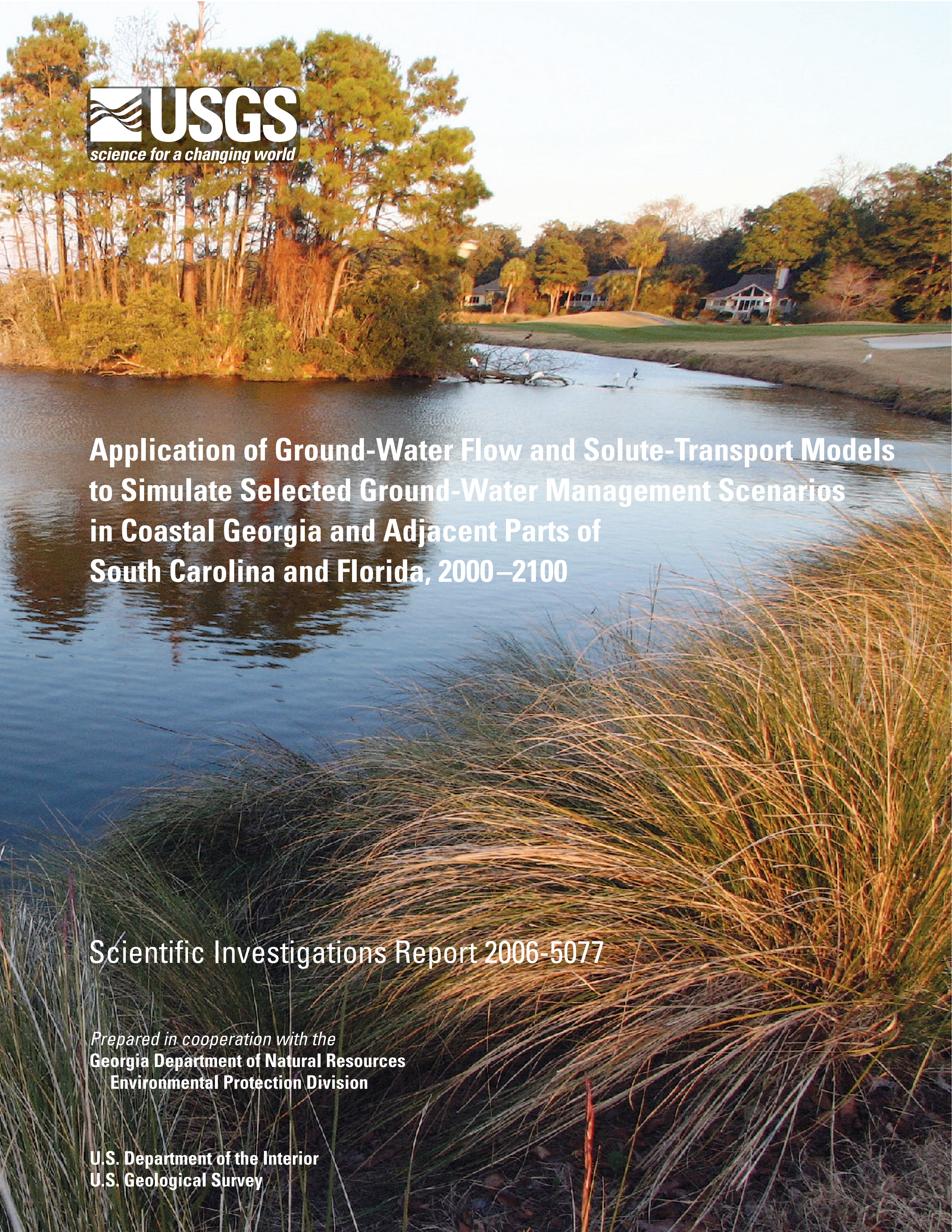


Application of Ground-Water Flow and Solute-Transport Models to Simulate Selected Ground-Water Management Scenarios in Coastal Georgia and Adjacent Parts of South Carolina and Florida, 2000–2100

Scientific Investigations Report 2006-5077

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

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

Cover photograph: Arthur Hills Golf Course, Palmetto Dunes, Hilton Head Island, South Carolina

Photograph by Alan M. Cressler, U.S. Geological Survey, 2006

Application of Ground-Water Flow and Solute-Transport Models to Simulate Selected Ground-Water Management Scenarios in Coastal Georgia and Adjacent Parts of South Carolina and Florida, 2000–2100

By Dorothy F. Payne, Alden M. Provost, Jaime A. Painter,
Malek Abu Rumman, and Gregory S. Cherry

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

Scientific Investigations Report 2006-5077

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

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

This report is a Web-only publication: *pubs.usgs.gov/sir/2006/5077/*

For more information about the USGS and its products:
World Wide Web: *http://www.usgs.gov*
Telephone: 1-888-ASK-USGS

Suggested citation:
Payne, D.F., Provost, A.M., Painter, J.A., Abu Rumman, Malek, Cherry, G.S., 2006, Application of Ground-Water Flow and Solute-Transport Models to Simulate Selected Ground-Water Management Scenarios in Coastal Georgia and Adjacent Parts of South Carolina and Florida, 2000–2100: U.S. Geological Survey Scientific Investigations Report 2006-5077, 86 p.

Contents

Figures

Tables

Conversion Factors, Datum, and Acronyms

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow/Transport rate	
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
feet per day (ft/d)	0.3048	meter per day (m/d)

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

°F = (1.8 x °C) + 32

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

°C = (°F –32) / 1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Historical data collected and stored as National Geodetic Vertical Datum of 1929 have been converted to NAVD 88 for this publication.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Historical data collected and stored as North American Datum 1927 have been converted to NAD 83 for this publication.

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

Acronyms used in this report:

CSSI	Coastal Sound Science Initiative
CWSP	County Comprehensive Water-Supply Plans
GaEPD	Georgia Environmental Protection Division
GIS	Geographic Information System
MODFLOW	Modular Ground-Water Flow Simulator
REMI	Regional Economic Models, Inc.
SCDHEC	South Carolina Department of Health and Environmental Control
SUTRA	Saturated-Unsaturated Transport Simulator
USGS	U.S. Geological Survey

Application of Ground-Water Flow and Solute-Transport Models to Simulate Selected Ground-Water Management Scenarios in Coastal Georgia and Adjacent Parts of South Carolina and Florida, 2000–2100

By Dorothy F. Payne, Alden M. Provost, Jaime A. Painter, Malek Abu Rumman, and Gregory S. Cherry

Abstract

Regional ground-water flow and solute-transport models for the coastal area of Georgia, and adjacent parts of Florida and South Carolina were used to evaluate the effects of current and hypothetical ground-water withdrawal on ground-water flow and saltwater transport. The models were designed to simulate the flow system at different scales while being as consistent as possible in framework, hydraulic properties, pumpage distribution, and boundary conditions. Simulation results for future pumpage scenarios were compared with those during 2000 (the Base Case), or during 2100 for 2000 pumpage applied after 2000. The regional MODFLOW model assumes steady-state ground-water flow, and is calibrated to 1980 and 2000 pumping conditions. The SUTRA model of the Savannah, Georgia–Hilton Head Island, South Carolina, area is run as a transient simulation from a predevelopment (1885) steady-state flow field to 2004, and calibrated to water levels in September 1998 and estimated chloride values in 2000, 2002, 2003, and 2004.

Scenario A illustrates the effects of implementing an interim strategy for managing saltwater intrusion in the Upper Floridan aquifer of southeastern Georgia. Results show a combination of rises and declines in head from 1997 to 2000 in response to changes in the pumping patterns and only minor changes in the chloride distribution in the Hilton Head Island, South Carolina, area. Generally, water levels rose in the Savannah–Hilton Head Island area, and declined in the area north of the Gulf Trough.

Scenario B simulates the effect of a 36-million-gallon-per-day reduction of pumpage at a major pumping center in Camden County, Georgia. Results show that the largest recovery is limited in extent to the area surrounding St. Marys, Georgia, but a smaller water-level rise of 1–2 feet extends as far north as southern Chatham County, Georgia, and inland toward the Gulf Trough. Nearest the area where the wells were turned off, the model predicts a smaller recovery than indicated by observed water levels.

Scenarios C1 and C2 illustrate the relative effects of pumping in Chatham County, Georgia, and southern Beaufort County, South Carolina, on ground-water levels and saltwater distribution and movement in that area. Results indicate that pumping in southern Beaufort County has a smaller effect on saltwater-plume development than pumping in Chatham County for plumes west of Hilton Head Island, South Carolina. Results also indicate that the effect of pumping on the plume at the northern end of Hilton Head Island in either Chatham County or southern Beaufort County is small, although pumping in southern Beaufort County may have a slightly greater effect on plume growth than pumping in Chatham County. Furthermore, model results indicate that eliminating pumping in Chatham County would result in a greater water-level increase at the southern end of Hilton Head Island than elimination of pumping in southern Beaufort County, and that eliminating pumping in southern Beaufort County would result in a greater water-level increase at the northern end of Hilton Head Island than elimination of pumping in Chatham County.

Scenarios D1 and D2 simulate the effect of projected pumpage during 2000–2035, based on two estimates of future ground-water needs. Results from both scenarios show substantial water-level declines from 2000 to 2035 and an increase of inflow at the source-sink boundaries. For the solute-transport simulations, pumpage at 2035 was held constant until 2100. For both scenarios, chloride plumes expand during 2000–2100, but show limited expansion relative to plumes that develop for 2000 pumpage applied until 2100. Although the total pumpage difference between Scenarios D1 and D2 during 2035 is 477 million gallons per day, and pumpage in both scenarios is substantially larger than that during 2000, distance and hydraulic features, such as the Gulf Trough, and high hydraulic conductivity in the southwestern part of the model area, limit the effects of these differences on the extent of resultant plumes.

Results obtained using the ground-water flow and solute-transport models used in this study are subject to the limitations of the models and scenario conditions. For example, pumpage for Scenario B may not accurately represent conditions during 2002 when the industrial wells were

turned off, and projected pumpage for 2010, 2020, and 2035 is substantially different in Scenarios D1 and D2. Generally, model results are less reliable for scenario conditions that are farther from calibration conditions. Conditions that differ substantially from calibration conditions may induce an unrealistic response from the model if the model assumptions are violated; for example, if influx from model boundaries is excessive. Excessive inflow from the model boundaries, particularly from the onshore area, may result in underestimated drawdown and inflow of saltwater. Model results are most reliable in areas where calibration data exist, and for the range of pumpage conditions for which the models are calibrated.

Introduction

Since the 1980s, population growth, increased tourism, and sustained industrial activity in the coastal area of Georgia, South Carolina, and Florida have resulted in increased ground-water pumpage. Recent periods of drought (for example, 1998–2002) also have increased stresses on the coastal ground-water system. The principal source of water in the coastal area is the Upper Floridan aquifer, an extremely permeable, high-yielding aquifer that was first developed during the late 1800s and has been used extensively in the area ever since. Pumping from the Upper Floridan aquifer has resulted in substantial water-level decline near Savannah, Georgia (Ga.), and saltwater intrusion at the northern end of Hilton Head Island, South Carolina (S.C.), and at Brunswick, Ga. This saltwater contamination has constrained further development of the Upper Floridan aquifer in the coastal area, which has created competing demands for the limited water supply. Projected increase in coastal population during the next several decades is expected to result in increased competition for ground water.

The Georgia Environmental Protection Division (GaEPD), as part of an interim water management strategy, capped permitted withdrawal from the Upper Floridan aquifer at 1997 withdrawal rates in parts of the coastal area during 1997–2005 to limit further saltwater intrusion (Georgia Environmental Protection Division, 1997). To develop a strategy to address these problems and manage projected future coastal water-resource needs, the GaEPD has implemented the Georgia Coastal Sound Science Initiative (CSSI), a series of scientific and feasibility investigations designed to assess ground-water resources in the coastal area and address issues of saltwater intrusion and resource sustainability. As part of this initiative, the GaEPD, Skidaway Institute of Oceanography, South Carolina Department of Health and Environmental Control (SCDHEC), U.S. Army Corps of Engineers, and the U.S. Geological Survey (USGS), as well as private consulting firms, collected and analyzed hydrogeologic data to refine the conceptual models of ground-water flow and saltwater transport. The USGS then synthesized this information into digital models that describe the ground-water flow system and movement of saltwater. The GaEPD will use these digital models to help design a ground-water permitting strategy for the coastal area.

The USGS developed digital models, as part of the CSSI, which must satisfy multiple objectives at varying scales. Objectives include simulation of (1) the regional flow system, including the Brunswick aquifer system and the Lower Floridan aquifer, in addition to the Upper Floridan aquifer (Payne and others, 2005); (2) subregional flow and localized seawater intrusion in the Savannah, Ga.–Hilton Head Island, S.C., area (Provost and others, 2006); and (3) localized saltwater intrusion at Brunswick, Ga. To satisfy these objectives, the USGS developed a set of ground-water flow and solute-transport models with consistent framework, hydraulic properties, pumpage, and boundary conditions; these models update and expand on earlier digital models of the area. This suite of models represents an approach to developing consistent, integrated modeling tools that simulate different aspects of a coastal ground-water flow system at varying scales for the purpose of addressing water-resource management issues. The hypothetical scenarios that were evaluated using the two models provide insight into the influence of stresses on ground-water flow and saltwater intrusion in Georgia and may provide insight to similar occurrences elsewhere in the Atlantic Coastal Plain.

Purpose and Scope

This report describes results from a variety of simulations using the regional flow model of Payne and others (2005) and the Savannah–Hilton Head Island solute-transport model of Provost and others (2006). These simulations were designed to evaluate the effects of current and hypothetical ground-water withdrawal, and the relative effects of pumping in specific areas on ground-water flow and saltwater transport. For each scenario simulated, this report describes the purpose, pumpage distribution, simulated head by aquifer unit, differences in simulated head relative to 2000 conditions, and simulated flow-budget components, including boundary fluxes. For most scenarios, the simulated chloride distribution in the Savannah–Hilton Head Island area also is presented. Finally, this report describes the limitations of the applications of these models and simulation results.

Payne and others (2005) and Provost and others (2006) describe in detail the models used in this study. The regional ground-water flow model was constructed using the USGS finite-difference, ground-water flow simulator MODFLOW-2000 (Harbaugh and others, 2000), and the Savannah–Hilton Head Island solute-transport model was constructed using the USGS finite-element, variable-density solute-transport simulator SUTRA (Voss and Provost, 2003). Only a brief description of the models is included in this report.

Description of Study Area

The GaEPD defines the coastal area of Georgia to include the 6 coastal counties and 18 adjacent counties, an area of about 12,240 square miles (mi^2) (fig. 1). To account for natural hydrologic boundaries used for model simulation, the regional

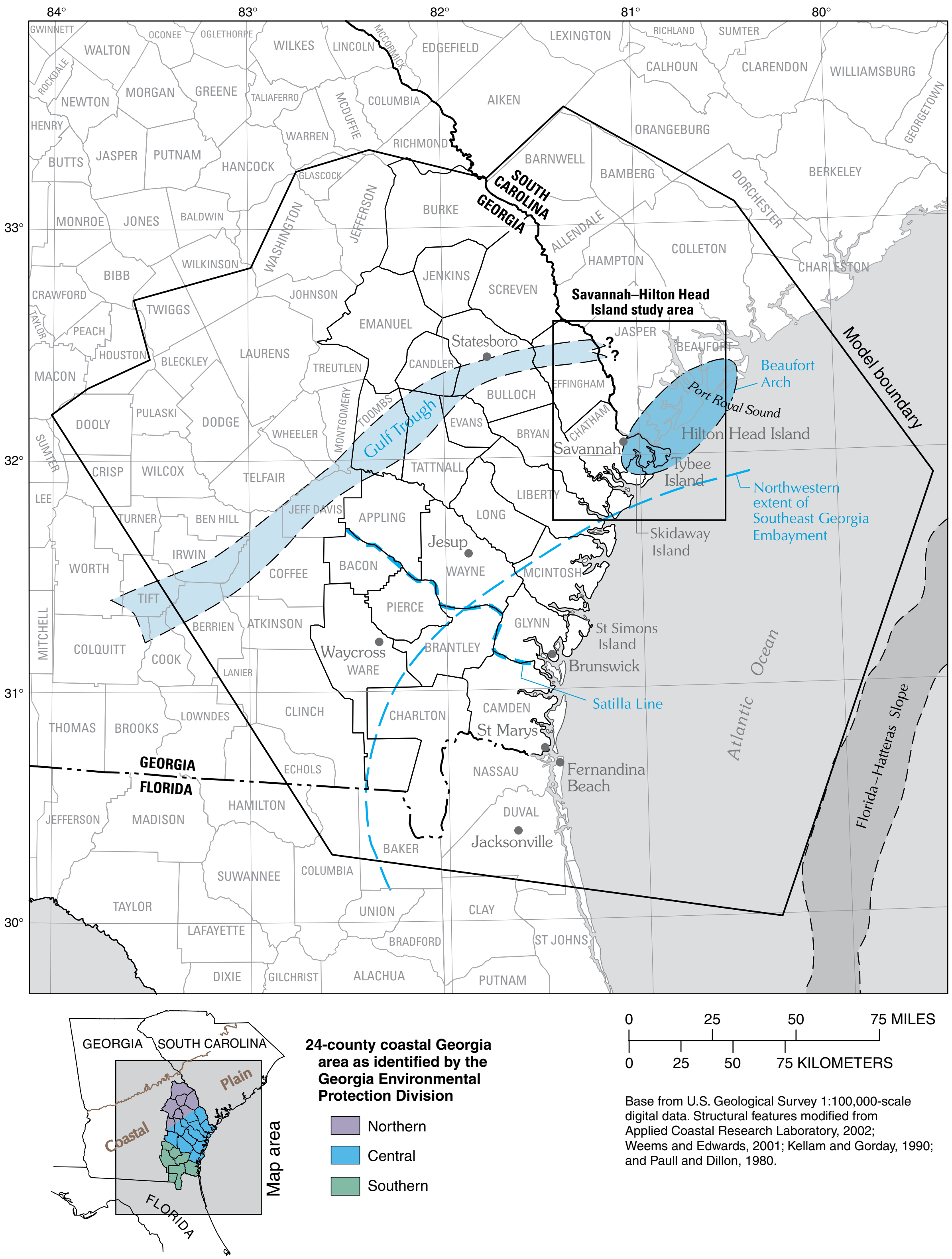


Figure 1. Location of model area, major structural features, and 24-county coastal Georgia area.

study area has been expanded to 42,155 mi^2, extending inland in Georgia and into northeastern Florida and southwestern South Carolina, and the adjacent offshore area. The Savannah–Hilton Head Island study area (fig. 1) encompasses about 3,000 mi^2 and includes Chatham County and parts of Bryan, Effingham, and Liberty Counties in Georgia, and Beaufort County and part of Jasper County in South Carolina and the adjacent offshore area. Payne and others (2005) and Provost and others (2006) describe the topography, climate, and land use in the regional and Savannah–Hilton Head study areas.

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

The Floridan aquifer system is the principal source of water for all uses in the coastal area. The aquifer consists of the predominantly carbonate Upper Cretaceous to Oligocene Upper and Lower Floridan aquifers (Miller, 1986; Krause and Randolph, 1989). Secondary sources of water include the shallow surficial and Brunswick aquifer systems, consisting of Miocene to Holocene siliciclastic units (Clarke, 2003).

The total estimated pumpage in the model area during 2000 was about 815 million gallons per day (Mgal/d) (table 1). Most of the pumping occurred in coastal counties (fig. 2), most notably Duval County, Florida (Fla.), for which the estimated pumpage was about 145 Mgal/d. For Chatham County, Ga., estimated pumpage during 2000 was about 71 Mgal/d, which is the largest estimated pumpage for counties in Georgia. The Upper Floridan aquifer is the most heavily pumped aquifer, from which an estimated 680 Mgal/d was pumped during 2000 (Payne and others, 2005). During 2000, estimated Lower Floridan aquifer pumpage was 130 Mgal/d, most of which was in Duval County, Fla., and estimated pumpage from the Brunswick aquifer system was less than 1 Mgal/d. The single largest concentration of pumping in Georgia is in Jesup, Wayne County, Ga. (fig. 1), at a rate of about 60 Mgal/d during 2000 in the Upper Floridan aquifer (Fanning, 2003).

Previous Coastal Sound Science Initiative Studies

The simulation results presented herein represent the culmination of studies implemented as part of the CSSI. Weems and Edwards (2001) provided a regional distribution of the sedimentary units that comprise the confined surficial and Brunswick aquifer systems. The distribution of the confining unit above the Upper Floridan aquifer was mapped in the Hilton Head Island and offshore area using seismic data (Foyle and others, 2001). Falls and others (2005a) examined the distribution and water-bearing properties of the Lower Floridan aquifer throughout the region. The framework and ground-water chemistry of the Upper Floridan aquifer system and overlying confining unit offshore from Hilton Head Island were examined by drilling and sampling four test wells (Falls and others 2005b). The present-day salinity distribution on Hilton Head Island was estimated with the installation and monitoring of specific-conductance monitors in wells (Camille Ransom III, South Carolina Department of Health and Environmental Control, written commun., 2004). Leeth and others (2005) used population projections by Regional Economic Models, Inc. (REMI), and Camp Dresser and McKee (2001) used County Comprehensive Water Supply Plans (CWSP), to estimate projected water use for 24 coastal counties in Georgia. After the abrupt shutdown of Durango Paper Company wells in Camden County, Ga., the USGS monitored water-level recovery and ground-water salinity, and Peck and others (2005) analyzed the hydrologic response.

Method of Study

Several pumpage scenarios were developed to examine ground-water flow system characteristics and the limitations of the models, and to address the effect of anticipated future demands on the system. The regional MODFLOW ground-water flow model was used to simulate all of the pumpage scenarios, whereas only scenarios that affected the hydrology in the Savannah–Hilton Head Island area were simulated using the SUTRA solute-transport model. Results from simulations using the MODFLOW model include simulated-head distributions, head differences relative to the Base Case simulation (2000 conditions), and flow-budget differences relative to the Base Case simulation. Results from simulations using the SUTRA solute-transport model include simulated chloride distribution and calculated heads in the Savannah–Hilton Head Island area.

Acknowledgments

The authors wish to thank Caryl J. Wipperfurth of the U.S. Geological Survey for preparation of illustrations and Patricia L. Nobles of the U.S. Geological Survey for preparation of the manuscript. William H. McLemore of the Georgia Environmental Protection Division helped design and focus the scenarios and Julia L. Fanning of the U.S. Geological Survey helped with development and implementation of the pumpage distributions for the scenarios. Michael F. Peck of the U.S. Geological Survey provided water-level data and interpretation. John S. Clarke of the U.S. Geological Survey assisted in implementation of the scenarios and in the approach to the documentation thereof.

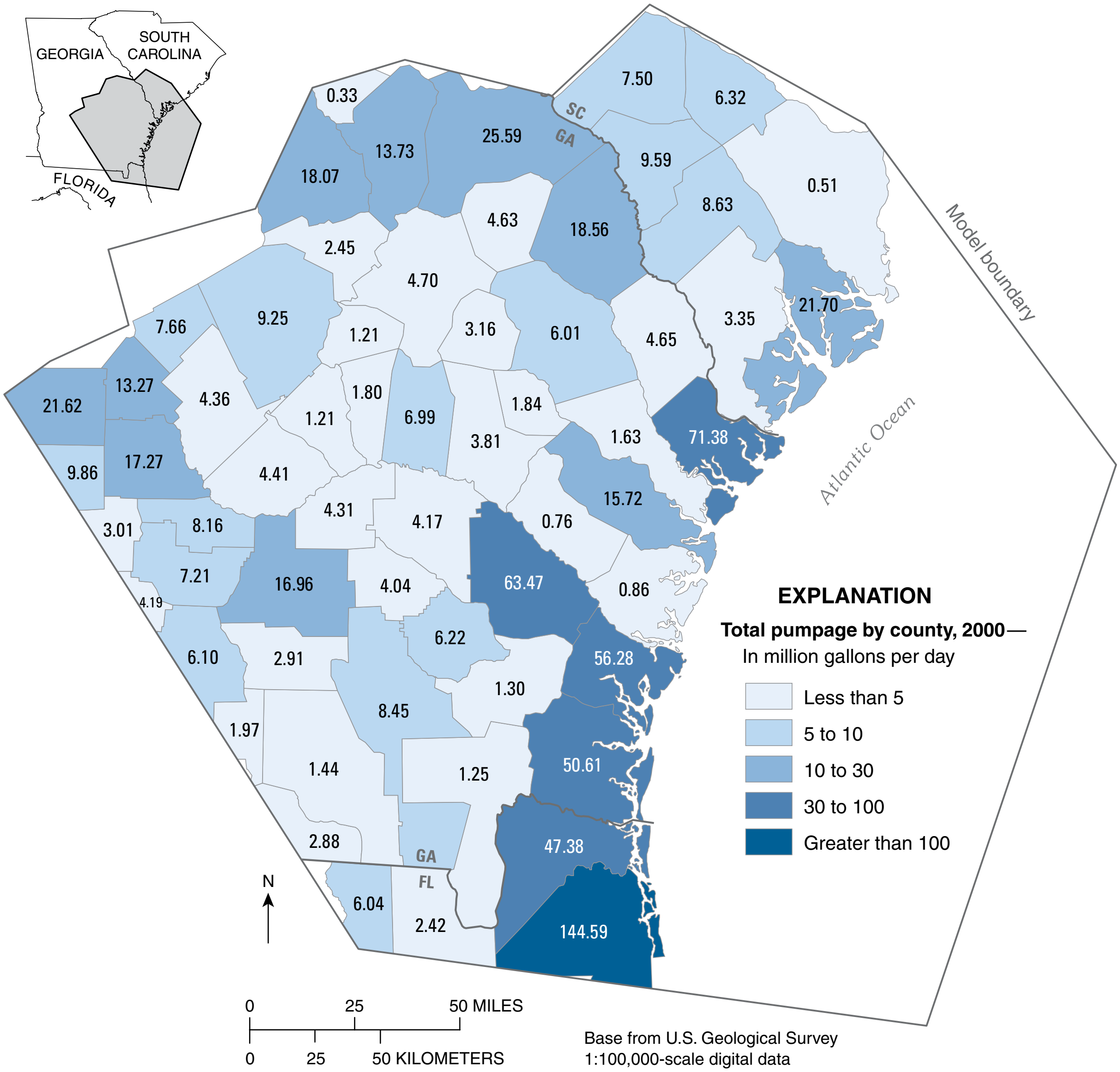


Figure 2. Pumpage distribution by county for 2000. Values represent sum of estimated pumpage for the Brunswick aquifer system, Upper Floridan aquifer, and Lower Floridan aquifer.

Ground-Water Flow and Solute-Transport Models

The two types of models used in the study, constructed using MODFLOW-2000 and SUTRA, address different objectives at different scales. MODFLOW-2000 (Harbaugh and others, 2000) is a finite-difference, constant-density flow simulator that is widely used and is appropriate for modeling regional ground-water flow systems. SUTRA (Voss and Provost, 2003) is a two- or three-dimensional, finite-element, ground-water flow and solute- or energy-transport simulator capable of explicitly simulating the effects of variable fluid density on the distribution and movement of saline water for a variety of saltwater intrusion mechanisms. These simulators share a common geographic information system (GIS)-based interface (Argus® ONE) that facilitates the transfer of model input between the two types of models (Winston, 2000; Winston and Voss, 2004).

The regional MODFLOW model is calibrated for 1980 and 2000 pumpage assuming steady-state flow. As the MODFLOW model was being constructed and calibrated, the common GIS-based interface was used to enable transfer of model datasets to a SUTRA model based on the same hydrogeologic information. Throughout the initial development process, hydraulic properties, model layering, and boundary conditions for the MODFLOW and SUTRA models were kept as mutually consistent as possible. After the regional

Table 1. Simulated pumpage by scenario and difference from Base Case (estimated 2000 pumpage) by county.-

[Difference is scenario pumpage minus Base Case (estimated 2000) pumpage; values rounded to the 0.1 million gallons per day; sum of Base Case pumpage and difference may not equal scenario pumpage because of rounding. Scenarios: A, 1997 pumpage; B, Durango Paper Company pumping eliminated; C1, Chatham County pumping eliminated; C1, southern Beaufort County pumping eliminated; D1, Regional Economic Models, Inc. projection; D2, County Comprehensive Water-Supply Plans, projection. –, minus; Fla., Florida; Ga., Georgia, S.C., South Carolina]

State	County	Base Case pumpage	Simulated pumpage by scenario and difference from Base Case (estimated 2000 pumpage), in million gallons per day																			
			A		B		C1		C2		D1, 2010		D1, 2020		D1, 2035		D2, 2010		D2, 2020		D2, 2035	
			Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference
Fla.	Baker	2.4	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0
	Columbia	6.0	6.6	.5	6.0	0.0	6.0	0.0	6.0	0.0	6.0	0.0	6.0	0.0	6.0	0.0	6.0	0.0	6.0	0.0	6.0	0.0
	Duval	144.6	149.9	5.3	144.6	0.0	144.6	0.0	144.6	0.0	144.6	0.0	144.6	0.0	144.6	0.0	144.6	0.0	144.6	0.0	144.6	0.0
	Hamilton	0.5	0.5	–0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0
	Nassau	47.4	46.8	–0.6	47.4	0.0	47.4	0.0	47.4	0.0	47.4	0.0	47.4	0.0	47.4	0.0	47.4	0.0	47.4	0.0	47.4	0.0
Ga.	Appling	4.2	2.5	–1.7	4.2	0.0	4.2	0.0	4.2	0.0	4.2	–0.0	4.4	0.2	4.7	0.5	7.7	3.5	8.6	4.4	10.0	5.9
	Atkinson	2.9	1.6	–1.3	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0
	Bacon	4.0	2.2	–1.8	4.0	0.0	4.0	0.0	4.0	0.0	2.4	–1.6	2.6	–1.5	2.8	–1.2	2.5	–1.5	3.2	–0.9	3.5	–0.6
	Ben Hill	8.2	12.3	4.1	8.2	0.0	8.2	0.0	8.2	0.0	8.2	0.0	8.2	0.0	8.2	0.0	8.2	0.0	8.2	0.0	8.2	0.0
	Berrien	6.1	5.3	–0.8	6.1	0.0	6.1	0.0	6.1	0.0	6.1	0.0	6.1	0.0	6.1	0.0	6.1	0.0	6.1	0.0	6.1	0.0
	Bleckley	7.7	2.7	–4.9	7.7	0.0	7.7	0.0	7.7	0.0	7.7	0.0	7.7	0.0	7.7	0.0	7.7	0.0	7.7	0.0	7.7	0.0
	Brantley	1.3	1.9	0.6	1.3	0.0	1.3	0.0	1.3	0.0	1.6	0.3	1.7	0.4	1.9	0.6	121.8	120.4	138.3	137.0	188.4	187.1
	Bryan	1.6	1.7	0.1	1.6	0.0	1.6	0.0	1.6	0.0	2.5	0.9	2.7	1.1	3.1	1.5	5.2	3.6	10.4	8.8	19.4	17.8
	Bulloch	6.0	5.4	–0.7	6.0	0.0	6.0	0.0	6.0	0.0	10.5	4.5	11.3	5.3	12.6	6.6	27.0	21.0	23.9	17.9	31.3	25.3
	Burke	25.6	9.5	–16.1	25.6	0.0	25.6	0.0	25.6	0.0	27.8	2.2	29.2	3.6	30.9	5.3	35.3	9.7	40.2	14.6	50.5	25.0
	Camden	50.6	46.0	–4.6	14.9	–35.7	50.6	0.0	50.6	0.0	42.0	–8.6	44.8	–5.8	51.1	0.5	54.6	4.0	59.4	8.8	66.5	15.9
	Candler	3.2	1.9	–1.3	3.2	0.0	3.2	0.0	3.2	0.0	2.7	–0.4	2.9	–0.3	3.0	–0.1	0.2	–2.9	0.2	–2.9	22.8	19.7
	Charlton	1.3	1.0	–0.3	1.3	0.0	1.3	0.0	1.3	0.0	1.5	0.2	1.6	0.3	1.8	0.5	52.5	51.3	52.8	51.6	53.5	52.2
	Chatham	71.4	74.4	3.1	71.4	0.0	0.0	–71.4	71.4	0.0	75.2	3.8	81.1	9.7	92.0	20.7	72.6	1.2	75.4	4.1	79.2	7.8
	Clinch	1.4	1.0	–0.4	1.4	0.0	1.4	0.0	1.4	0.0	1.4	0.0	1.4	0.0	1.4	0.0	1.4	0.0	1.4	0.0	1.4	0.0
	Coffee	17.0	8.0	–8.9	17.0	0.0	17.0	0.0	17.0	0.0	17.0	0.0	17.0	0.0	17.0	0.0	17.0	0.0	17.0	0.0	17.0	0.0
	Crisp	9.9	11.8	2.0	9.9	0.0	9.9	0.0	9.9	0.0	9.9	0.0	9.9	0.0	9.9	0.0	9.9	0.0	9.9	0.0	9.9	0.0
	Dodge	4.4	4.7	0.4	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0
	Dooly	21.6	10.5	–11.1	21.6	0.0	21.6	0.0	21.6	0.0	21.6	0.0	21.6	0.0	21.6	0.0	21.6	0.0	21.6	0.0	21.6	0.0
	Echols	2.9	1.8	–1.1	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0	2.9	0.0
	Effingham	4.7	4.5	–0.2	4.7	0.0	4.7	0.0	4.7	0.0	5.5	0.9	6.0	1.3	6.8	2.1	15.0	10.4	17.7	13.0	24.3	19.7
	Emanuel	4.7	5.1	0.3	4.7	0.0	4.7	0.0	4.7	0.0	5.1	0.4	5.4	0.7	5.8	1.1	3.8	–0.9	3.9	–0.8	10.4	–0.8
	Evans	1.8	1.5	–0.3	1.8	0.0	1.8	0.0	1.8	0.0	3.3	1.5	3.6	1.8	4.1	2.2	2.1	0.2	2.2	0.4	29.9	28.1
	Glascock	0.3	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0
	Glynn	61.2	61.8	0.6	61.2	0.0	61.2	0.0	61.2	0.0	63.2	2.0	67.6	6.4	77.3	16.1	67.1	5.9	72.1	10.9	78.9	17.7
	Irwin	7.2	6.6	–0.6	7.2	0.0	7.2	0.0	7.2	0.0	7.2	0.0	7.2	0.0	7.2	0.0	7.2	0.0	7.2	0.0	7.2	0.0
	Jeff Davis	4.3	3.5	–0.8	4.3	0.0	4.3	0.0	4.3	0.0	4.3	0.0	4.3	0.0	4.3	0.0	4.3	0.0	4.3	0.0	4.3	0.0

Table 1. Simulated pumpage by scenario and difference from Base Case (estimated 2000 pumpage) by county.—Continued

[Difference is scenario pumpage minus Base Case (estimated 2000) pumpage; values rounded to the 0.1 million gallons per day; sum of Base Case pumpage and difference may not equal scenario pumpage because of rounding. Scenarios: A, 1997 pumpage; B, Durango Paper Company pumping eliminated; C1, Chatham County pumping eliminated; C1, southern Beaufort County pumping eliminated; D1, Regional Economic Models, Inc. projection; D2, County Comprehensive Water-Supply Plans, projection. –, minus; Fla., Florida; Ga., Georgia, S.C., South Carolina]

State	County	Base Case pumpage	Simulated pumpage by scenario and difference from Base Case (estimated 2000 pumpage), in million gallons per day																			
			A		B		C1		C2		D1, 2010		D1, 2020		D1, 2035		D2, 2010		D2, 2020		D2, 2035	
			Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference	Scenario	Difference
Ga.	Jefferson	13.7	8.6	–5.1	13.7	0.0	13.7	0.0	13.7	0.0	13.7	0.0	13.7	0.0	13.7	0.0	13.7	0.0	13.7	0.0	13.7	0.0
	Jenkins	4.6	3.6	–1.0	4.6	0.0	4.6	0.0	4.6	0.0	5.1	0.5	5.4	0.7	5.7	1.1	6.7	2.0	9.1	4.5	13.3	8.6
	Johnson	2.4	2.1	–0.3	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0
	Lanier	2.0	2.0	0.1	2.0	0.0	2.0	0.0	2.0	0.0	2.0	0.0	2.0	0.0	2.0	0.0	2.0	0.0	2.0	0.0	2.0	0.0
	Laurens	9.2	6.8	–2.5	9.2	0.0	9.2	0.0	9.2	0.0	9.2	0.0	9.2	0.0	9.2	0.0	9.2	0.0	9.2	0.0	9.2	0.0
	Liberty	15.7	16.1	0.4	15.7	0.0	15.7	0.0	15.7	0.0	18.1	2.3	19.5	3.8	22.3	6.6	22.2	6.5	24.1	8.4	27.0	11.3
	Long	0.8	0.3	–0.5	0.8	0.0	0.8	0.0	0.8	0.0	0.9	0.2	1.0	0.3	1.2	0.4	4.9	4.1	4.8	4.0	5.4	4.6
	Mcintosh	0.9	1.1	0.2	0.9	0.0	0.9	0.0	0.9	0.0	1.2	0.3	1.3	0.4	1.5	0.6	2.3	1.5	3.0	2.2	3.9	3.0
	Montgomery	1.8	2.7	0.9	1.8	0.0	1.8	0.0	1.8	0.0	1.8	0.0	1.8	0.0	1.8	0.0	1.8	0.0	1.8	0.0	1.8	0.0
	Pierce	6.2	3.4	–2.8	6.2	0.0	6.2	0.0	6.2	0.0	5.8	–0.4	6.2	–0.0	6.6	0.4	5.7	–0.5	6.8	0.6	7.9	1.7
	Pulaski	13.3	9.9	–3.4	13.3	0.0	13.3	0.0	13.3	0.0	13.3	0.0	13.3	0.0	13.3	0.0	13.3	0.0	13.3	0.0	13.3	0.0
	Screven	18.6	7.6	–10.9	18.6	0.0	18.6	0.0	18.6	0.0	20.1	1.5	21.1	2.5	22.4	3.8	24.6	6.1	34.9	16.3	49.0	30.4
	Tattnall	3.8	3.9	0.1	3.8	0.0	3.8	0.0	3.8	0.0	6.4	2.6	6.8	3.0	7.3	3.5	34.3	30.5	53.6	49.8	60.9	57.1
	Telfair	4.4	7.2	2.7	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0	4.4	0.0
	Tift	4.2	4.5	0.3	4.2	0.0	4.2	0.0	4.2	0.0	4.2	0.0	4.2	0.0	4.2	0.0	4.2	0.0	4.2	0.0	4.2	0.0
	Toombs	7.0	4.4	–2.5	7.0	0.0	7.0	0.0	7.0	0.0	6.8	–0.2	7.2	0.2	7.7	0.7	17.2	10.2	20.9	13.9	26.4	19.4
	Treutlen	1.2	1.4	0.2	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0
	Turner	3.0	3.4	0.4	3.0	0.0	3.0	0.0	3.0	0.0	3.0	0.0	3.0	0.0	3.0	0.0	3.0	0.0	3.0	0.0	3.0	0.0
	Ware	8.5	6.0	–2.5	8.5	0.0	8.5	0.0	8.5	0.0	8.0	–0.5	8.6	0.2	9.5	1.0	11.7	3.2	13.9	5.4	19.5	11.0
	Washington	18.1	16.9	–1.2	18.1	0.0	18.1	0.0	18.1	0.0	18.1	0.0	18.1	0.0	18.1	0.0	18.1	0.0	18.1	0.0	18.1	0.0
	Wayne	63.5	63.6	0.1	63.5	0.0	63.5	0.0	63.5	0.0	65.0	1.5	72.3	8.8	85.6	22.1	64.0	0.5	60.5	–3.0	62.7	–0.8
	Wheeler	1.2	2.6	1.4	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0	1.2	0.0
	Wilcox	17.3	9.9	–7.4	17.3	0.0	17.3	0.0	17.3	0.0	17.3	0.0	17.3	0.0	17.3	0.0	17.3	0.0	17.3	0.0	17.3	0.0
S.C.	Allendale	9.6	9.9	0.3	9.6	0.0	9.6	0.0	9.6	0.0	9.6	0.0	9.6	0.0	9.6	0.0	9.6	0.0	9.6	0.0	9.6	0.0
	Bamberg	6.3	4.0	–2.3	6.3	0.0	6.3	0.0	6.3	0.0	6.3	0.0	6.3	0.0	6.3	0.0	6.3	0.0	6.3	0.0	6.3	0.0
	Barnwell	7.5	4.9	–2.6	7.5	0.0	7.5	0.0	7.5	0.0	7.5	0.0	7.5	0.0	7.5	0.0	7.5	0.0	7.5	0.0	7.5	0.0
	Beaufort	21.7	30.5	8.8	21.7	0.0	21.7	0.0	4.9	–16.8	21.7	0.0	21.7	0.0	21.7	0.0	21.7	0.0	21.7	0.0	21.7	0.0
	Colleton	0.5	0.5	–0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0
	Hampton	8.6	6.0	–2.6	8.6	0.0	8.6	0.0	8.6	0.0	8.6	0.0	8.6	0.0	8.6	0.0	8.6	0.0	8.6	0.0	8.6	0.0
	Jasper	3.4	2.1	–1.2	3.4	0.0	3.4	0.0	3.4	0.0	3.4	0.0	3.4	0.0	3.4	0.0	3.4	0.0	3.4	0.0	3.4	0.0
ALL		**815.2**	**741.7**	**–73.5**	**779.5**	**–35.7**	**743.9**	**–71.4**	**798.4**	**–16.8**	**829.0**	**13.8**	**858.3**	**43.1**	**911.8**	**96.6**	**1,105.3**	**290.0**	**1,184.3**	**369.1**	**1,388.9**	**573.7**

MODFLOW model and its SUTRA-based counterpart were satisfactorily calibrated, the SUTRA model was refined and recalibrated in the Savannah–Hilton Head Island study area to create a transport model suitable for simulating observed saltwater intrusion at and near Hilton Head Island. The SUTRA model was calibrated to estimated chloride values during 2000, 2002, 2003, and 2004, assuming a transient stress response, using variable time-step lengths. Payne and others (2005) and Provost and others (2006) describe details of the model development process for the MODFLOW model and the SUTRA model, respectively.

Model Framework

In general, the framework, including hydrologic unit layering, distribution of hydraulic conductivity and permeability, pumpage distribution, and model extent are common to both models. The model boundaries cover approximately the same area, comprising about 42,155 mi^2 (fig. 1). The models generally differ in discretization, calibration conditions, and to some degree, in distribution of hydraulic properties and boundary conditions. Provost and others (2006) describe in detail similarities and differences between the two models.

Hydrologic-Unit Layering

Both models comprise seven hydrologic units (fig. 3). These include, in descending order:

- the surficial aquifer system (unit 1),
- Brunswick aquifer system confining unit (unit 2),
- Upper and Lower Brunswick aquifers grouped together to form the Brunswick aquifer system (unit 3),
- Upper Floridan aquifer confining unit (unit 4),
- Upper Floridan aquifer (unit 5),
- Lower Floridan aquifer confining unit (unit 6), and
- Lower Floridan aquifer (unit 7).

In areas where the Brunswick aquifer system is absent, the Upper Floridan aquifer is separated from the surficial aquifer system by a composite of confining units 2, 3, and 4. Payne and others (2005) and Provost and others (2006) describe in detail the thickness, extent, and other hydraulic properties of these units.

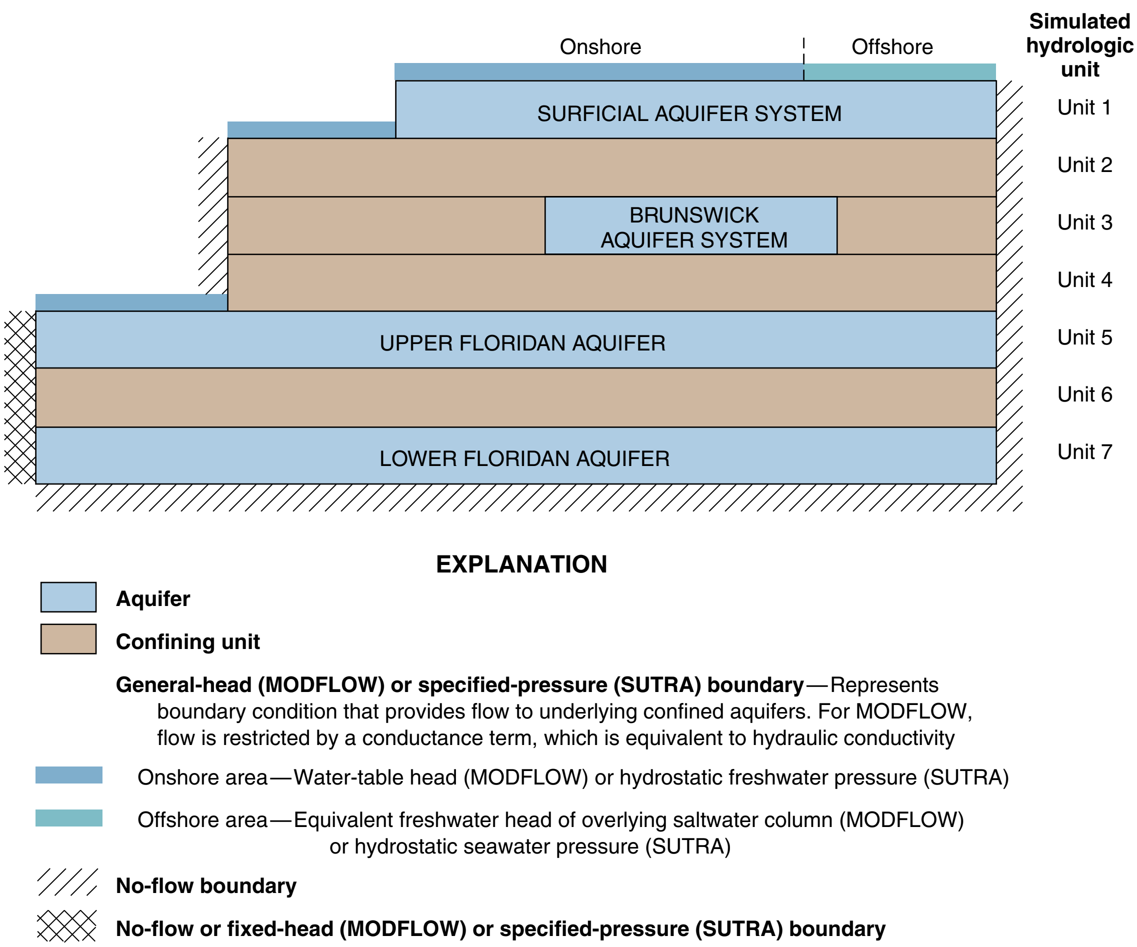


Figure 3. Schematic diagram showing model aquifers and confining units and boundary conditions for MODFLOW and SUTRA models (modified from Payne and others, 2005; Provost and others, 2006).

Hydraulic Properties

The models are designed to have a similar distribution of hydraulic properties that control ground-water flow. MODFLOW uses hydraulic conductivity, and SUTRA uses permeability and additional hydraulic parameters that control solute transport. The hydraulic conductivity distribution from the calibrated MODFLOW model was converted directly into permeability for the SUTRA model. During calibration of the SUTRA model, the permeability distribution was modified for the Savannah–Hilton Head Island study area. The hydraulic conductivity distribution of the MODFLOW model is shown in figure 4 to illustrate generally the distribution of hydraulic properties in the models.

Spatial Discretization

The finite-difference technique used by MODFLOW requires that the simulated area be divided into discrete cells, with uniform properties throughout each cell. The MODFLOW model is horizontally discretized using a variably spaced grid, with cell sizes ranging from about 4,000 by 5,000 feet (ft) to 16,500 by 16,500 ft (fig. 5A). Grid density is higher at Savannah and Brunswick to enable simulation of steeper head gradients near areas of concentrated pumping and to facilitate linkage with smaller-scale, solute-transport models being developed in those areas. Each hydrologic unit is represented with one layer of grid cells in the vertical dimension.

The finite-element technique used by SUTRA (Voss and Provost, 2003) requires that the simulated area be divided into discrete elements, with nodes at each corner of an element. In the SUTRA model, the finite-element mesh is refined laterally in the Savannah–Hilton Head Island study area to allow more detailed representation of the pumping and head distributions and coarsened elsewhere to minimize the number of elements and nodes, and thus the computational demands of the model (fig. 5B). The lateral discretization is further refined in selected areas where saltwater intrusion into the Upper Floridan aquifer has been observed (Camille Ransom III, South Carolina Department of Health and Environmental Control, written commun., 2004). The Upper Floridan aquifer is discretized vertically into 10 elements, and the Lower Floridan aquifer is discretized vertically into 4 elements. The remaining units are each discretized vertically into two elements. Along any given vertical column of nodes, the vertical spacing between nodes is uniform within each hydrologic unit. The mesh is constructed with 4,093 elements and 4,126 nodes in the horizontal dimension, and 24 elements and 25 nodes in the vertical direction. Element sizes range from about 0.003 mi^2 to 774 mi^2.

Boundary Conditions

The bottom boundary for each model is a no-flow boundary. The lateral boundaries on all sides of each model, except for the southern and southwestern sides, also are no-flow boundaries.

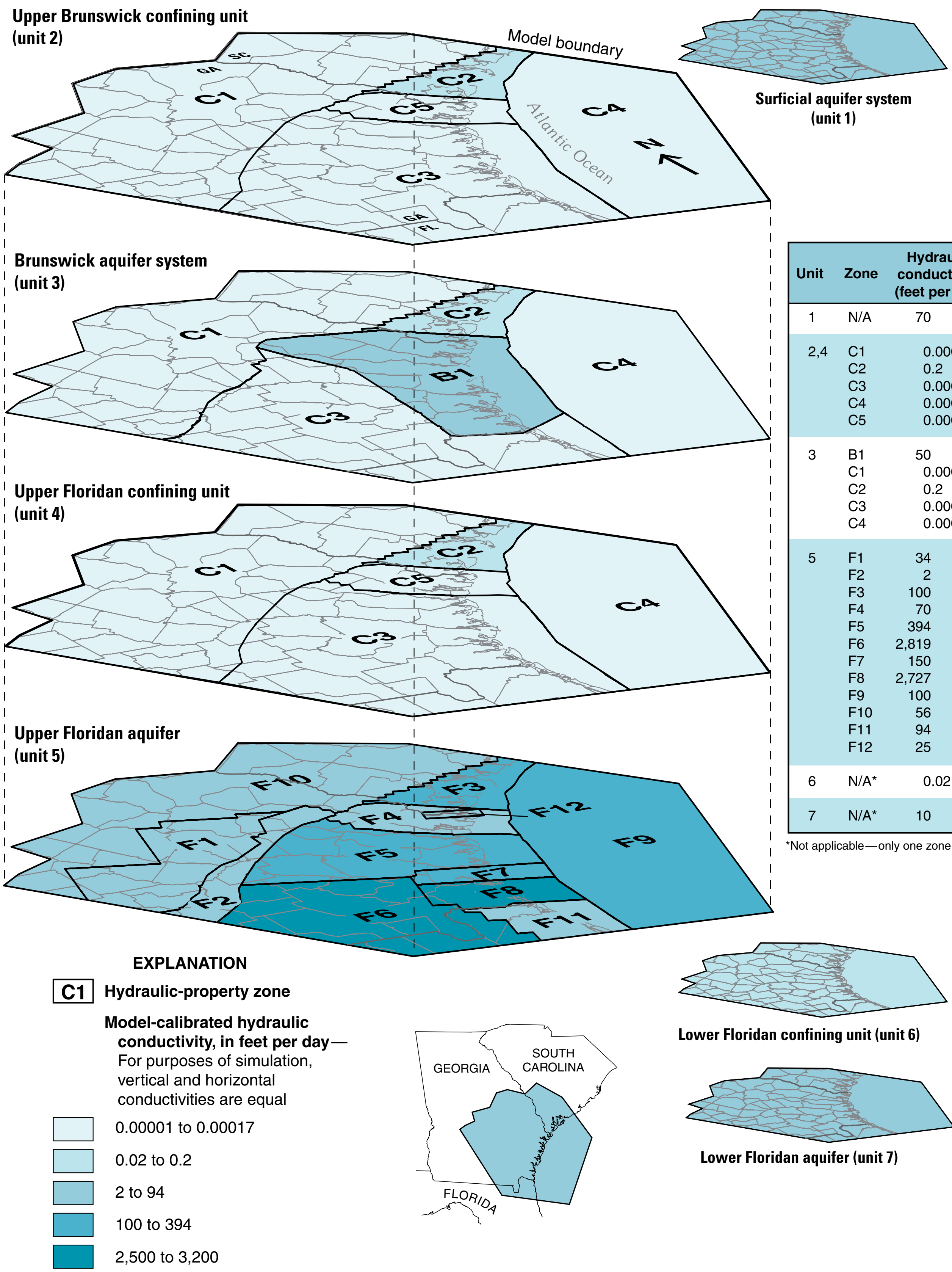
In the MODFLOW model, the southern and southwestern lateral boundaries are set as specified head for the units representing the Upper Floridan aquifer, the Lower Floridan aquifer, and the intervening confining unit. The head is set as uniform for each vertical stack of cells, using values for Upper Floridan aquifer head estimated from potentiometric-surface maps. For the SUTRA model, a corresponding pressure was calculated and applied to nodes representing the Upper Floridan aquifer at this boundary. Pressure is set at each of the nodes in a vertical stack assuming hydrostatic conditions in the middle of the Upper Floridan aquifer.

In the MODFLOW model, the top boundary is set as a head-dependent flux (or general-head) boundary condition, with a controlling specified head and a conductance term that regulates the flux into the top layer of the model. The controlling head is the water-table altitude in the onshore area, and the freshwater equivalent of sea-level altitude (NAVD 88) in the offshore area. In the onshore area, the conductance was calibrated to limit the amount of recharge entering the system in any given grid cell to less than the maximum estimated recharge from baseflow estimates, 10 inches (Payne and others, 2005). For the purpose of simplification, the conductance imposed in the offshore area is large, posing minimal resistance to flow in or out of the system, because little is known about hydraulic properties in the offshore area.

The top boundary for the SUTRA model is set as specified pressure, assuming a freshwater hydrostatic water table in the onshore area, and seawater hydrostatic sea level in the offshore area. The permeability distribution of the confining units above the Upper Floridan aquifer was adjusted in the SUTRA model to account for the resistance associated with the general-head boundary of the MODFLOW model.

Pumpage Distribution

Pumpage data and the method used to derive the spatial distribution of pumpage for model calibration (Taylor and others, 2003) are generally the same for both models, with the following exceptions: (1) the pumpage distribution is derived for more years for the SUTRA model than for the MODFLOW model; and (2) the placement of pumping locations differs in the two models because of differences in spatial discretization (figs. 6 and 7). For the steady-state MODFLOW model, county aggregate and site-specific data were used to estimate average annual pumpage for 1980, 1997, and 2000. For the transient SUTRA model, estimated industrial and public-supply pumpage values were used to estimate the pumpage distributions for 1915, 1920, 1930, 1937, 1940, 1955, 1965, 1970, and 1975; county aggregate and site-specific data were used to estimated pumpage distributions for 1980, 1985, 1990, 1995, September 1998, and 2000. Pumpage distributions were linearly interpolated for intervening years. Pumpage is assigned to hydrologic units 3 (Brunswick aquifer system), 5 (Upper Floridan aquifer), and 7 (Lower Floridan aquifer) for both models. Payne and others (2005) and Provost and others (2006) describe in more detail pumpage distributions used for model calibration.



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

*Not applicable—only one zone per unit

Figure 4. Schematic diagram showing simulated hydraulic-property zones by model unit for the MODFLOW model (modified from Payne and others, 2005).

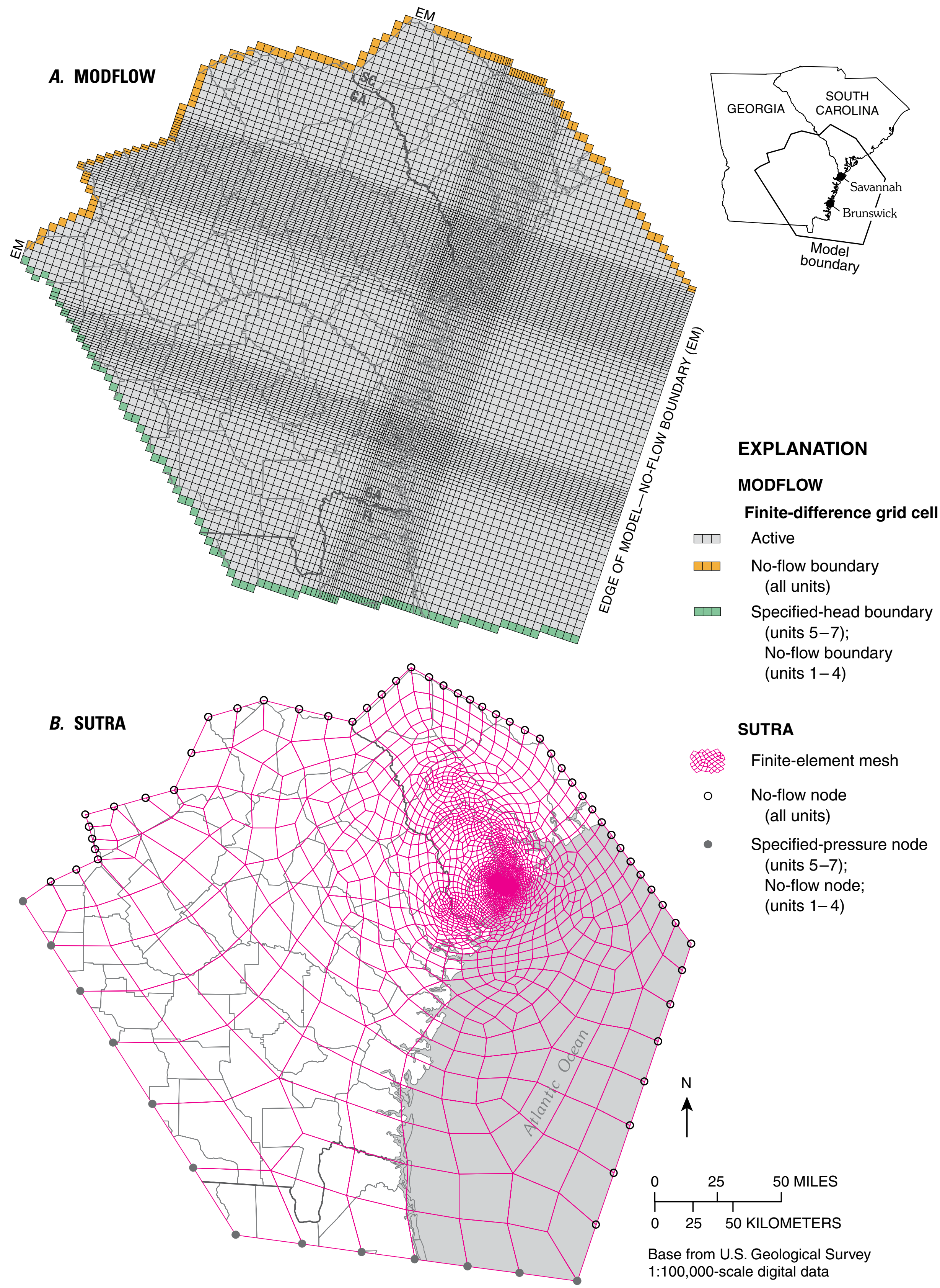


Figure 5. (*A*) Finite-difference grid from MODFLOW model and (*B*) finite-element mesh from SUTRA model (modified from Payne and others, 2005; Provost and others, 2006).

Several of the scenarios presented in this report are based on 2000 pumpage distributions (figs. 6 and 7).

For the MODFLOW model, the sum of site-specific and nonsite-specific pumpage values for 1980 and 2000 were assigned to the model grid cell in which their respective assigned locations and aquifers were situated. For the SUTRA model, site-specific pumpage associated with a given well was assigned to the vertical string of nodes that lies closest to the well (as measured within the horizontal plane) and is divided equally among the nodes that lie between the top and bottom surfaces of the aquifer to which the pumpage is attributed. Outside of Jasper and Beaufort Counties, S.C., nonsite-specific pumpage was located at the same points as in the MODFLOW model and was assigned to nodes in the same manner as site-specific pumpage. Within Jasper and Beaufort Counties, S.C., the total nonsite-specific pumpage for each county was redistributed among the nodes of the finite-element mesh within the counties in the study area in proportion to the area associated with each node. The area associated with each node was estimated by dividing the model volume associated with the node by the vertical node spacing within the aquifer.

Model Calibration

The regional MODFLOW model was calibrated to two assumed stressed, steady-state conditions for 1980 and 2000, using water-level data for the Brunswick aquifer system and the Upper and Lower Floridan aquifers. The SUTRA model was constructed as similarly as possible to the MODFLOW model and was initially calibrated assuming a uniform density distribution and steady-state flow conditions to Upper Floridan aquifer water levels in Beaufort, Hampton, and Jasper Counties, S.C., for September 1998 stress conditions. The SUTRA model was then modified to account for variable-density solute transport, run as a transient simulation from a predevelopment (1885) steady-state flow field to 2004, and calibrated to estimated chloride values during 2000, 2002, 2003, and 2004.

After both models were calibrated and the scenario simulations were run, an error was discovered in pumpage attributed to Durango Paper Company wells in St. Marys, Camden County, Ga. This error results in a 20-percent overestimate in the sum of pumpage for these wells during 2000, compared with reported values. To test the effect of this error on model and scenario results, the 2000 MODFLOW model was corrected and recalibrated. The resulting corrected and recalibrated model simulated heads a maximum of 2–3 ft higher than the original model in the area of the Durango wells. The calculated water-level recovery associated with the elimination of pumping at the Durango wells, however, was approximately the same in the uncorrected and corrected models. Thus, although the absolute simulated water levels differ for the uncorrected and corrected models, the responses to the scenarios, in terms of change in water levels, were principally the same for the uncorrected and corrected models, and the original calibrated (uncorrected) model was used.

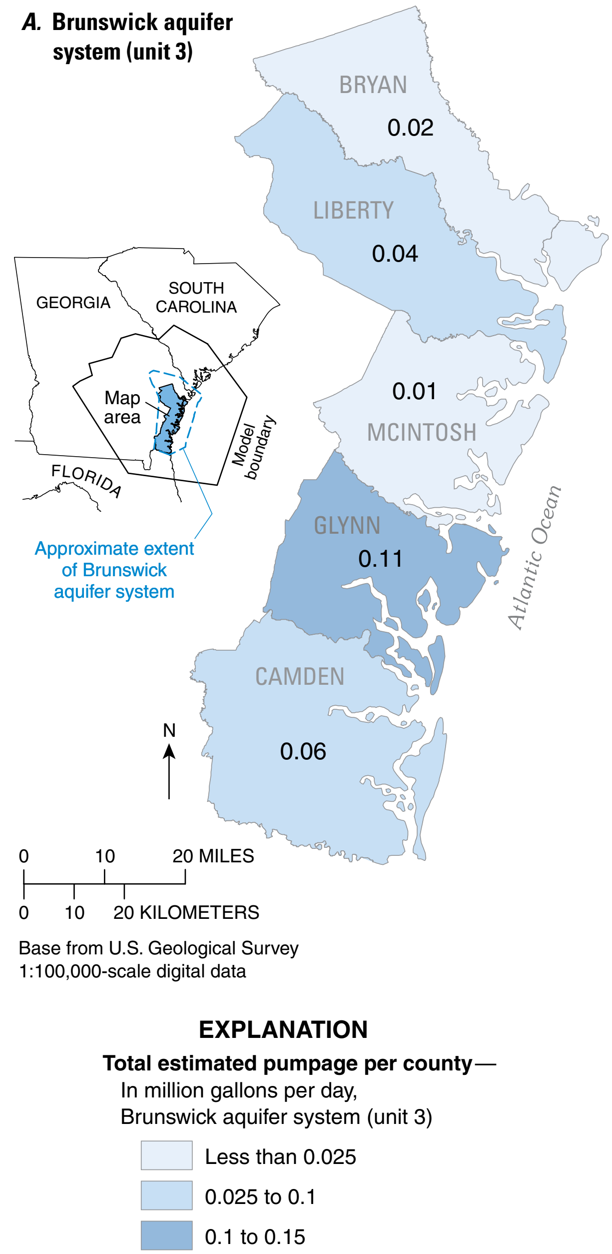


Figure 6. Distribution of ground-water pumpage by model unit for the MODFLOW model, 2000, for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), (*C*) Upper Floridan aquifer (unit 5)—enlarged view, and (*D*) Lower Floridan aquifer (unit 7). Values rounded to 0.01 million gallons per day, values may differ from values shown in table 2 and figure 11 because of rounding (modified from Payne and others, 2005).

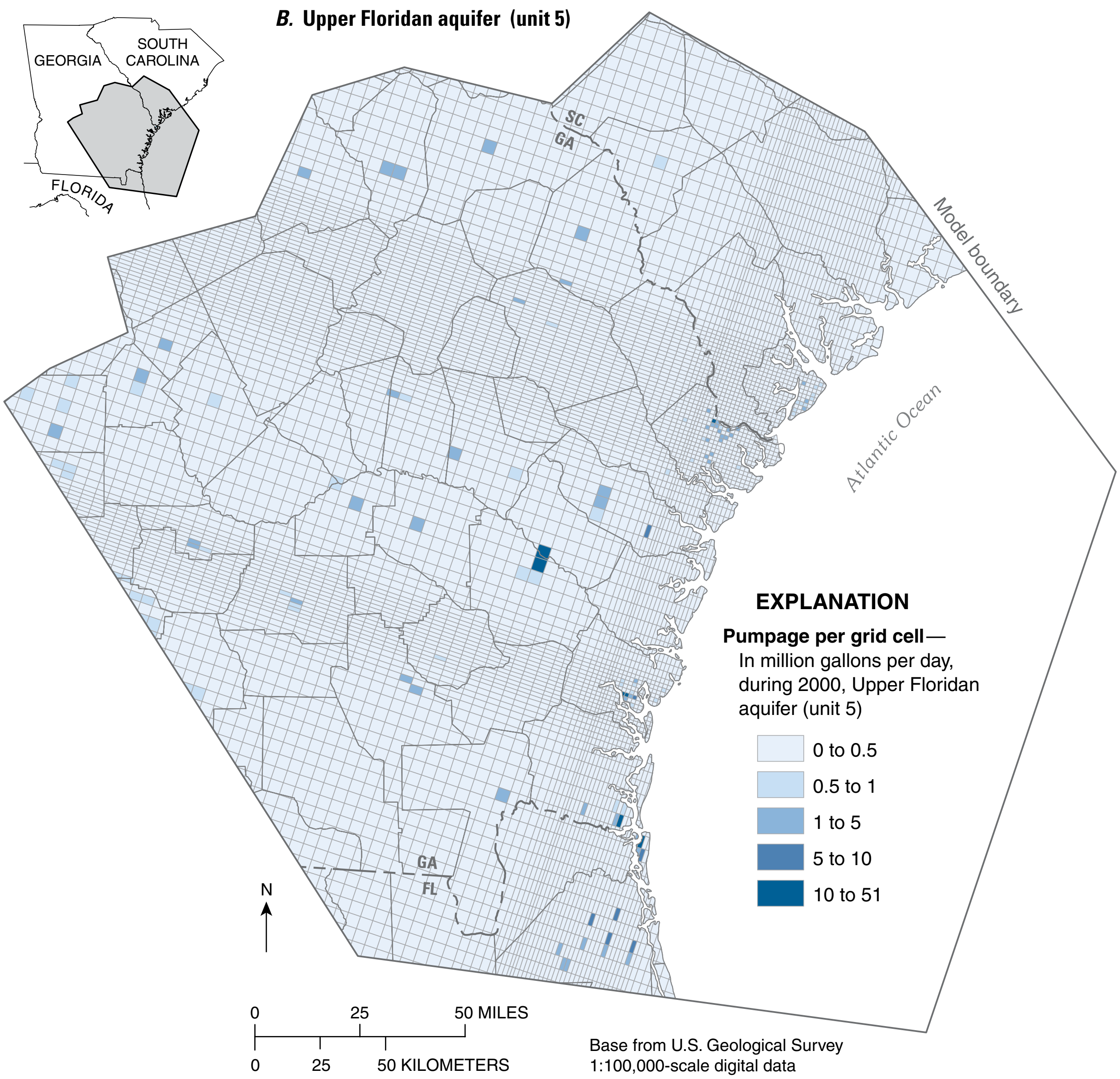


Figure 6. Distribution of ground-water pumpage by model unit for the MODFLOW model, 2000, for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), (*C*) Upper Floridan aquifer (unit 5)—enlarged view, and (*D*) Lower Floridan aquifer (unit 7) (modified from Payne and others, 2005)—continued.

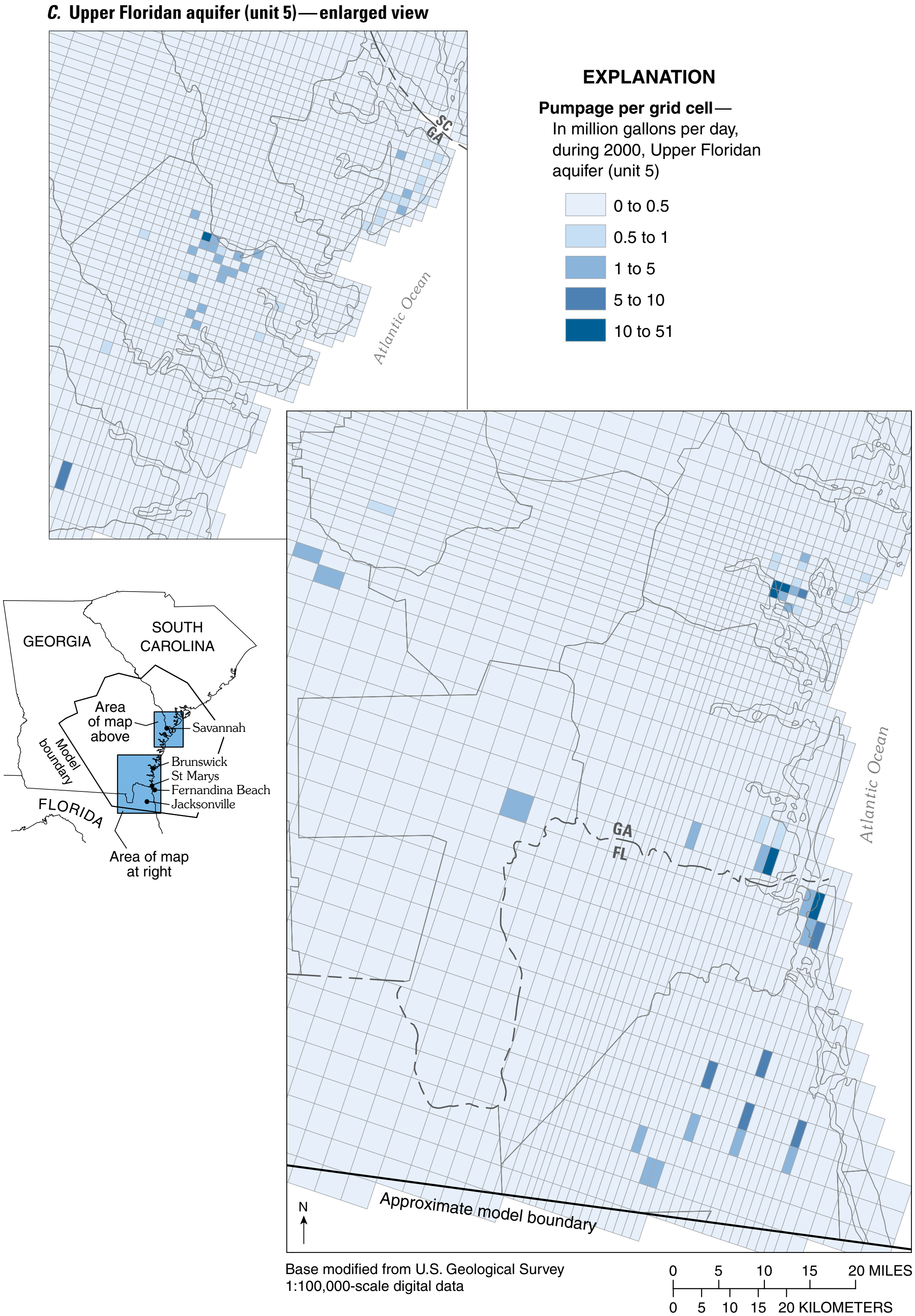


Figure 6. Distribution of ground-water pumpage by model unit for the MODFLOW model, 2000, for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), (*C*) Upper Floridan aquifer (unit 5)—enlarged view, and (*D*) Lower Floridan aquifer (unit 7) (modified from Payne and others, 2005)—continued.

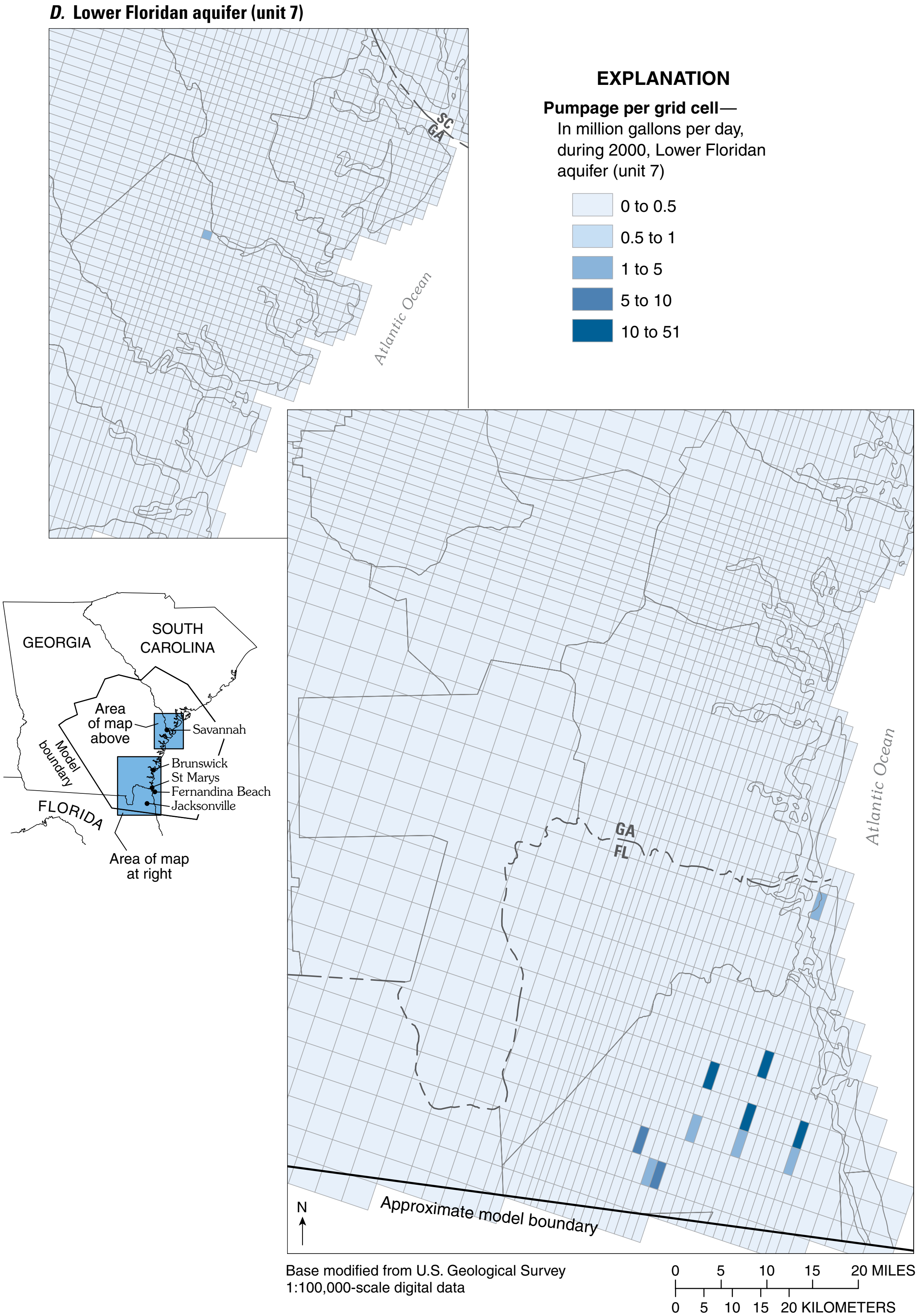


Figure 6. Distribution of ground-water pumpage by model unit for the MODFLOW model, 2000, for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), (*C*) Upper Floridan aquifer (unit 5)—enlarged view, and (*D*) Lower Floridan aquifer (unit 7) (modified from Payne and others, 2005)—continued.

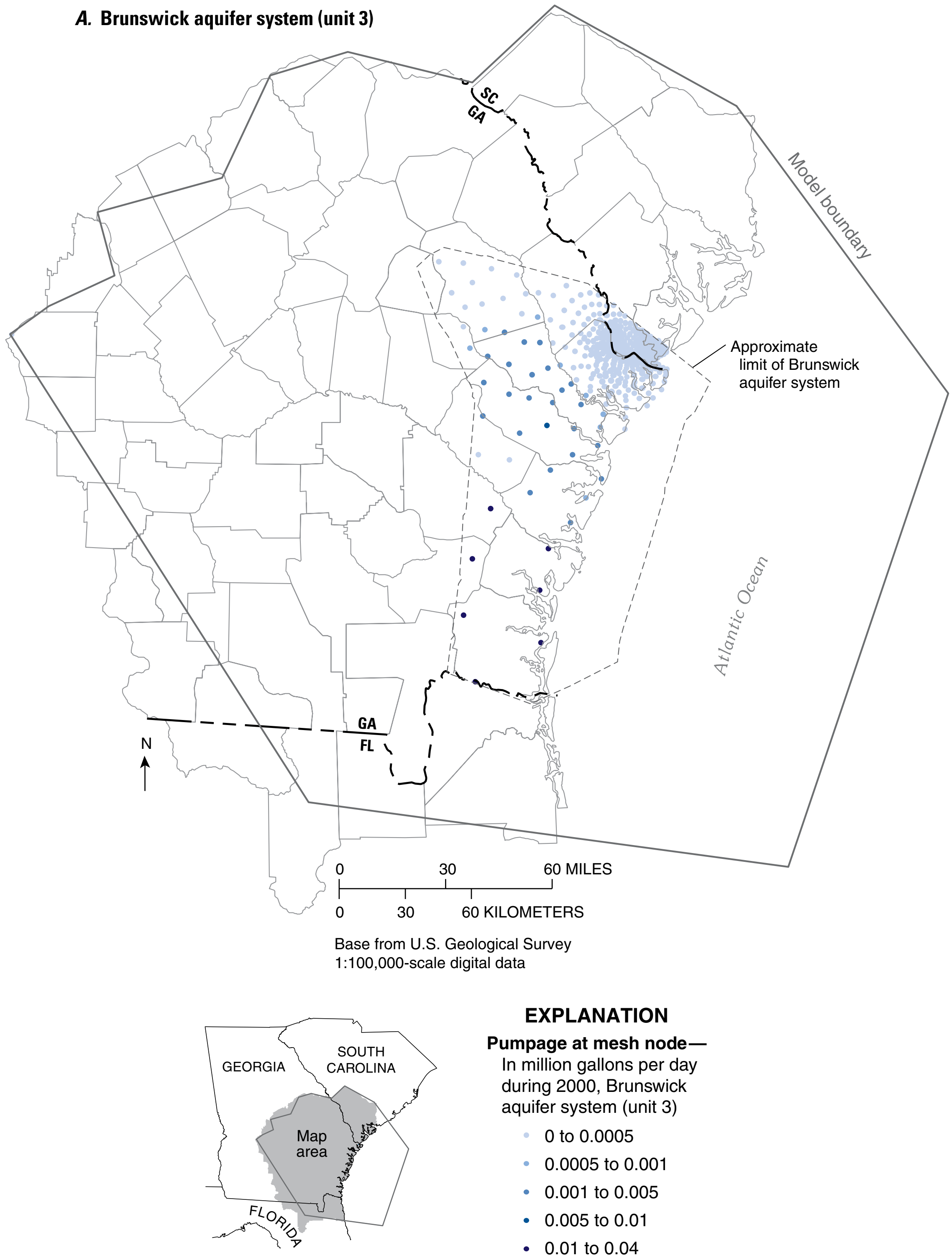


Figure 7. Distribution of ground-water pumpage by model unit for the SUTRA model, 2000, for the (*A*) Brunswick aquifer system (unit 3); (*B*) Upper Floridan aquifer (unit 5), model area; (*C*) Upper Floridan aquifer (unit 5), study area; (*D*) Lower Floridan aquifer (unit 7), model area; and (*E*) Lower Floridan aquifer (unit 7), study area.

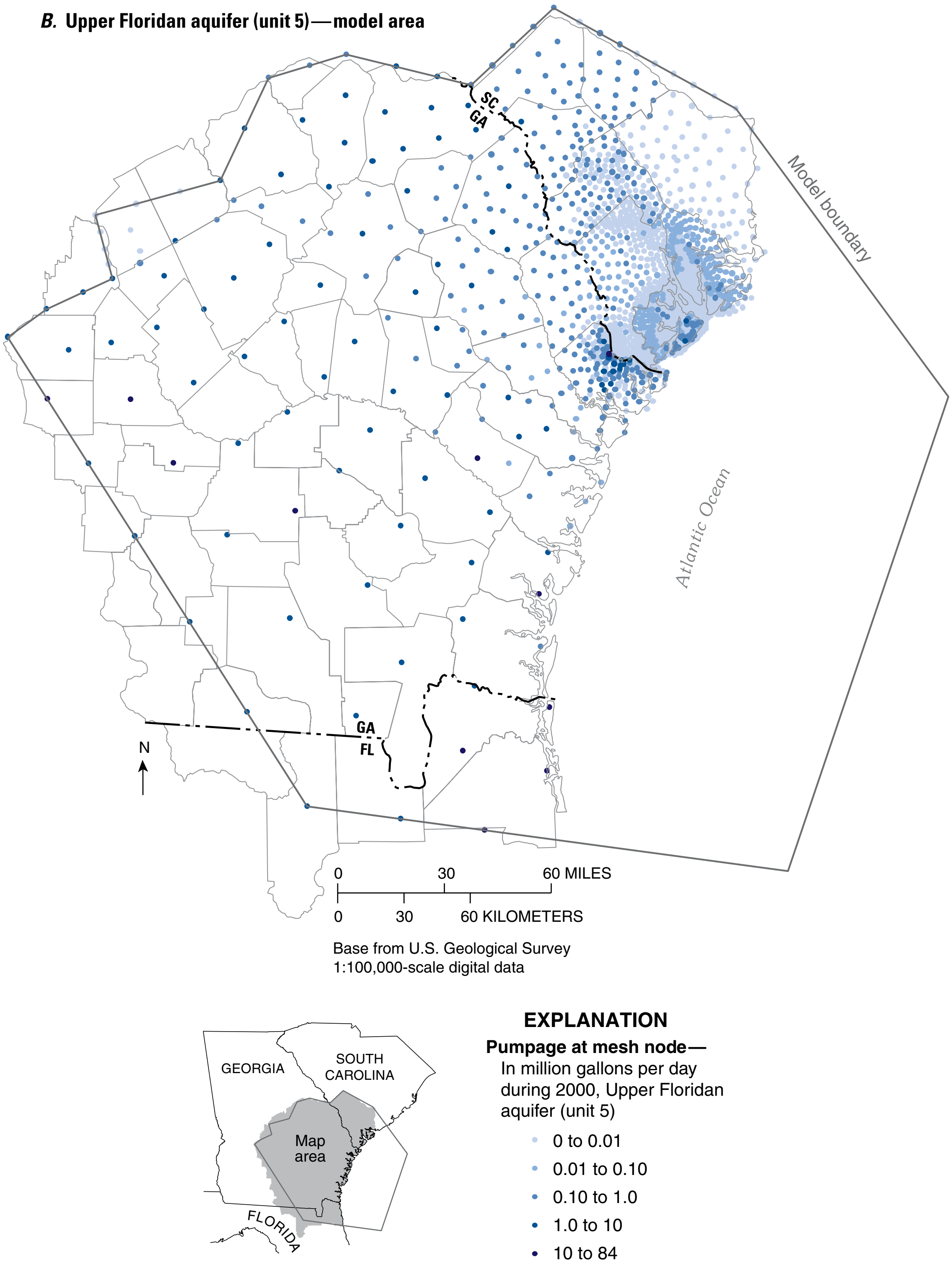


Figure 7. Distribution of ground-water pumpage by model unit for the SUTRA model, 2000, for the (*A*) Brunswick aquifer system (unit 3); (*B*) Upper Floridan aquifer (unit 5), model area; (*C*) Upper Floridan aquifer (unit 5), study area; (*D*) Lower Floridan aquifer (unit 7), model area; and (*E*) Lower Floridan aquifer (unit 7), study area—continued.

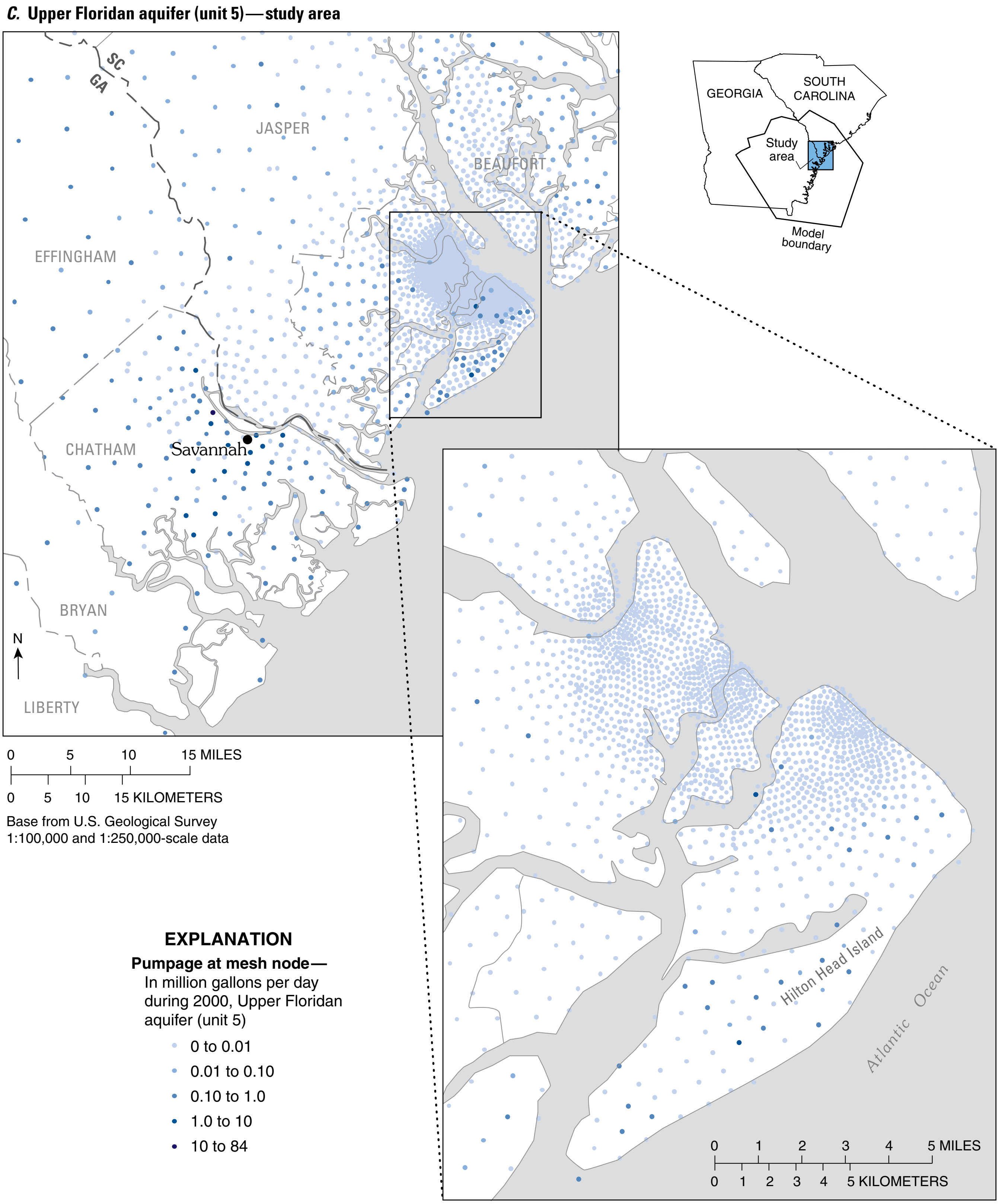


Figure 7. Distribution of ground-water pumpage by model unit for the SUTRA model, 2000, for the (*A*) Brunswick aquifer system (unit 3); (*B*) Upper Floridan aquifer (unit 5), model area; (*C*) Upper Floridan aquifer (unit 5), study area; (*D*) Lower Floridan aquifer (unit 7), model area; and (*E*) Lower Floridan aquifer (unit 7), study area—continued.

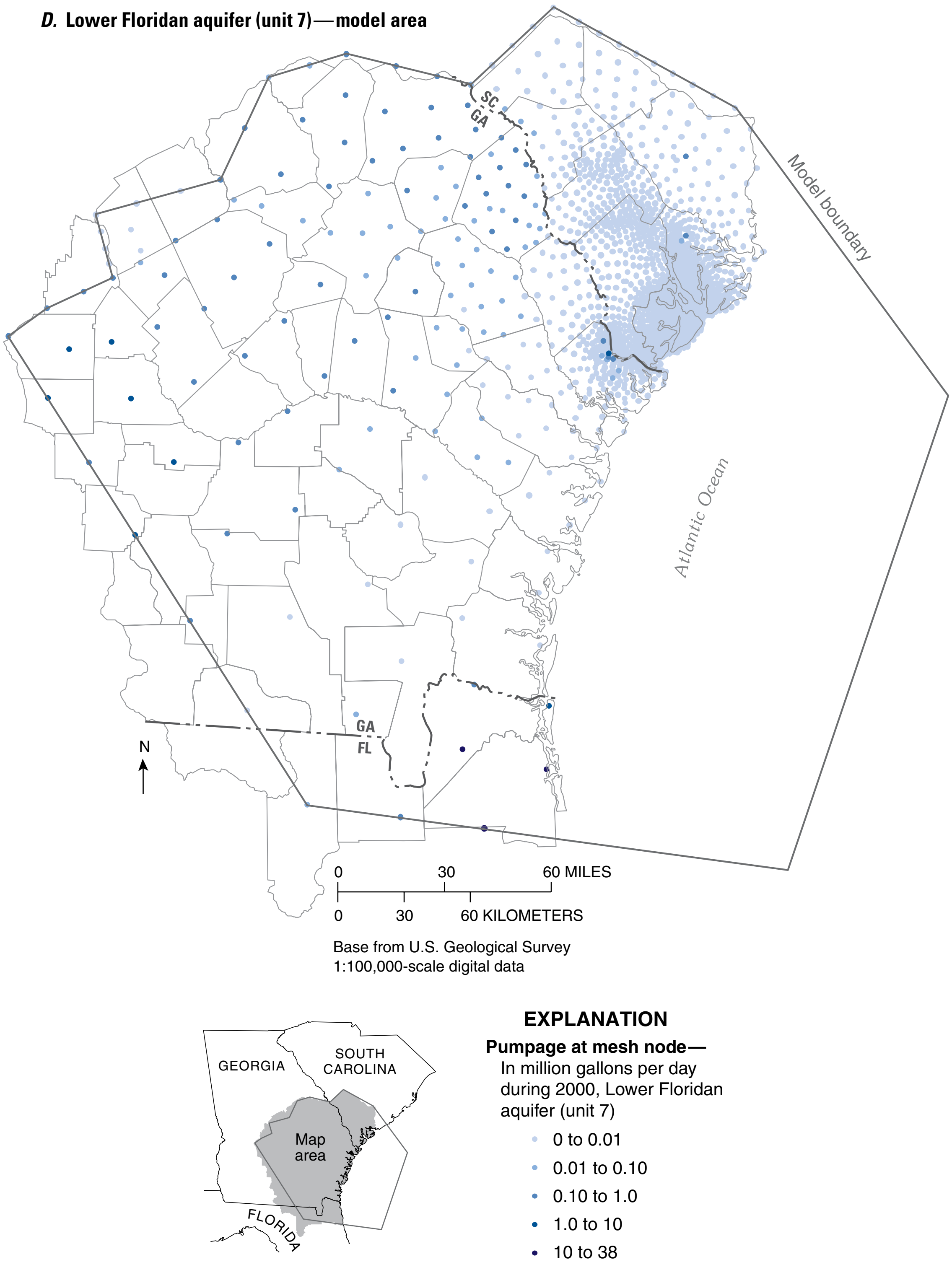
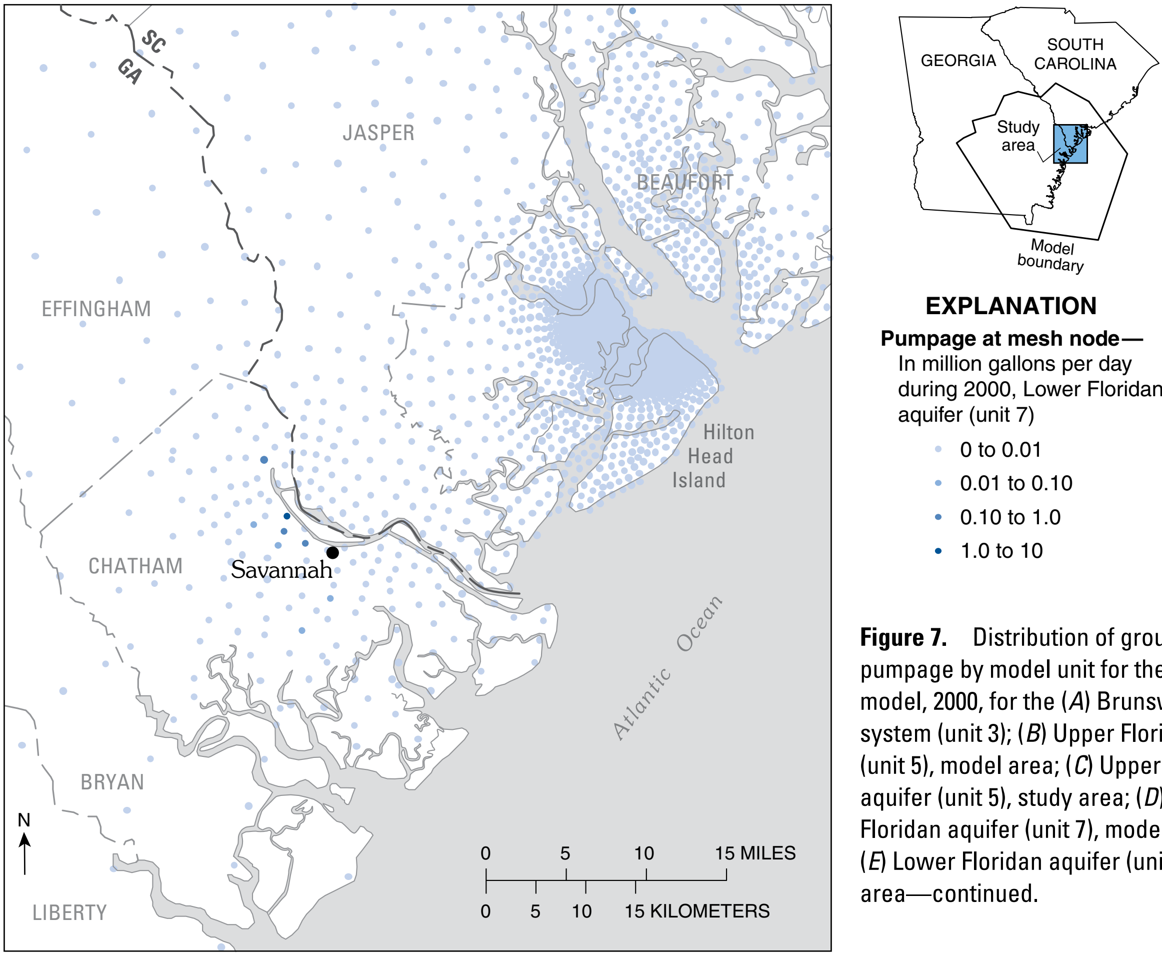


Figure 7. Distribution of ground-water pumpage by model unit for the SUTRA model, 2000, for the (*A*) Brunswick aquifer system (unit 3); (*B*) Upper Floridan aquifer (unit 5), model area; (*C*) Upper Floridan aquifer (unit 5), study area; (*D*) Lower Floridan aquifer (unit 7), model area; and (*E*) Lower Floridan aquifer (unit 7), study area—continued.

E. **Lower Floridan aquifer (unit 7)—study area**



Base from U.S. Geological Survey
1:100,000 and 1:250,000-scale data

Figure 7. Distribution of ground-water pumpage by model unit for the SUTRA model, 2000, for the (*A*) Brunswick aquifer system (unit 3); (*B*) Upper Floridan aquifer (unit 5), model area; (*C*) Upper Floridan aquifer (unit 5), study area; (*D*) Lower Floridan aquifer (unit 7), model area; and (*E*) Lower Floridan aquifer (unit 7), study area—continued.

Base Case Simulations: Representation of the Flow System during 2000

Simulation results for all scenarios are compared with those calculated for 2000, herein called the "Base Case." For the MODFLOW model, Base Case results are the product of a steady-state simulation for 2000 pumping conditions. For the SUTRA model, Base Case results are the product of a transient simulation using a time-varying, estimated pumping history from predevelopment to 2000, evaluated during 2000.

The regional MODFLOW model was calibrated to 2000 conditions. Major features in the potentiometric surface in the model area simulated by the MODFLOW model include the following: (1) a large cone of depression in the Chatham County, Ga., area, centered at Savannah; (2) a smaller cone of depression at Duval County, Fla., with the depression extending north to the southern part of Camden County, Ga.; (3) broadly spaced potentiometric contours in the southwestern part of the model area indicating a low head gradient; and (4) closely spaced potentiometric contours in the center of the model in the Gulf Trough area, representing a steep head gradient (fig. 8). Results for the Base Case simulation, as from all scenarios, also show an apparent similarity in predicted potentiometric surfaces for the Upper and Lower Floridan aquifers. Although the general similarity of simulated water levels indicates an interaquifer leakage response, Lower Floridan aquifer water-level data with which to calibrate the model are sparse, and there are few or no data to estimate the hydraulic conductivity of the Lower Floridan aquifer or the overlying confining unit (Payne and others, 2005). Additional information on the hydraulic properties of the Lower Floridan aquifer and the overlying confining unit are necessary to simulate more accurately the interaction between the Upper and Lower Floridan aquifers. Details on calibrated model fit are provided in Payne and others (2005). In the Savannah–Hilton Head Island study area, the predominant feature in the potentiometric surface simulated by the SUTRA model is the cone of depression centered in Savannah (fig. 9). Smaller potentiometric depressions and mounds superimposed on this surface represent localized pumping and recharge areas, respectively. Differences between potentiometric surfaces simulated by the regional MODFLOW model and the Savannah–Hilton Head Island solute-transport model are the result of different spatial discretization, calibration, and fundamental differences in simulators (Provost and others, 2006).

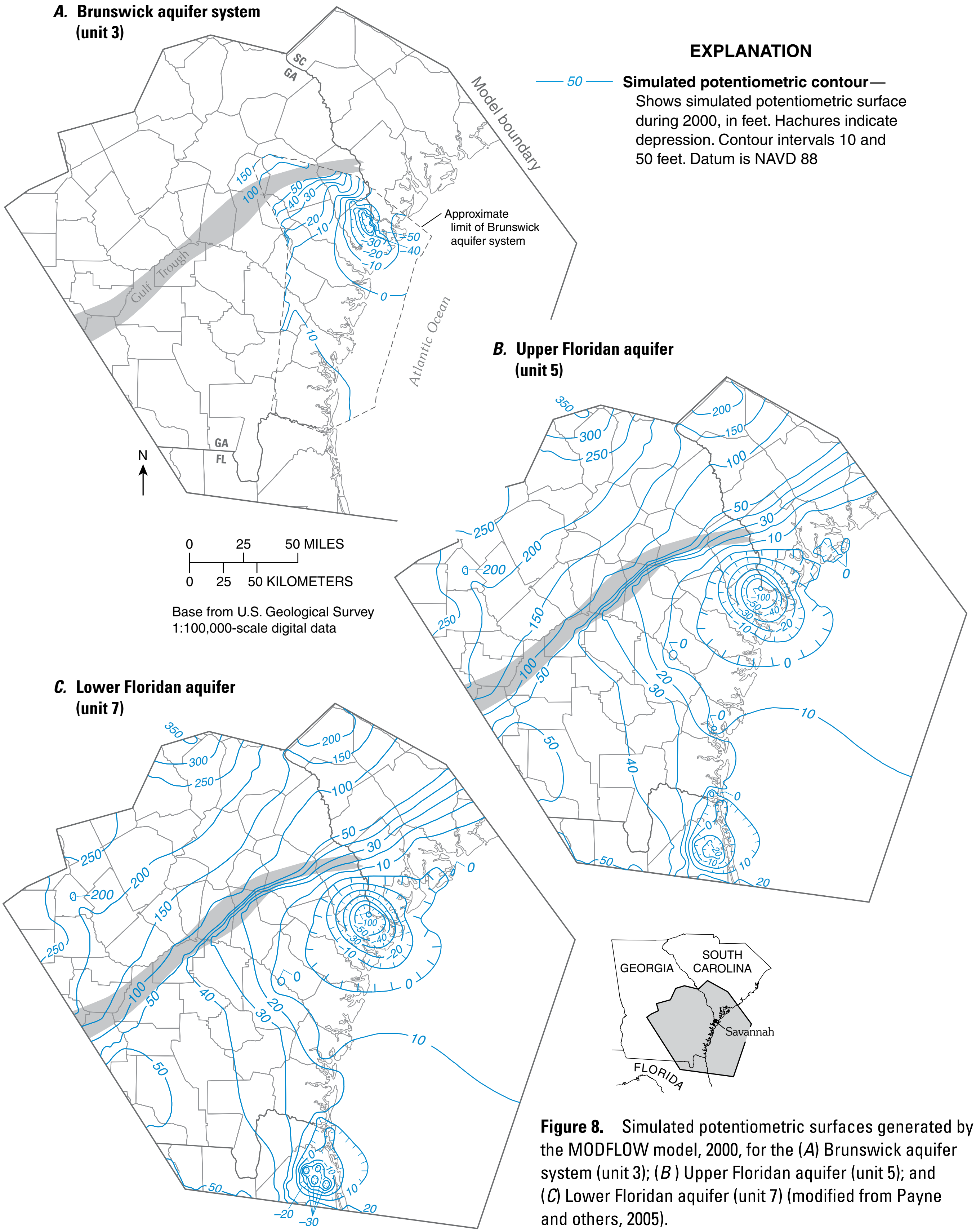


Figure 8. Simulated potentiometric surfaces generated by the MODFLOW model, 2000, for the (*A*) Brunswick aquifer system (unit 3); (*B*) Upper Floridan aquifer (unit 5); and (*C*) Lower Floridan aquifer (unit 7) (modified from Payne and others, 2005).

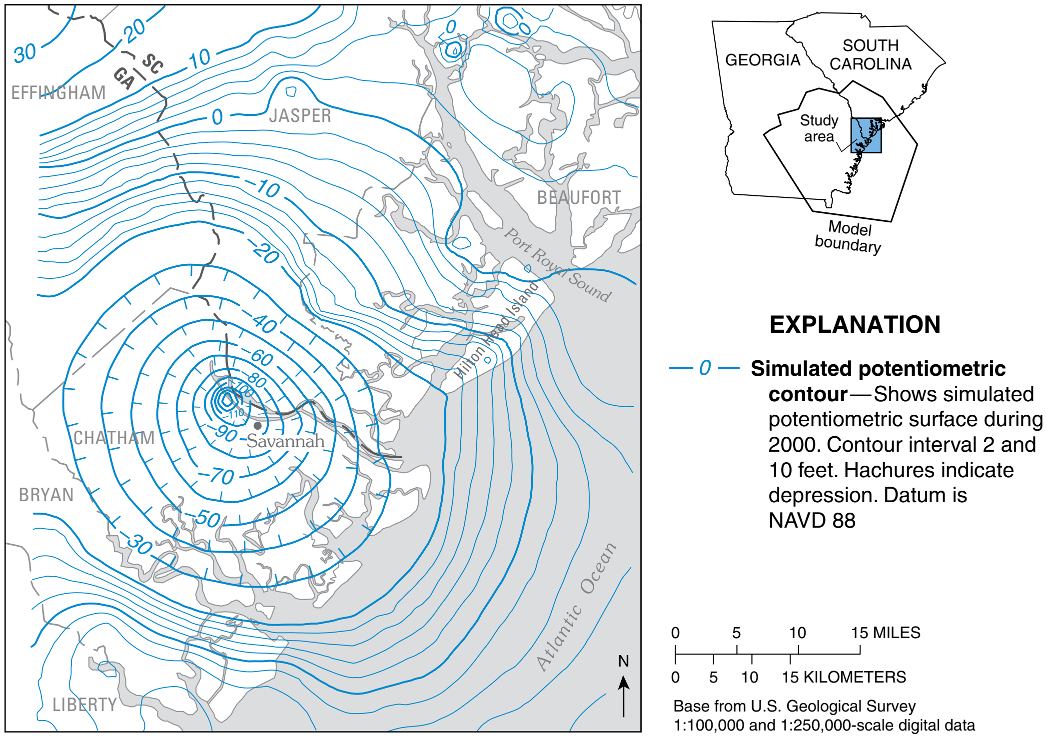


Figure 9. Potentiometric surface of the Upper Floridan aquifer generated by the SUTRA model, 2000 (modified from Provost and others, 2006).

Table 2. Flow-budget components for the Base Case, 2000.

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

Model unit	Inflow				Outflow				
	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
1	286.29	23.76	—	310.05	115.67	15.51	—	—	131.18
2	46.58	—	—	46.58	3.62	—	—	—	3.62
3	—	—	—	—	—	—	—	0.24	0.24
4	—	—	—	—	—	—	—	—	—
5	141.32	—	712.39	853.71	22.28	—	267.77	669.43	959.48
6	—	—	0.00	0.00	—	—	0.00	—	0.00
7	—	—	15.46	15.46	—	—	2.32	128.67	130.99
Total all units	**474.19**	**23.76**	**727.86**	**1,225.81**	**141.57**	**15.51**	**270.09**	**798.34**	**1,225.51**
Percent flow	**38.7**	**1.9**	**59.4**	**100.0**	**11.6**	**1.3**	**22.0**	**65.1**	**100.0**

Flow-budget components calculated from the 2000 MODFLOW simulation show major components of recharge to and discharge from the system, and are used as a base to compare with the scenarios (table 2; fig. 10). The simulated water budget for the Base Case indicates that the system is primarily recharged by inflow from the specified-head boundary in unit 5, the Upper Floridan aquifer (table 2; fig. 10). Most of the outflow from the system is discharge to wells, primarily in unit 5.

The SUTRA model accounts for the hypothesized downward leakage of saltwater from marine and estuarine sources through the Upper Floridan confining unit and the predominantly lateral flow along head gradients in the Upper Floridan aquifer. Specifically, the model is intended to simulate the observed occurrence of saltwater intrusion in the Upper Floridan aquifer at the northern end of Hilton Head Island, at Pinckney Island, and near the Colleton River, S.C., for 2000 (fig. 11), yet the model does not preclude the simulated occurrence of saltwater intrusion in other areas. In addition, the SUTRA model was used to simulate the system through 2100, maintaining the 2000 pumpage from 2000 to 2100. Results serve as a comparison with other scenarios for 2010, 2020, 2035 and 2100 (fig. 12). Details of the SUTRA model calibration to September 1998 water levels, and 2000, 2002, 2003, and 2004 chloride distributions are in Provost and others (2006).

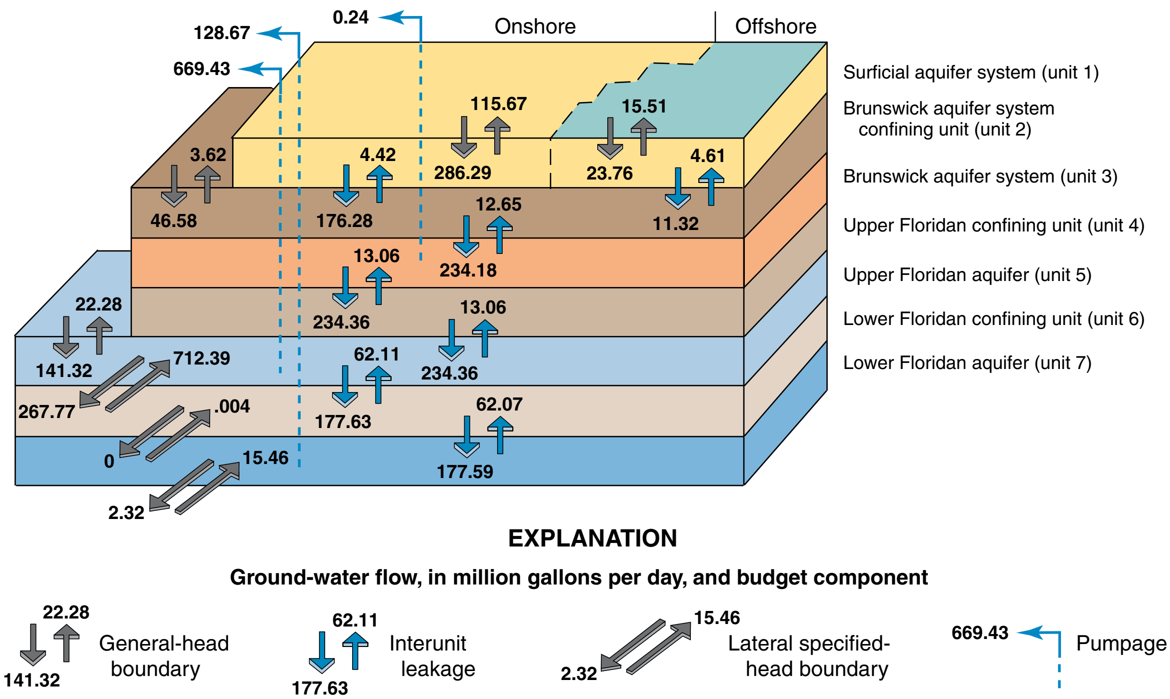


Figure 10. Schematic diagram showing simulated flow-budget components and values for the Base Case (2000) (modified from Payne and others, 2005).

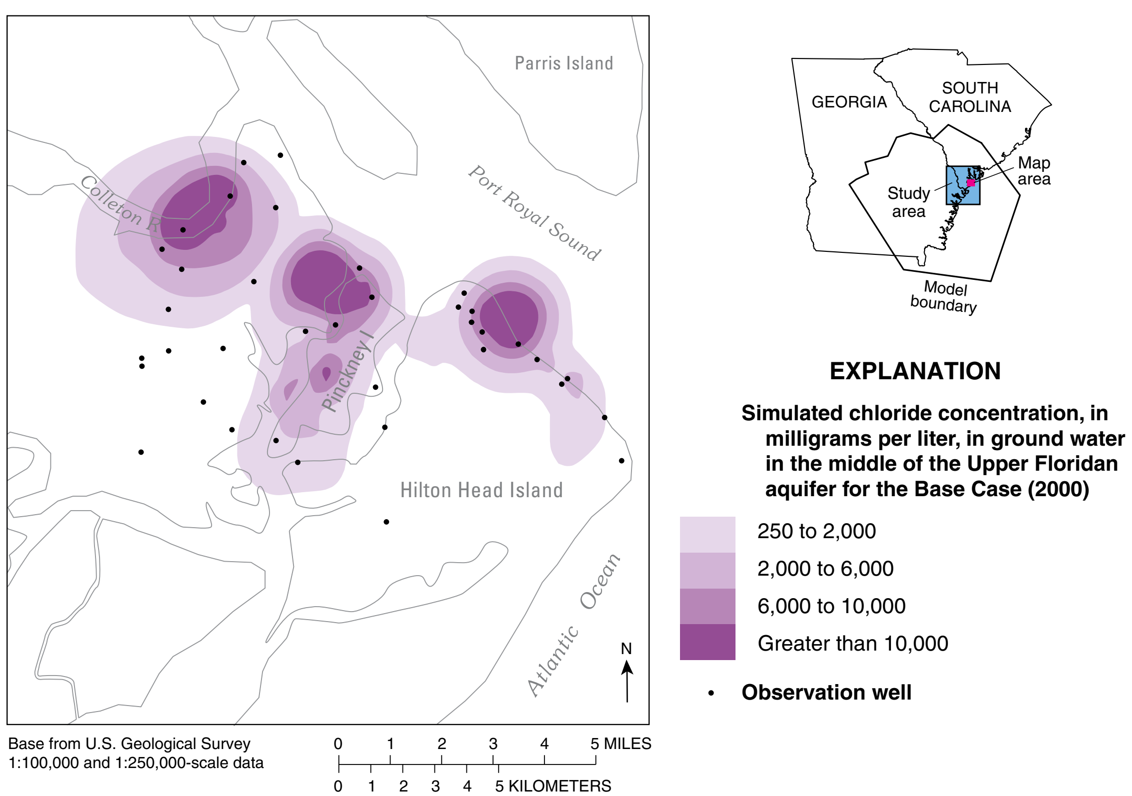


Figure 11. Simulated chloride concentration in ground water in the middle of the Upper Floridan aquifer in the Hilton Head Island, South Carolina, area for the Base Case (2000) (modified from Provost and others, 2006).

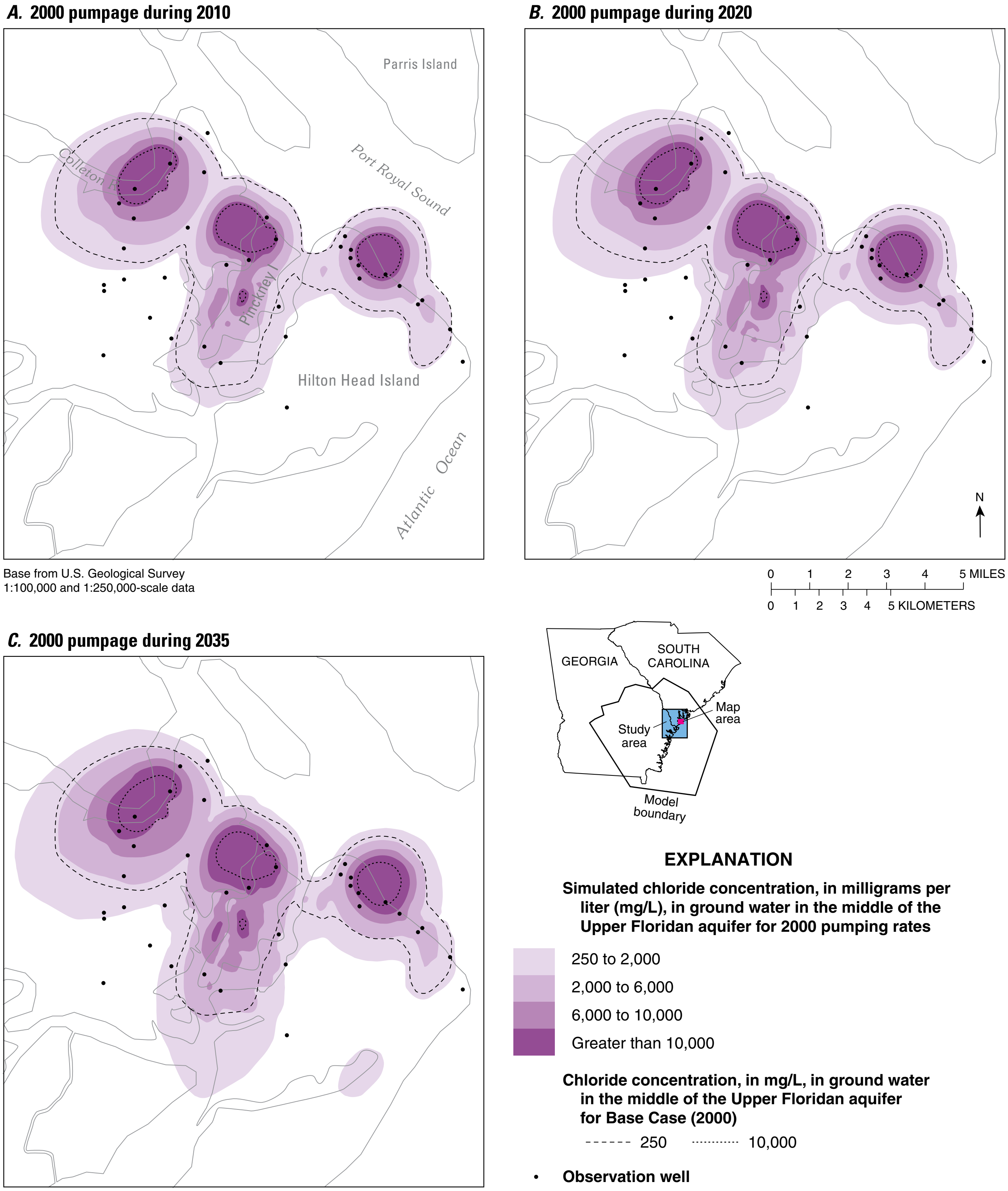


Figure 12. Simulated chloride concentration in ground water in the middle of the Upper Floridan aquifer in the Hilton Head Island, South Carolina, area for 2000 pumpage during (*A*) 2010, (*B*) 2020, (*C*) 2035, and (*D*) 2100 (larger area; modified from Provost and others, 2006).

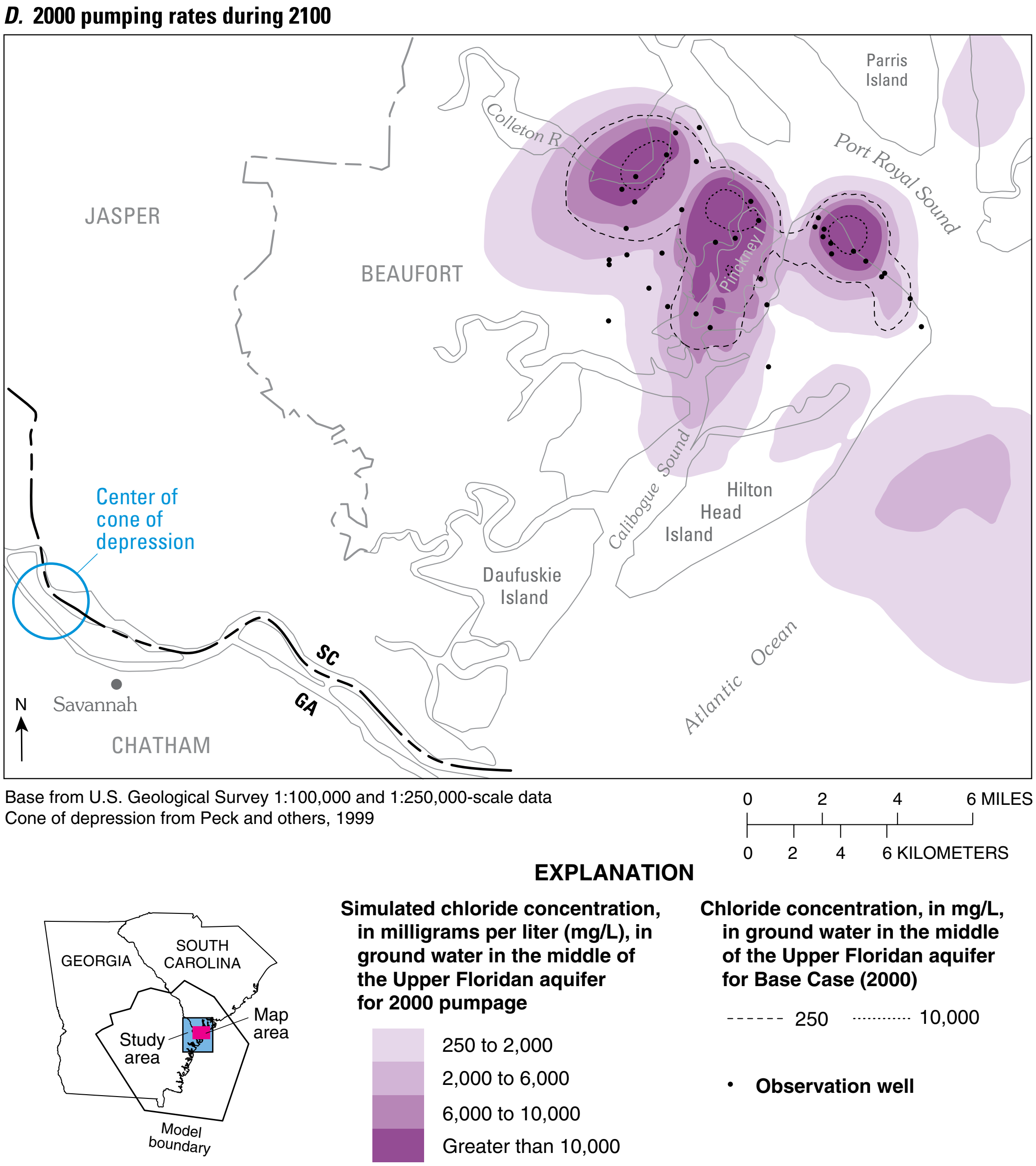


Figure 12. Simulated chloride concentration in ground water in the middle of the Upper Floridan aquifer in the Hilton Head Island, South Carolina, area for 2000 pumpage during (*A*) 2010, (*B*) 2020, (*C*) 2035, and (*D*) 2100 (larger area; modified from Provost and others, 2006)—continued. The center of the Upper Floridan aquifer potentiometric cone of depression identifies the most concentrated pumping in the Savannah, Georgia–Hilton Head Island area.

Simulation of Ground-Water Management Scenarios

The calibrated MODFLOW and SUTRA models were used to provide insight into the potential effect of six different pumping scenarios on regional ground-water flow and local ground-water flow and solute transport in the Savannah–Hilton Head Island area. The scenarios were designed to simulate (1) the flow system during 1997, and during 2002 after a major industrial well shutdown in Camden County, Ga. (Scenarios A and B, respectively); (2) the relative effects of eliminating pumping in Chatham County, Ga., and Beaufort County, S.C. (Scenarios C1 and C2, respectively); and (3) the effects of projected changes in the distribution and amount of ground-water withdrawal during 2000–2035 using two different methods to estimate future pumping (Scenarios D1 and D2). A brief description of and rationale for each scenario is presented in table 3.

Simulated-head and flow-budget components, and differences in these relative to the Base Case, are presented for all scenarios. For Scenarios C1 and C2, simulated-head distributions for the Savannah–Hilton Head Island study area also are presented from the SUTRA model, which is more finely discretized than the regional MODFLOW model. Simulated chloride distributions for the middle of the Upper Floridan aquifer are presented for Scenarios A, C1, C2, D1, and D2.

Pumpage distributions for specific points in time for all scenarios were based on the approach used in Payne and others (2005), using procedures to assign county-aggregate and site-specific data described in Taylor and others (2003). For the Base Case (2000) and Scenario A (1997) simulations, the MODFLOW model simulated 2000 and 1997 steady-state conditions, respectively, and the SUTRA model simulated the pumping history from predevelopment (1885) to 2000 and 1997, respectively. For all other scenarios, the pumpage distributions are based on projected changes in pumpage after 2000. Future water-use distributions for Scenarios D1 and D2 were based on two methods of projection (Leeth and others, 2005). Projected water use was applied to existing withdrawal locations as used for the 2000 simulations. Thus, although withdrawal rates were changed for these scenarios for years after 2000, the locations of pumping are unchanged.

The simulated per-county pumpage may differ from the estimated per-county pumpage for the following reasons (in order of overall importance of contribution to the discrepancy).

Table 3. Description of conditions for pumping scenarios.

[Mgal/d, million gallons per day; GaEPD, Georgia Environmental Protection Division; –, minus; Ga., Georgia; S.C., South Carolina]

Scenario	Description	Purpose	Total difference in pumping relative to the Base Case, (Mgal/d)	Regional flow model results presented (MODFLOW)	Solute-transport model results presented (SUTRA)	Model results presented for years					
						1997	2000	2010	2020	2035	2100
Base Case	2000 pumpage	Reference simulation	0.0	X	X		X	X	X	X	X
A	1997 pumpage	Conditions at time of implementation of GaEPD interim strategy	–73.6	X	X	X					
B	2000 pumpage minus pumpage at sites in St. Marys, Ga.	Model response to major change in localized stress	–35.7	X			X				
C1	2000 pumpage minus pumpage in Chatham County, Ga.	Effect of pumping in Chatham County on flow system	–71.4	X	X		X				
C2	2000 pumpage minus pumpage in southern Beaufort County, S.C.	Effect of pumping in southern Beaufort County on flow system	–16.8	X	X		X				
D1	2010, 2020, 2035, and 2100 pumpage based on Regional Economic Models, Inc.[1] projections to 2035	Projected water use based on economic forecasting, 24-coastal county area, Ga.	96.7 (during 2035)	X	X		X	X	X	X	X
D2	2010, 2020, 2035, and 2100 pumpage for County Comprehensive Water-Supply Plan[2] projections to 2035	Projected water use based on county water-supply plans, 24-coastal county area, Ga.	576.8 (during 2035)	X	X		X	X	X	X	X

[1]Fanning (2003)

[2]Camp Dresser and McKee, Inc. (2001)

- Discretization sometimes causes estimated pumpage from one county to be applied to another during simulation, if the grid cell is on the county boundary. For example, pumpage in county X is assigned to a grid cell for which the centroid is in county Y, so simulated county X pumpage is apparently less than the original estimate and simulated county Y pumpage is more.
- At the edge of the model, several counties are only partially included in the model, so pumpage applied to the model in these counties is less than the total estimated. This will cause total simulated pumpage to be less than total estimated pumpage.
- Wells that are in inactive cells of a model unit are not included in total pumpage applied to the model. This will also cause total simulated pumpage to be less than total estimated pumpage.
- Rounding or truncation errors will contribute to differences in precision.

The discrepancy caused by these factors is, at most, 2 percent for these scenarios. As a comparison, estimated pumpage could have a margin of error of at least 10 percent (Payne and others, 2005).

Scenario A: Representation of the Flow System during 1997

Scenario A is intended to represent the flow system during 1997, when the GaEPD implemented the “Interim Strategy for Managing Saltwater Intrusion in the Upper Floridan Aquifer of Southeast Georgia” (Georgia Environmental Protection Division, 1997). Simulated heads for Scenario A, generated using the MODFLOW model, were compared with available water-level observations for 1997, and model fit was calculated. A comparison of simulation results from the Base Case (representing 2000 conditions) (Payne and others, 2005) with those from Scenario A illustrates changes in the flow system resulting from implementation of the interim strategy. Both MODFLOW and SUTRA results are presented for this scenario.

During 1997, the total estimated ground-water pumpage was about 742 Mgal/d for the model area, about 74 Mgal/d (9 percent) less than during 2000 (table 1). During 1997–2000, the largest increases in pumpage generally occurred farther inland, and the largest decreases were closest to the coast, in Beaufort County, S.C., and in Duval County, Fla. (figs. 13 and 14). The total decreases in Chatham and Glynn Counties, Ga., are likely the result of implementation of the interim strategy, which capped permitted withdrawal from the Upper Floridan aquifer at 1997 withdrawal rates, and encouraged voluntary reductions in ground-water pumpage by the largest users.

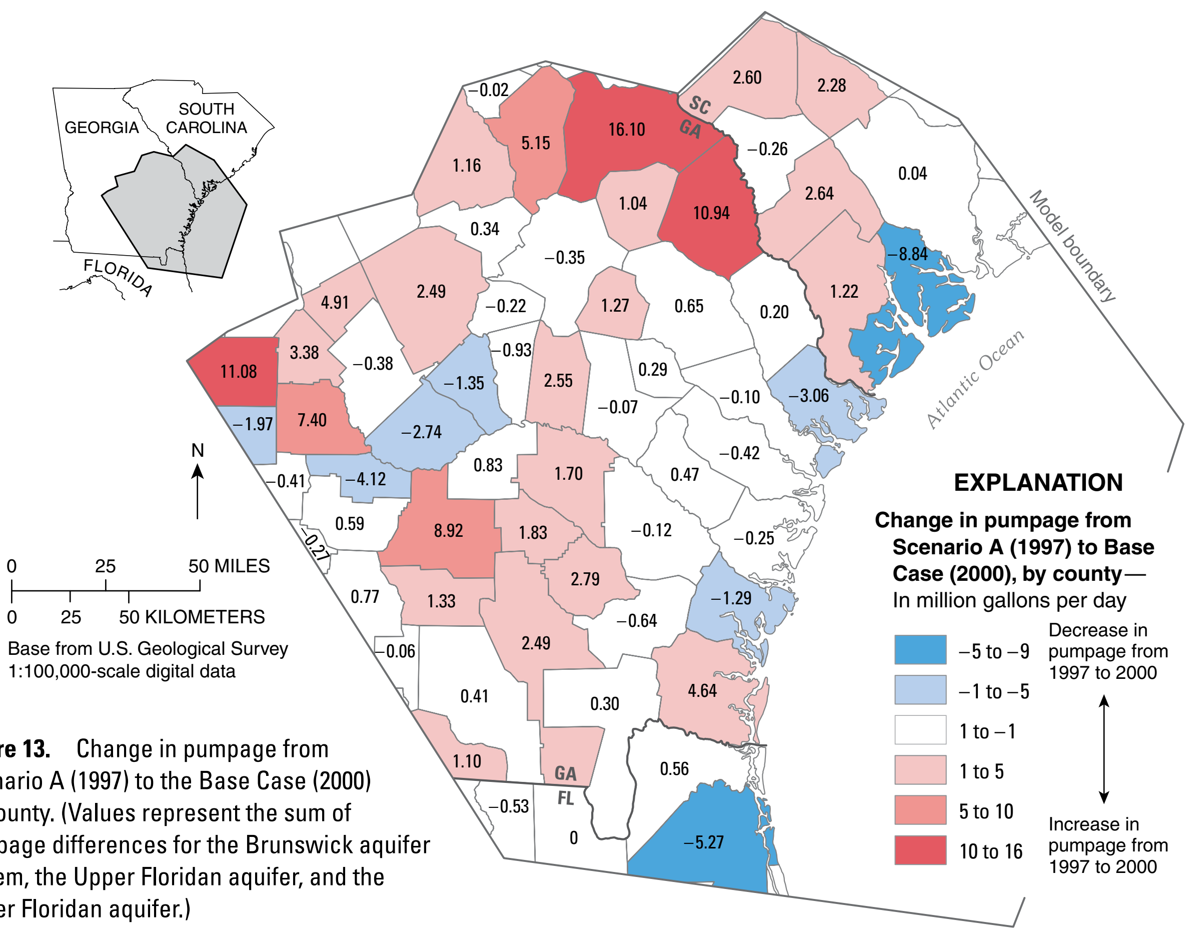


Figure 13. Change in pumpage from Scenario A (1997) to the Base Case (2000) by county. (Values represent the sum of pumpage differences for the Brunswick aquifer system, the Upper Floridan aquifer, and the Lower Floridan aquifer.)

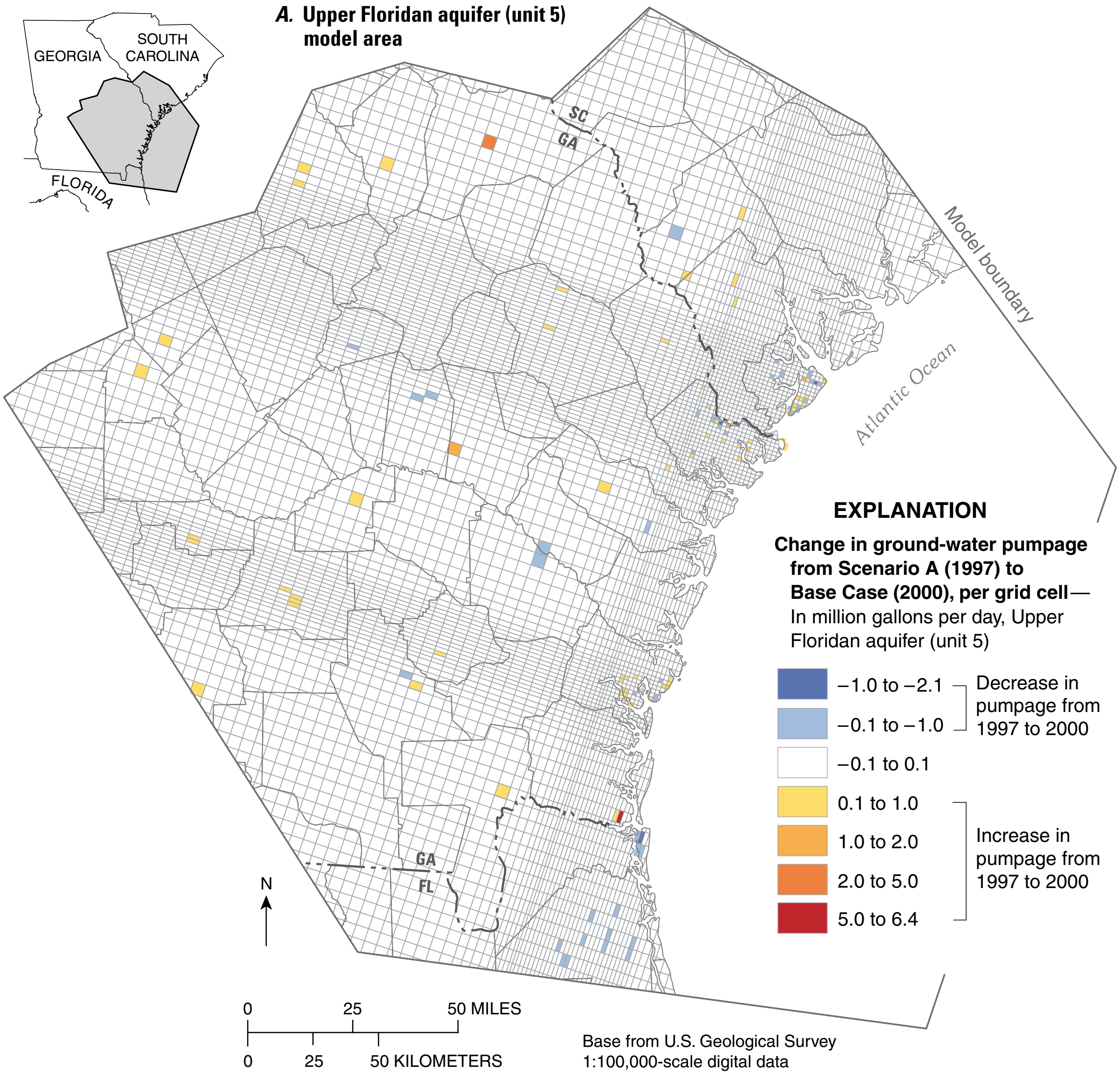


Figure 14. Change in ground-water pumpage from Scenario A (1997) to the Base Case (2000) for the Upper Floridan aquifer (*A*) model area, and (*B*) enlarged view.

Fit of Simulated Heads to Observed Heads Using the MODFLOW Model

Although the model was not calibrated to 1997 conditions, available withdrawal and water-level data for 1997 enabled comparison of simulated head (assuming steady-state conditions) and observed head as a further check on the quality of the calibrated model reported by Payne and others (2005). Characteristics of model fit during 1997 are shown using water-level measurements in 44 wells (table 4), of which 3 wells are completed in the Brunswick aquifer system (unit 3), 31 wells are completed in the Upper Floridan aquifer (unit 5), and 10 wells are completed in the Lower Floridan aquifer (unit 7). For the Upper Floridan aquifer wells, water-level residuals ranged from –29.9 to 24.0 ft, with a mean of –1.62 ft and a root mean square of 8.59 ft. For the Lower Floridan aquifer wells, residuals ranged from –13.7 to 17.2 ft, with a mean of 0.058 ft and a root mean square of 8.67 ft. Simulated heads were within the 10-ft calibration target of observed values for 100 percent of the Brunswick aquifer system wells, 84 percent of the Upper Floridan aquifer wells, and 70 percent of the Lower Floridan aquifer wells. Dividing the standard deviation of the residuals by the range of water-level variation yields a model fit of 0.025 for the Upper Floridan aquifer and 0.037 for the Lower Floridan aquifer, indicating a good fit of the data (Kuniansky and others, 2003). These residual statistics compare well with those for calibrated 1980 and 2000 pumping conditions (Payne and others, 2005).

B. **Upper Floridan aquifer (unit 5)—enlarged view**

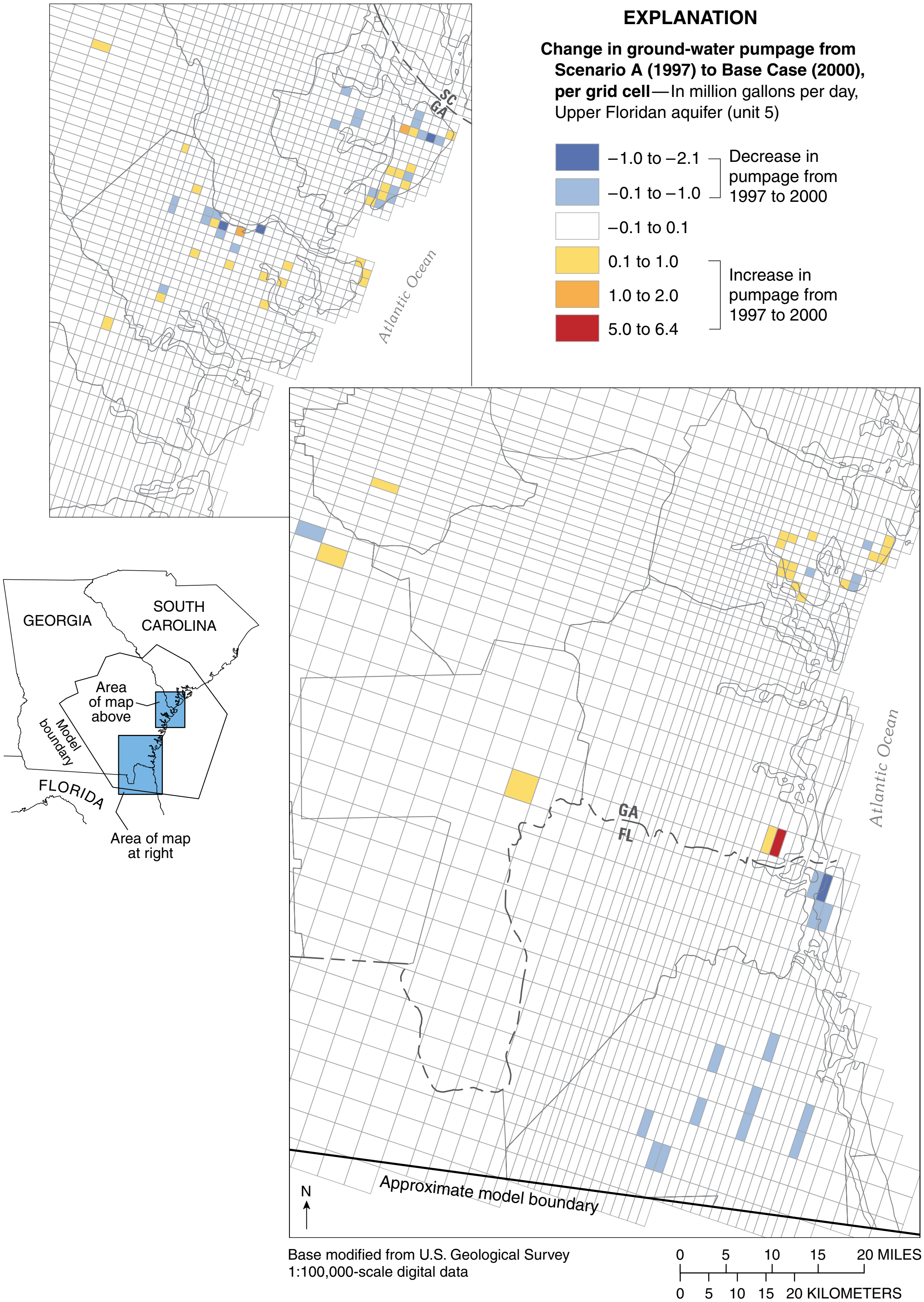


Figure 14. Change in ground-water pumpage from Scenario A (1997) to the Base Case (2000) for the Upper Floridan aquifer (*A*) model area, and (*B*) enlarged view—continued.

Table 4. Model-fit statistics for simulated heads for Scenario A, 1997 pumping conditions, for the MODFLOW model.

[–, minus; —, too few observations to calculate]

Calibration statistic	Brunswick aquifer system (unit 3)	Upper Floridan aquifer (unit 5)	Lower Floridan aquifer (unit 7)
Number of observations	3	31	10
Range of observations (feet)	20.9	345	246
Minimum residual[1] (feet)	–8.9	–29.9	–13.7
Maximum residual (feet)	2.7	24.0	17.2
Mean residual (feet)	–2.4	–1.6	0.6
Standard deviation of residuals (feet)	—	8.6	9.1
Root mean square residual (feet)	—	8.6	8.7
Percentage of simulated values within 10 foot error criteria	100	84	70
Calibration fit: Standard deviation of residuals divided by range of observed values (Kuniansky and others, 2003)	—	0.025	0.037

[1] Residual equals simulated minus observed head.

The spatial distribution of water-level residuals for Scenario A (fig. 15) also compares well with that for the calibration periods 1980 and 2000 (Payne and others, 2005), although there are fewer total observations, and most of those are in counties nearest to the coast. Similar to results for the calibration periods, for units 3 and 7, there are too few observations to discern spatial patterns of the residuals. For unit 5, residuals in the area closest to the coast are mostly between –10 and 10 ft, and residuals of larger magnitude are mostly farther inland in the northeastern part of the model area. For the 1980 and 2000 simulations, there is an observed correlation in the magnitude of residuals with physiography. The magnitudes of residuals in the northwestern part of the model area (north of the Gulf Trough) are largest and show the greatest variability (there are fewer observations in that area, even for the calibration datasets). Residuals are mostly of smaller magnitude in the coastal area (Payne and others, 2005). The model-fit statistics and the spatial pattern of residuals for 1997 conditions indicate that Scenario A model results represent 1997 ground-water flow conditions satisfactorily.

Ground-Water Flow

The 1997 simulated potentiometric surfaces for all hydrologic units (fig. 16) generated using the MODFLOW model are similar to the 2000 simulated potentiometric surfaces (fig. 8). The 1997 potentiometric surface for Upper Floridan aquifer (fig. 16B) also has prominent features similar to those found on potentiometric-surface maps for May 1998 (Peck and others, 1999), September 1998 (Ransom and White, 1999), and September 2000 (Peck and McFadden, 2004). These features include (1) a large cone of depression in the Savannah, Ga., area and smaller cones of depression in the Jesup, Ga., Brunswick, Ga., and the St. Marys, Ga.–Fernandina Beach, Fla., areas; (2) a steepening of the potentiometric gradient in the area of the Gulf Trough; (3) flattening of the regional potentiometric gradient in the southwestern part of the model area; and (4) potentiometric highs north of Port Royal Sound, S.C. (see locations, fig. 1).

The 1997 simulated potentiometric surface for the Lower Floridan aquifer (unit 7) (fig. 16C) is similar to that for the Upper Floridan for 1997 (fig. 16B), as well as to the simulated Lower Floridan aquifer potentiometric surface for 2000 (fig. 8C). The simulated potentiometric surfaces are similar for the Brunswick aquifer system (unit 3) for 1997 (fig. 16A) and 2000 (fig. 8A). The general similarity of 1997 to 2000 simulated water levels is the result of a similar pumpage distribution on a regional scale.

During 1997–2000, simulated water levels showed a combination of rises and declines in response to changing pumping patterns (fig. 17). During this period, total ground-water use increased (table 1), however, the distribution of withdrawal changed. The largest decreases, exceeding 1 Mgal/d, occurred in Beaufort County, S.C., Chatham and Glynn Counties, Ga., and Duval County Fla., and the largest increases, exceeding 5 Mgal/d, occurred in Burke, Coffee, Dooly, Jefferson, Screven, and Wilcox Counties, Ga. (table 1; fig. 13) (see locations, fig. 1).

Simulated drawdown exceeded 1 ft in the Upper Floridan aquifer across much of the model area to the northwest of the Gulf Trough, with drawdown exceeding 8 ft in Bleckley, Burke, Candler, Dooly, part of Effingham, Jenkins, Pulaski, and Screven Counties, Ga. (fig. 17B). These declines generally correspond to an increase in pumpage from the Upper Floridan aquifer in these areas (fig. 13). In Beaufort and Jasper Counties, S.C., Ben Hill, Telfair, Wheeler, and Chatham Counties, Ga., and Duval County, Fla., simulated water levels in the Upper Floridan aquifer rose several feet in response to decreased pumping (fig. 17B). Although total pumpage in Glynn County, Ga., decreased from 1997 to 2000 (fig. 13; table 1), local increases in pumpage (fig. 14) resulted in a slight decline in water level at Brunswick, Ga. (fig. 17B).

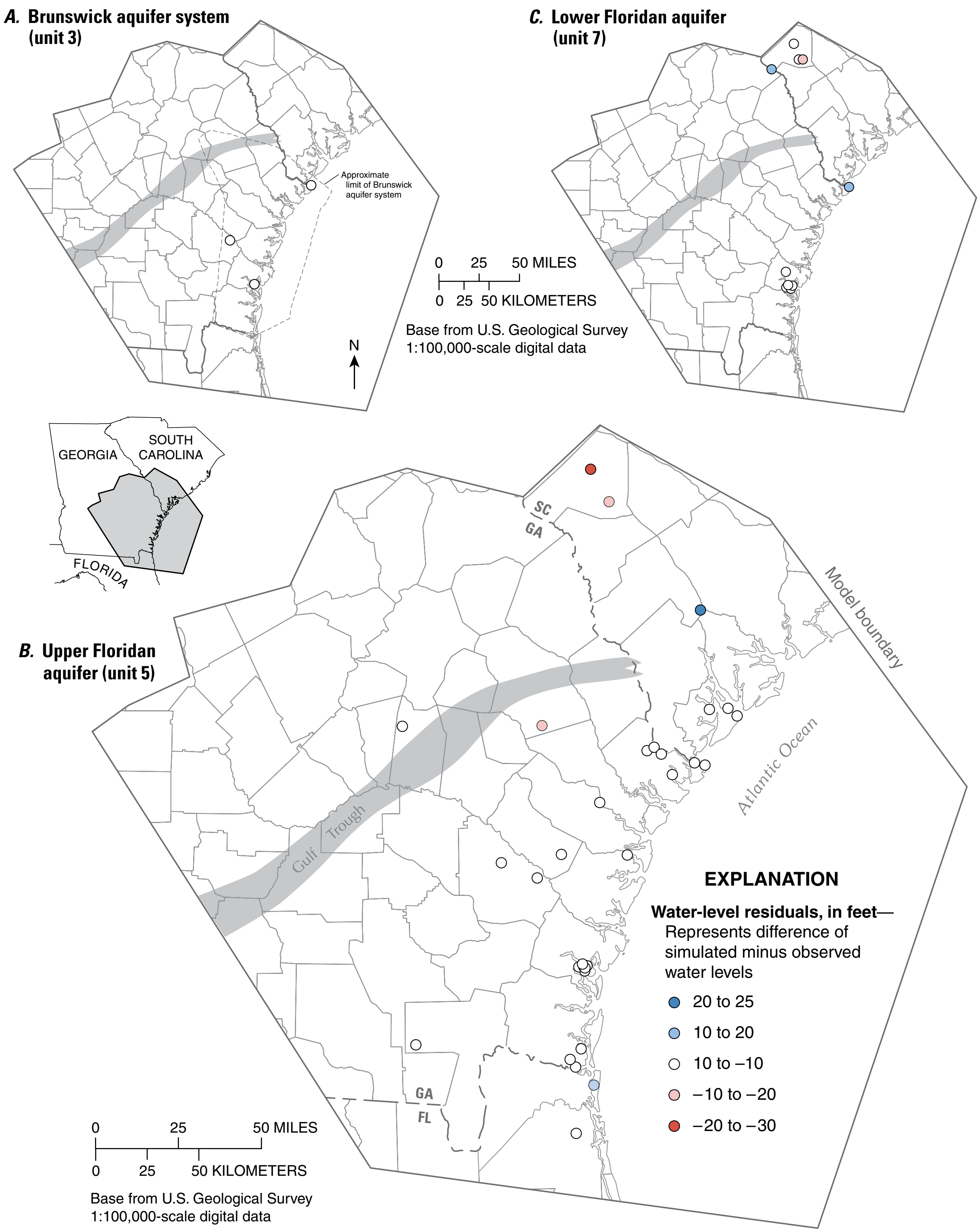


Figure 15. Difference between simulated and observed water levels (residuals) by model layer for Scenario A (1997). Results from MODFLOW model.

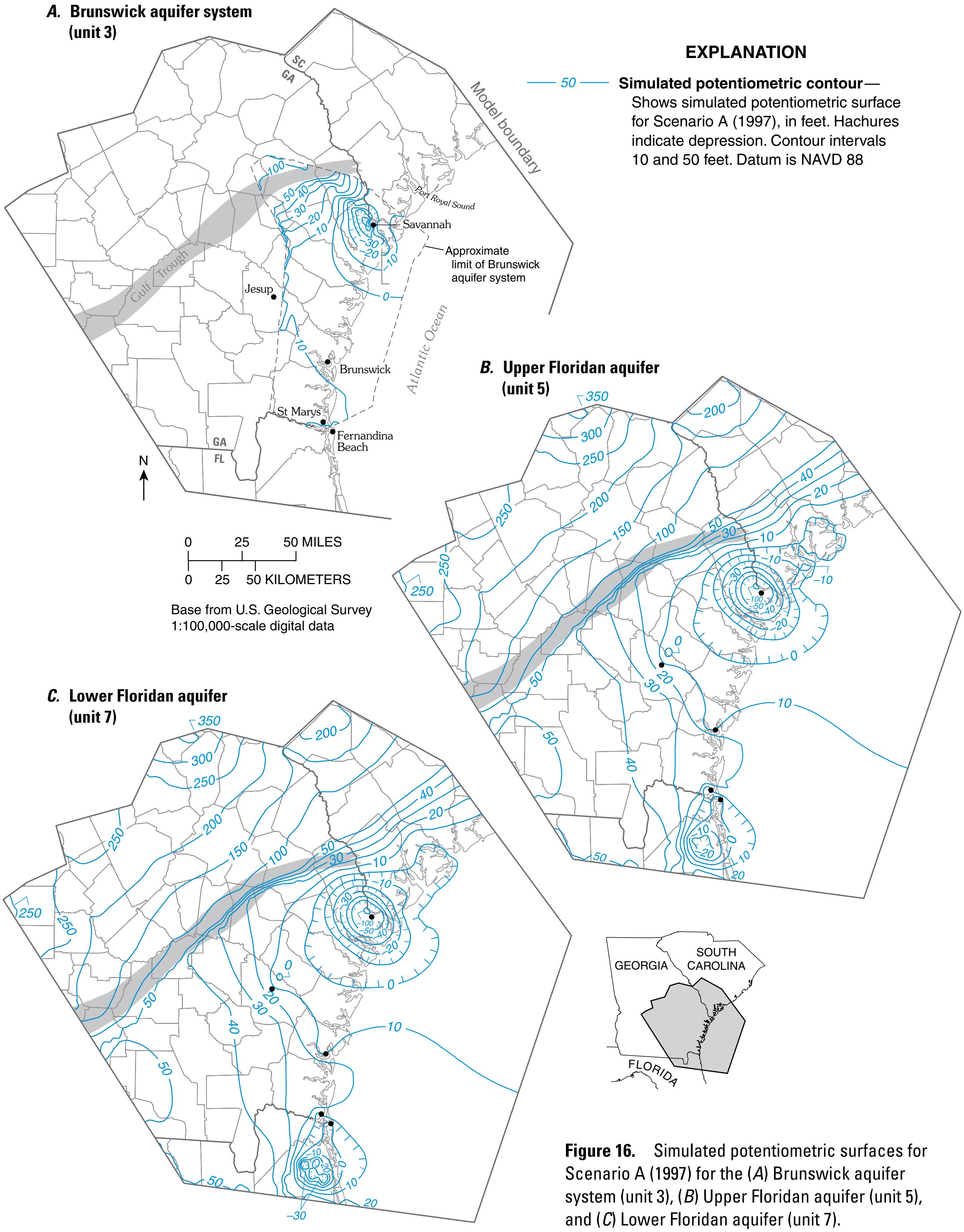


Figure 16. Simulated potentiometric surfaces for Scenario A (1997) for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).

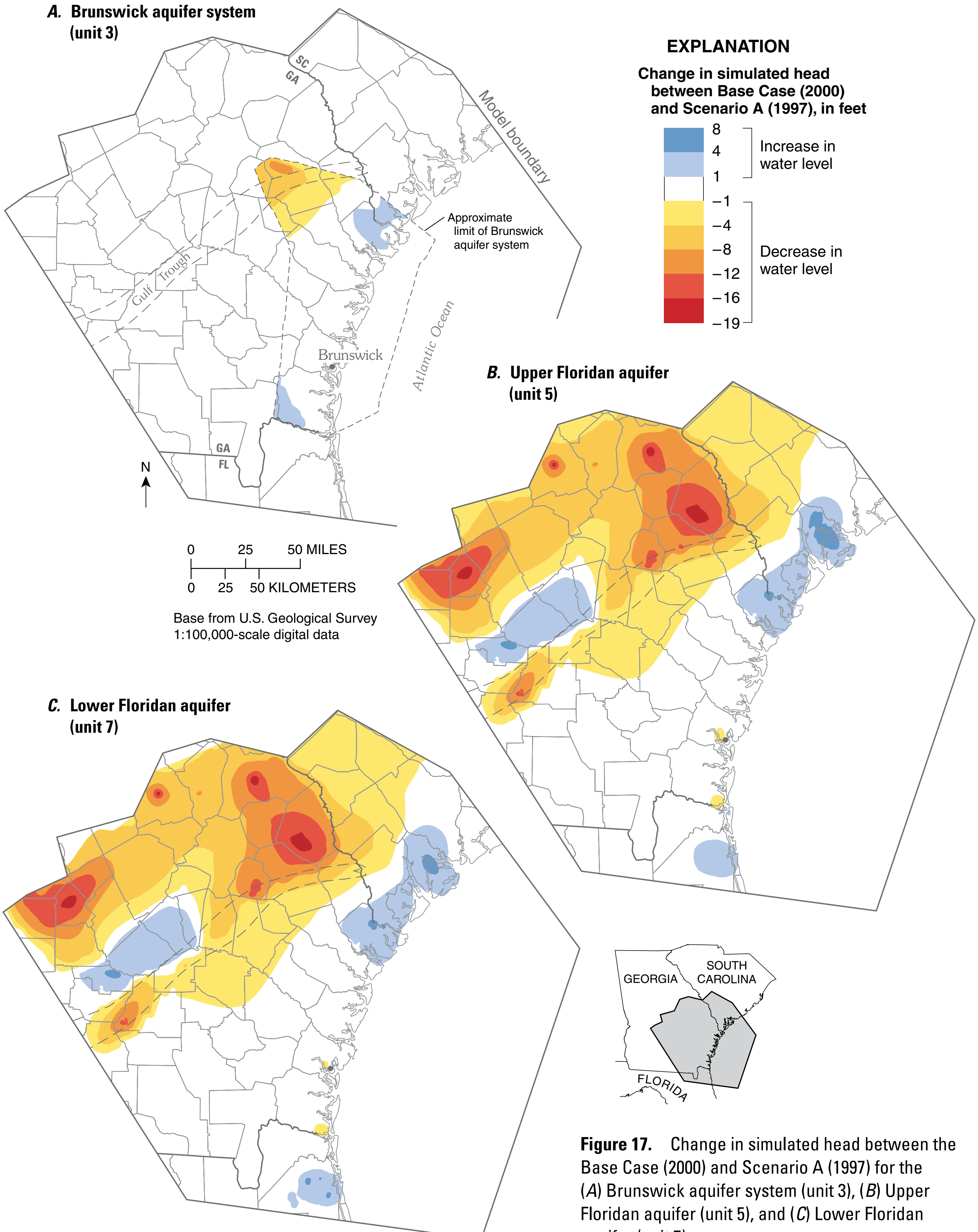


Figure 17. Change in simulated head between the Base Case (2000) and Scenario A (1997) for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).

Water levels in the Brunswick aquifer system and Lower Floridan aquifer also showed a combination of rises and declines during 1997–2000 (figs. 17A and 17C). Because these aquifers were not used widely in the coastal area during 1997–2000, most of the simulated changes were in response to changes in pumping patterns in the Upper Floridan aquifer, which induced a leakage response in the two aquifers. The pattern of change in simulated water levels for the Lower Floridan aquifer is similar to that for the Upper Floridan aquifer (figs. 17C and 17B). Rises and declines in water levels in the Brunswick aquifer system also are similarly distributed spatially compared with those for the Upper Floridan aquifer. The rise in Chatham County, however, is less pronounced and extensive than elsewhere, and there is a slight rise in water level in the southwestern part of Camden County, at the margin of the modeled extent of the Brunswick aquifer system (fig. 17A).

Major flow-budget components for Scenario A using the MODFLOW model are shown in table 5. Simulated ground-water pumpage increases in the model from about 727 Mgal/d during 1997 to about 798 Mgal/d during 2000 (tables 2 and 5). Figure 18 illustrates the difference in major flow-budget components between Scenario A (1997 pumping conditions) and the Base Case (2000 pumping conditions). Figure 18 shows that, as a result of the increase in pumpage, outflow from the system decreased while inflow increased, primarily at the onshore part of the general-head boundary, and to a lesser degree at the specified-head boundary. The effect was more pronounced on the flux at the general-head boundary, because the increase in pumpage was widespread, and occurred away from the southern specified-head boundary. Within the model boundaries, the change in stresses also resulted in a slight decrease in net landward flux from 1997 (Scenario A) to 2000 (Base Case) because, although the total stresses in the model area increased, the pumpage in several of the coastal counties decreased (figs. 13 and 19).

Table 5. Flow-budget components for Scenario A.

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

Model unit	Inflow				Outflow				
	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
1	282.24	24.66	—	306.89	117.22	15.48	—	—	132.70
2	39.99	—	—	39.99	5.20	—	—	—	5.20
3	—	—	—	—	—	—	—	0.47	0.47
4	—	—	—	—	—	—	—	—	—
5	111.44	—	699.93	811.37	31.47	—	275.08	601.97	908.53
6	—	—	0.00	0.00	—	—	0.00	—	0.00
7	—	—	15.90	15.90	—	—	2.48	124.48	126.96
Total all units	**433.67**	**24.66**	**715.84**	**1,174.16**	**153.89**	**15.48**	**277.57**	**726.93**	**1,173.86**
Percent flow	**36.9**	**2.1**	**61.0**	**100.0**	**13.1**	**1.3**	**23.6**	**61.9**	**100.0**

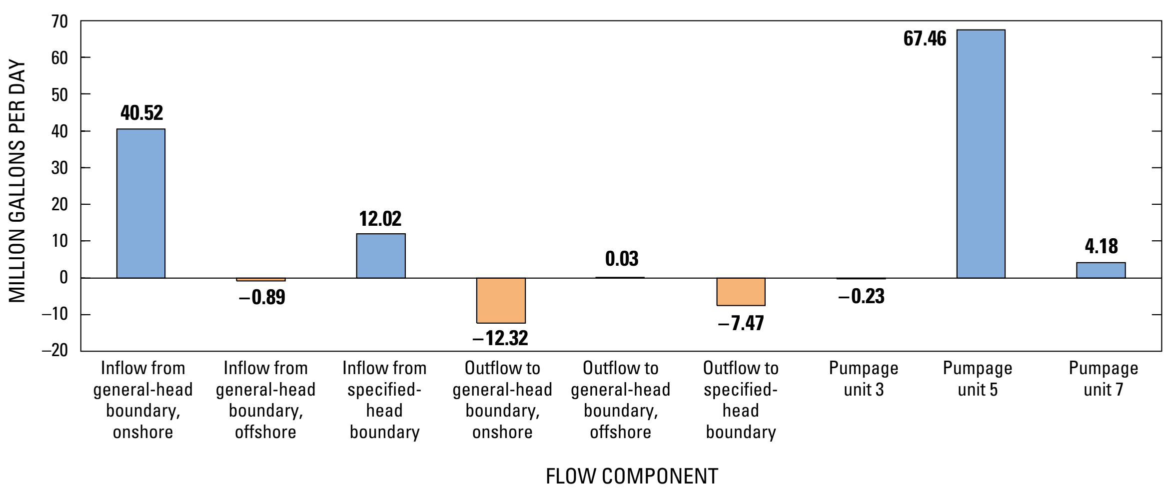


Figure 18. Simulated flow budget indicating changes from Scenario A (1997) conditions to Base Case (2000) conditions.

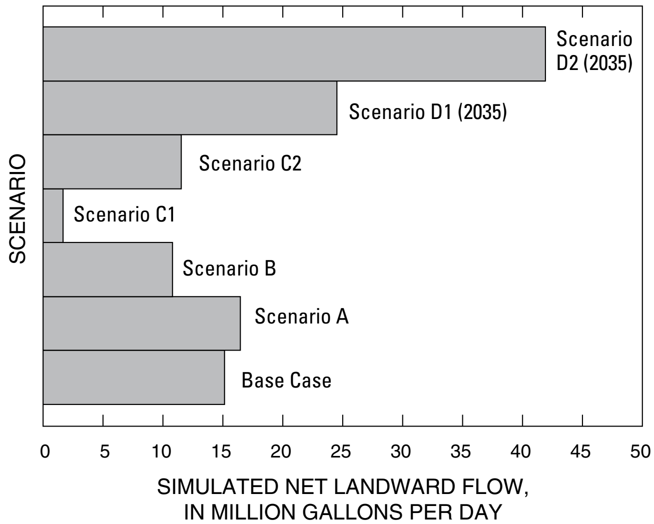


Figure 19. Comparison of simulated net landward flow for the Base Case (2000) and Scenario A (1997), Scenario B (Durango Paper Company pumping eliminated), Scenario C1 (Chatham County, Georgia, pumping eliminated), Scenario C2 (southern Beaufort County, South Carolina, pumping eliminated), Scenario D1 (projection based on Regional Economic Models, Inc.), and Scenario D2 (County Comprehensive Water-Supply Plans projection).

Solute Transport

The simulated chloride distribution in ground water during 1997 for Scenario A, generated using the SUTRA model, is similar to that during 2000, with the extent of the plumes slightly greater during 2000 than during 1997 (fig. 20). Although combined pumpage decreased only about 10 Mgal/d from 1997 to 2000 in Chatham County, Ga., and Beaufort and Jasper Counties, S.C., the plumes likely will continue to grow in response to established hydraulic gradients in the Upper Floridan aquifer.

Scenario B: Effects of an Industrial Well Field Shutdown

During October 2002, the Durango Paper Company in St. Marys, Camden County, Ga., ceased operations, resulting in an abrupt decrease of about 36 Mgal/d in ground-water pumpage from the Upper and Lower Floridan aquifers (Peck and others, 2005). Scenario B was designed to simulate the effect of this reduction. Regionwide pumpage data for 2002 were not available, so the reduction in pumpage caused by the shutdown was applied to the 2000 pumpage distribution. Because the observed response to the shutdown was limited mostly to the southernmost part of the model area (Peck and others, 2005), the scenario simulation was limited to the

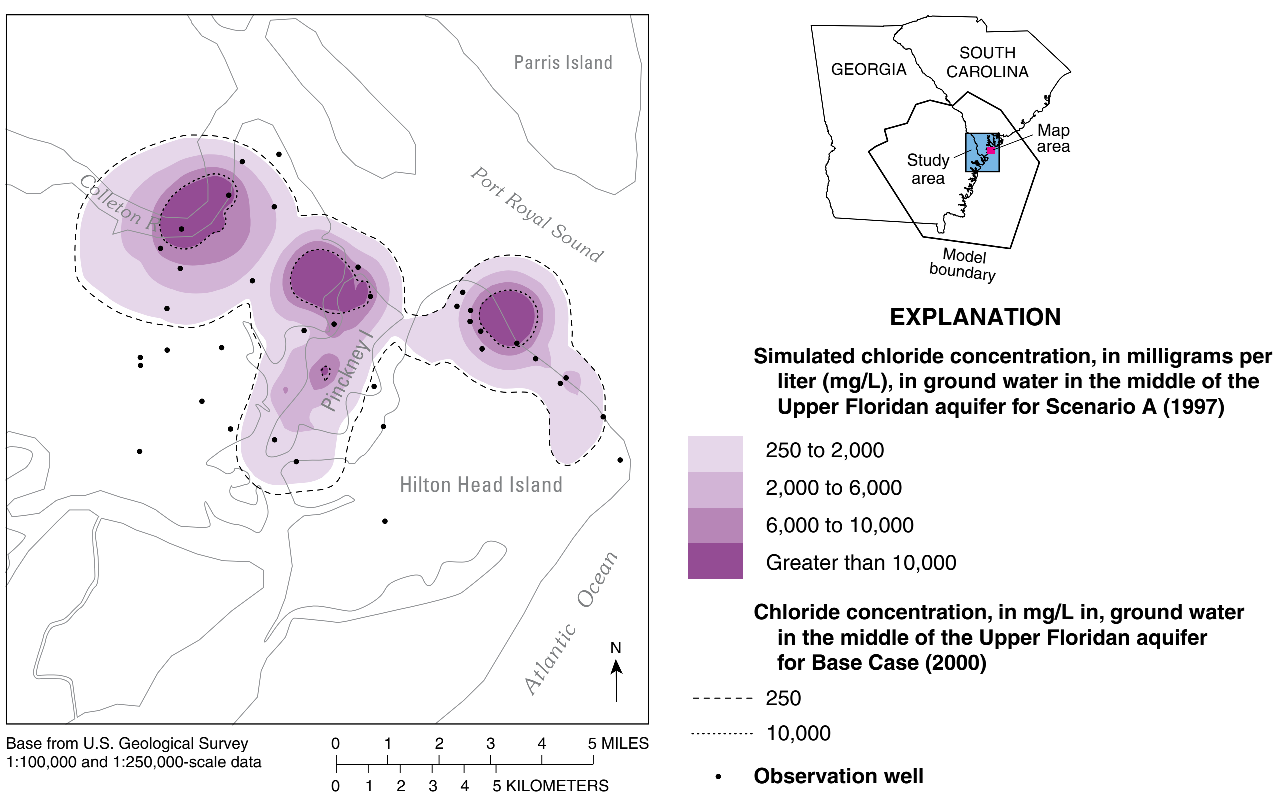


Figure 20. Simulated chloride concentration in ground water in the middle of the Upper Floridan aquifer in the Hilton Head Island, South Carolina, area for Scenario A (1997) (modified from Provost and others, 2006).

regional, steady-state MODFLOW model; the Savannah–Hilton Head Island transient, solute-transport SUTRA model was not used. The pumpage distribution for Scenario B is the same as for the Base Case, except that pumpage in hydrologic unit 5 (the Upper Floridan aquifer) was reduced by about 36 Mgal/d in cells where wells that were turned off during October 2002 are located (figs. 21 and 6C).

Simulated potentiometric surfaces for Scenario B (fig. 22) are similar to the 2000 simulated potentiometric surfaces (fig. 8) on a regional scale. The most notable difference in simulated head for the Upper and Lower Floridan aquifers is the seaward movement of the 20-ft contour offshore of Camden County, and the elimination of the cone of depression at St. Marys (fig. 22B). The reduction in localized pumping results in a water-level rise in the area. The simulated potentiometric surface for the Brunswick aquifer system (fig. 22A) shows little difference from 2000 (fig. 8A).

For Scenario B conditions, simulated water levels in all aquifers are higher relative to the Base Case in response to lower pumpage (fig. 23). The water-level difference is greatest near the pumping center for the Upper Floridan aquifer, where the Scenario B water level is about 29 ft higher than for the Base Case. The magnitudes of water-level differences are smaller for the Lower Floridan aquifer and Brunswick aquifer system, with simulated water levels 16 ft and 3 ft higher, respectively, than those for the Base Case. A water-level difference of 1–2 ft in all aquifers for Scenario B relative to the Base Case is simulated as far away from the pumping center as southern Chatham County, about 98 miles (mi), and extends inland as far as the Gulf Trough, about 109 mi.

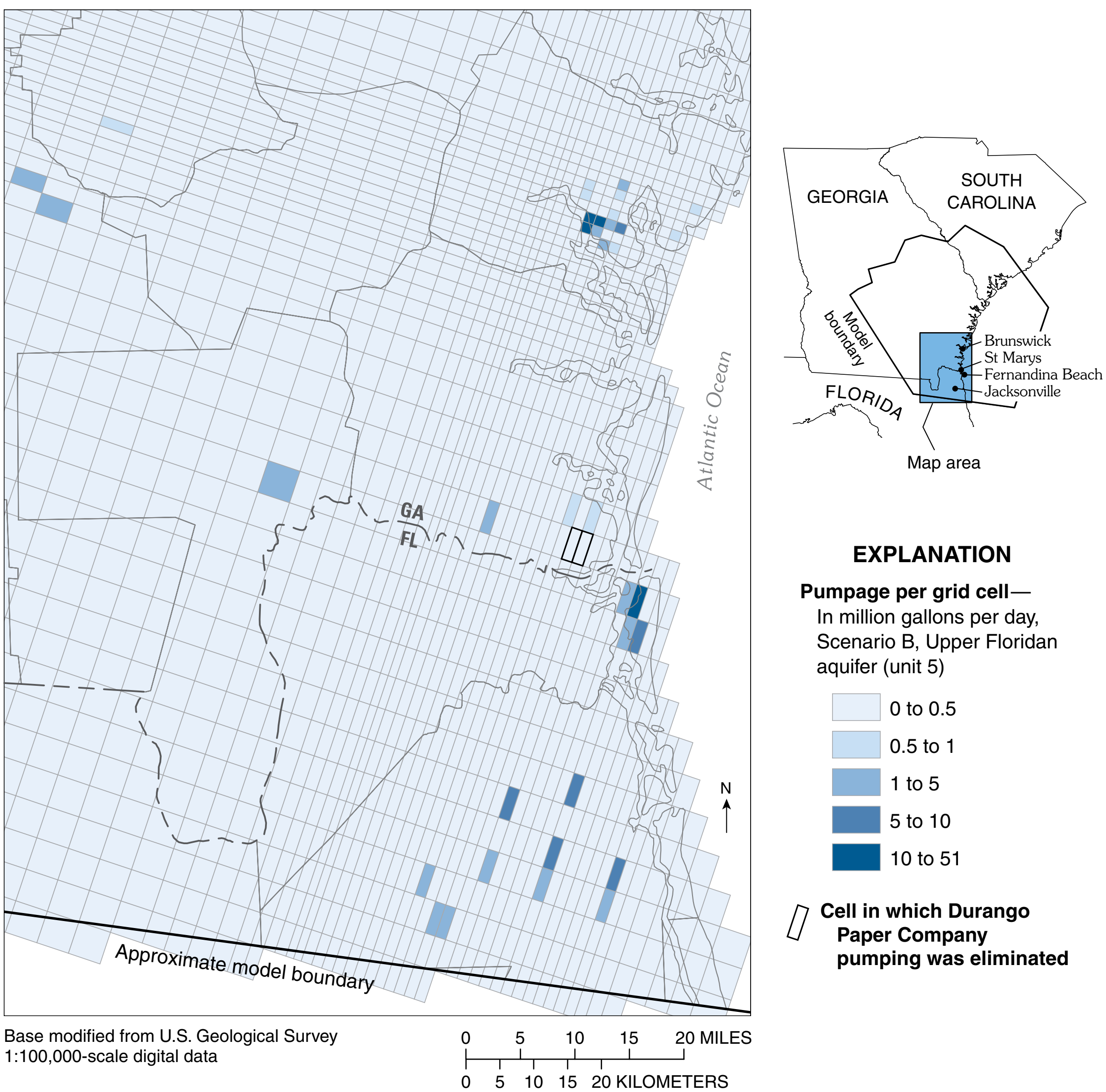


Figure 21. Distribution of ground-water pumpage for the Upper Floridan aquifer (unit 5) in the southern part of the model area for Scenario B (Durango Paper Company pumping eliminated).

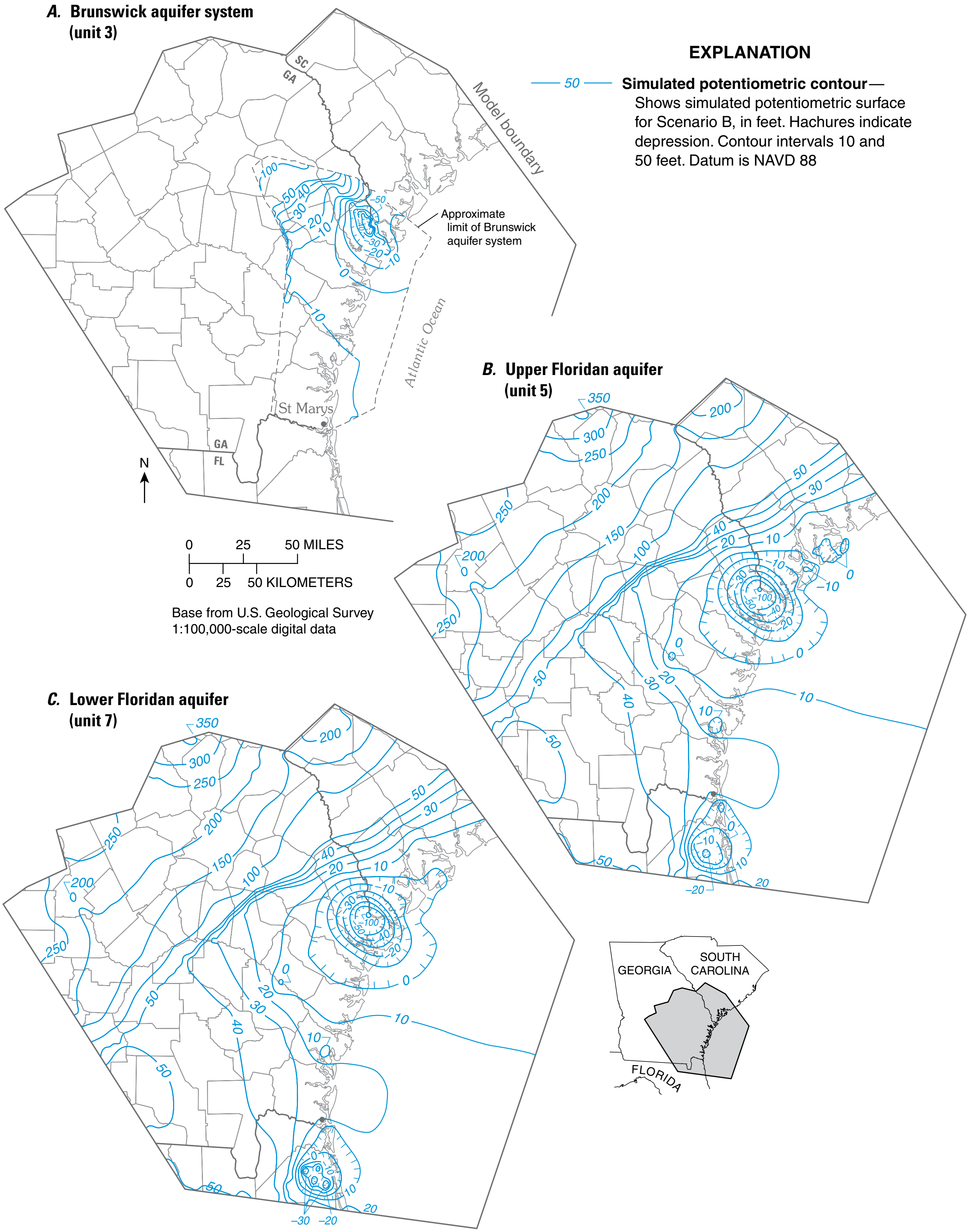


Figure 22. Simulated potentiometric surfaces for Scenario B (Durango Paper Company pumping eliminated) for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).

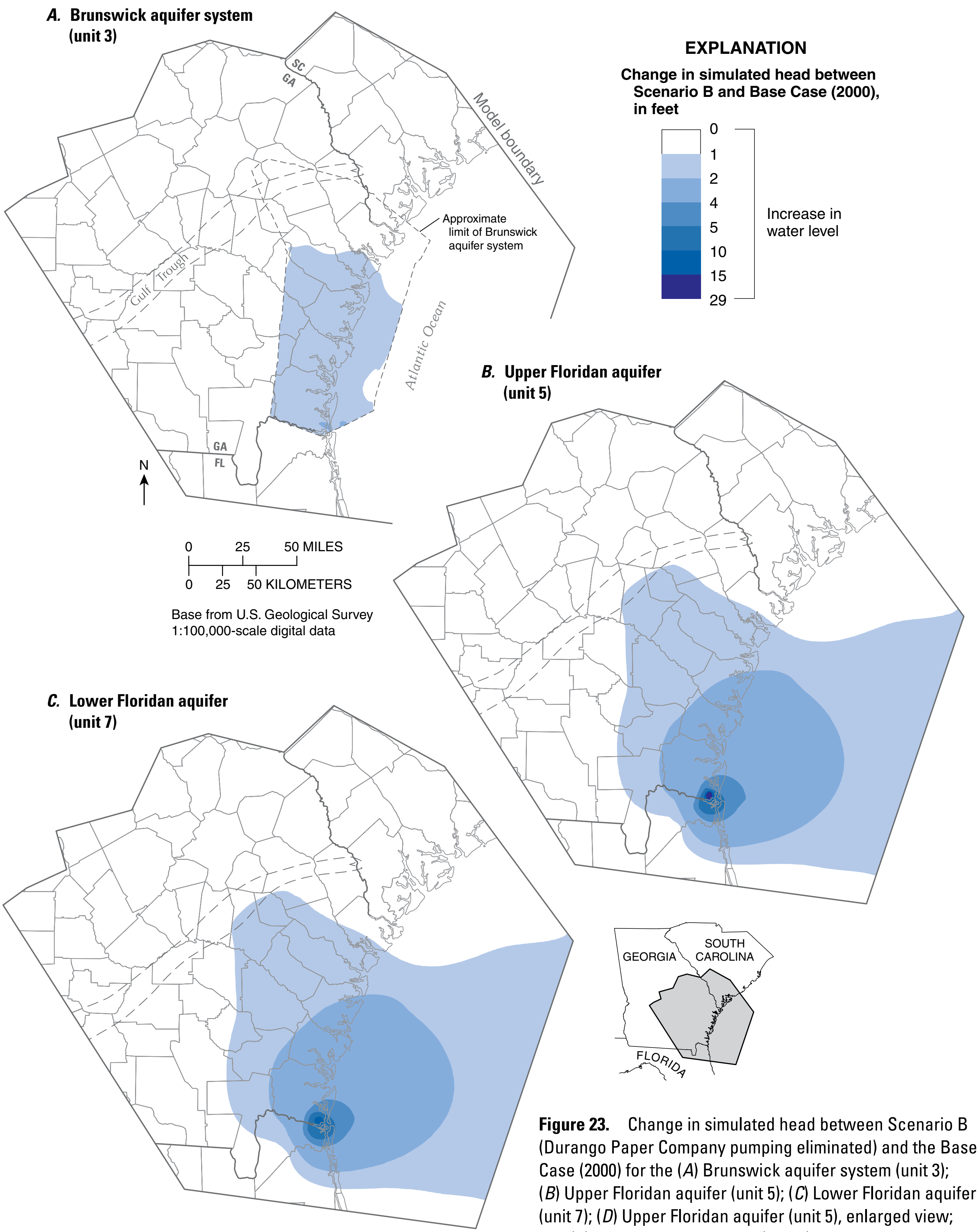


Figure 23. Change in simulated head between Scenario B (Durango Paper Company pumping eliminated) and the Base Case (2000) for the (*A*) Brunswick aquifer system (unit 3); (*B*) Upper Floridan aquifer (unit 5); (*C*) Lower Floridan aquifer (unit 7); (*D*) Upper Floridan aquifer (unit 5), enlarged view; and (*E*) Lower Floridan aquifer (unit 7), enlarged view.

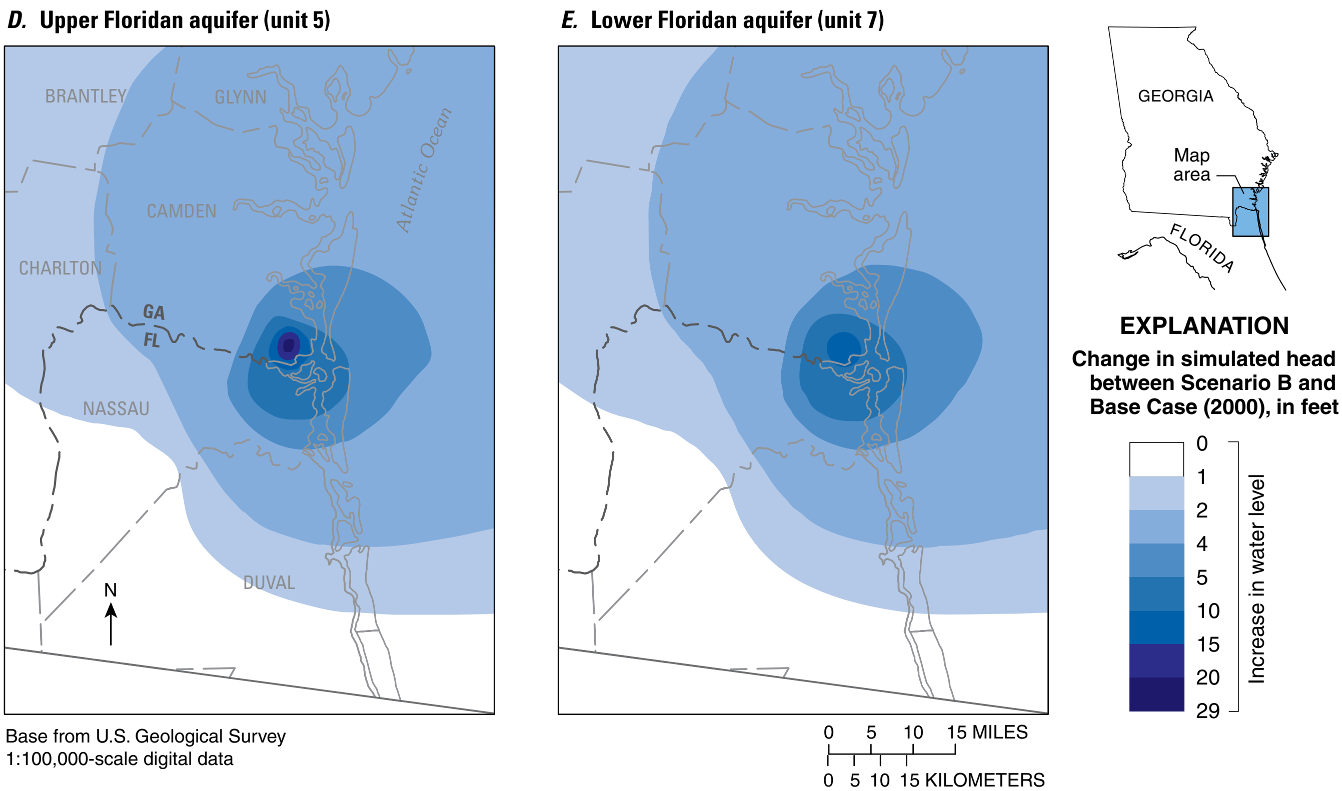
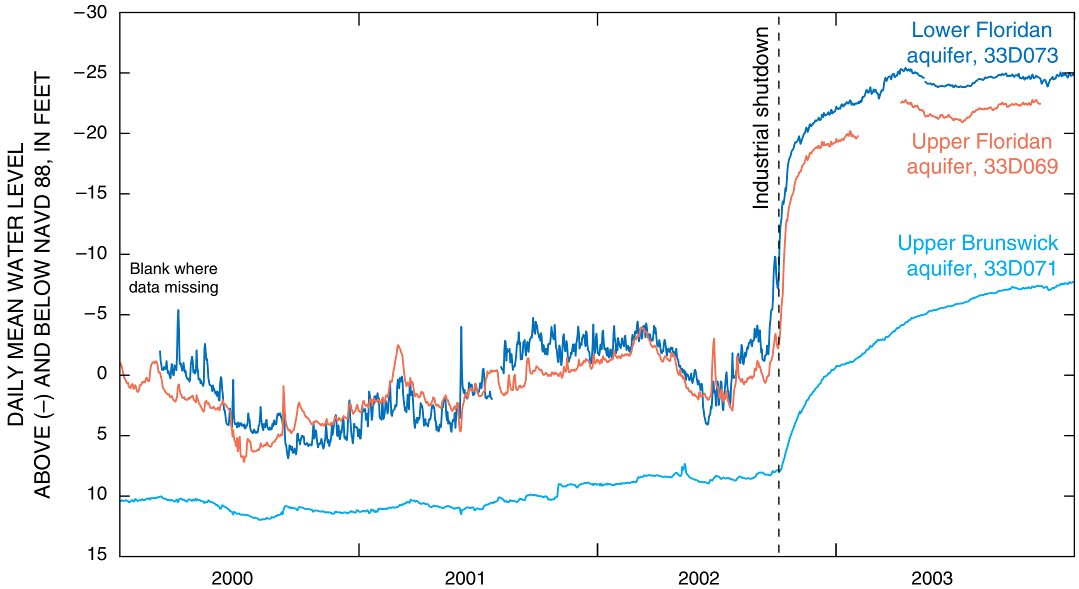


Figure 23. Change in simulated head between Scenario B (Durango Paper Company pumping eliminated) and the Base Case (2000) for the (*A*) Brunswick aquifer system (unit 3); (*B*) Upper Floridan aquifer (unit 5); (*C*) Lower Floridan aquifer (unit 7); (*D*) Upper Floridan aquifer (unit 5), enlarged view; and (*E*) Lower Floridan aquifer (unit 7), enlarged view—continued.

In Camden County, after the shutdown of wells at the Durango Paper Company, water levels in monitored wells in the Brunswick aquifer system, Upper Floridan aquifer, and Lower Floridan aquifer exhibited a distinct rise (fig. 24) (Peck and others, 2005). With increasing distance from the pumping center, the water-level rise decreased (fig. 25). At the center of pumping, the water level in the Upper Floridan aquifer rose an estimated 140 ft on average; observed water levels rose 21.5, 18, and 11.5 ft at locations 1.1, 2, and 4.6 mi from the pumping center, respectively (Peck and others, 2005). The center of the measured rise in water level is offset from the pumping center because wells within the plant were unavailable for water-level measurement, and the contours are based on the distribution of available data. If the difference in simulated water levels for Scenario B and the Base Case is considered a simulated recovery in response to the shutdown of the wells at the Durango Paper Company, then the model generally predicts a smaller recovery, by a maximum of about 10 ft, than was observed for water levels (fig. 25). Away from the pumping center, observed water-level changes resulting from the shutdown are difficult to discern from regional rises that began during 2000 (fig. 24; Peck and others, 2005). Close to the pumping center, some of the observed recovery may be attributed to the regional trend. For example, although the model simulates a rise of less than 3 ft in the Upper Floridan aquifer water level in western Camden County, Ga., and Nassau County, Fla., for Scenario B, the observed rise from 5 to 10 ft from 2001 through 2003 may be partly caused by regional effects and not the October 2002 shutdown. Some of the discrepancy between simulated and observed water levels also may occur because the model does not attempt to simulate regional pumping conditions accurately after October 2002. The proximity of the Scenario B pumpage change to the southern specified-head boundary in the MODFLOW model may diminish the simulated response, particularly in the direction of that boundary. Discretization of the model also may contribute to the discrepancy between observed water levels and simulated results.

Observed water levels for the Brunswick aquifer system and the Lower Floridan aquifer also indicate a distinct water-level recovery caused by the shutdown, although fewer observations exist to evaluate the effects. At a location 0.2 mi from the center of pumping, observed water levels in the Upper Brunswick aquifer recovered 12.9 ft during the 8 months following the shutdown. The water level in a Lower Floridan aquifer well located the same distance from the pumping center rose 18.2 ft during this time period. The magnitude of simulated recovery of 14 ft in the Lower Floridan aquifer is somewhat less than observed, and the simulated maximum recovery of 2 ft in the Brunswick aquifer system also is less than observed.



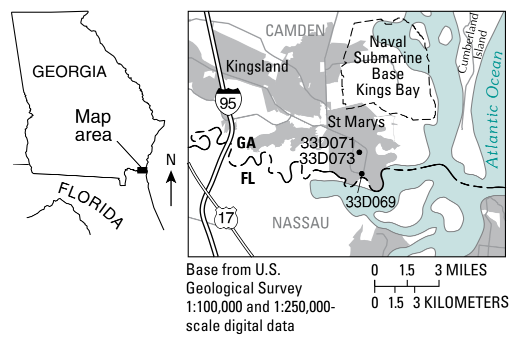


Figure 24. Hydrographs for St. Marys well cluster (33D071 and 33D073) and nearby National Park Service well (33D069), Camden County, Georgia, 2000–2003 (modified from Peck and others, 2005).

Simulated pumpage for Scenario B is lower by about 36 Mgal/d than simulated pumpage for the Base Case (tables 2 and 6). This resulted primarily in a decrease in the inflow from and an increase in the outflow to the specified-head boundary (fig. 26). The effect was larger on flows at the specified-head boundary because the change in pumpage was localized and proximal to the southern specified-head boundary. Within the model boundaries, the decrease in pumpage also resulted in a decrease in net landward flow relative to the Base Case (fig. 19).

Scenarios C1 and C2: Relative Effects of Pumping in Chatham County, Georgia, and Southern Beaufort County, South Carolina

Scenarios C1 and C2 illustrate the relative effects of pumping in Chatham County, Ga., and southern Beaufort County, S.C., on ground-water levels and saltwater distribution and movement in that area. In the Savannah, Chatham County, Ga., area, pumping has resulted in the development of a large cone of depression in the Upper Floridan aquifer potentiometric surface, which extends into Beaufort County, S.C. (figs. 8 and 9). In addition, increase in pumpage at Hilton Head Island since the 1960s likely has resulted in localized drawdown of the Upper Floridan aquifer potentiometric surface, as indicated by localized fluctuation of water levels in response to pumpage fluctuations (Hayes, 1979). To separate the effects of these two causes of drawdown, Scenario C1 simulates the flow system for a hypothetical pumping history to 2000, assuming pumping never occurred in Chatham County, Ga., and Scenario C2 simulates the flow system for a hypothetical pumping history to 2000, assuming pumping never occurred in southern Beaufort County, S.C. Results from these two simulations during 2000 are compared with each other and with those for the Base Case simulations to evaluate the individual and combined effects of stresses on the ground-water flow system and the transport of saltwater in these areas.

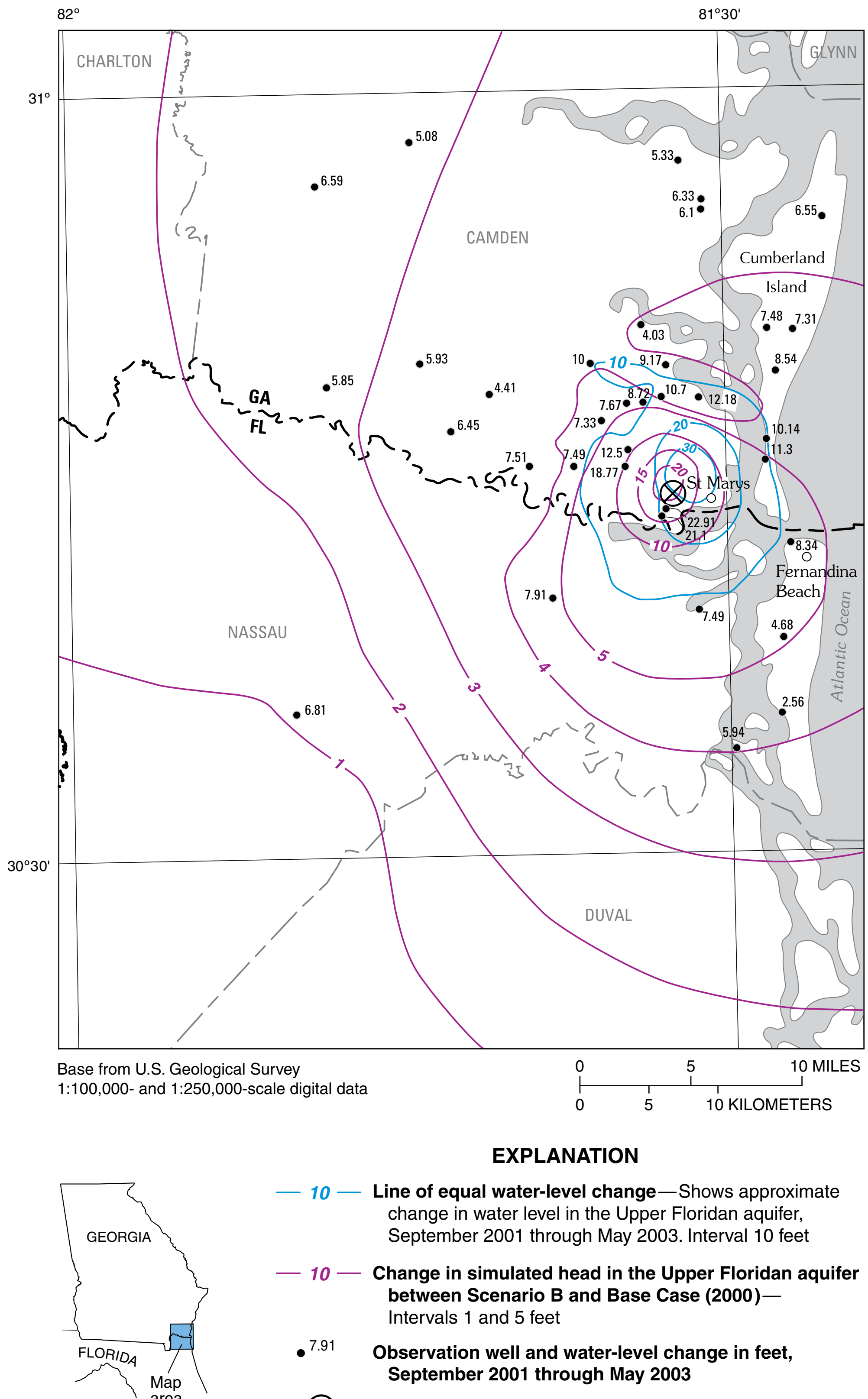


Figure 25. Observed water-level change from September 2001 through May 2003 in wells completed in the Upper Floridan aquifer (Peck and others, 2005) and simulated change in potentiometric surface for Scenario B (Durango Paper Company pumping eliminated) in Camden County, Georgia, and Nassau County, Florida.

Table 6. Flow-budget components for Scenario B.

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

Model unit	Inflow				Outflow				
	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
1	285.83	22.98	—	308.81	115.92	16.07	—	—	131.98
2	46.51	—	—	46.51	3.63	—	—	—	3.63
3	—	—	—	—	—	—	—	0.24	0.24
4	—	—	—	—	—	—	—	—	—
5	141.29	—	688.99	830.29	22.29	—	276.60	633.72	932.61
6	—	—	0.00	0.00	—	—	0.00	—	0.00
7	—	—	14.60	14.60	—	—	2.79	128.67	131.45
Total all units	**473.63**	**22.98**	**703.60**	**1,200.21**	**141.84**	**16.07**	**279.38**	**762.63**	**1,199.92**
Percent flow	**39.5**	**1.9**	**58.6**	**100.0**	**11.8**	**1.3**	**23.3**	**63.6**	**100.0**

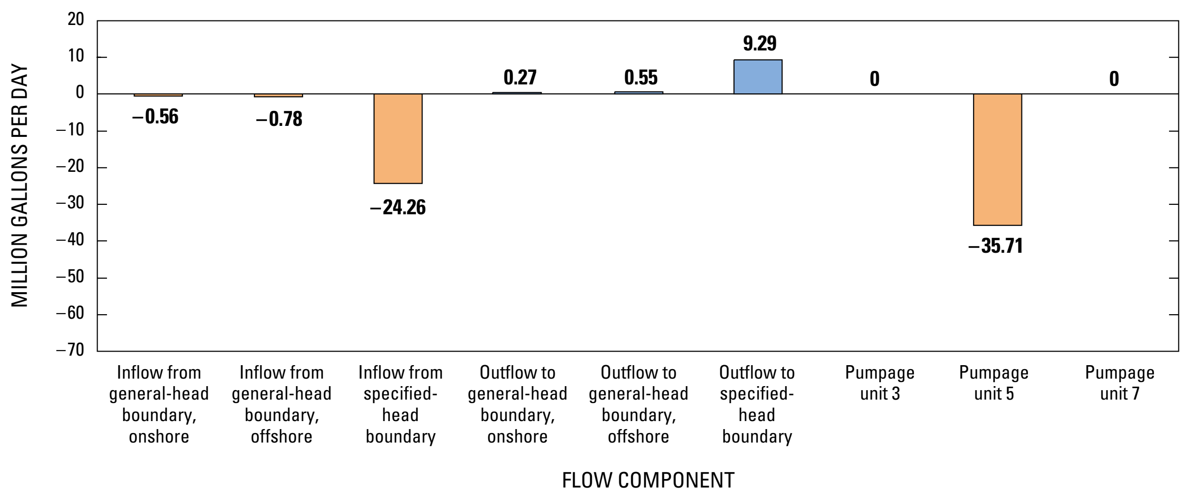


Figure 26. Simulated flow budget for Scenario B (Durango Paper Company pumping eliminated), relative to the Base Case (2000).

Scenario C1: Elimination of Pumping in Chatham County, Georgia

The pumpage distributions for Scenario C1 simulations are the same as for the Base Case simulations, except that pumpage in all hydrologic units is eliminated within Chatham County, Ga., from predevelopment to 2000. Table 1 shows a reduction in total pumpage of more than 71 Mgal/d in the model area during 2000 for Scenario C1 relative to the Base Case. Simulated water levels, water-level differences, flow-budget components, and chloride distributions are evaluated for Scenario C1 simulations during 2000.

Ground-Water Flow

Simulated potentiometric surfaces are presented for the Upper and Lower Floridan aquifers and the Brunswick aquifer system, as generated by the regional MODFLOW model, and for the Upper Floridan aquifer as generated by the SUTRA model of the Savannah–Hilton Head Island. Because of its finer resolution and calibration to local data, the SUTRA model provides a more precise depiction of ground-water flow in the Savannah–Hilton Head Island area.

The simulated potentiometric surfaces for Scenario C1 (figs. 27 and 28A) differ distinctly from the simulated potentiometric surfaces for the Base Case (figs. 8 and 9). The most notable differences are the elimination of the large cones of depression centered at Savannah, Ga., in the Upper Floridan aquifer, Lower Floridan aquifer, and Brunswick aquifer system. The elimination of pumpage in Chatham County reveals the presence of a simulated cone of depression in the Upper and Lower Floridan aquifers at Hilton Head Island (figs. 27 and 28A). The maximum depth of the depression in the Upper Floridan aquifer is almost 8 ft below NAVD 88 on the southern part of the island (fig. 28A).

Because of the lower simulated pumpage, simulated water levels in all aquifers for Scenario C1 are higher relative to those for the Base Case (figs. 28B and 29). The water-level difference in the Upper Floridan aquifer is greatest near the pumping center at Savannah, where the water level is about 140 ft higher for Scenario C1 than for the Base Case (fig. 28B). This simulated trend extends at least as far north as the northern part of Hilton Head Island, where the water level for Scenario C1 is about 2 ft higher than that for the Base Case (fig. 28B). Differences in water level between Scenario C1 and the Base Case are even higher for the Lower Floridan aquifer, with a maximum simulated difference of about 160 ft (fig. 29C). These large differences result from reductions in drawdown in the Lower Floridan aquifer attributable to (1) elimination of pumpage from the Lower Floridan aquifer, and (2) elimination of pumpage from the Upper Floridan aquifer, which reduces leakage from the Lower Floridan aquifer. In the Lower Floridan aquifer, a smaller reduction in pumpage is required to produce the same reduction in drawdown as in the Upper Floridan aquifer, because the Lower Floridan aquifer is assigned a lower hydraulic conductivity. The simulated water levels in the Brunswick aquifer system are about 80 ft higher for Scenario C1 than those for the Base Case because of reduced leakage to the Upper Floridan aquifer (fig. 29A).

Pumpage for Scenario C1 is about 72 Mgal/d lower than for the Base Case (tables 2 and 7). This relative decrease in pumpage resulted in a decrease in the inflow to and an increase in the outflow from all model boundaries (fig. 30). The change in boundary fluxes is evenly distributed among the boundaries, compared to other simulation results. Although the change in stress for Scenario C1 is localized in the northern part of the model area, its effect is widespread—the magnitude of change in flux at the southern specified-head boundary is similar to the magnitude of change in flux at the general-head boundary. Within the model boundaries, the decrease in pumpage also resulted in a notable decrease in net landward flow, relative to the Base Case (fig. 19), because of the proximity of the large change in stresses to the coastal area.

Solute Transport

Results of the Scenario C1 solute-transport simulation using the SUTRA model show the development of chloride plumes in the Upper Floridan aquifer in the same three locations as for the Base Case: Colleton River, Pinckney Island, and the northern end of Hilton Head Island (fig. 31). The plumes originating at Colleton River and Pinckney Island are of lesser extent for Scenario C1 than for the Base Case. The plume at the northern end of Hilton Head Island is approximately the same shape and only slightly smaller overall for Scenario C1 than for the Base Case. This indicates that pumping in Chatham County has a greater influence on chloride transport from the two western source areas than on chloride transport from the source area on the northern end of Hilton Head Island.

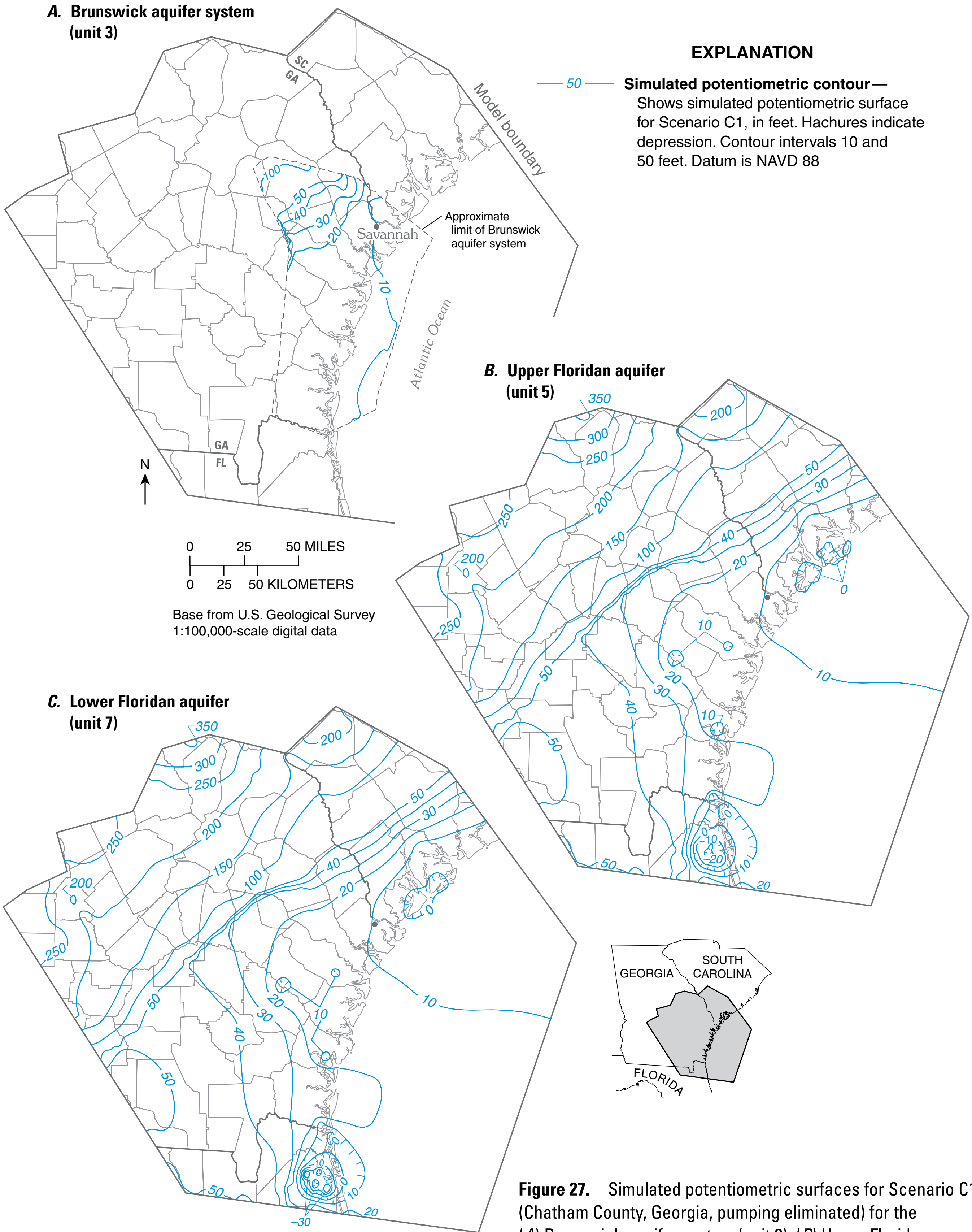


Figure 27. Simulated potentiometric surfaces for Scenario C1 (Chatham County, Georgia, pumping eliminated) for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).

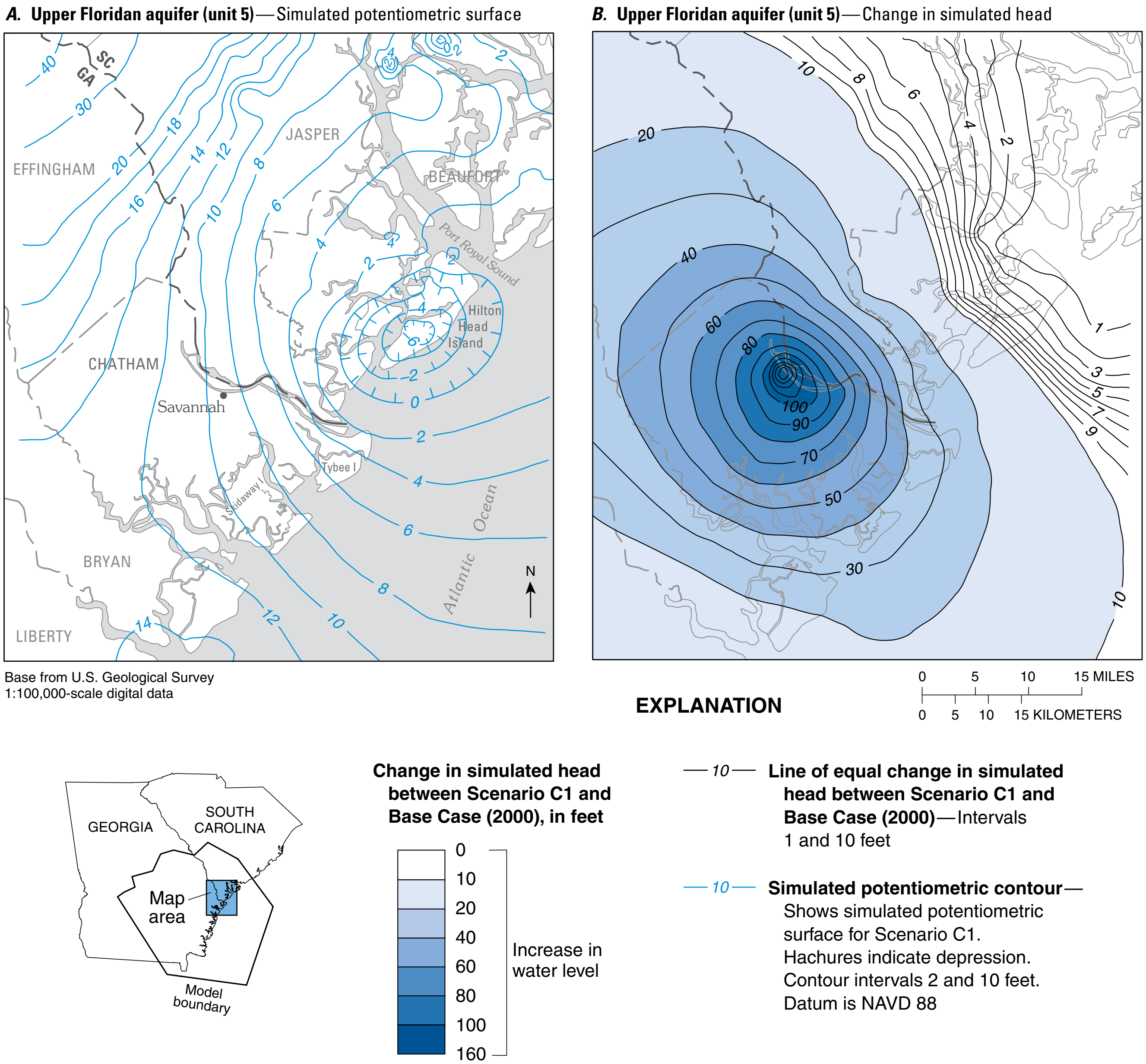


Figure 28. Results using solute-transport model for (*A*) simulated potentiometric surface for Scenario C1 (Chatham County, Georgia, pumping eliminated) and (*B*) change in simulated head between Scenario C1 and the Base Case (2000) for the Upper Floridan aquifer in Chatham County, Georgia, and southern Beaufort County, South Carolina.

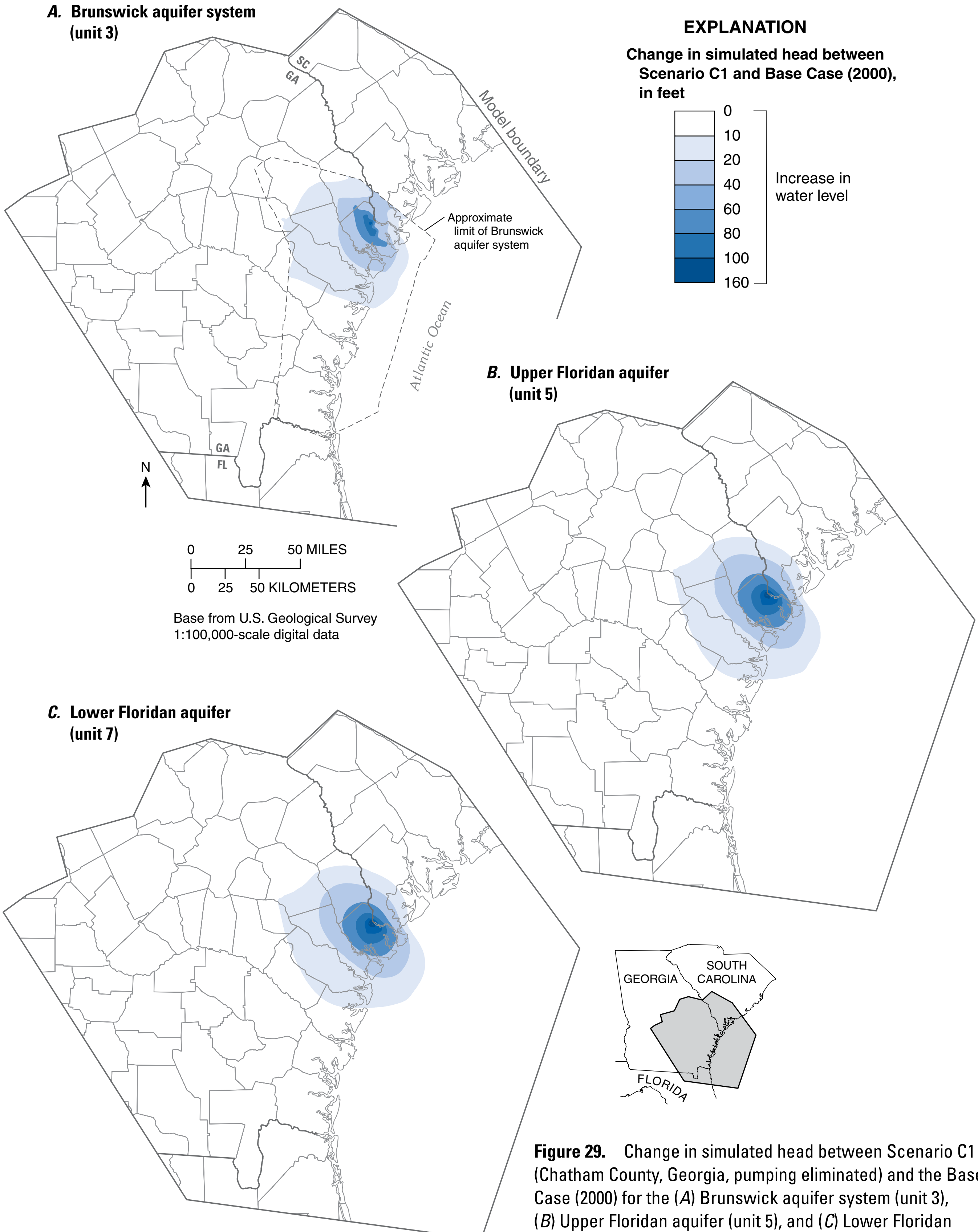


Figure 29. Change in simulated head between Scenario C1 (Chatham County, Georgia, pumping eliminated) and the Base Case (2000) for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).

Table 7. Flow-budget components for Scenario C1.

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

Model unit	Inflow				Outflow				
	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
1	262.58	14.69	—	277.28	122.96	18.87	—	—	141.83
2	45.26	—	—	45.26	3.98	—	—	—	3.98
3	—	—	—	—	—	—	—	0.24	0.24
4	—	—	—	—	—	—	—	—	—
5	140.77	—	695.41	836.18	22.63	—	275.78	600.76	899.17
6	—	—	0.00	0.00	—	—	0.00	—	0.00
7	—	—	14.99	14.99	—	—	2.74	125.43	128.17
Total all units	**448.61**	**14.69**	**710.40**	**1,173.71**	**149.57**	**18.87**	**278.52**	**726.44**	**1,173.40**
Percent flow	**38.2**	**1.3**	**60.5**	**100.0**	**12.7**	**1.6**	**23.7**	**61.9**	**100.0**

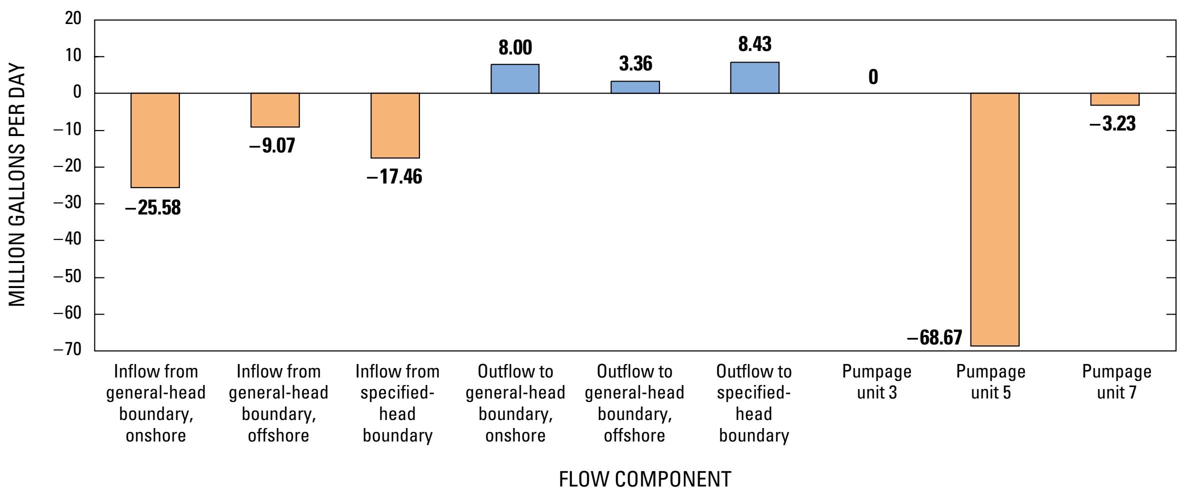


Figure 30. Simulated flow budget for Scenario C1 (Chatham County, Georgia, pumping eliminated), relative to the Base Case (2000).

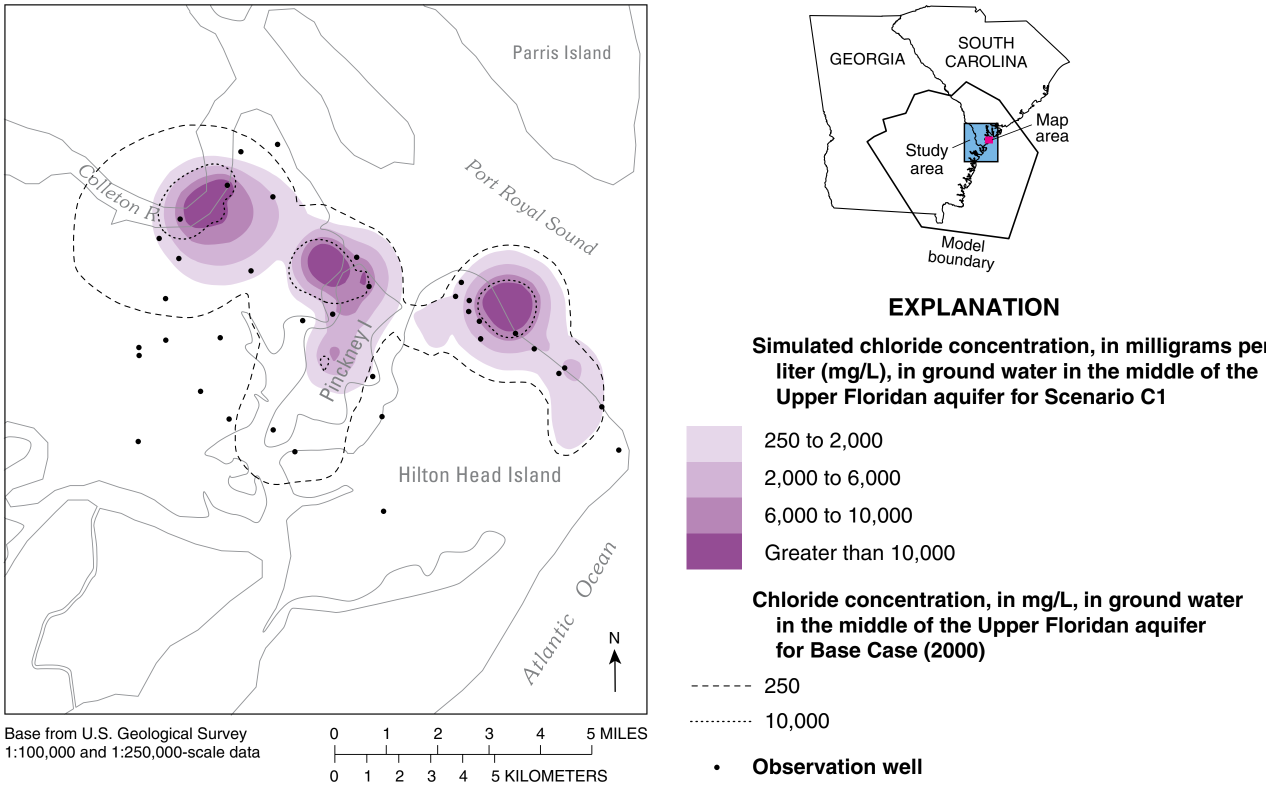


Figure 31. Simulated chloride concentration in ground water in the middle of the Upper Floridan aquifer in the Hilton Head Island, South Carolina, area for Scenario C1 (Chatham County, Georgia, pumping eliminated).

Scenario C2: Elimination of Pumping in Southern Beaufort County, South Carolina

Pumpage distributions for Scenario C2 simulations are the same as for the Base Case simulations, except that pumpage in all hydrologic units is eliminated within southern Beaufort County, S.C. (southwest of Port Royal Sound; fig. 1) from predevelopment to 2000. Table 1 shows a reduction in total pumpage of about 17 Mgal/d for the model area for Scenario C2 during 2000 relative to the Base Case. Simulated water levels, water-level differences, flow-budget components, and chloride distributions are evaluated for Scenario C2 simulations during 2000.

Ground-Water Flow

At a regional scale, simulated potentiometric surfaces for Scenario C2 generated using the steady-state MODFLOW model (fig. 32) appear similar to simulated potentiometric surfaces for Base Case (fig. 8). Differences are more apparent at the scale of the Savannah–Hilton Head Island study area, as shown for results generated using the transient SUTRA model (fig. 33A). Elimination of pumpage in southern Beaufort County results in higher water levels in the Upper Floridan aquifer for Scenario C2, relative to the Base Case, as indicated by a southwestern shift in the position of the 0- and –10-ft contours at Hilton Head Island (figs. 33A and 9). The resulting extent of the simulated Upper Floridan aquifer potentiometric cone of depression centered at Savannah is somewhat smaller for the Scenario C2 than for the Base Case. Elsewhere, the extent and magnitude of this cone of depression is generally the same for Scenario C2 as for the Base Case.

Simulated water levels in all aquifers for Scenario C2, are higher relative to those for the Base Case (figs. 33B and 34), mostly in the coastal area of Beaufort and Jasper Counties, S.C., and eastern Chatham County, Ga. This relative increase in Upper Floridan aquifer water levels is greatest at the northern end of Hilton Head Island (about 11 ft), and extends to Savannah, where the maximum increase is about 2 ft (fig. 33B). The simulated water-level increase in the Lower Floridan aquifer is similar to that for the Upper Floridan aquifer, and is generally less than 2 ft and limited to a small part of Jasper and Beaufort Counties for the Brunswick aquifer system (fig. 34). Because the presence and hydraulic characteristics of these units are poorly defined in South Carolina, these results are less reliable than those for the Upper Floridan aquifer.

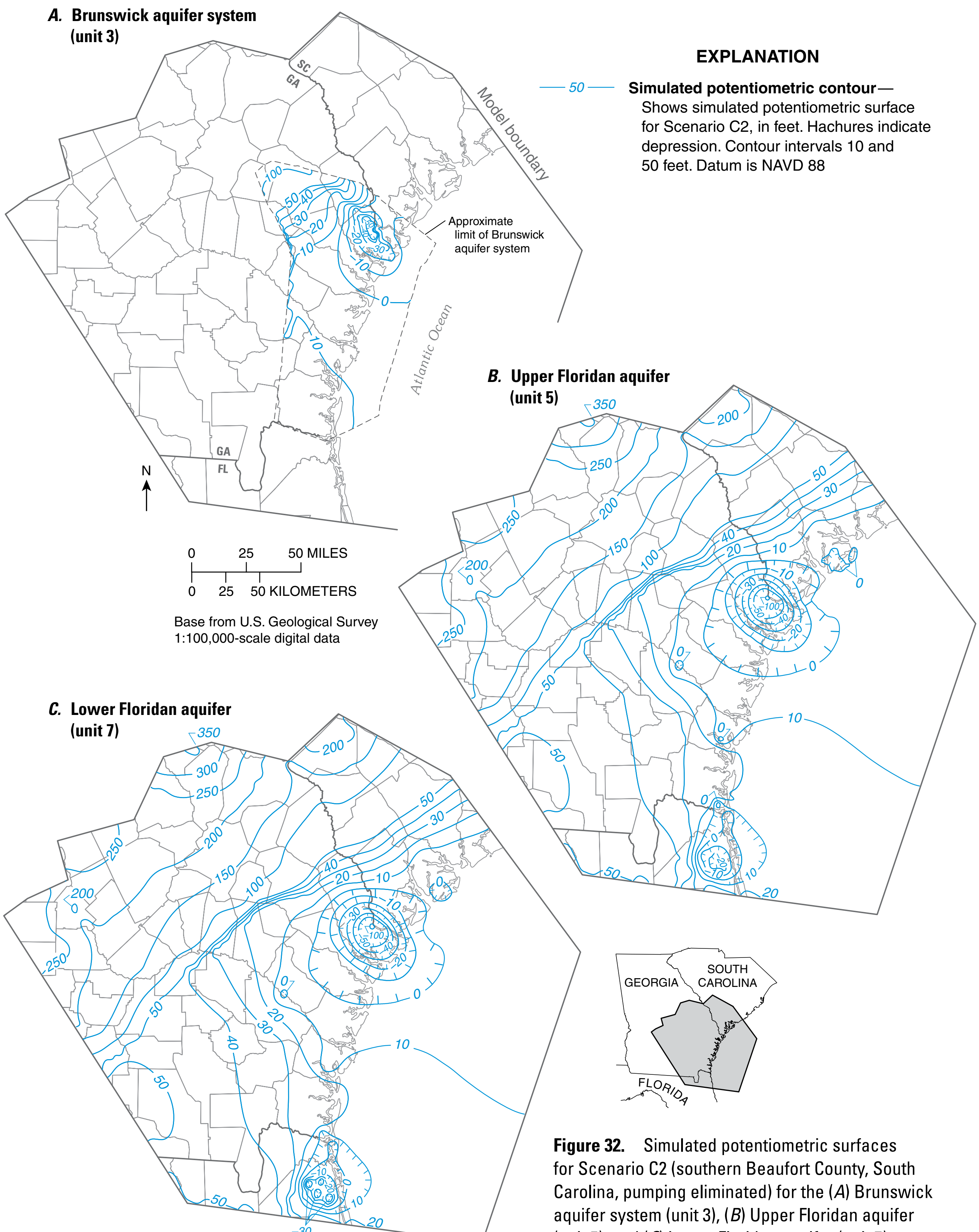


Figure 32. Simulated potentiometric surfaces for Scenario C2 (southern Beaufort County, South Carolina, pumping eliminated) for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).

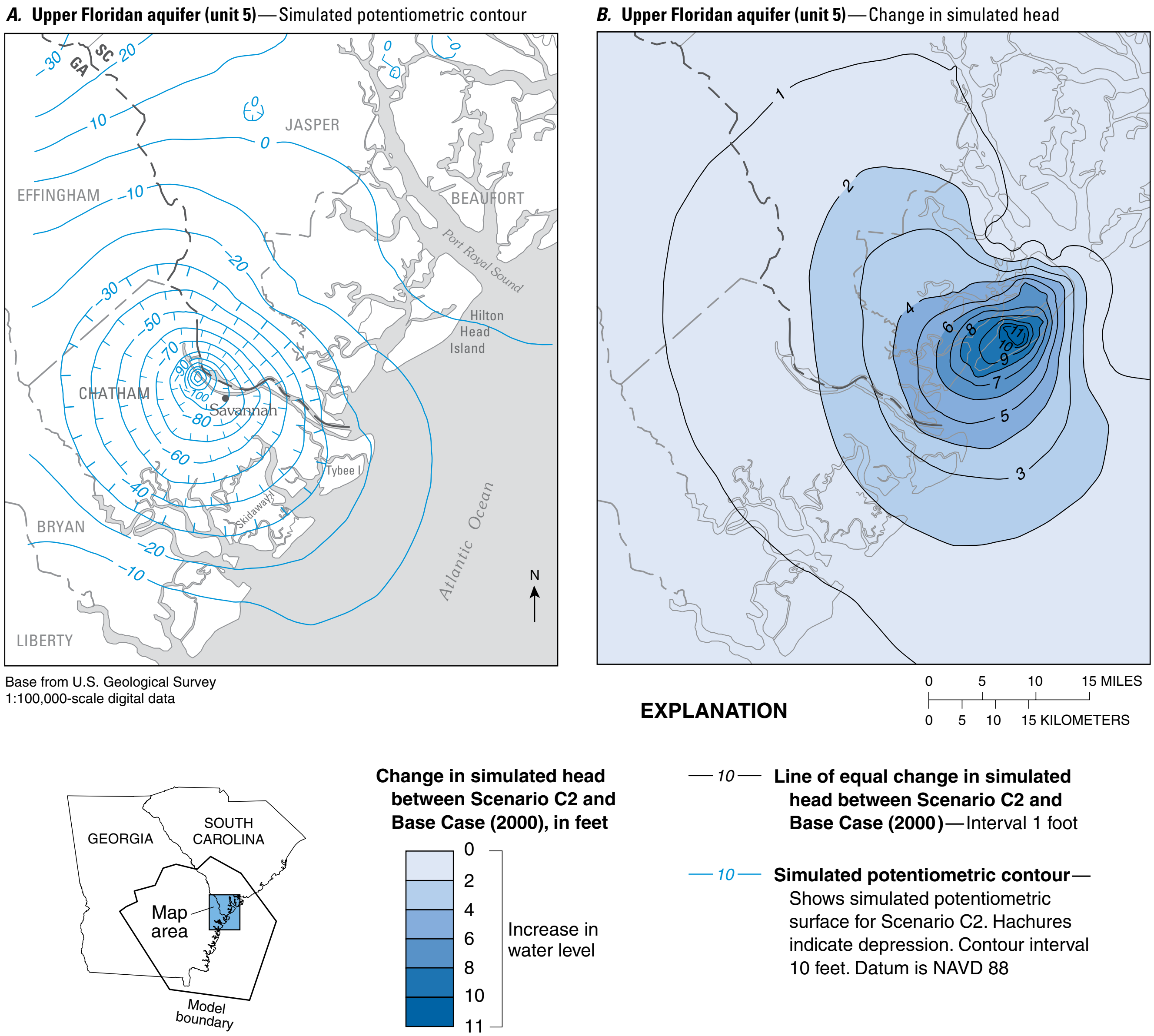


Figure 33. Results using solute-transport model for (*A*) simulated potentiometric surface for Scenario C2 (southern Beaufort County, South Carolina, pumping eliminated) and (*B*) change in simulated head between Scenario C2 and the Base Case (2000) for the Upper Floridan aquifer in Chatham County, Georgia, and southern Beaufort County.

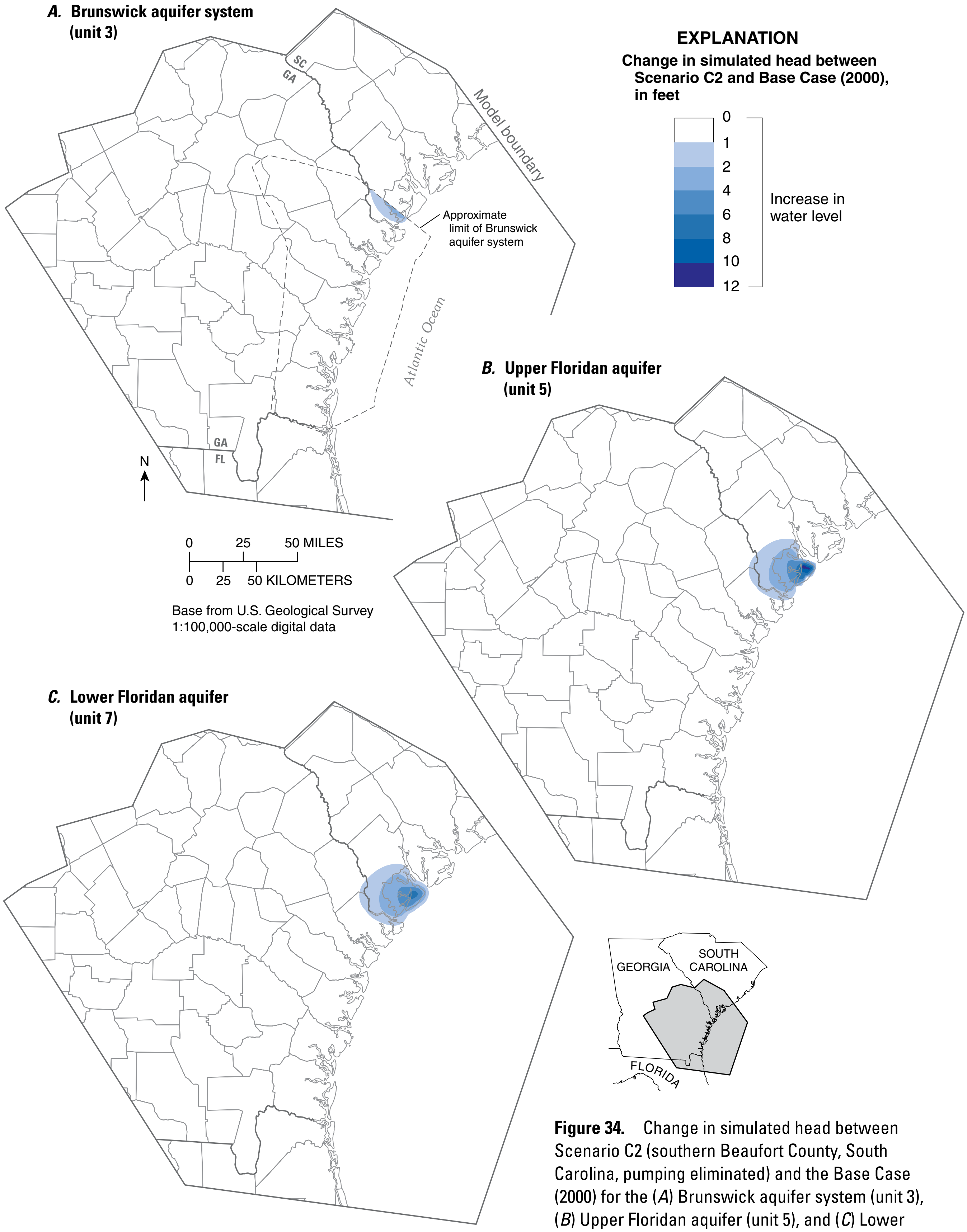


Figure 34. Change in simulated head between Scenario C2 (southern Beaufort County, South Carolina, pumping eliminated) and the Base Case (2000) for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).

Major components of the simulated water budgets for Scenario C2 using the MODFLOW model are summarized in table 8. The pumpage changes from about 798 Mgal/d for the Base Case to about 782 Mgal/d for Scenario C2 (tables 2 and 8). The primary response in boundary fluxes to this pumpage is a decrease in the inflow from the general-head boundary (fig. 35). The change in pumpage is small and localized, and it has a minimal effect on the flux at the southern specified-head boundary. The decrease in flow from the offshore general-head boundary indicates a reduced potential for saltwater intrusion relative to the Base Case. This decrease is less than that for Scenario C1 by about 6 Mgal/d, indicating that pumpage at Chatham County may have the potential to draw a larger amount of saltwater into the Upper Floridan aquifer than pumping at southern Beaufort County. Within the model boundaries, the decrease in pumpage also resulted in a slight decrease in landward flux from the offshore area, relative to the 2000 Base Case (fig. 19).

Solute Transport

Results of the solute-transport simulation using SUTRA for Scenario C2 show that all chloride plumes developed to a lesser extent than for the Base Case simulation (fig. 36). Comparison of Scenarios C1 and C2 indicates that, in general, elimination of all pumping in southern Beaufort County, S.C. (Scenario C2) has a smaller effect on plume development than elimination of all pumping in Chatham County, Ga. (Scenario C1; fig 31). Elimination of pumping in Chatham County has a greater effect on plume development west of Hilton Head Island. At the northern end of Hilton Head Island, the effect of both scenarios on plume development is small, although the effect of Scenario C2 appears to be slightly greater (compare figs. 31 and 36).

Table 8. Flow-budget components for Scenario C2.

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

Model unit	Inflow				Outflow				
	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
1	274.37	20.29	—	294.67	116.11	15.66	—	—	131.76
2	46.54	—	—	46.54	3.62	—	—	—	3.62
3	—	—	—	—	—	—	—	0.24	0.24
4	—	—	—	—	—	—	—	—	—
5	141.29	—	712.18	853.48	22.29	—	267.86	653.08	943.24
6	—	—	0.00	0.00	—	—	0.00	—	0.00
7	—	—	15.46	15.46	—	—	2.33	128.65	130.98
Total all units	**462.20**	**20.29**	**727.64**	**1,210.14**	**142.02**	**15.66**	**270.19**	**781.98**	**1,209.85**
Percent flow	**38.2**	**1.7**	**60.1**	**100.0**	**11.7**	**1.3**	**22.3**	**64.6**	**100.0**

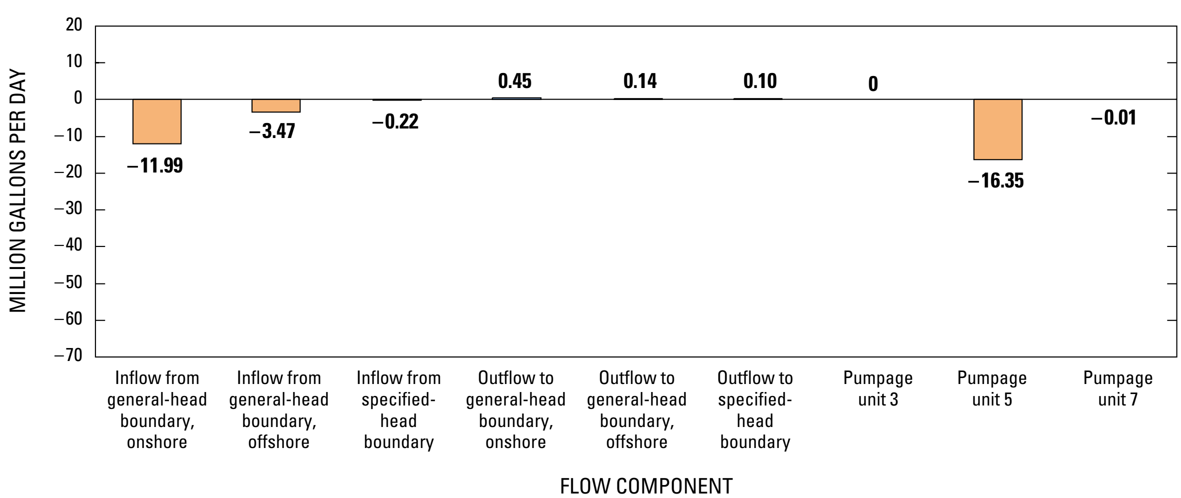


Figure 35. Simulated flow budget for Scenario C2 (southern Beaufort County, South Carolina, pumping eliminated), relative to the Base Case (2000).

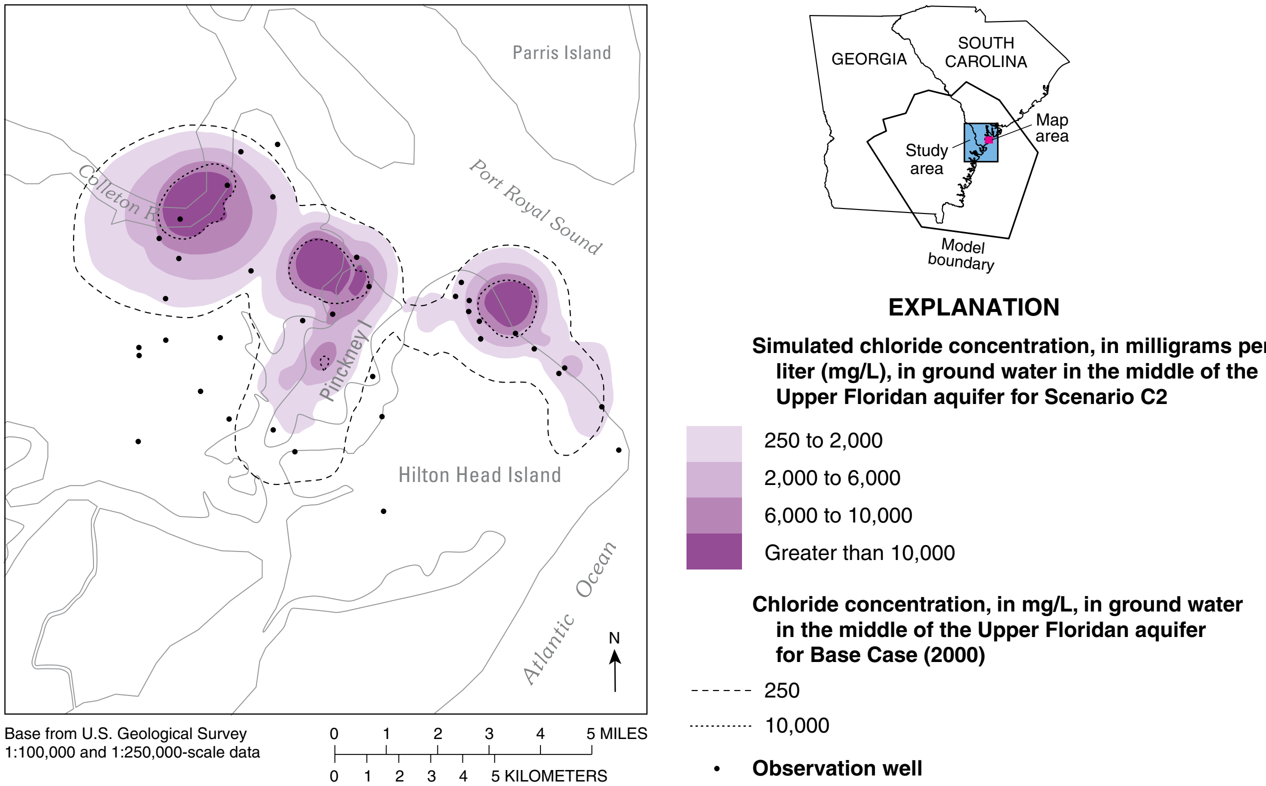


Figure 36. Simulated chloride concentration in ground water in the middle of the Upper Floridan aquifer in the Hilton Head Island, South Carolina, area for Scenario C2 (southern Beaufort County, South Carolina, pumping eliminated).

Comparison of Head Gradients in the Savannah–Hilton Head Island Area, Scenarios C1 and C2

Simulated water-level profiles for the Upper Floridan aquifer, along a cross section from Savannah to Port Royal Sound that is approximately parallel to the flow direction, were generated using results from SUTRA model simulations (fig. 37). The water-level profiles for predevelopment conditions and Base Case conditions represent end members, and those for Scenarios C1 and C2 represent intermediate members for which some pumping has been removed. The intent is to examine the relative effects of pumping at Chatham County, Ga., and southern Beaufort County, S.C. on water levels, head gradients, and flow directions in the Savannah–Hilton Head Island area.

For predevelopment conditions, the simulated potentiometric surface is above NAVD 88 along the entire profile, and the head gradient indicates a general flow direction from Savannah toward Port Royal Sound. For Base Case conditions (2000), the profile shows distinctly one side of the potentiometric cone of depression centered at Savannah, indicating a steep head gradient with direction of flow from Hilton Head Island toward Savannah. The profile also shows a smaller depression, superimposed on the larger feature, at Hilton Head Island.

The water-level profile for Scenario C1 indicates a head gradient similar to predevelopment with direction of flow from Savannah toward the southern part of Hilton Head Island. There is also a small cone of depression at Hilton Head Island, however, indicating a flow direction from Port Royal Sound southwestward toward the southern part of Hilton Head Island. The water levels for Scenario C1 are lower than for predevelopment conditions and higher than for the Base Case. Figure 37 indicates that eliminating pumping in Chatham County would have a discernible effect (about 1 ft) as far away as the northern end of Hilton Head Island.

For Scenario C2, the simulated water-level profile is similar to that for the 2000 Base Case, indicating a flow direction from Port Royal Sound toward Savannah. The head gradients are similar for Scenario C2 and the Base Case close to Savannah. Closer to and at Hilton Head Island, water-level profiles for Scenario C2 and the Base Case diverge, and simulated water levels on Hilton Head Island are higher for Scenario C2 than for the Base Case. No localized cone of depression at Hilton Head Island is present, as local pumping was eliminated for this scenario. The water levels for Scenario C2 are lower than for predevelopment conditions, and higher than for the Base Case 2000 pumping conditions. Figure 37 indicates that eliminating pumping in southern Beaufort County would have a discernible effect (about 5 ft) as far away as the Jasper–Beaufort county line.

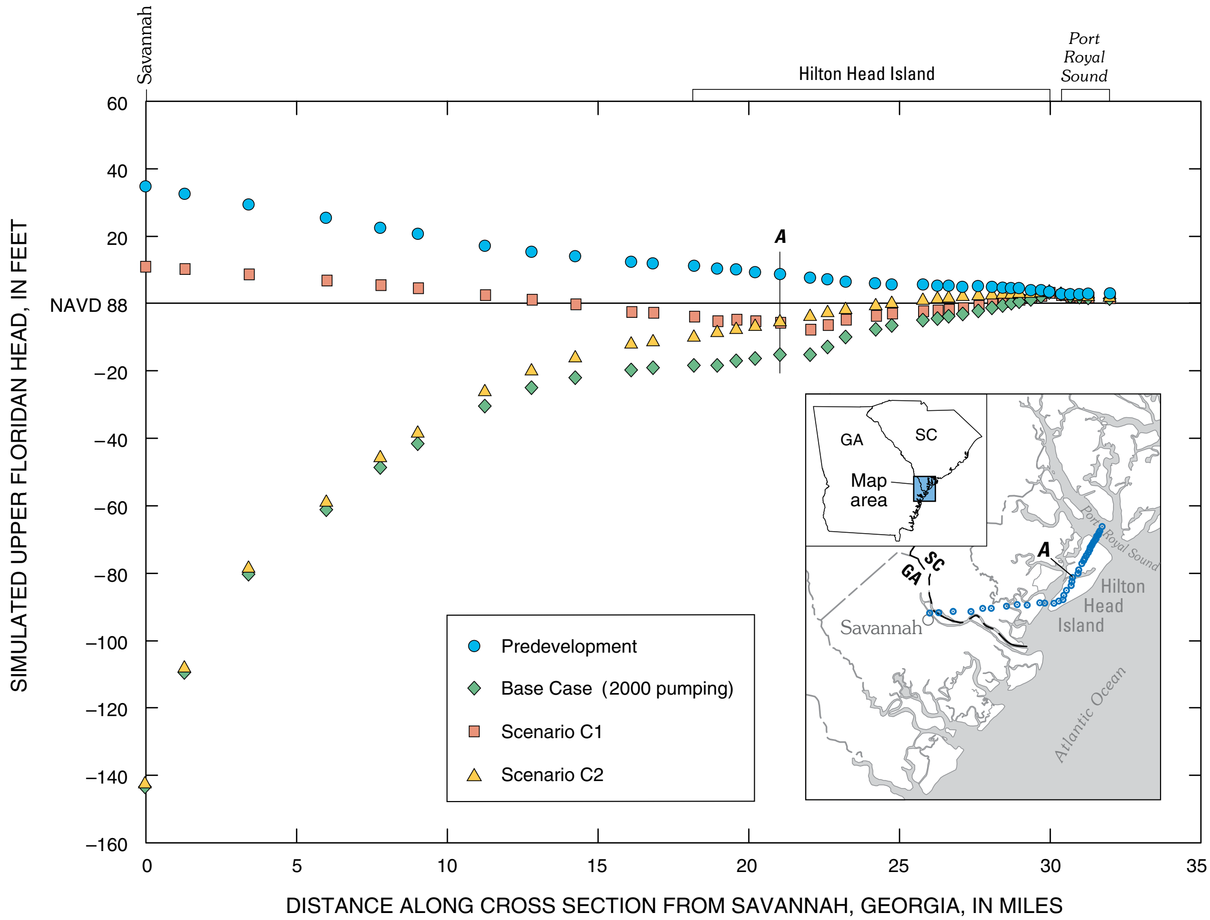


Figure 37. Cross section of potentiometric surfaces for the Upper Floridan aquifer for predevelopment, Base Case (2000), Scenario C1 (Chatham County, Georgia, pumping eliminated), and Scenario C2 (southern Beaufort County, South Carolina, pumping eliminated). Point A indicates location where the model predicts an equivalent effect on water levels by pumping at Chatham County, Georgia, and southern Beaufort County, South Carolina. Results from SUTRA model.

Comparison of the water-level profiles for Scenarios C1 and C2 shows a location on Hilton Head Island (point A, fig. 37) where simulated water levels are the same for both scenarios. The model predicts that pumping at Chatham County and pumping at southern Beaufort County have an equal effect on water levels at point A during 2000.

The model results indicate that, south of point A, eliminating pumping in Chatham County would result in a greater water-level increase relative to the Base Case than eliminating pumping in southern Beaufort County.

North of point A, eliminating pumping in southern Beaufort County would result in a greater water-level increase relative to the Base Case than eliminating pumping in Chatham County.

Scenarios D1 and D2: Projected Pumping to 2035

Scenarios D1 and D2 represent the flow-system response to projected pumpage in the 24-county coastal area of Georgia, based on two different water-use estimates (Leeth and others, 2005) (fig. 38). Pumpage for Scenario D1 is based on regional economic forecasting, and pumpage for Scenario D2 is based on county water-supply plans. Both scenarios assume no changes from 2000 pumpage in the model area outside of the 24-county coastal area of Georgia. These simulations are used to evaluate the response of the ground-water flow system to anticipated future needs, as well as the suitability of the model to evaluate substantial increases ground-water withdrawals. Results are presented from both the regional MODFLOW model and the SUTRA model of the Savannah–Hilton Head Island.

Scenario D1: Projection Based on Regional Economic Models, Inc.

The pumpage distribution for Scenario D1 is based on the estimated change in ground-water usage for the years 2010, 2020 and 2035, in the 24-county coastal area (fig. 1) in Georgia, as a function of population and employment projections by Regional Economic Models, Inc. (REMI) (Leeth and others, 2005) (fig. 39; table 1). A consistent approach based on historical trends and economic parameters was used to evaluate population projections for each county. Estimates of water use were derived from projected population and industrial growth. To distribute the pumpage, the estimated ground-water usage component was extracted from the overall usage projections. For each county, projected ground-water usage for specific years was distributed to the Upper and Lower Floridan aquifers based on methods described in Payne and others (2005), with the Upper Floridan aquifer comprising the greatest proportion. Pumpage projections were not applied to the surficial or Brunswick aquifer system. In some cases, water-use projections based on REMI estimate higher pumpage for 2000 than is used by the models because pumpage in the surficial aquifer system and aquifers deeper than the Floridan aquifer system are not accounted for in the models. Projected values for public-supply and industrial use were applied to existing public supply and industrial wells in the Upper and Lower Floridan aquifers, when available, based on the proportions during 2000. The remaining per-county pumpage values for other water-use categories were applied to the nonsite-specific distribution for the Upper Floridan and Lower Floridan aquifers on a county-by-county basis, as described previously. Some of the nonsite-specific pumpage is attributed to aquifers that are not simulated; thus, values for projected use per county are often less than the total provided in the forecast. During 2000 to 2035, the simulated pumpage increased by about 97 Mgal/d (12 percent) for Scenario D1.

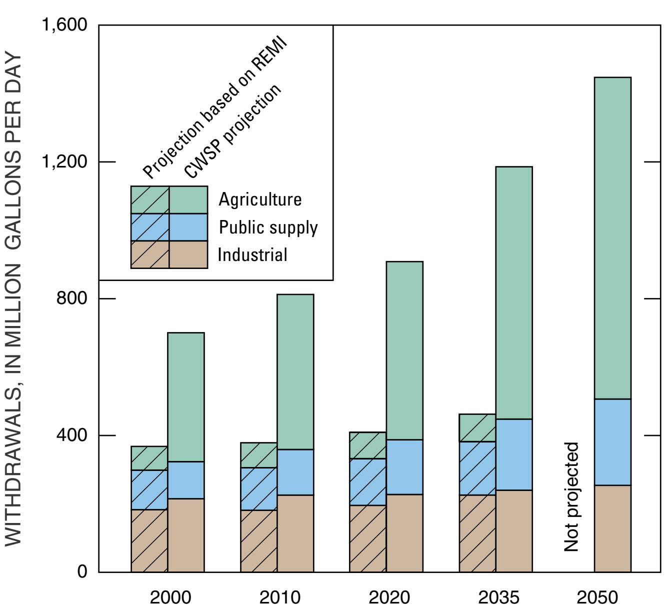


Figure 38. Projected ground-water use in the 24-county coastal area of Georgia, 2000–2050, by category (Regional Economic Models, Inc. [REMI]; County Comprehensive Water-Supply Plans [CWSP]) (modified from Leeth and others, 2005).

The regional MODFLOW model was run assuming steady-state conditions for 2035. To simulate solute transport using the SUTRA model, projected pumpage for the years 2010, 2020, and 2035 were added to the pumping history from 1885 to 2000, and the pumpage for the intervening years was linearly interpolated. Pumpage after 2035 was assumed to remain at 2035 levels for simulations through 2100. Water levels and flow-budget components are evaluated for steady-state conditions during 2035. Water-level changes are evaluated for steady-state conditions during 2000 and 2035. Chloride distributions are evaluated for 2010, 2020, 2035, and 2100, and are compared with chloride distributions for the Base Case, and with chloride distributions for simulations for which pumpage remains at 2000 levels through 2100.

Ground-Water Flow

For Scenario D1, the simulated potentiometric surfaces generated using the MODFLOW model for the Upper and Lower Floridan aquifers during 2035 (fig. 40) are similar and show large potentiometric cones of depression centered over Chatham County, Ga., with a smaller cones of depression in the Nassau–Duval county area of northern Florida. The simulated potentiometric surface of the Brunswick aquifer system shows a cone of depression at Chatham County, Ga., which results from leakage caused by pumping from the Upper Floridan aquifer. Relative to the Base Case, the 0-ft potentiometric contour in the Upper and Lower Floridan aquifer potentiometric surfaces has expanded inland in Georgia into Evans County, southwestward into Wayne County, and southward to Glynn County, to coalesce with smaller cones of depression at Jesup and Brunswick (fig. 40). The cones of depression in the Nassau–Duval county area also expanded northward in response to increased pumping in Georgia. Water-level declines also resulted in a landward shift in the position of the 20-ft contour of the Upper Floridan aquifer potentiometric surface. During 2000, this contour was offshore of Camden County, whereas for Scenario D1 during 2035, the contour shifted westward and onshore.

For Scenario D1, simulated water levels decline from 2000 to 2035 for all aquifer units (fig. 41). The extent of the decline is beyond the 24-county area, although the effects are most substantial within the 24-county area.

Maximum simulated water-level declines for Scenario D1 from 2000 to 2035 occur in the Savannah–Chatham County, and Statesboro–Bulloch County, Ga., areas (fig. 41). This pattern is similar for all of the three simulated aquifer units represented, with a maximum drawdown of about 34, 44, and 43 ft for the Brunswick aquifer system, and the Upper and Lower Floridan aquifers, respectively.

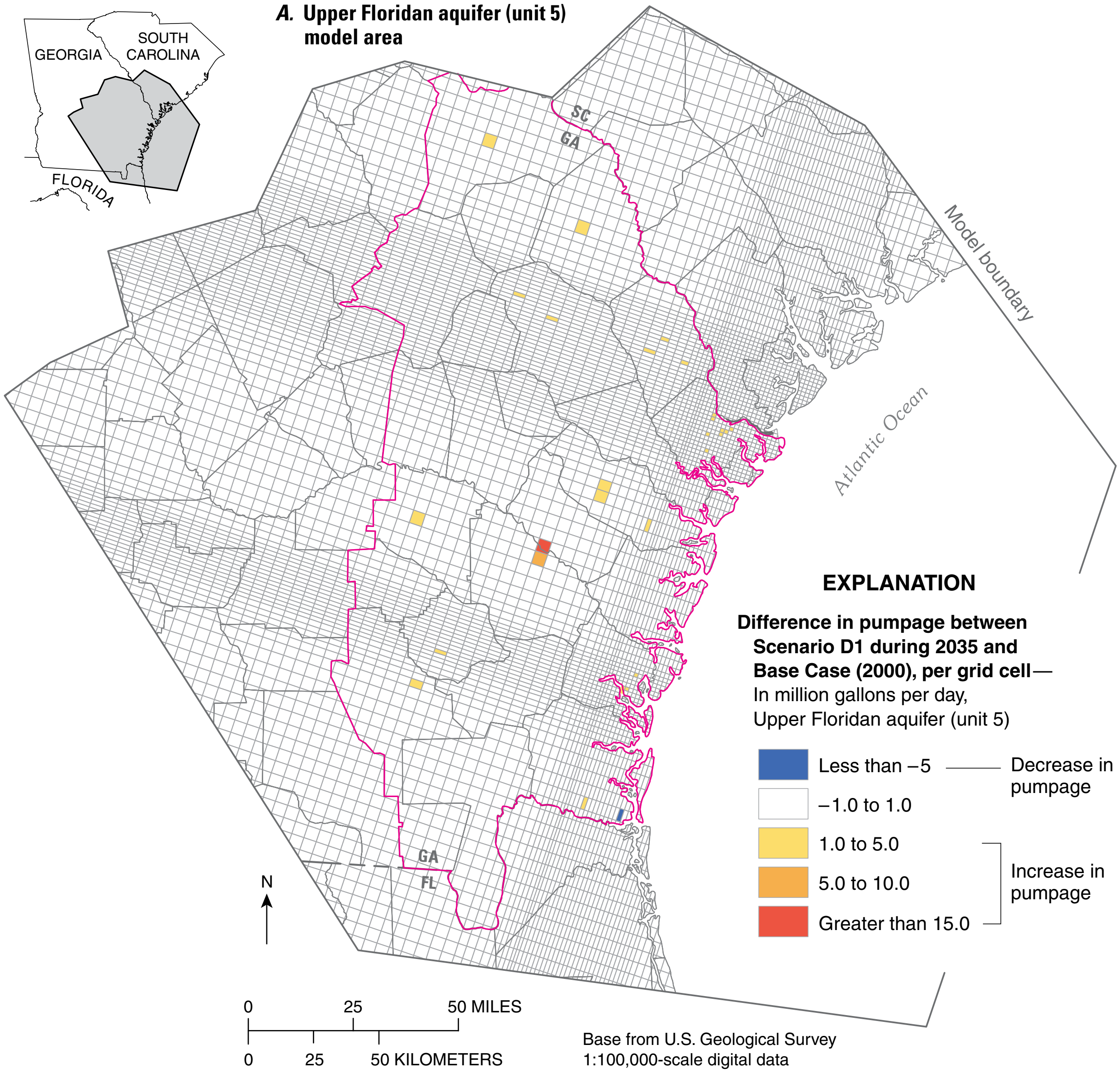


Figure 39. Distribution of the difference between ground-water pumpage for Scenario D1 (projection based on Regional Economic Models, Inc.) during 2035 and the Base Case (2000) in the Upper Floridan aquifer (*A*) model area (24-county coastal area outlined in magenta), and (*B*) enlarged view.

***B.* Upper Floridan aquifer (unit 5)—enlarged view**

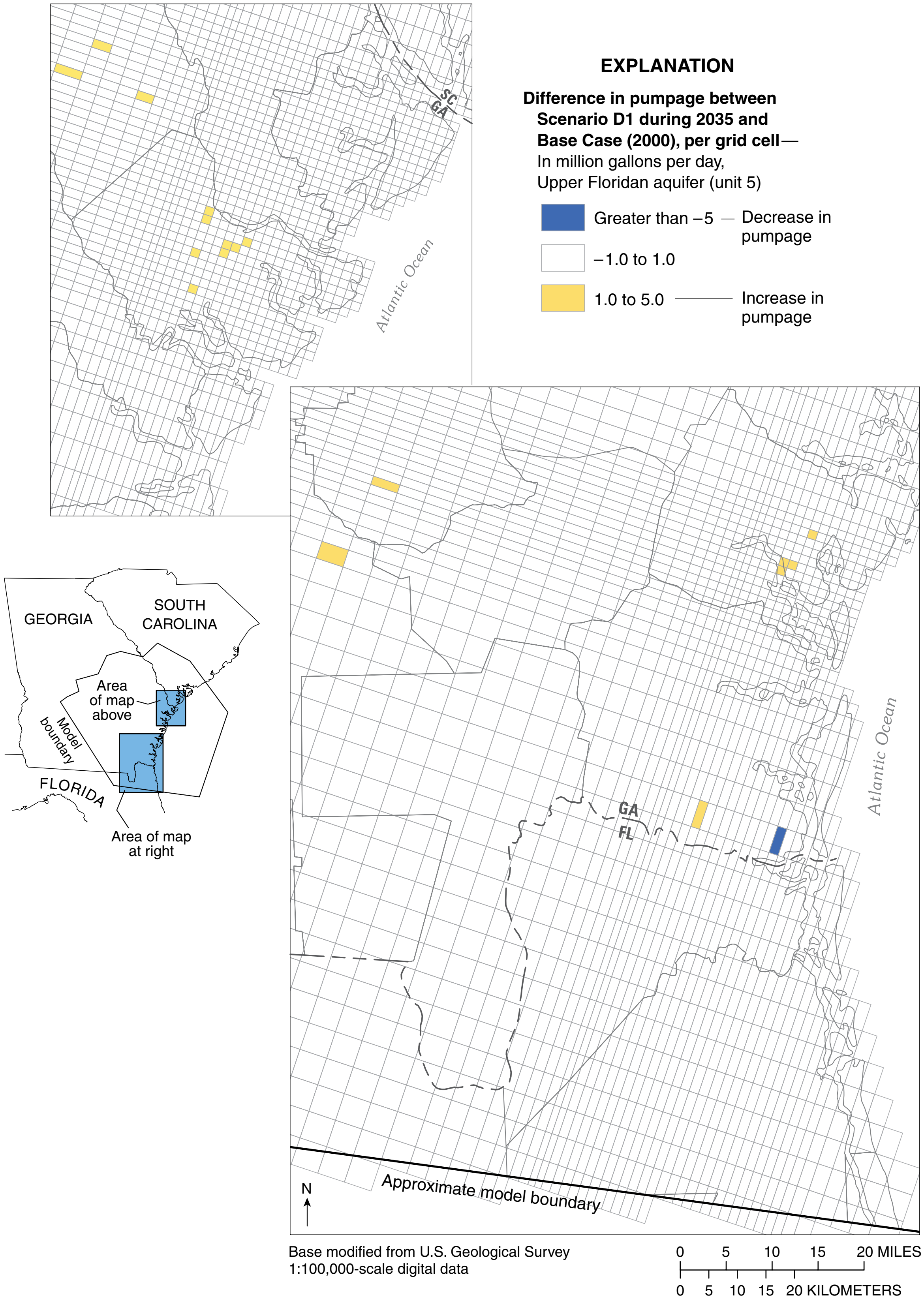


Figure 39. Distribution of the difference between ground-water pumpage for Scenario D1 (projection based on Regional Economic Models, Inc.) during 2035 and the Base Case (2000) in the Upper Floridan aquifer (*A*) model area (24-county coastal area outlined in magenta), and (*B*) enlarged view—continued.

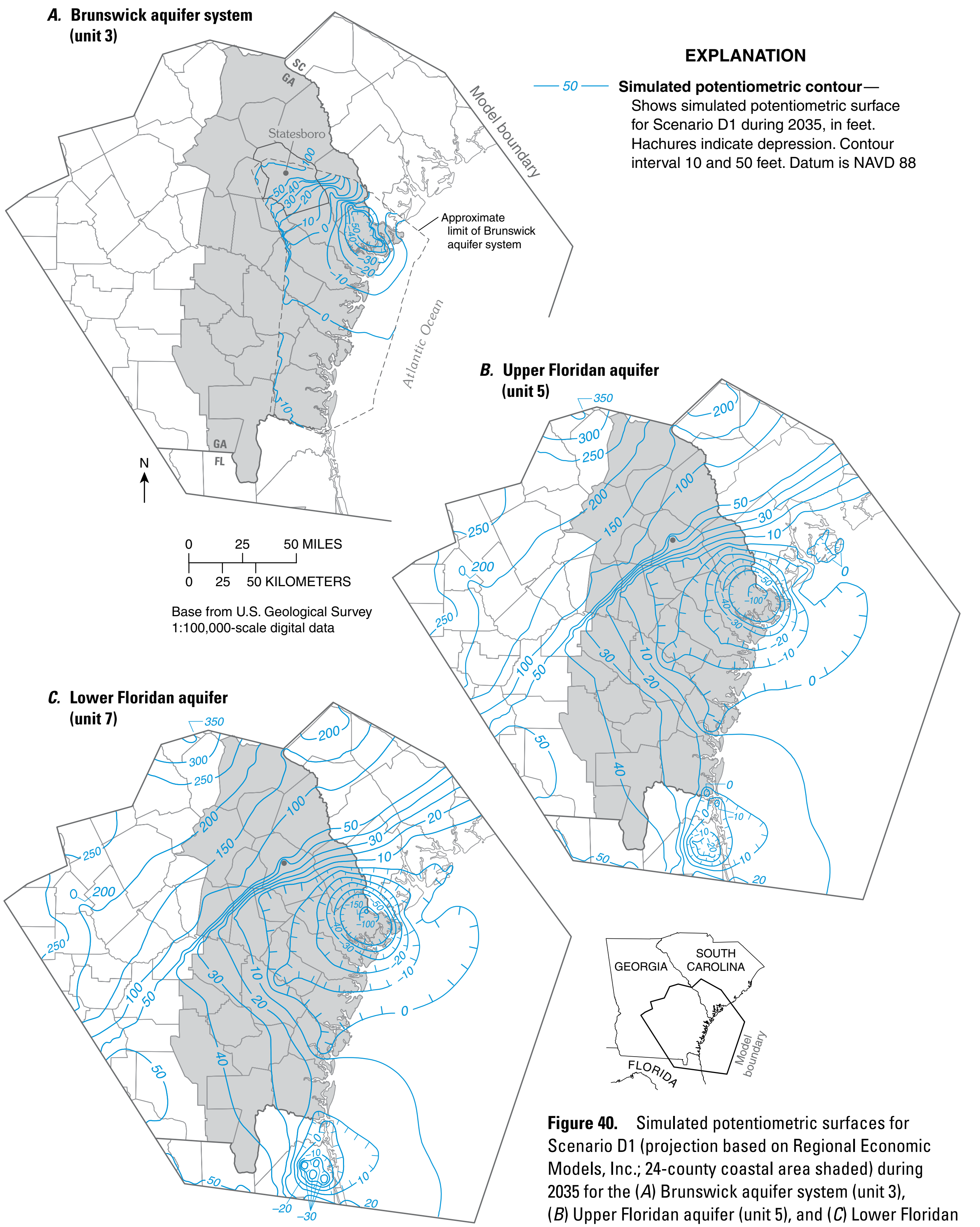
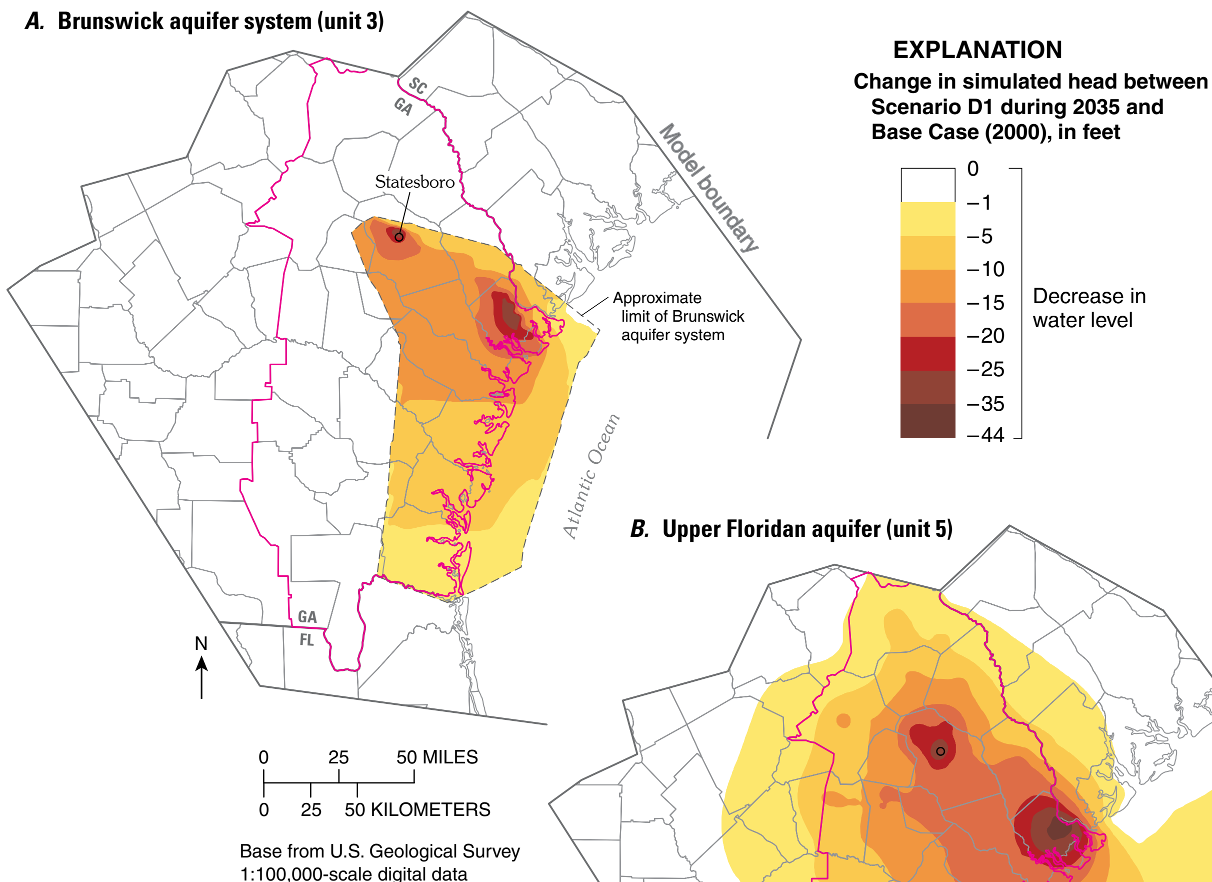
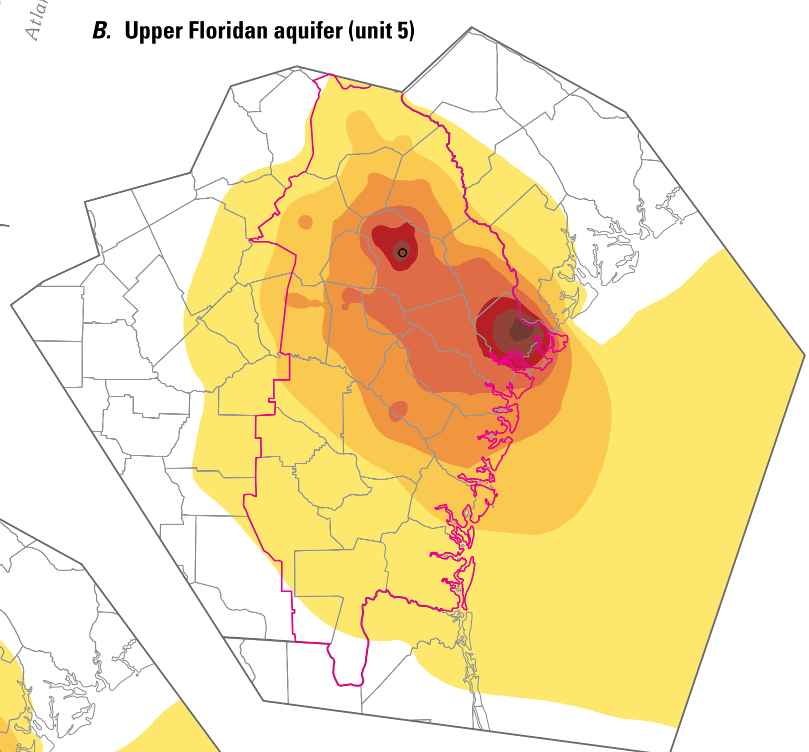


Figure 40. Simulated potentiometric surfaces for Scenario D1 (projection based on Regional Economic Models, Inc.; 24-county coastal area shaded) during 2035 for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).





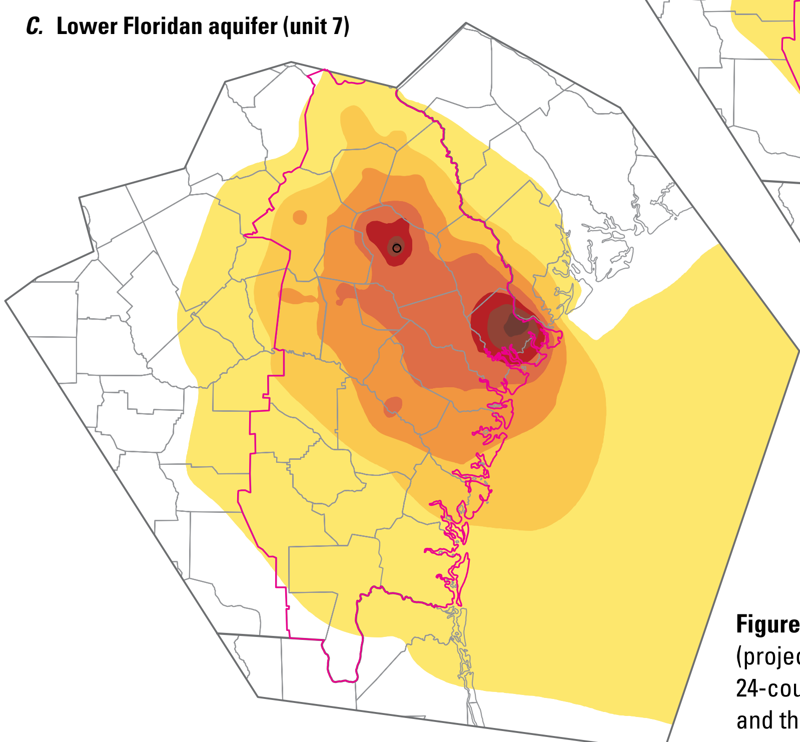


Figure 41. Change in simulated head between Scenario D1 (projection based on Regional Economic Models, Inc.; 24-county coastal area outlined in magenta) during 2035 and the Base Case (2000) for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).

Although by 2035 the total projected increase in pumpage at Bulloch County is only one-third that at Chatham County, the pumpage is localized at Statesboro, where the assigned hydraulic conductivity of the Upper Floridan aquifer is an order of magnitude lower than that in Chatham County. Thus, the effect of increases in pumpage at Bulloch County between 2000 and 2035 is intensified, resulting in greater drawdown.

One notable feature for Scenario D1 during 2000–2035 is an area of minimal drawdown in the Upper and Lower Floridan aquifers offshore of Hilton Head Island (fig. 41). This feature corresponds to an indent in the 0-ft potentiometric contours of the Upper and Lower Floridan aquifers, as demonstrated in the 2000 simulated results (fig. 8). In this area, the model units overlying the Upper Floridan aquifer (units 2, 3, and 4) comprise the Upper Floridan confining unit. For model calibration, the confining unit in this zone was assigned a hydraulic conductivity several orders of magnitude higher than the adjacent zones, in order to simulate recharge of water into the Upper Floridan aquifer near mounds on the potentiometric-surface map of the Upper Floridan aquifer and to match water-level data there (Payne and others, 2005). This area corresponds to the hydraulic conductivity zone C2, near where zone C2 is in contact with zones C4 and C5 (fig. 4). Because simulated leakage to the Upper Floridan aquifer occurs more readily in this zone, the effect of increased stress in Scenario D1 is mitigated in this zone relative to adjacent zones.

Simulated pumpage changes from about 798 Mgal/d during 2000 to about 896 Mgal/d during 2035 for Scenario D1 (tables 2 and 9). The simulated system responds by increasing inflow at all boundaries, and decreasing outflow at all boundaries during 2035, relative to the Base Case (fig. 42). The change

Table 9. Flow-budget components for Scenario D1, 2035.

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

Model unit	Inflow				Outflow				
	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
1	303.13	29.94	—	333.07	111.96	14.28	—	—	126.24
2	50.53	—	—	50.5	3.08	—	—	—	3.08
3	—	—	—	—	—	—	—	0.24	0.24
4	—	—	—	—	—	—	—	—	—
5	147.82	—	749.90	897.71	20.22	—	249.99	760.59	1,030.80
6	—	—	0.00	0.00	—	—	0.00	—	0.00
7	—	—	16.46	16.46	—	—	1.79	135.32	137.11
Total all units	**501.48**	**29.94**	**766.36**	**1,297.78**	**135.26**	**14.28**	**251.77**	**896.15**	**1,297.47**
Percent flow	**38.6**	**2.3**	**59.1**	**100.0**	**10.4**	**1.1**	**19.4**	**69.1**	**00.0**

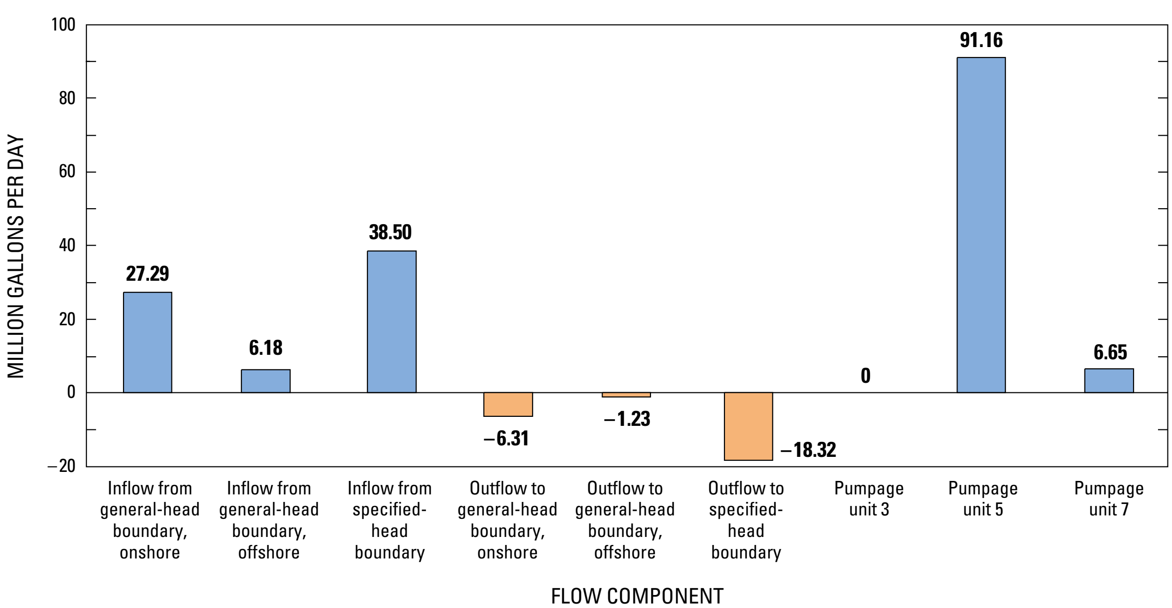


Figure 42. Simulated flow budget for Scenario D1 (projection based on Regional Economic Models, Inc.) during 2035, relative to the Base Case (2000).

in inflow and outflow at the southern specified-head boundary is larger than at the general-head boundary, likely because some of the increase in pumpage is occurring in the southern part of the model area, and the specified-head boundary allows unconstrained flow into and out of the modeled system, whereas flow to and from the general-head boundary is constrained to some degree by the general-head conductance term. The increase in the inflow from the general-head boundary in the offshore area indicates an increase in potential to recharge saltwater. Within the model boundaries, the change in stresses also resulted in a larger, net landward flux relative to the 2000 Base Case (fig. 19).

Solute Transport

The simulated chloride distribution shows a steady increase in the extent of the plumes with increasing pumpage for Scenario D1 (fig. 43). The two westernmost plumes, originating at Colleton River and Pinckney Island, show a greater increase in extent than the plume originating on the northern end of Hilton Head Island, relative to the plume distributions during 2000. The plumes generally grew southwestward from the source areas with advancing time. When Scenario D1 pumpage for 2035 is maintained until 2100, the plumes at Colleton River and Pinckney Island increase substantially more than that at the northern end of Hilton Head Island by 2100 (fig. 43D). In addition, during 2100 the plumes originating at Colleton River and Pinckney Island extend farther to the southwest than resulting plumes when 2000 pumpage is maintained until 2100. The plumes at the northern end of Hilton Head Island during 2100 are similar for Scenario D1 conditions and for 2000 conditions maintained until 2100. This indicates that the projected 97-Mgal/d increase in pumpage relative to 2000 pumpage (table 1) would have limited effect on chloride plume development in the Hilton Head Island area.

New plumes developed by the year 2035 beneath Broad Creek in the east-central part of the Hilton Head Island, in the area offshore to the east of Hilton Head Island, and beneath May River. The SUTRA solute-transport model has been calibrated only to the chloride plumes at the northern end of Hilton Head Island, Pinckney Island, and the Colleton River, so simulated plume development elsewhere must be interpreted with caution.

Scenario D2: County Comprehensive Water-Supply Plan Projection

The pumpage distribution for Scenario D2 is based on estimated change in ground-water use for the years 2010, 2020 and 2035, as derived from the County Comprehensive Water Supply Plans (CWSP) developed for each of the 24 coastal counties of Georgia (Camp Dresser and McKee, 2001; Leeth and others, 2005) (figs. 1 and 44; table 1). Each county provided its own estimate for 2010, 2020, and 2050 based on suggested guidelines; these estimates indicate that there is considerable inconsistency between counties. The analysis for Scenario D2 herein is extended only to 2035 for comparability with Scenario D1 results, using a linear interpolation between 2020 and 2050 to estimate water use for the year 2035. During 2000 to 2035, the simulated pumpage increased by about 574 Mgal/d (70 percent) for Scenario D2.

Using projections for these years, the pumpage was distributed as described for Scenario D1, and a steady-state simulation was run for the year 2035 using the MODFLOW model. For the solute-transport model, the years 2010, 2020, and 2035 were added to the pumping history from 1885 to the present, and pumpage for the intervening years was linearly interpolated. Simulation results during 2100 also are shown for which pumpage after 2035 was assumed to remain at 2035 pumpage through the year 2100.

Ground-Water Flow

The increase in pumpage for Scenario D2 from 2000 to 2035 produced changes in the configuration of the simulated potentiometric surfaces and widespread, substantial water-level declines using the MODFLOW model (figs. 45 and 46). As is the case for other simulations, the potentiometric surface of the Lower Floridan aquifer is similar to that of the Upper Floridan aquifer. Likewise, depressions in the potentiometric surface of the Brunswick aquifer system correspond to the potentiometric cones of depression in the Upper Floridan aquifer, although the maximum depth is not as great. The large increase in pumpage resulted in expansion of the Savannah area cone of depression southward and westward (fig. 45). The 0-ft contour of the Savannah area cone of depression expanded westward into Screven, northern Bulloch, Candler and Toombs Counties, Ga., and southward to coalesce with the 0-ft contour of the cone of depression centered at Duval County, Fla. A deep cone of depression, with a maximum depth of 333 ft below NAVD 88, developed in the Gulf Trough area, centered at Tattnall County, Ga., near the borders with Candler and Evans Counties.

For Scenario D2, simulated water-level declines during 2000–2035 exceed 20 ft across most of the 24-county coastal area in Georgia (fig. 46). Declines exceeding 100 ft occur in the Upper Floridan aquifer in Bulloch, Candler, Emanuel, Evans, Tattnall, and Toombs Counties, Ga. Maximum declines exceeding 250 ft coincide with the deepest part of the cone of depression in the Upper and Lower Floridan potentiometric surfaces (fig. 45), with a maximum decline of 400 ft. In the Brunswick aquifer system, maximum declines of more than 100 ft occur in Bulloch and Candler Counties, also coinciding with the cone of depression in the Upper and Lower Floridan aquifer potentiometric surfaces.

The deep potentiometric cone of depression and area of maximum water-level decline in the Candler, Evans, and Tattnall Counties, Ga., area are situated at the intersection of these counties with the hydraulic-conductivity zone representing the Gulf Trough (fig. 4). The deep cone of depression and widespread water-level decline reflect substantial increases in pumpage for these counties during 2000–2035 (table 1) and the very low hydraulic conductivity assigned to the Gulf Trough.

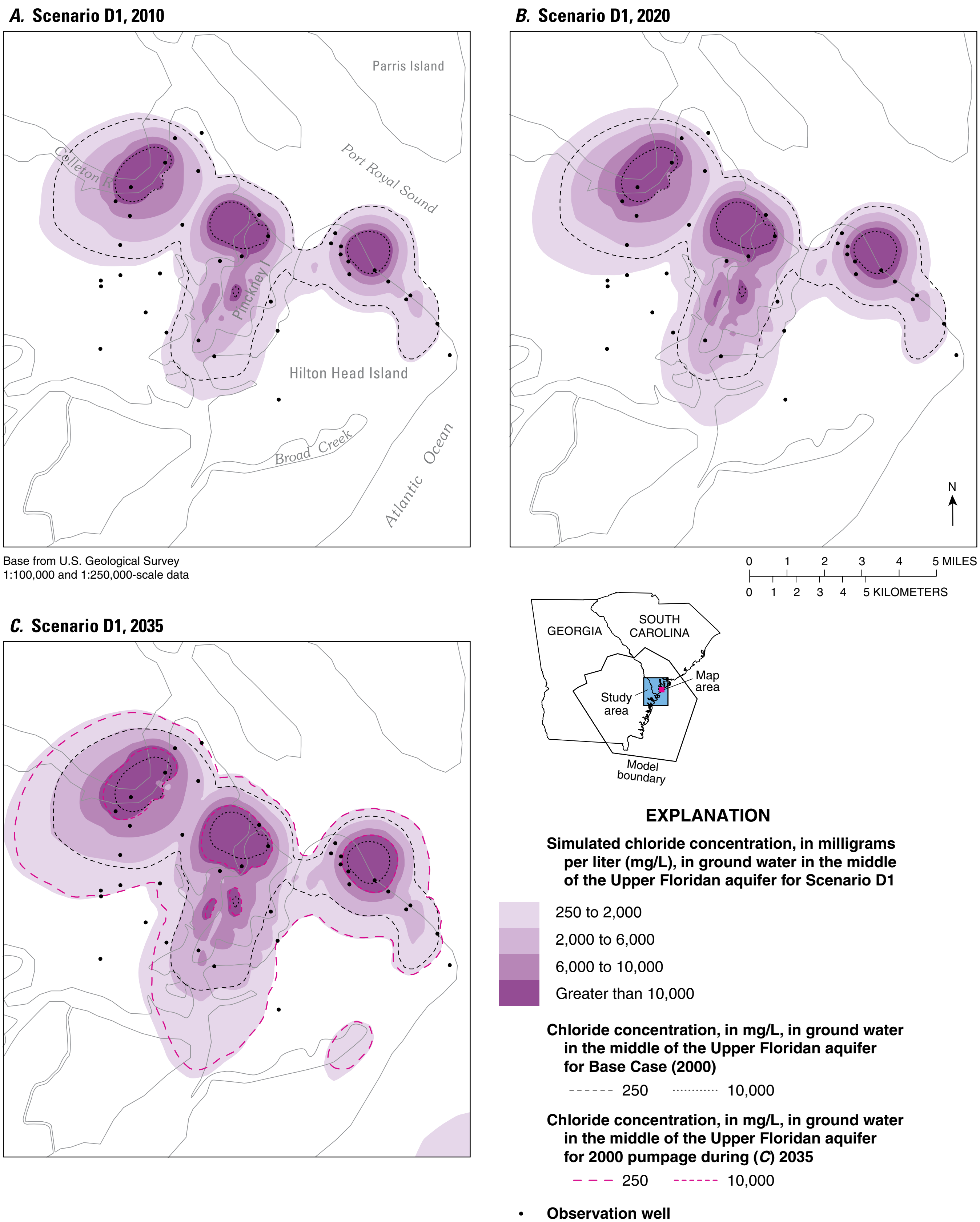
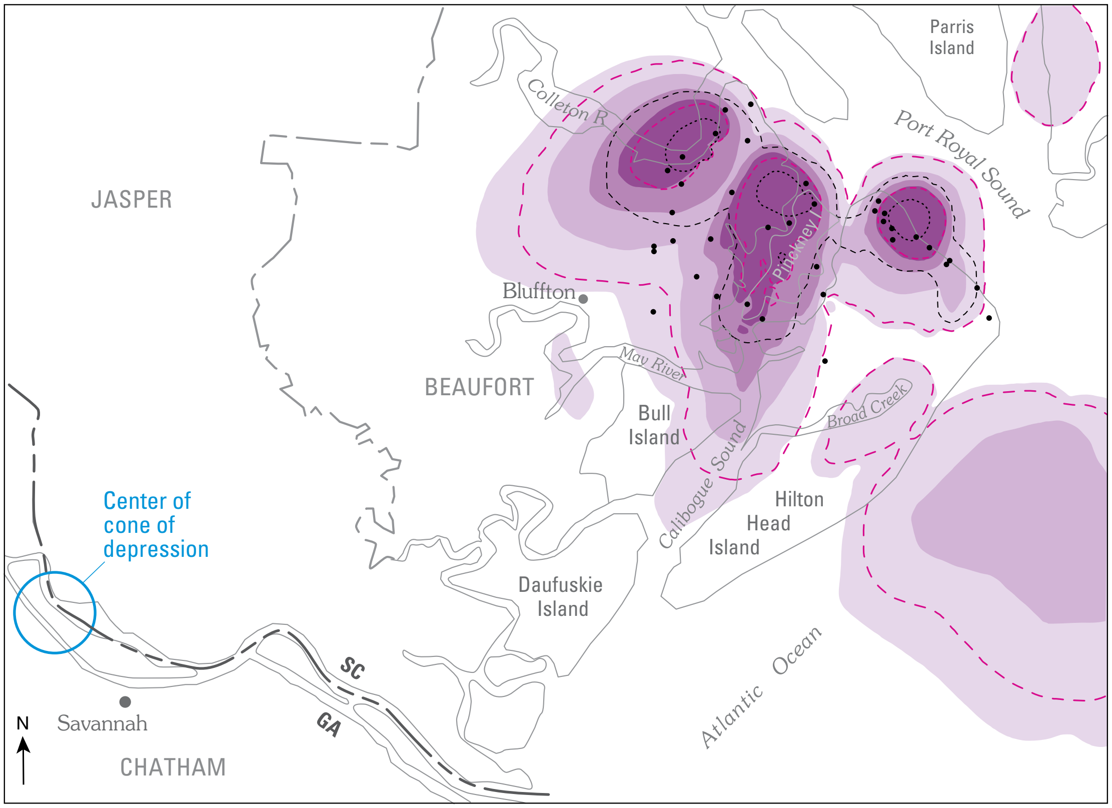
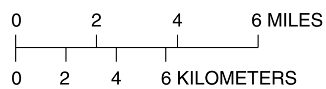


Figure 43. Simulated chloride concentration in ground water in the middle of the Upper Floridan aquifer in the Hilton Head Island, South Carolina, area for Scenario D1 (projection based on Regional Economic Models, Inc.) during (*A*) 2010, (*B*) 2020, (*C*) 2035, and (*D*) 2100 (larger area).

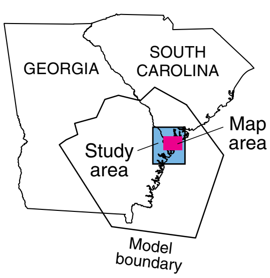
***D.* Scenario D1, 2100**



Base from U.S. Geological Survey 1:100,000 and 1:250,000-scale data
Cone of depression from Peck and others, 1999



EXPLANATION



Simulated chloride concentration, in milligrams per liter (mg/L), in ground water in the middle of the Upper Floridan aquifer for Scenario D1

- 250 to 2,000
- 2,000 to 6,000
- 6,000 to 10,000
- Greater than 10,000

Chloride concentration, in mg/L, in ground water in the middle of the Upper Floridan aquifer for Base Case (2000)

- 250
- 10,000

Chloride concentration, in mg/L, in ground water in the middle of the Upper Floridan aquifer for 2000 pumpage during (*D*) 2100

- 250
- 10,000

• **Observation well**

Figure 43. Simulated chloride concentration in ground water in the middle of the Upper Floridan aquifer in the Hilton Head Island, South Carolina, area for Scenario D1 (projection based on Regional Economic Models, Inc.) during (*A*) 2010, (*B*) 2020, (*C*) 2035, and (*D*) 2100 (larger area)—continued.

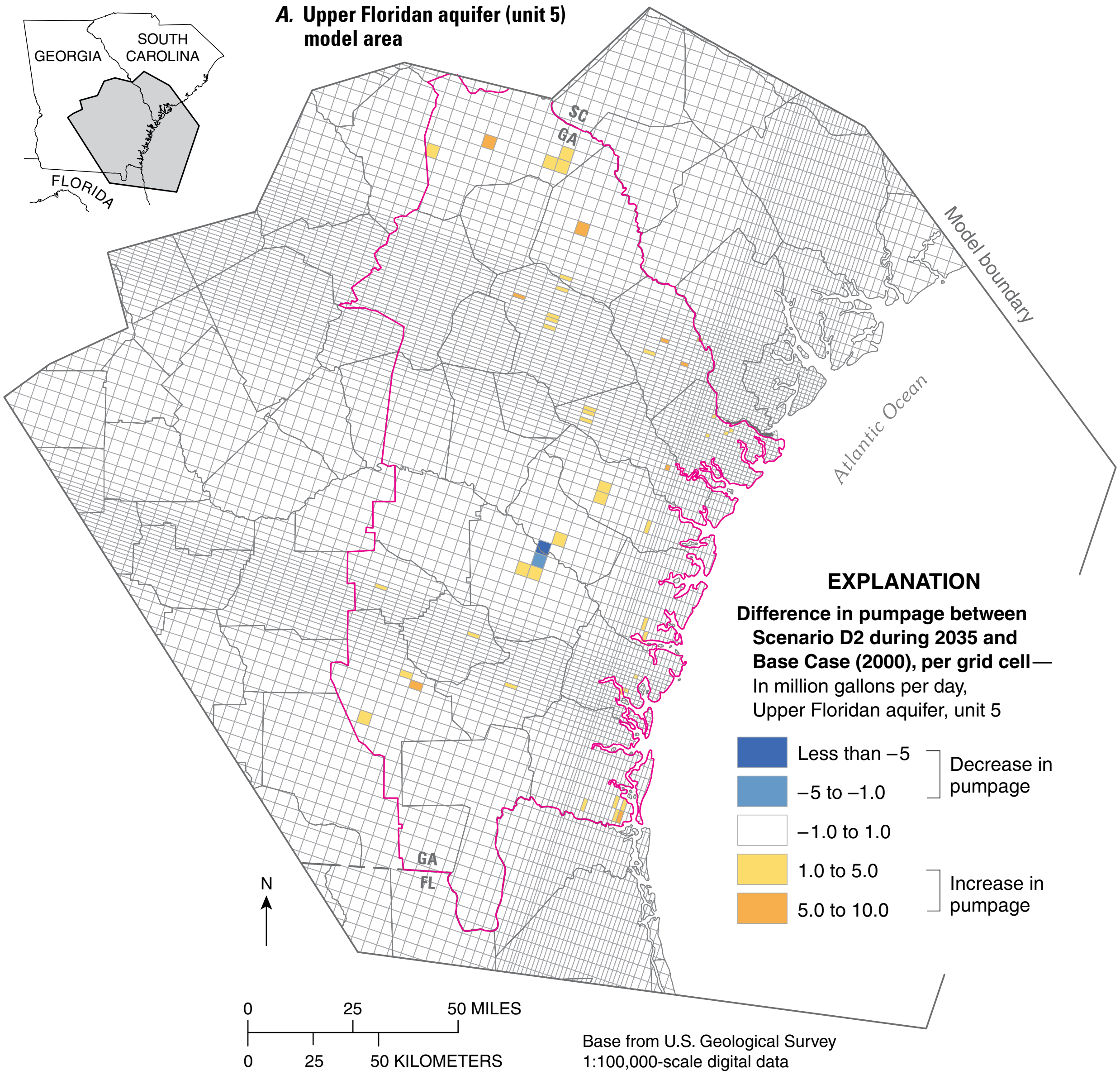


Figure 44. Distribution of the difference between ground-water pumpage for Scenario D2 (County Comprehensive Water-Supply Plans projection) during 2035 and the Base Case (2000) for the Upper Floridan aquifer (*A*) model area (24-county coastal area outlined in magenta), and (*B*) enlarged view.

B. **Upper Floridan aquifer (unit 5)—enlarged view**

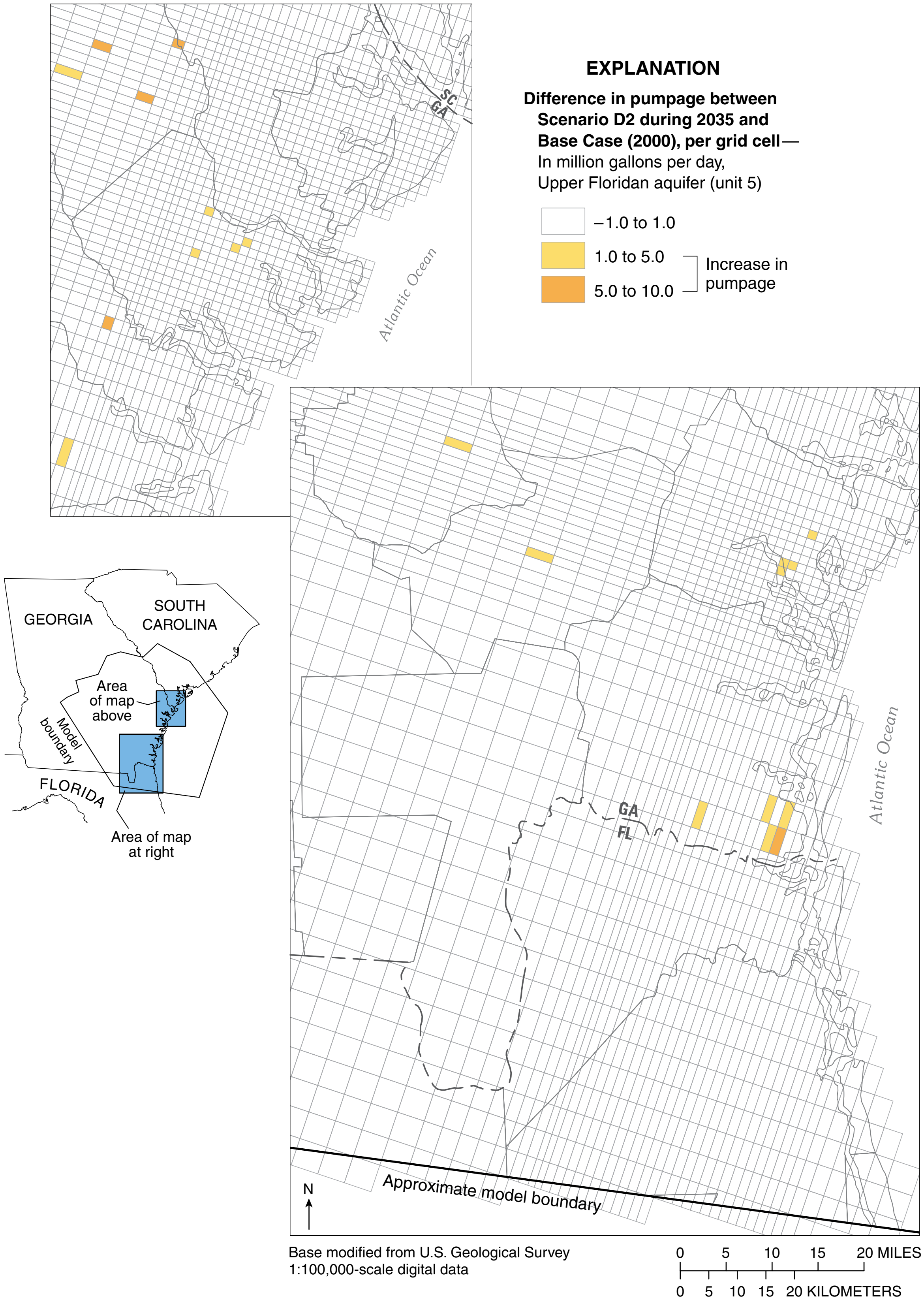


Figure 44. Distribution of the difference between ground-water pumpage for Scenario D2 (County Comprehensive Water-Supply Plans projection) during 2035 and the Base Case (2000) for the Upper Floridan aquifer (*A*) model area (24-county coastal area outlined in magenta), and (*B*) enlarged view—continued.

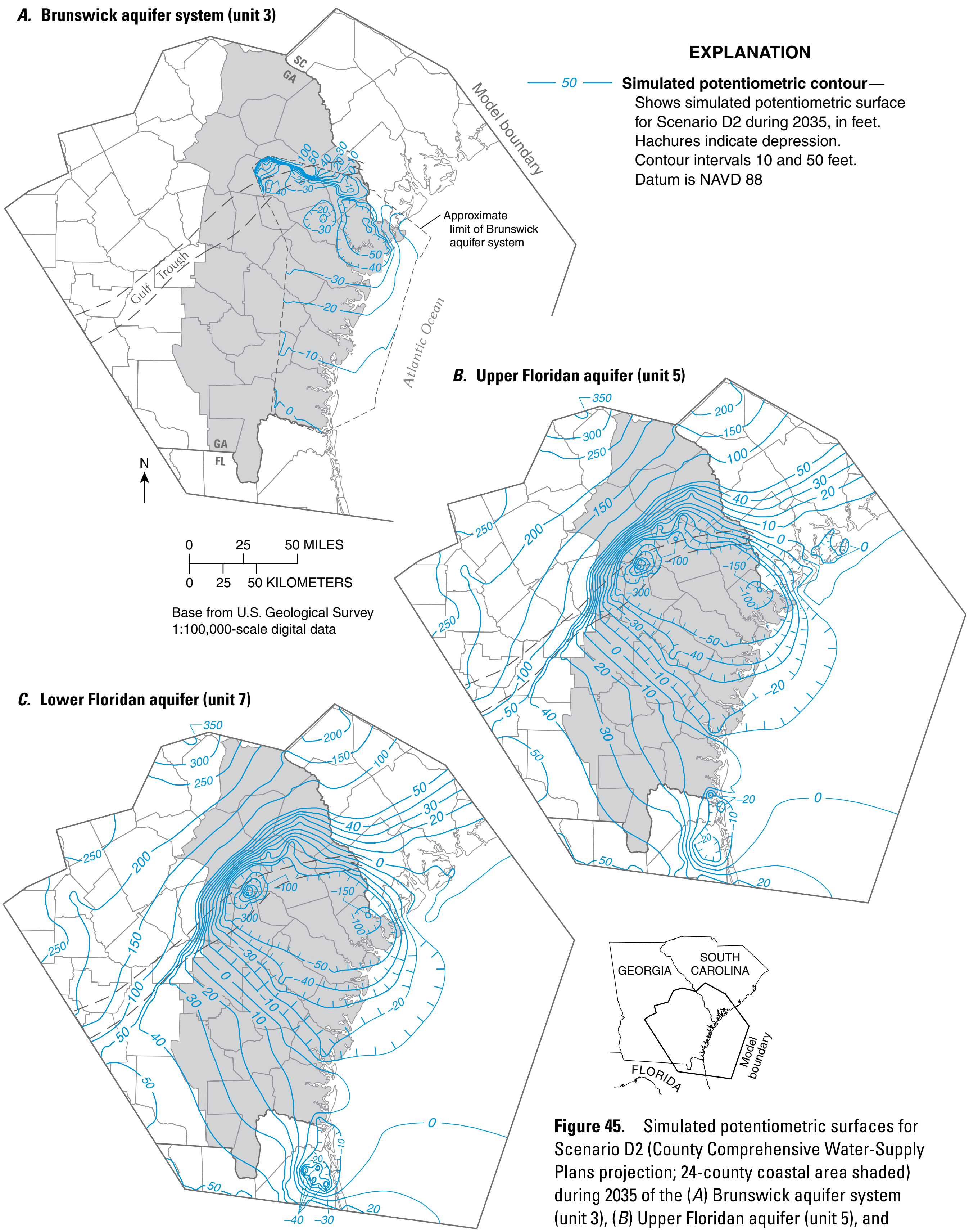


Figure 45. Simulated potentiometric surfaces for Scenario D2 (County Comprehensive Water-Supply Plans projection; 24-county coastal area shaded) during 2035 of the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).

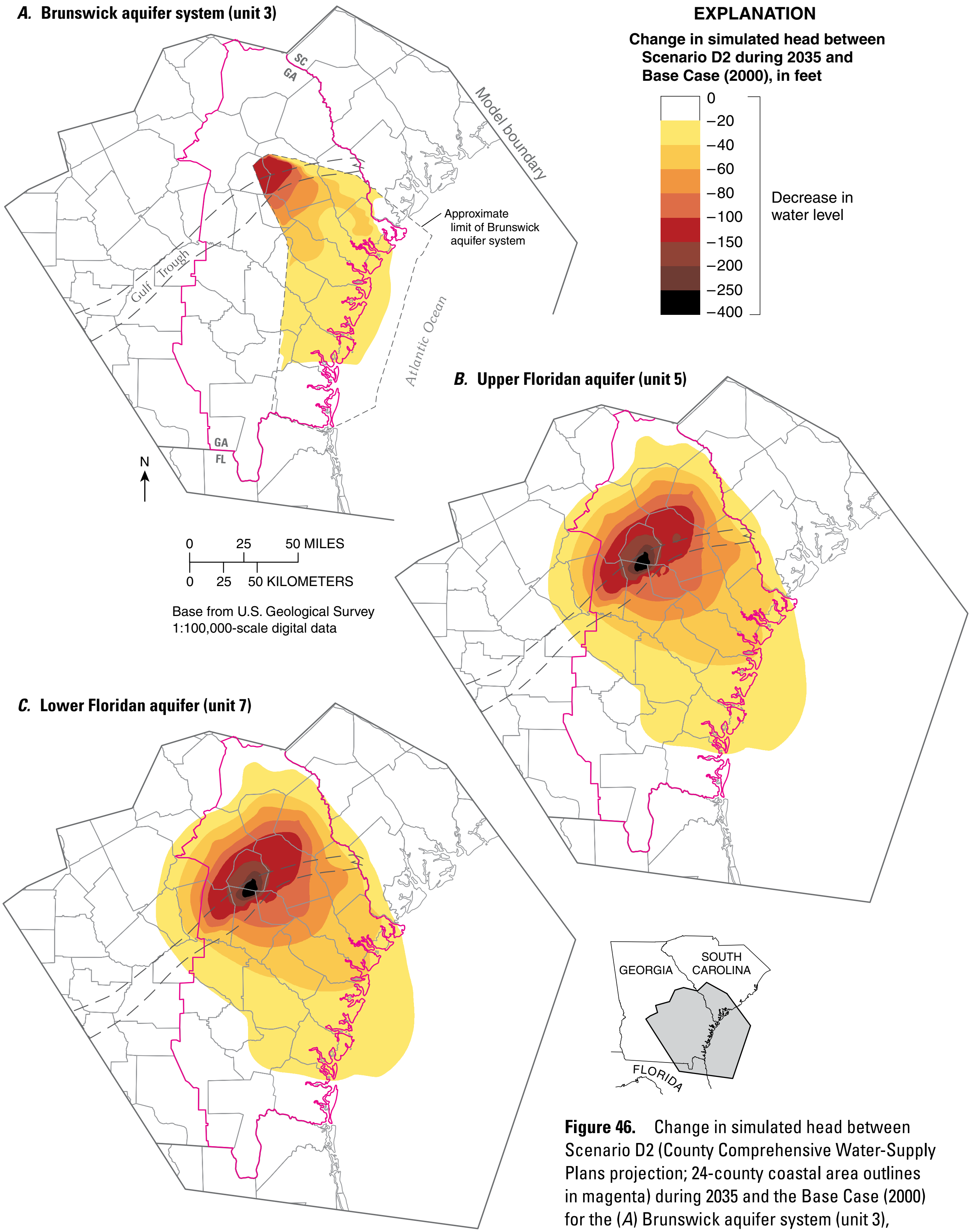


Figure 46. Change in simulated head between Scenario D2 (County Comprehensive Water-Supply Plans projection; 24-county coastal area outlines in magenta) during 2035 and the Base Case (2000) for the (*A*) Brunswick aquifer system (unit 3), (*B*) Upper Floridan aquifer (unit 5), and (*C*) Lower Floridan aquifer (unit 7).

The extent of this cone of depression is limited by the Gulf Trough hydraulic-conductivity zone—outside of this zone, the assigned hydraulic conductivity is higher and pumping is less concentrated. For example, in Brantley County, Ga., Scenario D2 ground-water use increases by 187 Mgal/d between 2000 and the year 2035 (table 1). In this area, the assigned hydraulic conductivity for the Upper Floridan aquifer is three orders of magnitude higher than in the Gulf Trough area; thus, drawdown is less and deep cones of depression do not develop.

Simulated pumpage for Scenario D2 during 2035, about 1,373 Mgal/d, is substantially larger than that during 2000 (tables 2 and 10). Correspondingly, for Scenario D2, simulated inflows increase and outflows decrease during 2035 relative to those during 2000 (fig. 47). Simulated inflow from the general-head boundary is about 139 Mgal/d (37 percent) higher for Scenario D2 during 2035 than during 2000, and simulated inflow from the southern specified-head boundary is about 293 Mgal/d (40 percent) higher than during 2000. Outflow to the general-head boundary in the onshore area is about 24 Mgal/d (17 percent) lower for Scenario D2 during 2035 than during 2000. Figure 48 shows that simulated per-cell recharge to the system increases in magnitude and extent and discharge decreases for Scenario D2 during 2035 relative to recharge and discharge during 2000. The maximum recharge rate of almost 5 inches per year (in/yr) for any given grid cell for Scenario D2 during 2035 is at the low end of calculated baseflow rates in the model area (from about 4.5 to 10 in/yr [Priest, 2004]), and within the range of acceptable per-cell recharge rates (Payne and others, 2005). The recharge rates are poorly constrained, however, and simulated recharge in some areas may exceed actual recharge. Substantial increases in recharge and decreases in discharge, as a response to large increases in pumpage, could affect the unconfined ground-water system or surface-water bodies. Because the boundary conditions used in the model provide an unlimited source of water to the system, the effects cannot be evaluated for unconfined aquifers or surface-water bodies. The increase in inflow from the general-head boundary in the offshore area also indicates an increase in potential to recharge saltwater for Scenario D2. Within the model boundaries, the change in stresses also resulted in a notably larger landward flux during 2035 relative to the 2000 Base Case (fig. 19). The substantial simulated increases in inflow at the model boundaries, however, may be an indication that the Scenario D2 pumpage is not realistic.

Table 10. Flow-budget components for Scenario D2, 2035.

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

Model unit	Inflow				Outflow				
	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
1	350.21	36.57	—	386.78	102.57	12.12	—	—	114.69
2	78.27	—	—	78.27	1.57	—	—	—	1.57
3	—	—	—	—	—	—	—	0.24	0.24
4	—	—	—	—	—	—	—	—	—
5	184.95	—	999.91	1,184.86	13.56	—	167.33	1,231.67	1,412.56
6	—	—	0.00	0.00	—	—	0.00	—	0.00
7	—	—	21.28	21.28	—	—	0.72	141.08	141.79
Total all units	**613.43**	**36.57**	**1,021.19**	**1,671.20**	**117.71**	**12.12**	**168.04**	**1,372.99**	**1,670.86**
Percent flow	**36.7**	**2.2**	**61.1**	**100.0**	**7.0**	**0.7**	**10.1**	**82.2**	**100.0**

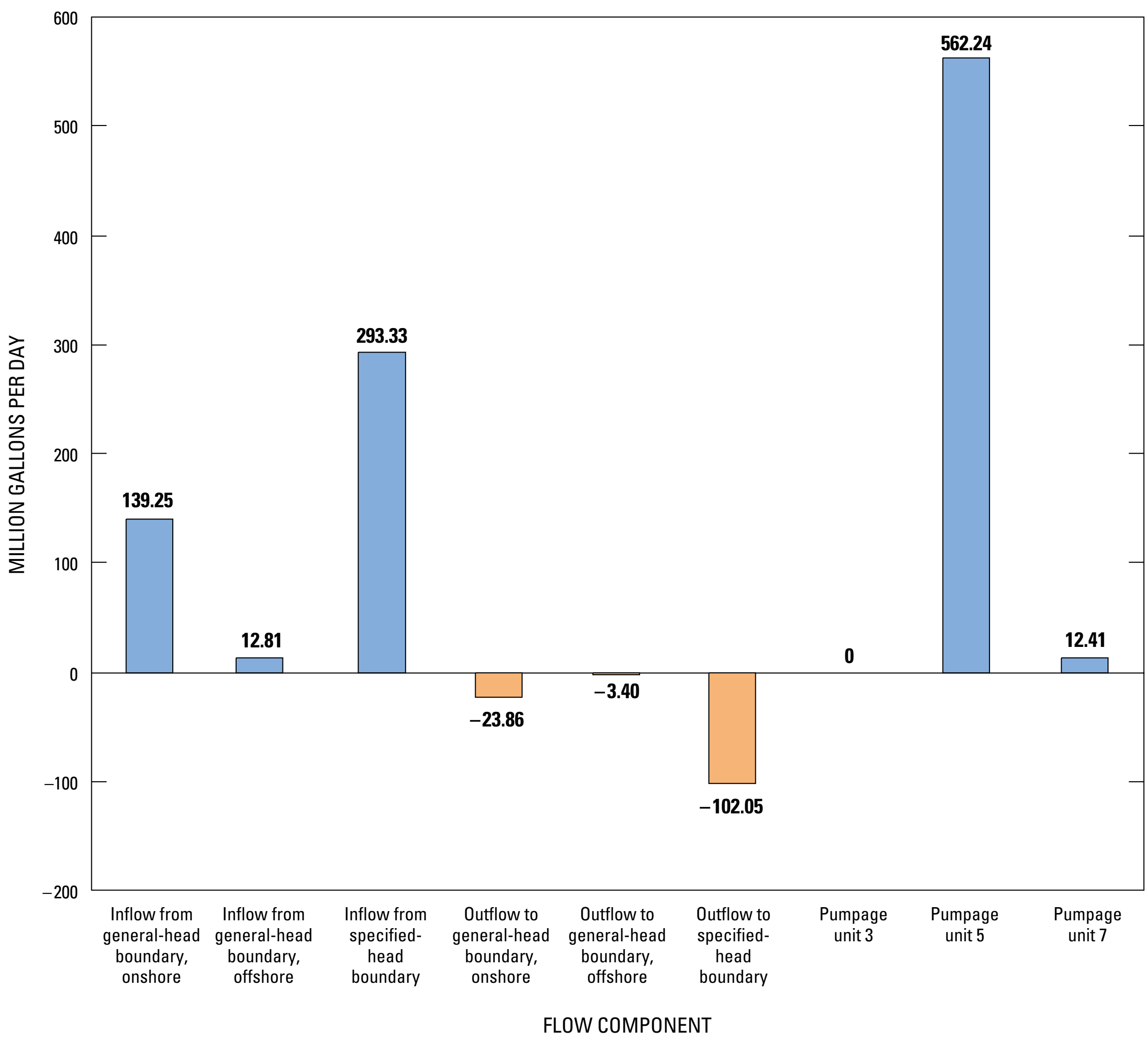


Figure 47. Simulated flow budget for Scenario D2 (County Comprehensive Water-Supply Plans projection) during 2035, relative to the Base Case (2000).

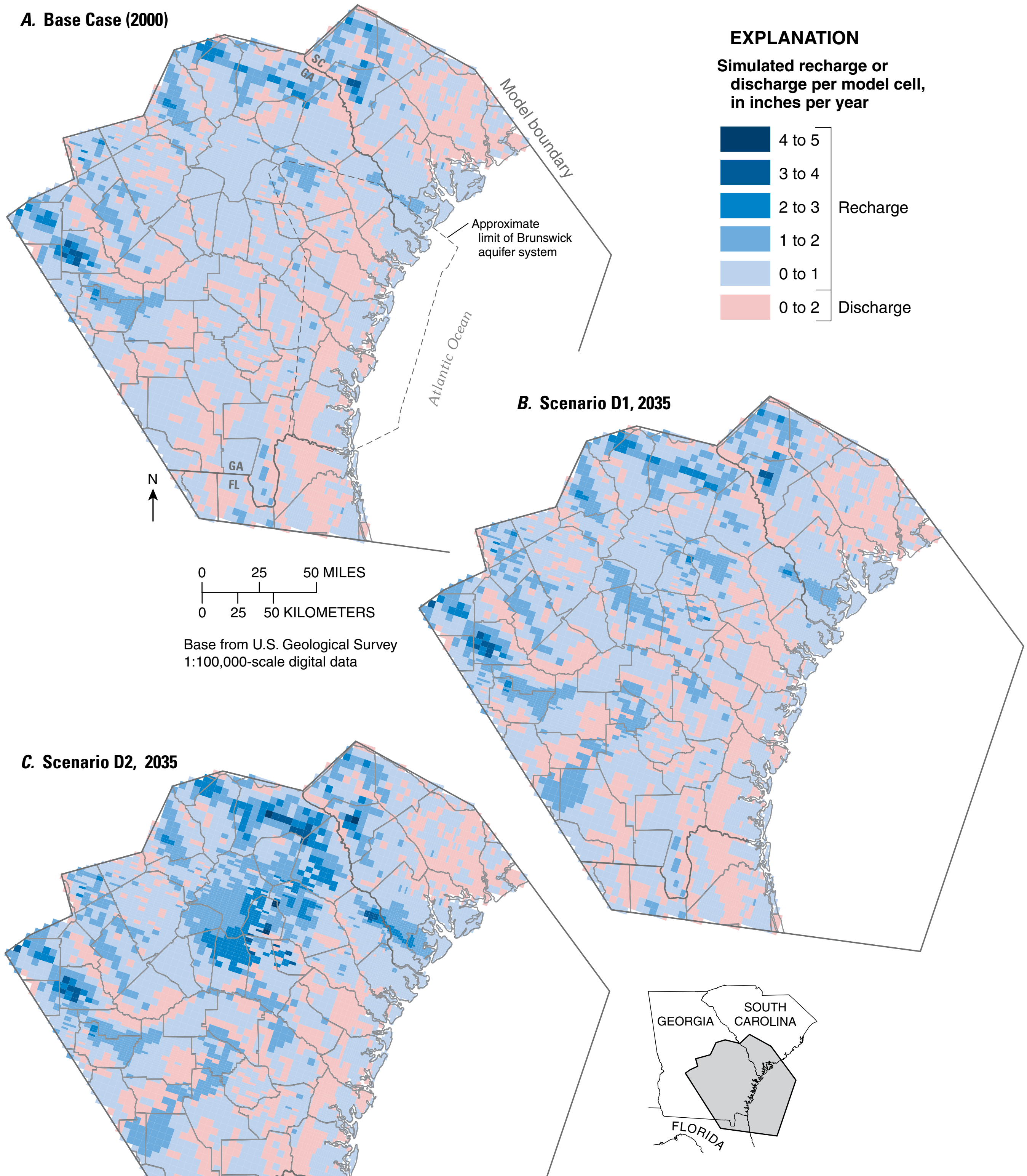


Figure 48. Simulated recharge or discharge (flow from or to general-head boundary) for (*A*) Base Case (2000); (*B*) Scenario D1 (projection based on Regional Economic Models, Inc.), 2035; and (*C*) Scenario D2 (County Comprehensive Water-Supply Plans projection), 2035.

Solute Transport

The simulated chloride distributions for Scenario D2 show an increase in extent during 2000–2035. As for Scenario D1, plumes emanating from Colleton River and Pinckney Island areas show a greater increase in extent than that at the northern end of Hilton Head Island by 2035 (figs. 12 and 49). When Scenario D2 pumpage for 2035 is maintained until 2100, the plumes continue to increase in extent, particularly those emanating from Colleton River and Pinckney Island (fig. 49D). When compared with plumes generated by maintaining 2000 pumpage conditions until 2100, the plumes originating at Colleton River and Pinckney Island generated under Scenario D2 conditions are larger in extent, by at most about 2 mi during 2100. The plume originating at the northern end of Hilton Head Island, however, is similar in extent during 2100 for simulations for which 2000 pumpage and Scenario D2 2035 pumpage are applied until 2100. This indicates that the projected 574-Mgal/d increase in pumpage relative to 2000 pumpage (table 1) would have a limited effect on chloride-plume development in the Hilton Head Island area. Plumes that develop away from the areas where calibration data are available or where present-day chloride concentrations are elevated (for example, at Broad Creek, at May River, and offshore of Hilton Head Island) are more speculative.

Despite a large difference in projected pumpage increases for Scenario D1 during 2035 and Scenario D2 during 2035 (477 Mgal/d), the simulated chloride distributions for Scenario D2 show only a slightly larger extent by 2035 and 2100 (fig. 49C, D) than those for Scenario D1 (43C, D). The three nearest counties to the Hilton Head Island area for which pumpage was projected are Bryan, Chatham, and Effingham Counties. Pumpage increases in these counties likely have a larger effect on the plume movement than pumpage in the rest of the model area. The projected pumpage for Chatham County is about 13 Mgal/d higher for Scenario D1 than for Scenario D2, and the projected pumpage for Bryan and Effingham Counties is higher for Scenario D2 than ScenarioD1 by a total of about 34 Mgal/d (table 1). These results indicate that the effect of relatively high stresses far from the Hilton Head Island area on plume development probably are dissipated by distance, and that the effect of the greater pumpage increases for Scenario D2 relative to Scenario D1 at Bryan and Effingham Counties is somewhat offset by the lesser pumpage increases at Chatham County.

Model Limitations

Model results must be interpreted in light of uncertainties and approximations inherent in the formulation of the model and the several scenarios that the model simulates. The ground-water flow and solute-transport models used in this study are simplified representations of natural processes and properties of a hydrologic system, and as such are subject to the limitations described by Payne and others (2005) and Provost and others (2006). These limitations include: (1) error and uncertainty in field measurements of water level and chloride concentration and in estimates of pumpage; (2) limitations of the conceptual models; approximations made in representing the physical properties of the flow system and errors inherent in estimating the spatial distribution of these properties; (3) approximations made in the formulation and application of model boundary and initial conditions; (4) errors associated with numerical approximation and solution of the mathematical model of the flow system; (5) uncertainty in interpretation of Base Case results, for example, the hydraulic interconnection between the Upper and Lower Floridan aquifers; and (6) assumptions made in using the models to predict the future behavior of the flow system. The discussion below, which addresses additional limitations associated with the model scenarios presented in this report, is intended as a supplement to the discussions of model limitations in Payne and other (2005) and Provost and others (2006).

The interpretation of scenario results is influenced by the assumptions and approximations made in the implementation of the scenarios, and how far the scenario conditions are removed from model calibration conditions. Generally, the further removed from calibration conditions the scenario conditions are, the less reliable are the model results. The conditions that define the scenarios may be inherently uncertain, for example the uncertainty in future pumpage. Additionally, conditions that are far removed from calibration conditions may induce unrealistic response from the model, if model assumptions are violated.

For Scenario B, the elimination of pumping at the industrial site in Camden County was intended to represent an actual permanent shutdown of wells that occurred during 2002. The nearest regional pumpage data, however, represented annual daily conditions for 2000, and may not accurately represent conditions during the period for which simulation results were compared with actual observation data. For example, Scenario B does not account for the possible causes of an observed regional rise in water levels after 2000, making uncertain the ability of the model to simulate accurately the effects of the shutdown. The physical construction of the model also may limit the reliability of the Scenario B results. For example, the scale and discretization of the MODFLOW model may be too coarse to represent accurately such a localized phenomenon. In addition, the proximity of the southern specified-head boundary to the simulated shutdown area may dissipate the simulated recovery toward the southern boundary and underestimate the response to the shutdown. The known error in the pumpage distribution of the calibrated model at this site probably affected the local calibrated hydraulic properties. Pumpage for Scenario B, however, is reduced by the actual observed amount, and the simulated recovery is likely similar to that, had Scenario B been simulated using a corrected and recalibrated model.

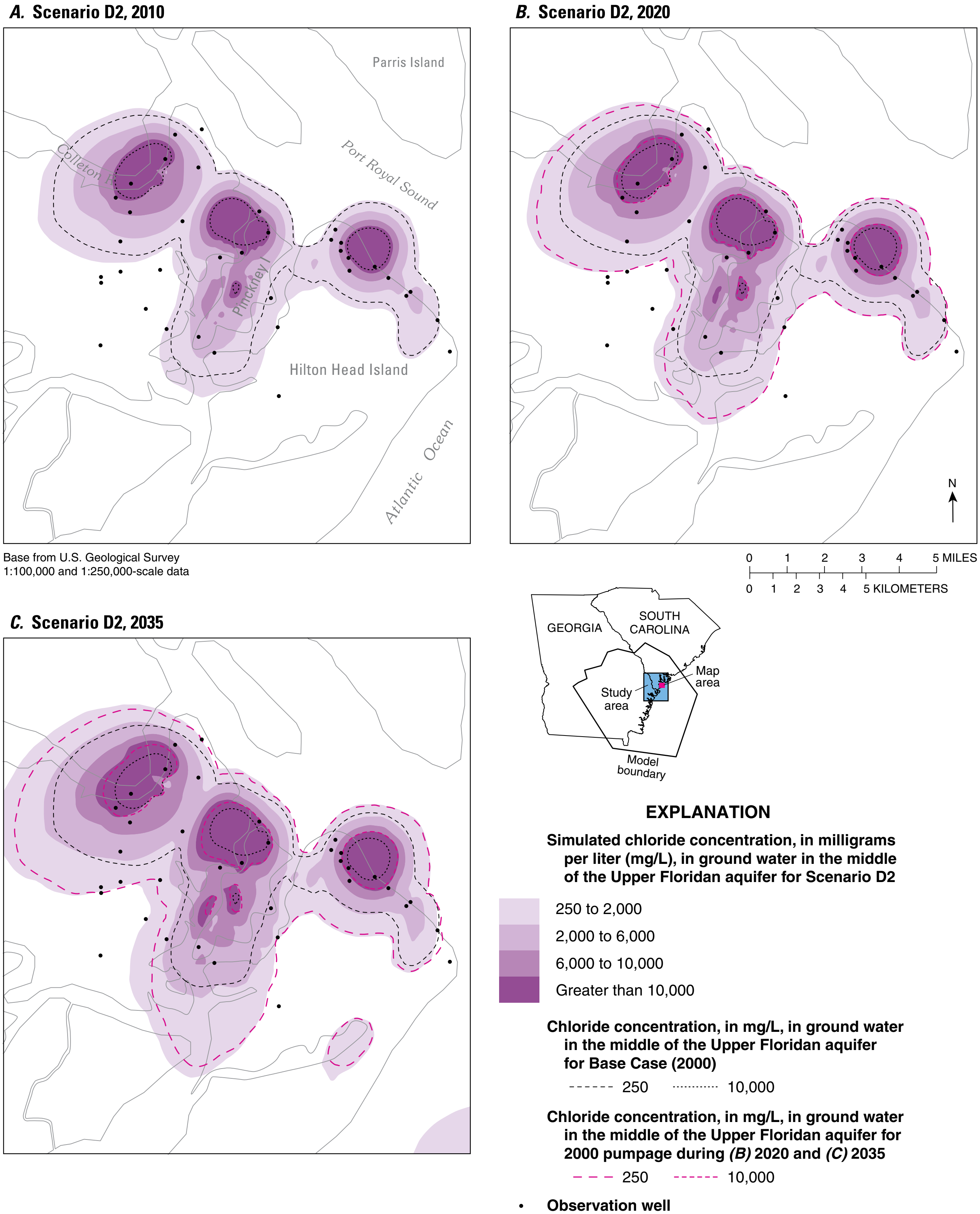


Figure 49. Simulated chloride concentration in ground water in the middle of the Upper Floridan aquifer in the Hilton Head Island, South Carolina, area for Scenario D2 (County Comprehensive Water-Supply Plans projection) during (*A*) 2010, (*B*) 2020, (*C*) 2035, and (*D*) 2100 (larger area).

***D.* Scenario D2, 2100**

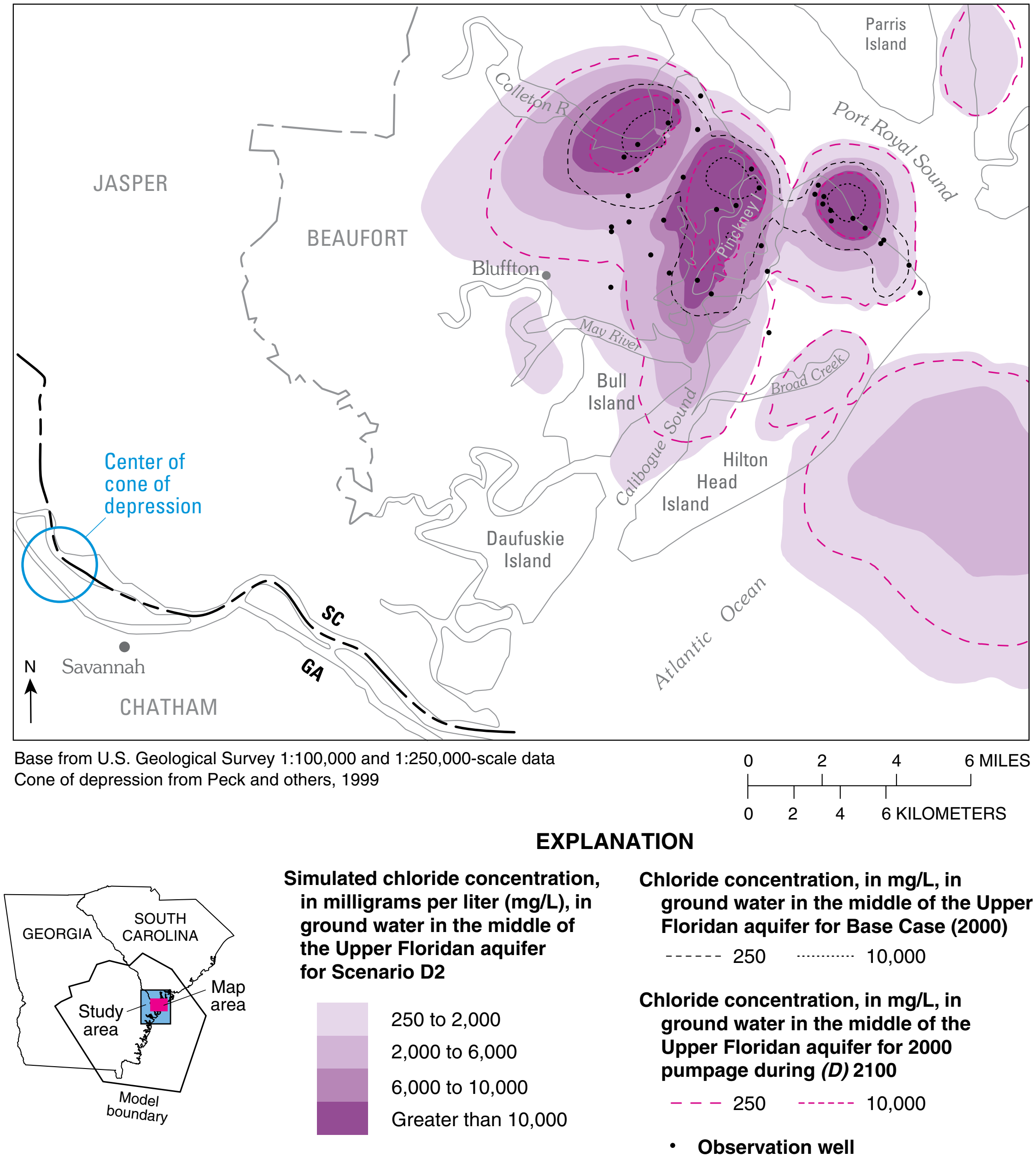


Figure 49. Simulated chloride concentration in ground water in the middle of the Upper Floridan aquifer in the Hilton Head Island, South Carolina, area for Scenario D2 (County Comprehensive Water-Supply Plans projection) during (*A*) 2010, (*B*) 2020, (*C*) 2035, and (*D*) 2100 (larger area)—continued.

Uncertainty in model results increases for simulations at increasingly distant future times because of unpredictable changes in future conditions. The two estimates of projected water use for Scenarios D1 and D2 were estimated using different methods, and the differences between these estimates indicates substantial uncertainty in projected water use and the future response of the ground-water flow system. In particular, the CWSP projection (Scenario D2) was based on each county's estimate of future growth, and in some cases may have been unrealistic. Furthermore, neither projection considered available water supply. Simulations are continued to 2100 for the 2000 pumpage distribution, and for the 2035 pumpage distribution for Scenarios D1 and D2. There is considerable uncertainty that these pumpage values would be maintained until 2100, although they may represent a maximum range of conditions. Thus, results of these simulations provide insight into general, long-term response to a range of stresses, rather than specific conditions during 2100. Also, future pumping is assumed to occur at increased rates at currently existing pumping sites; possible redistribution of pumpage to other aquifers, or by the introduction of new wells or retirement of existing wells is not considered. In addition to uncertainty in pumping conditions and distribution, potential changes in sea level, climate, and recharge rates could affect the ground-water flow system, and are not accounted for by any of the scenarios.

In applying predictive scenarios to ground-water flow models, it is important to examine where the model may be inappropriate to address stresses that exceed those for calibration conditions. The pumpage for Scenarios D1 and D2 is higher by about 12 percent and 71 percent, respectively, than the highest pumpage for which the models were designed (815 Mgal/d during 2000). An unintended consequence of this higher pumpage may be that larger inflow rates than realistically occur are induced from the source-sink-type boundary conditions (including head-dependent flux, specified-head, and specified-pressure boundary conditions). Source-sink-type boundary conditions can be used to simulate recharge to the system that is buffered by an unconfined aquifer with a consistently saturated thickness, or a confined aquifer that is far from the area of interest. This type of boundary condition allows flow into the model where the controlling head or pressure is higher than the simulated head or pressure in an adjacent confined aquifer, and out of the model where the controlling head or pressure is lower than the simulated head or pressure in an adjacent confined aquifer. If the confined aquifer is highly stressed, these boundary conditions can allow water to flow into the simulated system to an unlimited extent, as illustrated by the increase in area and rate of calculated recharge for Scenarios D1 and D2 (figs. 47 and 48). This may result in an underestimation of drawdown. Specifically, a source-sink boundary condition may be inappropriate to represent recharge in the onshore area because this type of boundary condition behaves as an unlimited source of water to the system. In the offshore area, on the other hand, the ocean may be an unlimited source. If the models allow more freshwater than is realistic to enter the system from the onshore area, then they also may underestimate the amount of saltwater entering the system from the offshore area.

Under the high stresses imposed in Scenarios D1 and D2, simulated heads for the Upper Floridan aquifer are below the top elevation of that unit in some areas (fig. 50). North and west of the Gulf Trough, and at a few locations along the southwestern boundary, these areas coincide with or are near cells where the controlling head of the boundary condition is below the top of the Upper Floridan aquifer. In the Savannah area, at the center of the potentiometric cone of depression, the predictive scenarios simulate heads for unit 5 that are below the top of the unit, by a maximum of 16 ft and 33 ft for Scenarios D1 and D2, respectively, during 2035. In this case, the drawdown is a result of high localized stresses and not proximal boundary conditions. For such highly stressed conditions, dewatering of the aquifer may occur, the models may not accurately represent the hydraulic properties for unsaturated conditions, and the assumed rates of withdrawal may not be sustainable. The steady-state response assumption of the MODFLOW model may be violated under such high stress conditions.

In interpreting the results of the solute-transport simulations, the conditions for which the SUTRA solute-transport model was calibrated must be taken into account. Results for conditions very different from the calibration conditions and in areas devoid of calibration data are speculative; for example, results of Scenarios C1, C2, D1, and D2 are uncertain, and at most indicate general trends and approximate rates of chloride-plume movement in response to time-varying stresses in different locations. Furthermore, the area is limited where data exist to calibrate the solute-transport model; thus, simulation results showing plume expansion beyond this area are subject to considerable uncertainty.

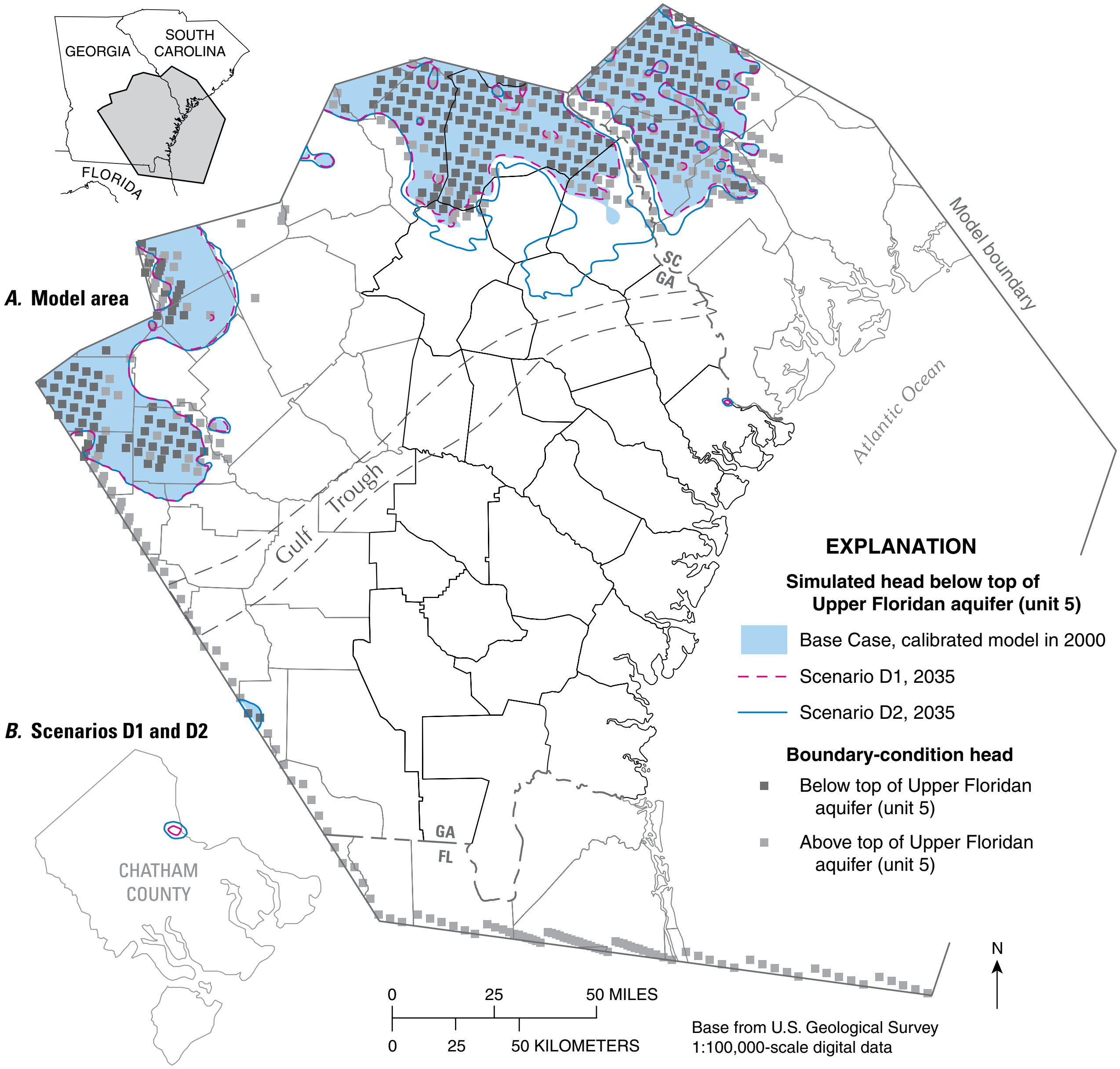


Figure 50. (*A*) Simulated head below the top the Upper Floridan aquifer for Base Case (2000), Scenarios D1 (projection based on Regional Economic Models, Inc.) and D2 (County Comprehensive Water-Supply Plans projection) during 2035, and boundary-condition head above and below the Upper Floridan aquifer, and (*B*) Chatham County, Georgia, enlarged view.

Summary

Increased ground-water pumpage in the coastal area of Georgia, South Carolina, and Florida has resulted in substantial water-level decline near Savannah, Georgia, and saltwater intrusion at the northern end of Hilton Head Island, South Carolina, and at Brunswick, Georgia. To develop a strategy to address these problems and manage projected future coastal water-resource needs, the Georgia Environmental Protection Division (GaEPD) has implemented the Georgia Coastal Sound Science Initiative (CSSI), a series of scientific and feasibility investigations designed to assess coastal-area ground-water resources and address issues of saltwater intrusion and resource sustainability. As part of this initiative, the U.S. Geological Survey (USGS) synthesized available and new data into new digital models that describe the ground-water flow system and saltwater transport. The GaEPD will use results of model simulations to help design a coastal-area, ground-water management strategy.

This report describes results of simulations using a regional MODFLOW ground-water flow model of coastal Georgia, and adjacent parts of Florida and South Carolina, and a more locally focused SUTRA solute-transport model of the Savannah–Hilton Head Island area to evaluate the effects of current and hypothetical ground-water withdrawal, and the relative effects of pumping in specific areas on ground-water flow and saltwater transport. The models used in this study are designed to be as consistent as possible in framework, hydraulic properties, pumpage distribution, and boundary conditions. The discretization of the models differs because they are designed to address different processes at different scales. The regional MODFLOW model assumes steady-state ground-water flow and is calibrated to 1980 and 2000 pumping conditions. The SUTRA model is run as a transient simulation from a predevelopment (1885) steady-state flow field to 2004, and calibrated to water levels during September 1998 and estimated chloride values during 2000, 2002, 2003, and 2004. Simulation results for future pumpage scenarios were compared with those during 2000 (the Base Case), and to a scenario for which 2000 pumpage is projected until 2100.

Scenario A represents the flow system during 1997, when the GaEPD implemented the “Interim Strategy for Managing Saltwater Intrusion in the Upper Floridan Aquifer of Southeast Georgia.” During 1997–2000, simulated water levels showed a combination of rises and declines in response to changing pumping patterns. Simulated potentiometric surfaces are similar to 2000 simulated potentiometric surfaces. The simulated chloride distribution for Scenario A shows a slightly smaller extent than that for the Base Case; saltwater plumes continued to expand during 1997–2000 because of persistent drawdown of heads in the Upper Floridan aquifer.

Scenario B was designed to simulate the effect of the Durango Paper Company well shutdown during 2002 by eliminating about 36 million gallons per day (Mgal/d) of pumpage. Although the maximum simulated recovery in the Upper Floridan aquifer is about 29 ft, and the maximum observed recovery is about 20 ft, located about 1 mile from the pumping center, the model generally predicts a smaller recovery than observed by approximately 10 feet (ft) near the center of pumping. This discrepancy may be attributed to (1) an observed regional water-level rise that began during 2000, which is not accounted for in the model; (2) the use of 2000 pumpage for the rest of the model area, instead of 2002 pumpage; or (3) proximity of the model boundary. A simulated recovery of 1–2 ft extends as far north as southern Beaufort County and as far inland as the Gulf Trough.

Scenarios C1 and C2 are used to illustrate the relative effects of pumping in Chatham County, Ga., and southern Beaufort County, S.C., on ground-water levels and saltwater distribution and movement in that area. Scenario C1 simulates a hypothetical pumping history to 2000, assuming pumping never occurred in Chatham County, Ga. Compared with the Base Case, the large potentiometric cone of depression centered at Savannah, Ga., disappears for Scenario C1, with a simulated recovery at the Savannah pumping center of about 140 ft. This simulated recovery extends at least as far north as the northern part of Hilton Head Island, where the maximum water-level increase was 2 ft. The resulting decrease in flow from the offshore general-head boundary indicates a reduced potential for saltwater intrusion. The plumes originating at Colleton River and Pinckney Island are of a lesser extent for Scenario C1 than for the year 2000 Base Case, and the plume at the northern end of Hilton Head Island is approximately the same shape and of only a slightly lesser extent overall. This indicates that pumping in Chatham County has a greater influence on chloride transport from the two western source areas, and less influence on chloride transport from the source area on the northern end of Hilton Head Island.

Scenario C2 simulates a hypothetical pumping history to 2000, assuming pumping never occurred in southern Beaufort County, S.C. The simulated water-level rise in the Upper Floridan aquifer is greatest at the northern end of Hilton Head Island (about 11 ft), and extends as far southwest as Savannah, where the maximum water-level increase is about 2 ft. The resulting decrease in flow from the offshore general-head boundary indicates a reduced potential for saltwater intrusion.

Comparison of results of Scenarios C1 and C2 indicates that, in general, pumping in southern Beaufort County has a smaller effect on plume development than pumping in Chatham County for the plumes west of Hilton Head Island. At the northern end of Hilton Head Island, the effect of both scenarios on plume development is small. Local pumping, however, in southern Beaufort County appears to have a slightly greater effect on the plume at the north end of Hilton Head Island, than does pumping in Chatham County. Comparison of water-level profiles for Scenarios C1 and C2 shows that eliminating pumping in Chatham County would result in a greater water-level recovery at the southern end of Hilton Head Island than eliminating pumping in southern Beaufort County, and that eliminating pumping in southern Beaufort County would result in a greater water-level recovery at the northern end of Hilton Head Island than eliminating pumping in Chatham County.

The pumpage distribution for Scenario D1 is based on the estimated change in pumpage in the 24-county coastal area in Georgia as a function of population and employment. Maximum simulated water-level declines for Scenario D1 occur in the Savannah–Chatham County, and Statesboro–Bulloch County, Ga., areas. The water budget for Scenario D1 shows increasing recharge at the general-head and specified-head boundaries during 2035 relative to 2000, and decreasing discharge to the these boundaries in response to the increased pumpage. The simulated chloride distributions during 2000–2035 are similar to those simulated for 2000 pumpage, with slightly greater extent of plumes originating at Colleton River and Pinckney Island for Scenario D1 pumping conditions. By 2100, the differences in plume extent are greater.

The pumpage distribution for Scenario D2 is based on estimated change in pumpage for the 24 coastal counties in Georgia as a function of each county's water-supply plan. For Scenario D2, the simulated potentiometric surface shows an extensive lowering of the potentiometric surface, and the development of small but deep cones of depression in inland counties where pumpage is increased and the assigned hydraulic conductivity is low. The simulated water-level declines during 2000–2035 exceed 20 ft across most of the 24-county coastal area in Georgia, and maximum declines exceed 250 ft in the Upper and Lower Floridan aquifers. In response to the increase in pumpage, recharge at the general-head and specified-head boundaries increases substantially during 2035 relative to 2000, and discharge to the specified-head boundary decreases.

The simulated chloride distributions for Scenario D2 show a larger extent during 2000–2100 than for the 2000 pumpage applied during the same years, particularly for plumes emanating from the Colleton River and Pinckney Island areas. The 250-milligram-per-liter chloride contour in the Upper Floridan aquifer during 2100 for Scenario D2, however, is less than 2 miles farther southwest than that for the 2000 pumpage conditions maintained until 2100. As is the case for Scenario D1, the plume originating at the northern end of Hilton Head Island shows little difference in extent relative to the plume generated for 2000 pumping conditions for 2010, 2020, 2035, and 2100.

Despite large differences in pumpage between 2000 conditions, Scenario D1 conditions for 2035, and Scenario D2 conditions for 2035, the simulated chloride distributions for 2100 are similar. This apparent lack of sensitivity of the plume growth to large differences in pumpage is because distance and hydrologic features reduce the effects of these increases on the flow system in the Hilton Head Island area.

The ground-water flow and solute-transport models used in this study are subject to the limitations of the models used and scenario conditions. Generally, the further removed from calibration conditions the scenario conditions are, the less reliable are the model results. The ability of the model to simulate accurately the effects of the well shutdown in Scenario B is limited by the use of 2000 instead of 2002 pumping conditions, not accounting for the regional water-level rise, the scale and discretization of the model, and the proximity of the area of concern to a model boundary. For Scenarios D1 and D2, there is considerable uncertainty in the assumed pumpage values and distribution, and considerable difference in pumpage between the two scenarios. In addition, the substantial drawdown resulting from these scenarios may indicate that these scenarios exceed the models' abilities to simulate accurately such stresses. Finally, the limited spatial and temporal conditions for which the SUTRA model was calibrated make model results uncertain beyond the areas of the known plumes and for increasing time into the future.

Selected References

Applied Coastal Research Laboratory, Georgia Southern University, 2002, Gulf Trough and Satilla Line data analysis: Georgia Geologic Survey Project Report 48, 15 p.

Camp Dresser and McKee, Inc., 2001, Southeast Georgia 24-county area water supply services, alternative sources to groundwater supply report, CD–ROM-2.

Clarke, J.S., 2003, The surficial and Brunswick aquifer systems—alternative ground-water resources for coastal Georgia: *in* Proceedings of the 2003 Georgia Water Resources Conference, April 23–24, 2003, The University of Georgia, K.J. Hatcher, ed., Institute of Ecology, the University of Georgia, Athens, Georgia, CD–ROM, accessed January 15, 2005, at *http://ga.water.usgs.gov/pubs/other/gwrc2003/pdf/Clarke-GWRC2003.pdf*

Falls, W.F., Harrelson, L.G., Conlon, K.J., and Petkewich, M.D., 2005a, Hydrogeology, water quality, and water-supply potential of the Lower Floridan aquifer, coastal Georgia 1999–2002: U.S. Geological Survey Scientific Investigations Report 2005-5124, 98 p., accessed July 28, 2005, at *http://pubs.usgs.gov/sir/2005/5124/*

Falls, W.F., Ransom, Camille, III, Landmeyer, J.E., Reuber, E.J., and Edwards, L.E., 2005b, Hydrogeology, water quality, and saltwater intrusion of the Upper Floridan aquifer in the offshore area near Hilton Head Island, South Carolina, and Tybee Island, Georgia, 1999–2002: U.S. Geological Survey Scientific Investigations Report 2005-5134, 48 p.

Fanning, J.L., 2003, Water use in Georgia by county for 2000 and water-use trends for 1980–2000: Georgia Geologic Survey Information Circular 106, 180 p.

Foyle, A.M., Henry, V.J., and Alexander, C.R., 2001, The Miocene aquitard and the Floridan aquifer of the Georgia/South Carolina coast: Geophysical mapping of potential seawater intrusion sites: Georgia Geologic Survey Bulletin 132, 61 p.

Georgia Environmental Protection Division, 1997, Interim strategy for managing saltwater intrusion in the Upper Floridan aquifer of southeast Georgia, April 23, 1997: Atlanta, Ga., Georgia Environmental Protection Division, 19 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hayes, L.R., 1979, The ground-water resources of Beaufort, Colleton, Hampton and Jasper Counties, South Carolina: South Carolina Water Resources Commission Report Number 9, 91 p.

Kellam, M.F., and Gorday, L.L., 1990, Hydrogeology of the Gulf Trough–Apalachicola Embayment area, Georgia: Georgia Geologic Survey Bulletin 94, 73 p.

Krause, R.E., and Randolph, R.B., 1989, Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina: U.S. Geological Survey Professional Paper 1403-D, 65 p.

Kuniansky, E.L., Gomez-Gomez, Fernando, and Torres-Gonzalez, Sigfredo, 2003, Effects of aquifer development and changes in irrigation practices on ground-water availability in the Santa Isabel area, Puerto Rico: U.S. Geological Survey Water-Resources Investigations Report 03-4303, 56 p.

Leeth, D.C., Clarke, J.S., Wipperfurth, C.J., and Craigg, S.D., 2005, Ground-water conditions and studies in Georgia, 2002–2003: U.S. Geological Survey Scientific Investigations Report 2005-5065, 128 p.

Miller, J.A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p.

Paull, C.K., and Dillon, W.P., 1980, Structure, stratigraphy, and geologic history of Florida–Hatteras Shelf and inner Blake Plateau: American Association of Petroleum Geologists Bulletin, v. 64/3, p. 339–358.

Payne, D.F., Abu Rumman, Malek, and Clarke, J.S., 2005, Simulation of ground-water flow in coastal Georgia and adjacent parts of South Carolina and Florida—Predevelopment, 1980, and 2000: U.S. Geological Survey Scientific Investigations Report 2005-5089, 91 p., accessed July 25, 2005, at *http://pubs.usgs.gov/sir/2005/5089/*

Peck, M.F., Clarke, J.S., Ransom, Camille, III, and Richards, C.J., 1999, Potentiometric surface of the Upper Floridan aquifer in Georgia and adjacent parts of Alabama, Florida, and South Carolina, May 1998, and water level-trends in Georgia, 1990–98: Georgia Geologic Survey Hydrologic Atlas 22, 1 sheet, scale 1:100,000.

Peck, M.F., and McFadden, K.W., 2004, Potentiometric surface of the Upper Floridan aquifer in the Coastal area of Georgia, September 2000: U.S. Geological Survey Open-File Report 2004-1030, accessed January 31, 2005, at *http://pubs.usgs.gov/of/2004/1030/*

Peck, M.F., McFadden, K.W., and Leeth, D.C., 2005, Effects of decreased ground-water withdrawal on ground-water levels and chloride concentration in Camden County, Georgia, and ground-water levels in Nassau County, Florida, from September 2001 to May 2003: U.S. Geological Survey Scientific Investigations Report 2004-5295, 36 p.

Priest, Sherlyn, 2004, Evaluation of ground-water contribution to streamflow in coastal Georgia and parts of Florida: U.S. Geological Survey, Scientific Investigations Report 2004-5265, p. 46.

Provost, A.M., Payne, D.F., and Voss, C.I., 2006, Simulation of saltwater movement in the Upper Floridan aquifer in the Savannah, Georgia–Hilton Head Island, South Carolina, area, predevelopment–2004, and projected movement for 2000 pumping conditions: U.S. Geological Survey Scientific Investigations Report 2006-5058, 132 p.

Ransom, Camille, III, and White, J.I., 1999, Potentiometric surface of the Floridan aquifer system in southern South Carolina: South Carolina Department of Health and Environmental Control, Bureau of Water Publication No. 02B-99, 1 sheet.

Taylor, D.A., Painter, J.A., and Payne, D.F., 2003, Development of a water-use database for use in coastal region ground-water models, Georgia, South Carolina, and Florida, 1980–2000, *in* Proceedings of the 2003 Georgia Water Resources Conference, April 23–24, 2003, The University of Georgia, K.J. Hatcher, ed., Institute of Ecology, The University of Georgia, Athens, Georgia, CD–ROM, accessed January 31, 2005, *http://ga.water.usgs.gov/pubs/other/gwrc2003/pdf/Taylor-GWRC2003.pdf*

Voss, C.I., and Provost, A.M., 2003, SUTRA: A model for saturated-unsaturated, variable-density ground-water flow with solute or energy transport: U.S. Geological Survey Water-Resources Investigations Report 02-4231, 250 p., accessed September 7, 2005, at *http://water.usgs.gov/nrp/gwsoftware/sutra/SUTRA_2D3D_1-documentation.pdf*

Weems, R.E., and Edwards, L.E., 2001, Geology of Oligocene, Miocene, and younger deposits in the coastal area of Georgia: Georgia Geologic Survey Bulletin 131, 124 p.

Winston, R.B., 2000, Graphical user interface for MODFLOW, Version 4: U.S. Geological Survey Open-File Report 00-315, 27 p., accessed August 22, 2000, at *http://water.usgs.gov/nrp/gwsoftware/mfgui4/Mfgui_40.pdf*

Winston, R.B., and Voss, C.I., 2004, SutraGUI—A graphical user interface for SUTRA, a model for ground-water flow with solute or energy transport: U.S. Geological Survey Open-File Report 03-285, 114 p., accessed January 30, 2004, at *http://water.usgs.gov/nrp/gwsoftware/sutra-gui/SutraGUI.pdf*

Manuscript approved for publication, March 21, 2006

Prepared by USGS Georgia Water Science Center

Edited by Patricia L. Nobles

Graphics by Caryl J. Wipperfurth

For more information concerning the research in this report, contact
USGS Georgia Water Science Center, Atlanta,
telephone: 770-903-9100