Prepared in cooperation with the Brunswick/Glynn County Joint Water and Sewer Commission

Groundwater Flow in the Brunswick/Glynn County Area, Georgia, 2000–04

Scientific Investigations Report 2015–5061

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

Cover. East River docks, Brunswick, Glynn County, Georgia (photograph by Alan M. Cressler, USGS).

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
million gallons (Mgal)	3,785	cubic meter (m^3)
Flow rate		
inch per year	25.4	millimeter per year
foot per day (ft/d)	0.3048	meter per day (m/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)
Transmissivity*		
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
Potentiometric gradient		
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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

$$°C = (°F - 32) / 1.8$$

Supplemental Information

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

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

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

Datums

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

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

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

Abbreviations

GaEPD	Georgia Environmental Protection Division
JWSC	Joint Water and Sewer Commission
LFA	Lower Floridan aquifer
LWBZ	lower water-bearing zone
NWIS	National Water Information System
RMSE	root mean square error
SCDHEC	South Carolina Department of Health and Environmental Control
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey
UWBZ	upper water-bearing zone
WRMAC	Water Resources Management Advisory Committee

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Groundwater Flow in the Brunswick/Glynn County Area, Georgia, 2000–04

By Gregory S. Cherry

Abstract

An existing regional steady-state model for coastal Georgia, and parts of South Carolina and Florida, was revised to evaluate the local effects of pumping on the migration of high chloride (saline) water in the Upper Floridan aquifer located in the Brunswick/Glynn County, Georgia (Ga.) area. Revisions were focused on enhancing the horizontal and vertical resolution of the regional model grid in the vicinity of saline water. Modifications to the regional model consisted of (1) limiting grid size to a maximum of 500 feet (ft) per side in the vicinity of chloride contamination; (2) representing the upper and lower Brunswick aquifers with distinct model layers; (3) similarly, representing upper and lower water-bearing zones of the Upper Floridan aquifer with distinct model layers in Glynn and Camden Counties, Ga.; and (4) establishing new hydraulic-property zones in the Upper Floridan aquifer. The revised model simulated steady-state conditions that were assumed to exist during 2000 and 2004.

Calibration of the revised steady-state model using pumping rates from 2000 indicates a "good" match (±10 ft) based on 181 observations, with median residuals (simulated minus observed water levels) in each of the active model layers ranging from –8.62 to 4.67 ft, and root mean square error (RMSE) ranging from 10.9 to 11.4 ft. In the Brunswick/Glynn County area, groundwater-level residuals in the upper water-bearing zone of the Upper Floridan aquifer (layer 7) indicate an "excellent" match (±5 ft) based on 41 observations with a median residual of –0.35 ft and RMSE of 4.32 ft.

Calibration of the revised steady-state model using 2004 pumping rates and adjusted specified-head input values in the Floridan aquifer system indicates a "good" match (±10 ft) based on 88 observations, with median residuals in each of the active model layers ranging from –6.31 to –2.05 ft, and RMSE ranging from –6.95 to 14.5 ft. In the Brunswick/Glynn County area, groundwater-level residuals in the upper water-bearing zone of the Upper Floridan aquifer (layer 7) indicate an "excellent" match (±5 ft) based on 32 observations with a median residual of –1.50 ft and RMSE of 5.34 ft.

Simulated potentiometric surfaces for 2000 and 2004 indicate coastward groundwater flow in the Upper and Lower Floridan aquifers influenced by pumping centers at Savannah, Jesup, and Brunswick, Ga., and indicate steep potentiometric gradients to the west and north of the Gulf Trough. In the Brunswick/Glynn County area, simulated industrial production wells located north of downtown Brunswick intercept local groundwater flow in the upper and lower water-bearing zones of the Upper Floridan aquifer and have created a cone of depression that locally alters the regional coastward flow direction.

Maps of simulated water-level change during the 2000–04 period show differences in groundwater levels in the Upper Floridan aquifer that range from −2.5 ft to more than 5 ft in areas of coastal Georgia, and more than 20 ft near the Georgia-Florida State Line. Positive values indicate higher simulated water levels during 2004 than during 2000, which were caused by reduced pumping in the Upper Floridan aquifer prompted by the shutdown of a paper mill near the southern model boundary in 2002 and increased recharge following a prolonged drought during 1998–2002.

Simulated potentiometric profiles for 2000 and 2004 were used to evaluate the potentiometric gradients in the upper water-bearing zone of the Upper Floridan aquifer (layer 7) near the chloride plume in the downtown Brunswick area. Four potentiometric profiles were constructed for 2000 to compare the simulated and observed water levels in 13 wells and were oriented outward from a primary well field. The simulated potentiometric gradients from the four profiles for 2000 ranged from 3.6 to 5.2 feet per mile (ft/mi) compared to observed values ranging from 4.1 to 5.6 ft/mi. The five potentiometric profiles constructed for 2004 allowed for a similar comparison using simulated and observed water levels in 18 wells. The simulated potentiometric gradients from the five profiles for 2000 ranged from 3.6 to 11.1 ft/mi compared to observed values ranging from 3.8 to 10.2 ft/mi. Simulated potentiometric gradients were higher for 2004 than for 2000 because of the inclusion of a well located within the cone of depression near downtown Brunswick.

Composite-scaled sensitivities of the model parameters indicate the revised model is most sensitive to pumping rates, followed by the horizontal hydraulic conductivity in the Upper Floridan aquifer for zones along coastal Georgia. The revised model is least sensitive to the horizontal hydraulic conductivity of the confining units and vertical hydraulic conductivity of the aquifers. For parameters defined by hydraulic-property

zones in the upper and lower water-bearing zones of the Upper Floridan aquifer, such as horizontal hydraulic conductivity, model sensitivity was not as great in the Brunswick/Glynn County area as other areas along coastal Georgia. The model exhibited more sensitivity to these parameters however, than to parameters representing the majority of zones defining the vertical hydraulic conductivity of the confining units, which originally were assumed to govern upward migration of chloride contamination into this aquifer.

Analysis of simulated water-budget components for 2000 and 2004 indicate that specified-head boundaries in the Floridan aquifer system to the south and southwest of the regional model area control about 70 percent of inflows and nearly 50 percent of outflows to the model region. Other water budget components indicate an 80-million-gallon-per-day decrease in pumping from the Floridan aquifer system during this period.

Introduction

In the Brunswick/Glynn County, Georgia (Ga.) area, saltwater intrusion has been contaminating the Upper Floridan aquifer (UFA) for more than 50 years. Presently (2014), within an area covering several square miles of downtown Brunswick, the aquifer yields water that has a chloride concentration greater than 2,000 milligrams per liter (mg/L), well above the 250-mg/L State and Federal secondary drinking-water standard (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000). Saltwater contamination has constrained further development of the UFA in the Brunswick area, prompting interest in the development of alternative sources of water supply, primarily from the shallower surficial and Brunswick aquifer systems. Further development of the UFA is limited to areas outside of the chloride plume and will be performed in a way that will minimize migration of groundwater with high-chloride concentrations and maintain hydraulic-head gradients toward active pumping centers in the area. The U.S. Geological Survey (USGS), in cooperation with the Brunswick/Glynn County Joint Water and Sewer Commission (JWSC) and the Georgia Environmental Protection Division (GaEPD), revised an existing groundwater model to investigate the effects of pumping on the migration of high-chloride water in the Brunswick/Glynn County area, thereby providing scientific information essential for managing water resources along the Georgia coast.

In this investigation, the horizontal and vertical resolutions of an existing regional groundwater-flow model (Payne and others, 2005) were increased to more accurately simulate the effects of pumping in the vicinity of the chloride plume near downtown Brunswick. The existing regional model, hereafter referred to as the original model, was modified by (1) reducing grid dimensions to a maximum of 500 feet (ft) per side in the vicinity of the chloride plume; (2) subdividing the Brunswick aquifer system into the upper and lower Brunswick aquifers; (3) subdividing the UFA into the upper and lower water-bearing zones (UWBZ and LWBZ, respectively) in Glynn and Camden Counties; and (4) establishing new hydraulic property zones in the UFA to improve model calibration in the Brunswick/Glynn County area. The revised model is intended to establish a framework for the Brunswick/Glynn County area that will allow future investigations to evaluate the long-term effects of selected pumping scenarios on groundwater levels and flow paths near areas of chloride contamination.

Purpose and Scope

The purpose of this report is to document the simulation of groundwater flow in the Brunswick/Glynn County area of Georgia during 2000–04. The report describes revisions to a previously published application of the USGS modular finite-difference computer program (MODFLOW–2000; Harbaugh and others, 2000) developed by Payne and others (2005) to simulate regional groundwater flow along the Georgia coast in the Brunswick and Floridan aquifer systems during 2000–04. These revisions to the original model include (1) increased spatial resolution near the downtown Brunswick, Ga., area, (2) additional hydraulic-property zones in the UFA near Brunswick/Glynn County area, and (3) subdivision of the Brunswick aquifer system and Floridan aquifer system into separate model layers to represent the local hydrogeology.

The purpose of the revised model is to simulate the long-term steady-state effect of changing mean-annual pumping during 2000 and 2004 on groundwater levels and evaluate changes in hydraulic gradients near pumping centers in the Brunswick area. Local hydraulic gradients control the direction and rate of chloride migration in the Floridan aquifer system. Steady-state simulation was considered appropriate given the regional groundwater-flow characteristics of the Floridan aquifer system and the years 2000 and 2004 were chosen because of available groundwater-level (see appendix 1) and pumpage data.

To fully document the model revision process, this report describes (1) revisions to the original model, (2) the boundary conditions used, (3) the approach used to calibrate the revised model, (4) water budget calculations, and (5) the sensitivity analysis. Additional maps and tables of groundwater levels and residuals (simulated minus observed groundwater levels) are included in support of the calibration process, along with a section that describes limitations of the model analysis.

Description of Study Area

Glynn County is located in the Coastal Plain physiographic province on Georgia's Atlantic Coast about 80 miles (mi) south of Savannah, Ga., and about 87 mi north of Jacksonville, Florida (Fla.; fig. 1). Glynn County encompasses about 422 square miles (mi^2) and is bordered on the north by the Altamaha River, which empties into the Atlantic Ocean north of St. Simons Island. Altitudes in Glynn County range from 0 ft along the coast to 40 ft in the northwestern part of the county.

The City of Brunswick is located on a peninsula in Glynn County and encompasses about 50 mi^2. The city is bordered by

St. Simons and Jekyll Islands to the east and by the Brunswick and Little Satilla Rivers to the west and south, respectively (fig. 1). Both rivers form tidally influenced estuaries in the Brunswick area.

The population of Glynn County was 79,626 in 2010 (U.S. Census Bureau, 2010). The primary population center of Glynn County is the City of Brunswick, and a secondary population center has developed into an urbanized area on the southern part of St. Simons Island. Outside the urbanized areas near the City of Brunswick and St. Simons Island, land use in Glynn County is a mixture of forest, grazed woodland, marsh, and swampland.

Glynn County has a climate classified as warm temperate and fully humid, with warm summers (Kottek and others, 2006). The average temperature for the climate-normal period of 1981–2010 was 68.1 degrees Fahrenheit, based on data compiled at St. Simons Island, Ga. (National Oceanic and Atmospheric Administration, 2014). Mean-annual precipitation for the same period is 45.0 inches, with the heaviest rainfall occurring during the months of June, August, and September. Glynn County is located in the central subarea of the 24-county coastal area designated by the GaEPD, which subdivided the area into northern, southern, and central subareas to facilitate water management practices (fig. 1).

Previous Investigations

Because this study uses a revised version of a previously developed model (Payne and others, 2005) to evaluate groundwater flow in the Brunswick/Glynn County area, the reader is referred to the original report for a complete list of the literature pertaining to hydrogeologic investigations for the regional model area. The publications listed here pertain to the Brunswick/Glynn County area.

Warren (1944) discussed the occurrence of brackish water in a city well at Brunswick and the possibility of saltwater encroachment in Glynn County. Wait (1962, 1965), Wait and Gregg (1973), and Gregg and Zimmerman (1974) documented the chloride contamination problem near downtown Brunswick, which included water-level and water-chemistry data. Krause and others (1984) identified wells in the Glynn County area that could be used to monitor chloride concentration and proposed sites for installation of additional monitor wells in the coastal area. Randolph and Krause (1990) developed a subregional groundwater model of Glynn County and the surrounding area that was linked to a regional model developed earlier (Krause and Randolph, 1989). Maslia and Prowell (1990) inferred major northeast-southwest-trending faults through the downtown Brunswick area based on structural analysis of geophysical data, northeastward elongation of the potentiometric surface of the UFA, and breaches in the local confining unit that influence the area of chloride contamination. As part of a regional evaluation of geology and groundwater resources, Clarke and others (1990) described water-bearing units in Miocene sediments in the Glynn County area. Jones and Maslia (1994) presented selected groundwater-level and water-quality data, and aquifer properties of the UFA for the Brunswick area. Clarke and Krause (2000) updated the subregional Brunswick/Glynn County model (Randolph and Krause, 1990) based on a comparison to other models developed in the area, and used the revised model to simulate a variety of water-management scenarios in the coastal area of Georgia. Jones and others (2002) presented evidence from 2,727-foot-deep test well 33H188 (TW-26) on Colonels Island, indicating localized faulting and dissolution within the Floridan aquifer system. Cherry (2007), Cherry and Clarke (2008), and Cherry and others (2010 and 2011) described changes in the chloride plume in the Brunswick area based on annual chloride sampling.

Methods of Study

This study updates and refines an existing regional groundwater-flow model of coastal Georgia and adjacent parts of South Carolina and Florida (Payne and others, 2005) to enable locally detailed simulation of groundwater flow in areas exceeding the 250-mg/L State and Federal secondary drinking-water standard for chloride near downtown Brunswick, Ga. (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000).

Information about groundwater withdrawals during 2000–04 was compiled from the records of South Carolina Department of Health and Environmental Control (SCDHEC), GaEPD, and USGS, which were developed into model input. The existing model grid was refined to enhance resolution of simulated groundwater levels in the Brunswick/Glynn County area. Two active model layers were added, based on the local hydrogeology, to represent additional water-bearing units within the Brunswick aquifer system and UFA. Water-level data for 2004 were compiled for 88 wells distributed throughout coastal Georgia. These data, together with data collected from 181 wells during 2000 (Payne and others, 2005), were used to calculate water-level residuals representing simulated minus observed water levels.

Georgia Well-Identification System

Wells described in this report are assigned a well identifier according to a system based on the index of U.S. Geological Survey (USGS) 7.5-minute topographic maps of Georgia. Each map in Georgia has been assigned a two- to three-digit number and letter designation (for example, 07H) beginning at the southwestern corner of the State. Numbers increase sequentially eastward and letters advance alphabetically northward. Quadrangles in the northern part of the State are designated by double letters: AA follows Z, and so forth. The letters “I,” “O,” “II,” and “OO” are not used. Wells inventoried in each quadrangle are numbered consecutively, beginning with 001. Thus, the fourth well inventoried in the 34H quadrangle is designated 34H004. In the USGS National Water Information System (NWIS) database, this information is stored in the “Station Name” field; in NWIS Web, it is labeled “Site Name.”

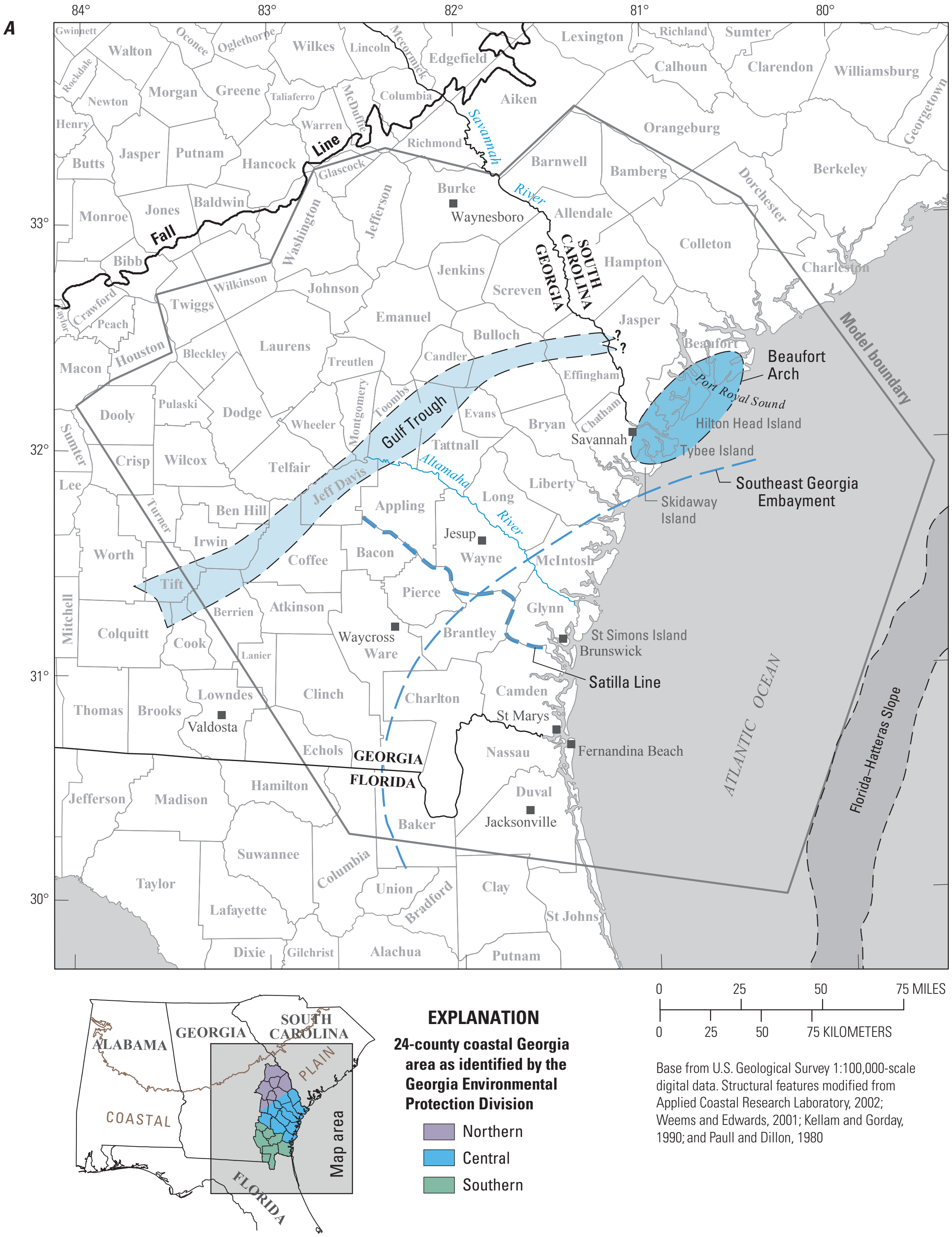


Figure 1. *A*, Location of 24-county coastal Georgia area, model area, major structural features, and *B*, 250-milligram-per-liter (mg/L) chloride concentration isochlor for June 2001 and 2005 near Brunswick, Georgia (modified from Payne and others, 2005; Leeth and others, 2003 and 2007).

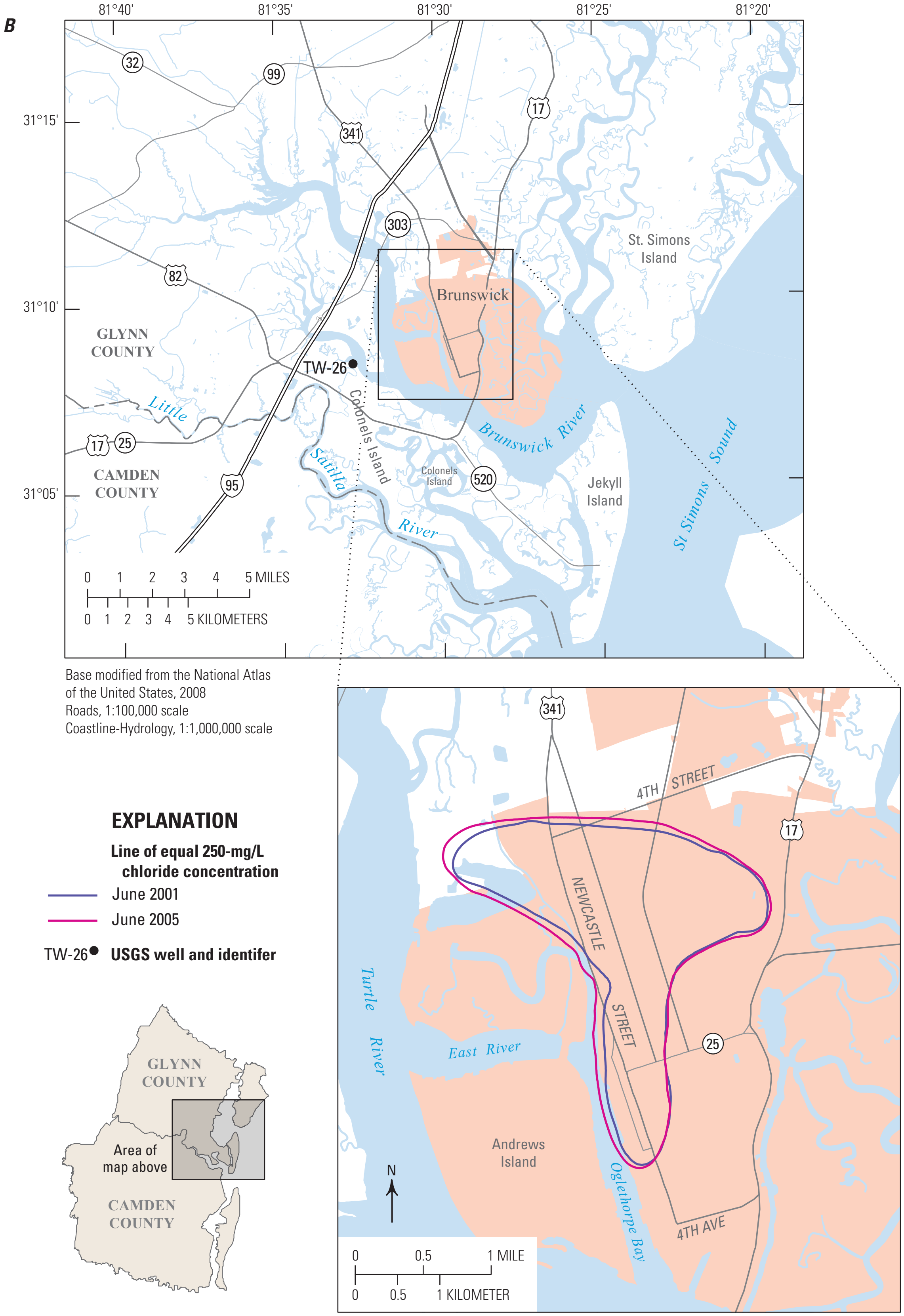


Figure 1. *A*, Location of 24-county coastal Georgia area, model area, major structural features, and *B*, 250-milligram-per-liter (mg/L) chloride concentration isochlor for June 2001 and 2005 near Brunswick, Georgia (modified from Payne and others, 2005; Leeth and others, 2003 and 2007).—Continued

Hydrogeologic Setting

Coastal Plain sediments consist of consolidated to unconsolidated layers of sand and clay, to semiconsolidated to dense layers of limestone and dolomite, which range in age from Late Cretaceous to Holocene (fig. 2). In general, these hydrogeologic units have been divided into aquifers and confining units based upon water-yielding characteristics, with relatively high permeability layers forming aquifers and low-permeability layers forming confining units. These sedimentary units unconformably overlie igneous, metamorphic, and sedimentary rocks of Paleozoic to Mesozoic age and reach a maximum thickness of 5,500 ft in Camden County (Wait and Davis, 1986). The thickness of sedimentary units varies and is influenced by major structural features in the area, such as the Southeast Georgia Embayment, Beaufort Arch, and Gulf Trough (fig. 1).

The Southeast Georgia Embayment (Miller, 1986) is a shallow east-to-northeast plunging syncline that accumulated Coastal Plain sediments to a maximum thickness in the Camden County area (fig. 1). It is postulated that subsidence occurred at a moderate rate from the Late Cretaceous to late Cenozoic, which allowed sediments to accumulate (Miller, 1986).

Series	Stage	Upper Coastal Plain[1] Geologic unit	Upper Coastal Plain[1] Hydrogeologic unit		Lower Coastal Plain[3] Geologic unit[4]	Lower Coastal Plain[3] Hydrogeologic unit (Savannah / Brunswick)		Model layer
Post-Miocene		Undifferentiated	Upper Three Runs aquifer	Floridan aquifer system	Undifferentiated	Water-table zone	Surficial aquifer system	GHB (not modeled)
Miocene	Upper	Undifferentiated	Upper Three Runs aquifer	Floridan aquifer system	Ebenezer Formation	Confining unit; Upper water-bearing zone; Lower water-bearing zone	Surficial aquifer system	1
Miocene	Middle	Undifferentiated	Upper Three Runs aquifer	Floridan aquifer system	Coosawhatchie Formation	Confining unit	Brunswick aquifer system	2
Miocene	Lower	Undifferentiated	Upper Three Runs aquifer	Floridan aquifer system	Marks Head Formation	Confining unit; Upper Brunswick aquifer	Brunswick aquifer system	3
Miocene	Lower	Undifferentiated	Upper Three Runs aquifer	Floridan aquifer system	Parachucla Formation	Confining unit	Brunswick aquifer system	4
Miocene	Lower	Undifferentiated	Upper Three Runs aquifer	Floridan aquifer system	Tigerleap Member of Parachucla Formation	Confining unit; Lower Brunswick aquifer	Brunswick aquifer system	5
Oligocene		Undifferentiated	Upper Three Runs aquifer	Floridan aquifer system	Lazaretto Creek Formation	Upper Floridan confining unit		6
Oligocene		Undifferentiated	Upper Three Runs aquifer	Floridan aquifer system	Suwannee Limestone	Upper Floridan aquifer: Upper water-bearing zone	Floridan aquifer system	7
Eocene	Upper	Barnwell Group	Upper Three Runs aquifer	Floridan aquifer system	Ocala Limestone	Upper Floridan aquifer: Upper Floridan semi-confining unit	Floridan aquifer system	8
Eocene	Upper	Barnwell Group	Upper Three Runs aquifer	Floridan aquifer system	Ocala Limestone	Upper Floridan aquifer: Lower water-bearing zone	Floridan aquifer system	9
Eocene	Middle	Santee Limestone	Confining unit	Floridan aquifer system	Avon Park Formation	Lower Floridan confining unit	Floridan aquifer system	10
Eocene	Middle	Santee Limestone	Confining unit	Floridan aquifer system	Avon Park Formation	Lower Floridan aquifer: Upper permeable zone[5]	Floridan aquifer system	11
Eocene	Lower	Congaree Formation	Gordon aquifer	Floridan aquifer system	Oldsmar Formation	Lower Floridan aquifer: Confining unit	Floridan aquifer system	11
Paleocene		Snapp Formation Ellenton Formation (undifferentiated)	Confining unit[2]		Cedar Keys Formation	Lower Floridan aquifer: Fernandina permeable zone	Floridan aquifer system	11
Upper Cretaceous		Steel Creek Formation Black Creek Group (undifferentiated)	Upper Dublin aquifer		Undifferentiated	Confining unit		Not modeled

[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.
[5]Modified from Clarke and others, 1990; Krause and Randolph, 1989.

Figure 2. Generalized correlation chart of geologic and hydrogeologic units and model layers (modified from Payne and others, 2005; GHB, general-head boundary).

The Beaufort Arch (Siple, 1960) elevated coastal plain sediments in the area northeast of Savannah, including Hilton Head Island, South Carolina (S.C.). The formation of the arch thinned Coastal Plain sediments and brought them close to land surface, where they dip and thicken southward toward the Southeast Georgia Embayment.

The Gulf Trough (Herrick and Vorhis, 1963) is a zone of low-permeability, fine-grained clastic sediments and clay-rich carbonates that act as a barrier and impede groundwater flow toward the coast. This feature is identified on potentiometric surfaces of the UFA as increased hydraulic gradients near the Gulf Trough that decrease south of the feature (Peck and McFadden, 2004).

Another feature, less prominent than the Gulf Trough, is the Satilla Line, which is a postulated hydrologic boundary identified by GaEPD that could influence groundwater flow in the UFA (fig. 1). The feature's existence is based on a change in the configuration of the potentiometric surface of the UFA, and by linear changes depicted on aeromagnetic, aeroradioactivity, gravity, and isopach maps; however, its geologic origin and nature are unknown.

The following descriptions of the surficial, Brunswick, and Floridan aquifer systems are based on their characteristics in the lower Coastal Plain physiographic province (fig. 2).

Surficial Aquifer System

The surficial aquifer system consists of interlayered lenses of sand, clay, and thin limestone beds of Miocene to Holocene age (Clarke, 2003). The surficial aquifer system contains a water-table zone and as many as two confined zones in the southern part of the study area where sediments are thickest (Southeast Georgia Embayment). In Glynn County, the surficial aquifer system contains a water-table zone and a single confined zone (Clarke and others, 1990). The reported transmissivity of the water-table zone ranges from 14 to 6,700 feet squared per day (ft^2/d), whereas the reported transmissivity of the confined zone ranges from 150 to 6,000 ft^2/d (Clarke, 2003). In the original model, one confined zone is recognized and grouped into the upper model layer with the confining units of the surficial and Brunswick aquifer systems (Payne and others, 2005, fig. 2).

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

Brunswick Aquifer System

The Brunswick aquifer system consists of two water-bearing zones—the upper Brunswick aquifer and the lower Brunswick aquifer (fig. 2; 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 is thinner, and as a result, has lower transmissivity than the lower Brunswick aquifer. Reported transmissivity of the upper Brunswick aquifer ranges from 20 to 3,500 ft^2/d, whereas the reported transmissivity of the lower Brunswick aquifer ranges from 2,000 to 4,700 ft^2/d (Clarke, 2003). The highest transmissivity values for both aquifers were reported near the Southeast Georgia Embayment where the units reach a maximum thickness in the Glynn County area (Clarke, 2003). The lower Brunswick confining unit (fig. 2) consists of weakly lithified shales and mudstones (Weems and Edwards, 2001). Outside the Southeast Georgia Embayment, the Brunswick aquifer system thins, or is discontinuous, and has a greater percentage of fine-grained sediments (Clarke, 2003). The original model of Payne and others (2005) considered the upper and the lower Brunswick aquifers as one model layer with combined thickness and one assigned hydraulic conductivity value. The current study subdivided this unit into two layers throughout the revised model to account for variability in layer thickness and hydraulic properties.

The Brunswick aquifer system is separated from the underlying Floridan aquifer system by a confining unit consisting of layers of silty clay and dense phosphatic dolomite of Oligocene age (fig. 2; Clarke, 2003). The reported vertical hydraulic conductivity of this confining unit ranges from 2.3×10^{-4} to about 3 ft/d (Clarke and others, 2004), with one value estimated to be 1.1×10^{-2} ft/d in the Brunswick area.

Floridan Aquifer System

The Floridan aquifer system consists of the UFA and Lower Floridan aquifer (LFA), which are composed of mostly Paleocene to Oligocene carbonate rocks that locally include Upper Cretaceous rocks (fig. 2; Miller, 1986; Krause and Randolph, 1989). The Floridan aquifer system extends from coastal areas in southeastern South Carolina, westward across the coastal plain of Georgia and Alabama, and southward, covering Florida. The thickness of the Floridan aquifer system in the model area varies from less than 100 ft in aquifer outcrop areas of South Carolina to about 2,600 ft near the City of Brunswick (Krause and Randolph, 1989).

The UFA is highly productive and consists of Eocene to Oligocene age limestone and dolomite (fig. 2; Clarke and others, 1990). The aquifer crops out at or near land surface in the northwestern part of the study area and near Valdosta in Lowndes County, Ga., where the aquifer is unconfined or semiconfined (fig. 1). 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 UFA (fig. 3). The transition from carbonate to clastic deposits generally occurs north of the Gulf Trough.

The reported transmissivity of the UFA and equivalent clastic units 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). Large variability in the range of transmissivity where the UFA is largely composed of carbonate may indicate the influence of fractures or solution openings and related anisotropic distribution of hydraulic properties (Warner and Aulenbach, 1999; Clarke and others, 2004). Maslia (1987) attributed greater anisotropy between local- and regional-scale tests at the City of Brunswick to preferential flow along vertical solution channels associated with high-angle reverse faults and fractures.

In the original model (Payne and others, 2005), the UFA was simulated as a single layer. For this study, the aquifer was subdivided into the UWBZ and LWBZ as identified by Wait and Gregg (1973) in the Brunswick/Glynn County area (fig. 2). Wait and Gregg (1973) concluded the UWBZ is more productive, as indicated by pumping data from a well that tapped both zones; the upper zone contributed 70 percent of the flow and lower zone contributed the remainder. However, large cavities have been reported in the LWBZ and one cavity present at a depth of 945 to 947 ft below land surface increased the flow from 600 gallons per minute (gal/min) to 4,200 gal/min (Wait, 1965). In the Brunswick area, the UWBZ is about 165 ft thick separated from the LWBZ by a semiconfining unit of about 160 ft of soft dolostone (fig. 2; Jones and Maslia, 1994). Locally the LWBZ has a thickness of 100 ft and extends to a depth of 970 ft. The UFA is underlain by a confining unit of dense recrystallized limestone and dolomite of middle to late Eocene age that hydraulically separates the UFA from the LFA by varying degrees (fig. 2). The UWBZ of the UFA is in the uppermost part of the Ocala Limestone and the Suwanee Limestone, which has been made extremely permeable by the development of secondary porosity caused by the migration of groundwater along bedding planes, joints, and fractures (L. Elliott Jones, U.S. Geological Survey, written commun., 2014).

Locally in the Brunswick area, the confining unit is breached by fractures or solution openings that enhance the exchange of water between the UFA and LFA (fig. 3; Krause and Randolph, 1989; Maslia and Prowell, 1990). These features probably have allowed saline water from the Fernandina permeable zone (described later) to migrate upward, primarily into the UWBZ of the UFA, where pressures are lower because of large-scale pumping by local industry. According to Maslia and Prowell (1990), four major northeast-southwest trending faults are indicated by geophysical data that show anomalous or irregular surfaces in the A–D marker beds near downtown Brunswick, which can be explained by a system of local folding and faulting. The marker beds, first recognized by Wait and Gregg (1973), represent natural gamma spikes interpreted as depositional unconformities that were created by a Miocene transgression. The marker beds form regular surfaces outside the Brunswick/Glynn County area. The LFA is composed mainly of dolomitic limestone of early and middle Eocene age; at the City of Brunswick, however, it includes highly permeable limestone of Paleocene and Late Cretaceous age (fig. 2; Krause and Randolph, 1989). In the northwestern part of the model area, the clastic Gordon aquifer (Brooks and others, 1985; Falls and others, 1997) is an updip unit that is hydraulically connected to the LFA (fig. 3). Reported transmissivity of the LFA 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).

In southeastern Georgia and northeastern Florida, the LFA includes a saline water-bearing unit known as the Fernandina permeable zone, which is deeply buried, cavernous, and highly permeable (fig. 3; Krause and Randolph, 1989). The lateral extent of this unit is uncertain because a deep drilling program conducted for the Coastal Sound Science Initiative identified the unit near downtown Brunswick, but not farther north on St. Simons Island and in McIntosh County (Falls and others, 2005). The Fernandina permeable zone is present at a depth of about 2,100 ft in USGS 2,727-ft-deep test well (TW–26) on Colonels Island and is important in the Brunswick area because it is probably the local source of saline water (Jones and others, 2002). Maslia and Prowell (1990) postulated a system of vertical fractures and faults serve as a pathway for saline water migration from the Fernandina permeable zone into shallower units (fig. 3). Additional evidence of the presence of this unit was also obtained in deep test well (TW–26) on Colonels Island in Glynn County, about 3 mi west-southwest of downtown Brunswick. Acoustic televiewer images inside the borehole indicated the presence of large dissolution cavities at a depth of 2,475 ft near what appeared to be a high-angle fault and (or) fracture zones (Jones and others, 2002).

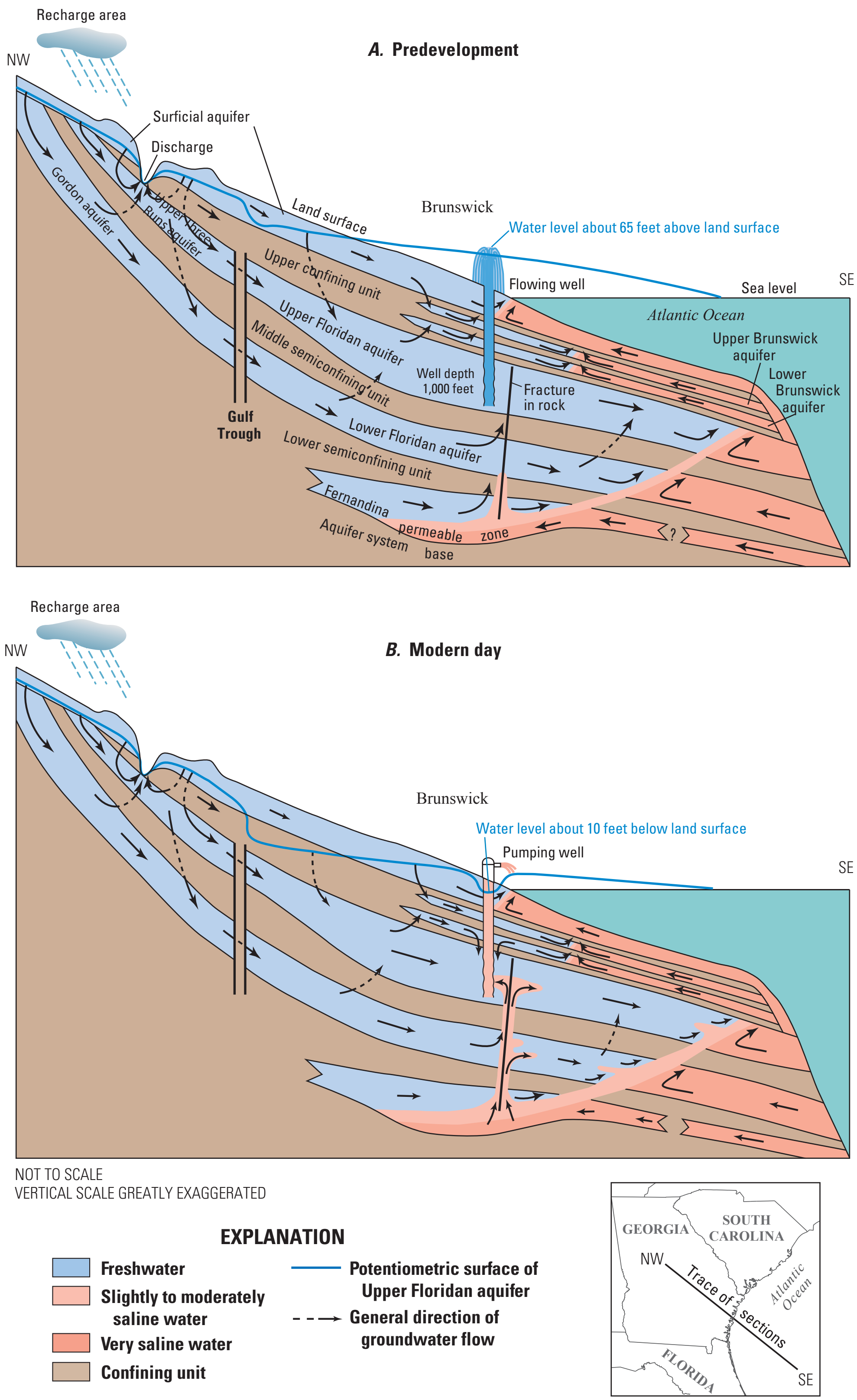


Figure 3. Schematic cross sections showing conceptual models of *A*, predevelopment (pre-1880s) and *B*, modern-day groundwater flow in the Floridan aquifer system from the outcrop area in the northwest (NW) to the offshore area in the southeast (SE), coastal Georgia (modified from Krause and Randolph, 1989).

Conceptualization of Groundwater Flow

Most of groundwater recharge to the system occurs in outcrop areas of the Floridan aquifer system northwest of the Gulf Trough (fig. 3). Precipitation infiltrates land surface as direct recharge to the surficial aquifer and continues to flow downward into the deeper units. Some shallow flow paths capture infiltrating precipitation and contribute base flow locally to streams.

Prior to development, groundwater flow laterally descended toward the coast and then moved upward from deeper to shallower units near the ocean. Currently (2014), groundwater flow paths are influenced by pumping from the UFA, which has induced increased upward groundwater flow into the aquifer from the underlying Fernandina permeable zone through vertical fractures and faults (fig. 3). Maslia and Prowell (1990) postulated the location of four major northeast-southwest-trending faults near the downtown Brunswick area, as well as fractures located at the intersection of these faults that have promoted the development of conduits, thereby allowing upward migration of saline groundwater into the UFA in response to pumping. This pumping in the UFA increased the natural upward hydraulic gradient from the Fernandina permeable zone toward the UFA and enhanced local groundwater flow from the overlying Brunswick aquifer system downward into the UFA to supply water to production wells.

Areas of groundwater recharge and discharge are influenced by outcrop locations of the hydrogeologic units and their subsurface extent beneath stream alluvium. Generally, recharge areas correspond to relatively high-altitude interstream divides, and discharge areas correspond to low-lying stream valleys (Clarke and West, 1998). Local recharge areas for the regional groundwater-flow system are south of the Fall Line and west of the Gulf Trough, with mean-annual recharge rates in the Savannah River Basin estimated at 14.5 inches per year (in/yr) (Faye and Mayer, 1990). East of the Gulf Trough, annual recharge to the regional groundwater-flow system ranges from near 0 to 2.4 in/yr, as inferred from estimates of stream base flow during a drought period (Priest, 2004). Base-flow estimates determined by Priest (2004) at 14 streamgaging stations ranged from 4.4 to 10.0 in/yr and were used as annual recharge rates for the original groundwater-flow model (Payne and others, 2005).

Groundwater-flow directions and water quality in the regional aquifer system respond to changes in recharge and pumping. When pumping exceeds recharge, saline water migrates upward through a network of faults and fractures located near downtown Brunswick. When recharge exceeds pumping, freshwater moving through the aquifer system does not completely flush the saline water from the aquifer, and residual solute can remain for an extended period of time. This condition can contribute to the long-term degradation of the aquifer once saline water has migrated into the system from below.

Chloride Contamination in the Brunswick Area

In the Brunswick area, saline water has been contaminating the UFA since the late 1950s and has constrained development of the aquifer. During 2009, the chloride contamination covered a 2-mi^2 area of downtown Brunswick and chloride concentrations within this area exceeded 2,000 mg/L (fig. 4; Cherry and others, 2011), well above the 250-mg/L State and Federal secondary drinking-water standard (Georgia Environmental Protection Division, 1997; U.S. Environmental Protection Agency, 2000).

Since the late 1950s, the USGS has collected water samples from the UFA in the Brunswick area and documented increasing chloride concentrations in response to increased groundwater withdrawals (fig. 4). Pumping resulted in lowered water levels and an upward hydraulic gradient between the saline portions of the Fernandina permeable zone and the normally fresh UFA. Saline water probably is entering the UFA through localized, vertically oriented conduits of relatively high permeability and moving laterally in response to pumpage within the UWBZ. Acoustic televiewer images from test well 33H188 (TW-26) provide evidence of features that appear to be high-angle fault and/or fracture zones at a depth near 2,475 ft (Jones and others, 2002). The chloride concentration of sea water is about 20,000 mg/L, and the water taken from the bottom of the Fernandina permeable zone at test well 33H188 was about 30,000 mg/L in 1982 (Krause and Randolph, 1989). The chloride plume has stabilized in recent years, most likely because local horizontal hydraulic gradients have been maintained and groundwater withdrawals by local industry and by regional groundwater users over the coastal region have decreased (Cherry, 2007; Cherry and Clarke, 2008; Cherry and others, 2010 and 2011).

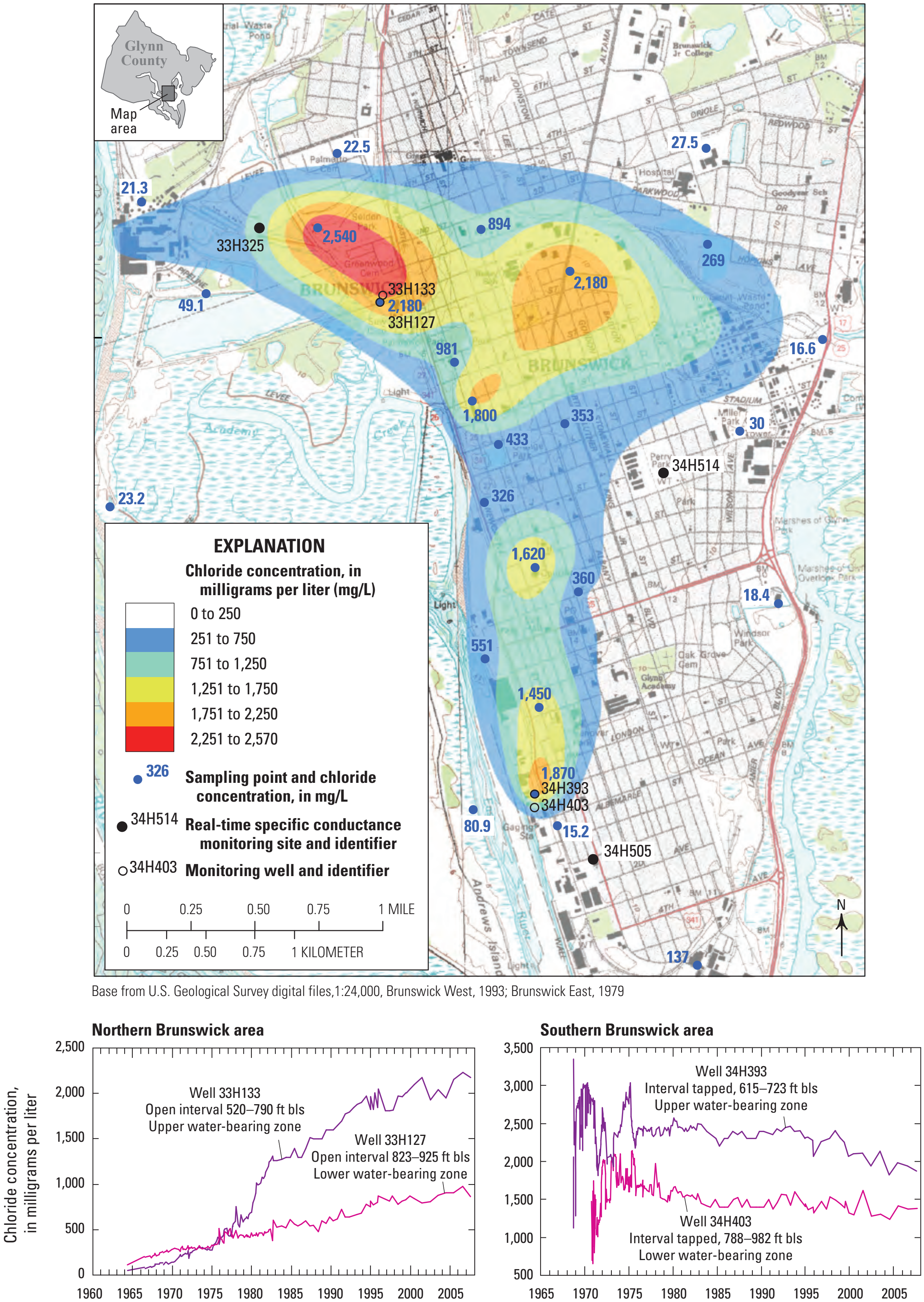


Figure 4. Chloride concentrations in the Upper Floridan aquifer near the downtown Brunswick area, August 2007, and chloride concentration in water for selected wells in the northern and southern Brunswick area, 1964–2007.

Groundwater Use and Water Levels, 2000–04

The location and magnitude of groundwater withdrawals at pumping centers may affect groundwater levels substantially in the Brunswick/Glynn County area. Changes in pumping rates and the addition of new pumping centers may alter the configuration of potentiometric surfaces, reverse groundwater-flow directions, and increase seasonal and long-term water-level fluctuations in the aquifers. During 2000–04, groundwater levels in the UFA in the Brunswick/Glynn County area were affected by the shutdown of the Durango Paper Company mill near St. Marys, Ga. (fig. 1). In addition, a prolonged drought adversely affected groundwater levels during 1998–2002. The following sections describe changes to groundwater use and groundwater levels during the 5-year period of model simulation.

Groundwater Use

The UFA and LFA supply the study area with sufficient quantities of groundwater, with average withdrawals during 2000 totaling 682 and 133 million gallons per day (Mgal/d), respectively (Payne and others, 2005). Groundwater withdrawals from the UFA and LFA in 2004 were less than during 2000, with average withdrawals totaling 612 and 116 Mgal/d, respectively. Pumping from the UFA and LFA during 1980–2004 is summarized in table 1 and shown in figure 5*A*, both of which indicate groundwater use increasing steadily and peaking during 2000. Considerably less groundwater was withdrawn from the Brunswick aquifer system during 2004 (1.75 Mgal/d) than from the UFA and LFA, although withdrawals from the Brunswick aquifer system have increased since 2000 as a result of GaEPD restrictions on further development of the UFA.

County aggregate and site-specific data were used to estimate average annual pumpage for 2000 and 2004 using procedures described by Taylor and others (2003). Groundwater-use data for 2000 were based on county aggregate pumping estimates for Florida (Marella, 2004), Georgia (Fanning; 2003), and South Carolina (W.L. Stringfield , U.S. Geological Survey, written commun., 2002). Site-specific data along with pumping rates were compiled for Georgia (J.L. Fanning, U.S. Geological Survey, written commun., 2002), South Carolina (P. Bristol, South Carolina Department of Health and Environmental Control, written commun., 2003), and Florida (Sepúlveda, 2002). Pumping estimates for 2004 reflect a combination of site-specific data for 2004 (J.L. Fanning,

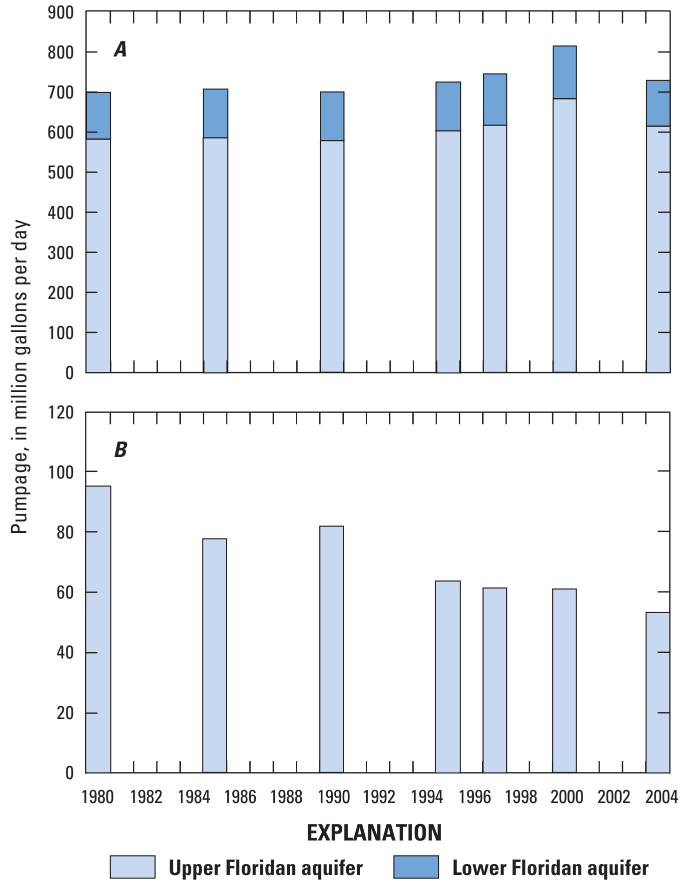


Figure 5. Estimated groundwater pumpage from the *A*, Upper and Lower Floridan aquifers in the model area, and *B*, Upper Floridan aquifer in the Glynn County area, 1980–2004. Table 1 provides county totals and data sources.

U.S. Geological Survey, written commun., 2006; P. Bristol, South Carolina Department of Health and Environmental Control, written commun., 2006; R.L. Marella, U.S. Geological Survey, written commun., 2006) and county aggregate data for 2000 (Marella, 2004; Fanning, 2003; W.L. Stringfield, U.S. Geological Survey, written commun., 2002). Because county aggregate data were not available for 2004, county aggregate estimates for 2000 were used as a basis for estimating usage for 2004. Use of these data for both time periods is considered reasonable for Glynn County because agricultural pumpage in the county is minimal, and rural population (domestic supply) showed little change during this period. In other parts of the coastal area, use of aggregate data for 2000 could have resulted in an overestimation of water use during 2004 because generally wetter conditions existed during 2004 compared to 2000.

Along the Georgia coast, the estimated pumping distributions during 2000 and 2004 were comparable at major pumping centers located near Savannah, Jesup, and Brunswick, Ga. Concerns about overdevelopment of the UFA prompted the GaEPD to implement an interim water management plan for coastal Georgia (Georgia Environmental Protection Division, 2005), which restricted withdrawal from the UFA in parts of the coastal area, resulting in decreased withdrawals overall (fig. 5).

In general, permitted groundwater withdrawals have decreased across the State since 2001 by about 12 percent because of conservation efforts made by industrial and municipal users (Leeth and others, 2007). The largest change in water use in coastal Georgia during 2000–04 was attributed to the shutdown of the Durango Paper Company mill in October 2002, which deactivated production wells at the facility. The paper mill near St. Marys was about 30 mi south of the City of Brunswick, and pumped 35.5 Mgal/d from the UFA while in operation (Peck and others, 2004).

Groundwater is an important resource in counties located along coastal Georgia and parts of coastal areas in Florida and South Carolina because of population growth and industrial development. The largest withdrawals from the UFA in 2004 occurred in Chatham (63 Mgal/d), Wayne (63 Mgal/d), and Glynn (54 Mgal/d) Counties, Ga. During 2000–04, the largest change in pumpage occurred in Camden County, which decreased from 51 Mgal/d in 2000 to 6.3 Mgal/d in 2004, with most of the decrease attributed to the shutdown of the Durango Paper Company mill in October 2002 (Peck and others, 2004). Average daily pumpage from the UFA and its updip equivalents during 2004 exceeded 10 Mgal/d in Duval and Nassau Counties, Fla.; in Beaufort County, S.C.; and in Burke, Chatham, Coffee, Dooly, Glynn, Jefferson, Liberty, Pulaski, Screven, Washington, Wayne, and Wilcox Counties, Ga. (table 1). Average daily pumpage in the LFA and its updip equivalents during 2004 exceeded 1 Mgal/d in Duval and Nassau Counties, Fla.; and in Burke, Coffee, Crisp, Dooly, Jefferson, Laurens, Pulaski, Screven, Washington, and Wilcox Counties, Ga. (table 1). The largest withdrawal from the LFA during 2004 occurred in Duval County, Fla., where pumpage exceeded 82 Mgal/d (table 1).

During 1980–2000, total daily pumpage from the UFA increased by 17 percent, from 583 Mgal/d during 1980, to a peak of 682 Mgal/d during 2000 (Payne and others, 2005). During 2004, estimated total daily pumpage from the UFA decreased to about 612 Mgal/d. The reduction could be lower than 612 Mgal/d because the 2000 aggregate water-use rate used for the 2004 estimate does not account for possible reduced agricultural usage that could have resulted from the generally wetter 2004 conditions compared with 2000.

Withdrawals from the LFA during 1980–2004 showed a similar pattern to those from the UFA. Estimated withdrawals from the LFA increased by 14 percent from a low of 117 Mgal/d during 1980 to a peak of 133 Mgal/d during 2000 (Payne and others, 2005), followed by a decrease to 116 Mgal/d during 2004 (table 1).

During 2000–04, total pumpage from the Brunswick aquifer system increased from 0.24 Mgal/d during 2000 to 3.25 Mgal/d during 2004 (Payne and others, 2005; Vicki Trent, Georgia Environmental Protection Division, written commun., November 15, 2010). The pumpage increase for the Brunswick aquifer can be attributed to greater use for golf-course irrigation in the Glynn County area and recently constructed public-supply wells in the Golden Isles area of Glynn County (Cherry and others, 2011).

Table 1. Estimated groundwater pumpage from the Upper and Lower Floridan aquifers in the coastal area of Georgia and adjacent parts of South Carolina and Florida, 1980–2004.

[UFA, Upper Floridan aquifer; LFA, Lower Floridan aquifer]

County	Pumpage, in million gallons per day					
	1980		1985		1990	
	UFA	LFA	UFA	LFA	UFA	LFA
Florida						
Baker	1.72	0.26	2.88	0.43	3.68	0.55
Columbia	3.05	0.00	4.79	0.00	5.07	0.00
Duval	53.96	92.52	47.44	99.13	41.91	100.46
Hamilton	0.10	0.00	0.30	0.00	0.44	0.00
Nassau	44.09	2.51	46.76	2.16	49.72	2.00
Georgia						
Appling	5.71	0.00	2.60	0.00	2.10	0.00
Atkinson	1.89	0.00	1.50	0.00	0.58	0.00
Bacon	2.63	0.00	2.28	0.00	2.11	0.00
Ben Hill	3.71	0.21	4.92	0.39	3.34	0.38
Berrien	2.43	0.41	3.26	0.53	2.80	0.45
Bleckley	5.59	0.87	4.28	0.63	3.29	0.41
Brantley	1.46	0.00	1.63	0.00	1.83	0.00
Bryan	0.67	0.00	0.87	0.00	1.03	0.00
Bulloch	3.75	0.23	2.71	0.20	5.87	0.16
Burke	10.30	1.60	6.34	0.92	5.82	0.83
Camden	37.12	0.00	42.98	0.00	45.74	0.00
Candler	1.83	0.26	2.57	0.34	1.64	0.17
Charlton	6.50	0.00	1.22	0.00	1.38	0.00
Chatham	79.75	3.58	78.98	3.20	85.54	4.13
Clinch	0.85	0.00	0.72	0.00	0.65	0.00
Coffee	12.59	1.49	7.98	0.78	5.60	0.25
Crisp	3.16	0.32	3.45	0.28	5.31	0.78
Dodge	7.02	1.01	3.95	0.52	2.40	0.22
Dooly	6.30	0.96	9.45	1.46	3.18	0.41
Echols	0.17	0.00	0.18	0.00	0.25	0.00
Effingham	2.26	0.02	2.06	0.01	4.98	0.03
Emanuel	7.34	0.85	5.30	0.68	4.18	0.36
Evans	0.38	0.05	0.31	0.04	0.38	0.05
Glascock	0.73	0.04	0.72	0.02	0.99	0.02
Glynn	95.40	0.00	77.84	0.00	82.02	0.00
Irwin	1.96	0.25	1.86	0.21	2.15	0.26
Jeff Davis	5.11	0.81	5.80	0.89	4.77	0.66
Jefferson	4.97	0.69	9.90	1.44	8.85	1.03
Jenkins	2.74	0.41	2.65	0.37	2.45	0.33
Johnson	1.37	0.17	1.81	0.26	0.92	0.12

Table 1. Estimated groundwater pumpage from the Upper and Lower Floridan aquifers in the coastal area of Georgia and adjacent parts of South Carolina and Florida, 1980–2004.—Continued

[UFA, Upper Floridan aquifer; LFA, Lower Floridan aquifer]

Pumpage, in million gallons per day								County
1995		1997		2000		2004		
UFA	LFA	UFA	LFA	UFA	LFA	UFA	LFA	
Florida								
2.11	0.32	2.11	0.32	2.11	0.32	3.24	0.44	Baker
6.92	0.00	6.57	0.00	6.04	0.00	6.04	0.00	Columbia
43.91	95.01	44.83	99.48	44.40	95.98	50.86	82.80	Duval
0.44	0.00	0.46	0.00	0.49	0.00	0.49	0.00	Hamilton
46.66	2.09	50.19	2.18	49.38	2.21	37.56	2.16	Nassau
Georgia								
2.38	0.00	2.47	0.00	4.17	0.00	4.08	0.00	Appling
1.58	0.00	1.58	0.00	2.91	0.00	3.07	0.00	Atkinson
2.47	0.00	2.21	0.00	4.04	0.00	4.63	0.00	Bacon
10.97	1.30	10.98	1.30	7.57	0.59	6.49	0.59	Ben Hill
4.65	0.67	4.66	0.67	5.33	0.77	5.33	0.75	Berrien
2.35	0.40	2.35	0.40	6.66	1.00	6.02	0.95	Bleckley
1.90	0.00	1.94	0.00	1.30	0.00	0.94	0.00	Brantley
1.06	0.00	1.70	0.00	1.60	0.00	2.63	0.00	Bryan
7.83	0.31	5.05	0.32	5.70	0.32	5.64	0.32	Bulloch
8.16	1.26	8.22	1.27	22.34	3.24	18.61	3.24	Burke
47.15	0.00	45.83	0.00	50.55	0.00	6.31	0.00	Camden
1.67	0.19	1.70	0.19	2.79	0.37	2.59	0.37	Candler
1.45	0.00	0.95	0.00	1.25	0.00	1.29	0.00	Charlton
75.84	3.76	70.66	3.78	68.15	3.23	63.24	0.09	Chatham
1.03	0.00	1.04	0.00	1.44	0.00	1.47	0.00	Clinch
7.59	0.47	7.52	0.53	15.23	1.73	14.37	1.73	Coffee
10.28	1.58	10.24	1.59	8.56	1.30	9.46	1.30	Crisp
4.28	0.46	4.28	0.46	3.96	0.41	5.22	0.41	Dodge
9.25	1.29	9.25	1.29	18.68	2.93	18.68	2.93	Dooly
1.04	0.00	1.77	0.00	2.88	0.00	2.88	0.00	Echols
5.98	0.04	4.42	0.03	4.62	0.03	6.85	0.03	Effingham
4.51	0.52	4.53	0.52	4.22	0.48	3.54	0.48	Emanuel
0.49	0.06	0.46	0.06	0.70	0.09	2.76	0.09	Evans
1.34	0.02	1.35	0.02	1.36	0.02	0.31	0.02	Glascock
63.68	0.00	61.61	0.00	61.14	0.00	53.60	0.00	Glynn
5.75	0.87	5.75	0.87	6.25	0.96	6.25	0.96	Irwin
3.09	0.40	3.09	0.40	3.84	0.47	3.84	0.47	Jeff Davis
7.76	0.76	7.62	0.97	12.06	1.68	12.06	1.68	Jefferson
3.19	0.47	3.13	0.46	4.03	0.61	3.92	0.61	Jenkins
1.83	0.27	1.83	0.27	2.12	0.32	2.12	0.32	Johnson

Table 1. Estimated groundwater pumpage from the Upper and Lower Floridan aquifers in the coastal area of Georgia and adjacent parts of South Carolina and Florida, 1980–2004.—Continued

[UFA, Upper Floridan aquifer; LFA, Lower Floridan aquifer]

County	Pumpage, in million gallons per day					
	1980		1985		1990	
	UFA	LFA	UFA	LFA	UFA	LFA
Georgia—Continued						
Lanier	3.07	0.00	2.92	0.00	1.69	0.00
Laurens	4.32	0.74	4.15	0.62	4.23	0.60
Liberty	13.62	0.00	14.58	0.00	17.97	0.00
Long	0.29	0.01	0.24	0.01	0.23	0.01
McIntosh	0.70	0.00	1.03	0.00	0.76	0.00
Montgomery	0.89	0.11	1.51	0.20	0.94	0.10
Pierce	2.64	0.00	2.03	0.00	1.80	0.00
Pulaski	6.94	1.11	8.27	1.31	6.87	1.09
Screven	7.90	1.18	7.19	1.03	7.87	0.40
Tattnall	1.56	0.06	1.89	0.09	1.77	0.08
Telfair	3.28	0.48	4.62	0.55	3.30	0.32
Tift	1.89	0.33	2.19	0.38	2.61	0.46
Toombs	2.87	0.24	3.91	0.31	3.61	0.20
Treutlan	0.49	0.06	0.54	0.05	0.79	0.06
Turner	1.02	0.17	1.00	0.17	0.93	0.16
Ware	6.25	0.00	7.25	0.00	6.20	0.00
Washington	10.01	1.52	12.24	1.89	13.02	1.96
Wayne	74.54	0.00	69.80	0.00	69.27	0.00
Wheeler	1.60	0.21	0.83	0.10	0.61	0.06
Wilcox	4.06	0.68	9.84	1.69	5.40	0.90
South Carolina						
Allendale	7.84	0.00	7.84	0.00	8.31	0.00
Bamberg	1.99	0.00	1.99	0.00	2.09	0.00
Barnwell	1.15	0.00	1.15	0.00	3.32	0.00
Beaufort	0.85	0.00	20.80	0.05	17.48	0.01
Colleton	0.00	0.35	0.00	0.55	0.00	0.56
Hampton	3.21	0.00	3.21	0.00	3.95	0.00
Jasper	1.25	0.01	1.16	0.00	1.97	0.00
Totals	**582.81**	**116.78**	**584.49**	**123.89**	**579.96**	**121.03**

Table 1. Estimated groundwater pumpage from the Upper and Lower Floridan aquifers in the coastal area of Georgia and adjacent parts of South Carolina and Florida, 1980–2004.—Continued

[UFA, Upper Floridan aquifer; LFA, Lower Floridan aquifer]

Pumpage, in million gallons per day								County
1995		1997		2000		2004		
UFA	LFA	UFA	LFA	UFA	LFA	UFA	LFA	
Georgia—Continued								
2.02	0.00	2.02	0.00	1.97	0.00	1.72	0.00	Lanier
5.78	0.97	5.81	0.95	7.94	1.31	7.96	1.31	Laurens
15.91	0.00	16.10	0.00	15.69	0.00	15.56	0.00	Liberty
0.27	0.02	0.27	0.02	0.69	0.07	1.20	0.07	Long
1.07	0.00	1.09	0.00	0.85	0.00	0.94	0.00	McIntosh
2.40	0.33	2.40	0.33	1.61	0.19	1.61	0.19	Montgomery
3.24	0.00	3.42	0.00	6.22	0.00	6.18	0.00	Pierce
8.59	1.31	8.53	1.35	11.46	1.81	11.46	1.81	Pulaski
6.36	0.66	6.93	0.69	16.24	2.32	15.25	2.32	Screven
3.53	0.28	3.59	0.28	3.66	0.15	2.74	0.15	Tattnall
6.33	0.83	6.33	0.82	4.00	0.42	4.36	0.42	Telfair
3.95	0.69	3.80	0.66	3.57	0.62	3.57	0.62	Tift
3.65	0.27	4.17	0.27	6.30	0.69	6.64	0.69	Toombs
1.31	0.12	1.31	0.12	1.10	0.11	1.13	0.11	Treutlan
2.91	0.50	2.92	0.50	2.57	0.44	2.57	0.44	Turner
5.51	0.00	5.97	0.00	8.45	0.00	5.82	0.00	Ware
14.39	2.16	14.88	2.04	16.01	2.07	16.01	2.07	Washington
64.89	0.00	63.59	0.00	63.47	0.00	63.12	0.00	Wayne
2.22	0.34	2.22	0.34	1.07	0.14	1.07	0.19	Wheeler
8.43	1.43	8.43	1.43	14.74	2.53	14.74	2.53	Wilcox
South Carolina								
9.44	0.00	9.85	0.00	9.59	0.00	9.25	0.00	Allendale
2.52	0.00	4.04	0.00	6.32	0.00	6.32	0.00	Bamberg
2.91	0.00	4.90	0.00	7.50	0.00	7.39	0.00	Barnwell
19.56	0.01	33.58	0.09	21.44	0.26	18.21	0.03	Beaufort
0.00	0.58	0.00	0.47	0.00	0.51	0.15	0.24	Colleton
4.32	0.00	5.99	0.00	8.63	0.00	7.97	0.00	Hampton
1.31	0.00	2.13	0.01	3.34	0.01	2.80	0.01	Jasper
603.42	**123.02**	**616.62**	**127.75**	**682.31**	**132.71**	**612.13**	**115.94**	**Totals**

Groundwater Levels

Groundwater levels vary seasonally and are affected by precipitation, evapotranspiration, and pumping. Groundwater levels generally are highest in the winter through early spring when evapotranspiration is lowest and irrigation withdrawals are minimal; groundwater levels are lowest during summer and fall when evapotranspiration and pumping rates are highest. A map and water-level hydrographs for selected wells in the Brunswick aquifer system, UFA, and LFA during 2000–04 for Glynn County are shown in figure 6.

During 2003–04, above-normal rainfall following the drought of 1998–2002 and the reduction in groundwater withdrawals from major aquifers resulted in increased water levels. Some wells recorded historic lows during the fall of 2002, but recovered to near normal levels, or in some cases above-normal levels in 2004 (Leeth and others, 2007). The most pronounced water-level rise was in the St. Marys, Camden County area, in response to closure of the Durango Paper Company mill in October 2002, which resulted in a water-level rise of more than 200 ft at the center of the cone of depression and water-level increases ranging from 4 to 10 ft in outlying areas of Camden County (Peck and others, 2004). During 2003–04, above-normal rainfall ended the cycle of drought in Georgia that lasted from 1998 to 2002. The rainfall amounts for 2003 at 10 stations located in hydrogeologic unit areas of outcrop (aquifer-recharge zones) ranged from 8 to 34 percent above normal (The Southeast Regional Climate Center, 2009). As a result of the increase in rainfall and recharge to the regional aquifer system, water levels for June 2004 in the Brunswick aquifer system, UFA, and LFA (fig. 6) generally were higher than during 2000. The exceptions occurred in two wells in the Savannah area (39Q026 and 39Q028) having open intervals in the Brunswick aquifer system and one well in Effingham County, (35T003) completed in the UFA, which indicated water-level declines from in 2000 to 2004. These wells could be influenced by localized pumping.

Data from eight observation wells open to the Brunswick aquifer system indicate a general water-level rise during 2000–04 throughout the study area (table 2). Overall, the differences in water-level measurements from 2000 to 2004 range from –1.04 ft (well 39Q028; Chatham County) to 19.29 ft (well 33D071; Camden County), with an average increase of 3.97 ft. In the Brunswick/Glynn County area, water levels in two observation wells rose 3.04 ft (well 34H437) and 4.56 ft (well 33G028) over the 5-year period (table 3). Graphs for wells 33J062 and 34H492, completed in the lower Brunswick and surficial aquifers, respectively, show water-level rises during 2000–04, with most of the rise occurring during 2002 (fig. 6). The largest rise occurred in well 33J062, located in the western part of Glynn County, away from any pumping centers.

In the UWBZ, water-level measurements taken in 35 wells during 2000–04 indicate water-level declines and rises ranging from –29.29 to 11.84 ft, respectively, with an average water-level rise of 4.03 ft (table 2). In the Brunswick/Glynn County area, water levels in 19 wells completed in the UWBZ rose from 1.05 to 7.93 ft, with an average water-level rise of 4.94 ft (table 3). Water levels in well 33H133 show a water-level rise during 2000–04, with about 6 ft of the rise occurring during 2002 (fig. 6). Water-level data for the LWBZ are sparse but indicate a water-level rise of 7.25 ft in one well in downtown Brunswick (33H127; table 3; fig. 6), which is consistent with water-level changes in the overlying UWBZ of the UFA.

In the LFA, 2000 and 2004 water-level data from eight observation wells indicate rises ranging from 1.73 to 27.09 ft, with an average increase of 7.14 ft (table 2). The 27.09-ft water-level rise observed in well 33D073 was due, in part to the shutdown of the Durango Paper Company mill during 2002 (Peck and others, 2004). In the Brunswick/Glynn County area, 2000 and 2004 water-level data from five observation wells indicate water-level rises ranging from 2.69 to 7.68 ft, with an average increase of 5.06 ft (table 3). Water levels in LFA well 34H436 rose during 2000–04, with most of the increase occurring during 2002 (fig. 6). In well 33H188, completed in the Fernandina permeable zone of the LFA, water levels declined from 2000 through early 2002, followed by a sharp rise thereafter (fig. 6).

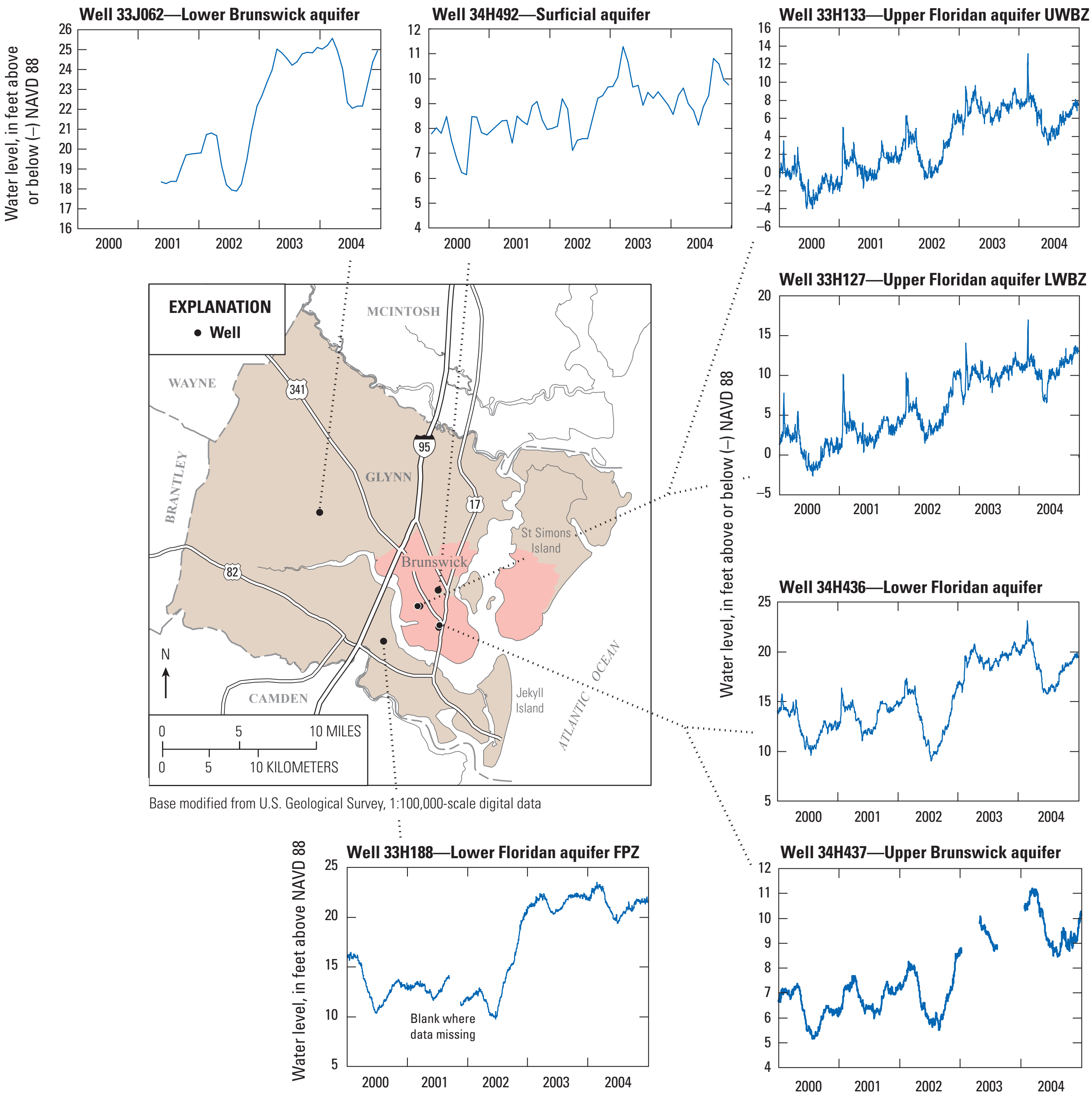


Figure 6. Selected water-level hydrographs for the surficial aquifer, upper Brunswick aquifer, lower Brunswick aquifer, Upper Floridan aquifer upper water-bearing zone (UWBZ), Upper Floridan aquifer lower water-bearing zone (LWBZ), Lower Floridan aquifer, and Lower Floridan aquifer Fernandina permeable zone (FPZ), in the Brunswick/Glynn County, Georgia area, 2000–04.

Table 2. Water-level measurements taken during 2000 and 2004 and observed water-level change during the same period.

[NAVD 88, North American Vertical Datum of 1988; see fig. 2–1 for well locations]

Well identifier	County	Water level, in feet above or below NAVD 88		Water-level change from 2000 to 2004, in feet
		2000	2004	
Upper Brunswick aquifer (UBA)				
32L016	Wayne	15.79	17.60	1.81
33D071	Camden	–2.07	17.22	19.29
33G028	Glynn	16.75	21.31	4.56
34H437	Glynn	5.88	8.92	3.04
39Q026	Chatham	–2.31	–3.29	–0.98
39Q028	Chatham	–2.21	–3.25	–1.04
35S008	Effingham	12.09	13.42	1.33
36N012	Bryan	–26.18	–22.43	3.75
			UBA mean	**3.97**
Upper water-bearing zone of Upper Floridan aquifer (UWBZUFA)				
21T001	Laurens	220.19	223.66	3.47
26R001	Toombs	103.85	106.63	2.78
27E004	Charlton	40.54	43.76	3.22
32L015	Wayne	8.22	13.48	5.26
32R002	Bulloch	18.01	22.35	4.34
33E007	Camden	15.26	27.10	11.84
33E027	Camden	23.51	34.11	10.60
33G008	Glynn	18.72	23.16	4.44
33H120	Glynn	–2.99	3.08	6.07
33H130	Glynn	–4.59	2.18	6.77
33H133	Glynn	–0.89	3.77	4.66
33H177	Glynn	21.16	28.24	7.08
33H207	Glynn	4.16	8.09	3.93
33M004	Long	0.40	6.36	5.96
34G002	Glynn	17.62	22.37	4.75
34G009	Glynn	35.50	38.73	3.23
34G016	Glynn	23.69	28.28	4.59
34G020	Glynn	26.18	30.10	3.92
34H112	Glynn	6.62	12.85	6.23
34H117	Glynn	4.54	10.47	5.93
34H125	Glynn	4.45	12.38	7.93
34H344	Glynn	3.25	6.22	2.97
34H355	Glynn	3.88	8.46	4.58
34H371	Glynn	10.83	15.54	4.71
34H373	Glynn	–1.07	3.98	5.05
34H393	Glynn	8.53	14.56	6.03
34H469	Glynn	5.56	6.61	1.05
35T003	Effingham	31.40	2.11	–29.29
36Q008	Chatham	–90.48	–82.07	8.41
36Q020	Chatham	–42.17	–38.20	3.97

Table 2. Water-level measurements taken during 2000 and 2004 and observed water-level change during the same period.—Continued

[NAVD 88, North American Vertical Datum of 1988; see fig. 2–1 for well locations]

Well identifier	County	Water level, in feet above or below NAVD 88		Water-level change from 2000 to 2004, in feet
		2000	2004	
Upper water-bearing zone of Upper Floridan aquifer (UWBZUFA)—Continued				
37P114	Chatham	–46.02	–43.63	2.39
37Q016	Chatham	–82.22	–76.98	5.24
37Q185	Chatham	–99.22	–95.22	4.00
38Q002	Chatham	–30.36	–28.11	2.25
39Q003	Chatham	–27.90	–25.21	2.69
			UWBZUFA mean	**4.03**
Lower water-bearing zone of Upper Floridan aquifer (LWBZUFA)				
33H127	Glynn	0.60	7.85	7.25
33H154	Glynn	–27.58	–17.85	9.73
34H334	Glynn	7.51	12.42	4.91
34H403	Glynn	10.12	16.27	6.15
			LWBZUFA mean	**7.01**
Lower Floridan aquifer (LFA)				
33D073	Camden	3.58	30.67	27.09
33H188	Glynn	12.46	20.14	7.68
33H206	Glynn	8.40	14.01	5.61
33J044	Glynn	13.89	19.13	5.24
34H391	Glynn	9.18	11.87	2.69
34H436	Glynn	11.70	15.80	4.10
35P109	Bryan	–21.83	–18.87	2.96
39Q024	Chatham	–31.67	–29.94	1.73
			LFA mean	**7.14**

Table 3. Water-level measurements taken during 2000 and 2004 and observed water-level change during the same period in the Brunswick/Glynn County area.

[NAVD 88, North American Vertical Datum of 1988; see fig. 2–1 for well locations]

Well identifier	Water level, in feet above or below NAVD 88		Water-level change from 2000 to 2004, in feet
	2000	2004	
Upper Brunswick aquifer (UBA)			
33G028	16.75	21.31	4.56
34H437	5.88	8.92	3.04
		Mean	**3.80**
Upper water-bearing zone of Upper Floridan aquifer (UWBZUFA)			
33G008	18.72	23.16	4.44
33H120	–2.99	3.08	6.07
33H130	–4.59	2.18	6.77
33H133	–0.89	3.77	4.66
33H177	21.16	28.24	7.08
33H207	4.16	8.09	3.93
34G002	17.62	22.37	4.75
34G009	35.50	38.73	3.23
34G016	23.70	28.28	4.58
34G020	26.18	30.10	3.92
34H112	6.62	12.85	6.23
34H117	4.54	10.47	5.93
34H125	4.45	12.38	7.93
34H344	3.25	6.22	2.97
34H355	3.88	8.46	4.58
34H371	10.80	15.54	4.74
34H373	–1.07	3.98	5.05
34H393	8.53	14.56	6.03
34H469	5.56	6.61	1.05
		Mean	**4.94**
Lower water-bearing zone of Upper Floridan aquifer (LWBZUFA)			
33H127	0.60	7.85	7.25
33H154	–27.58	–17.85	9.73
34H334	7.51	12.42	4.91
34H403	10.12	16.27	6.15
		Mean	**7.01**
Lower Floridan aquifer (LFA)			
33H188	12.46	20.14	7.68
33H206	8.40	14.01	5.61
33J044	13.89	19.13	5.24
34H391	9.18	11.87	2.69
34H436	11.70	15.80	4.10
		Mean	**5.06**

Simulation of Steady-State Groundwater Flow, 2000–04

The digital groundwater-flow model originally developed to simulate regional confined groundwater flow in the coastal area of Georgia, Florida, South Carolina, and adjacent offshore areas (Payne and others, 2005) was revised to evaluate hydraulic gradients in the Brunswick/Glynn County area. The original model was developed using MODFLOW–2000 (Harbaugh and others, 2000), and simulated steady-state flow for predevelopment, 1980, and 2000 conditions. Details of the original model development are provided in Payne and others (2005) and are briefly described in the following sections. Steady-state simulations were also considered reasonable for the revised model because of the focus on changes in mean-annual pumping for 2000 and 2004. According to Payne and others (2005), the original model was tested for transient response and the results indicated that relatively extreme changes in stress were required to affect a transient response. Locally in the Brunswick/Glynn County area, groundwater flow in the Upper Floridan aquifer is considered to be in equilibrium where recharge to the aquifer is balanced by natural discharge and pumping (Krause and Randolph, 1989). In addition, calculations comparing the estimated rate at which water derived from storage for the period from 1945 to 1986 with a mean pumping value of 70.8 Mgal/d from the Upper Floridan aquifer over the 42-year period indicated that less than 0.1 percent of the 1986 pumpage was derived from storage (L.E. Jones, U.S. Geological Survey, written commun., November 2014). Therefore, the assumption of nearly steady-state conditions for the Upper Floridan aquifer in Glynn County because of the negligible contributions of water from aquifer storage is reasonable.

Revision of Groundwater-Flow Model

To develop the revised model, the original model was modified in terms of grid size (discretization), model layers, hydraulic properties, boundary conditions, use of pumping rates for 2004, and recalibration to observed water levels. The original model focused on the Floridan aquifer system at a regional scale with reduced grid spacing in the Savannah and Brunswick areas for further evaluation, whereas the addition of layers/zones in the revised model based on the local hydrogeology improve the simulation of the steep hydraulic gradients that have formed in the Brunswick area as a result of pumping. These modifications allowed a more accurate computed solution of head in the Brunswick/Glynn County area along with head gradients and leakage rates that were not possible with the original model.

Discretization

The original model encompasses 42,155 mi² and consists of 119 rows and 108 columns, with cell sizes ranging from 4,000×5,000 ft (0.7 mi²) to 16,500×16,500 ft (9.8 mi²). Because of the focus on the Brunswick/Glynn County area in the current study, a refined grid spacing was chosen to enable more accurate simulation of the steep head gradients near cones of depression. Graphical grid-generation tools from the graphical user interface Argus ONE enabled visual adjustment of grid position and density. The revised grid configuration has the same orientation as the original model, but the number of rows and columns has been increased to 424 and 452, respectively (fig. 7). The variable cell sizes range from 500×500 ft (0.009 mi²) near downtown Brunswick, to 5,000×5,000 ft (0.90 mi²) near the edges of the model area. The irregular grid configuration results in elongated cells along the outer margins of the model having aspect ratios as large as 10:1 between row and column spacings. This large aspect ratio is approaching the recommended limit, above which numerical errors could occur (de Marsily, 1986, p. 351).

Model Layers

Layers used in the original model to vertically discretize groundwater flow were modified in the revised model to simulate the local hydrogeology in the Brunswick/Glynn County area. The original model contained layers for the surficial aquifer system (layer 1), Brunswick aquifer system (layer 3), UFA (layer 5), and LFA (layer 7), and for intervening confining units between these aquifers (layers 2, 4, and 6). The revised model contains four additional layers to detail the vertical representation of the Brunswick aquifer system and Upper Floridan aquifer. As shown in figure 8 and table 4, the Brunswick aquifer system has been subdivided into the upper Brunswick aquifer (layer 3) and lower Brunswick aquifer (layer 5) with an intervening confining unit (layer 4), and the UFA has been subdivided into the UWBZ (layer 7) and the LWBZ (layer 9) with an intervening confining unit (layer 8).

Published data were used to assign altitudes to the top of each unit represented in the original model. 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) provided information to construct contour maps showing the altitude of the top of each layer and this information was modified using well information collected as part of the Coastal Sound Science Initiative (Falls and others, 2001; Foyle and others, 2001). In the Brunswick/Glynn County area, the UWBZ and LWBZ (model layers 7 and 9) were extended to include all of Glynn County and neighboring Camden County. Beyond these

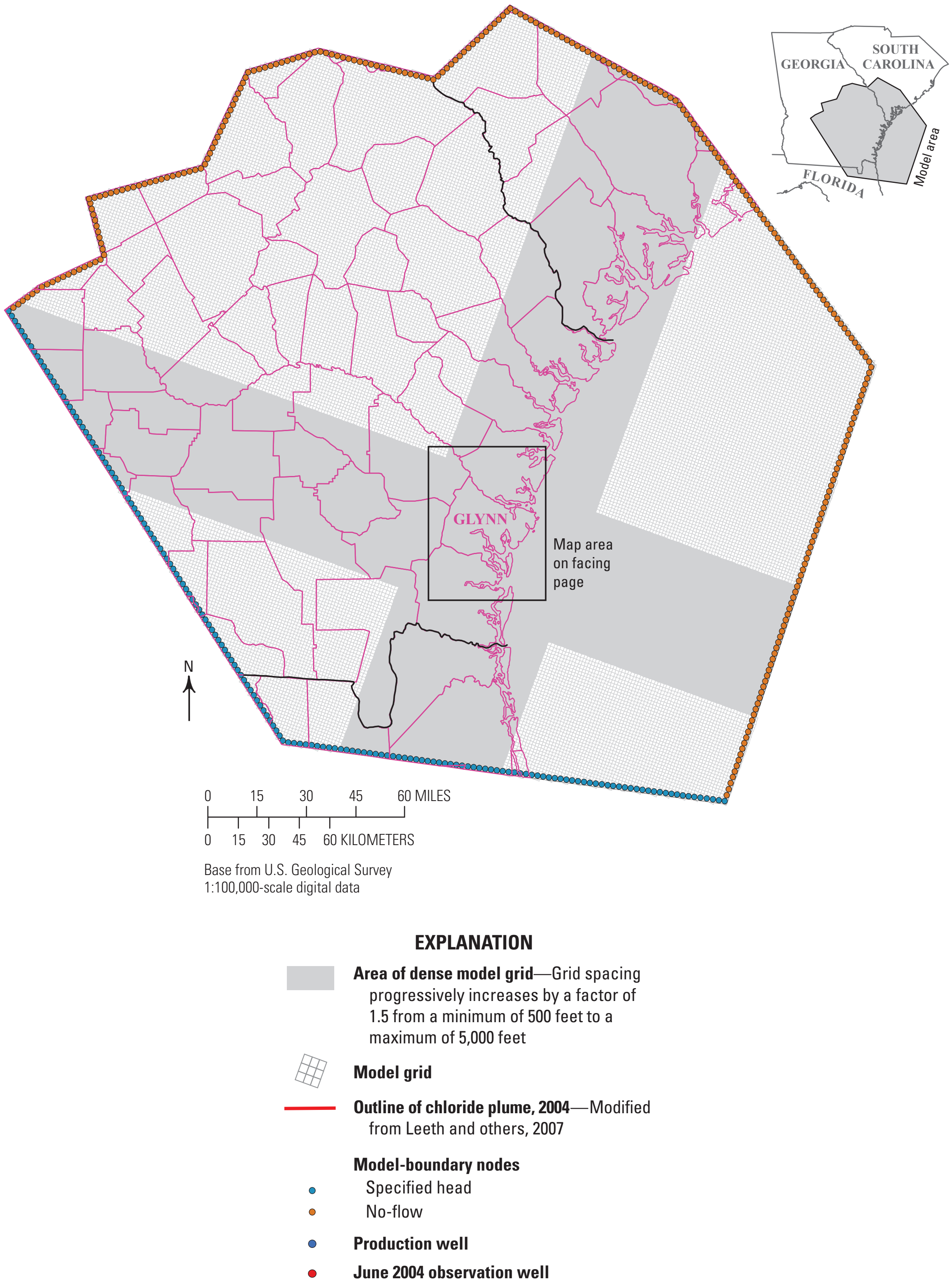
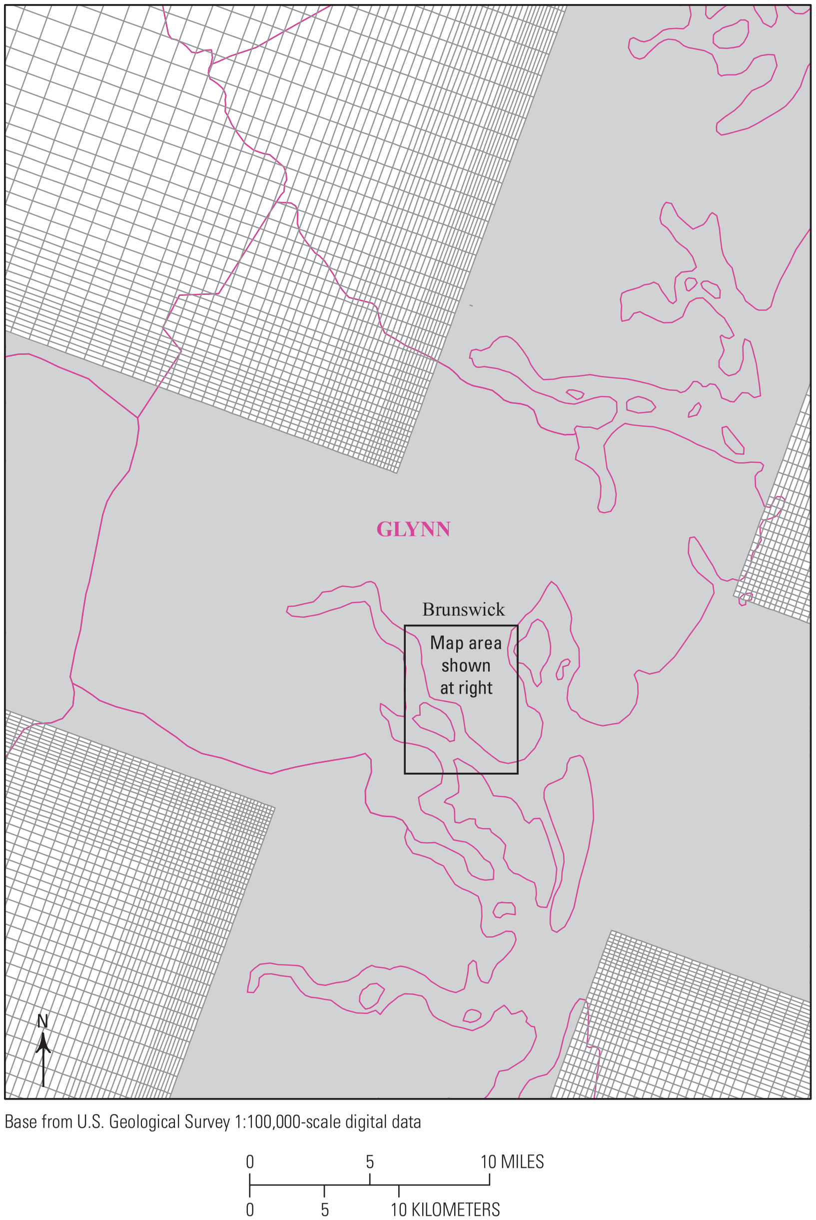


Figure 7. Revised model grid, major production wells, observation wells used during June of 2004, and outline of the 2004 chloride plume for the Upper Floridan aquifer in the Brunswick area.



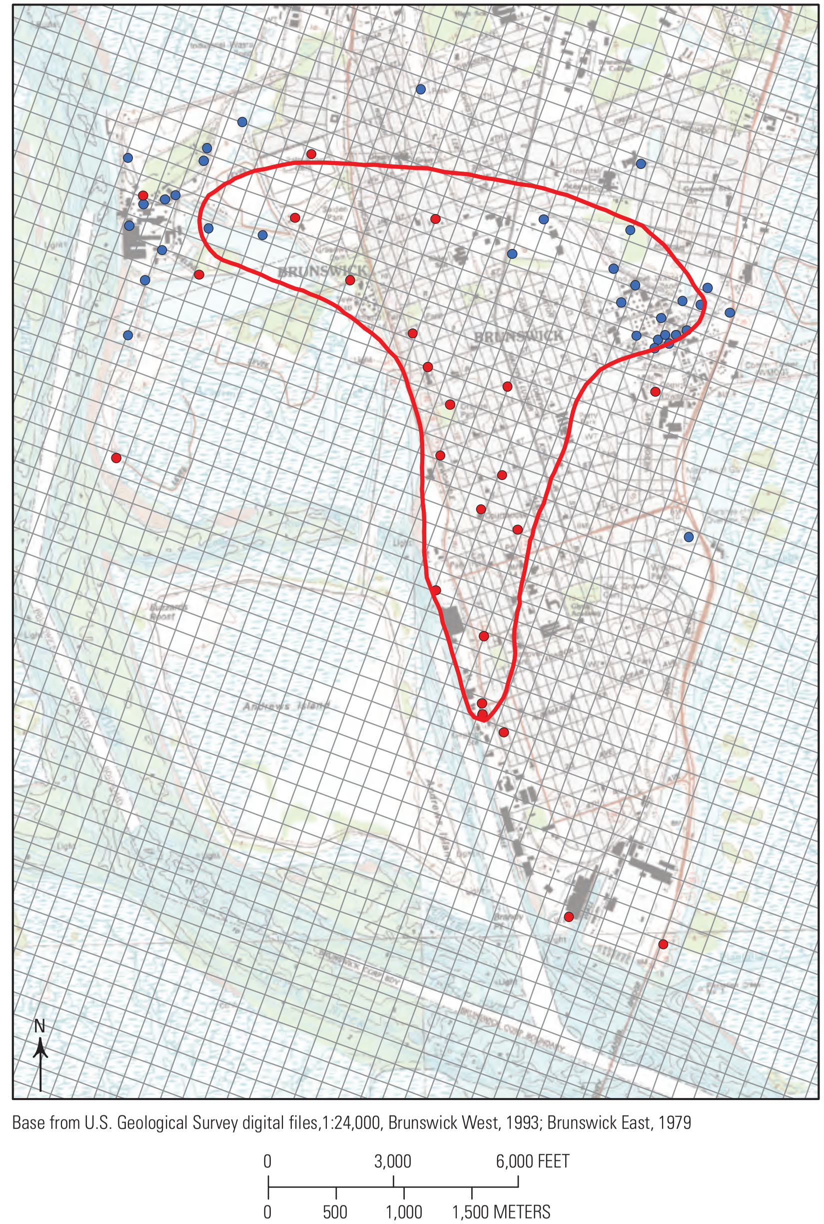


Figure 7. Revised model grid, major production wells, observation wells used during June of 2004, and outline of the 2004 chloride plume for the Upper Floridan aquifer in the Brunswick area.—Continued

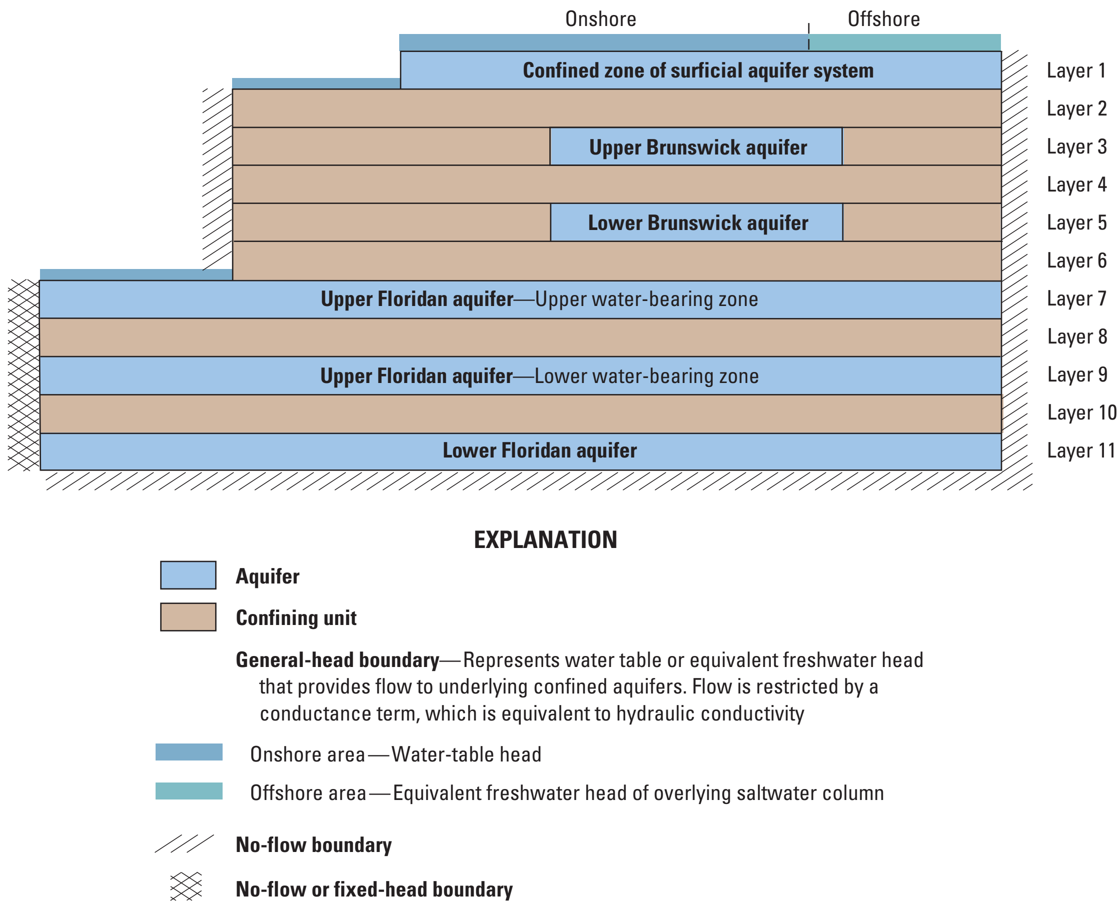


Figure 8. Schematic diagram showing model layers and boundary conditions.

areas, the UFA was considered to be one unit that includes model layers 7 through 9. In addition, where the UWBZ and LWBZ are absent, a minimal thickness of 1 ft was assigned to fulfill the requirements of MODFLOW–2000 (Harbaugh and others, 2000) for a continuous model layer to exist across the entire model area, and that layer of minimal thickness was assigned the hydraulic conductivity of the overlying layer. A schematic diagram (fig. 8) and hydrogeologic sections (fig. 9) along the approximate strike and dip of geologic formations illustrate how model layer thicknesses vary over the model domain. The Brunswick aquifer system (layers 3–5) varies in thickness, ranging from 300 to 400 ft along the Brunswick peninsula and thins to the north toward the Savannah area. The combined thickness of the UWBZ and LWBZ of the UFA and intervening confining unit (layers 7–9) reaches about 400 ft near the Brunswick peninsula. In the Glynn/Camden County area, the thickness of the UWBZ (layer 7) of the UFA is highly variable ranging from 26 to 266 ft with an average thickness of 139 ft. The semiconfining unit (layer 8) ranges in thickness from 34 to 265 ft with an average thickness of 85 ft. The thickness of the LWBZ (layer 9) of the UFA is less variable ranging from 86 to 193 ft with an average thickness of 163 ft. The UFA thins toward the Gulf Trough and thickens to 800 ft beneath the Atlantic Ocean. The hydrogeologic section along the Georgia coast (*B–B′*) illustrates how hydrogeologic units generally thicken toward the Southeast Georgia Embayment where the LFA reaches thicknesses greater than 2,000 ft (fig. 9).

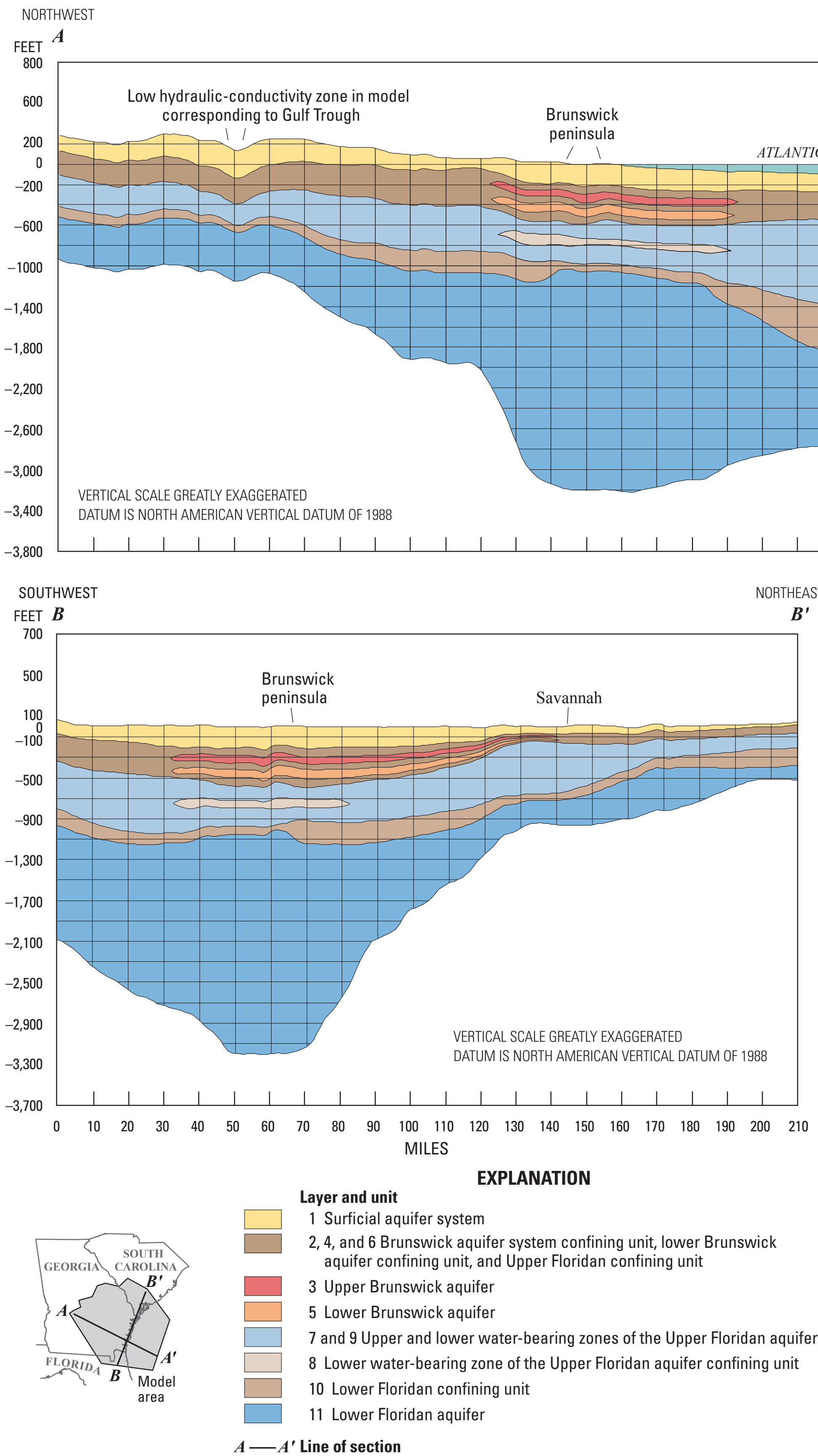


Figure 9. Hydrogeologic sections showing vertical discretization of hydrogeologic units simulated by the revised model.

Table 4. Horizontal and vertical hydraulic conductivity values assigned to hydraulic property zones for the original (Payne and others, 2005) and revised groundwater-flow models.

[—, not applicable; UWBZ, upper water-bearing zone; LWBZ, lower water-bearing zone; Kh, horizontal hydraulic conductivity; Kv, vertical hydraulic conductivity; ft/day, foot per day]

Unit	Layer	Payne and others (2005)		Unit	Layer	Revised model	
		Hydraulic property zone	Hydraulic conductivity, Kh and Kv, in feet per day			Hydraulic property zone (fig. 9)	Hydraulic conductivity, Kh and Kv, in feet per day
Surficial aquifer	1	—	70	Surficial aquifer	1	—	105
Confining unit	2	C1	0.00017	Confining unit	2	C1	0.00257
		C2	0.20000			C2	0.20000
		C3	0.00001			C3	0.00001
		C4	0.00010			C4	0.00010
		C5	0.00010			C5	0.00010
Brunswick aquifer system	3	B1	50	Upper Brunswick aquifer	3	B1	10
		C1	0.00017			C1	0.00257
		C2	0.20000			C2	0.20000
		C3	0.00001			C3	0.00001
		C4	0.00010			C4	0.00010
		—	—	Confining unit	4	B1	0.02
		—	—			C1	0.00257
		—	—			C2	0.20000
		—	—			C3	0.00001
		—	—			C4	0.00010
		—	—	Lower Brunswick aquifer	5	B1	20
		—	—			C1	0.00257
		—	—			C2	0.20000
		—	—			C3	0.00001
		—	—			C4	0.00010
Confining unit	4	C1	0.00017	Confining unit	6	C1	0.00257
		C2	0.20000			C2	0.20000
		C3	0.00001			C3	0.00001
		C4	0.00010			C4	0.00010
		C5	0.00010			C5	0.00010
Upper Floridan aquifer	5	F1	34	UWBZ of Upper Floridan aquifer	7	F1	40
		F2	2			F2	20
		F3	100			F3	150
		F4	70			F4	65
		F5	394			F5	225
		F6	2,819			F6	3,415
		F7	150			F7	750
		F8	2,727			F8	3,000
		F9	100			F9	150
		F10	56			F10	84
		F11	94			F11	126
		F12	25			F12	25
		—	—			F13	300
		—	—			F14	240
		—	—			F15	200
		—	—			F16[a]	76
		—	—			F17[b]	398

Table 4. Horizontal and vertical hydraulic conductivity values assigned to hydraulic property zones for the original (Payne and others, 2005) and revised groundwater-flow models.—Continued

[—, not applicable; UWBZ, upper water-bearing zone; LWBZ, lower water-bearing zone; Kh, horizontal hydraulic conductivity; Kv, vertical hydraulic conductivity; ft/day, foot per day]

		Payne and others (2005)				Revised model	
Unit	Layer	Hydraulic property zone	Hydraulic conductivity, Kh and Kv, in feet per day	Unit	Layer	Hydraulic property zone (fig. 9)	Hydraulic conductivity, Kh and Kv, in feet per day
Confining unit		—	—	Confining unit	8	F1	40
		—	—			F2	20
		—	—			F3	150
		—	—			F4	65
		—	—			F5	225
		—	—			F6	3,415
		—	—			F7	0.2
		—	—			F8	0.2
		—	—			F9	150
		—	—			F10	84
		—	—			F11	126
		—	—			F12	25
		—	—			F13	0.2
		—	—			F14	0.2
		—	—			F15	0.2
		—	—			F16[a]	76
		—	—			F17[b]	398
LWBZ of Upper Floridan aquifer		—	—	LWBZ of Upper Floridan aquifer	9	F1	40
		—	—			F2	20
		—	—			F3	150
		—	—			F4	65
		—	—			F5	225
		—	—			F6	3,415
		—	—			F7	750
		—	—			F8	3,000
		—	—			F9	150
		—	—			F10	84
		—	—			F11	126
		—	—			F12	25
		—	—			F13	270
		—	—			F14	200
		—	—			F15	125
		—	—			F16[a]	76
		—	—			F17[b]	398
Confining unit	6	—	0.02000	Confining unit	10	LFC1	0.02000
		—	—			LFC2[a]	0.20000
		—	—			LFC3[b]	10.00000
Lower Floridan aquifer	7	—	10	Lower Floridan aquifer	11	LF1	10
		—	—			LF2[a]	100
		—	—			LF3[b]	15.8

[a]Clarke and others (2010); LFC2 Kh = 0.2 ft/day, Kv = 0.02 ft/day

[b]Clarke and others (2011); LFC3 Kv = 0.2 ft/day, LF3 Kh = 15.8 ft/day, Kv = 1.6 ft/day

Hydraulic Properties

In the Brunswick/Glynn County area, the original model contained designated homogeneous and isotropic hydraulic property zones for all aquifers and confining units except the UFA, which consisted of two zones within Glynn County. For the revised model, additional zones were designated on the basis of available aquifer-test and geologic data (fig. 10; table 4). These data include the vertical (K_v) and horizontal (K_h) hydraulic conductivity for all model layers, which were used as initial estimates in the revised model prior to any model adjustments (Clarke and others, 2004). Additional zones were created (F13, F14, and F15) within the UFA (layers 7–9) near the Brunswick area to further adjust hydraulic properties within zone F7 of the original model. In addition, zones F16 and F17 were added based on aquifer tests in the Floridan aquifer system at Hunter Army Airfield and Fort Stewart (Clarke and others, 2010, 2011). During model calibration, adjustments were made to hydraulic property zones to provide a better match between observed and simulated water levels in the area.

The surficial aquifer (layer 1) was represented by a single zone and assigned a K_h value of 70 ft/d throughout the model domain in the original model. This value was increased to 105 ft/d in the revised model to provide a better match to observed values. The confining unit beneath the surficial aquifer (layer 2), was areally represented in both models by five zones that were assigned K_h values ranging from 0.00001 to 0.2 ft/d (table 4).

The Brunswick aquifer system was represented differently by the two models. In the original model, the Brunswick aquifer system was simulated by a single layer (3) that was areally subdivided into five zones with K_h values ranging from 0.00001 to 50 ft/d. Zone B1 in the original model corresponded to the approximate extent of the most permeable part of the aquifer system and was assigned a uniform value of 50 ft/d. In the revised model, three layers (3, 4, and 5) vertically subdivide the Brunswick aquifer system, and zone B1 represents a less permeable part of the aquifer (layer 4) juxtaposed between two more permeable parts (layers 3 and 5), with each layer assigned a uniform value for K_h and K_v (table 4). Within each model, the respective assigned values for C1, C2, C3, and C4 did not change between layers (table 4).

The UFA in the original model was represented as a single layer (5) areally subdivided into 12 hydraulic property zones, with K_h ranging from 2 ft/d in zone F2 (in the Gulf Trough region), to 2,819 ft/d in zone F6 (southwest of Glynn County) (fig. 10; table 4). By comparison, a single hydraulic property zone (F7) having a K_h of 150 ft/d was used in the original model to represent the UFA in the majority of Glynn County. To enable more detailed simulation of groundwater flow in the Brunswick/Glynn County area than was available using the original model, the UFA in the revised model has been vertically subdivided into the UWBZ (layer 7) and LWBZ (layer 9), separated by a confining unit (layer 8; fig. 8). Each of these new layers contained the same 12 zones used in the original model, plus an additional 3 zones in the Brunswick area to represent variations in K_h (fig. 10; table 4). The adjusted K_h of 750 ft/d for the revised model in hydraulic property zone (F7) multiplied by the average thickness of the UWBZ of 139 ft yields a simulated transmissivity of 104,000 ft²/d. Results from a subregional December 1962 aquifer test using 16 observation wells open to the UWBZ located at distances ranging from 15,400 to 71,400 ft from a pumping well tapping both the UWBZ and LWBZ near Brunswick indicated an average transmissivity value of 88,200 ft²/d for Glynn County (Jones and Maslia, 1994). Previously reported transmissivity values for the UFA in the Brunswick/Glynn County area were about 150,000 to 200,000 ft²/d, but likely included both the UWBZ and LWBZ (Wait and Gregg, 1973). A localized aquifer test in the Brunswick area performed during July 1985 using 16 observation wells open to the UWBZ and pumping from the UWBZ yielded much lower transmissivity values (Jones and Maslia, 1994). The time-drawdown plots were matched manually to the Hantush-Jacob type curve with an excellent fit in six observation wells located at distances ranging from 700 to 6,300 ft with an average transmissivity value for the UWBZ of 61,000 ft²/d. During December 1986, a localized aquifer test performed in the southern portion of the Brunswick peninsula using two observation wells open to the UWBZ and pumping from a public-supply well open to the UWBZ produced computed transmissivity values of 23,400 and 32,500 ft²/d, respectively (Jones and Maslia, 1994). Jones and Maslia (1994) reported on another aquifer test performed in April 1990 in which a public-supply well open to the UWBZ located just north of the chloride plume was pumped for 24-hours with a computed transmissivity value from a nearby UWBZ observation well of 57,000 ft²/d. Borehole flowmeter tests (Wait and Gregg, 1973) indicated that the UWBZ contained a higher K_h than the LWBZ, based on UWBZ contribution of 70 percent of the water from wells tapping both zones.

Zones in the UWBZ were designated as follows:

- Zone F13 (K_h=300 ft/d) represents an area of intensive groundwater pumping near the northwestern part of the chloride plume and also contains steep hydraulic gradients toward the pumping centers at the Georgia-Pacific Cellulose plant.
- Zone F14 (K_h=240 ft/d) represents a transitional area between the pumping centers to the north of downtown Brunswick and an area of low hydraulic conductivity at the southern end of the chloride plume to the south.
- Zone F15 (K_h=200 ft/d) contains steep hydraulic gradients in the potentiometric surface of the UFA that are not attributed to groundwater pumping, thus indicating a decrease in K_h.

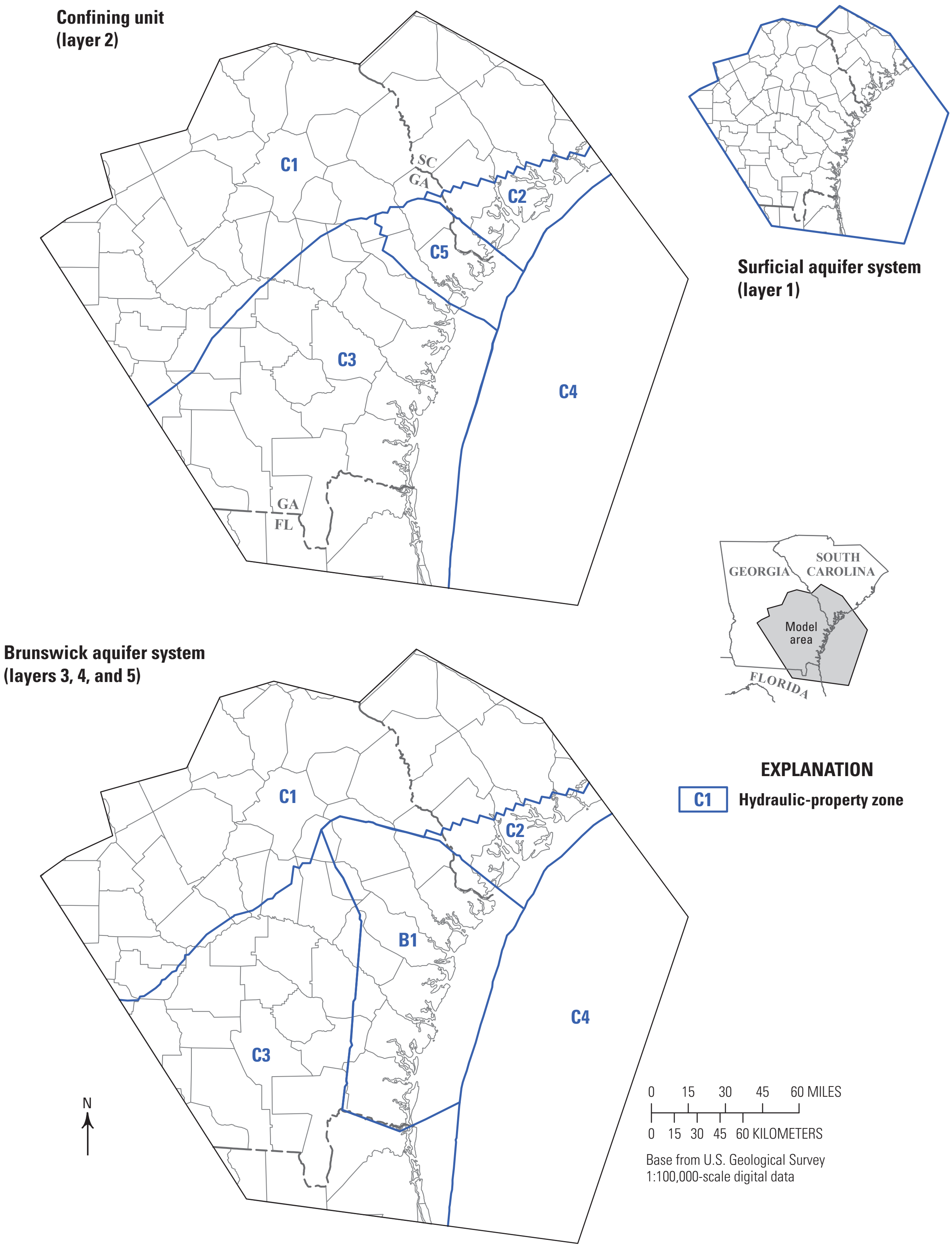


Figure 10. Hydraulic property zones for the regional model (Payne and others, 2005) near Brunswick/Glynn County, Georgia.

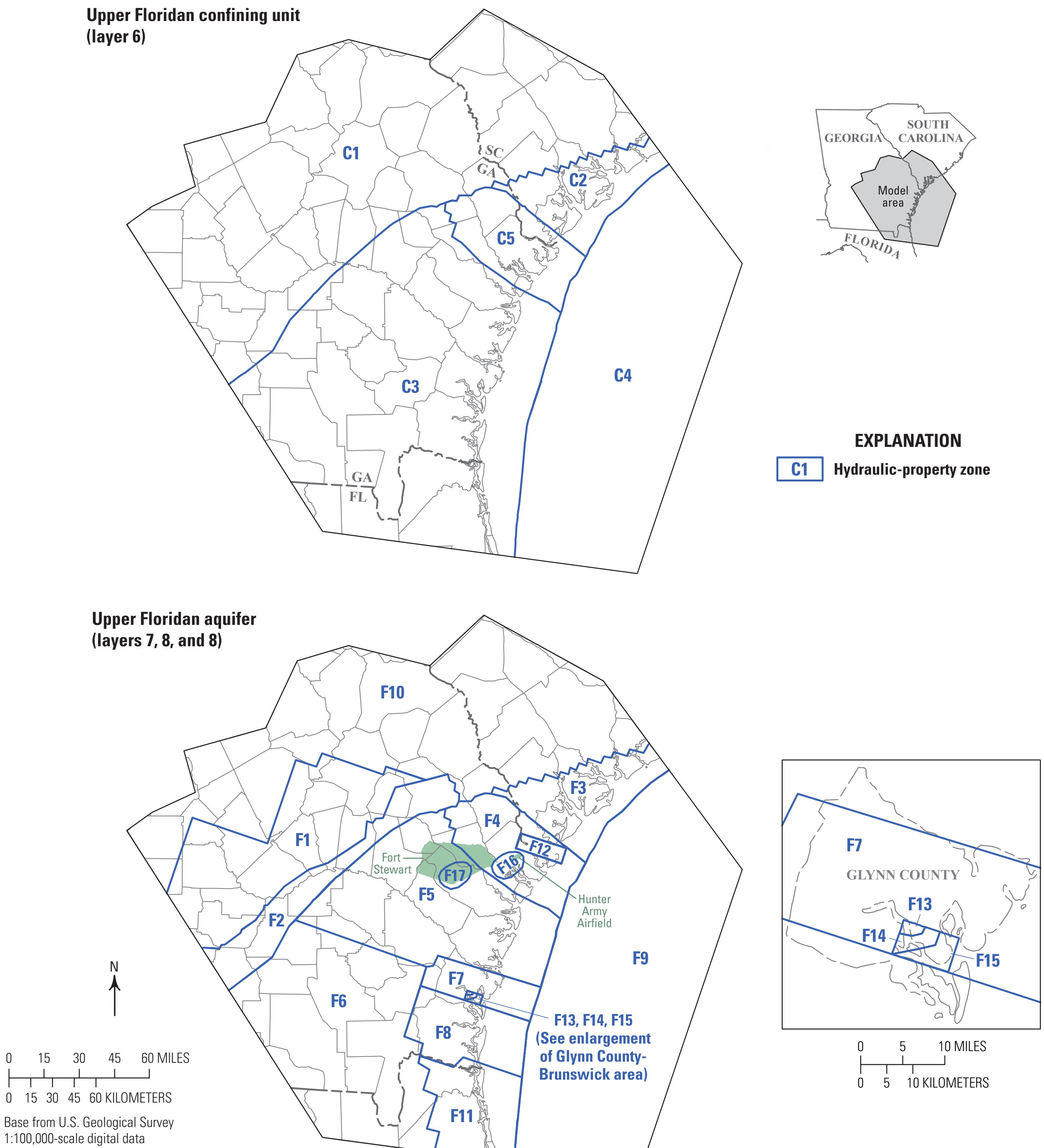


Figure 10. Hydraulic property zones for the regional model (Payne and others, 2005) near Brunswick/Glynn County, Georgia.—Continued

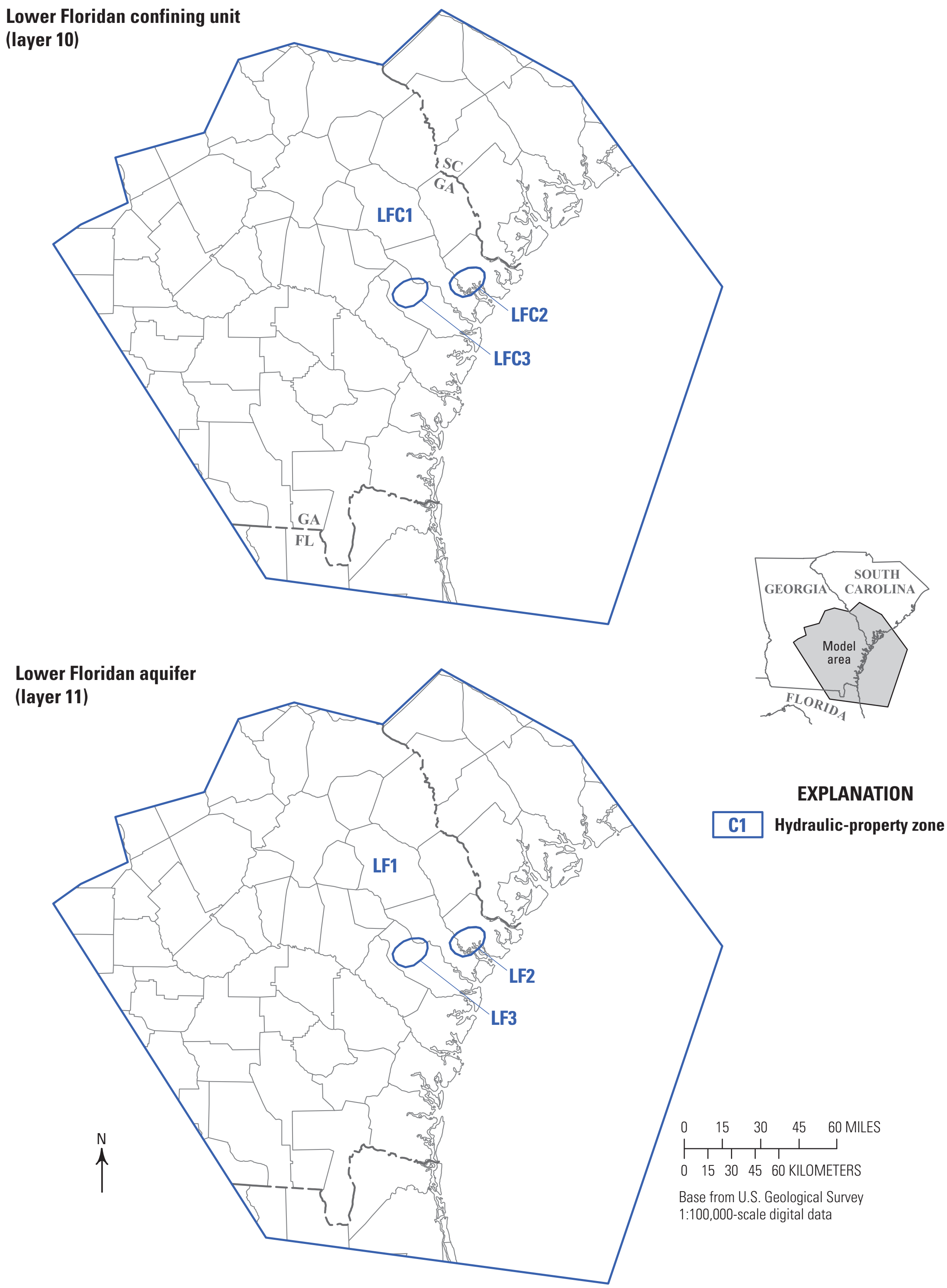


Figure 10. Hydraulic property zones for the regional model (Payne and others, 2005) near Brunswick/Glynn County, Georgia.—Continued

For the LWBZ, the following additional aquifer property zones provided detail to the computed potentiometric surface in the Brunswick/Glynn County area that was not available from simulations using the original model:

- Zone F13 (K_h=270 ft/d) represents a region of high groundwater flow to wells with correspondingly little groundwater-level decline.
- Zone F14 (K_h=200 ft/d) represents a transition zone between pumping centers to the north of downtown Brunswick and low-permeability, less productive aquifer material to the south.
- Zone F15(K_h=125 ft/d) represents an area of low-permeability material south of the pumping centers.

A K_v value of 0.2 ft/d was assigned to hydraulic property zones F7, F8, F13, F14, and F15 in the Camden/Glynn County area for the confining unit (layer 8) to allow leakage between the UWBZ and LWBZ of the UFA. This assigned K_v value was the same K_v value used for the confining unit to simulate interaquifer leakage from the UFA to the LFA in zone F17 located near Fort Stewart (Clarke and others, 2011). Outside of this subregional area consisting of five zones model layers 7, 8 and 9 representing the UFA have the same horizontal hydraulic conductivity. In general, hydraulic conductivity values were greater than those used in the original model for most of the zones in the UWBZ of the UFA (table 4), and a suitable fit between observed and simulated heads was achieved for calibration. One exception was for zones F4 and F5, where hydraulic conductivity values were decreased to better represent the cone of depression near Chatham County, Ga., with simulated groundwater levels.

Zones F16 and F17 (fig. 10) were based on the revised model's ability to simulate interaquifer leakage from the UFA to the LFA through the confining unit caused by pumping in newly constructed LFA wells near Hunter Army Airfield and Fort Stewart, Ga. (Clarke and others, 2010 and 2011). Based on 72-hour aquifer tests, two distinct zones of hydraulic conductivity were created in modified models of these areas to simulate hydraulic property variations in the lower confining unit of the LFA (fig. 10; table 4).

Boundary Conditions

Boundaries used in the revised model generally conformed to those used in the original model and are based on locations of natural-flow boundaries where available (figs. 7 and 8). Artificial boundaries were used where natural-flow boundaries were unavailable. Payne and others (2005) contains a complete discussion of boundary conditions used in the original model. The main adjustments to boundaries in the revised model involve updated changes to reflect hydrologic conditions during 2004, including adjustment of groundwater levels along specified-head boundaries.

Vertical Boundaries

The lowermost boundary represents the no-flow condition present at the contact between the LFA (layer 11) and underlying low-permeability sediments of Paleocene age and older. The altitude of this no-flow boundary varies greatly over the model area and depends on the orientation of this contact with regard to geologic structure (strike and dip). In general, this no-flow boundary reaches its greatest depth near the Southeast Georgia Embayment.

The uppermost boundary of the revised model represents a general-head condition; controlling heads represent the estimated water table for onshore areas (Peck and Payne, 2003), and a conductance term helps regulate the amount of recharge to, or discharge from, onshore and offshore areas. In the onshore area, this boundary condition was applied to the uppermost active aquifer cell in the model, which could be layer 1, 2, or 5, depending on which unit crops out at land surface. The conductance term and the simulated and controlling hydraulic heads along the boundary contributed to model computations of reasonable recharge rates that were compared with those derived from base-flow calculations (Priest, 2004) and others associated with similar hydrologic settings (Williamson and others, 1990). The general-head boundary represents a source-sink boundary in the unconfined portion of the surficial aquifer that facilitates water exchange into (recharge) and out of (discharge) the confined, regional groundwater system.

In the offshore area, a general-head boundary was placed above the top active cells of model layer 1. The controlling head in this area of the model represents the freshwater equivalent of the saltwater head; hydraulic conductance is assumed to be constant; and thickness between the controlling head and active cells of layer 1 generally is limited to several feet. Sensitivity analyses performed on the parameters that define the general-head boundary indicated that their values do not substantially affect simulated results, and that flow from the confined system in the offshore area is assumed to be controlled predominantly by the hydraulic properties of the confining units, model layers 2 through 6.

Lateral Boundaries

Lateral boundary conditions for the revised model were selected to coincide as closely with assumed no-flow boundaries or groundwater divides as defined by Payne and others (2005) in the original model. With the exception of the Floridan aquifer system (layers 7–11), lateral boundaries for all other layers are designated as no-flow boundaries.

Simulated flow in the Floridan aquifer system is bounded laterally by a combination of no-flow and specified-head boundaries. The northwestern boundary of the model is defined as a no-flow boundary because it is located at the approximate updip extent of the Floridan aquifer system or its equivalent, as defined by Miller (1986). The onshore part of the northeastern flow boundary was designated as a no-flow boundary because, according to Ransom and White (1999), estimated flow lines drawn on the potentiometric-surface map indicate parallel flow to this boundary. This boundary also extends offshore and is connected to the eastern no-flow boundary.

To the southwest and south of the model area, the Floridan aquifer system extends beyond the model boundaries;

therefore, a specified-head boundary was used to allow flow into the model. The original model assigned values to the specified-head boundary based on potentiometric surfaces of the UFA that correspond to specific years of the simulation to incorporate temporal changes in head that affect flow patterns and directions. Potentiometric-surface maps for May 1980 (Johnston and others, 1981), May 1998 (Peck and others, 1999), and September 2000 (Peck and McFadden, 2004) were used to assign heads along the specified-head boundary.

Heads along the southwestern boundary in the revised model were adjusted on the basis of observed water-level changes presented by Peck and others (2004). Water levels near the southwestern boundary were affected by the shutdown of the Durango Paper Company mill near St. Marys, Camden County, during 2002, which caused 5- to 10-ft water-level rises in the UFA by May 2003 (Peck and others, 2004). Specified-head values were adjusted accordingly in the UWBZ (layer 7) and LWBZ (layer 9) and the intervening confining unit (layer 8) to account for the increased water levels. Similarly, heads also were changed in the LFA (layer 11) and overlying confining unit (layer 10).

Groundwater Withdrawals

Groundwater withdrawals were compiled for input to the revised model in preparation for steady-state simulation of 2000 and 2004 conditions. Pumpage for 2004 was estimated using site-specific data for 2004 and county-aggregate estimates for 2000. Year 2000 estimates were used for 2004 because estimated values were not available for that year. Pumpage was assigned to nodes of the model cells using procedures described in Taylor and others (2003).

Pumpage assigned to single layers in the original model was redistributed to multiple layers representing the Brunswick and Floridan aquifer systems in the revised model based on the thickness of the aquifers, or water-bearing zones, because the actual contribution to pumpage from each water-bearing zone could not be determined. The redistribution of pumpage from single layers in the original model to one or more layers in the revised model involved the following reassignments:

- Brunswick aquifer system—layer 3 (original model) reassigned to layers 3 and 5 (revised model) to represent pumpage in the upper and lower Brunswick aquifers, respectively;
- UFA—layer 5 (original model) reassigned to layers 7 and 9 (revised model) to represent pumpage in the UWBZ and LWBZ, respectively;
- LFA—layer 7 (original model) represented as pumpage in layer 11 (revised model).

For the 2000 simulation, pumpage was aggregated to nodal locations in the model grid in model layers 3 and 5 (Brunswick aquifer system, fig. 11). Nodes representing pumpage in the multiple layers of the revised model corresponded with the nodal locations of pumpage in the single layer of the original model. Pumpage at actual well locations was not represented as such in the original model nor the revised model.

For the 2004 simulation, pumpage was identified at specific well locations in the Brunswick aquifer system in the Glynn County area (fig. 12). This pumpage was represented in the revised model as simulated withdrawal at the closest nodes in the model grid.

The 2000 and the 2004 steady-state simulations both show pumping centers in the UFA (layers 7 and 9) near Savannah, Jesup, and Brunswick, Ga. (figs. 11*C–D* and 12*C–D*). Production wells open to the UFA were assumed to penetrate the entire aquifer and pumping was distributed based on the thickness of the UWBZ and LWBZ of the UFA (layers 7 and 9). During the 2004 simulation, pumping was eliminated at the Durango Paper Company mill near St. Marys for a reduction of 36 Mgal/d in model layers 7 and 9 (fig. 12*C–D*). In the Brunswick/Glynn County area, the number of active industrial production wells decreased in the northern part of the city. Water-supply wells near Brunswick generally are open to the UWBZ and LWBZ, but do not tap water-bearing units beneath the UFA (L. Elliott Jones, U.S. Geological Survey, written commun., 2014). Current-meter data and well depth information at the Pinova and GP Cellulose well fields indicate that the estimated contribution from the UWBZ to total water pumped from the UFA ranged between 30 to 45 percent (Jones and Maslia, 1994; L. Elliott Jones, U.S. Geological Survey, written commun., 2014). Pumping in the LFA (layer 11) is concentrated mostly north of Jacksonville, Fla., in both simulations, with pumpage from some active wells located in Chatham County, Ga., during the 2000 simulation.

Model Calibration

The revised model was calibrated by adjusting hydraulic properties and boundary conditions so that simulated groundwater levels reasonably matched observed water levels during 2004. Although initial simulations utilized hydraulic properties derived from calibration of the original model, an improved match of simulated to observed groundwater levels was obtained for the UWBZ and upper and lower Brunswick aquifers with the revised model by rezoning and adjusting hydraulic conductivity values in the Brunswick/Glynn County area. The revised model was further evaluated using pumping estimates for 2000 in conjunction with observed water levels during 2000 to obtain the best possible match of simulated to observed water levels in the Brunswick/Glynn County area. Additionally, the calibrated revised model allowed grid refinement near the area of chloride contamination in the City of Brunswick to accurately simulate hydraulic gradients and groundwater-flow directions near industrial pumping centers. The simulated hydraulic gradients, or potentiometric gradients, near downtown Brunswick are important because they control the direction and rate of chloride movement within the plume area. Changes in potentiometric gradients over extended periods could alter the shape and the extent of the chloride plume.

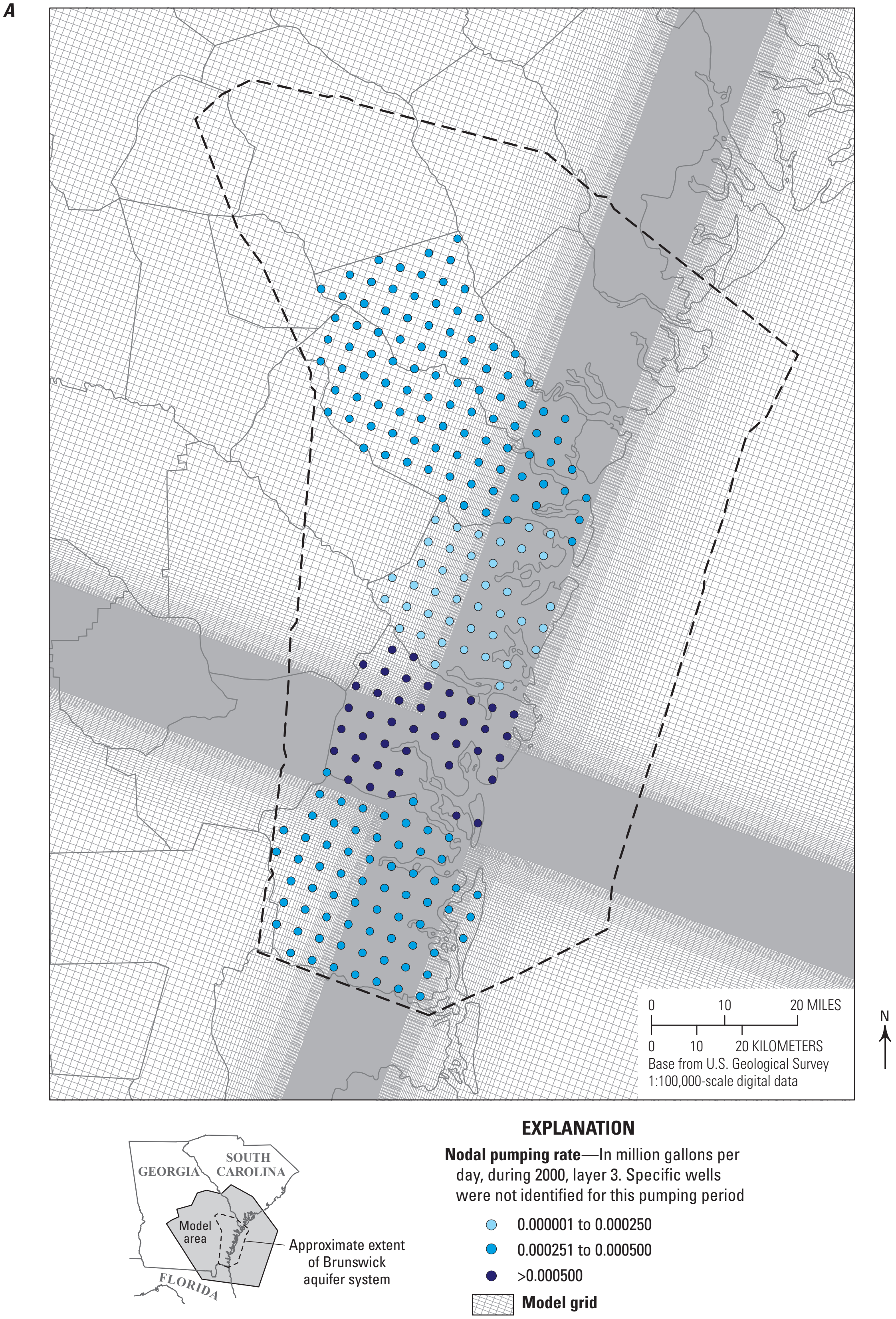
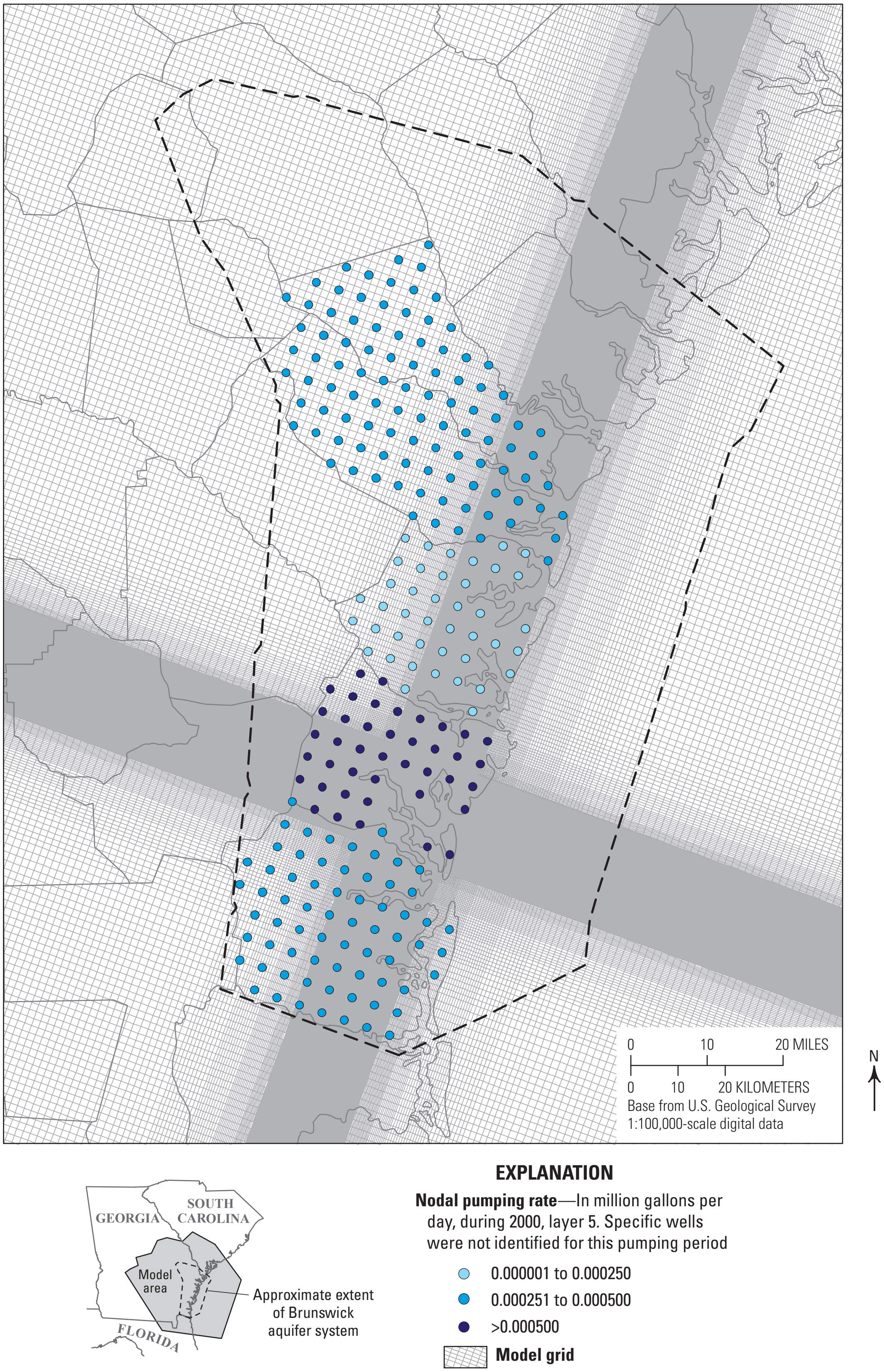


Figure 11. Distribution of groundwater pumpage for 2000 for *A*, model layer 3, upper Brunswick aquifer; *B*, model layer 5, lower Brunswick aquifer; *C*, model layer 7, Upper Floridan aquifer upper water-bearing zone; *D*, model layer 9, Upper Floridan aquifer lower water-bearing zone; and *E*, model layer 11, Lower Floridan aquifer.

B



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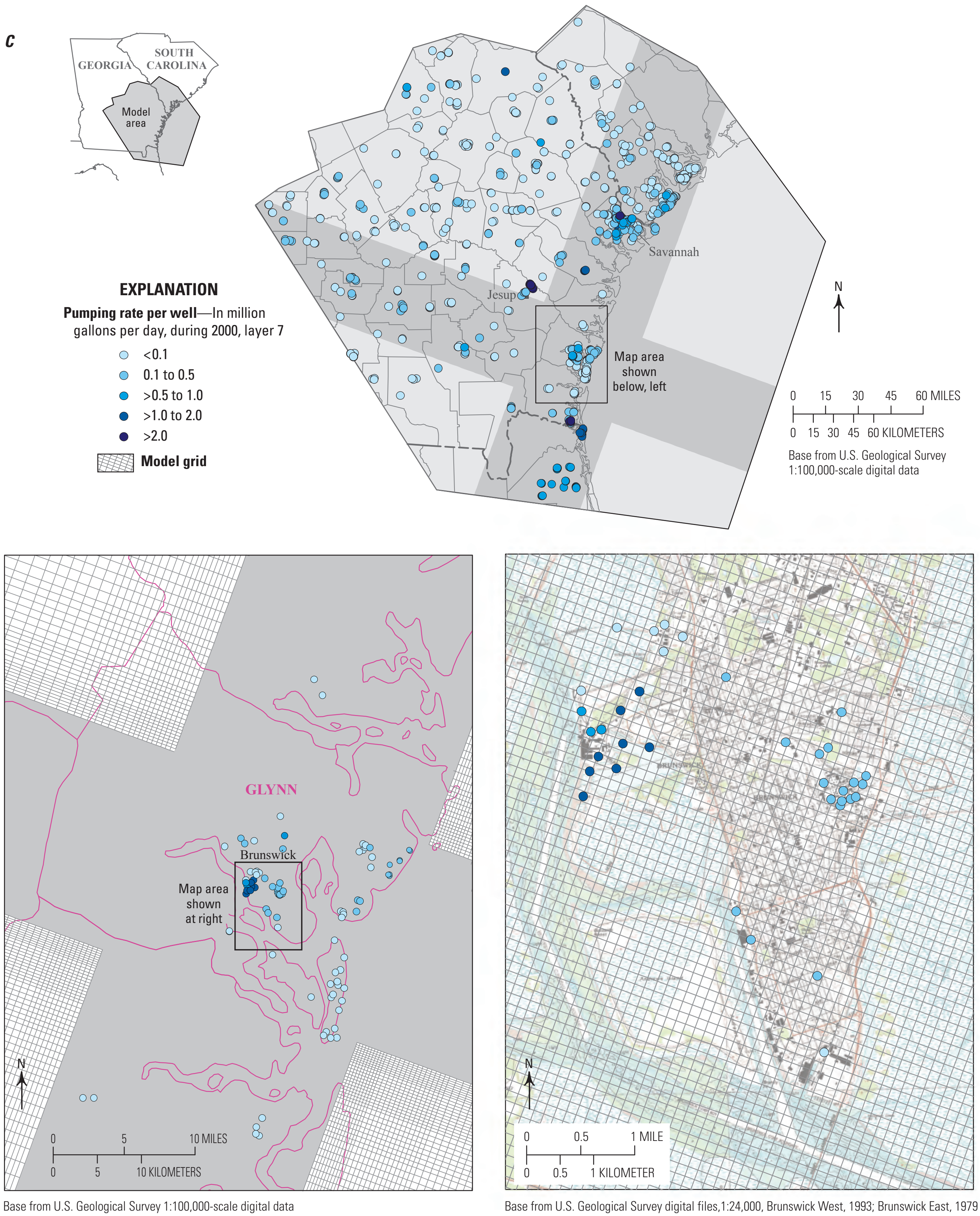
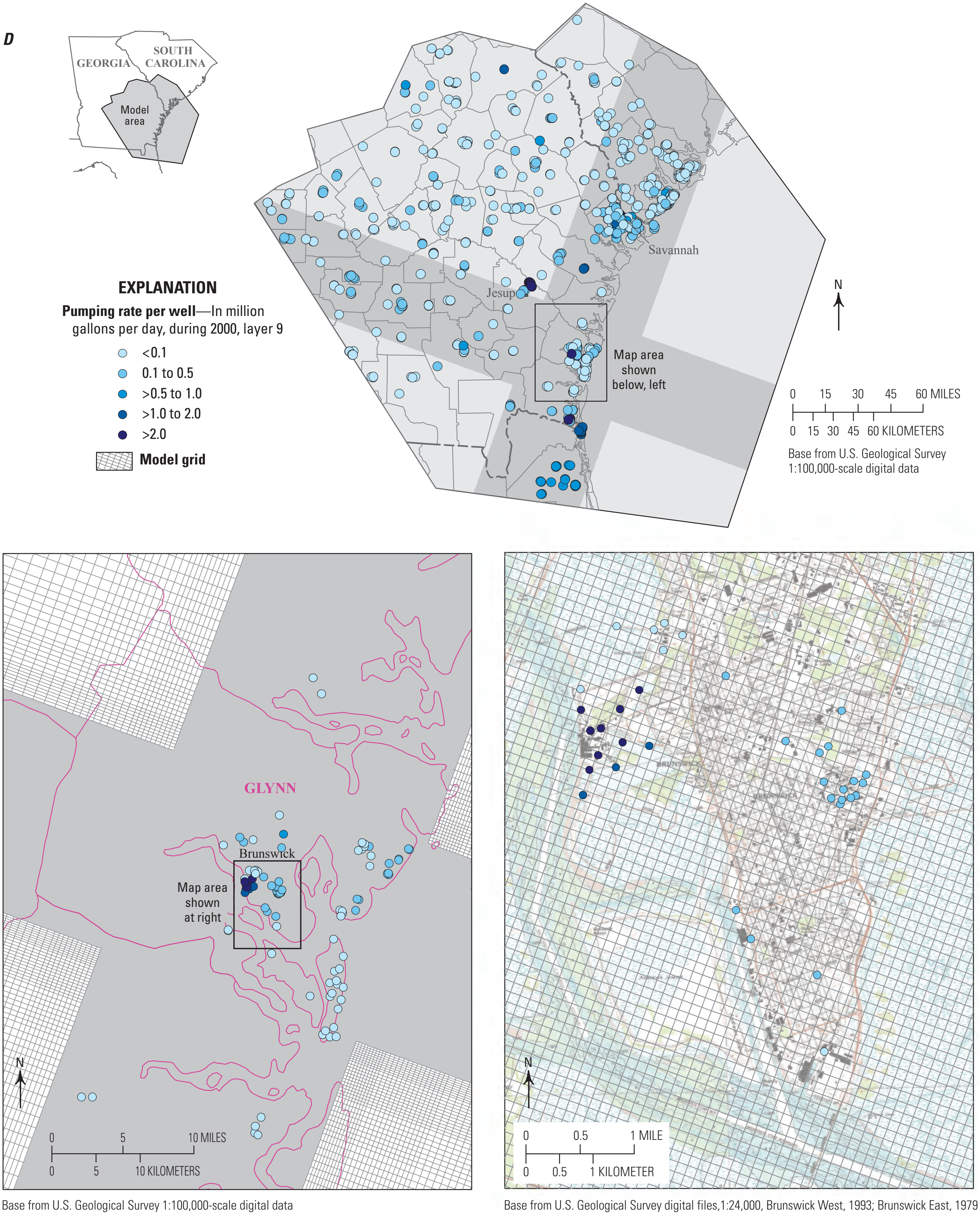


Figure 11. Distribution of groundwater pumpage for 2000 for *A*, model layer 3, upper Brunswick aquifer; *B*, model layer 5, lower Brunswick aquifer; *C*, model layer 7, Upper Floridan aquifer upper water-bearing zone; *D*, model layer 9, Upper Floridan aquifer lower water-bearing zone; and *E*, model layer 11, Lower Floridan aquifer.—Continued



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E

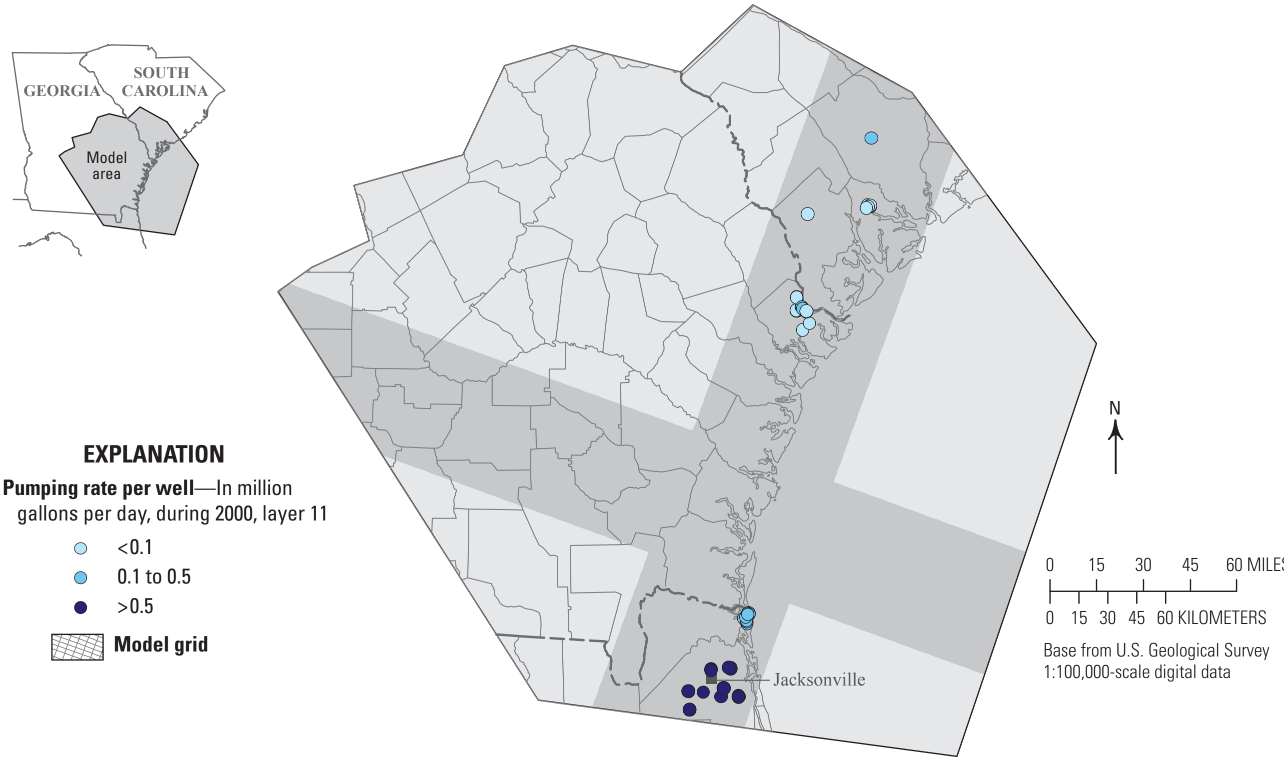


Figure 11. Distribution of groundwater pumpage for 2000 for *A*, model layer 3, upper Brunswick aquifer; *B*, model layer 5, lower Brunswick aquifer; *C*, model layer 7, Upper Floridan aquifer upper water-bearing zone; *D*, model layer 9, Upper Floridan aquifer lower water-bearing zone; and *E*, model layer 11, Lower Floridan aquifer.—Continued

A

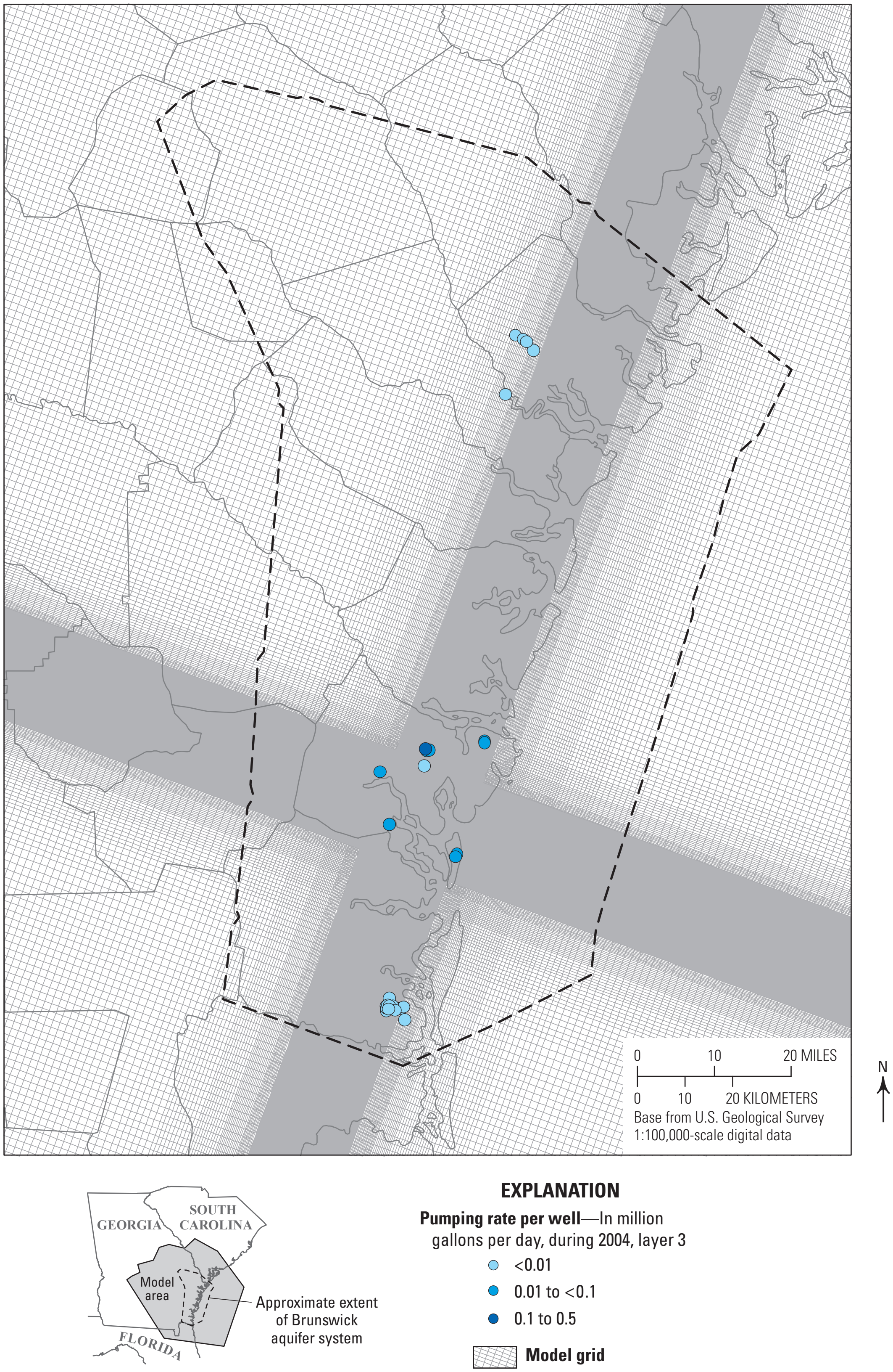


Figure 12. Distribution of groundwater pumpage for 2004 for *A*, model layer 3, upper Brunswick aquifer; *B*, model layer 5, lower Brunswick aquifer; *C*, model layer 7, Upper Floridan aquifer upper water-bearing zone; *D*, model layer 9, Upper Floridan aquifer lower water-bearing zone; and *E*, model layer 11, Lower Floridan aquifer.

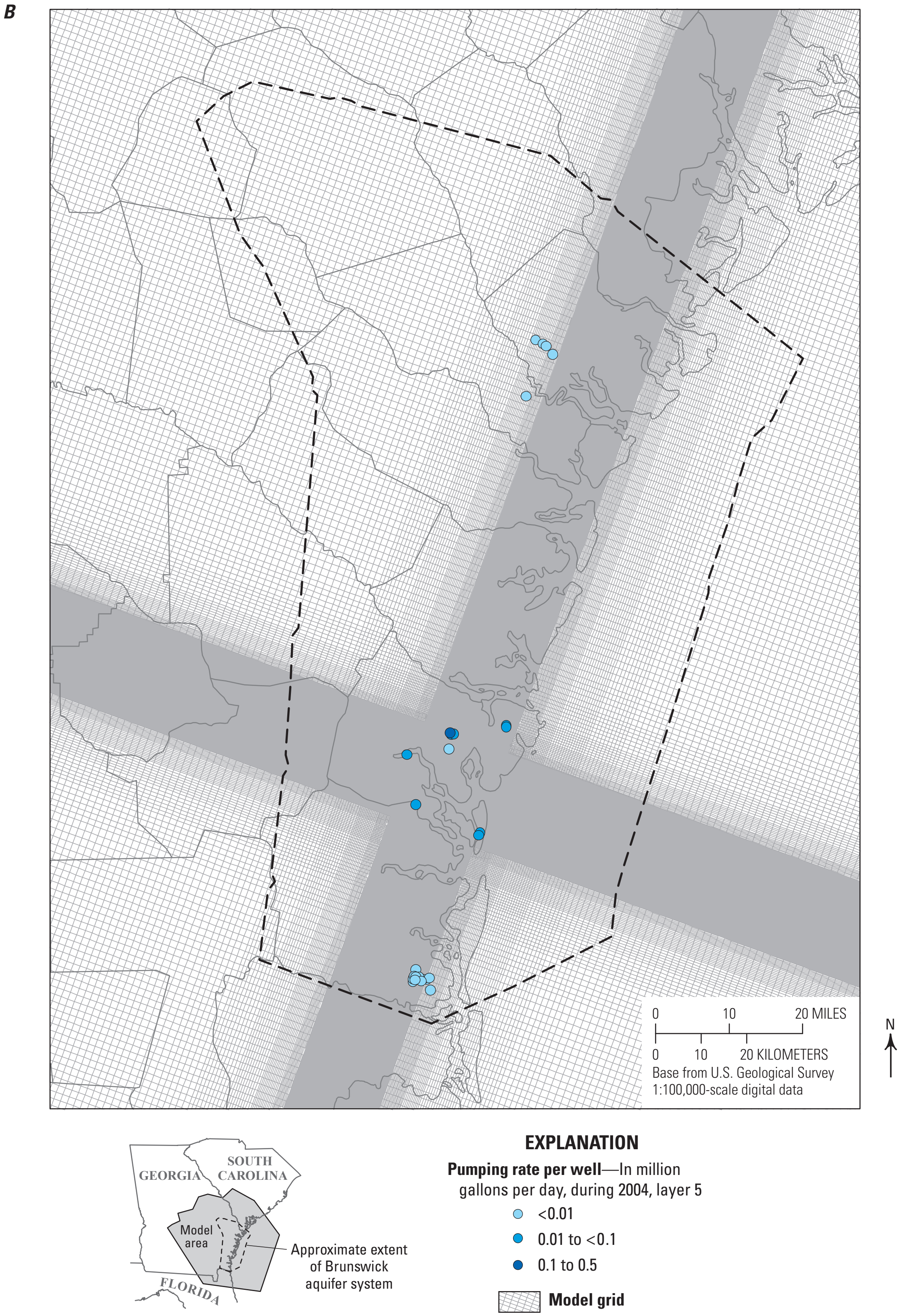
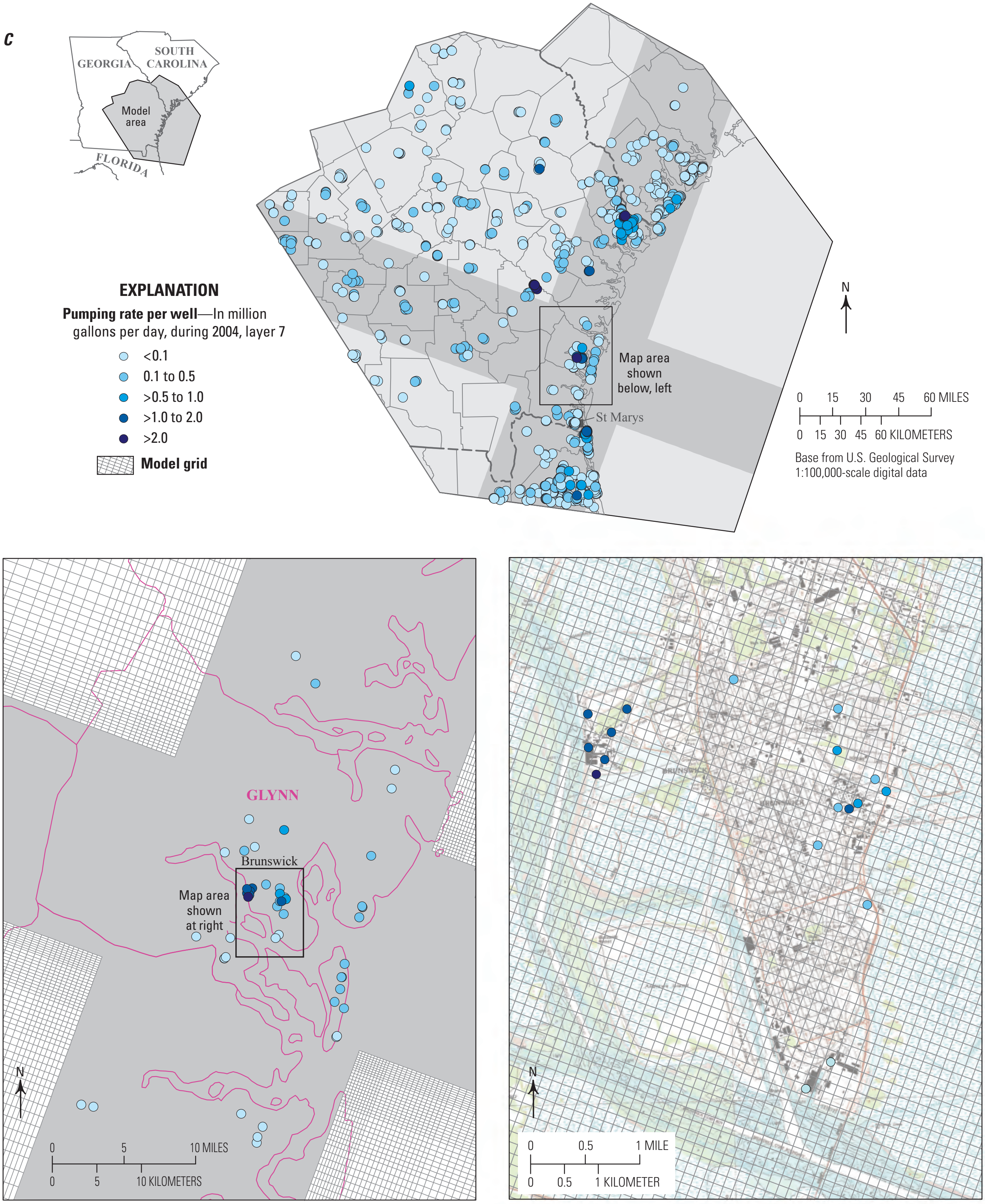


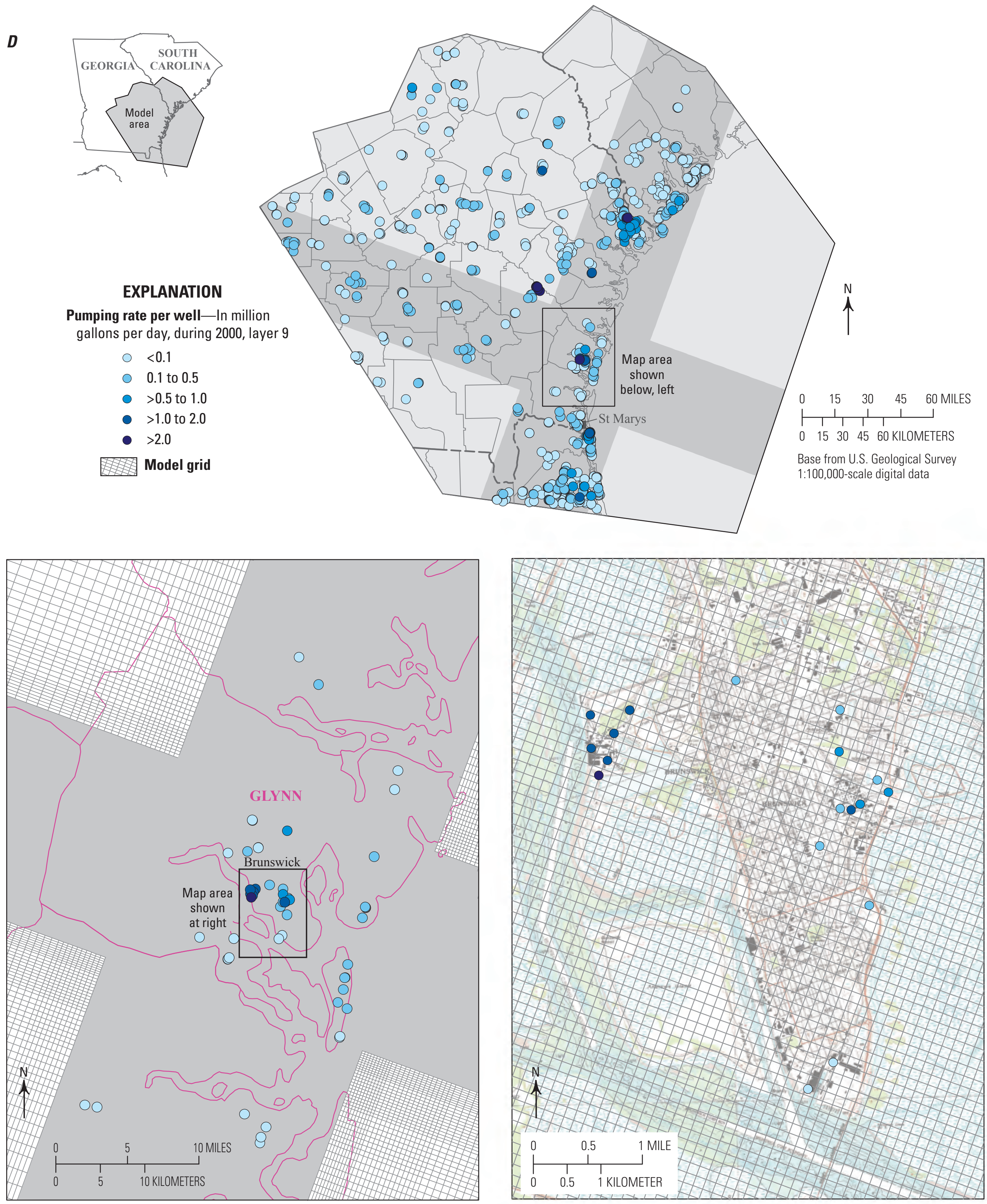
Figure 12. Distribution of groundwater pumpage for 2004 for *A*, model layer 3, upper Brunswick aquifer; *B*, model layer 5, lower Brunswick aquifer; *C*, model layer 7, Upper Floridan aquifer upper water-bearing zone; *D*, model layer 9, Upper Floridan aquifer lower water-bearing zone; and *E*, model layer 11, Lower Floridan aquifer.—Continued



Base from U.S. Geological Survey 1:100,000-scale digital data

Base from U.S. Geological Survey digital files,1:24,000, Brunswick West, 1993; Brunswick East, 1979

Figure 12. Distribution of groundwater pumpage for 2004 for *A*, model layer 3, upper Brunswick aquifer; *B*, model layer 5, lower Brunswick aquifer; *C*, model layer 7, Upper Floridan aquifer upper water-bearing zone; *D*, model layer 9, Upper Floridan aquifer lower water-bearing zone; and *E*, model layer 11, Lower Floridan aquifer.—Continued



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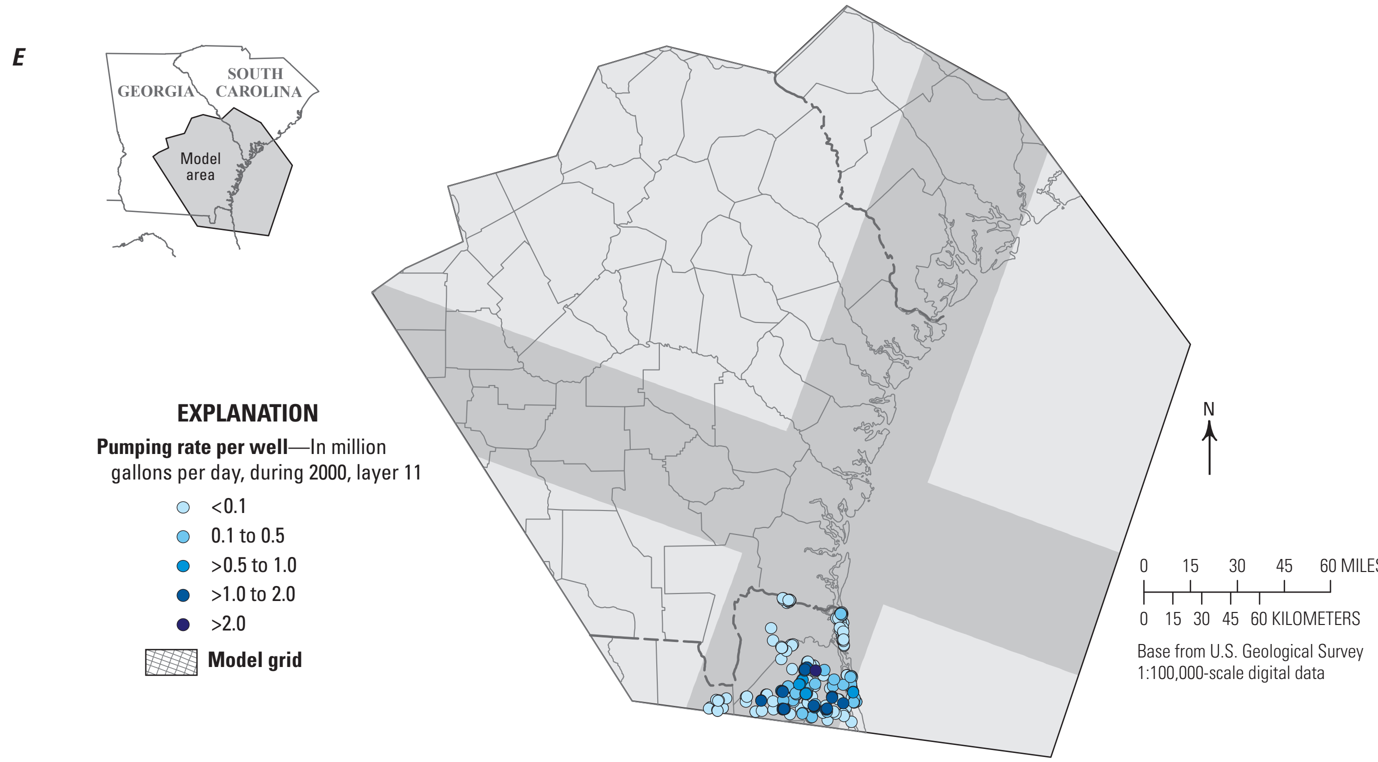

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Parameter-estimation techniques were used to adjust hydraulic properties in an efficient manner that (1) eliminated the need for time-intensive, trial-and-error, manual techniques of achieving calibration and (2) resulted in a distribution of hydraulic conductivity that nearly satisfied the calibration criterion of matching simulated to observed groundwater levels. Minor adjustments were made to the parameter estimation results to obtain a calibrated model of steady-state 2004 conditions. The calibrated model then simulated steady-state 2000 pumping and boundary conditions.

Acceptance Criteria

Model performance for 2000 and 2004 conditions was evaluated on the basis of differences (residuals) between simulated and observed water levels as well as their corresponding mean, median, and root-mean-square-error (RMSE) statistics (tables 5 and 6). The mean residual is a good indicator of bias in the differences between observed and simulated heads. The median residual eliminates the bias in the data and is more robust than the mean in the presence of outlier values. RMSE, derived from residuals as the square root of the average deviation of the residuals from zero, yields a measure of overall fit of simulated to observed groundwater levels. The calibration criteria used near the Brunswick/Glynn County area in the revised model were more stringent than those used in the original model because of the relatively low topographic relief in the area and the availability of 5-ft contour intervals on local topographic maps. For altitudes determined from topographic maps near the downtown Brunswick area, one-half the contour interval (2.5 ft) is considered to be the accuracy of well data, including groundwater-level measurements, formation altitudes, and so forth. Generally, the vertical accuracy of land-surface altitude is about 1 ft if the well location has been surveyed or global-positioning instrumentation has been utilized. The observation accuracy, therefore, is the assumed accuracy of water-level observations at a well and was determined to be 4.6 ft for 2000 water-level conditions used in the original model. The original model considered the accuracy of land-surface altitude and seasonal variability in water levels to have the largest influence on observation accuracy. Additional errors inherent to observations (Kuniansky and others, 2003) imply that a calibration criterion of twice the standard deviation of observational accuracy, or 9.2 ft for the 2000 water-level conditions, is reasonable. Therefore, the calibration criterion was rounded to 10 ft for the original model. For the revised model, the calibration target for the 2000 and 2004 simulations was 10 ft for areas outside Glynn County and 5 ft near downtown Brunswick. The primary objective of the calibration was to achieve the best possible match of simulated groundwater levels to observed values in the UWBZ of the UFA near the Brunswick/Glynn County area Few observations were available for calibration of the Brunswick aquifer system, LWBZ of the UFA, and the LFA.

Table 5. Calibration statistics for simulated heads for 2000 conditions.

[UWBZ, upper water-bearing zone; LWBZ, lower water-bearing zone; residual equals simulated minus observed head; —, not calculated because less than 10 values]

Calibration statistic	Upper Brunswick aquifer (layer 3)	Lower Brunswick aquifer (layer 5)	UWBZ of Upper Floridan aquifer (layer 7)	LWBZ of Upper Floridan aquifer (layer 9)	Lower Floridan aquifer (layer 11)
Regional model area					
Number of observations	7	3	155	5	11
Range of observations (feet)	30.2	38.3	319	34.2	142
Maximum negative residual (feet)	−8.82	−3.18	−19.5	−10.0	−6.10
Maximum positive residual (feet)	12.8	15.5	52.0	13.1	32.4
Mean residual (feet)	−1.39	5.66	0.92	−4.57	3.72
Median residual (feet)	−2.00	4.67	−0.76	−8.62	0.47
Root-mean square error residual (feet)	—	—	10.9	—	11.4
Residuals within 10-foot error criteria (percent)	86	67	77	40	82
Residuals within 5-foot error criteria (percent)	43	67	53	0	64
Glynn County					
Number of observations	2	1	41	5	7
Range of observations (feet)	8.48	—	40.1	34.2	18.3
Maximum negative residual (feet)	−6.01	—	−19.5	−10.0	−6.10
Maximum positive residual (feet)	2.69	—	4.29	13.1	9.38
Mean residual (feet)	−1.66	—	−1.30	−4.57	−0.42
Median residual (feet)	—	—	−0.35	−8.62	−1.93
Root-mean square error residual (feet)	—	—	4.32	—	—
Residuals within 10-foot error criteria (percent)	100	100	95	40	100
Residuals within 5-foot error criteria (percent)	50	100	88	0	71

Table 6. Calibration statistics for simulated heads for 2004 conditions.

[UWBZ, upper water-bearing zone; LWBZ, lower water-bearing zone; residual equals simulated minus observed head; —, not calculated because less than 10 values]

Calibration statistic	Upper Brunswick aquifer (layer 3)	Lower Brunswick aquifer (layer 5)	UWBZ of Upper Floridan aquifer (layer 7)	LWBZ of Upper Floridan aquifer (layer 9)	Lower Floridan aquifer (layer 11)
Regional model area					
Number of observations	14	4	52	5	13
Range of observations (feet)	144	44.5	319	34.2	91.7
Maximum negative residual (feet)	–28.6	–12.5	–18.9	–6.15	–37.6
Maximum positive residual (feet)	9.30	10.6	18.3	20.8	24.2
Mean residual (feet)	–5.60	–3.62	–2.64	1.20	–3.61
Median residual (feet)	–3.57	–6.31	–2.05	–3.30	–3.73
Root-mean square error residual (feet)	11.6	—	6.95	—	14.5
Residuals within 10-foot error criteria (percent)	79	50	83	80	54
Residuals within 5-foot error criteria (percent)	43	0	60	60	38
Glynn County					
Number of observations	6	2	32	5	7
Range of observations (feet)	33.8	13.6	42.9	34.2	12.1
Maximum negative residual (feet)	–13.7	–12.5	–18.9	–6.15	–10.9
Maximum positive residual (feet)	9.30	–6.26	3.98	20.8	1.98
Mean residual (feet)	–0.77	–9.38	–2.56	1.20	–4.50
Median residual (feet)	–0.66	—	–1.50	–3.30	–3.73
Root-mean square error residual (feet)	—	—	5.34	—	—
Residuals within 10-foot error criteria (percent)	83	50	91	80	86
Residuals within 5-foot error criteria (percent)	67	0	75	60	71

Year 2000 Calibration

Groundwater levels measured in 181 wells during 2000 (fig. 13*A*; table 5) were used to determine the acceptance of simulated groundwater levels as a criterion for calibrating the revised model. Of these 181 measurements, 7 were derived from the upper Brunswick aquifer (layer 3), 3 were from the lower Brunswick aquifer (layer 5), 155 were from the UWBZ of the UFA (layer 7), 5 were from the LWBZ of the UFA (layer 9), and 11 were from the LFA (layer 11).

Over the regional model area, residuals, or simulated minus observed water-level altitudes, calculated for 155 wells tapping the UWBZ of the UFA (layer 7) ranged from –19.5 to 52.0 ft, with a mean of 0.92 ft, a median of –0.76 ft, and an RMSE of 10.9 ft (fig. 13*A*; table 5). In the Brunswick/Glynn County area, the mean residual based on 41 measured groundwater levels was –1.30 ft, with a median value of –0.35 ft, and an RMSE of 4.32 ft (fig. 13*B*).

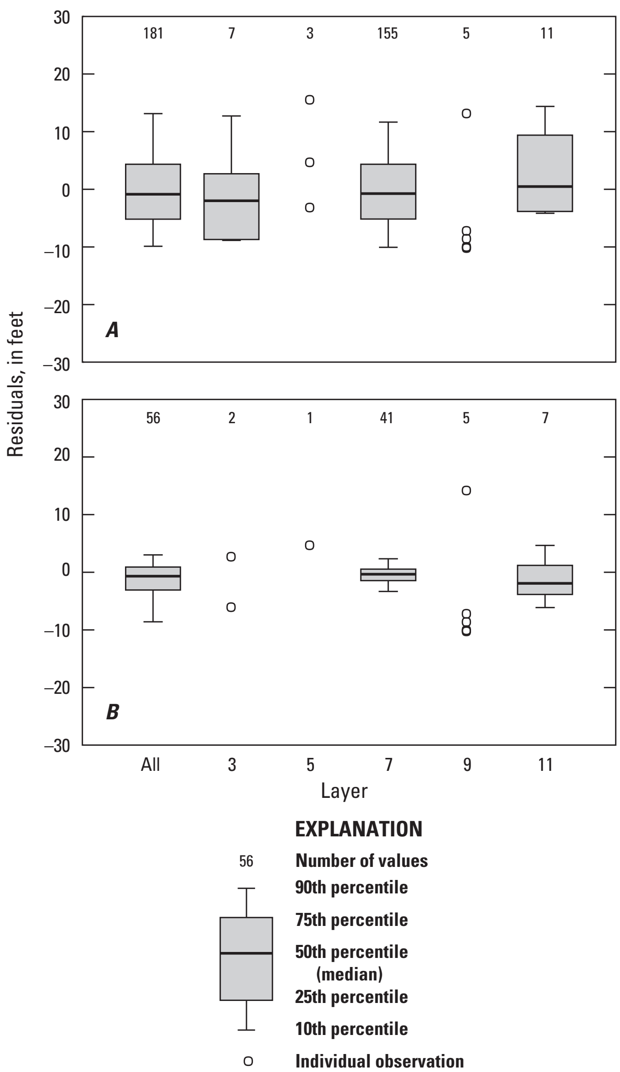


Figure 13. Boxplots showing difference (residuals) between simulated and observed heads for 2000 simulation in *A*, the regional model area and *B*, Brunswick/Glynn County area.

Residuals in the LWBZ of the UFA (layer 9) were derived from 5 observations and ranged from −10.0 to 13.1 ft with a mean residual of −4.57 ft and median residual of –8.62 ft, indicating poor model performance in the Brunswick/Glynn County area (fig. 13*B*; table 5). Mean residuals for the LFA (layer 11) were larger, with 3.72 ft for the regional model area and −0.42 ft in the Brunswick/Glynn County area, which was considered acceptable. This disparity was also evident in the median value of 0.47 ft for the regional model area versus −1.93 ft in the Brunswick/Glynn County area (fig.13*A*–*B*).

The maps shown in figure 14*A*–*B* indicate observation data were sparse for model layers 3 and 5, with the maximum residuals either located near the edge of model boundaries or near the cone of depression in Chatham County. The spatial distribution of the observation data and the influence of pumping in the Chatham County area did not allow adjustments to hydraulic conductivity that would provide a better fit. In the Brunswick/Glynn County area, groundwater-flow directions in model layers 3 and 5 were generally from west to east with a maximum residual of 2.69 ft and a minimum of −6.01 ft (fig. 14*A*–*B*; table 5).

Maps showing simulated 2000 potentiometric surfaces and water-level residuals by model layer: *A*, layer 3, upper Brunswick aquifer, model area; *B*, layer 5, lower Brunswick aquifer, model area; *C*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, model area; *D*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; *E*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, Glynn County and Brunswick area enlargement; and *F*, layer 11, Lower Floridan aquifer, model area. The distribution of residuals for model layer 7 shows generally positive values north of Glynn County and west of the Gulf Trough with a cluster of negative values at wells along the coastal plain of Georgia (fig. 14*C*), indicative of the model's inability to dissipate higher-than-observed simulated hydraulic head across the Gulf Trough. The increased hydraulic conductivity of the hydraulic property zone representing the Gulf Trough would lower simulated hydraulic head to the north and west of the Gulf Trough and, likewise, increase simulated hydraulic head downgradient of the Gulf Trough to the south and east along the Coastal Plain. The effect of increasing the simulated water-transmitting ability of the Gulf Trough on groundwater-level residuals would simultaneously drive the positive residuals upgradient of the Gulf Trough and the negative residuals downgradient of the Gulf Trough closer to zero, thereby improving calibration. In the Brunswick/Glynn County area, the distribution of residuals in model layer 7 indicates a good match outside the cone of depression, with generally negative residual values on the Brunswick peninsula (fig. 14*E*; table 5). The mean residual for the 2000 simulation in model layer 7 of −1.30 ft is generally well within the established error criterion of 5 ft, but the lower simulated heads could be caused by an overestimation of pumping in the Brunswick area, insufficient simulated interaquifer leakage from the LFA into the UFA, and (or) adjustments made to the specified-head boundary for the Floridan aquifer system (layers 7–11). The distribution

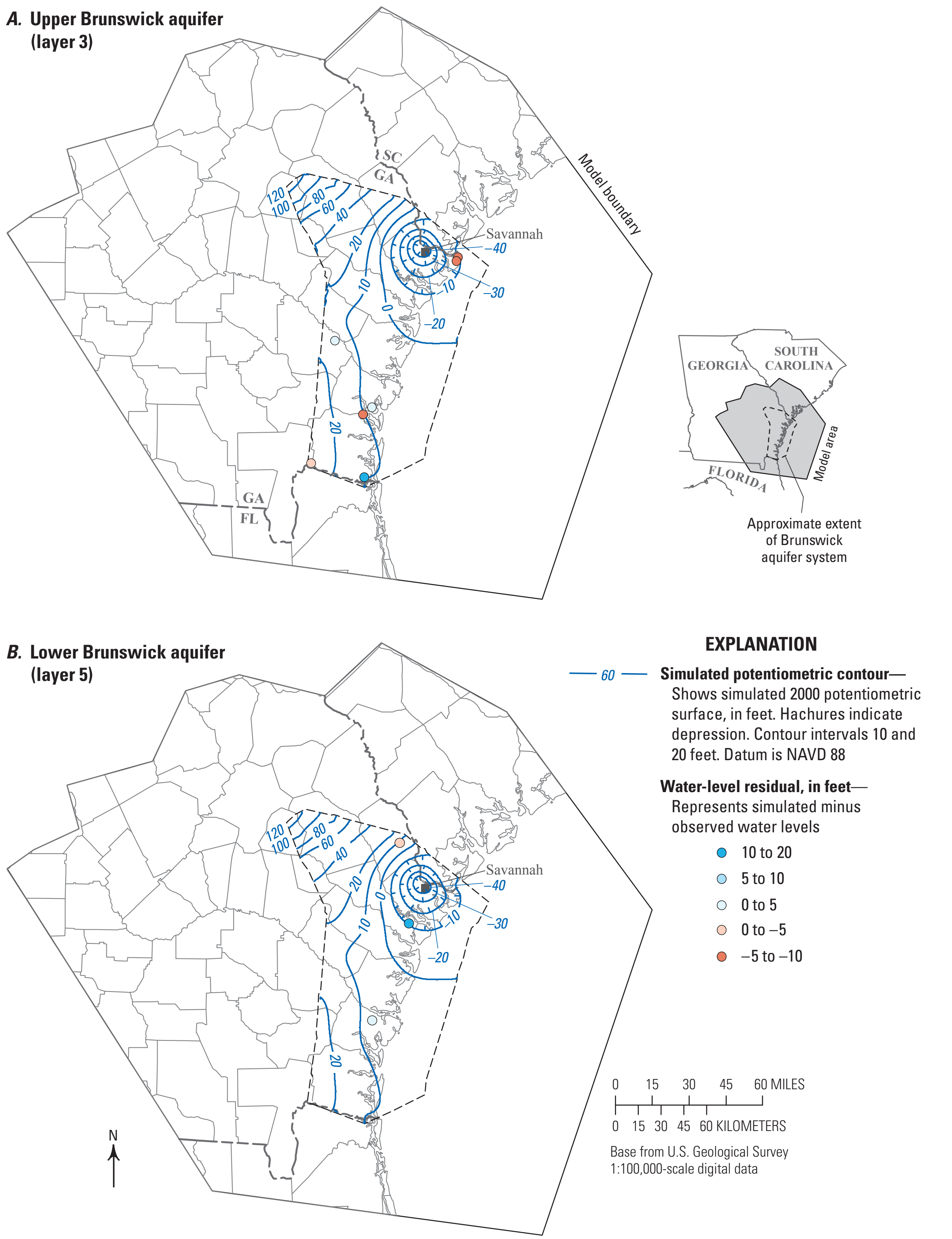


Figure 14. Simulated 2000 potentiometric surfaces and water-level residuals by model layer: *A*, layer 3, upper Brunswick aquifer, model area; *B*, layer 5, lower Brunswick aquifer, model area; *C*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, model area; *D*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; *E*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, Glynn County and Brunswick area enlargement; *F*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; and *G*, layer 11, Lower Floridan aquifer, model area and Glynn County enlargement.

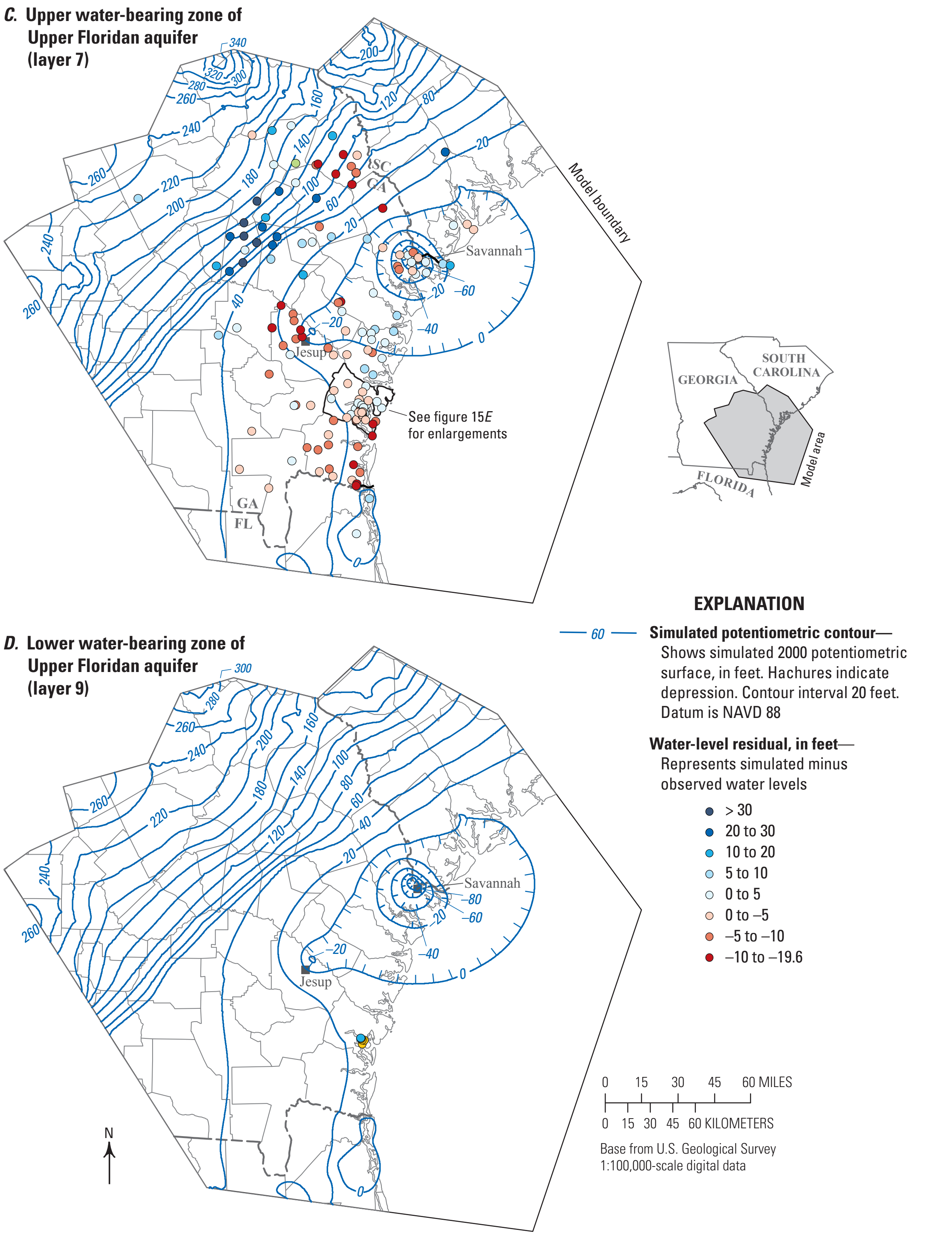


Figure 14. Simulated 2000 potentiometric surfaces and water-level residuals by model layer: *A*, layer 3, upper Brunswick aquifer, model area; *B*, layer 5, lower Brunswick aquifer, model area; *C*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, model area; *D*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; *E*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, Glynn County and Brunswick area enlargement; *F*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; and *G*, layer 11, Lower Floridan aquifer, model area and Glynn County enlargement.—Continued

E. **Upper water-bearing zone of Upper Floridan aquifer (layer 7)**

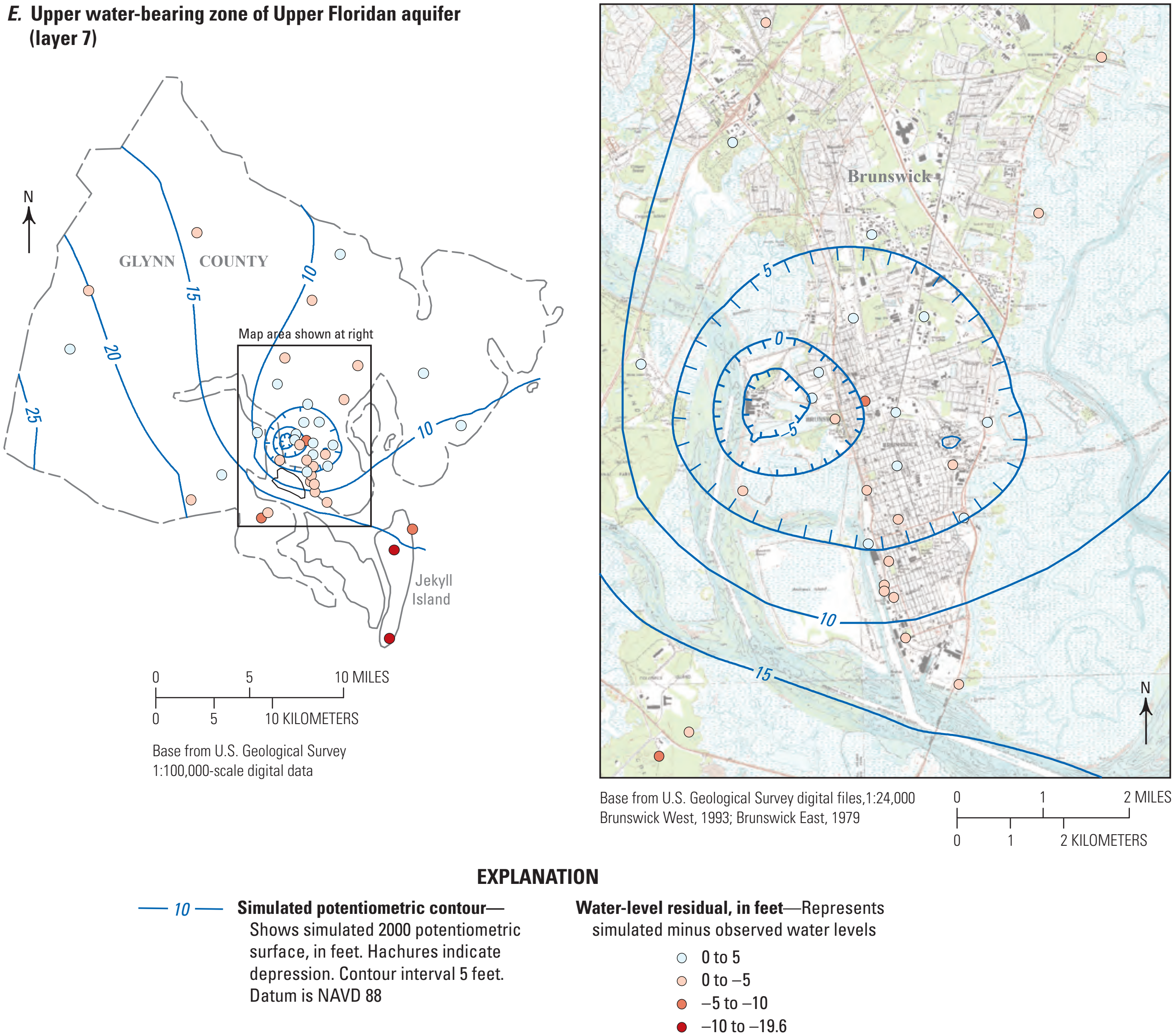


Figure 14. Simulated 2000 potentiometric surfaces and water-level residuals by model layer: *A*, layer 3, upper Brunswick aquifer, model area; *B*, layer 5, lower Brunswick aquifer, model area; *C*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, model area; *D*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; *E*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, Glynn County and Brunswick area enlargement; *F*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; and *G*, layer 11, Lower Floridan aquifer, model area and Glynn County enlargement.—Continued

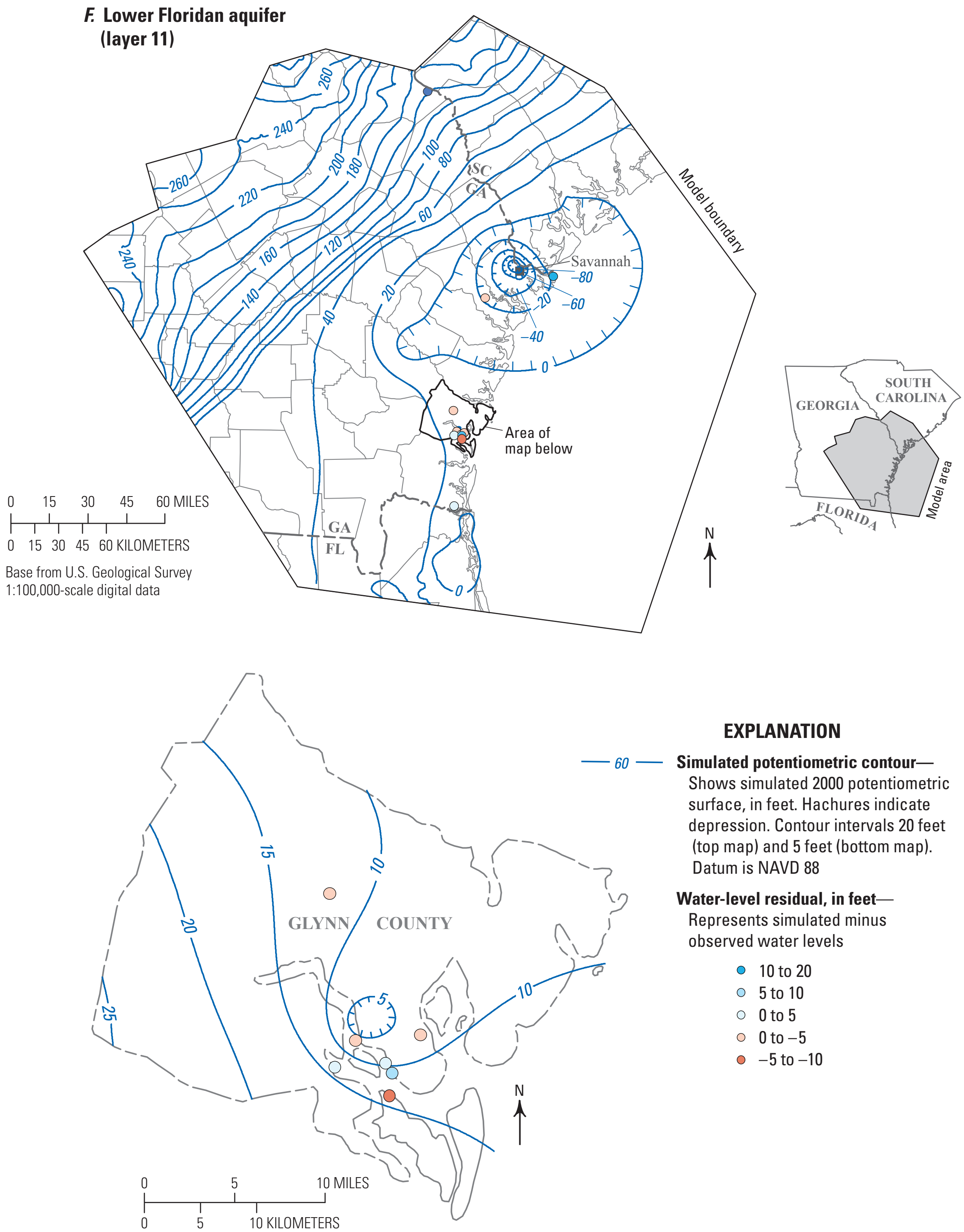


Figure 14. Simulated 2000 potentiometric surfaces and water-level residuals by model layer: *A*, layer 3, upper Brunswick aquifer, model area; *B*, layer 5, lower Brunswick aquifer, model area; *C*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, model area; *D*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; *E*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, Glynn County and Brunswick area enlargement; *F*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; and *G*, layer 11, Lower Floridan aquifer, model area and Glynn County enlargement.—Continued

of residuals for model layer 11 indicates generally positively skewed residuals in the northern part of the model and negatively skewed residuals to the south of Chatham County. In the Brunswick/Glynn County area, the distribution of residuals in model layer 11 shows mostly negative values near the area of influence for pumping in model layers 7 and 9 near downtown Brunswick with 5 of the 7 wells (71 percent) falling within the established 5-ft calibration criterion (fig. 14*F*).

Year 2004 Calibration

Groundwater levels measured in 88 wells during 2004 (fig. 15; table 6) were used to determine the acceptance of simulated groundwater levels as a criterion for calibrating the revised model. Of these 88 measurements, 14 were derived from the upper Brunswick aquifer (layer 3), 4 were from the lower Brunswick aquifer (layer 5), 52 were from the UWBZ of the UFA (layer 7), 5 were from the LWBZ of the UFA (layer 9), and 13 were from the LFA (layer 11). For the regional model area, residuals for model layer 7 ranged from −18.9 to 18.3 ft, with a mean of −2.64 ft, median of −2.05 ft, and an RMSE of 6.95 ft. In the Brunswick/Glynn County area, residuals from 32 observation wells in model layer 7 ranged from −18.9 to 3.98 ft, with a mean of −2.56 ft, median of −1.50 ft and an RMSE of 5.34 ft (fig. 15; table 6). For the regional model area for model layer 3, residuals from 14 observation wells open to the Brunswick aquifer system ranged from −28.6 to 9.30 ft, with a mean of −5.60 ft, median of −3.57 ft, and an RMSE of 11.6 ft. For model layer 5, residuals from four observation wells ranged from −12.5 to 10.6 ft, with a mean of −3.62 ft. For model layer 9, residuals from five wells located near downtown Brunswick ranged from −6.15 to 20.8 ft, with a mean of 1.20 ft and a median of −3.30 ft. Over the entire regional model area for model layer 11, residuals from the 13 observation wells ranged from −37.6 to 24.2 ft, with a mean of −3.61 ft, median of −3.73 ft, and an RMSE of 14.5 ft. The percentage of residuals within the 10-ft calibration target of observed values over the regional model area was 79 percent for model layer 3, 50 percent for model layer 5, 83 percent for model layer 7, 80 percent for model layer 9, and 54 percent for model layer 11. When the more stringent 5-ft calibration target was applied to residuals in the Brunswick/Glynn County area, the percentage within the target was 75 percent for model layer 7, 60 percent for model layer 9, and 71 percent for model layer 11.

For the year 2004 calibration, the map showing distribution of water-level residuals for the upper Brunswick aquifer (layer 3) indicates mostly negative values near the northern extent of the aquifer and in the Brunswick/Glynn County area except for several positive values located in northern Glynn County (fig. 16*A*). Water-level residuals for the lower Brunswick aquifer (layer 5) are negative, except for one positive value located in Bryan County (fig. 16*B*). Residuals for the UWBZ of the UFA (layer 7) are negative south of the Brunswick/Glynn County area and positive near the Gulf Trough and on the outer edge of the cone of depression in the Savannah area (fig. 16*C*). In the Brunswick/Glynn County area, the distribution of water-level residuals in the UWBZ of the UFA (layer 7) indicates a “good” match, with a mean residual of −2.56 ft and 75 percent of the values within the established error criterion of 5 ft (fig. 16*E*; table 6). However, the map showing the distribution of water-level residuals indicates an “excellent” match in the downtown Brunswick area but large negative values for wells located on Jekyll Island between the 15- and 20-ft simulated potentiometric contours. The map showing the distribution of water-level residuals for the LWBZ of the UFA (layer 9) includes 1 positive value and 4 negative values located south of and near the cone of depression, with a mean residual of 1.20 ft (fig. 16*F*; table 6). The map showing distribution of water-level residuals for the LFA (layer 11) indicates values are negatively skewed, except for several positive values in the Brunswick/Glynn County area and three others located within the cone of depression to the north (fig. 16*G*; table 6).

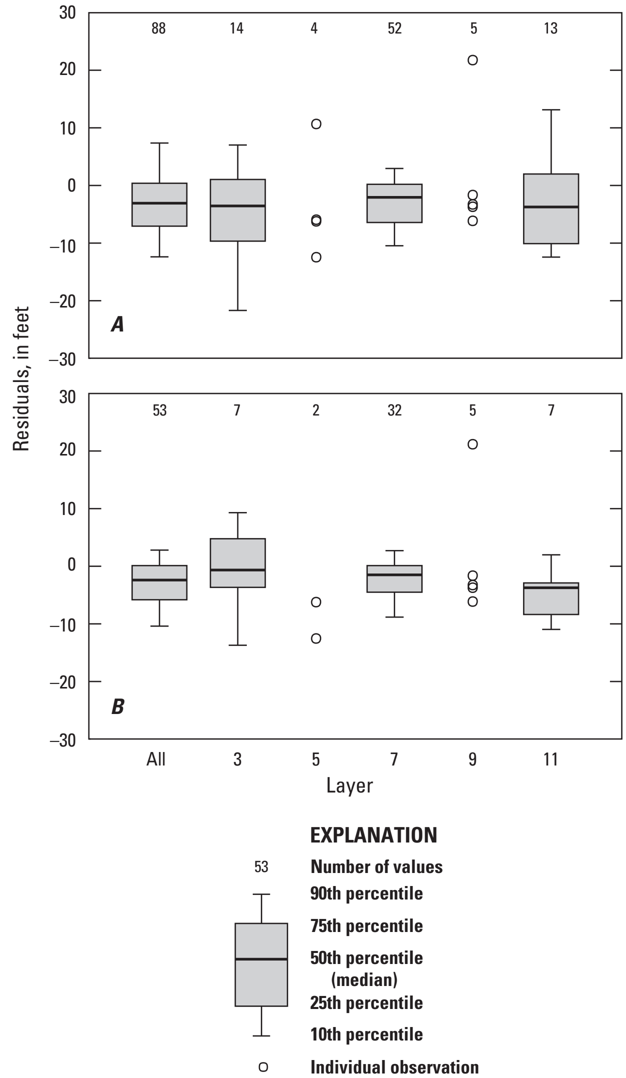


Figure 15. Boxplots showing difference (residuals) between simulated and observed heads for 2004 simulation in the *A*, regional model area, and *B*, Brunswick/Glynn County area.

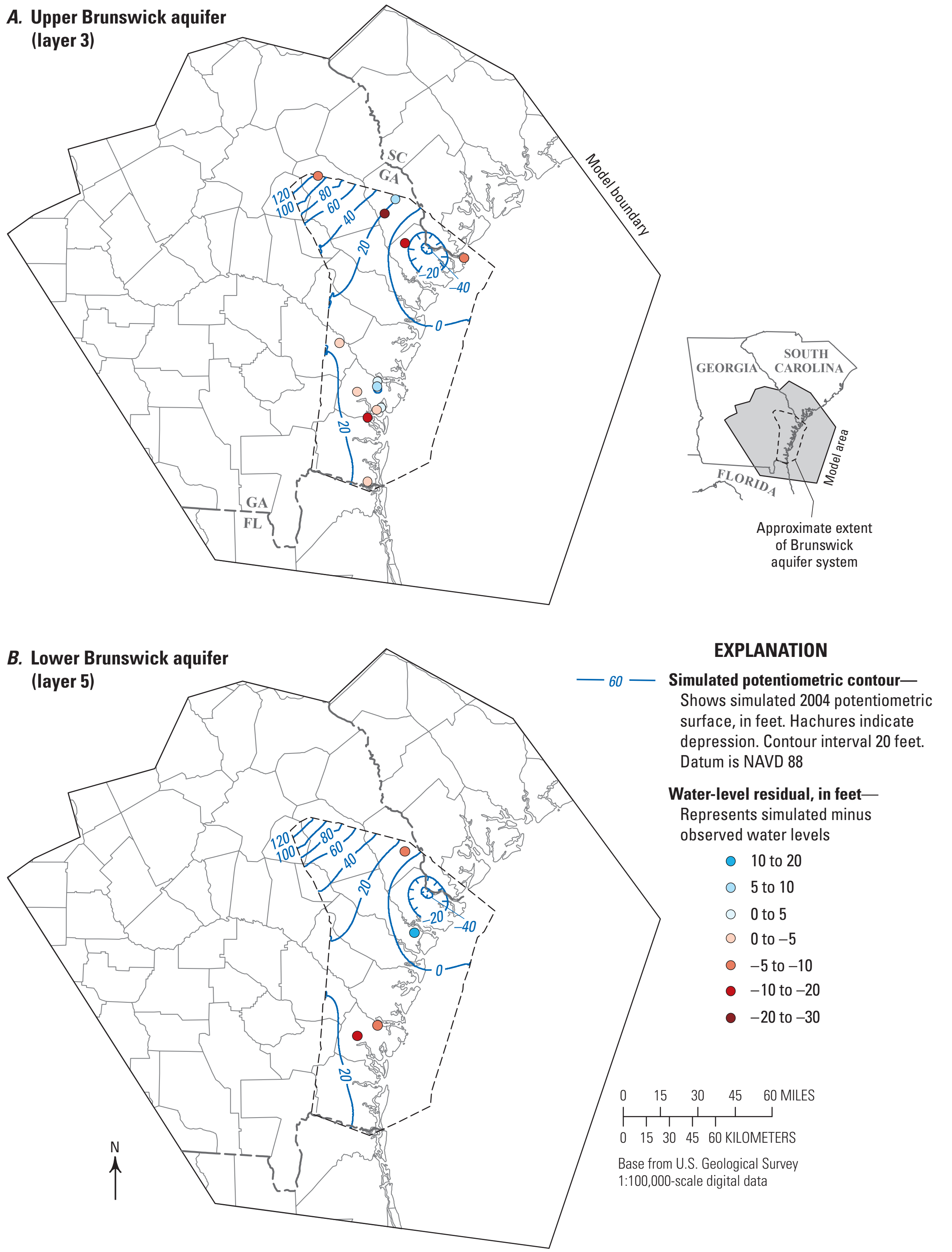


Figure 16. Simulated 2004 potentiometric surfaces and water-level residuals by model layer: *A*, layer 3, upper Brunswick aquifer, model area; *B*, layer 5, lower Brunswick aquifer, model area; *C*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, model area; *D*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; *E*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, Glynn County and Brunswick area enlargement; *F*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; and *G*, layer 11, Lower Floridan aquifer, model area and Glynn County enlargement.

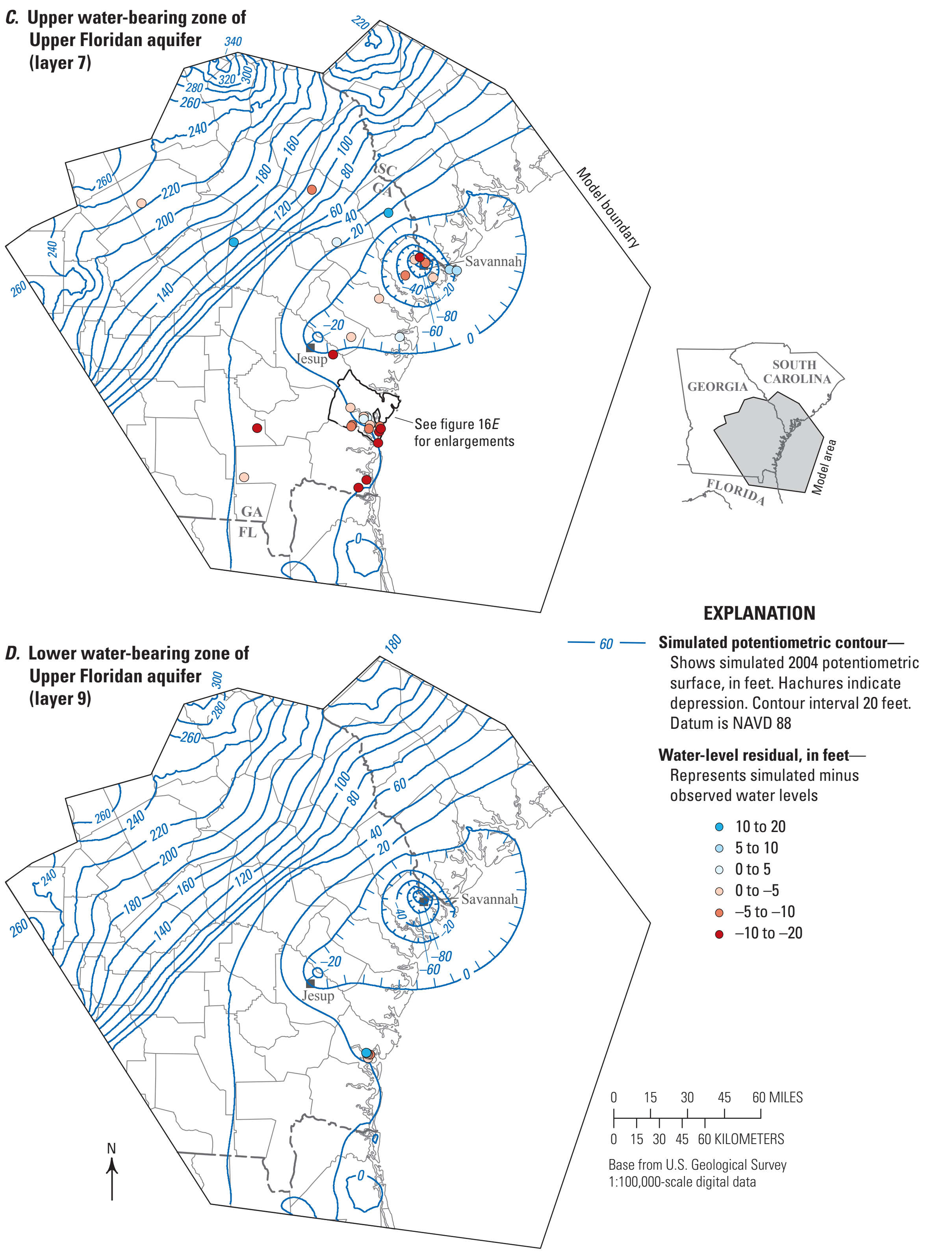
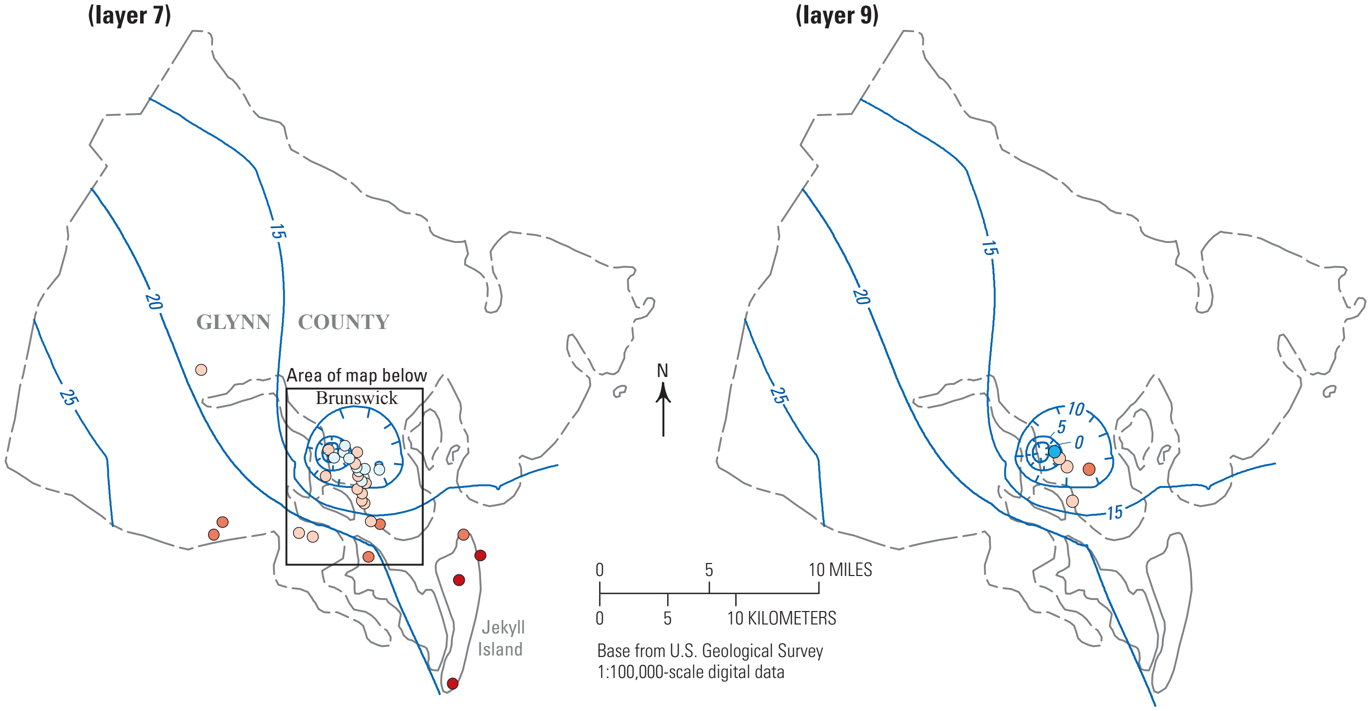


Figure 16. Simulated 2004 potentiometric surfaces and water-level residuals by model layer: *A*, layer 3, upper Brunswick aquifer, model area; *B*, layer 5, lower Brunswick aquifer, model area; *C*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, model area; *D*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; *E*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, Glynn County and Brunswick area enlargement; *F*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; and *G*, layer 11, Lower Floridan aquifer, model area and Glynn County enlargement.—Continued

E. **Upper water-bearing zone of Upper Floridan aquifer (layer 7)**

F. **Lower water-bearing zone of Upper Floridan aquifer (layer 9)**



Base from U.S. Geological Survey digital files,1:24,000, Brunswick West, 1993; Brunswick East, 1979

EXPLANATION

10 **Simulated potentiometric contour**—Shows simulated 2004 potentiometric surface, in feet. Hachures indicate depression. Contour interval 5 feet. Datum is NAVD 88

Water-level residual, in feet—Represents simulated minus observed water levels

- 10 to 20
- 5 to 10
- 0 to 5
- 0 to –5
- –5 to –10
- –10 to –20

Figure 16. Simulated 2004 potentiometric surfaces and water-level residuals by model layer: *A*, layer 3, upper Brunswick aquifer, model area; *B*, layer 5, lower Brunswick aquifer, model area; *C*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, model area; *D*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; *E*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, Glynn County and Brunswick area enlargement; *F*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; and *G*, layer 11, Lower Floridan aquifer, model area and Glynn County enlargement.—Continued

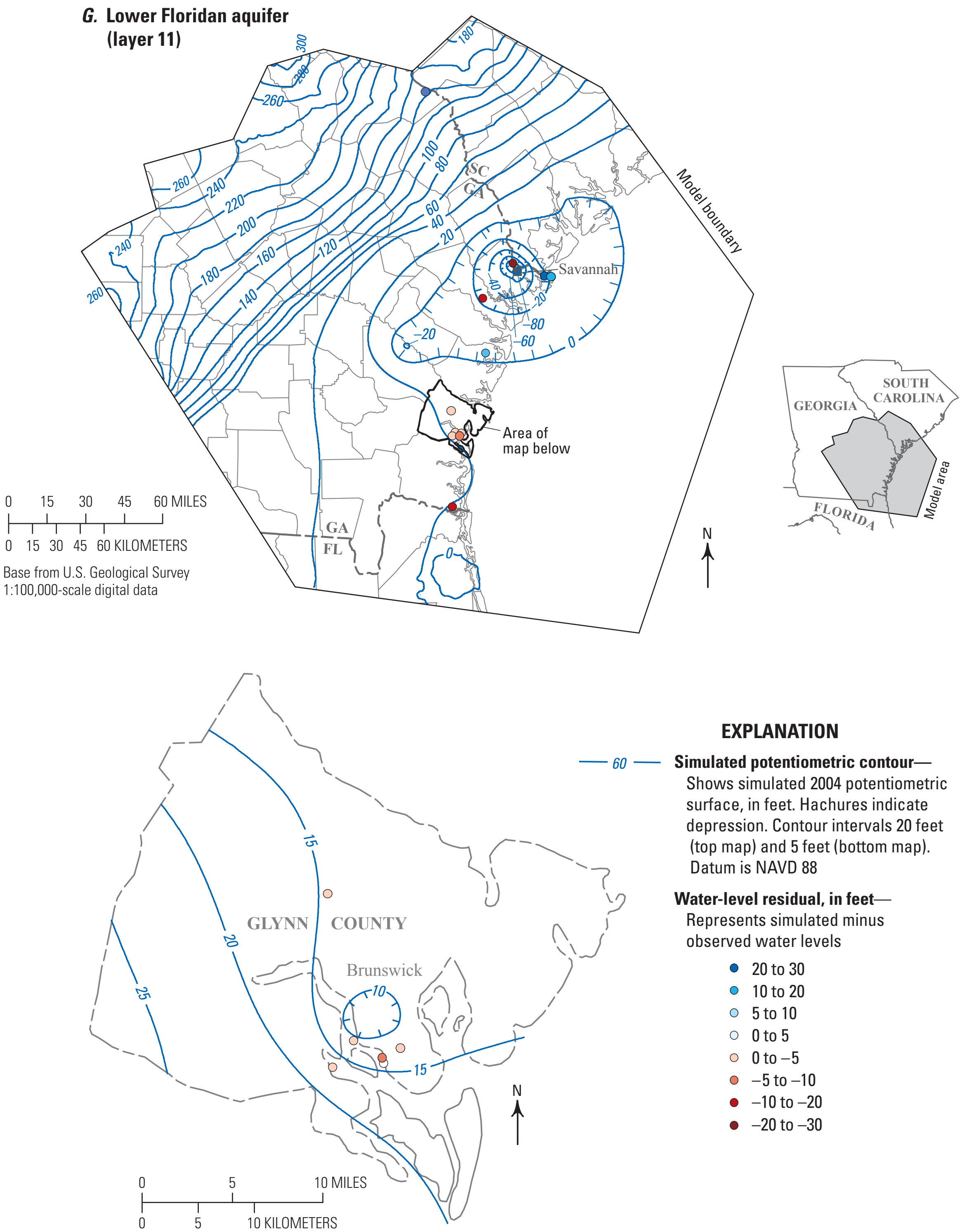


Figure 16. Simulated 2004 potentiometric surfaces and water-level residuals by model layer: *A*, layer 3, upper Brunswick aquifer, model area; *B*, layer 5, lower Brunswick aquifer, model area; *C*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, model area; *D*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; *E*, layer 7, upper water-bearing zone of the Upper Floridan aquifer, Glynn County and Brunswick area enlargement; *F*, layer 9, lower water-bearing zone of the Upper Floridan aquifer; and *G*, layer 11, Lower Floridan aquifer, model area and Glynn County enlargement.—Continued

Simulated Potentiometric Surfaces

The steady-state simulated potentiometric surfaces for 2000 and 2004 indicate groundwater flow from upland regions to the north and west toward the coast, where flow converges at pumping centers near Chatham County, Ga., and Brunswick/Glynn County, Ga. The simulated potentiometric surface maps also show impeded groundwater flow, evidenced by steep potentiometric gradients in upland areas north and west of the Gulf Trough and flatter gradients near the coast where the Floridan aquifer system is more productive.

2000 Conditions

Simulated potentiometric surfaces of the Brunswick aquifer system (layers 3 and 5) for 2000 indicate steep potentiometric gradients, with simulated water-level altitudes ranging from about 120 ft in the northwestern extent of the aquifer system to below −40 ft near the city of Savannah (fig. 14*A*–*B*). The simulated potentiometric contours for the Brunswick aquifer system indicate groundwater-flow patterns similar to those of the Floridan aquifer system (fig. 14*F*) and influenced by pumping in the underlying aquifer in the Chatham County area. Simulated potentiometric surface maps of the UFA (layers 7 and 9) for 2000 show steep potentiometric gradients in the upland areas north and west of the Gulf Trough, with groundwater flow toward the coast (fig. 14*C*–*D*). South and east of the Gulf Trough, potentiometric gradients flatten and groundwater-flow directions are influenced by a cone of depression centered in the Savannah area, which alters the regional coastward flow pattern. The broad area of influence for this cone of depression is indicated by the 0-ft contour, which extends to an area of pumping to the southwest near Jesup, Ga., and north into Jasper and Beaufort Counties, S.C. The simulated water-level altitudes near the center of pumping in Savannah are below −60 ft in layer 7 and below −80 ft in layer 9, respectively. In the Brunswick/Glynn County area, potentiometric contours indicate groundwater flow from west to east, with a cone of depression near downtown Brunswick locally altering the coastward flow pattern (fig. 14*E*). The cone of depression, centered in an active industrial well field, intercepts groundwater flow from the west and south with simulated head altitudes below −5 ft. The simulated potentiometric contour map for 2000 in the LFA (layer 11) indicates groundwater-flow patterns similar to those in the UFA, with a cone of depression influenced by pumping in the overlying layers in the Chatham County area (fig. 14*F*).

2004 Conditions

Simulated potentiometric surfaces of the Brunswick aquifer system (layers 3 and 5) for 2004 (fig. 16*A*–*B*) indicate groundwater flow from upland areas to the west toward the cone of depression in the Savannah area created by pumping in the underlying UFA. Another groundwater-flow direction parallels the coast from the Brunswick/Glynn County area northward toward the Savannah area. Simulated potentiometric surface maps of the UFA (layers 7 and 9) for 2004 show steep potentiometric gradients in the upland areas north and west of the Gulf Trough, with coastward groundwater flow (fig. 16*C*–*D*). Groundwater-flow directions are influenced by a cone of depression centered in the Savannah area that alters the coastward flow pattern. The broad area of influence for this cone of depression is evident by the 0-ft contour, which extends to an area of pumping to the southwest near Jesup, Ga., and north into Jasper and Beaufort Counties, S.C. Simulated potentiometric contours in the Savannah area show water-level altitudes below −60 ft in layer 7 and below −80 ft in layer 9, respectively. In the Brunswick/Glynn County area, potentiometric contours indicate groundwater flow from west to east, with a cone of depression near downtown Brunswick locally altering the coastward flow pattern (fig. 16*E*–*F*). The cone of depression near the active industrial well field intercepts groundwater flow from the west and south, with simulated head altitudes below −5 ft. The simulated potentiometric contour map for 2004 in the LFA (layer 11) indicates groundwater-flow patterns similar to those in the UFA with a cone of depression influenced by pumping in the overlying layers in the Chatham County area (fig. 16*G*).

Simulated Water-Level Changes, 2000–04

Steady-state simulations for 2000 and 2004 were compared for the regional model area by computing water-level changes, which indicated water-level rises because of a decrease in pumpage from 2000 to 2004. Changes in simulated groundwater levels for the Brunswick aquifer system (layers 3 and 5) were influenced by changes in pumping rates from 2000 to 2004. Simulated water levels (and changes) indicate water-level rises in Glynn County, corresponding to a decrease in pumpage during this period, with the exception of the Brunswick aquifer system (layers 3 and 5), which had an increase in pumping rates from 2000 to 2004 and resulted in a concurrent decrease in water levels. Simulated water levels and changes for 2000 and 2004 agree with water-level increases documented in continuous recording wells 33H133, 33H127, 34H436, and 33H188 (fig. 17). Simulated water levels and changes in well 34H437 for 2000 and 2004 indicated a decrease of 3.30 ft, while continuous water-level data indicated an increase of 3.04 ft.

Simulated water-levels declined from 2000 to 2004 in the Brunswick aquifer system (layers 3 and 5) in the Brunswick/Glynn County area in response to increased pumpage. During this period, water levels declined more than 10 ft near activated Golden Isles public-supply wells in northern Glynn County. Water-levels declined more than 5 ft near new golf-course irrigation wells on Jekyll Island in Glynn County (fig. 18*A*–*B*). These wells contributed to a 6-fold increase in combined pumpage from the Brunswick aquifer system (layers 3 and 5) during this period, from 0.24 Mgal/d in 2000 to 1.75 Mgal/d in 2004.

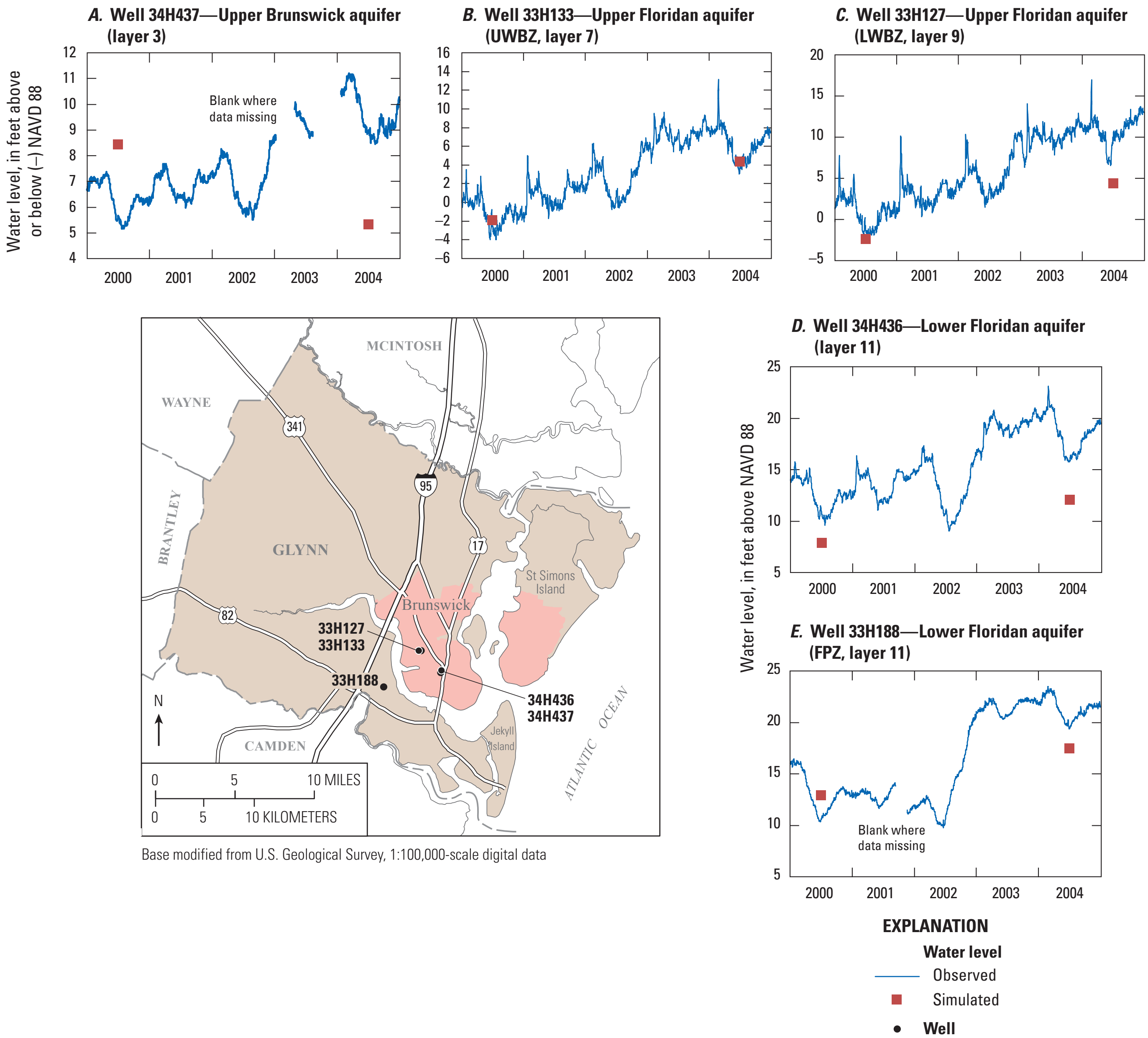


Figure 17. Hydrographs showing selected water-levels and simulated heads for *A*, upper Brunswick aquifer; *B*, Upper Floridan aquifer upper water-bearing zone (UWBZ); *C*, Upper Floridan aquifer lower water-bearing zone (LWBZ); *D*, Lower Floridan aquifer; and *E*, Lower Floridan aquifer Fernandina permeable zone (FPZ), Glynn County, Georgia, 2000–2004.

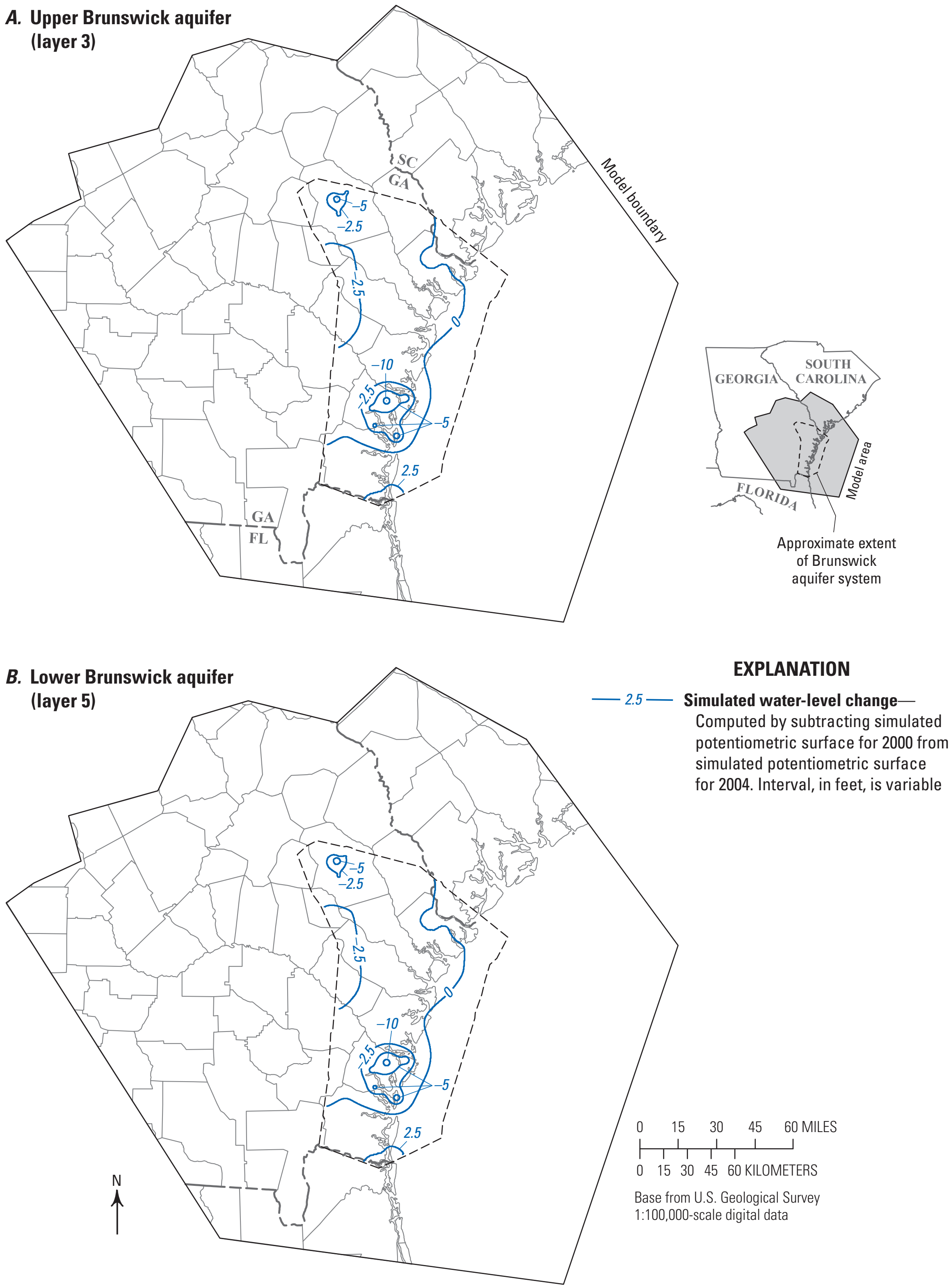


Figure 18. Simulated water-level change from 2000 to 2004 for *A*, model layer 3, upper Brunswick aquifer, *B*, model layer 5, lower Brunswick aquifer, *C*, upper water-bearing zone of Upper Floridan aquifer, *D*, lower water-bearing zone of Upper Floridan aquifer, and *E*, Lower Floridan aquifer.

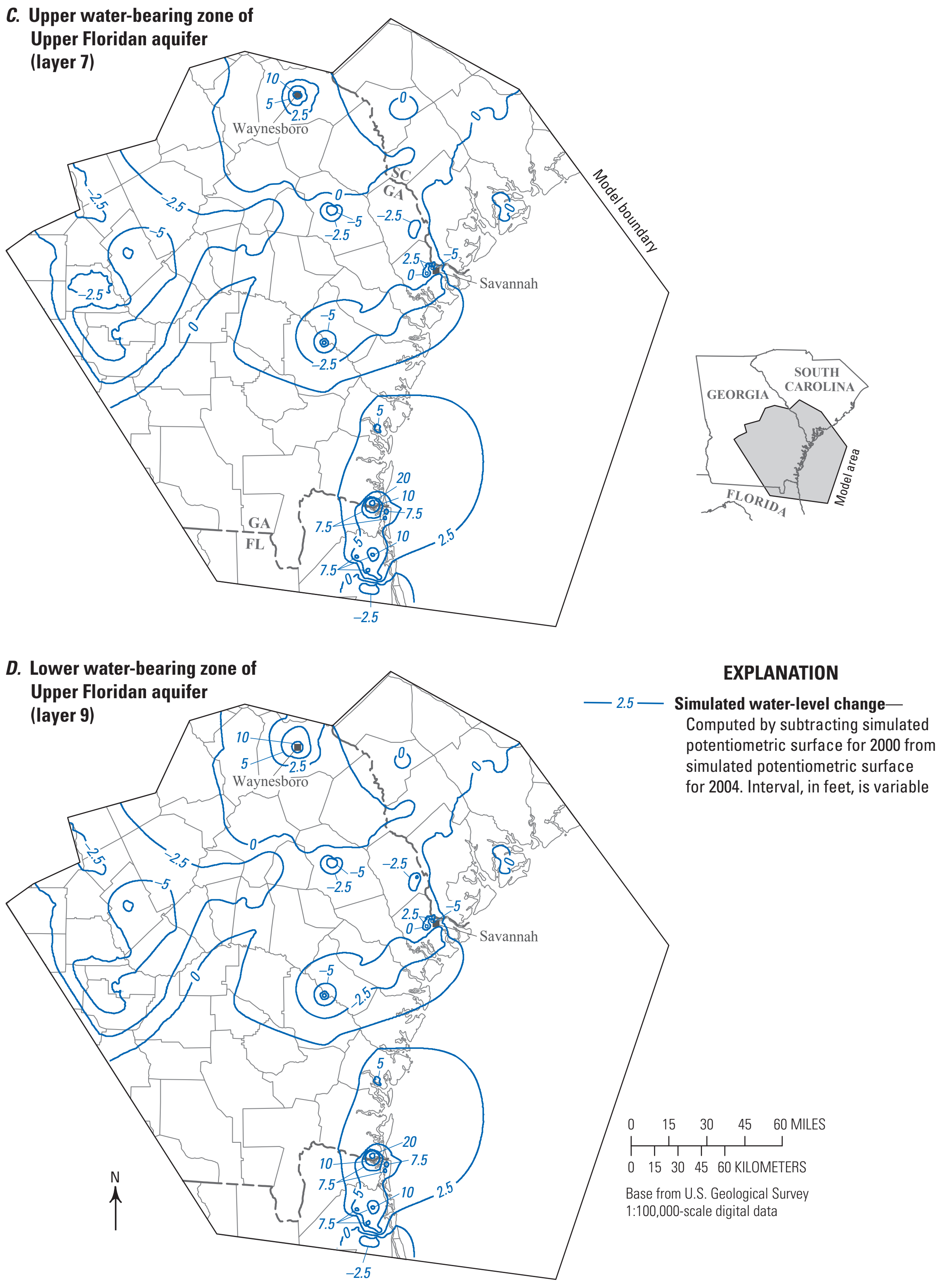


Figure 18. Simulated water-level change from 2000 to 2004 for *A*, model layer 3, upper Brunswick aquifer, *B*, model layer 5, lower Brunswick aquifer, *C*, upper water-bearing zone of Upper Floridan aquifer, *D*, lower water-bearing zone of Upper Floridan aquifer, and *E*, Lower Floridan aquifer.—Continued

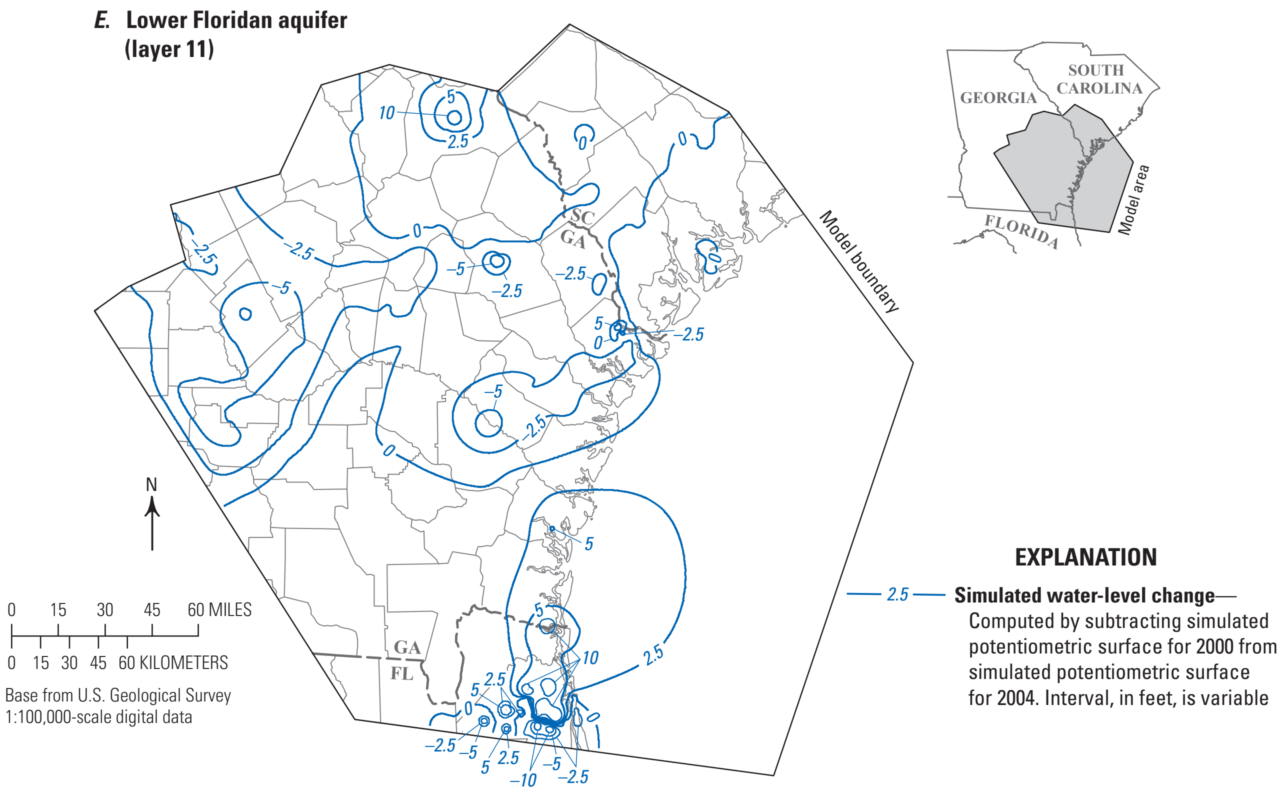


Figure 18. Simulated water-level change from 2000 to 2004 for *A*, model layer 3, upper Brunswick aquifer, *B*, model layer 5, lower Brunswick aquifer, *C*, upper water-bearing zone of Upper Floridan aquifer, *D*, lower water-bearing zone of Upper Floridan aquifer, and *E*, Lower Floridan aquifer.—Continued

Simulated water-level changes from 2000 to 2004 in the UFA (layers 7 and 9) were influenced by decreases in pumpage caused by the shutdown of the Durango Paper Company mill near St. Marys and local decreases in pumping rates near the cities of Savannah in Chatham County, Ga., and Waynesboro in Burke County, Ga. (fig. 18*C–D*). Closure of the Durango Paper Company mill corresponded with a 35.5 Mgal/d decrease in pumping rates in the UFA that, when simulated, caused more than 20 ft of groundwater-level rise near the pumping center and smaller water-level rises in the southern coastal area of Georgia ranging from 2.5 to more than 7.5 ft.

In Glynn County, simulated water-level increases in the UFA (layers 7 and 9) were caused by decreases in pumping rates represented in the steady-state models from 2000 to 2004. Simulated groundwater-level increases generally ranged between 2.5 and 5 ft, with the greatest simulated increase occurring near downtown Brunswick. Decreases in pumping rates in the UFA from 61 Mgal/d during 2000 to 53.8 Mgal/d during 2004, represented in the models, contributed to the rises in simulated water levels. Decreases in simulated pumping rates that correspond with pumpage decline near the city of Savannah caused localized simulated rises in water levels of up to 2.5 ft.

A similar decrease in pumping rates occurred in the UFA near Waynesboro in Burke County as in Savannah, discussed above; however, a corresponding simulated water-level rise of more than 10 ft resulted from this simulated pumpage reduction (fig. 18*C–D*). Inspection of hydraulic properties associated with both locations indicated that the lower hydraulic conductivity near Waynesboro, relative to Savannah, would elicit a larger groundwater-level response to pumpage there than in Savannah.

Simulated pumpage reductions corresponding to the shutdown of the Durango Paper Company mill had a similar effect on simulated water levels in the LFA (layer 11; fig. 18*E*) as on the UFA (fig. 18*C–D*). Simulated water-level rises of more than 10 ft occurred near the center of pumping, with the 2.5-ft contour extending through the central part of Glynn County. The simulated water-level rises in the LFA near the cities of Savannah and Waynesboro indicate that simulated groundwater levels responded to simulated pumpage reductions in the UFA (layers 7 and 9), indicating a strong hydraulic connection between the UFA and LFA.

Simulated Potentiometric Profiles

Simulated potentiometric profiles were constructed for 2000 and 2004 to evaluate hydraulic gradients in the UWBZ of the UFA (layer 7) near the chloride plume and the cone of depression caused by production wells in the area (figs. 19 and 20). The profiles for 2000 and 2004 were selected based on available water-level data and principle groundwater-flow directions within the chloride plume. The principle direction of groundwater flow in the downtown Brunswick area is from south to north, with flow paths toward the northwest near the major well field. Potentiometric gradients determine groundwater-flow direction and rate in addition to influencing the shape and extent of the chloride plume. Potential changes in pumping could alter potentiometric gradients, the direction of groundwater flow, and the shape of the chloride plume. Simulated potentiometric gradients for 2000 were based on four potentiometric profiles (*A*−*D*; fig. 19) constructed using water-level data from 13 observation wells having a collective mean residual of –0.19 ft. Simulated potentiometric gradients from these four profiles ranged from 3.6 to 5.2 feet per mile (ft/mi). Simulated potentiometric gradients for 2004 were based on five potentiometric profiles (*A*−*E*; fig. 20) constructed using water-level data from 18 observation wells having a collective mean residual of –0.18 ft. Simulated potentiometric gradients from these five profiles ranged from 4.3 to 11.1 ft/mi.

Simulated potentiometric gradients for 2000 approximated observed gradients in the four potentiometric profiles (*A*−*D*) constructed in close proximity to the chloride plume. In potentiometric profile *A*, simulated water levels were about 1 ft higher than observed water levels, with the simulated potentiometric gradient of 4.3 ft/mi, similar to the observed gradient of 4.5 ft/mi (fig. 19; table 7). In potentiometric profile *B*, the simulated potentiometric gradient of 5.2 ft/mi nearly matched the observed gradient of 5.6 ft/mi. Well 33H130, used to construct potentiometric profile *B*, represents the observation well located closest to the cone of depression caused by pumping, with a simulated water level of –4.10 ft and an observed water level of –4.59 ft. In potentiometric profile *C,* simulated water levels were slightly higher than observed water levels, but potentiometric gradients were similar with a simulated value of 4.4 ft/mi and observed value of 5.3 ft/mi. Potentiometric profile *C* covers an area where groundwater flow shifts to a northwesterly direction toward a major well field, as indicated by the potentiometric contours shown in figure 14. Potentiometric profile *D* consists of nine wells oriented parallel to a primary groundwater-flow direction from south to north toward industrial production wells. The water levels in potentiometric profile *D* illustrate the difficulty in matching observed and simulated values because of the apparent water-level fluctuations evident in wells 34H373 and 34H355. However, the plotted simulated and observed water levels indicate a reasonable match with a simulated potentiometric gradient of 3.6 ft/mi compared to an observed gradient of 4.1 ft/mi.

Table 7. Simulated and observed groundwater levels for 2000, and residuals in wells used to construct profiles in the Brunswick area.

[NAVD 88, North American Vertical Datum of 1988; —, not available; residual equals simulated minus observed water level; hydraulic gradients calculated using simulated heads at the endpoints of profiles; see figure 19 for location of profiles]

Well identifier	Profile(s)	2000 water level, in feet above or below (–) NAVD 88		Residual, in feet	Simulated potentiometric gradient, in feet per mile
		Simulated	Observed		
33H120	*A*	–1.69	–2.99	1.30	—
34H392	*A*	4.23	3.33	0.90	4.3 (A)
33H130	*B*	–4.10	–4.59	0.49	—
34H424	*B, D*	1.13	1.04	0.09	5.2 (B)
33H133	*C*	–1.51	–0.89	–0.62	—
34H355	*C, D*	2.46	3.88	–1.42	4.4 (C)
34H373	*D*	1.93	–1.07	3.00	—
34H125	*D*	4.10	4.45	–0.35	—
34H117	*D*	4.87	4.54	0.33	—
34H112	*D*	5.86	6.62	–0.76	—
34H393	*D*	7.27	8.53	–1.26	—
34H371	*D*	7.97	10.80	–2.83	—
34H097	*D*	10.40	11.80	–1.40	3.6 (D)

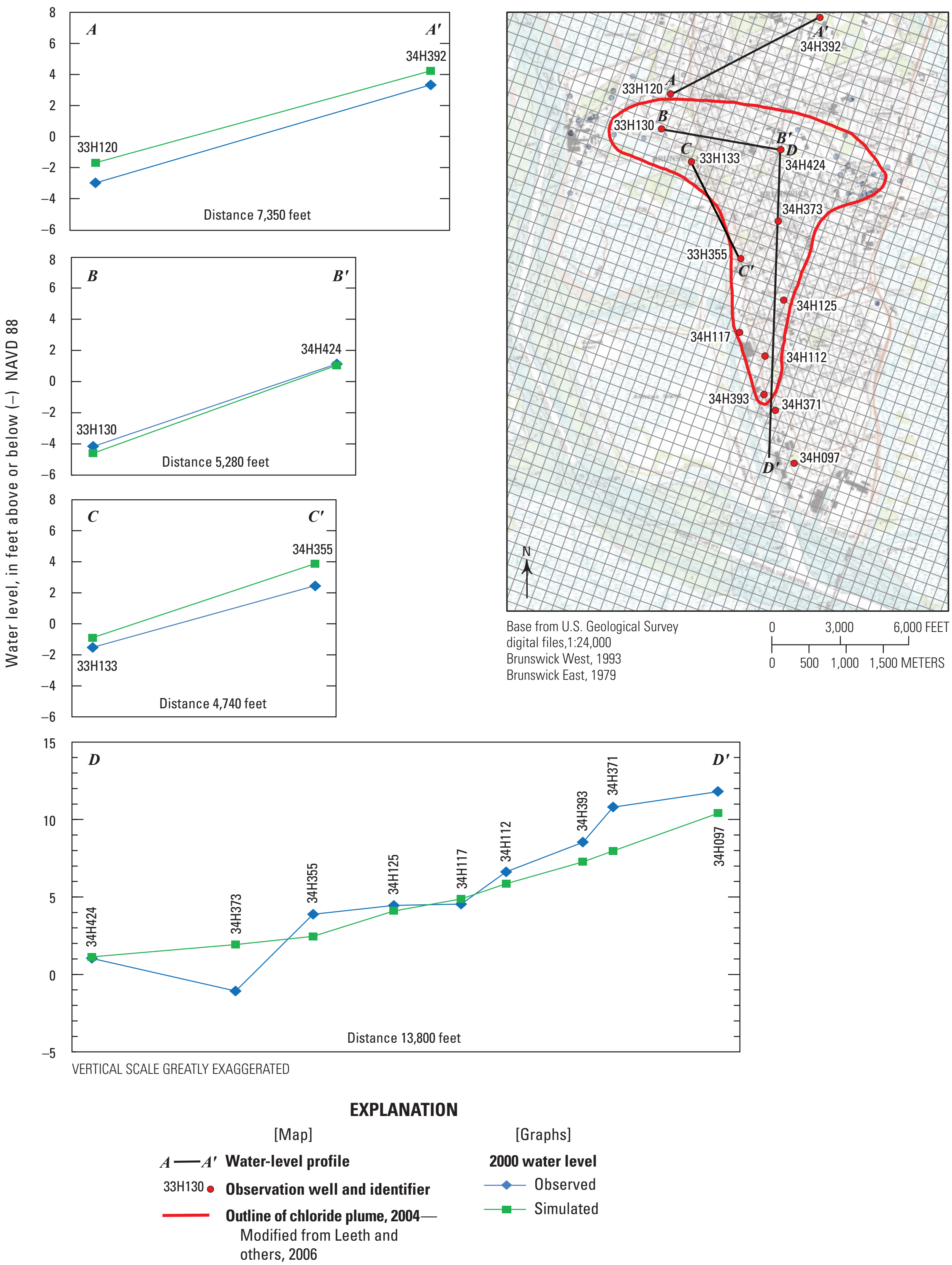


Figure 19. Simulated and observed potentiometric profiles near chloride plume during 2000.

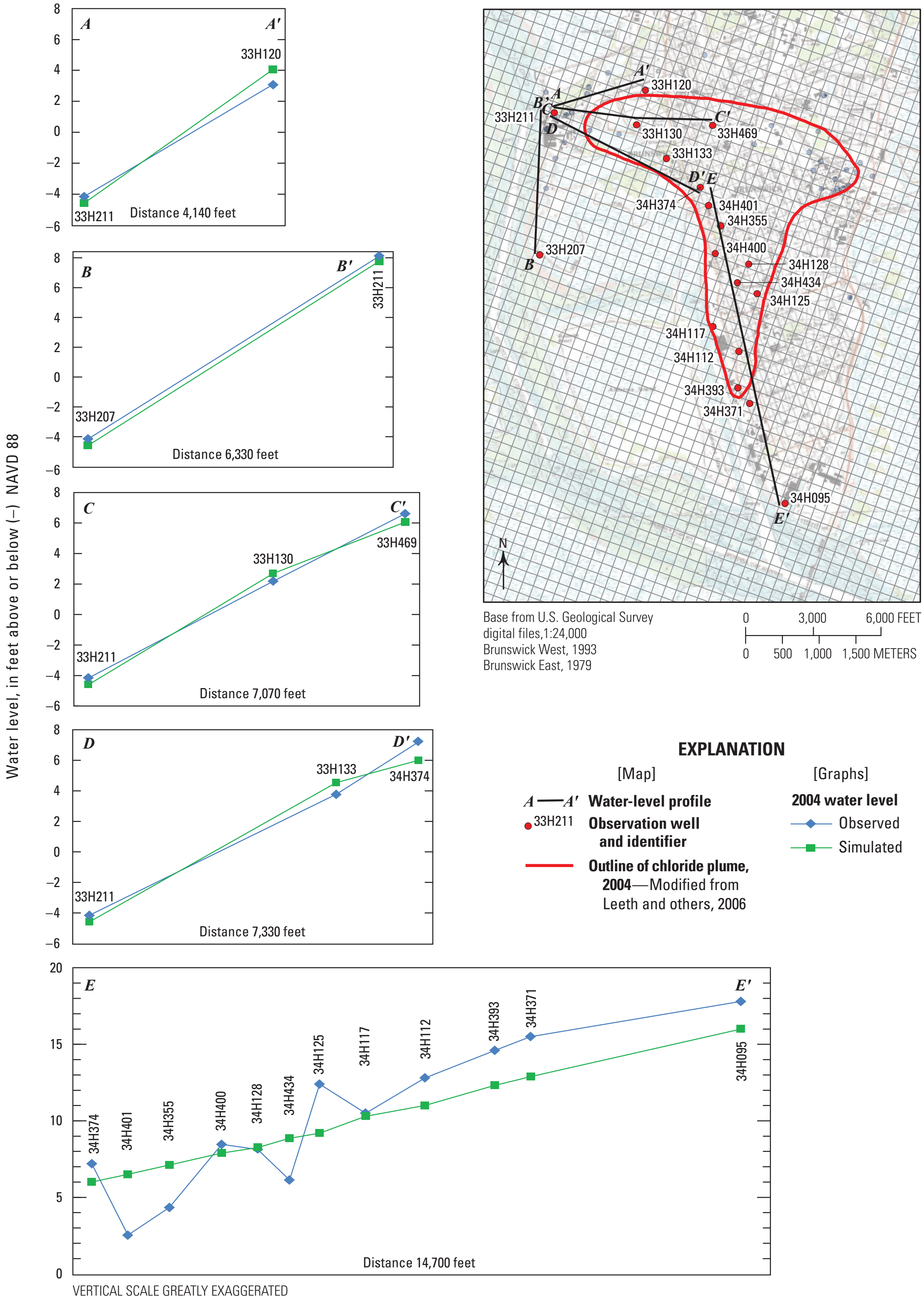


Figure 20. Simulated and observed potentiometric profiles near chloride plume during 2004.

Simulated potentiometric gradients for 2004 approximated observed gradients in the five potentiometric profiles (*A−E*) constructed in close proximity to the chloride plume. The potentiometric profiles for 2000 and 2004 differed slightly because the availability of observation water-level data differed between years (figs. 19 and 20; tables 7 and 8). In addition, water-level data available for well 33H211 allowed the 2004 potentiometric profiles to be constructed in close proximity to a major industrial well field. Consequently, simulated potentiometric gradients for 2004 were higher than the gradients for 2000. In potentiometric profile *A*, simulated water levels were lower than observed water levels in well 33H211 and higher than observed water levels in well 33H120, and have a simulated potentiometric gradient of 11.0 ft/mi, higher than the observed gradient of 9.2 ft/mi (fig. 20; table 8). In potentiometric profile *B*, simulated water levels nearly matched observed values and have a simulated potentiometric gradient of 11.1 ft/mi and an observed gradient of 10.2 ft/mi. In potentiometric profile *C,* simulated water levels were higher than observed water levels in well 33H130 and lower than observed values in wells 33H211 and 33H469 and have a simulated potentiometric gradient of 7.9 ft/mi compared to an observed gradient of 8.0 ft/mi. In potentiometric profile *D,* residuals in wells 33H211 and 33H133 of –0.43 and 0.77 ft, respectively, indicate a reasonable match over this part of the potentiometric profile, with a residual of –1.20 ft at the endpoint in well 34H374. The water levels have a simulated potentiometric gradient of 7.6 ft/mi, slightly lower than the observed gradient of 8.2 ft/mi. Potentiometric profile *E* consisted of 12 wells oriented parallel to a primary groundwater-flow direction from south to north toward industrial production wells. The observed water levels in potentiometric profile *E* show fluctuations of nearly 5 ft over the northern part of the profile without any apparent influence by localized pumping. Potentiometric profile *E* shows observed water levels are higher than simulated values in wells 34H374, 34H400, 34H125, 34H112, 34H393, 34H371, and 34H095, but a comparison of graphed water levels over the entire profile indicates a reasonable match between simulated and observed values. The plotted simulated and observed water levels show a similar trend, with a simulated potentiometric gradient of 3.6 ft/mi and an observed gradient of 3.8 ft/mi.

Table 8. Simulated and observed groundwater levels for 2004, and residuals in wells used to construct profiles in the Brunswick area.

[NAVD 88, North American Vertical Datum of 1988; —, not available; residual equals simulated minus observed water level; hydraulic gradients calculated using simulated heads at the endpoints of profiles; see figure 20 for location of profiles]

Well identifier	Profile(s)	2004 water level, in feet above NAVD 88		Residual, in feet	Simulated potentiometric gradient, in feet per mile
		Simulated	Observed		
33H211	*A, B, C, D*	–4.59	–4.16	–0.43	—
33H120	*A*	4.05	3.08	0.97	11.0 (A)
33H207	*B*	7.76	8.09	–0.33	11.1 (B)
33H130	*C*	2.69	2.18	0.51	—
33H469	*C*	6.05	6.61	–0.56	7.9 (C)
33H133	*D*	4.54	3.77	0.77	—
34H374	*D, E*	6.00	7.20	–1.20	7.4 (D)
34H401	*E*	6.51	2.53	3.98	—
34H400	*E*	7.12	4.34	2.78	—
34H355	*E*	7.90	8.46	–0.56	—
34H128	*E*	8.26	8.13	0.13	—
34H434	*E*	8.86	6.13	2.73	—
34H125	*E*	9.20	12.40	–3.20	—
34H117	*E*	10.30	10.50	–0.20	—
34H112	*E*	11.04	12.90	–1.86	—
34H393	*E*	12.32	14.60	–2.28	—
34H371	*E*	12.89	15.50	–2.61	—
34H095	*E*	15.99	17.90	–1.91	4.3 (E)

Simulated Water Budget

The simulated 2000 and 2004 water budgets consist of the following major components of inflow and outflow to the groundwater-flow system: (1) inflow from the general-head boundaries, (2) inflow across lateral specified-head boundaries, (3) outflow to the general-head boundary, (4) discharge to wells, and (5) outflow across lateral specified-head boundaries. The 2000 and 2004 flows were characterized using the MODFLOW postprocessor ZONEBUDGET (Harbaugh, 1990). Flow calculations were summarized by model layer and by zone within each layer. Some zones were established to account for inflow and outflow across specified- and general-head boundaries, flow between the layers, and flow along the coastline in a manner described by Payne and others (2005).

The entire simulated groundwater inflow to the model area for 2000 totaled 1,730 Mgal/d, of which 28.3 percent (489 Mgal/d) constituted inflow from the general-head boundaries and 71.7 percent (1,241 Mgal/d) represented inflow from lateral specified-head boundaries in model layers 7, 8, 9, and 11 (table 9; fig. 21*A*). Simulated groundwater outflow totaled 1,730 Mgal/d, of which 3.9 percent (67.1 Mgal/d) represented groundwater outflow to the general-head boundaries, and another 49.2 percent (852 Mgal/d) constituted outflow at lateral specified-head boundaries. Simulated discharge to wells totaled 811 Mgal/d, or 46.9 percent of outflow, and was divided among the Brunswick aquifer system (layers 3 and 5; 0.24 Mgal/d), the UWBZ and LWBZ of the UFA (layers 7 and 9; 679 Mgal/d), and the LFA (layer 11; 131 Mgal/d). Net inflow to the model area along lateral specified-head boundaries totaled about 370 Mgal/d for the UFA (layers 7–9) and 18.6 Mgal/d for the LFA (table 9; fig. 21*A*).

Simulated inflow to the model for 2004 totaled 1,540 Mgal/d, and was divided between general-head boundaries (470 Mgal/d, or 30.5 percent), and lateral specified-head boundaries in layers 7, 8, 9, and 11 (1,070 Mgal/d, or 69.5 percent) (table 9; fig. 21*B*). Outflow from the model totaled 1,540 Mgal/d, of which 4.8 percent (74.2 Mgal/d) represented groundwater outflow to the general-head boundaries, and another 47.6 percent (733 Mgal/d) was attributed to outflow at lateral specified-head boundaries. The remaining 47.6 percent (733 Mgal/d) represented simulated discharge to wells from the Brunswick aquifer system (layers 3 and 5; 1.75 Mgal/d), the UWBZ and LWBZ of the UFA (layers 7 and 9; 619 Mgal/d), and the LFA (layer 11; 112 Mgal/d). Net inflow along lateral specified-head boundaries totaled about 315 Mgal/d into the UFA (layers 7–9), and 22.1 Mgal/d into the LFA (table 9; fig. 21*B*).

A comparison of the major components for 2000 and 2004 indicates higher inflow values through the general-head boundary in layer 1 for the 2000 simulation. The 78-Mgal/d greater pumping rate during 2000, relative to 2004 induced an additional 19.3 Mgal/d of inflow through the general-head boundaries in layers 1, 2, and 7, and an additional 171 Mgal/d of inflow to the model through the specified-head boundary in layers 7, 8, 9, and 11 when compared to the 2004 budget. The comparison between the simulated water budgets for 2000 and 2004 indicates increased inflows in the UFA along the southern specified-head boundary. According to Payne and others (2005), these inflows are reasonable because the UFA extends far beyond this specified-head boundary throughout Florida (Miller, 1986) and potentially could contribute groundwater into the modeled area. The resulting inflows along this boundary decreased from 1,241 Mgal/d during 2000 to 1,070 Mgal/d for the 2004 simulation, which subdivided the UFA (layer 5) into the UWBZ and LWBZ (layers 7 and 9) and the intervening confining unit (layer 8).

An analysis similar to that described for general head-boundaries in the Brunswick/Glynn County area indicated that specified-head boundaries adjacent to Glynn County are located sufficiently far from the pumping centers to yield a significant contribution to the water budget (fig. 21*C*–*D*; table 10). In the Brunswick/Glynn County area, simulated pumping totaled 60.9 Mgal/d during 2000 and 55.2 Mgal/d during 2004. Outflows to the general-head boundary in model layer 1 of 4.0 and 5.8 Mgal/d (for 2000 and 2004 simulated conditions, respectively) exceeded inflows of 0.35 and 0.21 Mgal/d, respectively, along the same boundary.

Table 9. Flow-budget components for 2000 and 2004 for entire model area.

[Results from MODFLOW model; all values in million gallons per day; —, not applicable]

Model unit	From general-head boundary, onshore	From general-head boundary, offshore	From specified-head boundary	Total	To general-head boundary, onshore	To general-head boundary, offshore	To specified-head boundary	Discharge to wells	Total
	2000 inflow				2000 outflow				
1	264.00	1.29	—	265.29	33.08	0.54	—	—	33.62
2	77.39	—	—	77.39	8.07	—	—	—	8.07
3	—	—	—	—	—	—	—	0.11	0.11
4	—	—	—	—	—	—	—	—	—
5	—	—	—	—	—	—	—	0.13	0.13
6	—	—	—	—	—	—	—	—	—
7	138.20	—	461.53	599.73	21.32	—	323.10	320.31	664.73
8	—	—	252.20	252.20	—	—	175.34	—	175.34
9	—	—	500.00	500.00	—	—	344.99	359.11	704.10
10	—	—	0.01	0.01	—	—	—	—	—
11	—	—	27.13	27.13	—	—	8.50	131.49	139.99
Total, all units	**479.59**	**1.29**	**1,240.87**	**1,721.75**	**62.47**	**0.54**	**851.93**	**811.15**	**1,726.09**
Percentage of total flow	**27.9**	**0.1**	**72.1**	**100.0**	**3.6**	**0.03**	**49.4**	**47.0**	**100.0**
	2004 inflow				2004 outflow				
1	237.45	1.68	—	239.13	40.17	0.75	—	—	40.92
2	83.68	—	—	83.68	7.31	—	—	—	7.31
3	—	—	—	—	—	—	—	0.79	0.79
4	—	—	—	—	—	—	—	—	—
5	—	—	—	—	—	—	—	0.96	0.96
6	—	—	—	—	—	—	—	—	—
7	139.29	—	511.91	651.20	20.62	—	424.32	290.17	735.11
8	—	—	58.36	58.36	—	—	32.28	—	32.28
9	—	—	469.93	469.93	—	—	268.56	329.11	597.67
10	—	—	0.01	0.01	—	—	—	—	—
11	—	—	30.02	30.02	—	—	7.91	111.92	119.83
Total, all units	**460.42**	**1.68**	**1,070.23**	**1,532.33**	**68.10**	**0.75**	**733.07**	**732.95**	**1,534.87**
Percentage of total flow	**30.1**	**0.1**	**69.8**	**100.0**	**4.4**	**0.04**	**47.8**	**47.8**	**100.0**

Table 10. Flow-budget components for 2000 and 2004 in the Brunswick/Glynn County area.

[Results from MODFLOW model; all values in million gallons per day; —, not applicable]

Model unit	From general-head boundary, onshore	Across county boundaries	Total	To general-head boundary, onshore	Across county boundaries	Discharge to wells	Total
	2000 inflow			2000 outflow			
1	0.35	4.89	5.24	3.96	1.59	—	5.55
2	—	—	—	—	—	—	—
3	—	0.14	0.14	—	0.07	0.05	0.12
4	—	—	—	—	—	—	—
5	—	0.35	0.35	—	0.18	0.06	0.24
6	—	—	—	—	—	—	—
7	—	42.51	42.51	—	15.34	24.32	39.66
8	—	0.26	0.26	—	2.25	—	2.25
9	—	50.10	50.10	—	16.57	36.46	53.03
10	—	—	—	—	—	—	—
11	—	4.21	4.21	—	1.96	0.00	1.96
Total, all units	**0.35**	**102.46**	**102.81**	**3.96**	**37.96**	**60.89**	**102.81**
Percentage of total flow	**0.3**	**99.7**	**100.0**	**3.9**	**36.9**	**59.2**	**100.0**
	2004 inflow			2004 outflow			
1	0.21	8.12	8.33	5.80	2.62	—	8.42
2	—	—	—	—	—	—	—
3	—	0.31	0.31	—	0.05	0.64	0.69
4	—	—	—	—	—	—	—
5	—	0.78	0.78	—	0.12	0.81	0.93
6	—	—	—	—	—	—	—
7	—	38.31	38.31	—	14.56	19.64	34.20
8	—	0.02	0.02	—	0.47	—	0.47
9	—	45.19	45.19	—	15.64	34.14	49.78
10	—	—	—	—	—	—	—
11	—	3.84	3.84	—	2.29	0.00	2.29
Total, all units	**0.21**	**96.57**	**96.78**	**5.80**	**35.75**	**55.23**	**96.78**
Percentage of total flow	**0.2**	**99.8**	**100.0**	**6.0**	**36.9**	**57.1**	**100.0**

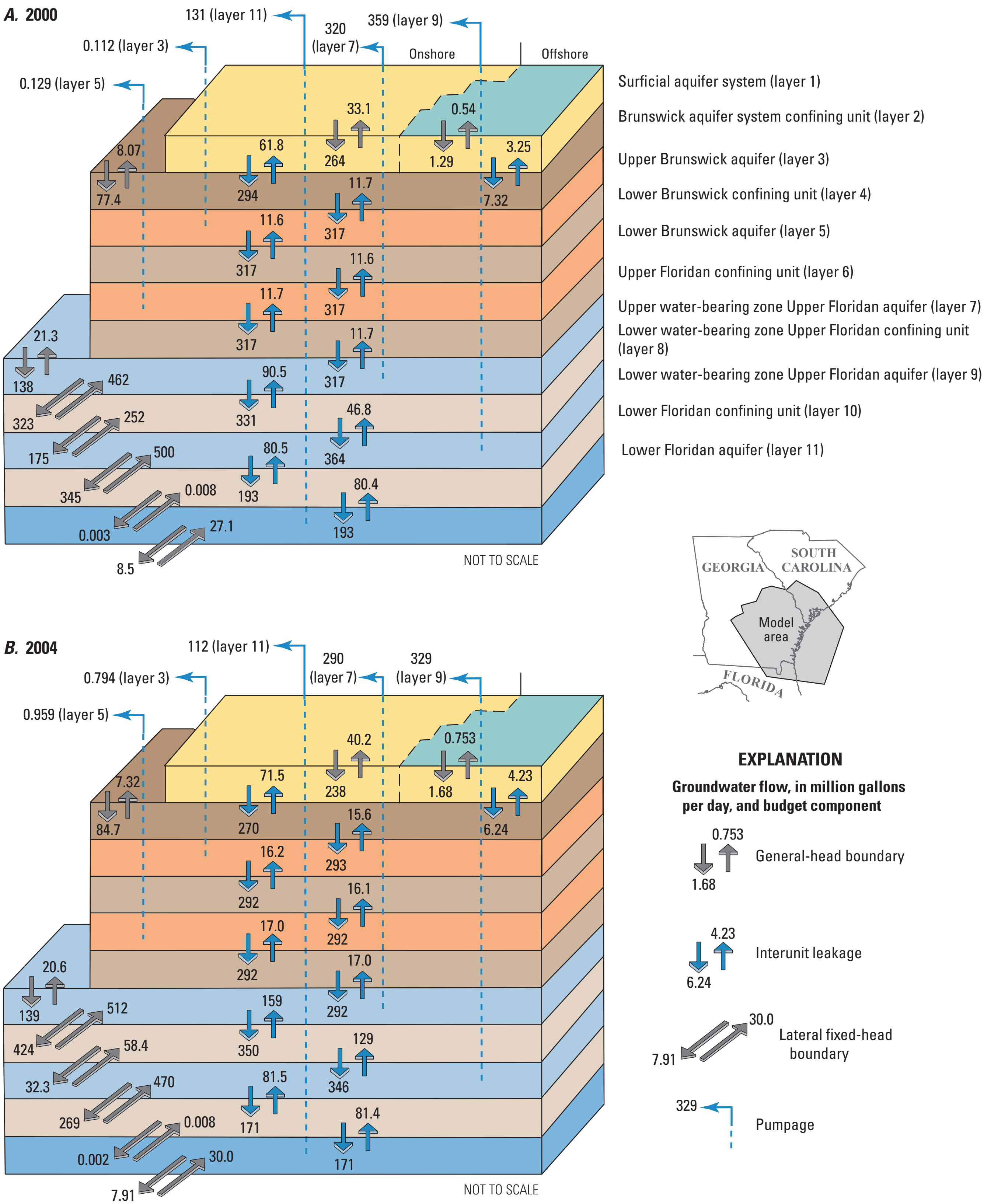


Figure 21. Schematic diagram showing simulated water budget for regional model during *A*, 2000 and *B*, 2004, and water budgets in Glynn County during *C*, 2000 and *D*, 2004.

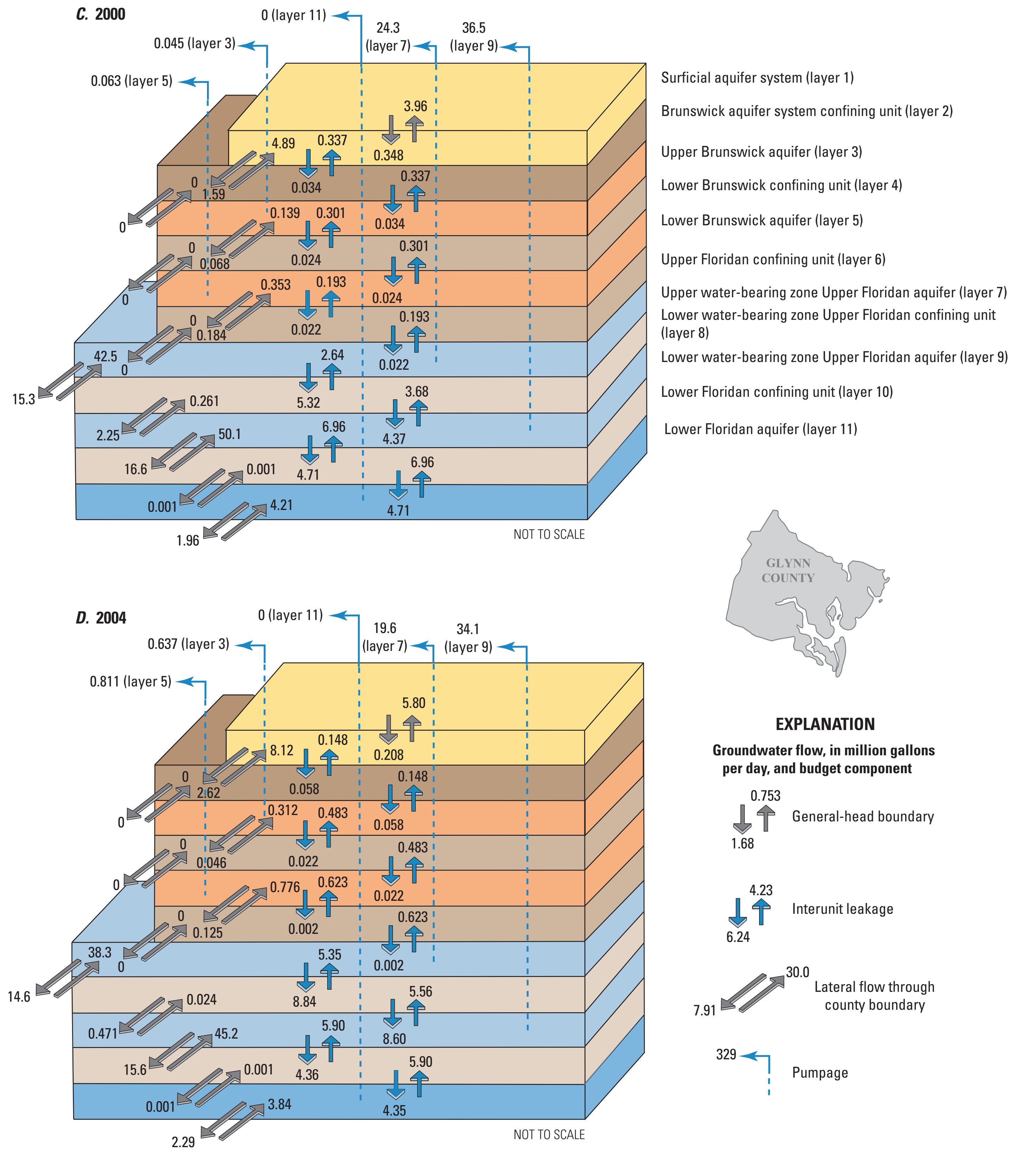


Figure 21. Schematic diagram showing simulated water budget for regional model during *A*, 2000 and *B*, 2004, and water budgets in Glynn County during *C*, 2000 and *D*, 2004.—Continued

Model Sensitivity

The sensitivity of the calibrated revised steady-state model was evaluated to determine the relative importance of introduced hydraulic conductivity parameters in the Brunswick/Glynn County area. The original model used the perturbation method to examine model sensitivity to pumping and to the specified-head boundary condition along the southern boundary (Payne and others, 2005). The composite-scaled sensitivity analysis for the original model indicated high sensitivity to pumping rates. Therefore, 2000 pumping rates were increased by 10 percent and the resulting changes in simulated heads and flow rates were documented. The specified-head boundary along the southern edge of the original model was increased by 10 ft and the resulting rise in simulated water levels mapped. Published maps indicate increases in simulated water levels in the Brunswick/Glynn County area of about 8 ft. The results of the 10-percent increase in 2000 pumping rates indicate simulated water-level decreases ranging between 2 and 6 ft in the Brunswick/Glynn County area. These perturbations were not repeated for the revised model because of similarities in model construction, and the reader is referred to Payne and others (2005) for full details of this analysis.

The current study focused on the composite-scaled sensitivity analysis of the revised model in the Brunswick/Glynn County area. Composite-scaled sensitivities for comparable parameters are calculated using the sensitivity equation described in MODFLOW–2000 (Hill and others, 2000), and as described in Hill (1998), composite-scaled sensitivity is a dimensionless measure of the change in calculated head with respect to the value of a parameter. The resulting sensitivities are independent of the actual values of the observations. A large composite-scaled sensitivity indicates a relatively high sensitivity of the model to changes in a given parameter, whereas a small composite-scaled sensitivity indicates low model sensitivity to such changes. Composite-scaled sensitivities were used to evaluate the relative sensitivities of the model to pumping rate, vertical and horizontal hydraulic conductivity, and the conductance of the general-head boundary.

Composite-scaled sensitivities for parameters in both the 2000 and 2004 simulations indicate that the model is approximately 5.2 and 4.5 times more sensitive to pumping rate (wells) for both years than to the parameter with the next highest composite-scaled sensitivity (fig. 22). Although the model is more sensitive to the horizontal hydraulic conductivity of the UFA (layers 7, 8, and 9) than to several vertical hydraulic conductivities (CU5Kv, CU1Kv, CU3Kv, and CU2Kv), composite-scale sensitivities (which range from 0.17 to 2.2) are about an order of magnitude or two less than the parameter with the highest composite-scaled sensitivity, wells. The other parameters representing vertical hydraulic conductivities in the aquifers (layers 3, 5, 7, 9, and 11) and horizontal hydraulic conductivities of the confining units (layers 2, 4, 6, 8, and 10) yielded negligible composite-scale sensitivities and are not included in figure 22. The horizontal hydraulic conductivity parameters having the highest composite-scaled sensitivity represented zones south of the Gulf Trough (UF4Kh, UF6Kh, UF5Kh, UF8Kh, UF12Kh, and UF7Kh).

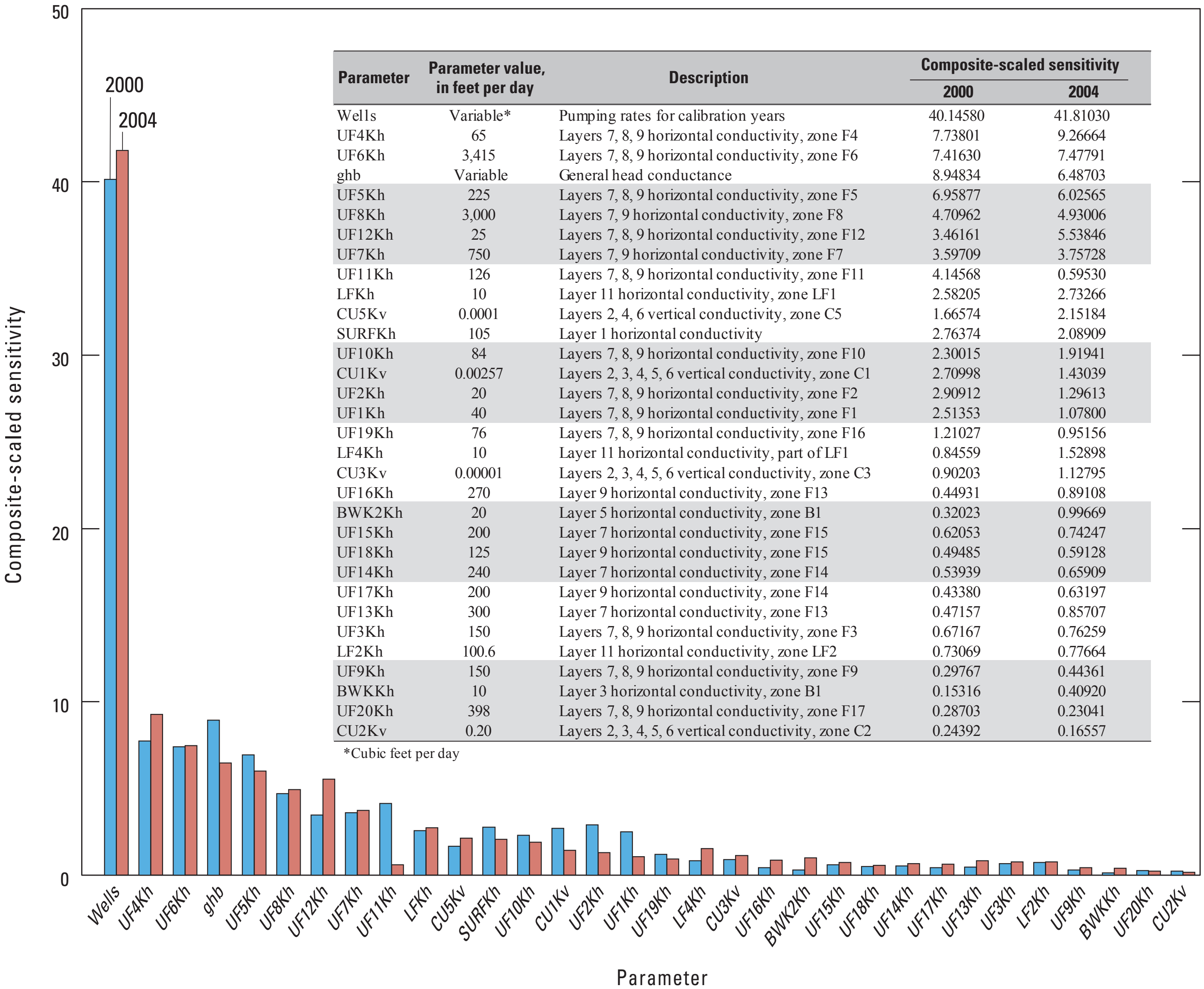
Parameters created for the revised model to subdivide the UWBZ and LWBZ of the UFA in the Brunswick/Glynn County area yielded composite-scaled sensitivities near or below one (UF16Kh, UF15Kh, UF18Kh, UF14Kh, UF17Kh, and UF13Kh, fig. 22). The calculated composite-scaled sensitivities varied between the 2000 and 2004 simulations, with the 2000 simulation having greater values (ghb, UF11Kh, SURFKh, CU1Kv, UF2Kh, and UF1Kh).

Model Limitations

The original model was constructed to simulate groundwater flow in the Floridan aquifer system, which encompasses parts of Georgia, South Carolina, Alabama, and all of Florida. The spatial representation of hydrogeologic units and discretization of these subsurface units into model layers generalize and simplify the subsurface and areal details of aquifer geometry, which imposes limitations on model accuracy. For example, the location of specified-head boundaries in the Floridan aquifer system permits groundwater to enter the model area near the Florida-Georgia State Line but does not allow groundwater levels to change along this boundary in response to pumping in the Brunswick/Glynn County area, located a few miles north of the state line.

The results obtained from steady-state simulations using the revised model developed for the Brunswick/Glynn County area are subject to uncertainty and errors inherent to the numerical approximation of the groundwater flow equation by finite-difference methods (Remson and others, 1971), and to the same limitations of model application inherent with discretization and sparse subsurface data as those documented in the original model (Payne and others, 2005).

All groundwater models represent a simplification of a complex natural physical system and undoubtedly limit its representation with incomplete information derived from sparse point data to define continuous subsurface phenomena at discrete locations. The use of a coarse finite-difference grid in the upland regions of the study area limits model representation of the geometry of the physical extent of aquifers and confining units. Because these upland regions are located far from the areas of interest containing pumpage, the effect of this limitation on the computed solution of hydraulic head is minimal. The constraint that finite-difference grids adhere to an orthogonal system of discretization limits the ability of the computed solution of hydraulic head to represent curvature or hydraulic gradients in potentiometric surfaces.



Parameter	Parameter value, in feet per day	Description	Composite-scaled sensitivity 2000	Composite-scaled sensitivity 2004
Wells	Variable*	Pumping rates for calibration years	40.14580	41.81030
UF4Kh	65	Layers 7, 8, 9 horizontal conductivity, zone F4	7.73801	9.26664
UF6Kh	3,415	Layers 7, 8, 9 horizontal conductivity, zone F6	7.41630	7.47791
ghb	Variable	General head conductance	8.94834	6.48703
UF5Kh	225	Layers 7, 8, 9 horizontal conductivity, zone F5	6.95877	6.02565
UF8Kh	3,000	Layers 7, 9 horizontal conductivity, zone F8	4.70962	4.93006
UF12Kh	25	Layers 7, 8, 9 horizontal conductivity, zone F12	3.46161	5.53846
UF7Kh	750	Layers 7, 9 horizontal conductivity, zone F7	3.59709	3.75728
UF11Kh	126	Layers 7, 8, 9 horizontal conductivity, zone F11	4.14568	0.59530
LFKh	10	Layer 11 horizontal conductivity, zone LF1	2.58205	2.73266
CU5Kv	0.0001	Layers 2, 4, 6 vertical conductivity, zone C5	1.66574	2.15184
SURFKh	105	Layer 1 horizontal conductivity	2.76374	2.08909
UF10Kh	84	Layers 7, 8, 9 horizontal conductivity, zone F10	2.30015	1.91941
CU1Kv	0.00257	Layers 2, 3, 4, 5, 6 vertical conductivity, zone C1	2.70998	1.43039
UF2Kh	20	Layers 7, 8, 9 horizontal conductivity, zone F2	2.90912	1.29613
UF1Kh	40	Layers 7, 8, 9 horizontal conductivity, zone F1	2.51353	1.07800
UF19Kh	76	Layers 7, 8, 9 horizontal conductivity, zone F16	1.21027	0.95156
LF4Kh	10	Layer 11 horizontal conductivity, part of LF1	0.84559	1.52898
CU3Kv	0.00001	Layers 2, 3, 4, 5, 6 vertical conductivity, zone C3	0.90203	1.12795
UF16Kh	270	Layer 9 horizontal conductivity, zone F13	0.44931	0.89108
BWK2Kh	20	Layer 5 horizontal conductivity, zone B1	0.32023	0.99669
UF15Kh	200	Layer 7 horizontal conductivity, zone F15	0.62053	0.74247
UF18Kh	125	Layer 9 horizontal conductivity, zone F15	0.49485	0.59128
UF14Kh	240	Layer 7 horizontal conductivity, zone F14	0.53939	0.65909
UF17Kh	200	Layer 9 horizontal conductivity, zone F14	0.43380	0.63197
UF13Kh	300	Layer 7 horizontal conductivity, zone F13	0.47157	0.85707
UF3Kh	150	Layers 7, 8, 9 horizontal conductivity, zone F3	0.67167	0.76259
LF2Kh	100.6	Layer 11 horizontal conductivity, zone LF2	0.73069	0.77664
UF9Kh	150	Layers 7, 8, 9 horizontal conductivity, zone F9	0.29767	0.44361
BWKKh	10	Layer 3 horizontal conductivity, zone B1	0.15316	0.40920
UF20Kh	398	Layers 7, 8, 9 horizontal conductivity, zone F17	0.28703	0.23041
CU2Kv	0.20	Layers 2, 3, 4, 5, 6 vertical conductivity, zone C2	0.24392	0.16557

*Cubic feet per day

Figure 22. Composite-scaled sensitivity of selected model parameters.

The original model discretized the study area into large grid cells on the fringes of the areas of interest, and used small grid cells to focus on providing a detailed simulation of hydraulic head in the areas of interest, namely, in and near the cities of Savannah and Brunswick. Grid cells as small as 4,000 by 5,000 ft were used in areas where detailed simulated groundwater levels were required to be computed with the original model, such discretization provided a computed solution of hydraulic head in the center of the grid cell. This computed value applied to the entire grid cell area, about 0.8 to 1 mi^2, which was inadequate for representing local pumping effects such as drawdown cones and changes in hydraulic gradient. Trial-and-error testing of alternate grid spacing indicated that square grid cells measuring 500 ft per side would provide adequate representation of pumping effects on the potentiometric surfaces in and near pumping centers in the UFA at Savannah and in the Brunswick/Glynn County area. This fine grid spacing was expanded near the City of Savannah, however, to improve computational efficiency of the model, which sacrificed accuracy in the computed solution in Chatham County.

Additional data have become available for the Brunswick aquifer system since the original model was constructed that allowed the upper and lower Brunswick aquifers to be included in the revised model. Most of the new aquifer-test data are from the vicinity of Glynn County, however, and the lateral extent of the system as well as the aquifer properties remain uncertain outside this area. The units are assumed to be continuous but could be isolated in areas because of locally reduced permeabilities and aquifer thinning.

The UFA was represented by layer 5 in the original model and was subdivided in the revised model into the UWBZ, intervening confining unit, and the LWBZ, represented as layers 7 through 9, respectively. The extent of this subdivision was limited to Glynn and Camden Counties, however. Outside these counties, the intervening confining unit was assigned the same hydraulic conductivity as the model layers above and below because the extent of distinct water-bearing zones in the UFA remained uncertain. Water-level data were available from only five wells for the LWBZ of the UFA (layer 9), which provided few points to calibrate simulated water levels against and proved difficult to match in both 2000 and 2004. The pumping distribution was assigned for model layers 7 and 9 in the Brunswick/Glynn County area based on aquifer thickness, but the flowmeter data needed to determine the relative contributions from each of the units were either uncertain or conflicting.

The revised groundwater-flow model was calibrated to hydrologic conditions during September 2000 and June 2004 using steady-state simulations that did not account for temporal variations. Transient simulations would consider small-scale changes and seasonal responses to recharge and pumping but were beyond the scope of this study. Groundwater hydrographs (fig. 6) indicate time-varying water levels, which give rise to time-varying hydraulic gradients and configurations of the potentiometric surface. Pumping rates are not sufficiently constant over time, nor are boundary conditions, to warrant the use of a steady-state model. Storage effects in the aquifer and confining units delay the drawdown response to pumping, and such aquifer and confining unit responses may not be fully realized before the pumping stress changes, which creates another condition to which the aquifer and confining unit would respond through time. The steady-state models of 2000 and 2004 conditions do not represent such time-varying elements of the groundwater-flow system, which severely limits the model's usefulness in comparing computed steady-state solutions of hydraulic head to water levels measured in a non-steady-state aquifer condition.

Boundary conditions play an important role in the calibration of the revised model, but impose a severe limitation on the model's ability to represent the actual aquifer response to pumping. The flow budgets for the 2000 and 2004 steady-state simulations indicate the specified-head boundaries in model layers 7 through 11 account for nearly 70 percent of the inflows (1,240 Mgal/d, year 2000; 1,070 Mgal/d, year 2004) and about 50 percent of the outflows (852 Mgal/d, year 2000; 733 Mgal/d, year 2004). Almost all of the water pumped is derived from either induced inflow or reduced outflow across specified-head boundaries. The general-head boundary in model layers 1, 2, and 5 supplies about 30 percent of the inflows (480 Mgal/d, 2000; 460 Mgal/d, 2004) as simulated recharge, with the amount controlled by a conductance term, but the specified-head boundary can become an unlimited supply of simulated recharge to the groundwater system and can be increased by increasing pumping. The observed head data for 2004 were limited but were used to assign specified-head values along the extent of this boundary. This boundary condition will supply limitless quantities of water in response to pumping and cannot be constrained, such as assigning recharge to specific areas of the model. The inherent assumption is that the specified-head boundary is sufficiently far from the area of primary interest such that cones of depression do not intersect the specified-head boundary during the simulation. The same assumption applies to general-head boundaries.

Pumping uncertainty results from errors in data-collection procedures, errors in reporting, overestimating or underestimating county-wide water use, and uncertainties in the assignment of pumping to model layers. Large discrepancies can exist between site-specific and non-site-specific data, which would assign higher pumping rates to non-site-specific wells and possibly alter input hydraulic-property data to a given area of the model.

Summary

Modifications to the original regional MODFLOW groundwater-flow model of coastal Georgia and adjacent parts of Florida and South Carolina allowed a revised model to be utilized in the evaluation of hydraulic gradients in the Upper Floridan aquifer near downtown Brunswick for 2000 and 2004. Reducing the finite-difference grid spacing in the downtown Brunswick area from the original 4,000×5,000 feet (ft) to 500×500 ft permitted the simulation of hydraulic gradients that closely matched observed hydraulic gradients near a cone of depression resulting from large-scale pumping near active production wells. Modifications to model layering for the revised model consisted of (1) subdividing the Brunswick aquifer system into two aquifer layers (layers 3 and 5) separated by an intervening confining unit (layer 4) and (2) subdividing the Upper Floridan aquifer into upper and lower water-bearing zones with distinct layers (layers 7 and 9) separated by a confining unit (layer 8). Additional hydraulic property zones were established for the Brunswick aquifer system (layers 3–5) and Floridan aquifer system (layers 7–9) based on additional aquifer-test data and hydrogeologic structure. Additional adjustments to hydraulic-property zones improved the match between simulated and observed water levels for 2000 and 2004.

Calibration of the revised model using 2000 pumping rates from the original model indicated a “good” match (±10 ft), with mean residuals (simulated minus observed water level) in each of the active model layers ranging from –4.57 to 5.66 ft, median residuals ranging from –8.62 to 4.67 ft, and root mean square error (RMSE) ranging from 10.9 to 11.4 ft. In the Brunswick/Glynn County area, calibration in the upper water-bearing zone of the Upper Floridan aquifer (layer 7) for 2000 improved with a mean residual of –1.30 ft, median residual of –0.35 ft, and a RMSE of 4.32 ft.

Calibrations of the revised model using of 2004 pumping and boundary conditions indicate a “good’ match (±10 ft), with mean residuals in each active model layer ranging from –5.60 to 1.20 ft, median residuals ranging from –6.31 to –2.05 ft, and a RMSE ranging from 6.95 to 14.5 ft. The match between simulated and observed water levels in the upper water-bearing zone of the Upper Floridan aquifer (layer 7) for 2004 improved from the original model results, with a mean residual of –2.56 ft, median residual of –1.50 ft, and a RMSE of 5.34 ft.

Comparison of simulated water levels from 2000 to 2004 indicate water-level rises, with the exception of the Brunswick aquifer system (layers 3 and 5), where pumpage increases resulted in groundwater-level declines. Simulated water-level changes in the Upper Floridan aquifer ranged from –2.5 to 5 ft in coastal Georgia and exceeded 20 ft near the Georgia-Florida State Line because of pumpage reductions following closure of a nearby paper mill during 2002. In the Brunswick/Glynn County area, the simulated water levels for 2000 and 2004 matched the rising water levels in four continuous recording wells. An increase in simulated pumping during 2004 in the Brunswick aquifer system (layers 3 and 5) resulted in a 3.30-ft decline in simulated water levels from 2000 to 2004 near well 34H437, although observed water levels indicated a rise of 3.04 ft.

Simulated potentiometric profiles for 2000 and 2004 were used to evaluate the potentiometric gradients in the upper water-bearing zone of the Upper Floridan aquifer (layer 7) near the chloride plume and the cone of depression caused by production wells in the area. In the Brunswick area, groundwater-flow directions were consistent for both years, with flow paths oriented from south to north and southeast to northwest close to the cone of depression. For 2000, four potentiometric profiles were constructed and simulated and observed water levels were compared in 13 wells, yielding a mean residual of –0.19 ft. The simulated potentiometric gradients of the four profiles, which ranged from 3.6 to 5.2 feet per mile (ft/mi), were comparable to the observed values, which ranged from 4.1 to 5.6 ft/mi. For 2004, five potentiometric profiles were constructed and simulated and observed water levels were compared in 18 wells, yielding a mean residual of –0.18 ft. The simulated potentiometric gradients of the five profiles, which ranged from 3.6 to 11.1 ft/mi, were comparable to the observed values, which ranged from 3.8 to 10.2 ft/mi. Simulated potentiometric gradients were higher for 2004 than 2000, because four of the 2004 profiles included a well located within the cone of depression near downtown Brunswick.

Composite-scaled sensitivities of key hydrologic parameters indicate that the revised model is most sensitive to changes in pumping rates, and at least an order of magnitude more so than to changes in the horizontal hydraulic conductivity of zones in the Upper Floridan aquifer and the conductance of the general-head boundary. The revised groundwater-flow model is least sensitive to changes in the horizontal hydraulic conductivity of the confining units and the vertical hydraulic conductivity of the aquifers.

The revised model is subject to the limitations documented in the original model associated with the relatively sparse data available to assign parameters to the groundwater-flow system and inaccuracies with numerically representing complex aquifer geometry and curved potentiometric surfaces with an orthogonal-grid-based approximation using finite-different techniques embodied in MODFLOW–2000. The values assigned to specified-head boundaries in the Floridan aquifer system (layers 7–11) have the greatest effect on water inflows to pumping centers in the Brunswick/Glynn County area and are based on sparse data for 2000 and 2004. The flow budgets for 2000 and 2004 indicate the specified-head boundaries in the Floridan aquifer system (layers 7–11) provide nearly 70 percent of the model inflows and about 50 percent of the model outflows. A major limitation of the revised model’s ability to assess the effects of pumpage on the aquifer system and chloride migration hinges on the model’s dependence on flow from specified-head boundaries to supply most of the water to the pumping centers. These boundary conditions regulate changes to hydraulic gradients in response to pumpage changes by supplying limitless quantities of water to satisfy pumping demand.

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Appendix 1

Table 1–1. Simulated and observed groundwater levels, 2000 and 2004.

[Simulated and observed groundwater levels are above or below (–) NAVD 88; observed values for 2000 are during September; observed values for 2004 are during June; see fig. 2–1 for well locations; —, no data]

Well identifier	Model layer	Simulated and observed groundwater levels and difference, in feet						Water-level change, in feet, from 2000 to 2004	
		2000 calibration			2004 calibration				
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
30E002	3	25.88	27.87	–1.99	—	—	—	—	—
31U009	3	—	—	—	112.46	122.13	–9.67	—	—
32L016	3	16.15	15.79	0.36	14.13	17.60	–3.47	1.81	–2.02
33D071	3	10.69	–2.07	12.76	14.08	17.22	–3.14	19.29	3.39
33J065	3	—	—	—	9.54	11.91	–2.37	—	—
33G028	3	10.74	16.75	–6.01	7.59	21.31	–13.72	4.56	–3.15
34H144	3	—	—	—	4.64	3.60	1.04	—	—
34H437	3	8.56	5.88	2.68	5.26	8.92	–3.66	3.04	–3.30
34J077	3	—	—	—	–3.16	–12.46	9.30	—	—
34J081	3	—	—	—	2.28	–2.50	4.78	—	—
34S008	3	—	—	—	17.15	45.76	–28.61	—	—
35Q050	3	—	—	—	–18.98	2.73	–21.71	—	—
35T005	3	—	—	—	20.16	13.14	7.02	—	—
39Q026	3	–11.02	–2.31	–8.71	–10.34	–3.29	–7.05	–0.98	0.68
39Q028	3	–11.03	–2.21	–8.82	–10.34	–3.25	–7.09	–1.04	0.69
33J062	5	—	—	—	9.57	22.09	–12.52	—	—
34J078	5	6.38	3.71	2.67	—	—	—	—	—
34J080	5	—	—	—	2.28	8.55	–6.27	—	—
35S008	5	8.90	12.10	–3.20	7.06	13.41	–6.35	1.31	–1.84
36N012	5	–10.67	–26.18	15.51	–11.78	–22.43	10.65	3.75	–1.11
21T001	7	226.54	220.19	6.35	223.03	223.66	–0.63	3.47	–3.51
25Q001	7	107.49	96.75	10.74	—	—	—	—	—
26M003	7	41.29	35.84	5.45	—	—	—	—	—
26Q002	7	76.88	49.95	26.93	—	—	—	—	—
26R001	7	127.24	103.85	23.39	124.97	106.63	18.34	2.78	–2.27
27E004	7	38.91	40.54	–1.63	39.14	43.76	–4.62	3.22	0.23
27G003	7	—	—	—	37.50	44.53	–7.03	—	—
27G006	7	37.40	40.48	–3.08	—	—	—	—	—
27M001	7	37.74	33.07	4.67	—	—	—	—	—
27Q002	7	76.68	44.97	31.71	—	—	—	—	—
27R003	7	121.43	90.67	30.76	—	—	—	—	—
27R004	7	97.39	92.42	4.97	—	—	—	—	—
27S002	7	138.45	99.21	39.24	—	—	—	—	—
28D001	7	36.68	37.79	–1.11	—	—	—	—	—
28K001	7	35.11	44.39	–9.28	—	—	—	—	—
28R001	7	92.25	59.40	32.85	—	—	—	—	—

Table 1–1. Simulated and observed groundwater levels, 2000 and 2004.—Continued

[Simulated and observed groundwater levels are above or below (–) NAVD 88; observed values for 2000 are during September; observed values for 2004 are during June; see fig. 2–1 for well locations; —, no data]

Well identifier	Model layer	Simulated and observed groundwater levels and difference, in feet						Water-level change, in feet, from 2000 to 2004	
		2000 calibration			2004 calibration				
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
28S003	7	122.08	106.51	15.57	—	—	—	—	—
28S004	7	115.66	88.15	27.51	—	—	—	—	—
28T001	7	155.33	103.29	52.04	—	—	—	—	—
29L005	7	21.37	27.08	–5.71	—	—	—	—	—
29M002	7	24.19	36.04	–11.85	—	—	—	—	—
29N003	7	20.62	32.16	–11.54	—	—	—	—	—
29Q001	7	38.04	29.59	8.45	—	—	—	—	—
29R001	7	65.42	33.05	32.37	—	—	—	—	—
29R003	7	59.92	34.98	24.94	—	—	—	—	—
29T009	7	136.53	113.32	23.21	—	—	—	—	—
29V001	7	164.70	160.00	4.70	—	—	—	—	—
29W002	7	179.53	167.92	11.61	—	—	—	—	—
30E007	7	32.99	32.30	0.69	—	—	—	—	—
30F004	7	29.53	34.70	–5.17	—	—	—	—	—
30H003	7	32.14	27.58	4.56	—	—	—	—	—
30H005	7	31.99	37.35	–5.36	—	—	—	—	—
30L003	7	2.06	13.95	–11.89	—	—	—	—	—
30L011	7	21.82	20.91	0.91	—	—	—	—	—
30L012	7	9.59	19.53	–9.94	—	—	—	—	—
30M003	7	0.97	11.03	–10.06	—	—	—	—	—
30M007	7	9.53	19.26	–9.73	—	—	—	—	—
30N002	7	11.73	21.25	–9.52	—	—	—	—	—
30P003	7	18.70	5.12	13.58	—	—	—	—	—
30R005	7	31.20	23.74	7.46	—	—	—	—	—
30U005	7	119.67	114.98	4.69	—	—	—	—	—
30V002	7	136.70	138.79	–2.09	—	—	—	—	—
30X003	7	164.80	161.82	2.98	—	—	—	—	—
31E001	7	26.40	30.10	–3.70	—	—	—	—	—
31F022	7	26.86	32.77	–5.91	—	—	—	—	—
31H005	7	29.38	32.70	–3.32	—	—	—	—	—
31R001	7	27.97	23.64	4.33	—	—	—	—	—
31S008	7	33.46	41.96	–8.50	—	—	—	—	—
31T010	7	78.58	54.95	23.63	—	—	—	—	—
31U008	7	—	—	—	110.07	117.01	–6.94	—	—
31V008	7	107.34	122.83	–15.49	—	—	—	—	—
31V014	7	109.39	118.09	–8.70	—	—	—	—	—
32E031	7	23.35	29.56	–6.21	—	—	—	—	—
32E038	7	21.98	25.46	–3.48	—	—	—	—	—
32F008	7	24.34	32.28	–7.94	—	—	—	—	—
32G007	7	24.46	27.09	–2.63	—	—	—	—	—

Table 1–1. Simulated and observed groundwater levels, 2000 and 2004.—Continued

[Simulated and observed groundwater levels are above or below (–) NAVD 88; observed values for 2000 are during September; observed values for 2004 are during June; see fig. 2–1 for well locations; —, no data]

Well identifier	Model layer	Simulated and observed groundwater levels and difference, in feet						Water-level change, in feet, from 2000 to 2004	
		2000 calibration			2004 calibration				
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
32G015	7	23.20	29.95	–6.75	—	—	—	—	—
32H001	7	22.10	21.56	0.54	—	—	—	—	—
32J003	7	20.06	23.34	–3.28	—	—	—	—	—
32L004	7	7.84	10.55	–2.71	—	—	—	—	—
32L015	7	4.29	8.22	–3.93	2.10	13.48	–11.38	5.26	–2.19
32N010	7	–1.57	10.14	–11.71	—	—	—	—	—
32N012	7	–0.97	4.49	–5.46	—	—	—	—	—
32R002	7	23.27	18.01	5.26	22.60	22.35	0.25	4.34	–0.67
32U005	7	81.36	96.50	–15.14	—	—	—	—	—
33D004	7	–11.10	1.91	–13.01	—	—	—	—	—
33D069	7	–8.55	2.99	–11.54	—	—	—	—	—
33E007	7	11.46	15.26	–3.80	21.17	27.10	–5.93	11.84	9.71
33E009	7	17.94	30.97	–13.03	—	—	—	—	—
33E027	7	15.98	23.51	–7.53	22.54	34.11	–11.57	10.60	6.56
33F003	7	17.78	26.15	–8.37	—	—	—	—	—
33G002	7	—	—	—	20.93	23.48	–2.55	—	—
33G003	7	17.75	22.86	–5.11	—	—	—	—	—
33G008	7	17.53	18.72	–1.19	20.74	23.16	–2.42	4.44	3.21
33G024	7	—	—	—	22.68	29.87	–7.19	—	—
33H120	7	–1.69	–2.99	1.30	4.05	3.08	0.97	6.07	5.74
33H130	7	–4.10	–4.59	0.49	2.69	2.18	0.51	6.77	6.79
33H133	7	–1.51	–0.89	–0.62	4.54	3.77	0.77	4.66	6.05
33H141	7	9.18	7.24	1.94	—	—	—	—	—
33H164	7	17.37	15.08	2.29	—	—	—	—	—
33H174	7	8.99	9.33	–0.34	—	—	—	—	—
33H177	7	19.72	21.16	–1.44	22.39	28.20	–5.81	7.04	2.67
33H180	7	3.14	–1.15	4.29	—	—	—	—	—
33H190	7	8.05	8.03	0.02	—	—	—	—	—
33H193	7	—	—	—	19.14	22.38	–3.24	—	—
33H207	7	2.64	4.16	–1.52	7.76	8.09	–0.33	3.93	5.12
33H211	7	—	—	—	–4.59	–4.16	–0.43	—	—
33H213	7	—	—	—	–1.62	–1.72	0.10	—	—
33J027	7	14.20	14.31	–0.11	—	—	—	—	—
33L027	7	6.13	6.98	–0.85	—	—	—	—	—
33M004	7	–0.70	0.40	–1.10	–3.17	6.36	–9.53	5.96	–2.47
33N089	7	–2.12	–5.48	3.36	—	—	—	—	—
33U009	7	62.42	67.18	–4.76	—	—	—	—	—
33U019	7	58.16	73.10	–14.94	—	—	—	—	—
33U021	7	62.31	71.15	–8.84	—	—	—	—	—
33U023	7	57.92	75.30	–17.38	—	—	—	—	—

Table 1–1. Simulated and observed groundwater levels, 2000 and 2004.—Continued

[Simulated and observed groundwater levels are above or below (–) NAVD 88; observed values for 2000 are during September; observed values for 2004 are during June; see fig. 2–1 for well locations; —, no data]

Well identifier	Model layer	Simulated and observed groundwater levels and difference, in feet						Water-level change, in feet, from 2000 to 2004	
		2000 calibration			2004 calibration				
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
33V020	7	70.67	76.70	–6.03	—	—	—	—	—
33V021	7	85.97	98.50	–12.53	—	—	—	—	—
34G002	7	12.64	17.60	–4.96	16.44	22.40	–5.96	4.80	3.80
34G003	7	—	—	—	20.14	25.90	–5.76	—	—
34G009	7	16.03	35.50	–19.47	19.81	38.70	–18.89	3.20	3.78
34G016	7	14.25	23.70	–9.45	17.92	28.30	–10.38	4.60	3.67
34G017	7	—	—	—	17.28	26.10	–8.82	—	—
34G020	7	15.46	26.20	–10.74	19.10	30.10	–11.00	3.90	3.64
34H062	7	3.25	0.26	2.99	—	—	—	—	—
34H085	7	5.15	4.23	0.92	—	—	—	—	—
34H095	7	—	—	—	15.99	17.85	–1.86	—	—
34H097	7	10.40	11.80	–1.40	—	—	—	—	—
34H112	7	5.86	6.62	–0.76	11.04	12.90	–1.86	6.28	5.18
34H117	7	4.87	4.54	0.33	10.30	10.50	–0.20	5.96	5.43
34H125	7	4.10	4.45	–0.35	9.20	12.40	–3.20	7.95	5.10
34H128	7	—	—	—	8.26	8.13	0.13	—	—
34H328	7	8.94	8.78	0.16	—	—	—	—	—
34H344	7	1.97	3.25	–1.28	6.24	6.22	0.02	2.97	4.27
34H355	7	2.46	3.88	–1.42	7.90	8.46	–0.56	4.58	5.44
34H357	7	7.85	8.74	–0.89	—	—	—	—	—
34H371	7	7.97	10.80	–2.83	12.89	15.50	–2.61	4.70	4.92
34H373	7	1.93	–1.07	–2.65	7.02	3.98	3.04	5.05	10.74
34H374	7	—	—	—	6.00	7.20	–1.20	—	—
34H392	7	4.23	3.33	0.90	—	—	—	—	—
34H393	7	7.27	8.53	–1.26	12.32	14.60	–2.28	6.07	5.05
34H400	7	—	—	—	7.12	4.34	2.78	—	—
34H401	7	—	—	—	6.51	2.53	3.98	—	—
34H403	7	7.65	10.10	–2.45	—	—	—	—	—
34H408	7	5.40	2.25	3.15	—	—	—	—	—
34H410	7	6.67	7.85	–1.18	—	—	—	—	—
34H424	7	1.13	1.04	0.09	—	—	—	—	—
34H434	7	—	—	—	8.86	6.13	2.73	—	—
34H469	7	0.38	5.56	–5.18	6.05	6.61	–0.56	1.05	5.67
34J029	7	9.42	8.09	1.33	—	—	—	—	—
34J051	7	9.64	9.65	–0.01	—	—	—	—	—
34K073	7	7.17	1.97	5.20	—	—	—	—	—
34K095	7	7.04	1.78	5.26	—	—	—	—	—
34L048	7	2.70	8.06	–5.36	—	—	—	—	—
34L060	7	–0.54	–3.00	2.46	—	—	—	—	—
34L061	7	2.47	4.17	–1.70	—	—	—	—	—

Table 1–1. Simulated and observed groundwater levels, 2000 and 2004.—Continued

[Simulated and observed groundwater levels are above or below (–) NAVD 88; observed values for 2000 are during September; observed values for 2004 are during June; see fig. 2–1 for well locations; —, no data]

Well identifier	Model layer	Simulated and observed groundwater levels and difference, in feet						Water-level change, in feet, from 2000 to 2004	
		2000 calibration			2004 calibration				
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
34M070	7	–1.59	–6.32	4.73	—	—	—	—	—
34M075	7	–3.73	–9.49	5.76	—	—	—	—	—
34M076	7	–2.27	–4.20	1.93	—	—	—	—	—
34N089	7	–10.56	–14.30	3.74	–13.28	–9.60	–3.68	4.70	–2.72
34R039	7	0.02	–5.48	5.50	—	—	—	—	—
34V004	7	71.45	74.60	–3.15	—	—	—	—	—
35H044	7	10.27	9.94	0.33	—	—	—	—	—
35K069	7	3.21	–0.79	4.00	—	—	—	—	—
35L068	7	–0.72	–2.83	2.11	—	—	—	—	—
35M013	7	–4.21	–11.90	7.69	–5.06	–6.40	1.34	5.50	–0.85
35R018	7	–22.38	–18.10	–4.28	—	—	—	—	—
35T003	7	16.22	31.40	–15.18	15.27	2.11	13.16	–29.29	–0.95
36M018	7	–8.99	–16.90	7.91	—	—	—	—	—
36Q008	7	–86.74	–90.50	3.76	–86.81	–82.10	–4.71	8.40	–0.07
36Q019	7	–47.60	–38.10	–9.50	—	—	—	—	—
36Q020	7	–47.27	–42.20	–5.07	–48.65	–38.20	–10.45	4.00	–1.38
36Q300	7	–56.26	–54.30	–1.96	—	—	—	—	—
37P005	7	–50.36	–52.50	2.14	—	—	—	—	—
37P006	7	–56.91	–54.40	–2.51	—	—	—	—	—
37P114	7	–43.59	–46.00	2.41	–44.61	–43.60	–1.01	2.40	–1.02
37Q016	7	–83.53	–82.20	–1.33	–85.21	–77.00	–8.21	5.20	–1.68
37Q033	7	–75.34	–75.80	0.46	—	—	—	—	—
37Q043	7	–56.68	–57.00	0.32	—	—	—	—	—
37Q185	7	–108.99	–99.20	–9.79	–110.21	–95.20	–15.01	4.00	–1.22
38Q002	7	–23.12	–30.40	7.28	–22.32	–28.10	5.78	2.30	0.80
39Q003	7	–17.52	–27.90	10.38	–17.15	–25.20	8.05	2.70	0.37
BFT–1810	7	–4.20	–0.75	–3.45	—	—	—	—	—
BFT–1813	7	–4.88	–3.50	–1.38	—	—	—	—	—
BFT–429	7	–4.30	–5.90	1.60	—	—	—	—	—
D–3840	7	–12.46	–13.20	0.74	—	—	—	—	—
HAM–83	7	25.82	4.40	21.42	—	—	—	—	—
N–62	7	–7.92	–17.90	9.98	—	—	—	—	—
33H127	9	–2.17	0.60	–2.77	4.55	7.85	–3.30	7.25	6.72
33H154	9	–4.78	–27.58	22.80	2.99	–17.90	20.89	9.68	7.77
34H334	9	2.40	7.51	–5.11	6.27	12.40	–6.13	4.89	3.87
34H402	9	—	—	—	6.53	8.20	–1.67	—	—
34H403	9	7.65	10.12	–2.47	12.57	16.30	–3.73	6.18	4.92
32Y033	11	142.71	110.00	32.71	—	—	—	—	—
33D073	11	4.67	3.58	1.09	18.26	30.70	–12.44	27.12	13.59
33H188	11	13.67	12.50	1.17	17.24	20.10	–2.86	7.60	3.57

Table 1–1. Simulated and observed groundwater levels, 2000 and 2004.—Continued

[Simulated and observed groundwater levels are above or below (–) NAVD 88; observed values for 2000 are during September; observed values for 2004 are during June; see fig. 2–1 for well locations; —, no data]

Well identifier	Model layer	Simulated and observed groundwater levels and difference, in feet						Water-level change, in feet, from 2000 to 2004	
		2000 calibration			2004 calibration				
		Simulated	Observed	Difference	Simulated	Observed	Difference	Observed	Simulated
33H206	11	6.47	8.40	–1.93	11.01	14.00	–2.99	5.60	4.54
33J044	11	11.81	13.90	–2.09	14.57	19.10	–4.53	5.20	2.76
34G036	11	13.99	20.10	–6.11	—	—	—	—	—
34H391	11	9.65	9.18	0.47	13.86	11.90	1.96	2.72	4.21
34H399	11	11.14	1.76	9.38	—	—	—	—	—
34H436	11	7.85	11.70	–3.85	12.07	15.80	–3.73	4.10	4.22
34H495	11	—	—	—	13.06	24.00	–10.94	—	—
34H500	11	—	—	—	13.05	21.40	–8.35	—	—
35L085	11	—	—	—	–2.76	–10.10	7.34	—	—
35P109	11	–25.94	–21.80	–4.14	–28.98	–18.90	–10.08	2.90	–3.04
37Q186	11	—	—	—	–98.59	–61.00	–37.59	—	—
38Q201	11	—	—	—	–22.36	–46.60	24.24	—	—
39Q024	11	–17.28	–31.70	14.42	–16.83	–29.90	13.07	1.80	0.45

Appendix 2

A

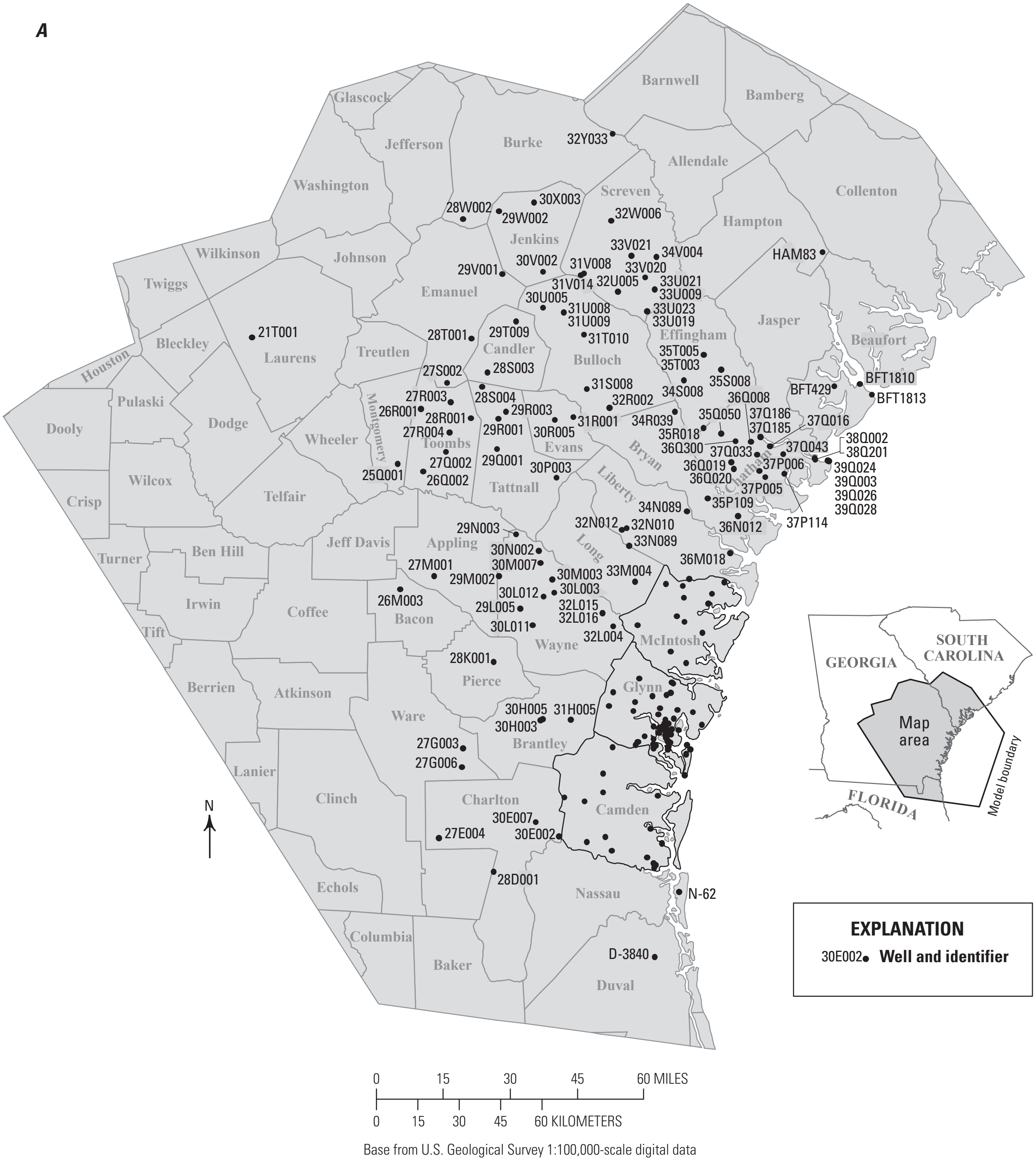
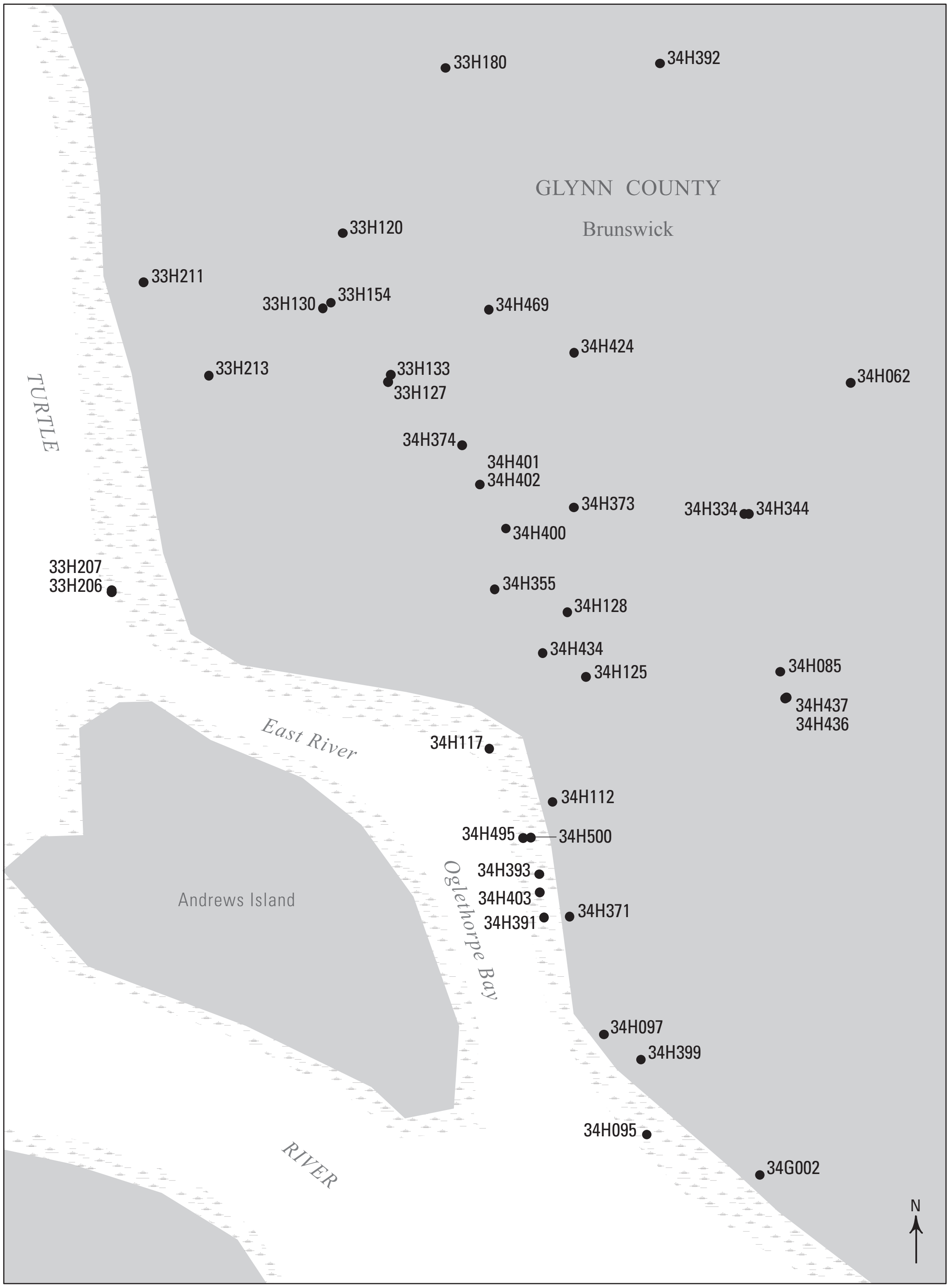


Figure 2–1. Location of wells used for 2000 and 2004 simulations in *A*, study area; *B*, McIntosh, Glynn, and Camden Counties (enlarged); and *C*, Brunswick (enlarged).

Figure 2–1. Location of wells used for 2000 and 2004 simulations in *A*, study area; *B*, McIntosh, Glynn, and Camden Counties (enlarged); and *C*, Brunswick (enlarged).—Continued

C



Base from U.S. Geological Survey
1:100,000-scale digital data

0 0.2 0.4 0.6 0.8 1 MILE

0 0.2 0.4 0.6 0.8 1 KILOMETER

EXPLANATION

34H095 ● **Well and identifier**

Figure 2–1. Location of wells used for 2000 and 2004 simulations in *A*, study area; *B*, McIntosh, Glynn, and Camden Counties (enlarged); and *C*, Brunswick (enlarged).—Continued

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