates generally are found in interstream areas at higher altitudes than adjacent areas.

Simulated discharge from the ground-water flow system in the onshore area was 257 Mgal/d (fig. 18). Computed rates of interaquifer leakage indicate there is a dominant upward component of flow in the study area. Most of this flow occurs south of the Gulf Trough (see location, fig. 1), where vertical flow gradients are upward in low-lying areas along the coast. Highest rates of simulated discharge to the general-head boundary (fig. 19) occur along major rivers north of the Gulf Trough, including the Savannah (see locations, figs. 1 and 6) and the Ocmulgee Rivers (see location, fig. 6).

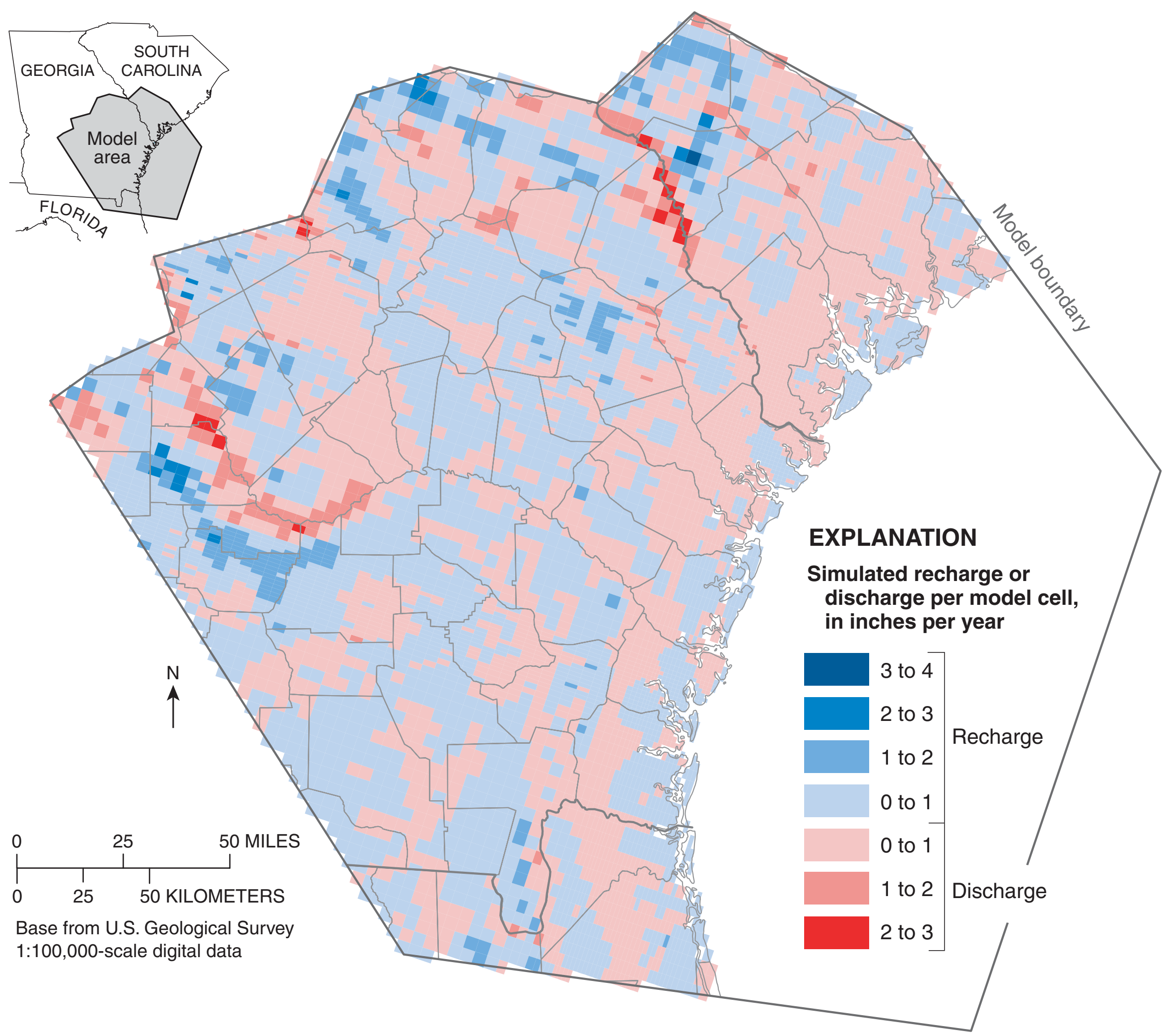


Figure 19. Simulated recharge or discharge during predevelopment.

A total of 199 Mgal/d recharge the surficial aquifer system (layer 1) in the onshore area, with 172 Mgal/d discharged to streams or wetlands, leaving 27 Mgal/d available to recharge deeper units (fig. 18). The Brunswick aquifer system (layer 3) is not known to crop out in the study area, and the only mechanism for water to enter the aquifer is through leakage from adjacent units (fig. 18). Simulated leakage to the Brunswick aquifer system is provided mostly from layer 4 (87.7 Mgal/d) and layer 2 (80.6 Mgal/d).

Simulated recharge to the Upper Floridan aquifer (layer 5) is provided by direct recharge from the general-head boundary, by flow from lateral fixed-head boundaries, and from inter-aquifer leakage (fig. 18). During predevelopment, most of the flow to the Upper Floridan aquifer was from lateral fixed-head boundaries (192 Mgal/d) along the southern part of the simulated area. Simulated recharge from the general-head boundary was 69.1 Mgal/d, and leakage to the Upper Floridan aquifer was 79.7 Mgal/d from overlying units and 44.9 Mgal/d from underlying units (fig. 18). Net inflow from the lateral fixed-head boundary, approximately 18 Mgal/d, was greater than net inflow from the general-head boundary, and net flow to adjacent layers 4 and 6 was 8.0 and 12.6 Mgal/d, respectively.

The Lower Floridan aquifer (layer 7) is recharged mostly by leakage from layer 6 and by flow from lateral boundaries (fig. 18). During predevelopment, total flow to the Lower Floridan aquifer was 59.0 Mgal/d, of which 97 percent was leakage from layer 6.

To assess the movement of water offshore and along the coastline, several zones were designated and flow rates summarized using ZONEBUDGET (Harbaugh, 1990) (fig. 18). During predevelopment conditions, water both entered and discharged from the surficial aquifer system into the general-head boundary in the offshore area, with discharge exceeding recharge by 33.6 Mgal/d.

Steady-State Simulation of 1980 and 2000 Flow System

Mean-annual conditions for 1980 and 2000 were simulated using the steady-state approximation. Simulated head and water budget are summarized and compared.

Calibration of Simulated Head

Ground-water conditions during 1980 were calibrated on the basis of water-level measurements in 297 wells (table 6; fig. 20; appendix A): 3 are completed in the Brunswick aquifer system (layer 3), 285 are completed in the Upper Floridan aquifer (layer 5), and 9 are completed in the Lower Floridan aquifer (layer 7). For the Upper Floridan aquifer wells, the residual, or difference between simulated minus observed ground-water levels, ranged from –37.0 to 44.2 ft, with a mean of –0.470 ft and a root-mean square of 13.0 ft (table 6, fig. 20). For the three Brunswick aquifer system wells, residuals ranged from –14.0 to 18.9 ft; and for the nine Lower Floridan aquifer wells, residuals ranged from –5.20 to 20.1 ft. Residuals for the Upper Floridan aquifer were normally distributed, with 70 percent of the simulated values within the 10-ft calibration target of observed values. Dividing the standard deviation of the residuals for the Upper Floridan aquifer by the range of observed water-levels yields a calibration fit of 0.031, indicating a good fit of the data (Kuniansky and others, 2003).

Ground-water conditions during 2000 were calibrated on the basis of water-level measurements in 175 wells: 10 are completed in the Brunswick aquifer system (layer 3), 154 are completed in the Upper Floridan aquifer (layer 5), and 11 are completed in the Lower Floridan aquifer (layer 7) (table 7; fig. 20; appendix A). For the 10 Brunswick aquifer system wells, residuals ranged from –7.67 to 13.3 ft, with a mean of 1.79 ft and a root-mean square of 5.91 ft. For the Upper Floridan aquifer wells, water-level residuals ranged from –44.4 to 36.4 ft, with a mean of –0.843 ft and a root-mean square of 9.94 ft. For the Lower Floridan aquifer wells, residuals ranged from –3.62 to 21.5 ft, with a mean of 5.20 ft and a root-mean square of 9.15 ft. Residuals for all layers were normally distributed; simulated values were within the 10-ft calibration target of observed values for 80 percent of the Brunswick aquifer system wells, 79 percent of the Upper Floridan wells, and 73 percent of the Lower Floridan wells (table 7). Dividing the standard deviation of the residuals by the range of water-level variation yields a calibration fit of 0.142 for the Brunswick aquifer system, 0.031 for the Upper Floridan aquifer, and 0.056 for the Lower Floridan aquifer, indicating a good fit of the data (Kuniansky and others, 2003).

Table 6. Calibration statistics for simulated heads for 1980 conditions.

[Residual equals simulated minus observed head; –, minus; —, not calculated because less than 10 values]

Calibration statistic	Brunswick aquifer system (layer 3)	Upper Floridan aquifer (layer 5)	Lower Floridan aquifer (layer 7)
Number of observations	3	285	9
Range of observations (feet)	37.2	414	253
Minimum residual (feet)	–14.0	–37.0	–5.20
Maximum residual (feet)	18.9	44.2	20.1
Mean residual (feet)	–2.25	–0.470	4.98
Standard deviation of residuals (feet)	—	13.0	—
Root-mean square residual (feet)	—	13.0	—
Percentage of simulated values within 10-foot error criteria	0	70	67
Calibration fit: Standard deviation of residuals divided by range of observed values (Kuniansky and others, 2003)	—	0.031	—

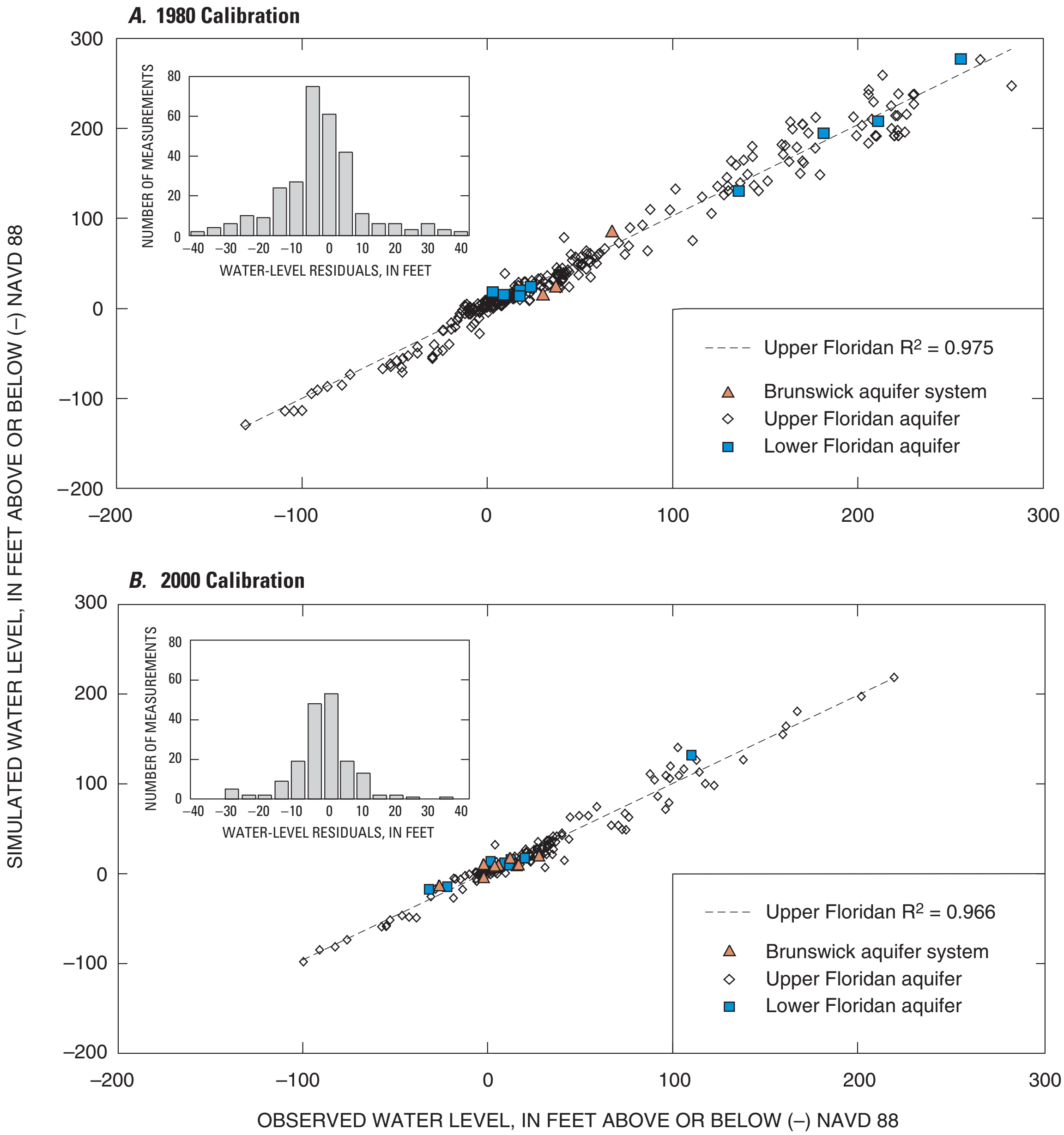


Figure 20. Observed and simulated water levels (residuals) for 1980 and 2000.

Table 7. Calibration statistics for simulated heads for 2000 conditions.

[Residual equals simulated minus observed head; –, minus]

Calibration statistic	Brunswick aquifer system (layer 3)	Upper Floridan aquifer (layer 5)	Lower Floridan aquifer (layer 7)
Number of observations	10	154	11
	54.1	319	142
Minimum residual (feet)	–7.67	–44.4	–3.62
	13.3	36.4	21.5
Mean residual (feet)	1.79	–0.843	5.20
	7.65	9.94	7.89
Root-mean square residual (feet)	5.91	9.94	9.15
	80	79	73
Calibration fit: Standard deviation of residuals divided by range of observed values (Kuniansky and others, 2003)	0.142	0.031	0.056

The spatial distribution of residuals provides some indication of potential bias in the model. Water-level residuals for the Brunswick aquifer system (layer 3) and Upper and Lower Floridan aquifers (layers 5 and 7) are shown for 1980 in figure 21 and for 2000 in figure 22. Generally, for layers 3 and 7, there are too few observations to discern spatial patterns of the residuals. For layer 5, however, there is an observed correlation in the magnitude of residuals with physiography for both the 1980 and 2000 simulations—in the northwestern part of the model area (north of the Gulf Trough), residuals are largest and show the greatest variability; in the coastal area, residuals are mostly of smaller magnitude. A likely reason for this correlation is greater topographic relief and a larger degree of stream-aquifer interaction north of the Gulf Trough, which result in a more irregular potentiometric surface. The model has a poorer fit in these areas, because the model cell size is not sufficient to depict this scale of heterogeneity.

A more subtle feature is the clustering of positive and negative residuals in parts of the updip area. It is possible that there are subregional scale variations in hydraulic conductivity that are not accounted for in the model because of a lack of data. An additional source of error may be inaccuracy of pumping data in the northwestern area, particularly for the 1980 simulation. Because much of the withdrawal in this area is for irrigation, pumpage estimates have a large margin of error and may not be accurately accounted for in the simulations.

Another spatial pattern of the residuals is evident for the 1980 simulation near the cone of depression at Savannah. Here, residuals generally are negative (simulated heads lower than observed) and probably reflect pumping data inaccuracy in this heavily stressed area.

Ground-Water Flow

Simulated 1980 and 2000 potentiometric surfaces (figs. 23 and 24, respectively) for the Upper Floridan aquifer have similar prominent features to those shown on potentiometric-surface maps for May 1980 (Johnston and others, 1981), May 1998 (Peck and others, 1999), September 1998 (Ransom and White, 1999), and September 2000 (Peck and McFadden, 2004). These features include large cones of depression in the Savannah, Ga., and Jacksonville, Fla., areas; smaller cones of depression at Jesup, Brunswick, and the St. Marys, Ga.–Fernandina Beach, Fla., areas; a steepening of the potentiometric gradient in the area of the Gulf Trough; flattening of the potentiometric gradient in the southwestern part of the model area; and potentiometric highs north of Port Royal Sound, S.C. (see locations, fig. 1).

The simulated potentiometric surfaces for the Lower Floridan aquifer (layer 7) are similar to those for the Upper Floridan for 1980 and 2000 conditions, indicating interaquifer leakage through layer 6 (figs. 23 and 24). Differences in simulated water levels for the Upper and Lower Floridan aquifers result from the vertical hydraulic conductivity of the intervening confining unit (layer 6), the generally lower transmissivity of the Lower Floridan aquifer, and the distribution of pumping from the Lower Floridan aquifer. Simulated water levels in the Lower Floridan aquifer are lower in the Savannah, Ga., and Fernandina Beach and Jacksonville, Fla., areas, where the aquifer is utilized for water supply. Although the general similarity of simulated water levels suggests an interaquifer leakage response, data are sparse for the Lower Floridan aquifer (layer 7) and the overlying confining unit (layer 6). Additional information on the hydraulic properties of the Lower Floridan aquifer and overlying confining unit are necessary to more accurately simulate interaction between the Upper and Lower Floridan aquifers.

The simulated potentiometric surfaces are similar (figs. 23 and 24) for the Brunswick aquifer system (layer 3) for 1980 and 2000. Flow generally is to the southeast, with part of the flow captured by a cone of depression in the Savannah area. Because there is no known pumpage from the Brunswick aquifer system in this area, this cone of depression results from interaquifer leakage to the heavily pumped Upper Floridan aquifer. A lower hydraulic gradient in the southeastern model area reflects the greater thickness and transmissivity of the aquifer system near the Southeast Georgia Embayment.

Vertical Distribution of Head

To provide an indication of how well the model simulates vertical-head relations among aquifers, simulated water levels for 2000 were compared to observed data from selected well clusters in the coastal area (fig. 25). These clusters consist of two or more wells completed in several hydrogeologic units.

Some of the well clusters were constructed after the year 2000 and, thus, have water levels that reflect changes that occurred after the model was calibrated. With the exception of head relations between the Upper and Lower Floridan aquifers, which have similar values of head in parts of the area, water-level changes after 2000 do not affect the relative difference in head between layers. For example, if the difference in head between two layers indicated upward flow during 2000, that same relation would be apparent during 2001, 2002, or 2003, despite changing water levels. To minimize the effect of variations in vertical gradients because of seasonal changes, mean-monthly water levels for September 2003—a period when water levels were available for most of the well clusters—were selected for analysis where available. In some instances mean-monthly data were not available and discrete water-level measurements were used.

Simulated and observed water levels show similar vertical flow potential in most of the area. In the northern part of the area, simulated and observed water levels at the Hopeulikit and Bulloch South well clusters both show downward gradients, reflecting aquifer recharge (fig. 25).

Near the Savannah area cone of depression, water levels in the Upper Floridan aquifer are depressed as a result of heavy pumping and flow gradients mostly are downward from the surficial aquifer system to the Upper Floridan aquifer for both simulated and observed water levels. This downward gradient is indicated at the Springfield, Pineora, Hutchinson Island, Tybee Island, Skidaway, Fort Pulaski, and Richmond Hill well clusters. In parts of this area—at the Springfield, Fort Pulaski, and Tybee Island well clusters—simulated water levels indicate slightly upward gradients from the Lower Floridan aquifer to the Upper Floridan aquifer; observations at the Fort Pulaski and Tybee Island well clusters, however, indicate that the flow gradient mostly is downward in these areas. This discrepancy probably reflects the model's simplification of the hydrologic system because of a lack of hydrogeologic data for the Lower Floridan and its overlying confining unit.

At the Gardi well cluster, observed water levels indicate a downward gradient from the surficial aquifer system to the Upper Floridan aquifer. Ground-water pumpage at Jesup, about 10 mi north of the site, lowered water levels in the Upper Floridan aquifer and created a downward flow gradient. Simulated water levels at the site also show a downward flow gradient from the surficial aquifer system to the Brunswick aquifer system; however, simulated water levels indicate upward flow from the Upper Floridan into the Brunswick aquifer system. This discrepancy with observed conditions may result from a lower simulated hydraulic conductivity assigned to the Brunswick aquifer system, which resulted in lower simulated water levels.

In the Brunswick–Glynn County area, observed and simulated vertical-head profiles reflect the complexity of the flow system in that area. In the downtown Brunswick area, flow gradients generally are upward from the Brunswick aquifer system to the surficial aquifer system, as indicated by the simulated and observed vertical-head profiles at the Coffin Park and Georgia Pacific South well clusters. Although there are no observed data, this relation also is indicated by simulated head at the Georgia Ports Authority well cluster at Brunswick.

Head relations among the Brunswick aquifer system and the Upper and Lower Floridan aquifers in the downtown Brunswick area are complex and variable. Simulated-head profiles in this area indicate that the Upper Floridan aquifer has the lowest water levels relative to surrounding units and, thus, is a "hydrologic sink" that receives flow from both overlying and underlying units. Partial profiles based on observations in this area indicate that head gradients generally are upward. Well clusters in that area, however, do not provide observations for all of the units; thus, the characterization of flow gradients is incomplete. Despite the lack of observations in some of the units, the simulated-head profiles seem reasonable because ground-water pumpage from the Upper Floridan aquifer has lowered ground-water levels and created flow gradients toward the aquifer.

Near the Altamaha River at the Ebenezer Bend well cluster, observed water levels indicate that the upper Brunswick aquifer has the lowest water levels relative to surrounding units and is a hydrologic sink, receiving flow from the underlying lower Brunswick aquifer and overlying surficial aquifer system. The reason for this condition is unclear; however, ground-water pumpage from the Brunswick aquifer system is occurring within 2.25 mi of the site, which may have lowered water levels relative to adjacent units. Simulated head at this location indicates that flow is downward from the surficial aquifer system to the Upper Floridan aquifer. This apparent discrepancy results because the model did not simulate flow in both the upper and lower Brunswick aquifers, but grouped these units together into a single layer (3) and, thus, could not provide an indication of flow within the Brunswick aquifer system.

At St. Marys, Camden County, the Upper Floridan aquifer has the lowest simulated water levels relative to surrounding units and is a hydrologic sink, receiving flow from the underlying Lower Floridan aquifer and overlying Brunswick aquifer system. Although there are no observations in the Upper Floridan aquifer at this site, data from nearby wells indicate that water levels in the aquifer are lowered as a result of pumping for industrial and public supply (Peck and others, 2005). During 2000, the aquifer supplied 36.7 Mgal/d (Fanning 2003), and potentiometric surface maps (Peck and McFadden, 2004) indicate the presence of a cone of depression during 2000.

Water-Level Change

To assess the effect of development on the ground-water system, maps were developed showing simulated changes in ground-water level. Water-level changes from predevelopment to 2000 conditions are shown in figure 26, and from 1980 to 2000 in figure 27.

Predevelopment to 2000

From predevelopment to 2000, ground-water levels declined in each of the simulated layers, with the most pronounced declines occurring in the Upper Floridan aquifer. In the Upper Floridan aquifer, simulated drawdown from predevelopment to 2000 exceeded 20 ft throughout most of the area and was greatest near the center of the cone of depression at Savannah, where water levels declined more than 100 ft (fig. 26). Simulated drawdown exceeded 60 ft in a large area that includes the Savannah cone of depression and adjacent pumping centers in Bryan, Liberty, and Long Counties; in the Brunswick area; in the Jacksonville–Fernandina Beach, Fla., and St. Marys, Ga., areas; and in the area surrounding Sandersville in Washington County. Most of these declines resulted from direct pumping from the Upper Floridan; however, declines in the Jacksonville, Fla., area likely are due to interaquifer leakage through layer 6 in response to pumping from the Lower Floridan aquifer. At Jacksonville, Fla., the Lower Floridan aquifer is used for water supply; estimated withdrawal during 2000 was 96 Mgal/d (see Duval County, table 2, fig. 16D) (see locations, fig. 1).

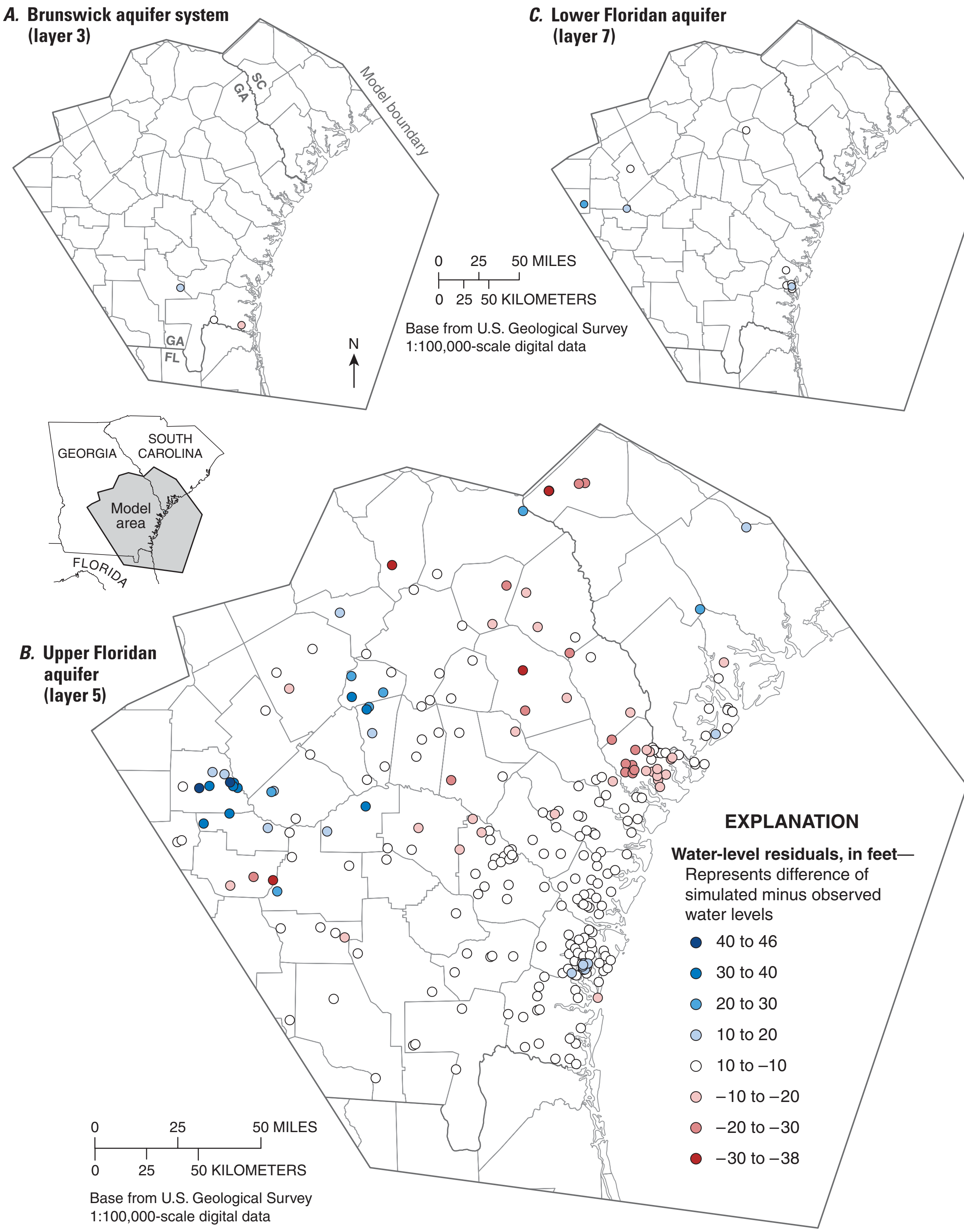


Figure 21. Difference between simulated and observed water levels (residuals) by model layer for 1980.

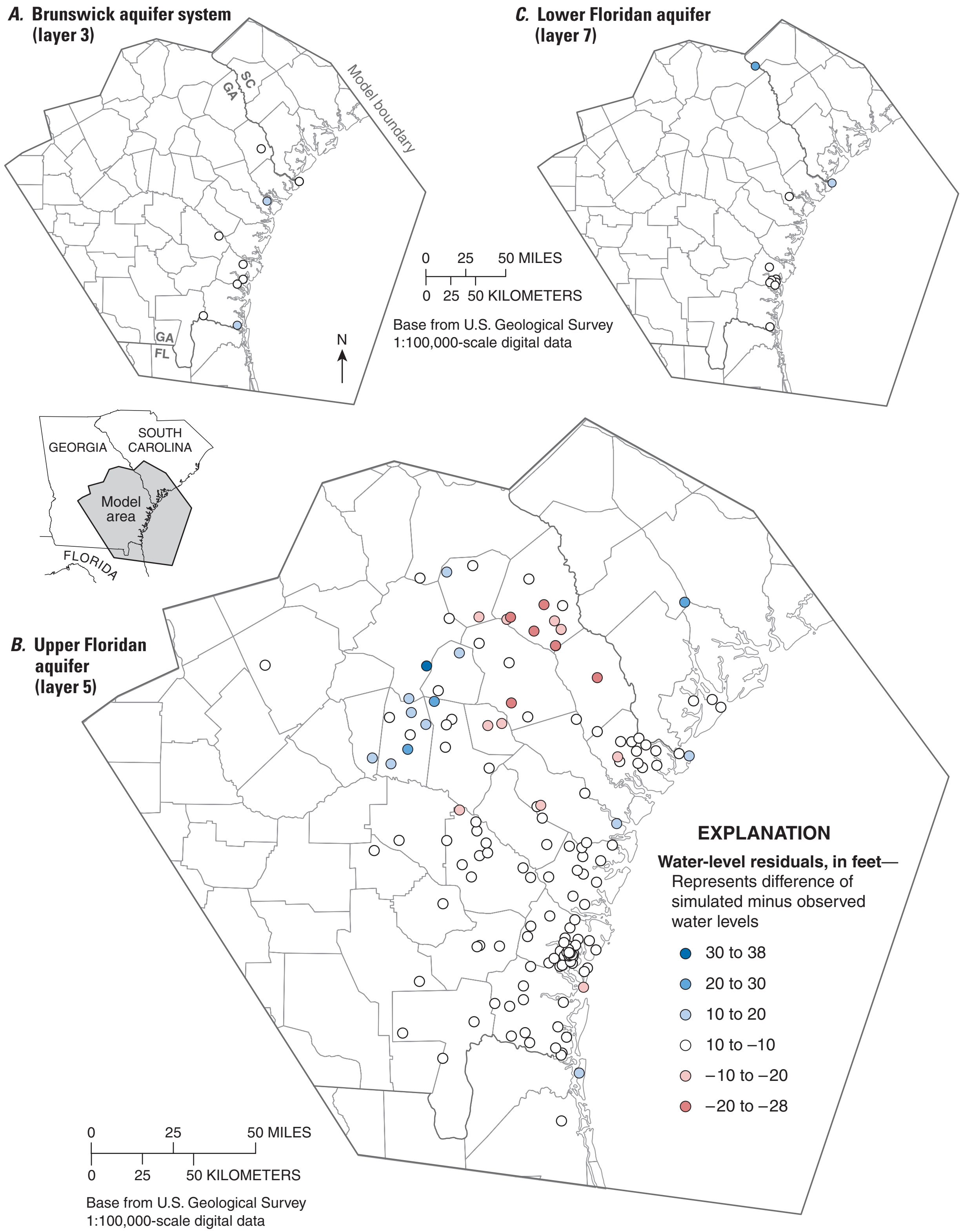


Figure 22. Difference between simulated and observed water levels (residuals) by model layer for 2000.

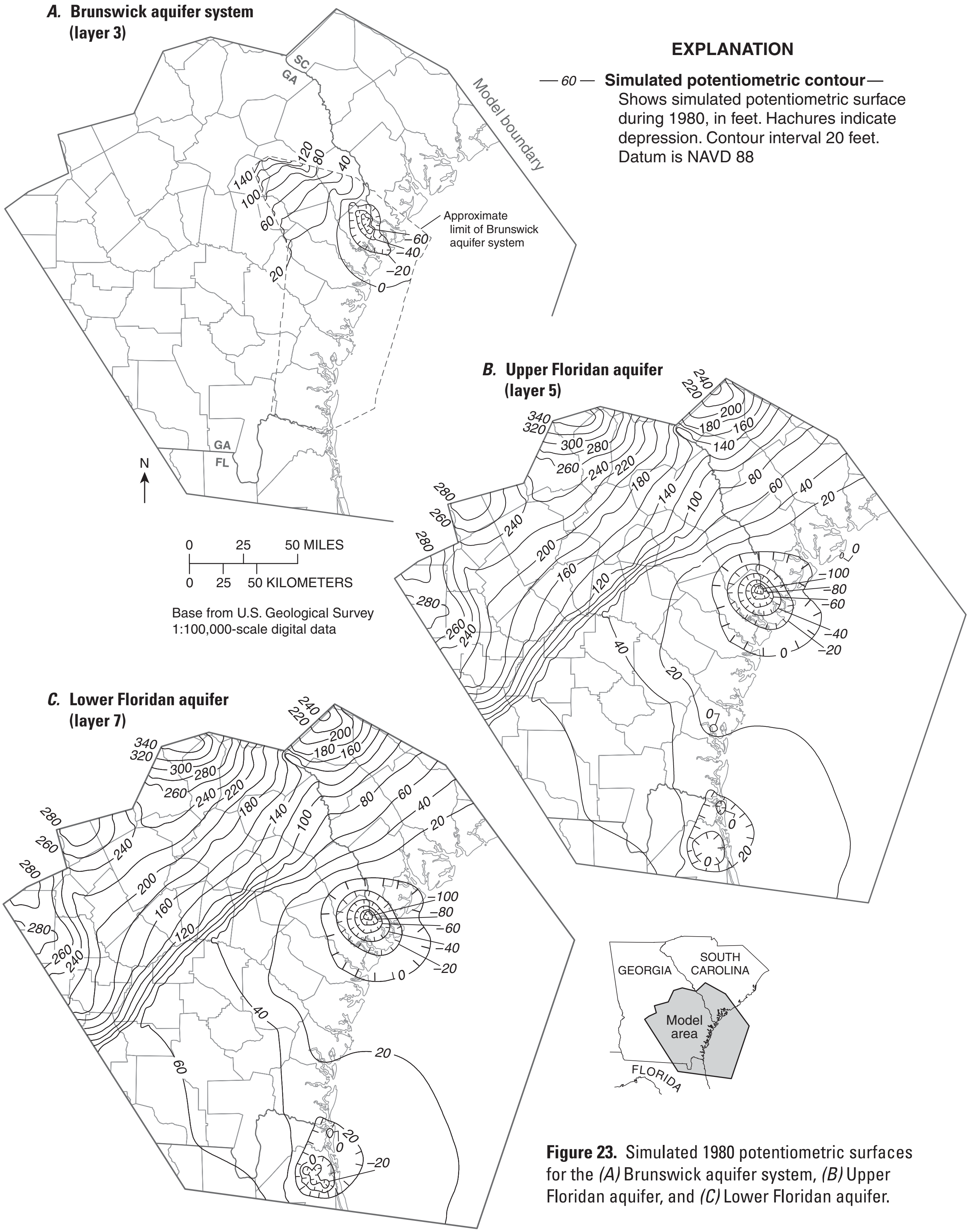
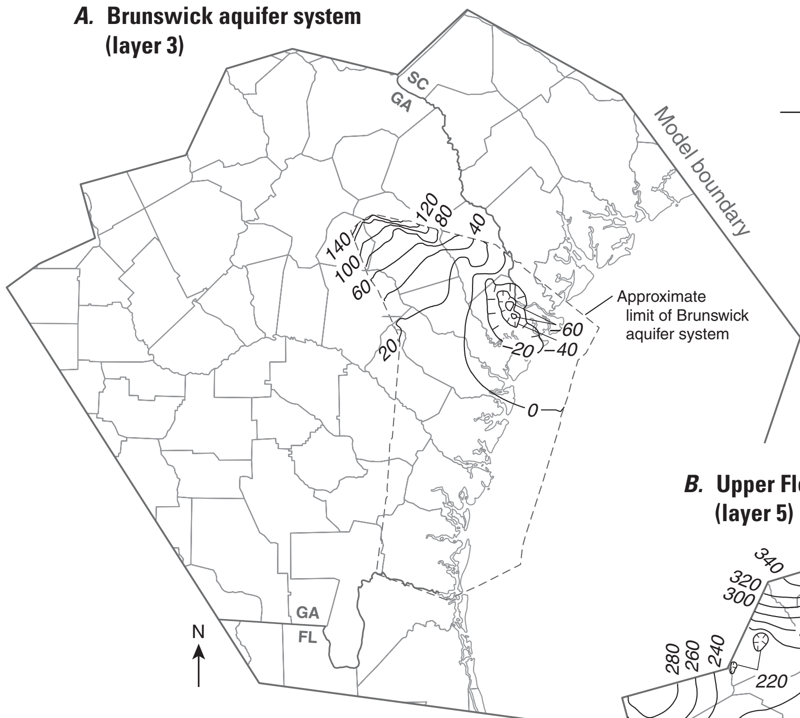
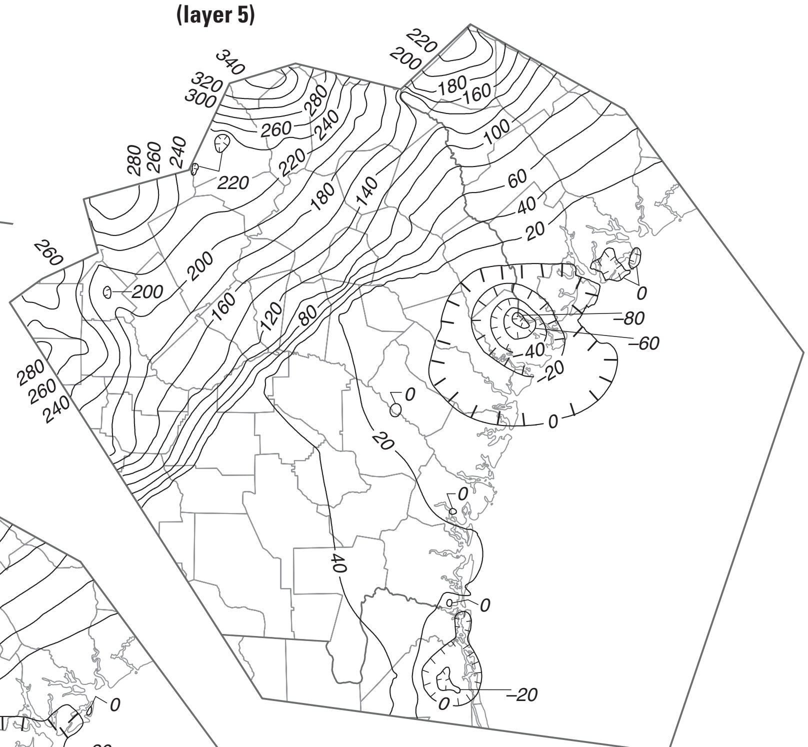


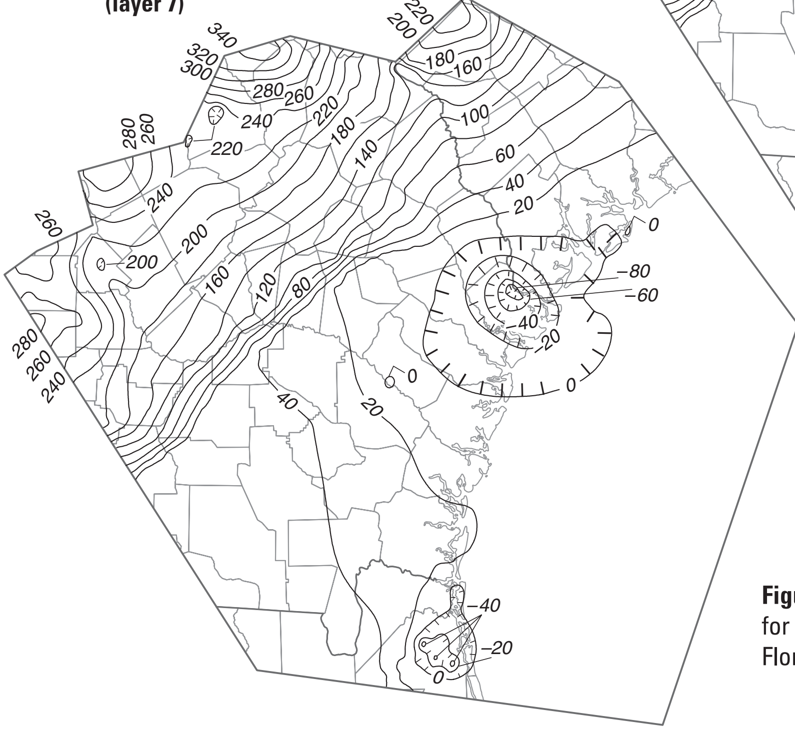
Figure 23. Simulated 1980 potentiometric surfaces for the *(A)* Brunswick aquifer system, *(B)* Upper Floridan aquifer, and *(C)* Lower Floridan aquifer.



EXPLANATION

— 60 — **Simulated potentiometric contour**—Shows simulated potentiometric surface during 2000, in feet. Hachures indicate depression. Contour interval 20 feet. Datum is NAVD 88





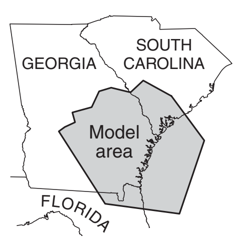


Figure 24. Simulated 2000 potentiometric surfaces for the *(A)* Brunswick aquifer system, *(B)* Upper Floridan aquifer, and *(C)* Lower Floridan aquifer.

Hopeulikit, Bulloch County (September 2000)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
—	168.8	1
116.5	146.2	3
—		
112.0	102.3	5
—	102.0	7

Pineora, Effingham County (January 2003)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
—	57.2	1
42.2	14.1	3
—		
—	–1.7	5
2.6	–1.6	7

Springfield, Effingham County (September 2003)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
—	54.8	1
13.6	31.0	3
4.1	5.7	5
—	6.5	7

Hutchinson Island, Chatham County (September 2000)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
—	2.5	1
—	–36.7	3
—		
–99.2	–101.4	5
—	–107.2	7
* –64.8	NS	NS

Fort Pulaski, Chatham County (September 2003)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
–2.9	NS	NS
–5.7	–2.3	1
—	–5.9	3
—		
–26.9	–25.9	5
—	–25.7	7
* –47.4	NS	NS

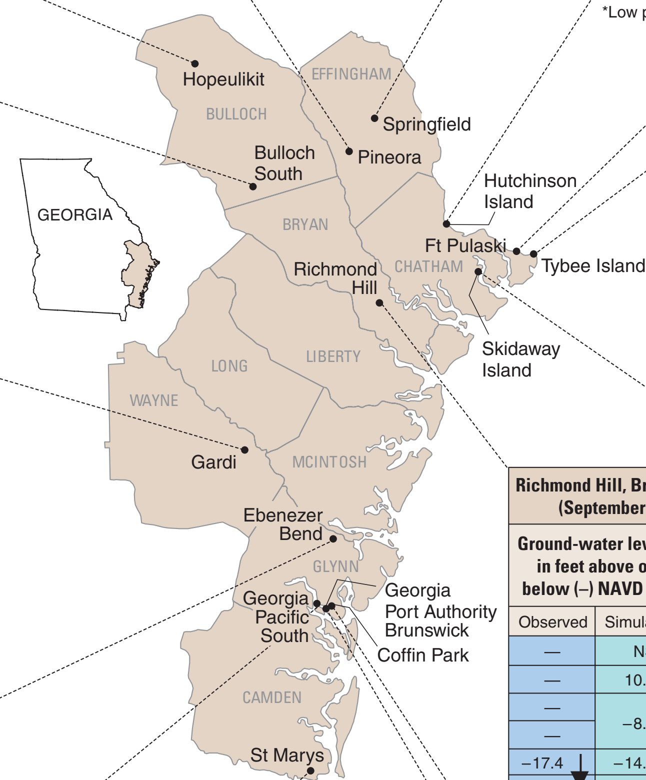
*Low permeability unit beneath Lower Floridan aquifer

Bulloch South, Bulloch County (September 2003)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
109.6	96.3	1
—	34.3	3
—		
34.9	10.1	5
—	10.1	7

Tybee Island, Chatham County (September 2003)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
–1.4	NS	NS
—	0.2	1
–3.1	–3.9	3
—		
–26.9	–17.6	5
–30.0	–17.0	7



Gardi, Wayne County (September 2000)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
28.8	36.0	1
15.8	9.5	3
—		
8.2	10.4	5
—	10.4	7

Richmond Hill, Bryan County (September 2003)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
—	10.8	1
—	–8.5	3
—		
–17.4	–14.8	5
–17.7	–14.9	7

Skidaway Island, Chatham County (September 2000)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
2.4	NS	NS
—	1.7	1
—	–20.0	3
—		
–46.0	–47.2	5
—	–47.1	7

Ebenezer Bend, Glynn County (September 2003)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
8.7	9.2	1
–1.3	8.9	3
10.6		
—	8.4	5
—	8.5	7

St. Marys, Camden County (September 2000)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
—	3.7	1
–2.1	10.9	3
—		
—	1.0	5
3.6	7.8	7

Georgia Port Authority Brunswick, Glynn County (September 2003)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
—	0.3	1
—	10.1	3
—		
—	9.1	5
24.7	11.0	7
*** 25.7		

***Fernandina permeable zone

Coffin Park, Glynn County (September 2000)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
4.1	0.8	1
5.9	9.9	3
—		
—	7.4	5
11.7	9.3	7

Georgia Pacific South, Glynn County (September 2000)

Ground-water level, in feet above or below (–) NAVD 88: Observed	Simulated	Model layer
—	NS	NS
3.5	1.7	1
—	10.2	3
—		
4.2	5.8	5
8.4	10.1	7

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Aquifer system	Water-bearing unit (observed and simulated)	Model layer
Surficial	Water-table zone	NS
	Confined zone	1
Brunswick	Upper Brunswick	3
	Lower Brunswick	
Floridan	Upper Floridan	5
	Lower Floridan	7
	Fernandina PZ**	

**Brunswick area

Figure 25. Simulated and observed water levels and vertical flow directions (arrows) at well-cluster sites (NS, not simulated; —, no observed value; Upper Brunswick; Upper Brunswick aquifer; Lower Brunswick; Lower Brunswick aquifer; Upper Floridan, Upper Floridan aquifer; Lower Floridan, Lower Floridan aquifer; PZ, permeable zone).

At Sandersville, Ga., withdrawal from the Upper Floridan aquifer was relatively low at 16 Mgal/d (see Washington County, table 1, fig. 16B), and the large decline may have resulted from hydraulic properties assigned to model layer 5. Here, the aquifer is known to be thin, largely clastic and has low transmissivity. Another reason for the large simulated decline may be the proximity of the pumping center to the northern no-flow boundary of the model.

Simulated drawdown in the Lower Floridan aquifer from predevelopment to 2000 also occurred across a wide area and was similar in magnitude to the Upper Floridan aquifer (fig. 26). In the Jacksonville, Fla., area, the Lower Floridan aquifer supplied an estimated 96 Mgal/d during 2000, which produced a simulated drawdown exceeding 80 ft near the centers of pumping and exceeding 60 ft across the surrounding area. Elsewhere in the study area, the Lower Floridan aquifer provides considerably less water (generally less than 4 Mgal/d per county), and the similarity of drawdown patterns to that in the Upper Floridan aquifer suggests an interaquifer leakage response to pumping from the Upper Floridan aquifer.

Simulated drawdown in the Brunswick aquifer system from predevelopment to 2000 exceeded 20 ft throughout most of its area of occurrence (fig. 26). The largest declines of greater than 80 ft were near the center of pumping in Savannah. Because the Brunswick aquifer system is not widely used in the area (withdrawal during 2000 was 0.24 Mgal/d), the simulated decline is largely due to interaquifer leakage in response to pumping from the Upper Floridan aquifer.

1980–2000

During 1980–2000, simulated water levels showed a combination of rises and declines in response to changing pumping patterns (fig. 27; appendix A). During this period, total ground-water use increased; however, the distribution of withdrawal changed—decreases exceeding 10 Mgal/d occurred in Chatham and Glynn Counties, and increases exceeding 10 Mgal/d occurred in Burke, Camden, Dooly, and Wilcox Counties, Ga., and in Beaufort County, S.C. (tables 1–2; fig. 7) (see locations, fig. 1).

Simulated drawdown exceeded 10 ft in the Upper Floridan aquifer across much of the western half of the model area, with drawdown exceeding 20 ft along parts of the western, northern, and southern boundaries (fig. 27; appendix A). These declines correspond to a general increase in pumpage from the Upper Floridan aquifer in these areas and match observed water-level trends in the area (fig. 8). In the Savannah area, simulated water levels in the Upper Floridan aquifer at the center of pumping rose more than 20 ft in response to decreased pumping, whereas observed water levels rose by a maximum of about 9 ft during the same period (figs. 8 and 27; appendix A). A less pronounced rise in water levels occurred in the Brunswick area in response to decreased pumping—simulated water levels rose as much as 8 ft and observed water levels rose by as much as 14 ft during 1980–2000.

Water levels in the Lower Floridan aquifer and Brunswick aquifer system also showed a combination of rises and declines during 1980–2000. Because these aquifers were not widely utilized in the coastal area during 1980–2000, most of the simulated changes were in response to changes in pumping patterns in the Upper Floridan aquifer, which induced a leakage response in the two aquifers. Water-level rises during 1980–2000 were simulated in both the Brunswick aquifer system and Lower Floridan aquifer at the center of the cone of depression at Savannah (fig. 27). Simulated water-level rises exceeded 20 ft in these aquifers; however, there are no water-level observations that span this period to confirm these changes. It is possible that some of the simulated rise in the Lower Floridan aquifer at Savannah may result from decreased pumpage from the aquifer in that area; however, estimated pumpage from the aquifer showed only a minor decrease of less than 0.4 Mgal/d during 1980–2000 (table 2).

Simulated and observed water levels in the Lower Floridan aquifer in the Brunswick area during 2000 showed little change, and were mostly within +/– 5 ft of 1980 levels (fig. 27). In the northern and western parts of the area, simulated water levels in the Lower Floridan aquifer showed a similar pattern of change, as that in the Upper Floridan aquifer; however, there are no water-level observations that span this period to confirm these changes.

Simulated water levels in the Brunswick aquifer system during 2000 were mostly within +/– 5 ft of 1980 water levels across most of the area, with the exception of the Savannah area (described above), and an area along the northwestern limit of the aquifer system, where water-level declines exceed 5–10 ft (fig. 27). Most of the simulated changes were in response to changes in pumping patterns in the Upper Floridan aquifer, which induced a leakage response in the aquifers. There are no water-level observations, however, that span this period to confirm these changes.

Water Budget

The water budgets are similar for the 1980 and 2000 simulations. Pumpage captures a large percentage of the flow that had left the study area via lateral boundaries in the predevelopment simulation. The simulated water budgets for the 1980 and 2000 simulations are illustrated in figure 28 and summarized in tables 8 and 9, respectively.

For the 1980 simulation, of the total simulated inflow rate of 1,082 Mgal/d, 37.3 percent (404 Mgal/d) is contributed by leakage from the general-head boundary, and 62.7 percent (679 Mgal/d) is contributed as inflow from lateral specified-head boundaries in layers 5 and 7 (table 8). Based on the total 1,082 Mgal/d outflow rate, 17.5 percent is attributed to ground-water discharge to the general-head boundary, 18.6 percent to outflow at lateral specified-head boundaries, and 63.9 percent as discharge to wells. Along the lateral specified-head boundary, the net flow is about 462 Mgal/d into the model area in the Upper Floridan aquifer and 15.8 Mgal/d into the model area in the Lower Floridan aquifer.

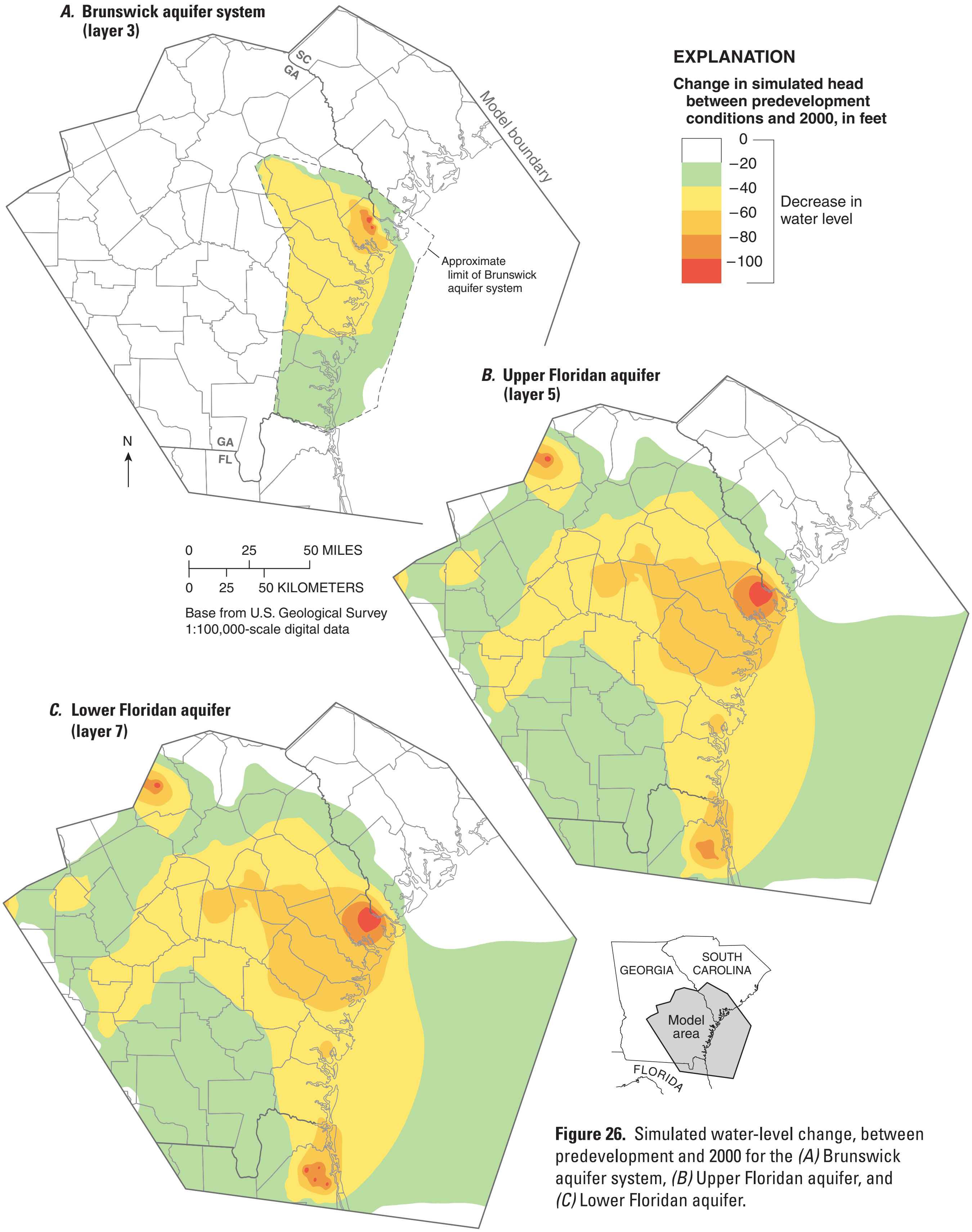


Figure 26. Simulated water-level change, between predevelopment and 2000 for the *(A)* Brunswick aquifer system, *(B)* Upper Floridan aquifer, and *(C)* Lower Floridan aquifer.

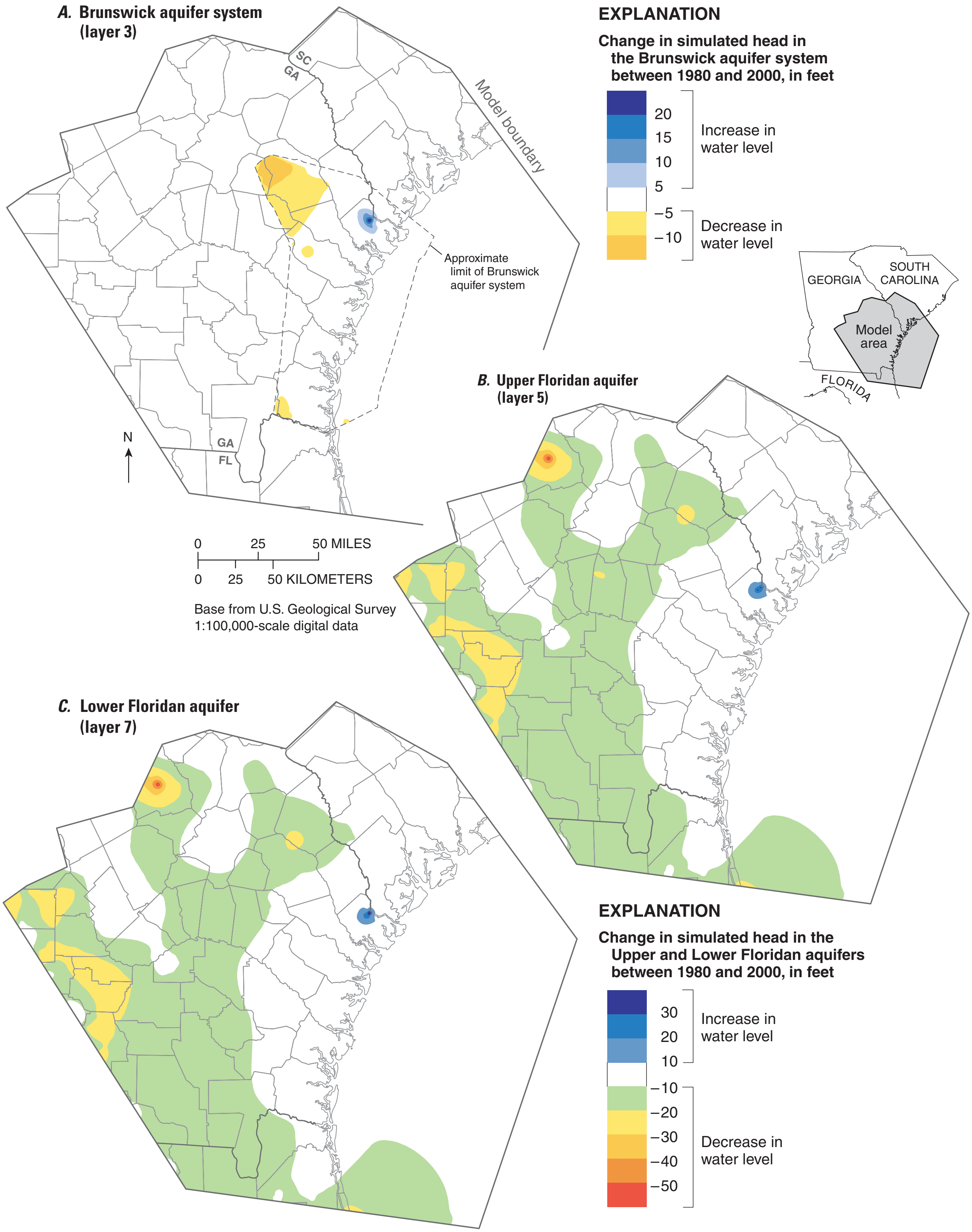


Figure 27. Simulated water-level change, between1980 and 2000 for the (*A*) Brunswick aquifer system, (*B*) Upper Floridan aquifer, and (*C*) Lower Floridan aquifer.

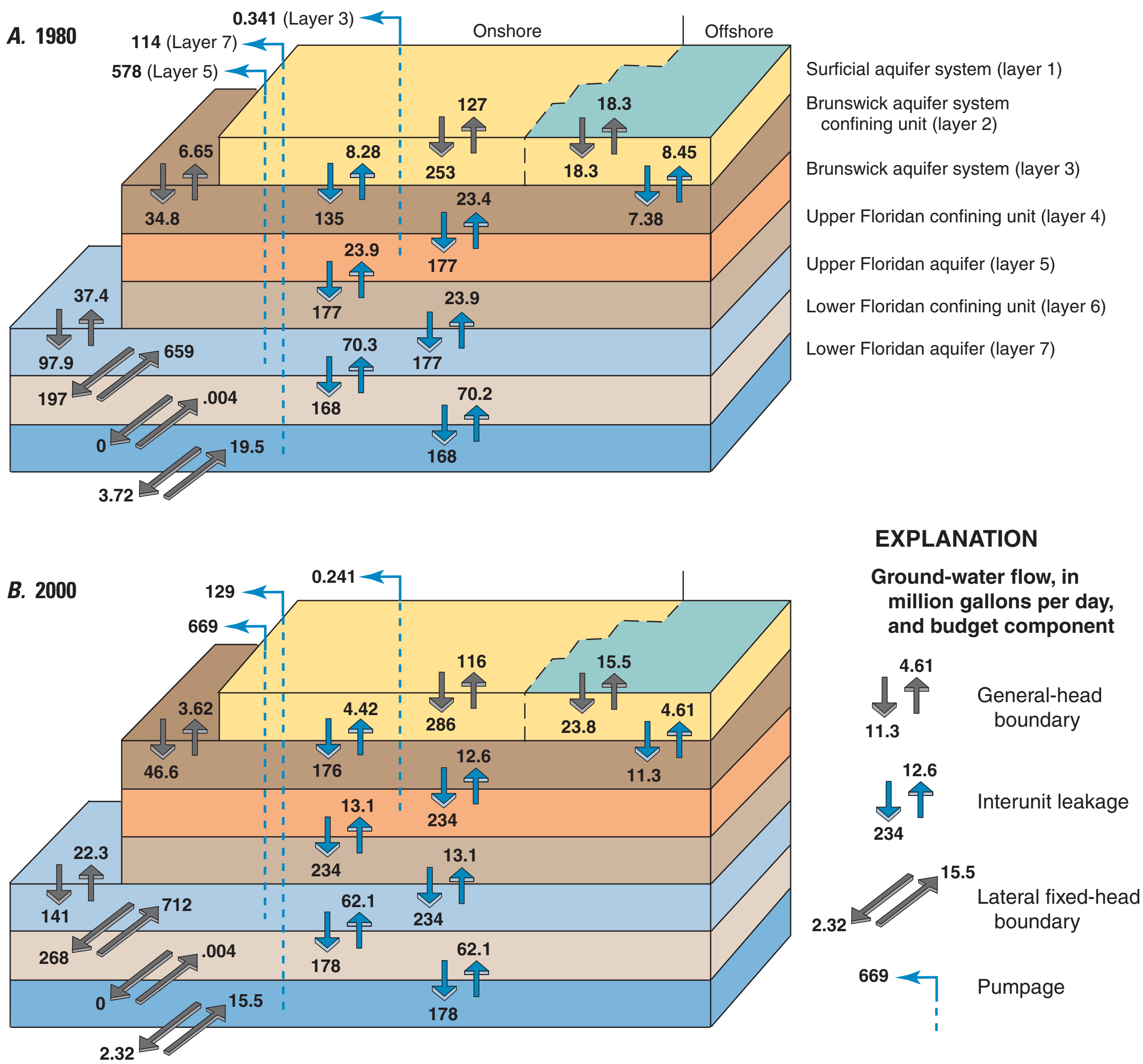


Figure 28. Schematic diagram showing simulated water budget for (*A*) 1980 and (*B*) 2000. (Values rounded to three significant digits. Values do not agree with those shown in figures 15A and 16A because of rounding.)

Table 8. Simulated 1980 water budget by model layer.

[Values reported to three significant digits and may not sum to totals due to independent rounding; well discharge for the Brunswick aquifer system does not match total pumpage on figure 15A because of rounding; well discharges for Upper and Lower Floridan aquifers do not agree with totals listed in tables 1 and 2 because some counties listed in these tables are partially outside of the simulated area and, thus, are not accounted for by the model; —, not applicable]

Model layer	Hydrogeologic unit	Inflow, in million gallons per day			Outflow, in million gallons per day			
		Inflow from general-head boundary	Inflow across lateral boundaries	Total	Outflow to general-head boundary	Outflow across lateral boundaries	Discharge to wells	Total
1	Surficial aquifer system	271	—	271	145	—	—	—
2	Confining unit	34.8	—	34.8		—	—	—
3	Brunswick aquifer system	—	—	—	—	—	0.341	0.341
4	Confining unit	—	—	—		—	—	—
5	Upper Floridan aquifer	97.9	659	757	37.4	197	578	578
6	Confining unit	—	0.004	0.004		0.000	—	—
7	Lower Floridan aquifer	—	19.5	19.5	—	3.72	114	114
	Total all layers	404	679	1,082		201	692	1,082
	Percentage of flow	37.3	62.7	100		18.6	63.9	100

Table 9. Simulated 2000 water budget by model layer.

[Values reported to three significant digits and may not sum to totals because of independent rounding; well discharge for the Brunswick aquifer system does not match total pumpage on figure 16A because of rounding; well discharges for Upper and Lower Floridan aquifers do not agree with totals listed in tables 1 and 2 because some counties listed in these tables are partially outside of the simulated area and, thus, are not accounted for by the model; —, not applicable]

Model layer	Hydrogeologic unit	Inflow, in million gallons per day			Outflow, in million gallons per day			
		Inflow from general-head boundary	Inflow across lateral boundaries	Total	Outflow to general-head boundary	Outflow across lateral boundaries	Discharge to wells	Total
1	Surficial aquifer system	310	—	310	132	—	—	132
2	Confining unit	46.6	—	46.6		—	—	3.62
3	Brunswick aquifer system	—	—	—	—	—	0.241	0.241
4	Confining unit	—	—	—		—	—	—
5	Upper Floridan aquifer	141	712	854	22.3	268	669	959
6	Confining unit	—	0.004	0.004		0.000	—	0.000
7	Lower Floridan aquifer	—	15.5	15.5	—	2.32	129	131
	Total all layers	498	728	1,226		270	798	1,226
	Percentage of flow	40.6	59.4	100		22.0	65.1	100

For the 2000 simulation, of the total simulated inflow rate of 1,226 Mgal/d, 40.6 percent (498 Mgal/d) is contributed by leakage from the general-head boundary, and 59.4 percent (728 Mgal/d) is contributed as inflow from lateral specified-head boundaries in layers 5 and 7 (table 9). Based on the total 1,226 Mgal/d outflow rate, 12.8 percent is attributed to ground-water discharge to the general-head boundary, 22.0 percent to outflow at lateral specified-head boundaries, and 65.1 percent as discharge to wells. Along the lateral specified-head boundary, the net flow is about 444 Mgal/d into the model area in the Upper Floridan aquifer and 13.2 Mgal/d into the model area in the Lower Floridan aquifer.

Major components of the simulated water budgets for predevelopment, 1980, and 2000 are compared and summarized in figure 29. As ground-water pumpage increased in the area, water-level declines occurred in the Upper Floridan aquifer resulting in changes in the flow rate into, out of, and within the ground-water system. These changes include (1) increased inflow from and decreased outflow to the general-head boundaries in both the onshore and offshore areas; (2) increased outflow to, and increased inflow from, lateral fixed-head boundaries; and (3) increased landward and seaward flow rates, with net flow along the coastline increasing landward.

Fixed-head and general-head boundaries provide additional water to the flow system in response to pumping stresses. Most of the increase in flow occurs in the Upper Floridan aquifer along the southern fixed-head boundary—more water is entering the system through this boundary than through all other boundaries combined. This is not unreasonable because the Upper Floridan aquifer extends far beyond that boundary throughout Florida (Miller, 1986), and potentially could be a substantial source of ground water into the modeled area.

Simulated recharge (inflow from the general-head boundary in the onshore area) showed increases between predevelopment, 1980, and 2000 (fig. 29). Total simulated recharge in the onshore area during predevelopment was 285 Mgal/d (0.21 in), during 1980 was 385 Mgal/d (0.28 in), and during 2000 was 474 Mgal/d (0.35 in). These increases correspond to declining

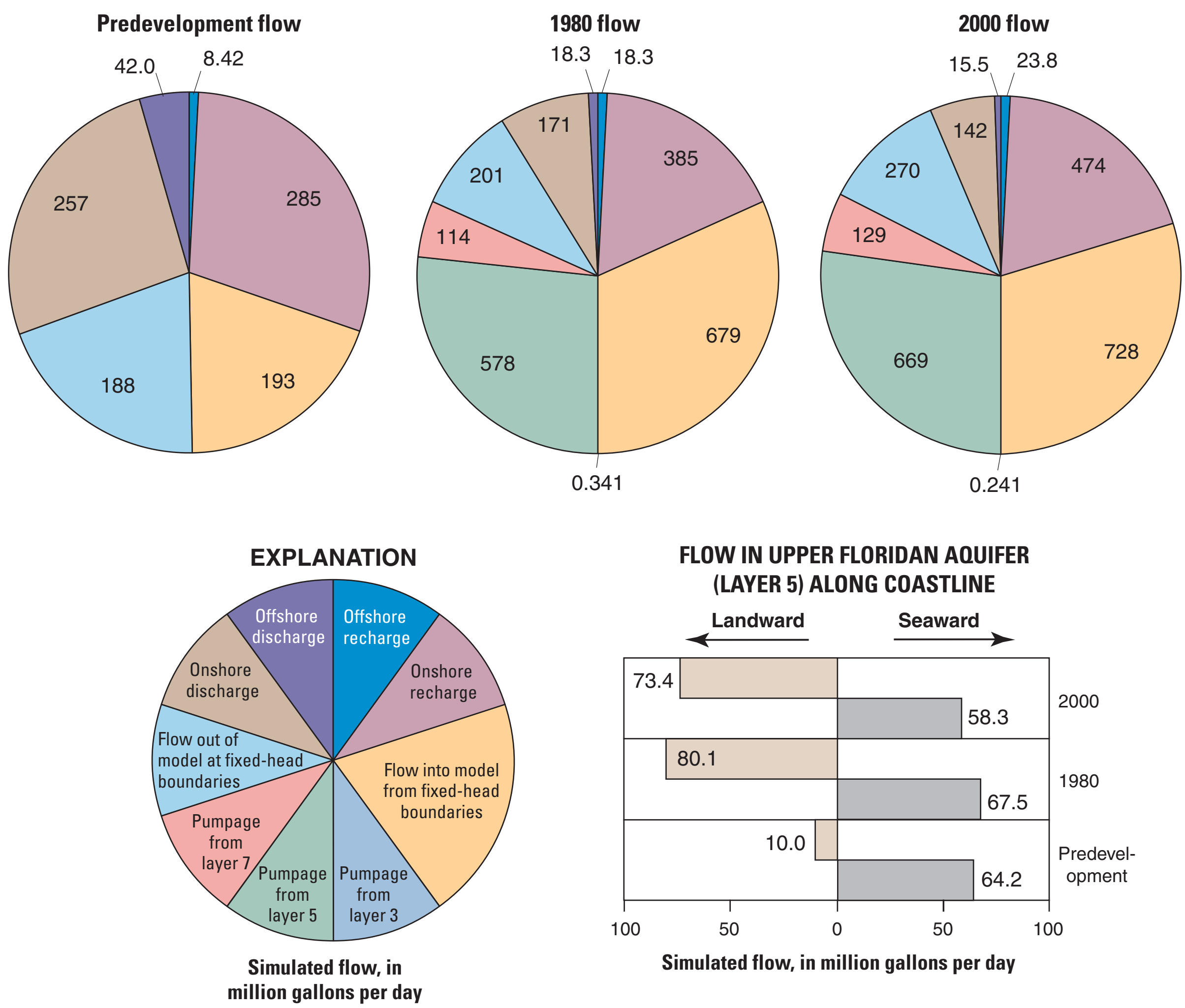


Figure 29. Comparison of major components of predevelopment, 1980, and 2000 simulated water budgets. (Values rounded to three significant digits. Values do not agree with those shown in figures 15A and 16A because of rounding.)

water levels in the Upper Floridan aquifer, which produced a downward hydraulic gradient and induced increased flow from the surficial aquifer system into deeper units. Pumpage also reduces simulated discharge to the source-sink boundary in the offshore area.

A map showing simulated recharge and discharge for 2000 (fig. 30) indicates a similar areal distribution of simulated recharge and discharge as the predevelopment map (fig. 19), with the following exceptions:

1. Areas of recharge north of the Gulf Trough have increased in extent and magnitude of recharge.
2. Discharge rates to major streams have decreased throughout the area, with flow gradients beneath downstream reaches of the Savannah and Altamaha Rivers reversing, so that these areas now recharge underlying aquifers.
3. A similar reversal in flow gradient beneath the major pumping center in the Savannah area, in Beaufort and Jasper Counties, S.C., and in the central part of the model area has induced simulated downward flow into underlying confined aquifers.

Seaward and Landward Flow

In the offshore area and along the coastline, simulated quantities of flow have changed since predevelopment and may have important implications for saltwater intrusion. The simulated quantity of water discharging from the surficial aquifer layer into the Atlantic Ocean has decreased since predevelopment, whereas flow has increased (fig. 29) from the ocean into the surficial aquifer layer. Along the coastline, the ratio of seaward to landward flow within the Upper Floridan aquifer has changed since predevelopment, when more of the flow in the aquifer was seaward; whereas during 1980 and 2000, more of the flow was landward.

The direction and magnitude of horizontal onshore-offshore flow in the Upper and Lower Floridan aquifers during predevelopment and 2000 conditions at various locations along the coastline are shown in figure 31. The onshore-offshore interface was subdivided into zones on the basis of designated hydraulic-property zones for the Upper Floridan aquifer (fig. 12).

Simulated predevelopment flow was from onshore to offshore for all zones in both aquifers, with the greatest flow rates in the southern part of the simulated area (fig. 31A). In the Upper Floridan aquifer, the largest simulated offshore flow rate was in zone F8 in the Camden County area, and is probably the result of relatively high hydraulic conductivity of the aquifer in that area (zone F8, fig. 12). Lower Floridan flow rates are less than those for the Upper Floridan because of its lower hydraulic conductivity.

The simulated flow direction for 2000 pumping conditions in both aquifers generally is landward, as a result of onshore pumping (fig. 31B). An exception is along the coast in zone F8 in Camden County area, where flow in both aquifers is predominantly offshore similar to predevelopment. This area is characterized by a high hydraulic conductivity zone (F8, fig. 12) located between two relatively lower hydraulic conductivity zones (F7 and F11), which contain major pumping centers at Brunswick and St. Marys, Ga.–Fernandina Beach, Fla., respectively. During predevelopment conditions, the regional potentiometric gradient in the area of Glynn, Camden, and Nassau Counties (zones F7, F8 and F11) is low relative to present-day conditions, so the offshore flux in the area is lower than during 2000. Pumping at the two major pumping centers has resulted in the development of a large regional potentiometric gradient and even larger localized gradients around cones of depression in the potentiometric surface of the Upper Floridan aquifer (fig. 5). Thus, even though the water levels are lower during 2000 than during predevelopment, the potentiometric gradient is steeper, resulting in higher flow rates in the offshore direction. These larger fluxes channel through the higher hydraulic conductivity zone in Camden County (zone F8) toward the offshore area and curl back landward toward the pumping centers in the adjacent zones (F7 and F11).

Model Sensitivity

The sensitivity of the calibrated steady-state model was evaluated to determine the relative importance of several model parameters on simulated ground-water levels and flow rates. Ground-water models are variably sensitive to model input used to describe the physical aspects of a system. This includes aquifer properties and well pumping rates; structural features of the model, such as grid resolution, model layering, and temporal discretization; and location and type of model boundaries. For the parameters for which the model is most sensitive, small variations in those parameters will result in large differences in simulated water levels. Furthermore, if the model is more sensitive to one parameter than to others, the degree of uncertainty of that parameter will have a greater effect on the uncertainty of the model results than that of other parameters.

To evaluate the sensitivity of the coastal ground-water flow model, it was assumed that the model layering and types of model boundaries are set, and that the grid discretization has been optimized for the distribution of input data and observations. Because the model simulates steady-state conditions, temporal discretization is not considered as part of the analysis.

The sensitivity analysis includes composite-scaled sensitivities of comparable parameters calculated using the sensitivity equation method described in MODFLOW-2000 (Hill and others, 2000), as well as from the perturbation method. The composite-scaled sensitivity as described in Hill (1998) is a dimensionless measure of the change in calculated head with respect to the value of a parameter and is independent of the actual values of the observations. A larger composite-scaled sensitivity indicates a relatively larger sensitivity of the model to a given parameter. Composite-scaled sensitivities were used to evaluate the relative sensitivities of pumping rate, vertical and horizontal hydraulic conductivity, and the conductance of the general-head boundary.

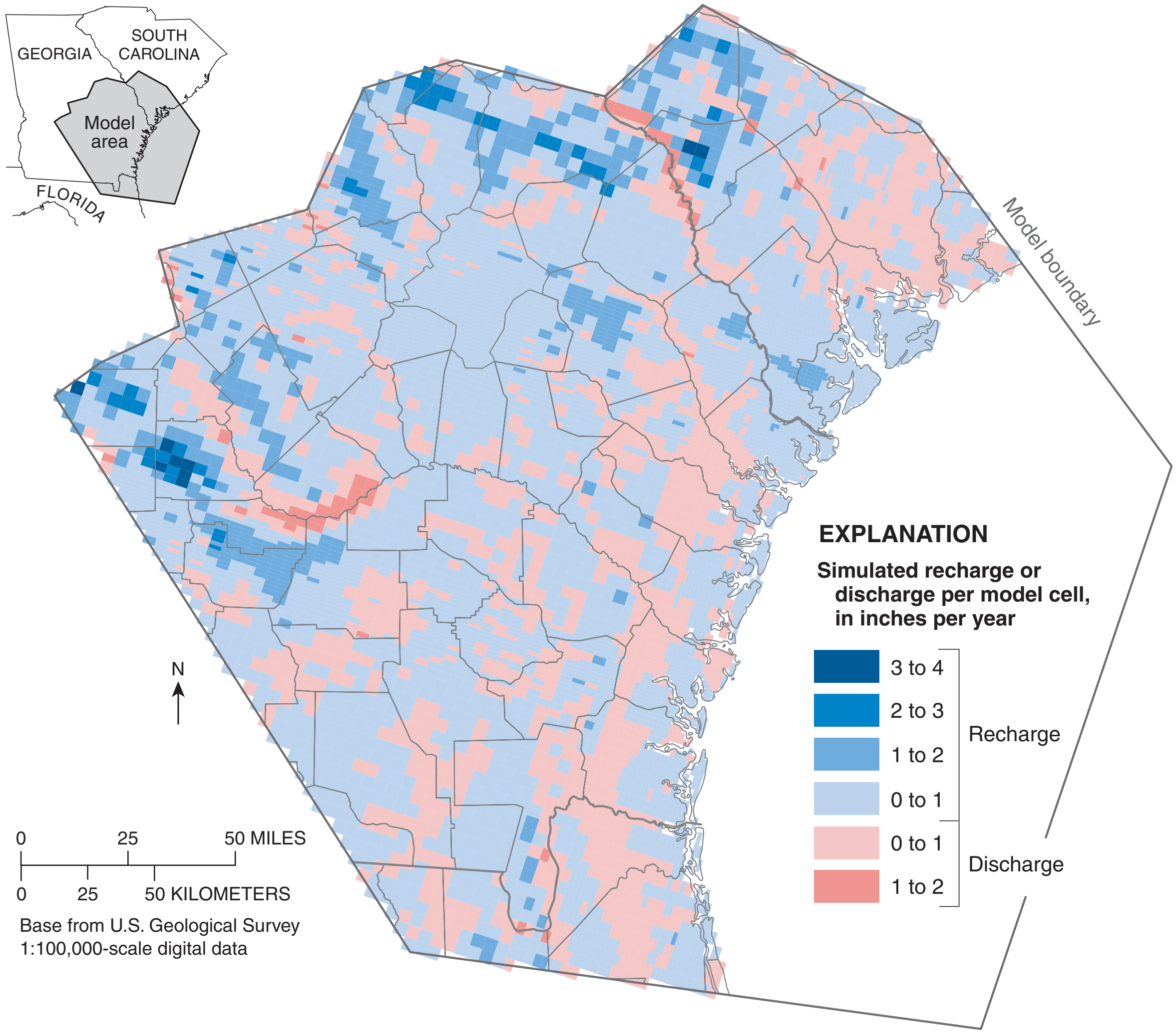


Figure 30. Simulated recharge or discharge during 2000.

The perturbation method was used to examine model sensitivity to pumping and to the fixed-head boundary condition. Because the composite-scaled sensitivity analysis indicated a high sensitivity to pumping rates, a simulation was conducted, whereby 2000 pumping was increased by 10 percent, and the resulting decline in water levels mapped. An additional simulation was conducted to test the sensitivity of the southern fixed-head boundary, which contributes a substantial portion of water to the flow system. Because the value of the controlling head at this boundary cannot be compared using composite-scaled sensitivity, the head at this boundary was increased by 10 ft, and the resulting rise in simulated water levels was mapped.

Composite-Scaled Sensitivities

Composite-scaled sensitivities for pumping rate, vertical and horizontal hydraulic conductivity for each zone, and the conductance of the general-head boundary for both the 1980 and 2000 simulations are shown in figure 32. The general pattern of relative sensitivity is similar for the 1980 and 2000 simulations, with minor differences in the order of sensitivities. The sensitivity of vertical hydraulic conductivity for the aquifer units (layers 1, 3, 5, and 7) and horizontal hydraulic conductivity for the confining units (layers 2, 4, and 6) was negligible and are not shown on figure 32.

The model is most sensitive to pumping by a wide margin. Of the remaining parameters, the model is most sensitive to the horizontal hydraulic conductivity of the Upper Floridan aquifer (layer 5) in the coastal area (zones UF6Kh, UF4Kh, UF5Kh, and UF7Kh) and in the area north of the Gulf Trough (zone UF1Kh), and to the vertical hydraulic conductivity of the Upper Floridan confining unit (layers 2, 3, and 4, zone CU1Kv). The model is less sensitive to other hydraulic conductivity zones, either because of fewer water-level observations (for example, BWKh for layer 3, or LFKh for layer 7) or to a lesser influence on overall model results. The model is relatively insensitive to the conductance of the general-head boundary.

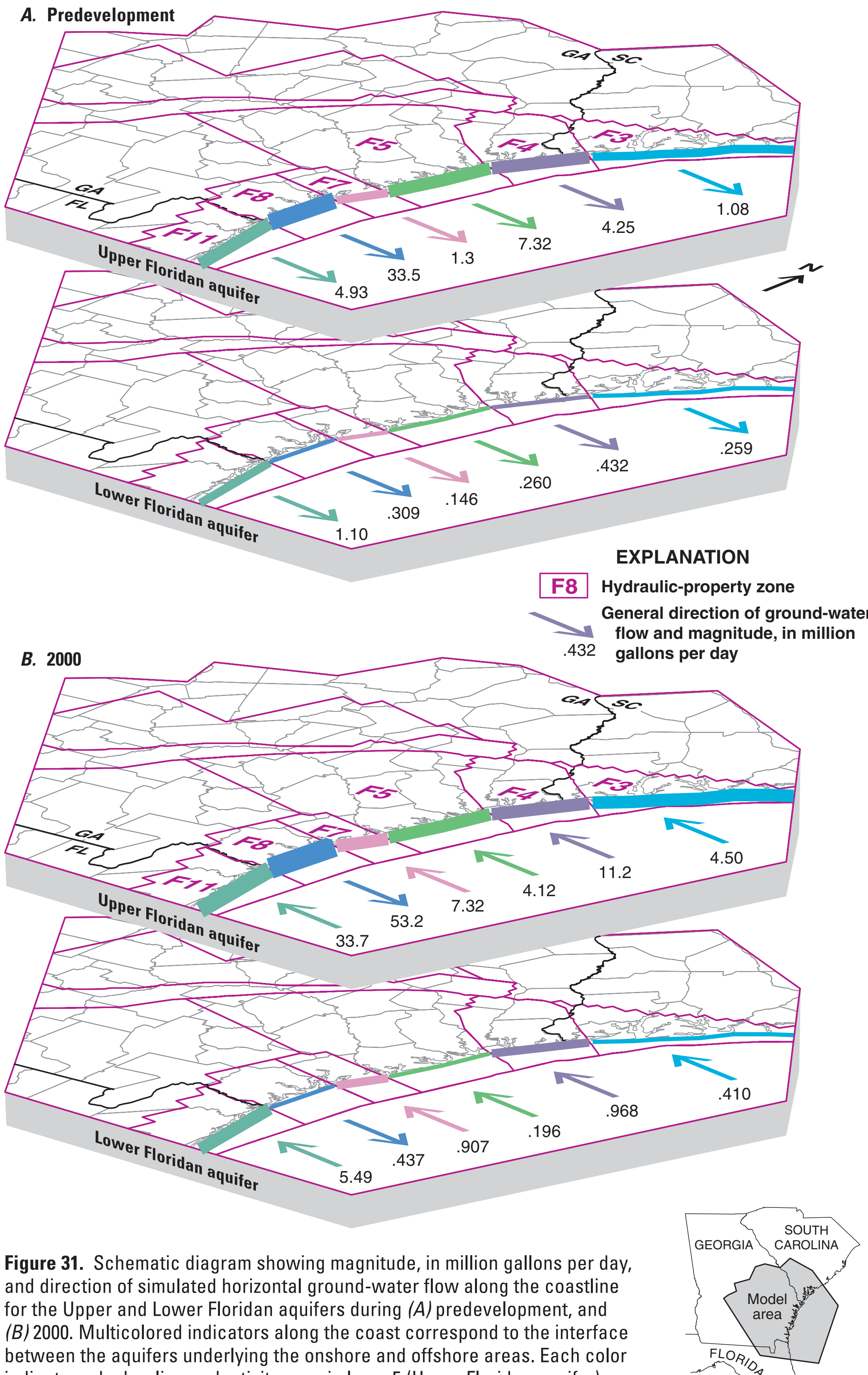
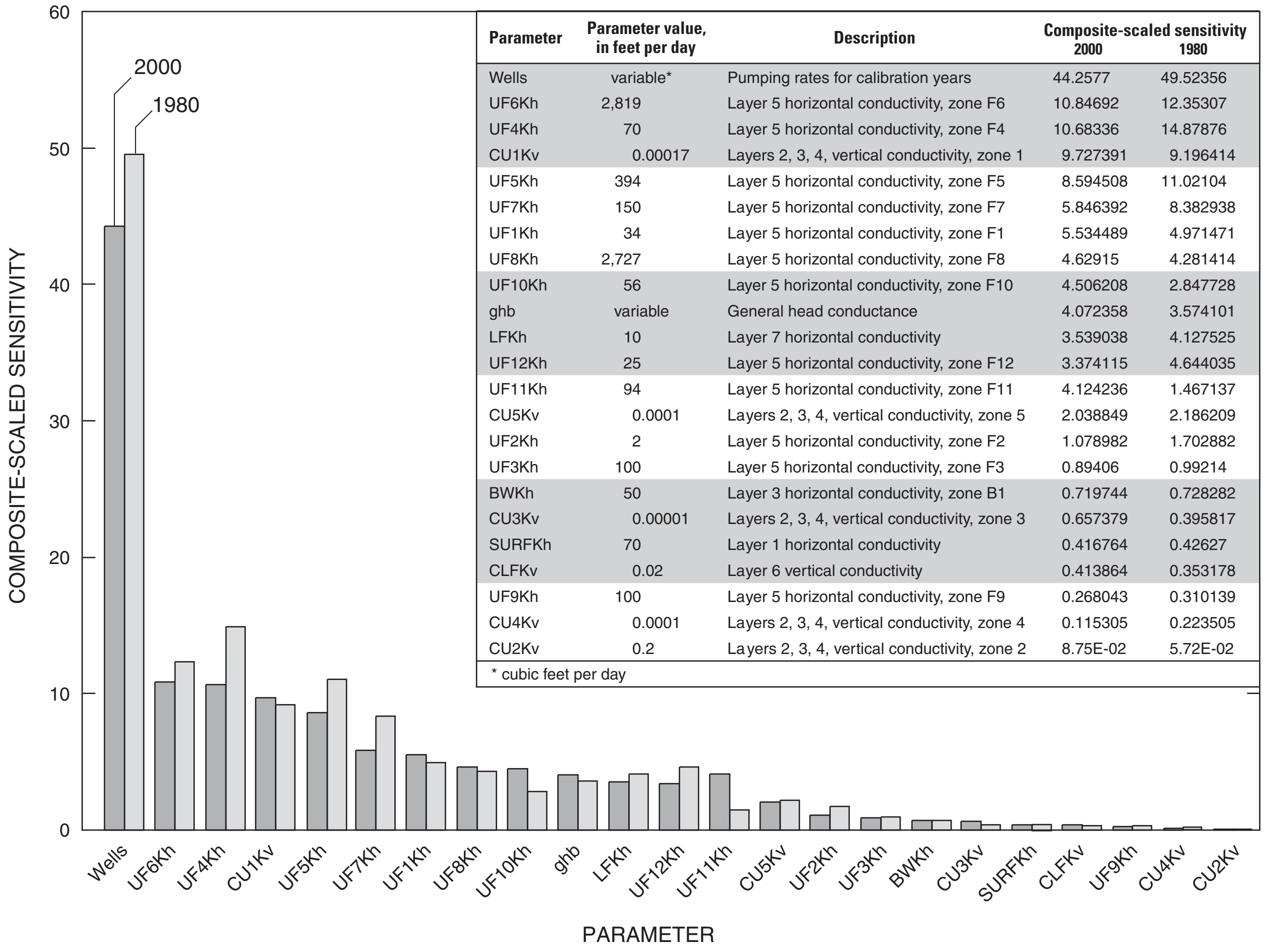


Figure 31. Schematic diagram showing magnitude, in million gallons per day, and direction of simulated horizontal ground-water flow along the coastline for the Upper and Lower Floridan aquifers during *(A)* predevelopment, and *(B)* 2000. Multicolored indicators along the coast correspond to the interface between the aquifers underlying the onshore and offshore areas. Each color indicates a hydraulic conductivity zone in layer 5 (Upper Floridan aquifer).



Parameter	Parameter value, in feet per day	Description	Composite-scaled sensitivity 2000	Composite-scaled sensitivity 1980
Wells	variable*	Pumping rates for calibration years	44.2577	49.52356
UF6Kh	2,819	Layer 5 horizontal conductivity, zone F6	10.84692	12.35307
UF4Kh	70	Layer 5 horizontal conductivity, zone F4	10.68336	14.87876
CU1Kv	0.00017	Layers 2, 3, 4, vertical conductivity, zone 1	9.727391	9.196414
UF5Kh	394	Layer 5 horizontal conductivity, zone F5	8.594508	11.02104
UF7Kh	150	Layer 5 horizontal conductivity, zone F7	5.846392	8.382938
UF1Kh	34	Layer 5 horizontal conductivity, zone F1	5.534489	4.971471
UF8Kh	2,727	Layer 5 horizontal conductivity, zone F8	4.62915	4.281414
UF10Kh	56	Layer 5 horizontal conductivity, zone F10	4.506208	2.847728
ghb	variable	General head conductance	4.072358	3.574101
LFKh	10	Layer 7 horizontal conductivity	3.539038	4.127525
UF12Kh	25	Layer 5 horizontal conductivity, zone F12	3.374115	4.644035
UF11Kh	94	Layer 5 horizontal conductivity, zone F11	4.124236	1.467137
CU5Kv	0.0001	Layers 2, 3, 4, vertical conductivity, zone 5	2.038849	2.186209
UF2Kh	2	Layer 5 horizontal conductivity, zone F2	1.078982	1.702882
UF3Kh	100	Layer 5 horizontal conductivity, zone F3	0.89406	0.99214
BWKh	50	Layer 3 horizontal conductivity, zone B1	0.719744	0.728282
CU3Kv	0.00001	Layers 2, 3, 4, vertical conductivity, zone 3	0.657379	0.395817
SURFKh	70	Layer 1 horizontal conductivity	0.416764	0.42627
CLFKv	0.02	Layer 6 vertical conductivity	0.413864	0.353178
UF9Kh	100	Layer 5 horizontal conductivity, zone F9	0.268043	0.310139
CU4Kv	0.0001	Layers 2, 3, 4, vertical conductivity, zone 4	0.115305	0.223505
CU2Kv	0.2	Layers 2, 3, 4, vertical conductivity, zone 2	8.75E-02	5.72E-02

* cubic feet per day

Figure 32. Composite-scaled sensitivity of selected model parameters.

Pumping Sensitivity

To provide an illustration of how a change in pumping would affect simulated head, a 10-percent increase during 2000 pumping rates was simulated and the resulting change in water levels mapped (fig. 33). A value of 10 percent was used because pumping rates could have a margin of error at least this large in some parts of the model area. This increase in pumpage resulted in widespread decline in water level greater than 2 ft across most of the simulated area that diminished toward the southern boundary and into South Carolina. As would be expected, the largest differences in simulated head are in areas where pumping is most concentrated and rates are highest; water-level declines exceeded 10 ft the Upper and Lower Floridan aquifers (layers 5 and 7) in the Savannah, Ga., and at least 4 ft in Jacksonville, Fla., areas. Simulated head also decreased substantially in an area near the northwestern no-flow boundary where the Upper and Lower Floridan aquifers are relatively thin and have low hydraulic conductivities. A reduction in pumping rates of 10 percent would show rises in water level of similar distribution and magnitude.

Fixed-Head Boundary Condition Sensitivity

To evaluate the sensitivity of the southern fixed-head boundary, a simulation was conducted, whereby the head along the boundary was increased by 10 ft, and the difference in simulated water levels was mapped (fig. 34). A 10-ft change was considered a reasonable variation, based on water-level changes observed in some wells in the area. As would be expected, water-level rises are greatest close to the boundary and diminish with distance from the boundary. In the Upper Floridan aquifer, the lateral extent of a water-level rise greater than 8 ft is dependent on the hydraulic conductivity of the aquifer—the higher the hydraulic conductivity, the further the rise is propagated in the aquifer (zones F6, F8, and F11, and part of F7, fig. 12). The Lower Floridan aquifer shows a similar pattern of water-level response as the Upper Floridan aquifer; the Lower Floridan aquifer, however, is assigned uniform hydraulic properties; thus, the rise is a result of an interaquifer leakage response. The simulated water-level rise is subdued toward the low-permeability Gulf Trough (zone F2, fig. 12), and in the relatively lower permeability Chatham County area (zones F4 and F12, fig. 12). A reduction of fixed-head values along the southern boundary of the same magnitude would result in a similar distribution and magnitude of simulated water-level decline.

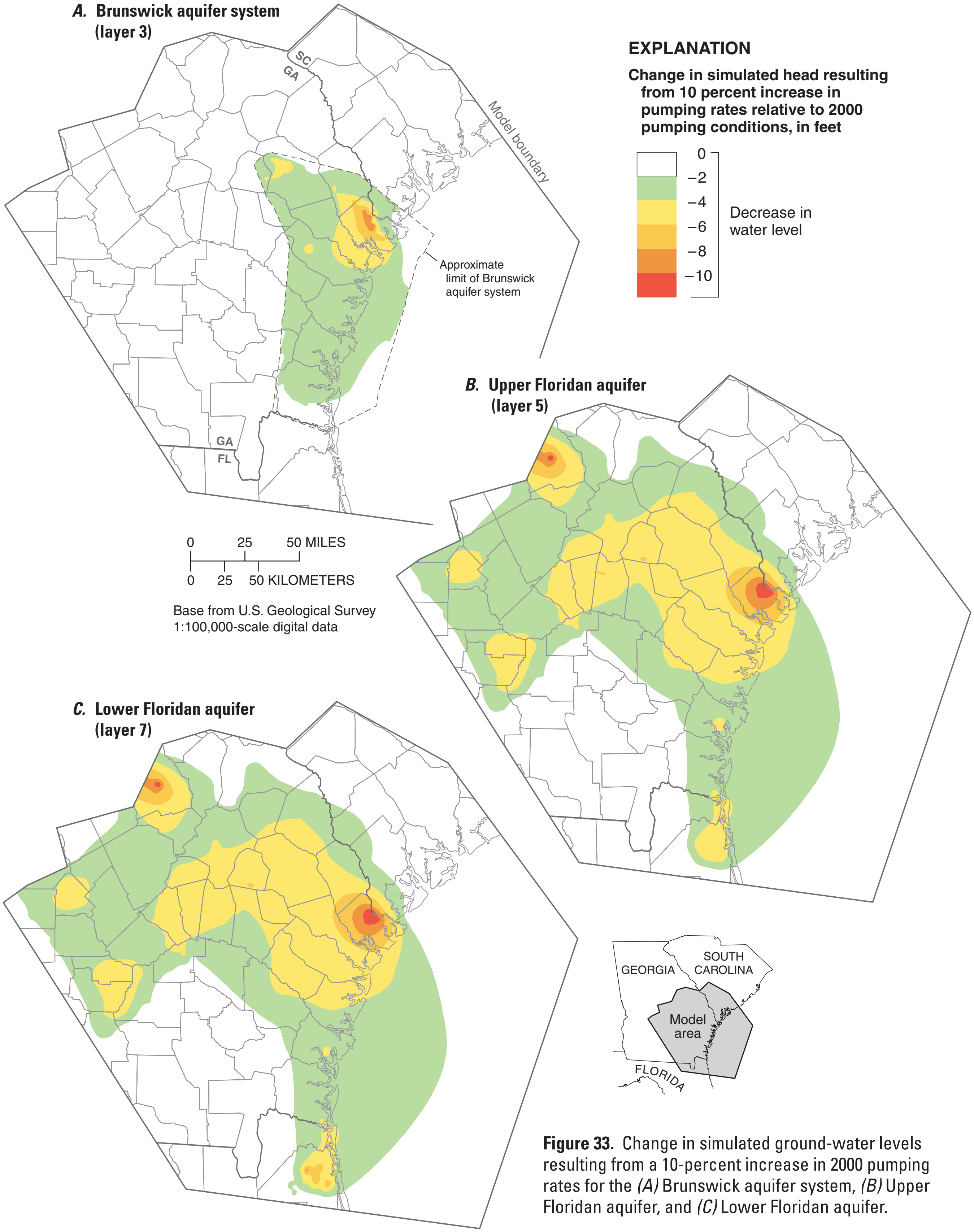


Figure 33. Change in simulated ground-water levels resulting from a 10-percent increase in 2000 pumping rates for the *(A)* Brunswick aquifer system, *(B)* Upper Floridan aquifer, and *(C)* Lower Floridan aquifer.

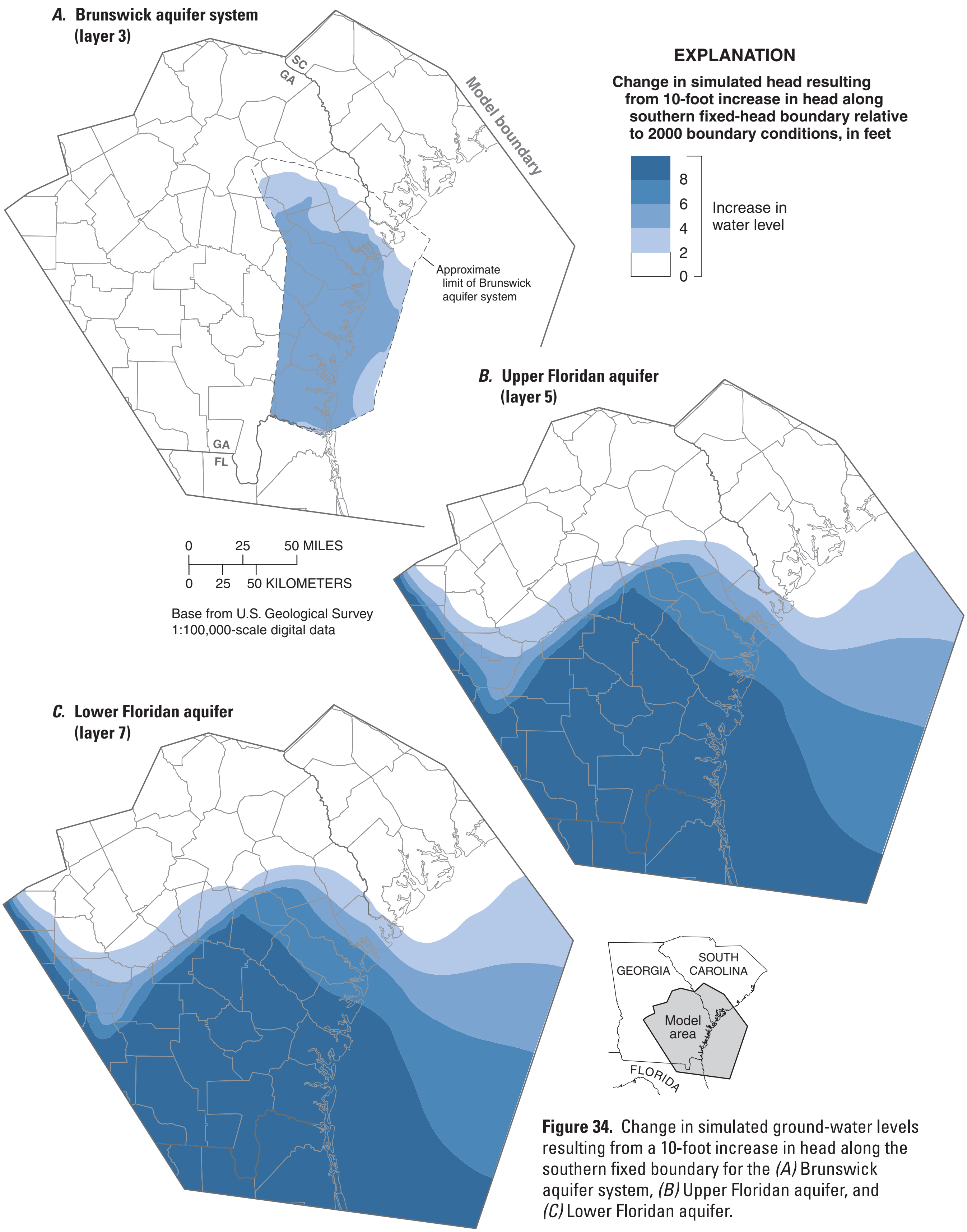


Figure 34. Change in simulated ground-water levels resulting from a 10-foot increase in head along the southern fixed boundary for the *(A)* Brunswick aquifer system, *(B)* Upper Floridan aquifer, and *(C)* Lower Floridan aquifer.

Model Limitations

A ground-water flow model is a simplified representation of natural processes and properties of a hydrologic system and, as such, is subject to limitations. These limitations affect the degree to which the model accurately represents the system and the reliability of the model to predict system characteristics at any location or time. Limitations are inherent in the theoretical and computational aspects of the model (such as the equation of flow used), as well as in the specifics of model construction, including spatial and temporal model scales and discretization, types of boundary conditions applied, and data used to describe the physical characteristics of the system. Most of the data are not analyzed for error or uncertainty, limiting the ability to quantify resultant model uncertainty with any reliability. Emphasis herein is placed on limitations of the model construction, because it is not within the scope of this report to analyze limitations of numerical models of Darcian flow. In general, an attempt is made to discuss model limitations qualitatively and analyze the contributing causes of model uncertainty.

The ability of the model to address specific aspects of the ground-water flow system is limited by its spatial scale and discretization. This model encompasses a large area and is designed to simulate the regional-scale flow system characteristics; it is not designed to simulate more localized features. The scale and discretization of this model limit its ability to simulate accurately the surficial aquifer system and related surface-water/ground-water interactions. A more appropriately scaled model to simulate the shallow flow system would consist of grid cells that are small enough to capture local-scale changes in topography and flow gradients near streams.

Appropriate discretization is important for calibration of the model and depicting spatial distribution of physical properties and stresses; it is limited, however, by the extent to which data are available to define the flow system. In the study area, the discretization of aquifer and confining units limits the interpretation of interaquifer flow. For example, although the Brunswick aquifer system is simulated as a single, laterally continuous unit, there is uncertainty in the lateral extent and continuity of permeable deposits that compose the aquifer system. Thus, in the model, pumping in one area may affect simulated head in another area of the aquifer, when in reality the two areas may be isolated from each other by zones of low permeability or aquifer thinning. There also is some uncertainty in the consistency with which aquifers are defined; for example, the permeable zones that define the Upper and Lower Floridan aquifers. If inconsistently or incorrectly defined, this may result in the model incorrectly interpreting response in the Upper Floridan aquifer to stresses in the Lower Floridan aquifer, or vice versa.

This model is designed to provide a regional approximation of the ground-water system over time on the scale of tens of years and is not intended to simulate short-term annual or seasonal changes. These longer time-scale changes were simulated with successive steady-state approximations for predevelopment, 1980, and 2000. Transient response testing indicates that the steady-state approximation is reasonable for these time periods and hydrogeologic conditions (appendix B). To simulate short-term transient response in the flow system would require transient simulation and greater temporal resolution of stresses, boundary conditions, and observation data.

Boundary conditions are another area of uncertainty in the model because they are difficult to quantify. Reliable estimates of recharge require information on climatic factors, such as rainfall and evapotranspiration rates; soil characteristics (permeability and thickness); and streamflow (used to compute runoff and baseflow). This model simulates recharge to the regional flow system using a general-head boundary as a simplification of the flow system. Thus, increased recharge is induced by increased pumpage. It is possible that recharge is more (or less) limited than that allowed by this boundary condition. This type of boundary does not account for all of the aforementioned factors controlling recharge, but was used as a control to limit the quantity of water entering the flow system within or below estimates derived from stream baseflow data (Priest, 2004).

In the absence of a physical hydrologic boundary and sufficient data to quantify flow, a fixed-head boundary based on observed water levels was used to define the southern boundary of the model. This type of boundary serves as a source-sink boundary, whereby water is allowed to flow into and out of the model area in response to head gradients. Because fixed-head cells provide an unlimited supply of water, simulated head near this boundary may be overpredicted (high). Increased pumpage near this boundary, in excess of that used to calibrate the model, may induce unrealistic quantities of flow into the model and result in an underprediction of drawdown. Furthermore, the proportions of water entering the system from this boundary and the general-head boundary are uncertain and constrained only by imprecise limits on regional recharge. It is possible that a different proportion of water entering from these boundaries could result in an acceptable solution to these simulations, but a different solution for other scenarios.

Sensitivity testing indicates that the model is very sensitive to the rate and distribution of pumpage. There is uncertainty in the rate and distribution of nonsite-specific and site-specific pumping, even though the locations of site-specific stresses are known. Also, estimates of earlier pumping rates and distributions are even more uncertain; for example, there is less certainty in the values and distribution of pumping during 1980 than during 2000.

Pumping uncertainty results from limited metering in the model area, errors in self-reporting by some users, errors in countywide estimates for several categories of water use, uncertainty about which aquifer each well is tapping, and errors in estimating annual rates for a seasonally varying value (such as irrigation). Because the model is calibrated to simulate average annual conditions, errors in annual pumping rate and distribution can lead to errors in the calibration. For example, if the estimated pumping is substantially lower than actual pumping, the calibrated hydraulic conductivity may be too low, and the model may predict a greater response to future stresses than the system may actually demonstrate.

The model also is limited by uncertainty in available hydraulic-property data and in the application of these data to the model. The availability of field hydraulic-property data is highly variable, both spatially within a unit and among different units. In areas or units of high data density, there may be considerable variation in field values; for example, hydraulic conductivity of the Upper Floridan aquifer varies by two orders of magnitude in the Brunswick area. This variation may be due to measurement error, error in estimation of transmissivity or hydraulic conductivity, or localized heterogeneity in aquifer properties. Because the objective of the model is to describe the regional flow system characteristics, the hydraulic conductivity of each unit is subdivided only into subregional-sized zones. It is possible that in some areas, however, aquifer properties may vary at the model-grid cell scale, especially for units that have heterogeneous aquifer properties such as the carbonate portion of the Floridan aquifer system.

Although zoning hydraulic properties on a cell-by-cell basis may give a better match of calculated heads with observed heads, it may not represent a better or more accurate physical model and, thus, may not always be justifiable. In areas of low data density, for example confining units, initial hydraulic-property values are only approximations and may be incorrect by several orders of magnitude.

Another source of uncertainty is a nonunique distribution of hydraulic properties that results in acceptable model calibration. These uncertainties may limit the ability of the model to predict the system response to stress changes. For example, if the calibrated hydraulic conductivity is too high in one area, the model may underestimate response to stress changes there; alternatively, if the calibrated hydraulic conductivity is too low, the model may overestimate response to stress changes. As another example, if the calibrated hydraulic conductivity is too high near a source-sink boundary, this may allow too much flow across that boundary, resulting in an overall incorrect budget and flow system. Uncertainty in confining-unit hydraulic conductivity also may result in incorrect estimates of flow among units and a misrepresentation of interaquifer leakage.

It is likely that the greatest sources of uncertainty in the model are the boundary conditions, including pumping. In areas that are sufficiently removed from model boundaries, and for which the location of most pumping is known and for which the rate is accurately estimated, the model likely represents the characteristics of flow reasonably well and can provide a reasonable assessment of effects of changing stresses. Such areas include the coastal areas between Camden County, Ga., and Beaufort County, S.C.

Despite the limitations of the model, one of its most useful characteristics is the illustration of those aspects of uncertainty that, with improved data density or quality, could best improve the model and the general understanding of the flow system in the region. Because the sensitivity analysis indicated that pumpage is the most sensitive parameter of the calibrated model, more accurate estimates of ground-water pumpage and distribution could improve substantially the model simulation. Improved characterization of boundary conditions would also improve model simulation—more accurate recharge and discharge estimates would provide more reasonable constraints on flow into and out of the flow system.

Sensitivity analysis indicates that the model could be improved with additional hydraulic-property information. In particular, information on the hydraulic conductivity of the Upper Floridan aquifer in zones F4, F5, and F6 (fig. 12) may help improve model accuracy. Additional data on the vertical hydraulic conductivity of the Upper Floridan confining unit (layer 4 and parts of layers 2 and 3) also would improve the calibration.

Summary

This report documents a digital ground-water flow model used to simulate the regional ground-water flow system in coastal Georgia and adjacent parts of Florida and South Carolina, including the Floridan aquifer system and the Brunswick aquifer system. The model was used to update and refine previous regional-scale flow models for the region, and to (1) understand and refine the conceptual model of regional ground-water flow, (2) create a framework for the development of digital subregional ground-water flow and solute-transport models, and (3) evaluate hypothetical pumping distribution scenarios.

The single-density ground-water flow model was developed using the U.S. Geological Survey finite-difference code MODFLOW-2000, and encompasses a 42,155-square-mile area in coastal Georgia, Florida, and South Carolina, including the adjacent offshore area. A steady-state approximation was used to simulate ground-water flow and mean-annual conditions for predevelopment (pre–1900) and the years 1980 and 2000. The steady-state approximation is appropriate because the purpose of the model is to simulate the ultimate effect on the flow system resulting from changes in average annual pumping, and because unreasonably extreme changes in stress are required to affect a transient response.

The model was calibrated by adjusting hydraulic properties and boundary conditions to get a satisfactory match with observed water levels, and to agree with spatial distributions of recharge and discharge areas and directions of flow between aquifers, while maintaining "realistic" values of hydraulic properties as defined by field data. Final calibration targets for simulated ground-water levels are 10 feet (ft) for both the 1980 and 2000 simulations, based on observation accuracy and observed seasonal variations in ground-water levels. The maximum allowable recharge into any model cell is limited to approximately 10 inches per year (in/yr).

The simulated and estimated predevelopment potentiometric-surface maps for the Upper Floridan aquifer show a pronounced interaction with streams in the northwestern part of the area, a steepening of the potentiometric gradient in the area of the Gulf Trough, a flattening of the potentiometric gradient in the southwestern part of the model area, and flow toward a potentiometric low in coastal South Carolina near Hilton Head

Island and Port Royal Sound. Sixty percent of the total simulated inflow is contributed by leakage from the general-head boundary, and 40 percent is contributed as inflow from lateral specified-head boundary. Thirty-nine percent of the total outflow discharges to the general-head boundary, and 61 percent is attributed to outflow at the lateral specified-head boundary. Total simulated recharge averages about 0.21 in/yr across the entire onshore area. Along the coastline, there is a net flow of ground-water seaward from onshore toward offshore.

Ground-water conditions during 1980 were calibrated on the basis of water-level measurements in 297 wells, mostly completed in the Upper Floridan aquifer. Residuals for the Upper Floridan aquifer were normally distributed, with a root-mean square of 13.0 ft, and 70 percent of the simulated values within the 10-ft calibration target of observed values. Dividing the standard deviation of the residuals for the Upper Floridan aquifer by the range of observed water-level variation yielded a good calibration fit of 0.031.

Ground-water conditions during 2000 were calibrated on the basis of water-level measurements in 175 wells, mostly completed in the Upper Floridan aquifer. The root-mean square of residuals was 5.91 ft for the Brunswick aquifer system, 9.94 ft for the Upper Floridan aquifer, and 9.15 ft for the Lower Floridan aquifer. Residuals for all layers were normally distributed; simulated values were within the 10-ft calibration target of observed values for 80 percent of the Brunswick aquifer system wells, 79 percent of the Upper Floridan aquifer wells, and 73 percent of the Lower Floridan aquifer wells. Dividing the standard deviation of the residuals by the range of water-level variation yielded a calibration fit of 0.142 for the Brunswick aquifer system, 0.031 for the Upper Floridan aquifer, and 0.056 for the Lower Floridan aquifer.

Residuals in the Upper Floridan aquifer show a correlation in the magnitude of residuals with physiography and geology for both the 1980 and 2000 simulations—north of the Gulf Trough, residuals are largest and show the greatest variability; in the coastal area, residuals are mostly of smaller magnitude. The model cell size is not sufficient to capture the greater topographic relief and a larger degree of stream-aquifer interaction north of the Gulf Trough; thus, larger residuals are expected there. Clustering of positive and negative residuals in parts of the updip area are possibly a result of subregional scale variations in hydraulic conductivity that are not accounted for in the model either from lack of data or inaccuracy of pumping data. For the 1980 simulation near the cone of depression at Savannah, residuals generally are negative, reflecting site-specific pumping data inaccuracy in this heavily stressed area.

Simulated 1980 and 2000 potentiometric surfaces for the Upper Floridan aquifer have similar prominent features to those shown on estimated 1980 and later potentiometric-surface maps. These features include large cones of depression in the Savannah, Ga., St. Marys, Ga.–Fernandina Beach, Fla., and Jacksonville, Fla., areas; smaller cones of depression at Jesup and Brunswick, Ga.; a steepening of the potentiometric gradient in the area of the Gulf Trough; flattening of the potentiometric gradient in the southwestern part of the model area; and potentiometric highs north of Port Royal Sound, S.C. The simulated potentiometric surfaces for the Lower Floridan aquifer generally mimic those for the Upper Floridan for 1980 and 2000 conditions, indicating interaquifer leakage through the confining unit. The simulated potentiometric surfaces also are similar for the Brunswick aquifer system for 1980 and 2000.

Simulated and observed water levels show similar vertical flow potential in most of the study area. Where the simulated and observed vertical flow potentials do not agree, the likely causes are lack of detailed data to define local hydraulic properties, and also the simplification of the conceptual system.

From predevelopment to 2000, simulated drawdown of the Upper Floridan aquifer exceeded 20 ft throughout most of the area and was greatest near the center of the major pumping center at Savannah, where water levels declined more than 100 ft. Simulated drawdown in the Lower Floridan was of similar magnitude. In the Brunswick aquifer system, simulated drawdown exceeded 20 ft throughout most of its extent.

During 1980–2000, water levels in all aquifers showed a combination of rises and declines. Simulated drawdown exceeded 10 ft in the Upper Floridan aquifer across much of the western half of the model area, with drawdown exceeding 20 ft along parts of the western, northern, and southern boundaries. At the Savannah and Brunswick pumping centers, simulated water levels in the Upper Floridan aquifer rose more than 20 ft and 8 ft, respectively, in response to decreased pumping in those areas. Water-level changes in the Lower Floridan aquifer and Brunswick aquifer system were mostly in response to changes in pumping patterns in the Upper Floridan aquifer.

The water budgets for the 1980 and 2000 simulations are similar and show changes from the predevelopment flow budget, including: (1) increased inflow from and decreased outflow to the general-head boundaries in both the onshore and offshore areas; (2) increased outflow to, and inflow from, lateral fixed-head boundaries; and (3) increased landward and decreased seaward flow rates, with net flow along the coastline changing from seaward to landward.

Simulated recharge and discharge for 2000 conditions differ from those for predevelopment conditions: (1) areas of recharge north of the Gulf Trough have increased in areal extent and magnitude of recharge; (2) discharge rates in model cells containing major streams have decreased throughout the area, with some of the flow reversing to recharge; and (3) reversal from discharge to recharge conditions has occurred in all cells beneath the major pumping centers.

Composite-scaled sensitivities indicate the model is very sensitive to pumping and moderately sensitive to hydraulic conductivities in the Upper Floridan and overlying confining unit. A 10-percent increase in pumping rates results in widespread decline in water level of greater than 2 ft across most of the simulated area, with declines exceeding 10 ft in areas of concentrated pumping. A 10-ft increase in head along the southern model boundary resulted in an increase in simulated head extending from this boundary northward to Chatham County, Ga.

Model limitations include: (1) the model's spatial scale and discretization, (2) the extent to which data are available to physically define the flow system, (3) the type of boundary conditions and controlling parameters used, (4) uncertainty in the distribution of pumping, and (5) uncertainty in field-scale hydraulic properties. The model could be improved with more accurate estimates of ground-water pumpage and better characterization of recharge and discharge.

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Appendix A. Observed and Simulated Ground-Water Levels, 1980 and 2000

Figure A1. Locations of wells used for 1980 simulation in (*A*) study area; (*B*) Chatham, Bryan, and Liberty Counties (enlarged); and (*C*) McIntosh, Glynn, and Camden Counties (enlarged).

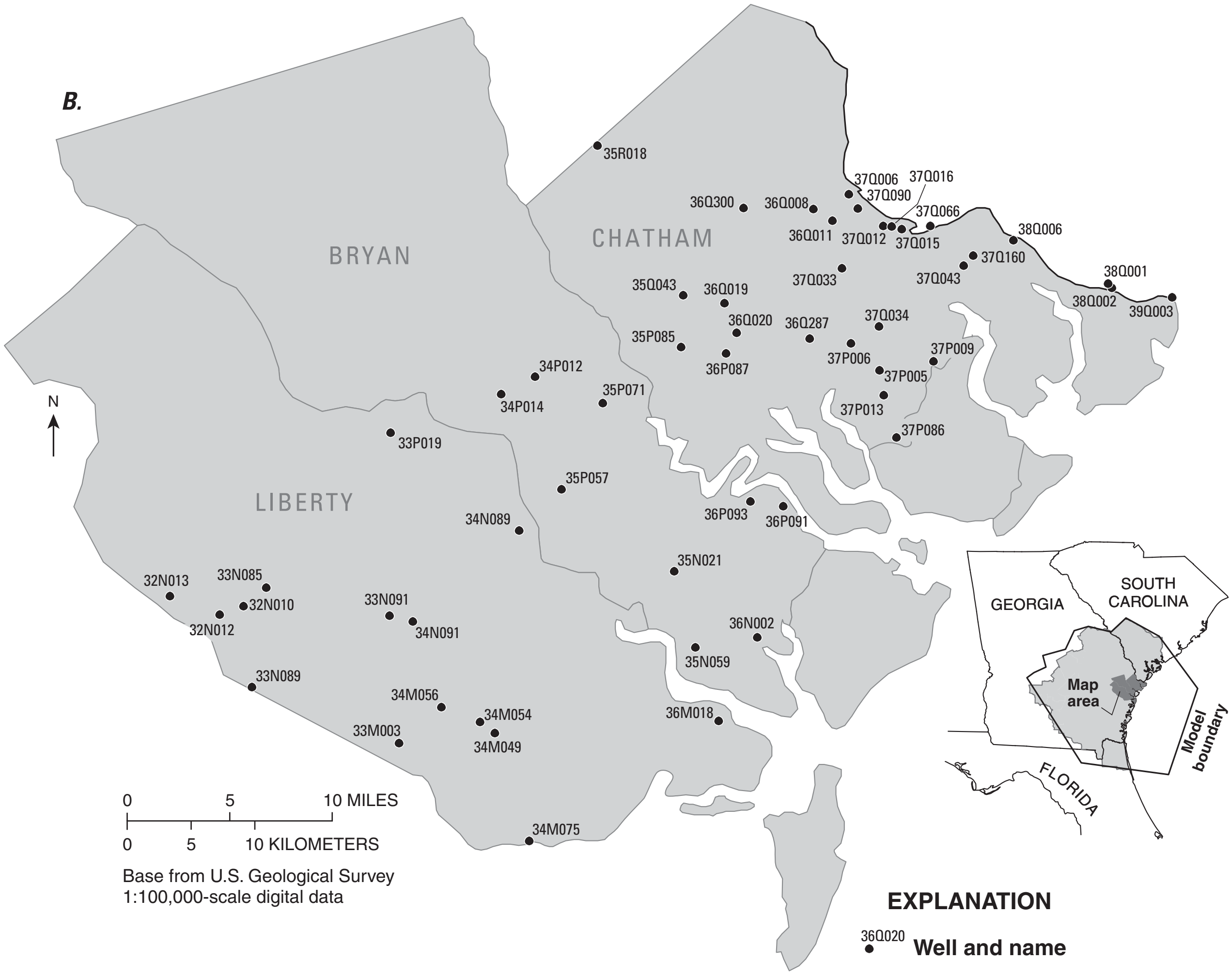

Figure A1. Locations of wells used for 1980 simulation in (*A*) study area; (*B*) Chatham, Bryan, and Liberty Counties (enlarged); and (*C*) McIntosh, Glynn, and Camden Counties (enlarged)—continued.

Figure A1. Locations of wells used for 1980 simulation in (*A*) study area; (*B*) Chatham, Bryan, and Liberty Counties (enlarged); and (*C*) McIntosh, Glynn, and Camden Counties (enlarged)—continued.

Figure A2. Locations of wells used for 2000 simulation in (*A*) study area, (*B*) Chatham, Bryan, and Liberty Counties (enlarged), and (*C*) McIntosh, Glynn, and Camden Counties (enlarged).

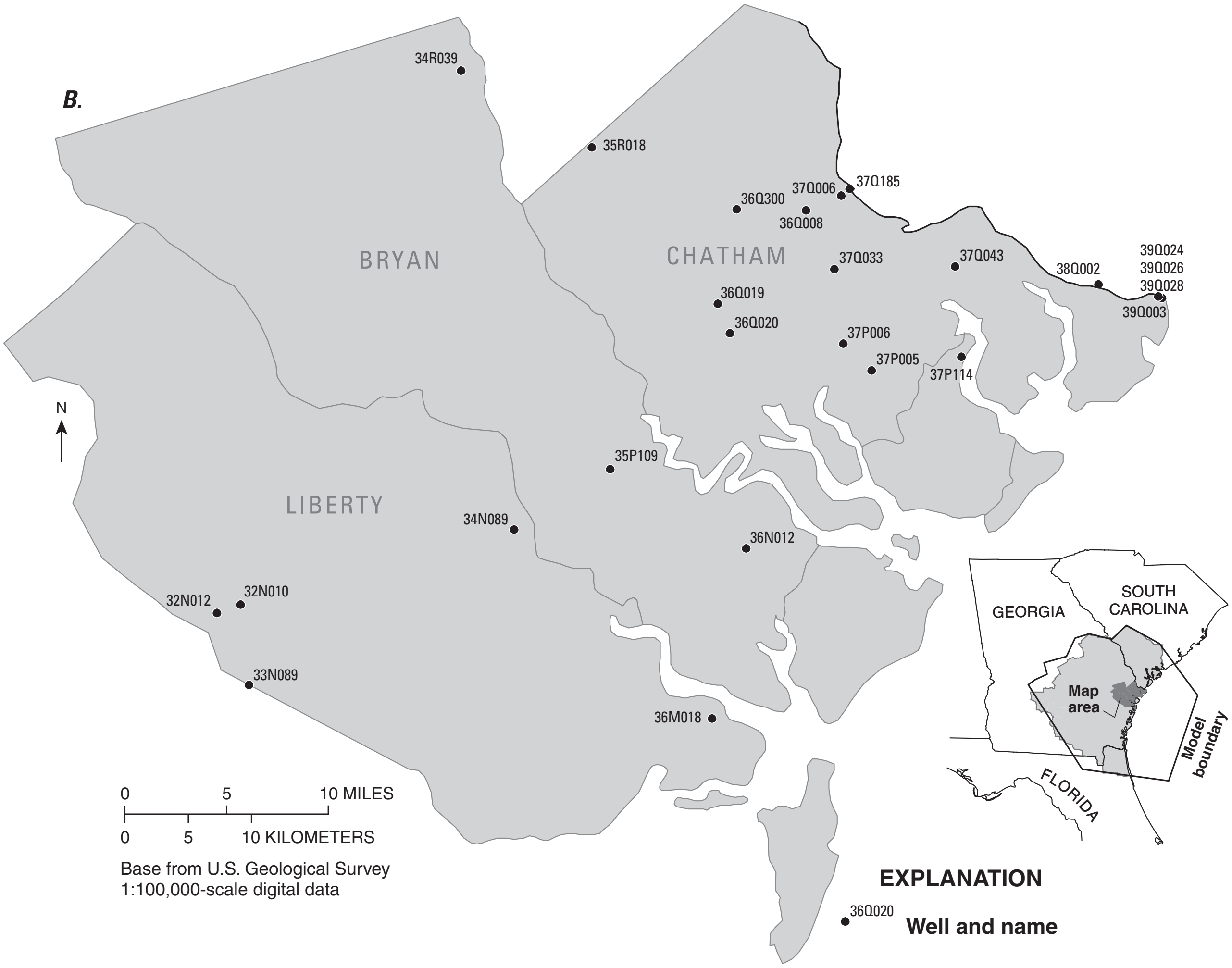

Figure A2. Locations of wells used for 2000 simulation in (*A*) study area; (*B*) Chatham, Bryan, and Liberty Counties (enlarged); and (*C*) McIntosh, Glynn, and Camden Counties (enlarged)—continued.

Table A1. Simulated and observed ground-water levels, 1980 and 2000.

[Observed values for 1980 are for May; observed values for 2000 are for September; values in bold are for wells that have continuous recorders and water levels that are mean-monthly values for either May 1980 or September 2000; —, data]

Well number	Model layer	Simulated and observed ground-water levels and difference, in feet						Water-level change, in feet	
		1980 calibration			2000 calibration			1980–2000	
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
27G005	3	86.22	67.34	18.88	—	—	—	—	—
30E002	3	25.27	36.90	–11.63	20.20	27.87	–7.67	–9.03	–5.07
32L016	**3**	**—**	**—**	**—**	**9.51**	**15.79**	**–6.28**	**—**	**—**
33D071	**3**	**—**	**—**	**—**	**10.68**	**–2.07**	**12.75**	**—**	**—**
33E002	3	16.09	30.11	–14.02	—	—	—	—	—
33G028	**3**	**—**	**—**	**—**	**10.58**	**16.75**	**–6.17**	**—**	**—**
34H437	**3**	**—**	**—**	**—**	**9.93**	**5.88**	**4.05**	**—**	**—**
34J078	**3**	**—**	**—**	**—**	**9.09**	**3.71**	**5.39**	**—**	**—**
35S008	3	—	—	—	17.80	12.09	5.71	—	—
36N012	3	—	—	—	–12.89	–26.18	13.29	—	—
39Q026	**3**	**—**	**—**	**—**	**–3.86**	**–2.31**	**–1.54**	**—**	**—**
39Q028	**3**	**—**	**—**	**—**	**–3.86**	**–2.21**	**–1.65**	**—**	**—**
17M007	5	236.73	230.14	6.59	—	—	—	—	—
17M009	5	237.20	230.86	6.34	—	—	—	—	—
17P001	5	274.50	266.56	7.94	—	—	—	—	—
18N003	5	237.20	206.06	31.14	—	—	—	—	—
18P001	5	257.95	213.76	44.19	—	—	—	—	—
18P002	5	241.62	206.43	35.19	—	—	—	—	—
18Q002	5	228.40	208.87	19.53	—	—	—	—	—
19L001	5	199.20	218.68	–19.48	—	—	—	—	—
19N002	5	211.22	177.56	33.66	—	—	—	—	—
19P001	5	203.65	170.59	33.06	—	—	—	—	—
19P003	5	206.37	164.02	42.35	—	—	—	—	—
19P006	5	203.99	170.46	33.53	—	—	—	—	—
19P007	5	198.75	165.22	33.53	—	—	—	—	—
19Q001	5	211.82	198.00	13.82	—	—	—	—	—
20L002	5	182.96	206.14	–23.18	—	—	—	—	—
21J001	5	65.62	63.73	1.89	—	—	—	—	—
21K001	5	131.87	102.05	29.82	—	—	—	—	—
21L001	5	147.85	179.85	–32.00	—	—	—	—	—
21N002	5	178.20	167.43	10.77	—	—	—	—	—
21P001	5	181.46	159.31	22.15	—	—	—	—	—
21P002	5	180.43	161.11	19.32	—	—	—	—	—
21S001	5	213.34	220.69	–7.35	—	—	—	—	—
21T001	**5**	**226.20**	**230.68**	**–4.48**	**217.71**	**220.19**	**–2.48**	**–10.49**	**–8.49**
22F001	5	71.92	71.33	0.59	—	—	—	—	—
22M003	5	135.86	144.38	–8.52	—	—	—	—	—
22N001	5	162.49	163.21	–0.72	—	—	—	—	—
22N003	5	160.87	171.10	–10.23	—	—	—	—	—
22Q004	5	170.37	160.09	10.28	—	—	—	—	—
22T001	5	214.99	226.57	–11.58	—	—	—	—	—
23G001	5	63.23	53.76	9.47	—	—	—	—	—
23J006	5	59.72	54.05	5.67	—	—	—	—	—
23J007	5	60.25	61.12	–0.87	—	—	—	—	—
23N001	5	109.14	88.30	20.84	—	—	—	—	—
23U008	5	224.52	218.42	6.10	—	—	—	—	—

Table A1. Simulated and observed ground-water levels, 1980 and 2000.—Continued

[Observed values for 1980 are for May; observed values for 2000 are for September; values in bold are for wells that have continuous recorders and water levels that are mean-monthly values for either May 1980 or September 2000; —, data]

Well number	Model layer	Simulated and observed ground-water levels and difference, in feet						Water-level change, in feet	
		1980 calibration			2000 calibration			1980–2000	
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
24H001	5	59.17	60.42	–1.25	—	—	—	—	—
24J001	5	59.37	74.64	–15.27	—	—	—	—	—
24L004	5	56.83	59.50	–2.67	—	—	—	—	—
24S001	5	179.37	143.45	35.92	—	—	—	—	—
24T002	5	194.39	173.58	20.81	—	—	—	—	—
24V002	5	237.86	222.23	15.63	—	—	—	—	—
25D001	5	60.29	55.81	4.48	—	—	—	—	—
25N003	5	78.01	41.80	36.21	—	—	—	—	—
25P002	5	125.30	128.09	–2.79	—	—	—	—	—
25Q001	**5**	**122.89**	**116.25**	**6.64**	**108.53**	**96.75**	**11.78**	**–19.50**	**–14.35**
25R001	5	144.80	129.70	15.10	—	—	—	—	—
25S002	5	163.09	131.95	31.14	—	—	—	—	—
25S003	5	163.89	138.65	25.24	—	—	—	—	—
25S004	5	167.93	143.58	24.35	—	—	—	—	—
25U003	5	202.63	202.61	0.02	—	—	—	—	—
26M002	5	50.92	56.07	–5.15	—	—	—	—	—
26M003	5	52.47	54.89	–2.42	40.97	35.84	5.13	–19.05	–11.51
26Q002	5	—	—	—	63.79	49.95	13.84	—	—
26R001	**5**	**—**	**—**	**—**	**108.60**	**103.85**	**4.75**	**—**	**—**
26T001	5	177.24	177.28	–0.04	—	—	—	—	—
26X005	5	246.41	283.45	–37.04	—	—	—	—	—
27E002	5	56.08	50.90	5.18	—	—	—	—	—
27E003	5	56.16	48.17	7.99	—	—	—	—	—
27E004	**5**	**—**	**—**	**—**	**44.47**	**40.54**	**3.93**	**—**	**—**
27G006	5	52.83	54.99	–2.16	41.76	40.48	1.28	–14.51	–11.07
27M001	5	47.09	51.05	–3.96	36.22	33.07	3.15	–17.98	–10.87
27N005	5	42.85	53.84	–10.99	—	—	—	—	—
27Q002	5	—	—	—	62.15	44.97	17.18	—	—
27Q005	5	88.74	77.40	11.34	—	—	—	—	—
27R003	5	—	—	—	103.75	90.67	13.08	—	—
27R004	5	—	—	—	85.61	92.42	–6.81	—	—
27R005	5	108.66	99.07	9.59	—	—	—	—	—
27S001	5	135.16	130.15	5.01	—	—	—	—	—
27S002	5	134.62	124.64	9.98	118.90	99.21	19.69	–25.43	–15.72
27W001	5	213.67	221.81	–8.14	—	—	—	—	—
28D001	5	52.64	46.18	6.46	41.20	37.79	3.41	–8.39	–11.43
28H004	5	49.48	59.50	–10.02	37.98	—	—	—	—
28K001	5	48.36	51.70	–3.34	—	44.39	–44.39	–7.31	–48.36
28P001	5	34.02	56.23	–22.21	—	—	—	—	—
28R001	5	91.67	84.13	7.54	73.69	59.40	14.29	–24.73	–17.97
28S003	5	130.03	130.54	–0.51	115.72	106.51	9.21	–24.03	–14.31
28S004	5	—	—	—	110.12	88.15	21.97	—	—
28T001	5	148.44	140.83	7.61	139.72	103.29	36.43	–37.54	–8.72
28W002	5	—	—	—	196.48	202.54	–6.06	—	—
28W004	5	209.75	208.00	1.75	—	—	—	—	—
29F001	5	49.02	51.37	–2.35	—	—	—	—	—

Table A1. Simulated and observed ground-water levels, 1980 and 2000.—Continued

[Observed values for 1980 are for May; observed values for 2000 are for September; values in bold are for wells that have continuous recorders and water levels that are mean-monthly values for either May 1980 or September 2000; —, data]

Well number	Model layer	Simulated and observed ground-water levels and difference, in feet						Water-level change, in feet	
		1980 calibration			2000 calibration			1980–2000	
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
29H002	5	47.60	48.89	–1.29	—	—	—	—	—
29K002	5	39.90	44.62	–4.72	—	—	—	—	—
29L005	5	35.55	38.22	–2.67	26.34	27.08	–0.74	–11.14	–9.22
29M002	5	36.41	49.69	–13.28	26.70	36.04	–9.34	–13.65	–9.70
29M004	5	27.55	38.78	–11.23	—	—	—	—	—
29N003	5	30.01	40.41	–10.40	20.57	32.16	–11.59	–8.25	–9.44
29Q001	5	—	—	—	19.88	29.59	–9.71	—	—
29R001	5	49.15	49.50	–0.35	36.39	33.05	3.34	–16.45	–12.76
29R003	5	—	—	—	35.70	34.98	0.72	—	—
29T009	5	138.94	136.97	1.97	125.67	113.32	12.35	–23.65	–13.27
29V001	5	162.85	170.40	–7.55	154.32	160.00	–5.68	–10.40	–8.53
29W002	5	—	—	—	179.74	167.92	11.82	—	—
30E007	5	—	—	—	36.09	32.30	3.79	—	—
30F004	5	41.77	43.84	–2.07	32.45	34.70	–2.25	–9.14	–9.32
30H003	5	44.34	37.93	6.41	34.88	27.58	7.30	–10.35	–9.46
30H005	5	44.10	40.88	3.22	34.68	37.35	–2.67	–3.53	–9.42
30K004	5	32.45	29.39	3.06	—	—	—	—	—
30L003	**5**	**20.68**	**25.03**	**–4.35**	**13.08**	**13.95**	**–0.87**	**–11.08**	**–7.60**
30L011	5	35.71	32.78	2.93	26.62	20.91	5.71	–11.87	–9.09
30L012	5	26.18	34.04	–7.86	18.01	19.53	–1.52	–14.51	–8.17
30M003	5	—	—	—	11.62	11.03	0.59	—	—
30M005	5	16.36	23.36	–7.00	—	—	—	—	—
30M007	5	24.02	15.30	8.72	15.58	19.26	–3.68	3.96	–8.44
30M011	5	23.38	29.21	–5.83	—	—	—	—	—
30N002	5	24.63	33.26	–8.63	15.97	21.25	–5.28	–12.01	–8.66
30P003	5	21.90	30.86	–8.96	12.44	5.12	7.32	–25.74	–9.46
30R005	5	—	—	—	13.67	23.74	–10.07	—	—
30U005	5	—	—	—	112.32	114.98	–2.66	—	—
30V002	5	140.56	151.63	–11.07	126.01	138.79	–12.78	–12.84	–14.55
30X003	5	—	—	—	163.49	161.82	1.67	—	—
31E001	5	39.09	41.58	–2.49	29.66	30.10	–0.44	–11.48	–9.43
31F022	5	39.43	42.98	–3.55	30.12	32.77	–2.65	–10.21	–9.31
31H005	5	41.15	38.89	2.26	32.19	32.70	–0.51	–6.19	–8.97
31L001	5	26.80	25.30	1.50	—	—	—	—	—
31M006	5	6.30	10.26	–3.96	—	—	—	—	—
31M022	5	8.46	10.52	–2.06	—	—	—	—	—
31M024	5	7.69	0.43	7.26	—	—	—	—	—
31M033	5	10.48	11.21	–0.73	—	—	—	—	—
31M034	5	12.44	14.49	–2.05	—	—	—	—	—
31R001	5	21.91	39.73	–17.82	12.34	23.64	–11.30	–16.09	–9.57
31S008	5	23.30	44.63	–21.33	13.99	41.96	–27.97	–2.67	–9.30
31T010	5	74.62	111.25	–36.63	63.76	54.95	8.81	–56.30	–10.86
31V008	5	—	—	—	97.60	122.83	–25.23	—	—
31V014	5	—	—	—	99.60	118.09	–18.49	—	—
31W010	5	129.83	146.92	–17.09	—	—	—	—	—
31W025	5	149.24	169.30	–20.06	—	—	—	—	—

Table A1. Simulated and observed ground-water levels, 1980 and 2000.—Continued

[Observed values for 1980 are for May; observed values for 2000 are for September; values in bold are for wells that have continuous recorders and water levels that are mean-monthly values for either May 1980 or September 2000; —, data]

Well number	Model layer	Simulated and observed ground-water levels and difference, in feet						Water-level change, in feet	
		1980 calibration			2000 calibration			1980–2000	
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
31Z085	5	158.61	134.69	23.92	—	—	—	—	—
32E031	5	36.85	41.44	−4.59	27.33	29.56	−2.23	−11.88	−9.52
32E033	5	34.52	38.59	−4.07	—	—	—	—	—
32E038	5	—	—	—	26.37	25.46	0.91	—	—
32F008	5	37.19	43.01	−5.82	27.96	32.28	−4.32	−10.73	−9.23
32F048	5	36.82	38.24	−1.42	—	—	—	—	—
32G004	5	36.78	37.64	−0.86	—	—	—	—	—
32G007	5	37.12	40.11	−2.99	28.02	27.09	0.93	−13.02	−9.09
32G015	5	35.78	38.06	−2.28	26.90	29.95	−3.05	−8.11	−8.87
32H001	5	29.87	24.53	5.34	22.77	21.56	1.21	−2.97	−7.10
32J003	5	—	—	—	19.55	23.34	−3.79	—	—
32L004	5	18.01	19.51	−1.50	11.22	10.55	0.67	−8.96	−6.78
32L015	**5**	**—**	**—**	**—**	**10.24**	**8.22**	**2.02**	**—**	**—**
32M001	5	9.99	14.47	−4.48	—	—	—	—	—
32M009	5	11.01	12.67	−1.66	—	—	—	—	—
32N010	5	7.77	23.10	−15.33	0.40	10.14	−9.74	−12.96	−7.38
32N012	5	8.63	17.96	−9.33	0.98	4.49	−3.51	−13.47	−7.65
32N013	5	10.36	12.18	−1.82	—	—	—	—	—
32R002	**5**	**—**	**—**	**—**	**10.17**	**18.01**	**−7.84**	**—**	**—**
32U005	5	—	—	—	70.85	96.50	−25.65	—	—
32V007	5	104.53	121.32	−16.79	—	—	—	—	—
32W006	5	7.02	—	—	105.44	98.95	6.49	—	—
33D004	5	—	4.26	−4.26	−1.80	1.91	−3.71	−2.35	−1.80
33D069	**5**	**—**	**—**	**—**	**0.60**	**2.99**	**−2.39**	**—**	**—**
33E004	5	31.31	36.32	−5.01	—	—	—	—	—
33E007	**5**	**22.76**	**22.92**	**−0.16**	**13.26**	**15.26**	**−2.00**	**−7.66**	**−9.50**
33E009	5	—	—	—	22.45	30.97	−8.52	—	—
33E023	5	32.36	41.13	−8.77	—	—	—	—	—
33E027	**5**	**—**	**—**	**—**	**20.55**	**23.51**	**−2.96**	**—**	**—**
33F001	5	31.30	36.36	−5.06	—	—	—	—	—
33F003	5	—	—	—	22.40	26.15	−3.75		
33G002	5	28.69	20.27	8.42	—	—	—	—	—
33G003	5	—	—	—	21.81	22.86	−1.05	—	—
33G005	5	31.19	36.25	−5.06	—	—	—	—	—
33G006	5	31.29	41.02	−9.73	—	—	—	—	—
33G008	5	28.35	20.90	7.45	20.64	18.72	1.92	−2.18	−7.71
33H038	5	11.43	15.40	−3.97	—	—	—	—	—
33H052	5	9.03	10.98	−1.95	—	—	—	—	—
33H079	5	2.34	7.88	−5.54	—	—	—	—	—
33H100	5	−5.63	−3.75	−1.88	—	—	—	—	—
33H110	5	−13.80	−15.75	1.95	—	—	—	—	—
33H120	5	—	—	—	−3.55	−2.99	−0.56	—	—
33H130	5	−10.55	−15.22	4.67	−2.46	−4.59	2.13	10.63	8.08
33H133	**5**	**−6.74**	**−11.73**	**4.99**	**−0.65**	**−0.89**	**0.24**	**10.84**	**6.09**
33H139	5	28.13	17.20	10.93	—	—	—	—	—
33H141	**5**	**1.21**	**3.92**	**−2.71**	**4.75**	**7.24**	**−2.49**	**3.32**	**3.54**

Table A1. Simulated and observed ground-water levels, 1980 and 2000.—Continued

[Observed values for 1980 are for May; observed values for 2000 are for September; values in bold are for wells that have continuous recorders and water levels that are mean-monthly values for either May 1980 or September 2000; —, data]

Well number	Model layer	Simulated and observed ground-water levels and difference, in feet						Water-level change, in feet	
		1980 calibration			2000 calibration			1980–2000	
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
33H164	5	24.36	16.96	7.40	18.53	15.08	3.45	–1.88	–5.84
33H174	5	—	—	—	6.74	9.33	–2.59	—	—
33H177	5	32.23	27.94	4.29	23.68	21.16	2.52	–6.78	–8.55
33H180	5	–7.06	–8.57	1.51	0.19	–1.15	1.34	7.42	7.24
33H190	5	4.31	7.94	–3.63	5.29	8.03	–2.74	0.09	0.97
33H207	**5**	**—**	**—**	**—**	**4.37**	**4.16**	**0.21**	**—**	**—**
33J026	5	15.09	18.19	–3.10	—	—	—	—	—
33J027	5	—	—	—	11.66	14.31	–2.65		
33J028	5	12.89	15.32	–2.43	—	—	—	—	—
33J034	5	11.46	12.69	–1.23	—	—	—	—	—
33K005	5	16.57	16.32	0.25	—	—	—	—	—
33K016	5	13.69	11.40	2.29	—	—	—	—	—
33K019	5	13.55	11.72	1.83	—	—	—	—	—
33L010	5	11.76	11.31	0.45	—	—	—	—	—
33L027	5	14.46	16.80	–2.34	8.15	6.98	1.17	–9.82	–6.30
33M003	5	4.96	2.73	2.23	—	—	—	—	—
33M004	**5**	**9.71**	**11.45**	**–1.74**	**3.21**	**0.40**	**2.81**	**–11.05**	**–6.50**
33N085	5	6.84	10.43	–3.59	—	—	—	—	—
33N089	5	7.92	8.45	–0.53	0.77	–5.48	6.25	–13.93	–7.15
33N091	5	3.37	5.65	–2.28	—	—	—	—	—
33P019	5	2.40	8.37	–5.97	—	—	—	—	—
33S010	5	23.15	38.96	–15.81	—	—	—	—	—
33U009	5	—	—	—	53.31	67.18	–13.87	—	—
33U019	5	—	—	—	48.46	73.11	–24.65	—	—
33U021	5	68.47	76.68	–8.21	53.17	71.15	–17.98	–5.53	–15.30
33U023	5	63.36	86.89	–23.53	48.21	75.31	–27.10	–11.58	–15.15
33V020	5	—	—	—	62.20	76.70	–14.50	—	—
33V021	5	—	—	—	78.25	98.46	–20.21	—	—
34G002	5	20.83	15.96	4.87	15.34	17.62	–2.28	1.66	–5.49
34G009	5	29.77	40.53	–10.76	20.64	35.50	–14.86	–5.03	–9.13
34G016	5	—	—	—	18.65	23.69	–5.04	—	—
34G020	5	28.97	30.68	–1.71	20.07	26.18	–6.11	–4.50	–8.90
34H062	5	2.43	–11.84	14.27	3.72	0.26	3.46	12.10	1.28
34H085	5	8.22	1.06	7.16	7.35	4.23	3.12	3.17	–0.87
34H097	5	—	—	—	13.10	11.78	1.32	—	—
34H112	5	10.11	2.08	8.03	8.58	6.62	1.96	4.54	–1.53
34H117	5	8.14	–0.81	8.95	7.51	4.54	2.97	5.35	–0.63
34H122	5	7.30	0.03	7.27	—	—	—	—	—
34H125	**5**	**—**	**—**	**—**	**6.46**	**4.45**	**2.01**	**—**	**—**
34H128	5	4.22	–4.73	8.95	—	—	—	—	—
34H133	5	–0.24	–8.62	8.38	—	—	—	—	—
34H204	5	21.27	23.63	–2.36	—	—	—	—	—
34H328	5	13.96	12.18	1.78	9.23	8.78	0.45	–3.40	–4.74
34H344	**5**	**3.73**	**–10.61**	**14.34**	**4.63**	**3.25**	**1.38**	**13.86**	**0.90**
34H345	5	7.77	–0.13	7.90	—	—	—	—	—
34H355	**5**	**2.58**	**–4.00**	**6.58**	**4.36**	**3.88**	**0.48**	**7.88**	**1.78**

Table A1. Simulated and observed ground-water levels, 1980 and 2000.—Continued

[Observed values for 1980 are for May; observed values for 2000 are for September; values in bold are for wells that have continuous recorders and water levels that are mean-monthly values for either May 1980 or September 2000; —, data]

Well number	Model layer	Simulated and observed ground-water levels and difference, in feet						Water-level change, in feet	
		1980 calibration			2000 calibration			1980–2000	
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
34H357	5	9.59	9.78	–0.19	6.99	8.74	–1.75	–1.04	–2.60
34H358	5	15.08	12.77	2.31	—	—	—	—	—
34H363	5	13.14	8.36	4.78	—	—	—	—	—
34H366	5	9.23	2.10	7.13	—	—	—	—	—
34H371	**5**	**—**	**—**	**—**	**10.70**	**10.83**	**–0.13**	**—**	**—**
34H372	5	11.80	1.83	9.97	—	—	—	—	—
34H373	5	1.29	–11.08	12.37	3.67	–1.07	4.74	10.01	2.38
34H381	5	17.30	14.08	3.22	—	—	—	—	—
34H383	5	15.35	13.23	2.12	—	—	—	—	—
34H392	5	–0.86	–2.24	1.38	2.70	3.33	–0.63	5.57	3.56
34H393	5	12.67	7.69	4.98	9.98	8.53	1.45	0.84	–2.69
34H400	5	0.67	–9.04	9.71	—	—	—	—	—
34H401	5	–1.25	–10.04	8.79	—	—	—	—	—
34H403	**5**	**—**	**—**	**—**	**10.36**	**10.12**	**0.24**	**—**	**—**
34H408	5	–0.53	3.54	–4.07	3.01	2.25	0.76	–1.29	3.54
34H410	5	6.67	6.23	0.44	5.76	7.85	–2.09	1.62	–0.90
34H424	**5**	**–3.02**	**–9.26**	**6.24**	**0.98**	**1.04**	**–0.06**	**10.30**	**3.99**
34H469	5	–6.85	–9.45	2.60	–0.75	5.56	–6.31	—	—
34J009	5	12.61	5.05	7.56	—	—	—	—	—
34J021	5	10.74	10.44	0.30	—	—	—	—	—
34J029	5	12.84	12.41	0.43	8.30	8.09	0.21	–4.32	–4.55
34J051	5	11.47	12.31	–0.84	8.13	9.65	–1.52	–2.66	–3.34
34K012	5	12.75	12.47	0.28	—	—	—	—	—
34K073	5	13.29	10.51	2.78	7.68	1.97	5.71	–8.54	–5.60
34K081	5	13.24	14.82	–1.58	—	—	—	—	—
34K082	5	13.47	11.22	2.25	—	—	—	—	—
34K083	5	12.36	12.85	–0.49	—	—	—	—	—
34K084	5	12.80	9.01	3.79	—	—	—	—	—
34K085	5	12.21	13.63	–1.42	—	—	—	—	—
34K095	5	13.20	9.01	4.19	7.72	1.78	5.94	–7.23	–5.48
34L048	5	10.58	12.52	–1.94	4.76	8.06	–3.30	–4.46	–5.81
34L060	5	7.54	6.65	0.89	1.68	–3.00	4.68	–9.65	–5.86
34L061	5	10.38	13.96	–3.58	4.49	4.17	0.32	–9.79	–5.89
34M049	5	1.95	–0.16	2.11	—	—	—	—	—
34M054	5	1.61	–1.88	3.49	—	—	—	—	—
34M056	5	3.01	3.58	–0.57	—	—	—	—	—
34M070	5	7.14	5.27	1.87	1.07	–6.32	7.39	–11.59	–6.07
34M075	5	4.56	1.43	3.13	–1.24	–9.49	8.25	–10.92	–5.81
34M076	5	5.99	4.45	1.54	0.11	–4.20	4.31	–8.65	–5.88
34N089	**5**	**–1.36**	**–1.39**	**0.03**	**–7.02**	**–14.29**	**7.27**	**–12.90**	**–5.66**
34N091	5	2.76	1.71	1.05	—	—	—	—	—
34P012	5	–11.32	–3.94	–7.38	—	—	—	—	—
34P014	5	–4.92	0.91	–5.83	—	—	—	—	—
34R039	5	—	—	—	–8.91	–5.48	–3.43	—	—
34U008	5	48.24	52.00	–3.76	—	—	—	—	—
34V004	5	—	—	—	66.19	74.60	–8.41	—	—

Table A1. Simulated and observed ground-water levels, 1980 and 2000.—Continued

[Observed values for 1980 are for May; observed values for 2000 are for September; values in bold are for wells that have continuous recorders and water levels that are mean-monthly values for either May 1980 or September 2000; —, data]

Well number	Model layer	Simulated and observed ground-water levels and difference, in feet						Water-level change, in feet	
		1980 calibration			2000 calibration			1980–2000	
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
35H037	5	20.44	20.93	−0.49	—	—	—	—	—
35H044	5	17.90	16.43	1.47	11.54	9.94	1.60	−6.49	−6.35
35K069	5	11.50	6.79	4.71	5.74	−0.79	6.53	−7.58	−5.75
35L067	5	8.38	3.18	5.20	—	—	—	—	—
35L068	5	7.32	7.97	−0.65	1.62	−2.83	4.45	−10.80	−5.70
35M013	**5**	**2.61**	**−1.43**	**4.04**	**−2.82**	**−11.87**	**9.05**	**−10.44**	**−5.42**
35N021	5	−4.56	−8.19	3.63	—	—	—	—	—
35N059	5	−2.84	−7.34	4.50	—	—	—	—	—
35P057	5	−3.38	−3.82	0.44	—	—	—	—	—
35P071	5	−18.16	−6.84	−11.32	—	—	—	—	—
35P085	5	−40.49	−20.15	−20.34	—	—	—	—	—
35Q043	5	−47.45	−23.57	−23.88	—	—	—	—	—
35R018	5	−29.06	−3.68	−25.38	−27.84	−18.07	−9.77	−14.39	1.22
35T003	5	—	—	—	6.35	31.40	−25.06	—	—
36M018	5	−1.50	−6.81	5.31	−6.61	−16.89	10.28	—	—
36N002	5	−4.20	−5.68	1.48	—	—	—	—	—
36P087	5	−48.71	−26.50	−22.21	—	—	—	—	—
36P091	5	−23.76	−19.13	−4.63	—	—	—	—	—
36P093	5	−21.44	−16.92	−4.52	—	—	—	—	—
36Q008	**5**	**−114.15**	**−99.60**	**−14.55**	**−85.35**	**−90.48**	**5.13**	**9.12**	**28.80**
36Q011	5	−114.76	−103.95	−10.81	—	—	—	—	—
36Q019	5	−56.58	−29.33	−27.25	−49.58	−38.06	−11.52		
36Q020	5	−54.46	−29.11	−25.35	−48.73	−42.17	−6.56	−13.06	5.73
36Q287	5	−66.24	−45.92	−20.32	—	—	—	—	—
36Q300	5	−71.64	−45.51	−26.13	−58.33	−54.33	−4.00	—	—
36S004	5	−21.17	−8.22	−12.95	—	—	—	—	—
37P005	5	−56.64	−45.12	−11.52	−52.38	−52.52	0.14	−7.40	4.26
37P006	5	−65.30	−51.62	−13.68	−59.10	−54.44	−4.66	−2.82	6.20
37P009	5	−53.78	−42.50	−11.28	—	—	—	—	—
37P013	5	−50.55	−37.22	−13.33	—	—	—	—	—
37P086	5	−41.40	−28.32	−13.08	—	—	—	—	—
37P114	**5**	**—**	**—**	**—**	**−47.38**	**−46.02**	**−1.36**	**—**	**—**
37Q006	5	−130.28	−130.13	−0.15	—	—	—	—	—
37Q012	5	−95.37	−94.44	−0.93	—	—	—	—	—
37Q015	5	−91.60	−91.14	−0.46	—	—	—	—	—
37Q016	**5**	**−87.52**	**−85.82**	**−1.70**	**−82.00**	**—**	**—**	**—**	**—**
37Q033	5	−85.97	−77.95	−8.02	−74.13	−75.59	1.46	2.36	11.84
37Q034	5	−67.97	−56.07	−11.90	—	—	—	—	—
37Q043	5	−62.57	−51.92	−10.65	−59.72	−56.99	−2.73	−5.07	2.85
37Q066	5	−74.41	−73.62	−0.79	—	—	—	—	—
37Q090	5	−115.00	−108.92	−6.08	—	—	—	—	—
37Q160	5	−59.04	−48.53	−10.51	—	—	—	—	—
37Q185	**5**	**—**	**—**	**—**	**−98.41**	**−99.22**	**0.81**	**—**	**—**
38Q001	5	−25.14	−23.16	−1.98	—	—	—	—	—
38Q002	**5**	**−25.48**	**−23.60**	**−1.88**	**−25.99**	**−30.36**	**4.37**	**−6.76**	**−0.51**
38Q006	5	−43.90	−37.28	−6.62	—	—	—	—	—
39Q003	**5**	**−16.97**	**−18.94**	**1.97**	**−17.84**	**−27.90**	**10.06**	**−8.96**	**−0.87**

Table A1. Simulated and observed ground-water levels, 1980 and 2000.—Continued

[Observed values for 1980 are for May; observed values for 2000 are for September; values in bold are for wells that have continuous recorders and water levels that are mean-monthly values for either May 1980 or September 2000; —, data]

Well number	Model layer	Simulated and observed ground-water levels and difference, in feet						Water-level change, in feet	
		1980 calibration			2000 calibration			1980–2000	
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
BFT–121	5	8.72	23.19	–14.48	—	—	—	—	—
BFT–1810	**5**	**—**	**—**	**—**	**–1.95**	**–0.08**	**–1.87**	**—**	**—**
BFT–1813	5	—	—	—	–3.97	–3.50	–0.47	—	—
BFT–304	5	–6.80	–14.47	7.67	—	—	—	—	—
BFT–315-1	5	0.21	0.17	0.04	—	—	—	—	—
BFT–315-2	5	0.24	–0.83	1.07	—	—	—	—	—
BFT–429	5	–2.31	–2.81	0.50	–6.21	–5.90	–0.31	–3.09	–3.90
BFT–439	5	–2.86	–13.09	10.23	—	—	—	—	—
BFT–444	5	–0.25	–7.04	6.79	—	—	—	—	—
BFT–453	5	4.74	–2.44	7.18	—	—	—	—	—
BFT–786	5	0.39	1.96	–1.57	—	—	—	—	—
BFT–787	5	0.39	–2.42	2.81	—	—	—	—	—
BW–151	5	196.97	221.75	–24.78	—	—	—	—	—
BW–154	5	195.42	225.82	–30.40	—	—	—	—	—
BW–644	5	191.21	209.76	–18.55	—	—	—	—	—
BW–646	5	191.02	222.28	–31.26	—	—	—	—	—
BW–647	5	191.05	222.27	–31.22	—	—	—	—	—
BW–650	5	191.11	199.59	–8.48	—	—	—	—	—
BW–652	5	191.14	219.96	–28.82	—	—	—	—	—
BW–653	5	191.16	220.25	–29.09	—	—	—	—	—
BW–654	5	190.99	210.46	–19.47	—	—	—	—	—
COL–_97	5	59.22	45.46	13.76	—	—	—	—	—
D–3840	5	—	—	—	–18.30	–13.25	–5.05	—	—
HAM–83	5	37.98	9.97	28.01	31.56	4.40	27.16	–5.57	–6.42
N–62	**5**	**—**	**—**	**—**	**–5.67**	**–17.86**	**12.19**	**—**	**—**
16P004	7	275.72	255.58	20.14	—	—	—	—	—
20N005	7	194.48	181.66	12.82	—	—	—	—	—
20R003	7	207.76	211.03	–3.27	—	—	—	—	—
30U002	7	130.47	135.66	–5.19	—	—	—	—	—
32Y033	**7**	**—**	**—**	**—**	**131.78**	**110.27**	**21.51**	**—**	**—**
33D073	**7**	**—**	**—**	**—**	**6.81**	**3.58**	**3.23**	**—**	**—**
33H188	**7**	**20.20**	**17.72**	**2.47**	**15.73**	**12.46**	**3.27**	**–5.26**	**–4.47**
33H206	**7**	**—**	**—**	**—**	**9.52**	**8.41**	**1.12**	**—**	**—**
33J044	**7**	**13.61**	**17.63**	**–4.02**	**10.27**	**13.89**	**–3.62**	**–3.74**	**–3.35**
34G036	7	23.93	23.62	0.31	17.39	20.09	–2.70	–3.53	–6.55
34H391	**7**	**15.35**	**9.01**	**6.34**	**12.11**	**9.18**	**2.92**	**0.17**	**–3.25**
34H399	7	18.20	3.03	15.17	13.77	1.76	12.01	–1.27	–4.43
34H436	**7**	**—**	**—**	**—**	**9.56**	**11.70**	**–2.14**	**—**	**—**
35P109	**7**	**—**	**—**	**—**	**–14.41**	**–21.83**	**7.42**	**—**	**—**
39Q024	**7**	**—**	**—**	**—**	**–17.46**	**–31.67**	**14.22**	**—**	**—**

Appendix B. Transient Response Testing

To determine whether a transient calibration would be required to represent the ground-water flow system accurately, a preliminary version of the calibrated model was used to examine the rate of response of the simulated system to a change in stress using a reasonable value for storage coefficient, based on available data. If tests indicate that the flow system responds rapidly to changes in stress during representative time periods and, thus, behaves like a steady-state system, then transient simulation is neither efficient nor useful. Transient simulation would increase the complexity of the modeling effort by requiring the calibration of additional time-dependent parameters and multiple sets of observations. Because the purpose of the model is to examine the ultimate effect of pumping stress on the flow system, and not to depict how the system responds to these changes over time, steady-state simulation would be a more effective means to meet project objectives.

Some storage coefficient data are available for the study area, primarily for the Upper Floridan aquifer, but these data vary by several orders of magnitude and show no discernible spatial pattern. For the following tests, a constant storage coefficient value of 0.0004 was used based on the median value of available data for the region (Clarke and others, 2004). The median value is within the limits of suggested values for confined aquifers (Freeze and Cherry, 1979).

A test was designed to determine how rapidly a steady-state condition was approached at several locations. For this test, the initial condition was predevelopment steady state. Pumping conditions for 2000 were applied for five 1-year transient time steps, and the calculated heads at several locations were compared with the steady-state heads during 2000 conditions. Figure B1 shows the difference between calculated head in layer 5, the Upper Floridan aquifer, at each time step and at the steady-state solution. At each of the locations shown, the calculated head after a 5-year transient simulation was very close to the calculated steady-state head.

Another test was designed to determine whether the system is likely to behave in a transient or steady-state manner during the 1980–2000 simulation period, assuming reasonable hydraulic properties and using a time step reasonable for available pumping data. To simplify the model, the initial condition was predevelopment steady state, and four 5-year time steps followed, each at 2000 pumping conditions, although this represents a more extreme change than if initial conditions were set to 1980 steady state. The fraction of drawdown achieved relative to total steady-state drawdown is calculated as follows:

$$\frac{(predevelopment\_head) - (transient\_head)}{(predevelopment\_head) - (steady\text{-}state\_head)}$$

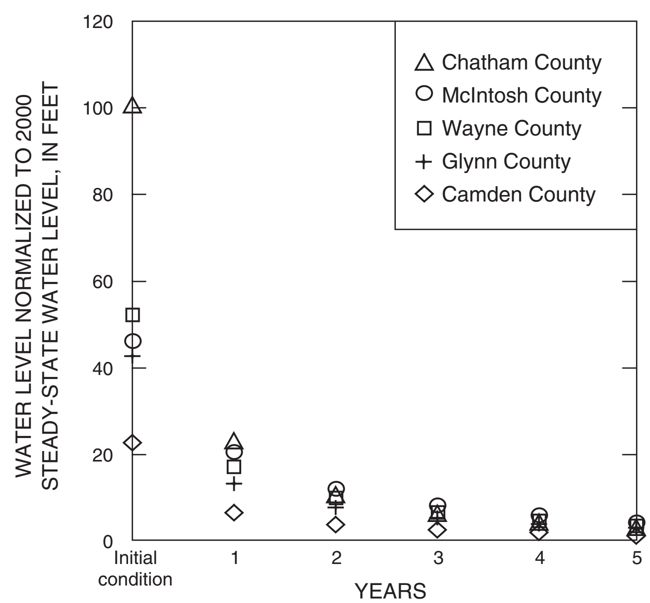

Figure B1. Water-level elevation relative to steady-state water level at 2000 pumping rates during five 1-year time steps at 2000 pumping rates at five Georgia locations. Value at 0 years is water level under steady-state predevelopment conditions relative to water level under steady-state 2000 conditions.

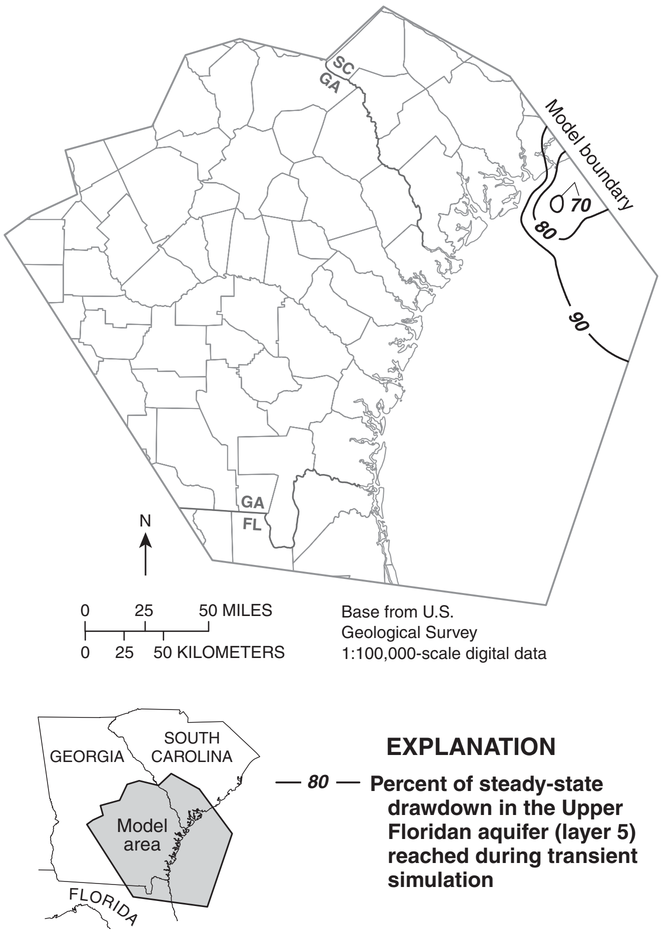

Figure B2. Percent of steady-state conditions reached in the Upper Floridan aquifer (layer 5) during transient simulation after 25 years of pumping using 5-year time steps at 2000 pumping conditions.

For example, a fractional drawdown value of 0.9 indicates that 90 percent of total steady-state drawdown was achieved by the end of the 20-year transient simulation. Figure B2 shows that fractional drawdown in layer 5, the Upper Floridan aquifer, is greater than 0.9 for almost the entire model area. For more realistic changes in stress, the transient response may be even more subdued. Near the northeastern offshore boundary, the fractional drawdown is less than 0.7 across a small offshore area, although maximum drawdown is less than 4 feet. A possible cause of the more transient response in this small area might be the thinness of the layer, which in combination with the constant storage coefficient results in a large specific storage value. The smaller fractional drawdown, however, was considered insignificant, and a steady-state approximation for the system was considered reasonable, because (1) total drawdown in this area is small, (2) data control on the hydrologic-unit thickness or hydraulic properties is limited, and (3) there are no potentiometric data. No further testing was warranted.

The rate of pumping change in these simulations is considerably more than what realistically occurs in the model area, except perhaps in localized areas; for example, agricultural areas where seasonal pumping rates may fluctuate substantially. These tests demonstrate that under extreme rates of pumping change, simulated heads for most of the model area very closely approach the steady-state heads within 5–20 years. For this reason, the steady-state approximation is considered a reasonable way to simulate the flow system.

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