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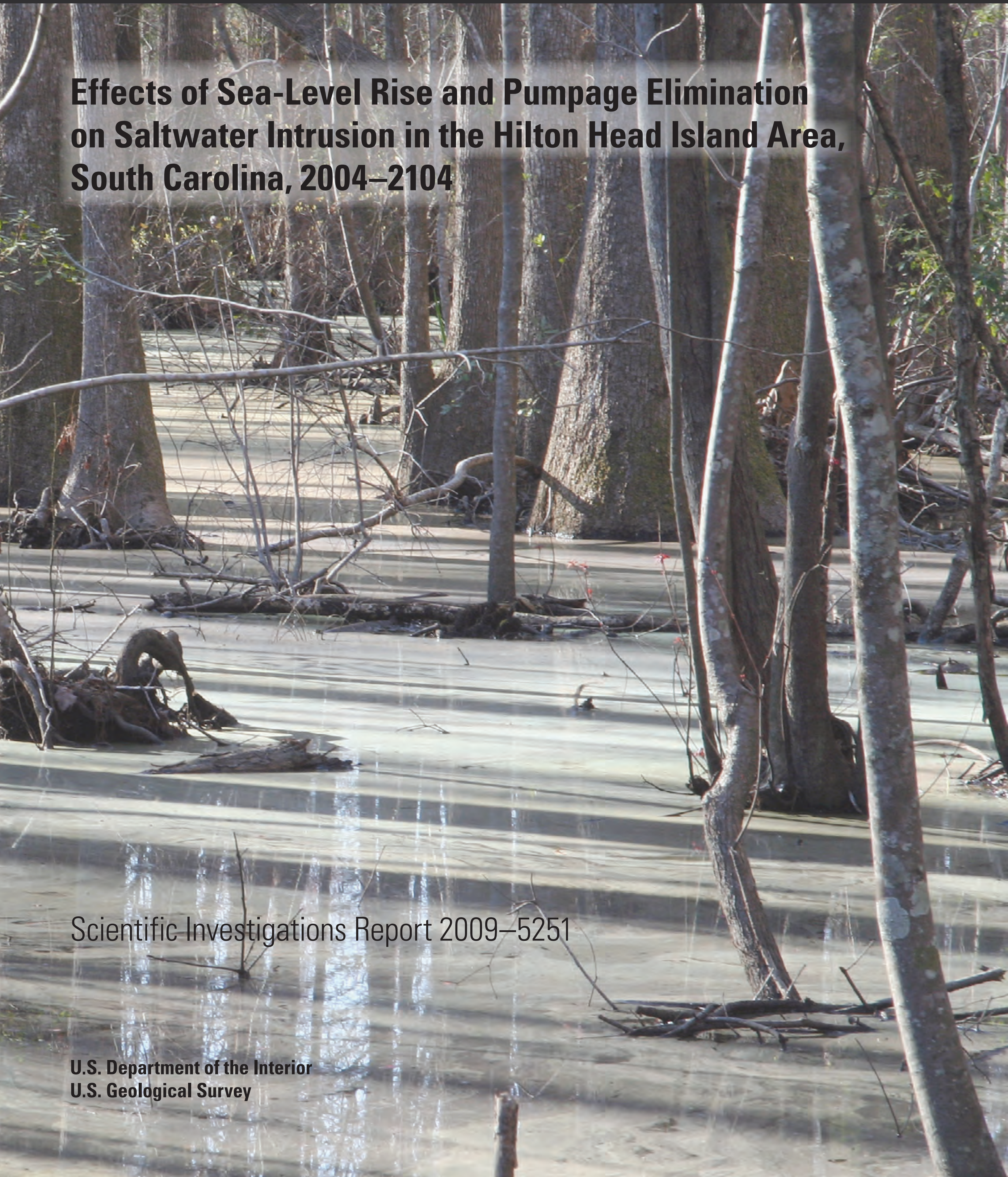

Effects of Sea-Level Rise and Pumpage Elimination on Saltwater Intrusion in the Hilton Head Island Area, South Carolina, 2004–2104

Scientific Investigations Report 2009–5251

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

Cover. Hardwood Swamp, Savannah River National Wildlife Refuge, Jasper County, South Carolina. Photo by Alan M. Cressler, USGS.

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By Dorothy F. Payne

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

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch	2.54	centimeter (cm)
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Leakance	
foot per day per foot [(ft/d)/ft]	1	meter per day per meter [(m/d)/m]
inch per year per foot [(in/yr)/ft]	83.33	millimeter per year per meter [(mm/yr)/m]

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

$$°F = (1.8 \times °C) + 32$$

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

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) and to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

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

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

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

Abbreviations Used in This Report

CSSI	Coastal Sound Science Initiative
DEM	Digital elevation map
GaEPD	Georgia Environmental Protection Division
MODFLOW	Modular Groundwater Model
RMSE	root mean square error
SUTRA	Saturated-Unsaturated Transport Simulator
TDS	total dissolved solids
USEPA	U.S. Environmental Protection Agency

Effects of Sea-Level Rise and Pumpage Elimination on Saltwater Intrusion in the Hilton Head Island Area, South Carolina, 2004–2104

By Dorothy F. Payne

Abstract

Saltwater intrusion of the Upper Floridan aquifer has been observed in the Hilton Head area, South Carolina since the late 1970s and currently affects freshwater supply. Rising sea level in the Hilton Head Island area may contribute to the occurrence of and affect the rate of saltwater intrusion into the Upper Floridan aquifer by increasing the hydraulic gradient and by inundating an increasing area with saltwater, which may then migrate downward into geologic units that presently contain freshwater. Rising sea level may offset any beneficial results from reductions in groundwater pumpage, and thus needs to be considered in groundwater-management decisions. A variable-density groundwater flow and transport model was modified from a previously existing model to simulate the effects of sea-level rise in the Hilton Head Island area. Specifically, the model was used to (1) simulate trends of saltwater intrusion from predevelopment to the present day (1885–2004) and evaluate the conceptual model, (2) project these trends from the present day into the future based on different potential rates of sea-level change, and (3) evaluate the relative influences of pumpage and sea-level rise on saltwater intrusion.

Four scenarios were simulated for 2004–2104: (1) continuation of the estimated sea-level rise rate over the last century, (2) a doubling of the sea-level rise, (3) a cessation of sea-level rise, and (4) continuation of the rate over the last century coupled with an elimination of all pumpage. Results show that, if present-day (year 2004) pumping conditions are maintained, the extent of saltwater in the Upper Floridan aquifer will increase, whether or not sea level continues to rise. Furthermore, if all pumpage is eliminated and sea level continues to rise, the simulated saltwater extent in the Upper Floridan aquifer is reduced. These results indicate that pumpage is a strong driving force for simulated saltwater intrusion, more so than sea-level rise at current rates. However, results must be considered in light of limitations in the model, including, but not limited to uncertainty in field data, the conceptual model, the physical properties and representation of the hydrogeologic framework, and boundary and initial conditions, as well as uncertainty in future conditions, such as the rate of sea-level rise.

Introduction

Saltwater intrusion of the Upper Floridan aquifer has been observed in South Carolina in the Parris Island and Beaufort areas since the early 1900s and in the Hilton Head Island area since the late 1970s. Rising sea level and groundwater pumpage contribute to the occurrence of and affect the rate of saltwater contamination of aquifers in coastal areas by affecting hydraulic gradients. Furthermore, rising sea level also may result in a larger land area inundated by saltwater, which then may migrate downward into units that presently contain freshwater. During the last century, population growth, increased tourism, and sustained industrial activity in the coastal area of Georgia and South Carolina, have resulted in increased groundwater pumpage from the Upper Floridan aquifer and subsequent water-level declines. Long-term monitoring indicates that sea level has risen about 1 foot (ft) in the area since the 1920s (National Oceanic and Atmospheric Administration, 2008). In an attempt to slow or halt further saltwater contamination, restrictions on groundwater pumping have been implemented in Georgia and South Carolina. Rising sea level could offset any beneficial results from reductions in groundwater pumpage. For this reason, the possible effects of rising sea level need to be considered when making water-management decisions.

To provide information required for development of a water-management strategy to address these problems and the effect of projected future coastal water-resource needs, in 1997 the Georgia Environmental Protection Division (GaEPD) implemented the Georgia Coastal Sound Science Initiative (CSSI), a series of scientific and feasibility investigations designed to assess coastal-area groundwater resources and address issues of saltwater intrusion and resource sustainability. As part of this initiative, the U.S. Geological Survey (USGS) developed a three-dimensional, variable-density, groundwater flow and solute-transport model (Provost and others, 2006; henceforth referred to as the "original" model) that was calibrated to 1998 water levels and estimated chloride concentrations for 2000. The original model was used to simulate a variety of scenarios, including hypothetical historical scenarios, future pumpage-increase scenarios (Payne and others, 2006), and pumpage-reduction scenarios (Payne, 2007).

To address the effects of possible sea-level rise, the original model required some refinement, particularly to the discretization of the land-surface altitude and bathymetry, and some modifications to the boundary conditions at the top boundary of the model in the area of saltwater intrusion. The model documented in this report is an update of the original model and is used here to simulate the effects of different potential rates of sea-level rise and pumpage elimination on saltwater intrusion in the Upper Floridan aquifer in the Hilton Head Island area.

Purpose and Scope

The model documented in this report is used to simulate the effects of different rates of sea-level rise and the elimination of pumpage. Specific modifications made to the original model include time-varying sea level, more accurate discretization of land-surface altitude and bathymetry, modification of the geometry of permeability zones, modification of effective porosity values, a modified specified-pressure boundary condition for onshore nodes, a modified offshore boundary condition, and an extension to 2004 pumpage conditions. 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 (fig. 1), although it does not preclude the simulated occurrence of saltwater intrusion in other areas. The analysis focuses on evaluating a conceptual model for saltwater intrusion in which saline surface water enters the Upper Floridan aquifer through localized areas where the upper confining units are thin or absent. The model was used to (1) simulate trends of saltwater intrusion from predevelopment to the present day (1885–2004) and evaluate the conceptual model, (2) project these trends from present day into the future based on different potential rates of sea-level change, and (3) evaluate the relative influences of pumpage and sea-level rise on saltwater intrusion. Discussions in this report include the conceptual model and historical and predicted sea-level rise; modeling approach and modifications made to the previous solute-transport model; calibration approach and calibrated model results and goodness-of-fit characteristics; sensitivity testing and analysis; simulated future chloride distributions for a range of future sea-level changes and for elimination of pumpage; and limitations of the model.

Methods

The original model (Provost and others, 2006) was modified and used to simulate effects of sea-level rise on groundwater flow and saltwater contamination. The model was developed using the USGS three-dimensional, finite-element, variable-density, solute-transport simulator SUTRA 2.1 (Voss and Provost, 2008), henceforth referred to as the SUTRA simulator. The computer code for this simulator was modified for this study to allow time-dependent pumping and sea level change. The model documented in this report used the same model mesh and hydrogeologic framework as the original model, but used modified boundary conditions and hydraulic properties. The pumpage distribution was extended to include estimated 2004 pumping conditions. The revised model was calibrated by adjusting the permeability distribution of the Upper Floridan aquifer and the overlying confining units. The calibrated model was used to simulate a variety of scenarios incorporating different rates of sea-level rise.

Previous Investigations

Previous investigations include a regional, steady-state groundwater flow model (Payne and others, 2005) and a more localized transient solute-transport model (Provost and others, 2006) that were developed to simulate regional and local groundwater flow conditions, and localized saltwater intrusion in the Hilton Head Island area, respectively. These models were used to examine relative influences of pumping in specified sub-areas, and hypothetical future pumpage changes on groundwater levels and chloride concentrations (Payne and others, 2006; Payne, 2007). The groundwater flow system and saltwater transport in the Hilton Head Island area are described in detail in Payne and others (2005) and Provost and others (2006).

Acknowledgments

The author extends thanks to members of a Georgia Environmental Protection Division technical advisory committee that provided advice and recommendations on solute-transport modeling in the Savannah–Hilton Head Island area. Members of this group include: Robert Faye, retired U.S. Geological Survey; James Kennedy, Georgia Environmental Protection Division; Lenny Konikow, U.S. Geological Survey; Mark Maimone, Camp Dresser and McKee; and Drennan Park, South Carolina Department of Natural Resources.

Thanks are also extended to several U.S. Geological Survey employees for their technical assistance: Alden Provost helped with model modifications and the development of pre- and post-processing tools; Jaime Painter helped develop the 2004 pumping distribution; Victor Ferreira helped develop the specific conductance–chloride concentration function.

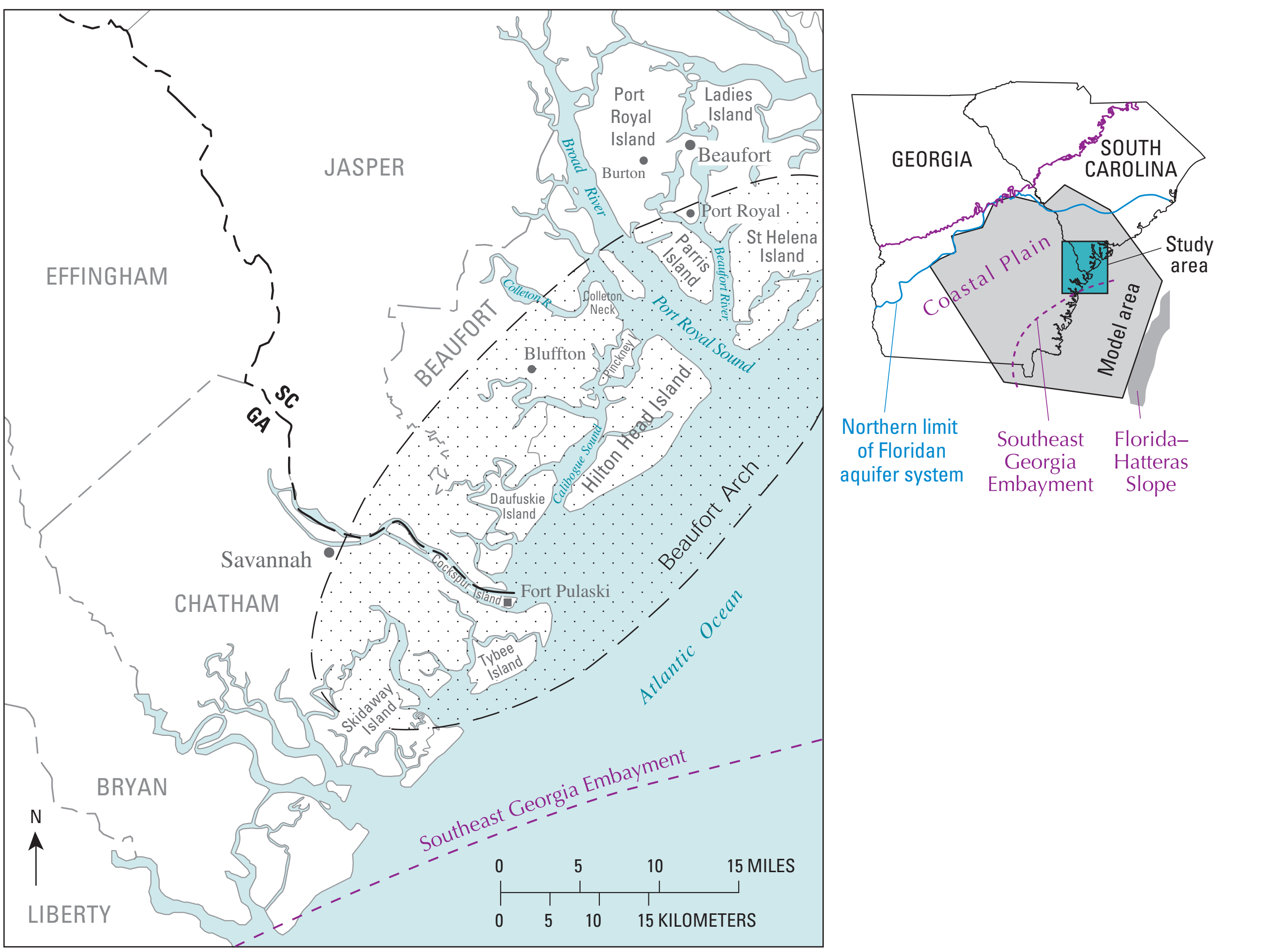
Description of Study Area

The Savannah-Hilton Head Island study area encompasses about 3,000 square miles (mi^2), including Chatham County and parts of Bryan and Effingham Counties in Georgia, and Beaufort County and part of Jasper County in South Carolina and the adjacent offshore area (fig. 1). The study area lies within a larger, 42,155-mi^2 model area, which extends to some natural hydrologic boundaries that enable a more realistic simulation of the groundwater flow system in the area of interest.

Hydrogeologic Setting

The hydrogeology and flow-system characteristics of the study area are described in detail in Provost and others (2006). Coastal Plain sediments of varying permeability compose the aquifer and confining units in the study area (fig. 2). In order of increasing depth, the aquifer units are the surficial aquifer system, composed of Miocene to Holocene interlayered sand, clay, and thin limestone beds (Dale, 1995; Clarke, 2003); the Brunswick aquifer system, consisting of poorly sorted, fine to coarse, slightly phosphatic and dolomitic quartz sand and dense phosphatic limestone (Clarke and others, 1990); and the Floridan aquifer system, composed of mostly Paleocene to Oligocene carbonate rocks that locally include Upper Cretaceous rocks. Confining units of relatively lower permeability separate these water-bearing units.

The principal source of water for all uses in the coastal area is the Floridan aquifer system, which consists of the Upper and Lower Floridan aquifers in the study area (Miller, 1986; Krause and Randolph, 1989), and the *middle Floridan* aquifer near Hilton Head Island, S.C. (Gawne and Park, 1992; Ransom and White, 1999). The thickness of the Floridan aquifer system in the study area ranges from less than 100 ft



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

Structural feature from Weems and Edwards, 2001

Figure 1. Location of solute-transport model study area, model area, and major structural features (modified from Provost and others, 2006).

Series		Geologic unit[1]	Hydrogeologic unit[2] (Savannah, Ga.; Hilton Head Island, S.C.)		Model unit
Post-Miocene		Undivided	Water-table zone	SURFICIAL AQUIFER SYSTEM	1
Miocene	Upper	Ebenezer Formation	Confining unit	SURFICIAL AQUIFER SYSTEM	1
Miocene	Middle	Coosawhatchie Formation	Confining unit; Upper Brunswick aquifer	BRUNSWICK AQUIFER SYSTEM	2; 3
Miocene	Lower	Marks Head Formation	Upper Brunswick aquifer	BRUNSWICK AQUIFER SYSTEM	3
Miocene	Lower	Parachucla Formation		BRUNSWICK AQUIFER SYSTEM	3
Miocene	Lower	Tiger Leap Formation	Lower Brunswick aquifer	BRUNSWICK AQUIFER SYSTEM	3
Oligocene		Lazaretto Creek Formation	Upper Floridan confining unit		4
Oligocene		Suwannee Limestone	Upper Floridan aquifer[3]	FLORIDAN AQUIFER SYSTEM	5
Eocene	Upper	Ocala Limestone	Upper Floridan aquifer[3]	FLORIDAN AQUIFER SYSTEM	5
Eocene	Middle	Avon Park Formation[4]	Upper Floridan aquifer[3]; Lower Floridan confining unit[3]; Lower Floridan aquifer[6]	FLORIDAN AQUIFER SYSTEM	5; 6; 7
Eocene	Lower	Oldsmar Formation[5]	Lower Floridan aquifer[6]	FLORIDAN AQUIFER SYSTEM	7
Paleocene		Cedar Keys Formation[5]	Lower Floridan aquifer[6]	FLORIDAN AQUIFER SYSTEM	7
Upper Cretaceous		Undivided	Confining unit		Not modeled

[1] Modified from Randolph and others, 1991; Weems and Edwards, 2001
[2] Modified from Randolph and others, 1991; Clarke and Krause, 2000; Clarke, 2003
[3] In the Hilton Head Island, S.C., area, these units contain the middle confining unit and the middle Floridan aquifer, but the exact correlation is uncertain
[4] The equivalent age unit in South Carolina is the Santee Limestone
[5] The equivalent age unit in South Carolina is the Black Mingo Formation
[6] The presence of the Lower Floridan aquifer at Hilton Head Island, S.C., is uncertain

Figure 2. Generalized correlation of geologic, hydrogeologic, and model units (modified from Provost and others, 2006).

where it is shallow and thin in Beaufort County, S.C., to about 1,000 ft in southern Chatham and Bryan Counties, Ga. (Miller, 1986). The Upper Floridan aquifer ranges in thickness from about 20 ft at the northeasternmost part of the study area to about 600 ft in southern Chatham County. The Lower Floridan aquifer (fig. 2) is composed mainly of dolomitic limestone of early to middle Eocene age. On Hilton Head Island, the aquifer units below the middle Floridan aquifer are little used, and the presence of the Lower Floridan aquifer as a permeable unit is uncertain (Gawne and Park, 1992).

The Floridan aquifer system is not as confined in the study area relative to surrounding parts of the model area as a result of structural features and sea-level history. The sediments composing the hydrologic units in the study area overlie the Beaufort Arch (fig. 1), which is a prominent structural feature centered near Beaufort, S.C., that interrupts the regional southeastward dip of the sediments in that area (fig. 3). The units overlying and confining the Upper Floridan aquifer are thinner here than in areas to the south and east. Additionally, about 18,000 years ago, sea level was at a low stand, about 300 ft below the present-day sea level, and the coast was located about 60 mi offshore (Foyle and others, 2001). Before and since then, rivers and creeks have cut into and locally eroded the Miocene sediments where exposed; with transgression, these areas have been filled in with more recent sediments of varying permeability (Falls and others, 2005). Even at present, currents in coastal creeks and sounds may be eroding the Miocene sediments. This erosion has resulted in a thinning of the Miocene and younger units, and thus a reduction in the confinement above the Upper Floridan aquifer, particularly in the Beaufort Arch area.

Groundwater Flow

Groundwater flow in a confined aquifer system is controlled mainly by rates and distribution of recharge and discharge, the extent and effects of confinement, the capacity of the aquifer to transmit and store water, groundwater withdrawal, and the dips of the aquifer and confining units. Northwest of the study area, the Floridan aquifer system is shallow or exposed at land surface, and receives recharge directly from precipitation. From these northern areas, groundwater flows mostly southeastward toward the coast and discharges into overlying units and surface-water bodies, including major streams, estuaries, and the Atlantic Ocean.

Prior to the initiation of groundwater pumping during the 1880s, recharge to the Floridan aquifer system was offset by natural discharge to springs (both on land and offshore), rivers, and other surface-water bodies, and by diffuse upward leakage. Groundwater flowed from the updip recharge areas downgradient toward the coast (fig. 4*A*). Some groundwater from the Upper Floridan aquifer may have discharged into the Atlantic Ocean through the overlying confining unit or submarine outcrops (Counts and Donsky, 1963). Landmeyer and Belval (1996) suggested the historical presence of submarine springs in Calibogue Sound, and anecdotal evidence indicates the presence of submarine springs in the Beaufort River (Counts and Donsky, 1963). The hydraulic head in the Upper Floridan aquifer was sufficiently high that the earliest wells flowed at land surface throughout much of the coastal area, with water levels at Savannah 30–40 ft above NAVD 88 (Johnston and others, 1980; Krause and Clarke, 2001; fig. 5*A*).

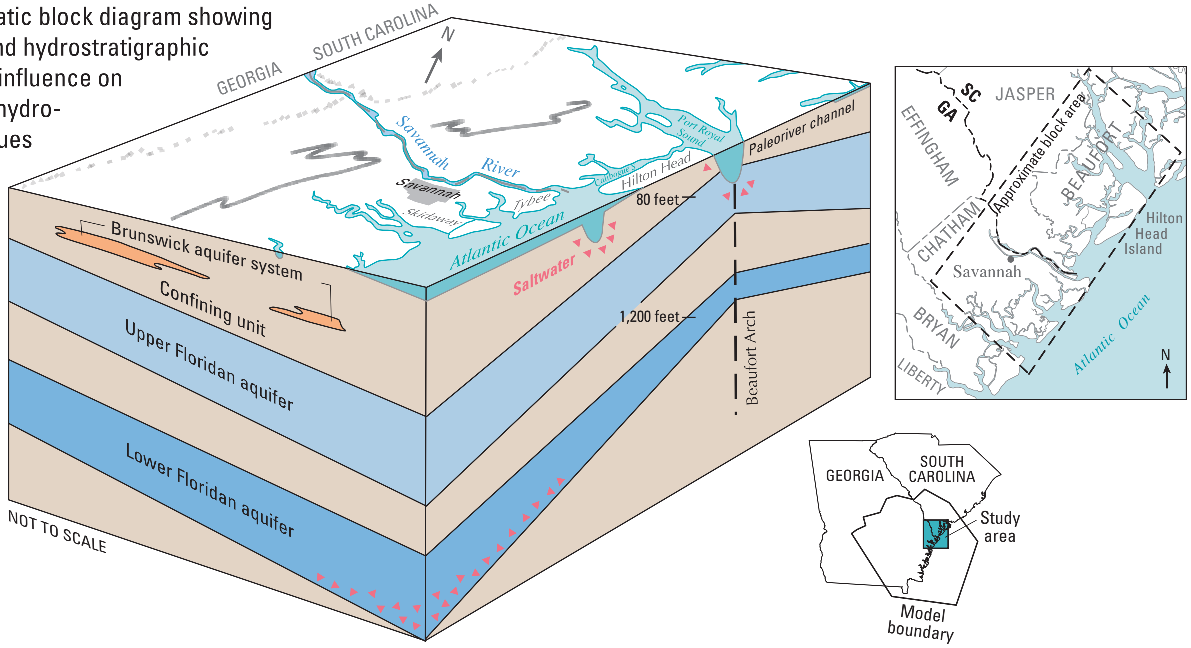
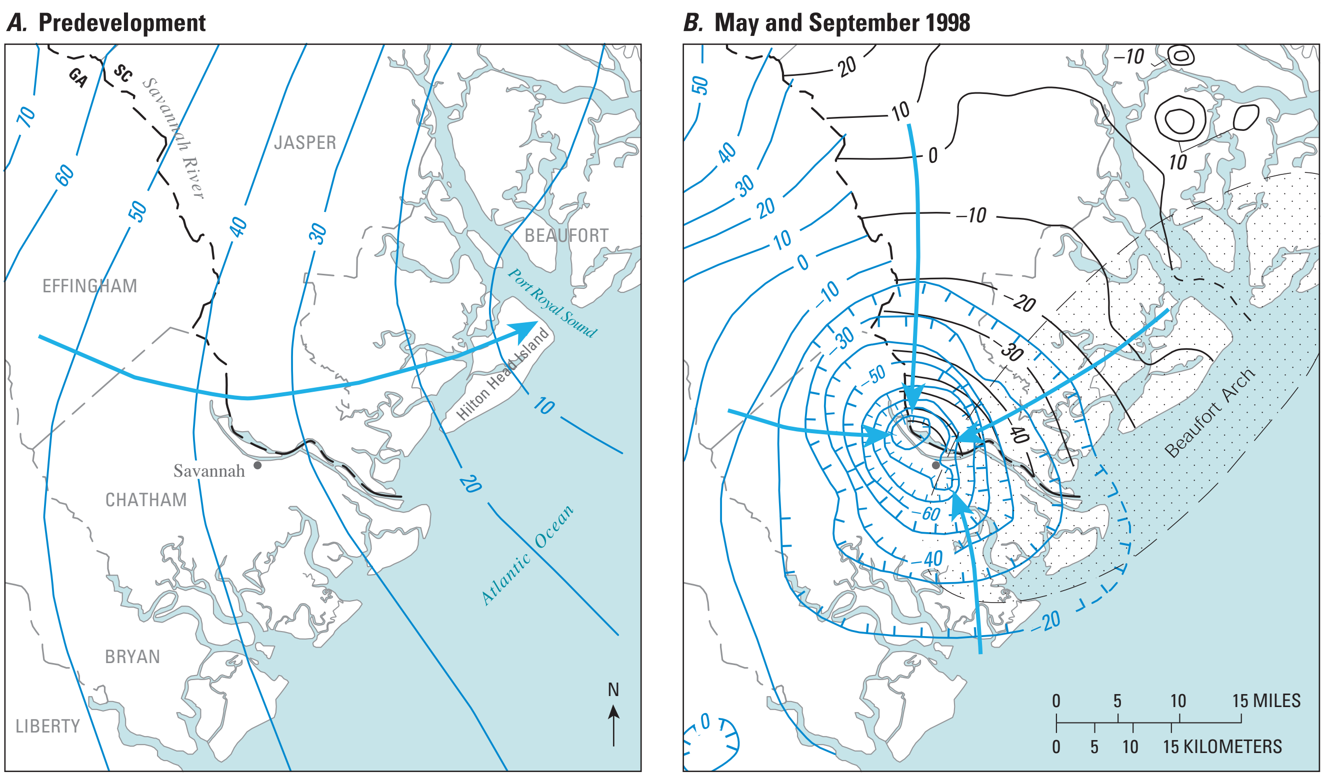


Figure 3. Schematic block diagram showing major structural and hydrostratigraphic features and their influence on the distribution of hydrogeologic units (values are depth from land surface; modified from Provost and others, 2006).



Base from U.S. Geological Survey
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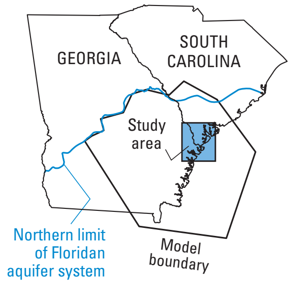


Figure 4. Potentiometric surface of the Upper Floridan aquifer in the Savannah, Georgia—Hilton Head Island, South Carolina, area: *(A)* predevelopment and *(B)* May and September 1998 (modified from Johnston and others, 1980; Peck and others, 1999; and Ransom and White, 1999).

EXPLANATION

0 — Potentiometric contour—Shows altitude at which water level would have stood in tightly cased wells. Blue contours show predevelopment and May 1998. Black contours show September 1998. Hachures indicate depression. Contour interval 10 feet. Dashed where approximate. Datum for predevelopment is NGVD 29; datum for May and September 1998 is NAVD 88

→ General direction of groundwater flow

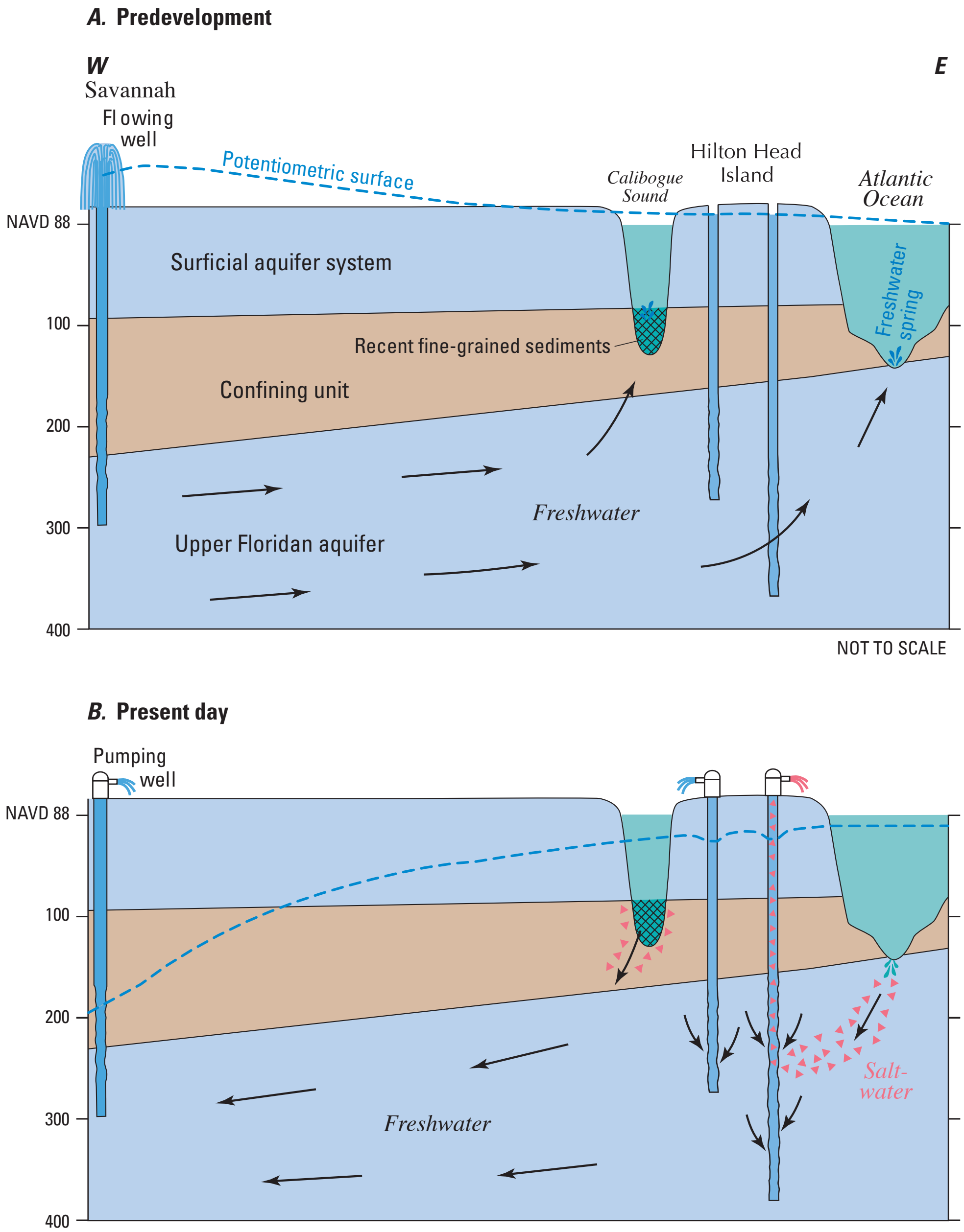
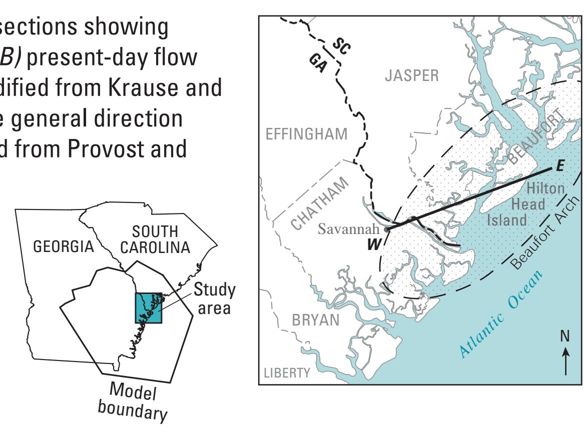


Figure 5. Schematic cross sections showing the *(A)* predevelopment and *(B)* present-day flow system in the study area (modified from Krause and Clarke, 2001). Arrows indicate general direction of groundwater flow (modified from Provost and others, 2006).



The present-day flow system reflects changes that have occurred as a result of groundwater development (withdrawal) (figs. 4*B* and 5*B*). Groundwater withdrawal has lowered water levels, induced additional recharge, reduced natural discharge, and increased the chloride concentration in groundwater along the coast. An extensive cone of depression in the Upper Floridan aquifer potentiometric surface is centered in the Savannah, Ga., area (fig. 4*B*) and is the result of large pumping rates and decreasing transmissivity of the aquifer as it thins toward the Beaufort Arch. Water-level altitudes at the center of the cone of depression in 2000 were below –100 ft (Peck and McFadden, 2004). The cone of depression has "captured" groundwater flow, which, prior to development, may have discharged offshore. The pumping has resulted in a reversal of the seaward head gradient east and north of Savannah. In addition, diffuse upward leakage of water from the Upper Floridan aquifer into overlying units, streams, and wetlands may have decreased or ceased, and wells no longer flow at land surface.

Local geology also affects groundwater flow in the Hilton Head Island area. In the Beaufort Arch area near Port Royal Sound, the Upper Floridan aquifer thins and is at shallow depth; in localized areas, little or no confinement is above the aquifer (figs. 3 and 5*B*). During predevelopment, groundwater levels in this area were above sea level, and groundwater discharged into Port Royal Sound. After the initiation of groundwater pumping, however, water levels fell below sea level, and seawater entered the Upper Floridan aquifer, resulting in saltwater contamination. Potentiometric mounds occur northeast of Port Royal Sound on St. Helena Island, on Ladies Island, and near Burton, S.C. (figs. 4*B* and 1), indicating local recharge areas for the Upper Floridan aquifer (Johnston and others, 1981; Hughes and others, 1989; Ransom and White, 1999; Hockensmith, 2001). Geochemical data showing a meteoric component in groundwater, combined with potentiometric data and lithologic information, indicate that freshwater recharge has occurred at the northern part of Hilton Head Island (Back and others, 1970).

Groundwater Pumpage

The Upper Floridan aquifer is the principal source of fresh groundwater in the study area. Since the initiation of pumpage at Savannah in 1885, groundwater withdrawals in the study area steadily increased, and by 1990 reached a maximum estimated total withdrawal of 114 million gallons per day (Mgal/d) for Beaufort and Jasper Counties, S.C., and Bryan, Chatham, and Effingham Counties, Ga. Around 1900, Savannah withdrew about 6 Mgal/d (Warren, 1944; Counts and Donsky, 1963). Wells were drilled during 1899 at Parris Island, S.C., but were abandoned within several years because of elevated salinity. Groundwater pumpage increased markedly in Savannah in the mid- to late 1930s, and again in the 1950s (Counts and Donsky, 1963). During the 1940s, pumpage started to increase in the Port Royal Island, S.C., area, and increased salinities were observed in Beaufort, S.C. During the 1960s and 1970s, pumpage in Savannah and Hilton Head Island areas increased with the onset of rapid residential and recreational development. Pumpage in the Savannah area peaked at about 89 Mgal/d in 1990 (Fanning, 2003) and in Beaufort County, S.C., at more than 20 Mgal/d in 2000 (Whitney Stringfield, U.S. Geological Survey, written commun., 2002). Pumpage in the study area decreased beginning in 1997 and appears to have stabilized at about 100 Mgal/d since 2000 (fig. 6).

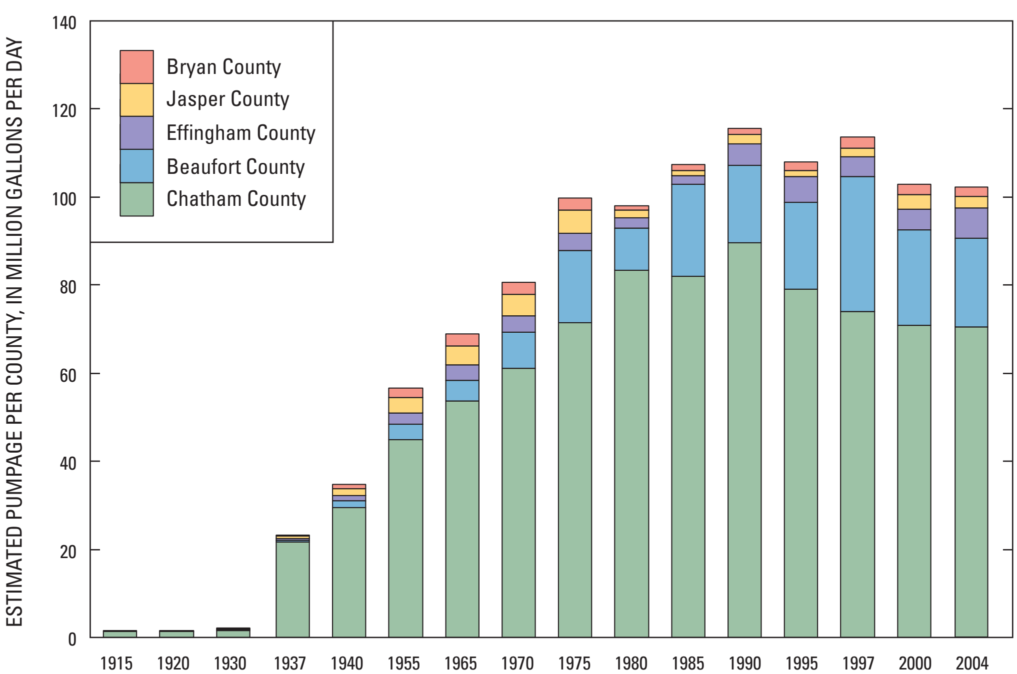


Figure 6. Estimated pumpage per county for Bryan, Chatham, and Effingham Counties, Georgia, and Beaufort and Jasper Counties, South Carolina, 1915–2004 (county locations shown in figure 1; modified from Provost and others, 2006).

Saltwater Contamination

The distribution of salinity in groundwater in the study area is complex and indicates several possible sources and mechanisms of transport. During predevelopment, the distribution of salinity is uncertain because no data exist indicating the occurrence of saline groundwater. The earliest indication of saltwater intrusion in the area is at Parris Island, S.C., where shortly after water-supply wells were drilled and used for groundwater supply in the late 1800s, salinity levels in the Upper Floridan aquifer increased to an unacceptable level (Hayes, 1979). Samples collected in the study area during the 1960s and frequent sampling since the early 1960s at the northern end of Hilton Head Island indicate elevated salinity in units below the Upper Floridan aquifer (Counts and Donsky, 1963; Back and others, 1970). During the late 1970s, chloride concentration started to increase in the Upper Floridan aquifer at the northern end of Hilton Head Island and, by the 1990s, was greater than 10,000 milligrams per liter (mg/L; equivalent to 4 log mg/L; seawater concentration is about 19,000 mg/L; fig. 7).

Landmeyer and Belval (1996) mapped the salinity distribution during 1984 at the top and bottom of the Upper Floridan aquifer beneath Port Royal Sound using data from Burt and others (1987). They interpreted a higher salinity at the base, by one or two orders of magnitude, than at the top of the aquifer. Landmeyer and Belval noted that some of the values were from wells open to both the Upper Floridan aquifer and underlying confining unit, which generally has a higher chloride concentration.

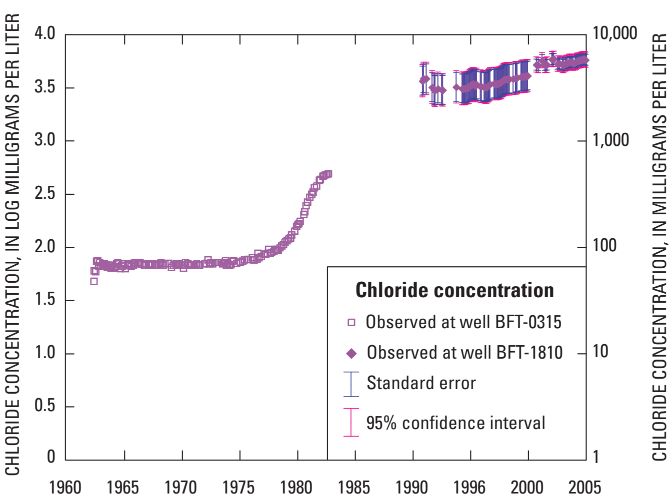


Figure 7. Observed chloride concentration at well BFT-0315 and estimated chloride concentration from observed specific conductance at well BFT-1810. Both wells are open to and recording water-quality conditions in the Upper Floridan aquifer. (See Appendix 1, figure 1–2 for location.)

Specific conductance monitoring at wells in the study area (mostly southern Beaufort County) was used to estimate chloride concentrations using a simple linear regression analysis (Childress and Ransom, 2005). This type of relation, however, overestimates chloride concentrations for specific conductance values less than about 2,000 microsiemens per centimeter at 25 degrees Celsius (µS/cm), or about 700 mg/L chloride, which exceeds the U.S. Environmental Protection Agency (USEPA) secondary standard for drinking water of 250 mg/L for chloride concentration. For this study, a more complex relation between specific conductance and chloride concentration is established and used to determine the chloride concentration calibration target (Appendix 1), and to more accurately estimate concentrations that exceed USEPA standards. In 2004 the highest estimated chloride concentrations were at the northern end of Hilton Head Island, at Pinckney Island, and near the Colleton River (fig. 8). A multi-lobed chloride plume has been interpreted based on this spatial distribution (Camille Ransom, South Carolina Department of Health and Environmental Control, written commun., 2006). At some of these sites, a marked increase in specific conductance (thus chloride concentration) was observed at the base of the Upper Floridan aquifer and into the underlying confining unit.

During 2000, several wells were drilled in the area offshore of Hilton Head Island and Tybee Island and in Calibogue Sound, and aquifer and confining unit sediments were sampled, groundwater levels were measured, and groundwater samples were analyzed (Falls and others, 2005). The wells are located in the general direction of flow in the Upper Floridan aquifer in areas where the confining unit overlying the Upper Floridan aquifer is partially eroded by paleoriver channels (Foyle and others, 2001). Analyses of samples collected at various depths from each site indicated decreasing concentrations of chloride from the top of the confining unit to the top of the Upper Floridan aquifer (fig. 9).

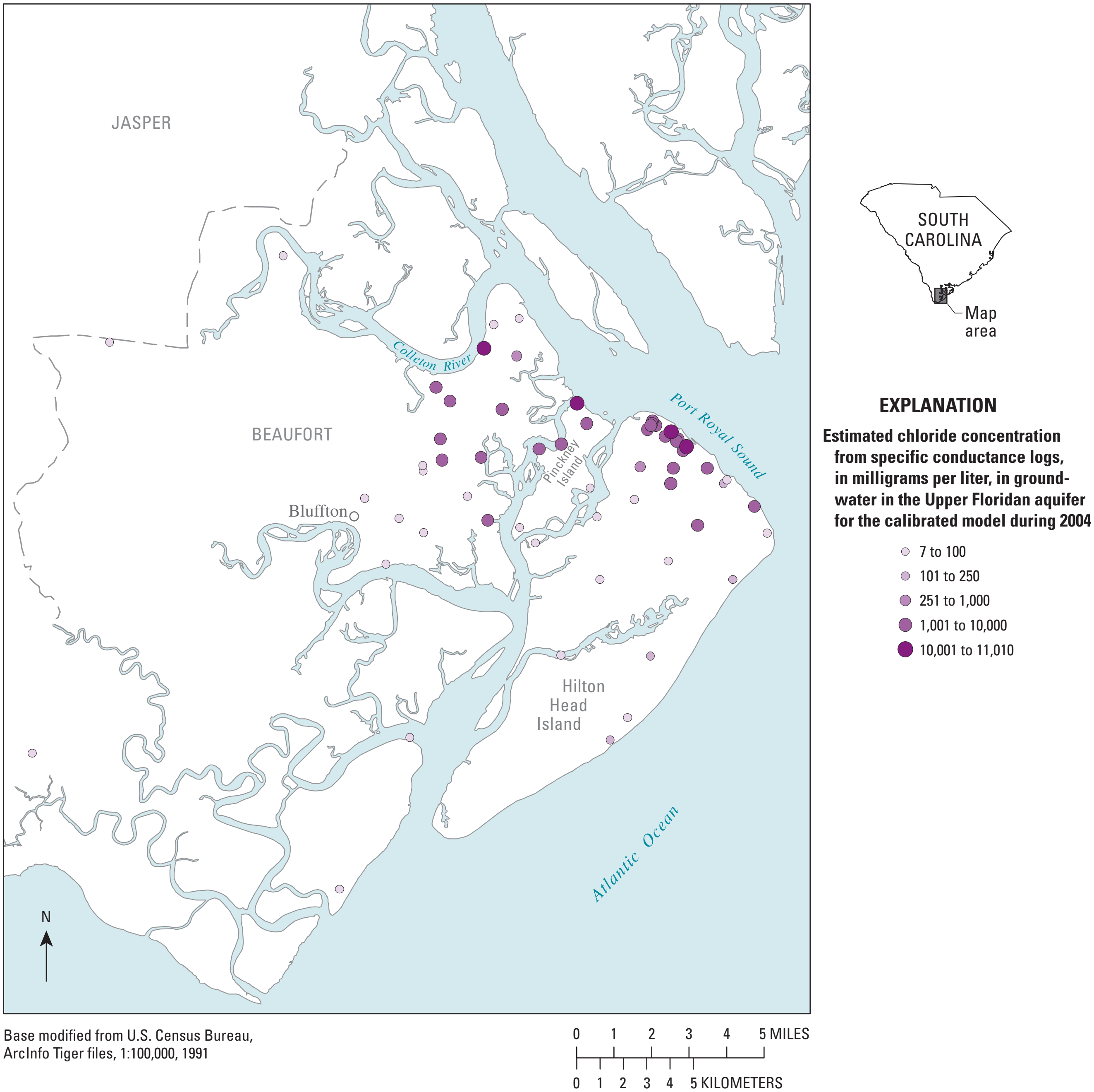


Figure 8. Estimated chloride concentration from specific conductance logs in groundwater in the Upper Floridan aquifer for the calibrated model in the Hilton Head Island area, South Carolina, during 2004. (See Appendix 1, table 1–3 and figure 1–2, for well-site information.)

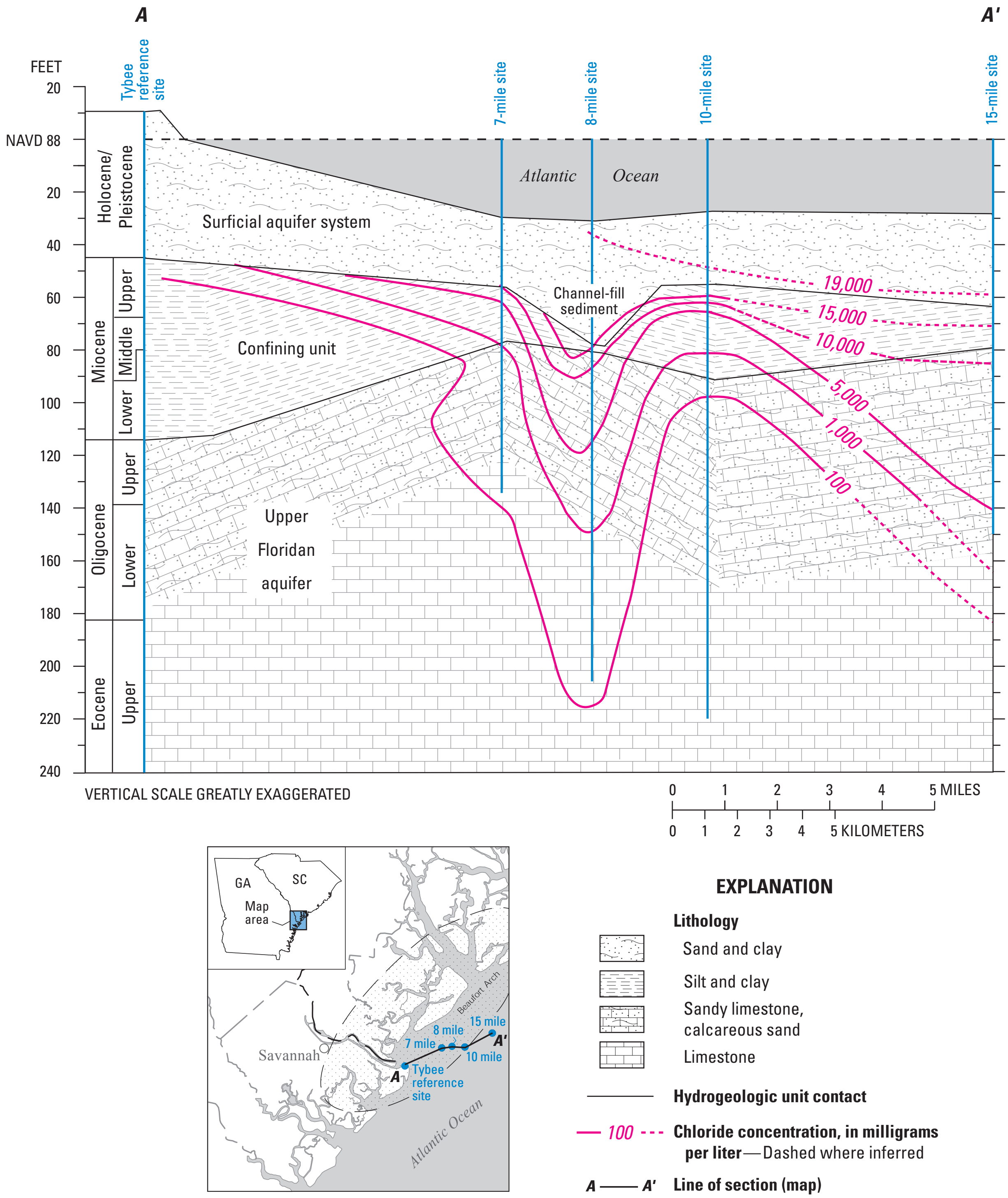
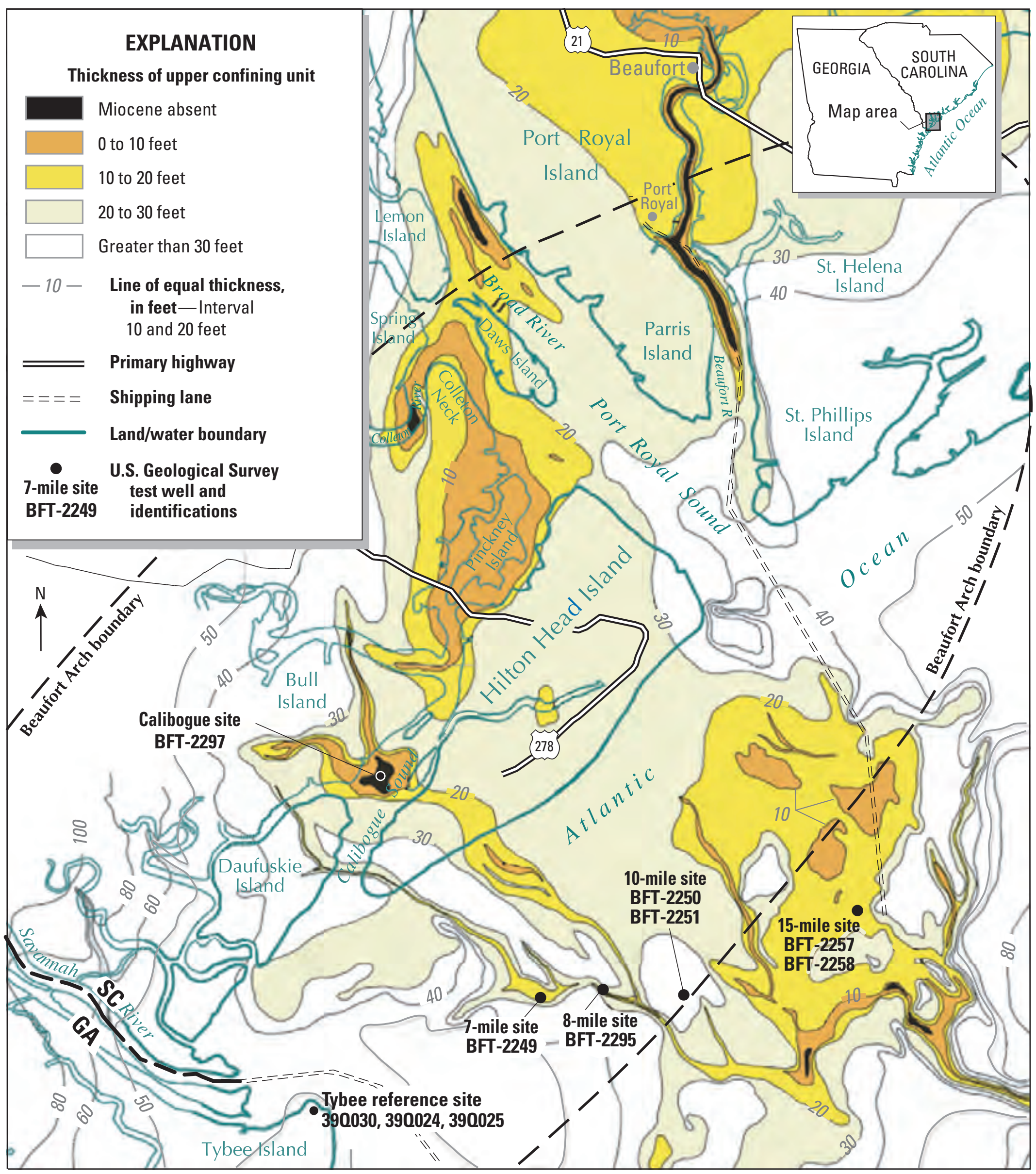


Figure 9. Hydrogeologic section *A–A′* and chloride distribution from the Tybee reference site at the northern end of Tybee Island, Georgia, to the 15-mile site on the Beaufort Arch seaward of Hilton Head Island, South Carolina (modified from Falls and others, 2005).

Conceptual Model

The groundwater flow and solute-transport model developed for this study is based on a conceptual model of saltwater contamination using available geologic, hydrologic, and water-quality data. This conceptual model assumes that the confining unit is particularly thin over the Beaufort Arch, and that local pumping of the Upper Floridan aquifer on Hilton Head Island and regional pumping centered at Savannah have lowered the potentiometric surface of the Upper Floridan aquifer in the study area, resulting in a downward gradient from the water table and the ocean-seafloor interface (fig. 5). Offshore of Hilton Head Island, and in the Savannah River channel, observed chloride concentration decreases with depth in the confining unit, and chloride concentration in the Upper Floridan aquifer is greatest at the top (Falls and others, 2005; Smith and McIntosh, 2005). After brackish estuarine water or seawater enters the Upper Floridan aquifer, it may then either be diluted or accumulate and move laterally along the hydraulic gradient toward pumping centers. If the saline water is not diluted once it enters a permeable unit, density effects may result in an accumulation of the denser, more saline water at the bottom of the permeable unit. Interpreted seismic data indicate that there are breaches in the Upper Floridan aquifer confining unit offshore of Hilton Head Island, in Calibogue Sound, at the Colleton River, and in the Beaufort and Broad Rivers (fig. 10). Seawater and brackish water overlie the aquifer at these locations. The regional potentiometric gradient



Base from 1:100,000-scale
Digital Line Graph, Beaufort, 1978

0 2 4 6 MILES
0 2 4 6 KILOMETERS

Figure 10. Thickness of the upper (Miocene) confining unit and location of onshore Georgia and offshore Coastal Sound Science Initiative wells (modified from Foyle and others, 2001; Falls and others, 2005).

is perpendicular to the contours of the cone of depression, and flow is toward Savannah on a regional scale (fig. 4*B*). In addition, localized pumping centers on Hilton Head Island deflect the potentiometric contours and lateral flow to these locations in the Upper Floridan aquifer. Some wells at the northern end of Hilton Head Island, at Pinckney Island, and near the Colleton River that have been monitored for specific conductance indicate an increase in salinity with depth in the Upper Floridan aquifer (Childress and Ransom, 2005).

Although this is the primary conceptual model tested in this study, other mechanisms may exist by which saltwater could enter and contaminate the Upper Floridan aquifer in the study area. One possibility is that salty water from the confining unit underlying the Upper Floridan aquifer migrates upward because of an upward hydraulic gradient. In the Hilton Head Island and Port Royal Sound area, geophysical logs and samples from the deepest part of the Upper Floridan aquifer and the underlying confining unit indicate that the confining unit is saline (Burt and others, 1987). This water is possibly unflushed connate water from the previous sea-level high stand, as indicated by estimated ages from this unit (Back and others, 1970). The likely low permeability of the confining unit between the Upper and Lower Floridan aquifers, however, could prevent the movement of saltwater in quantities large enough to result in the development of large saltwater plumes.

Alternatively, saltwater intrusion may result from the lateral movement of a proximal steady-state saltwater-freshwater interface, established under predevelopment conditions, in response to a pumping-induced lateral hydraulic gradient. It has been suggested that a predevelopment interface existed in the Port Royal Sound area, and that with increases in pumping and a reversal in the hydraulic gradient, this interface started migrating along the flow paths toward the pumping centers (Bush, 1988; Smith, 1994; Landmeyer and Belval, 1996; Krause and Clarke, 2001). The presence of freshwater in the Upper Floridan aquifer offshore of Hilton Head Island (Falls and others, 2005), however, raises doubt about the presence of the predevelopment steady-state interface as close to the study area as previously suggested.

Sea-Level Rise

Rising sea level may affect the extent of saltwater intrusion in coastal aquifers because an increasing area may become submerged by brackish water or seawater, particularly in low-lying areas such as in the Hilton Head Island area. Also, as sea level rises, increasing downward pressure is exerted at the sea floor (or at the sediment-water interface in tidal creeks, rivers, or emergent wetlands) as the height of the overlying saltwater column increases. Rising sea level also may change the water-table configuration and thus freshwater recharge/discharge processes close to the shoreline, or the spatial relation of the water table to the freshwater/saltwater interface (Masterson and Garabedian, 2007), adding complexity to the dynamics of saltwater intrusion processes.

During the last century, sea level in coastal Georgia and South Carolina has been observed to rise at a rate of about 1 ft per century (fig. 11; National Oceanic and Atmospheric Administration, 2008). Prehistoric reconstructions of sea level in the region show a long-term rise in sea level over the past several thousand years (Meisler and others, 1985; Colquhoun and Brooks, 1986), and sea level is predicted to continue to rise during the next century (Intergovernmental Panel on Climate Change, 2007). Predictions of the total sea-level rise by the end of the 21st century are rather uncertain, ranging from about 0.66 ft to almost 4.9 ft (Church and White, 2006; Intergovernmental Panel on Climate Change, 2007; Rahmstorf, 2007).

Simulation of Variable-Density Groundwater Flow and Solute Transport, Predevelopment—2004

Provost and others (2006) developed a three-dimensional, variable-density, digital groundwater flow and solute-transport model for the Savannah-Hilton Head Island area, including surrounding counties and the adjacent offshore area, using the SUTRA version 2.1 simulator (Voss and Provost, 2008). This “original” SUTRA model was used to simulate saltwater intrusion from 1885 to 2004 (though calibrated to 1998 and 2000 conditions), project the trends into the future, evaluate pumpage-reduction scenarios for management purposes, and evaluate the relative effects of pumping in different areas on saltwater intrusion. The revised model described in this report was modified from the original SUTRA model and calibrated to 2004 conditions. This model was used to simulate sea-level-rise scenarios for 100 years into the future. SUTRA version 2.1 was modified to account for the time-dependent boundary conditions (pumping and sea-level-rise history from 1885 to 2004), and the SutraGUI graphical modeling interface (Winston, 2000; Winston and Voss, 2004) based on Argus ONE® was used to convert spatially referenced datasets into model-input datasets. The model was calibrated to match October 2004 water levels and estimated 2004 chloride concentrations in the Upper Floridan aquifer. To allow transient simulation of saltwater intrusion and transport, the model uses an estimated pumping history from predevelopment through 2004. Simulations were carried out through 2104 to estimate and allow comparison of the future evolution of the chloride distribution in the Upper Floridan aquifer for different rates of sea-level rise and for an elimination of pumping.

Some data are conventionally reported in metric units, for example chloride or total dissolved solids (TDS) concentrations, and some hydraulic and fluid properties (tables 1 and 2). For simulation purposes, all model input were converted to consistent metric units. Many of the other data used to construct and calibrate the model, however, are typically reported in

Imperial units, for example area, land surface, water level and other altitudes, pumpage, and recharge rates. Here these are reported in Imperial units, even if converted to metric units for simulation input. For comparison purposes, still other data that have been reported originally in metric units are converted in this report to Imperial units, for example sea-level rise rates.

Model Construction

The layering and spatial discretization and some of the hydraulic and transport properties and boundary conditions for this model are identical to the original SUTRA model (Provost and others, 2006). Specifically, this model uses a different distribution of permeability for hydrologic units 1–5 (the Upper Floridan aquifer and all overlying units) in the study area, a different set of uniform effective porosity values for the aquifer and confining units, a different boundary condition at the top of the model in the onshore area, and a different boundary condition at the offshore lateral boundary of the model. The initial conditions also differ because they are established using the physical properties and boundary conditions of the calibrated model.

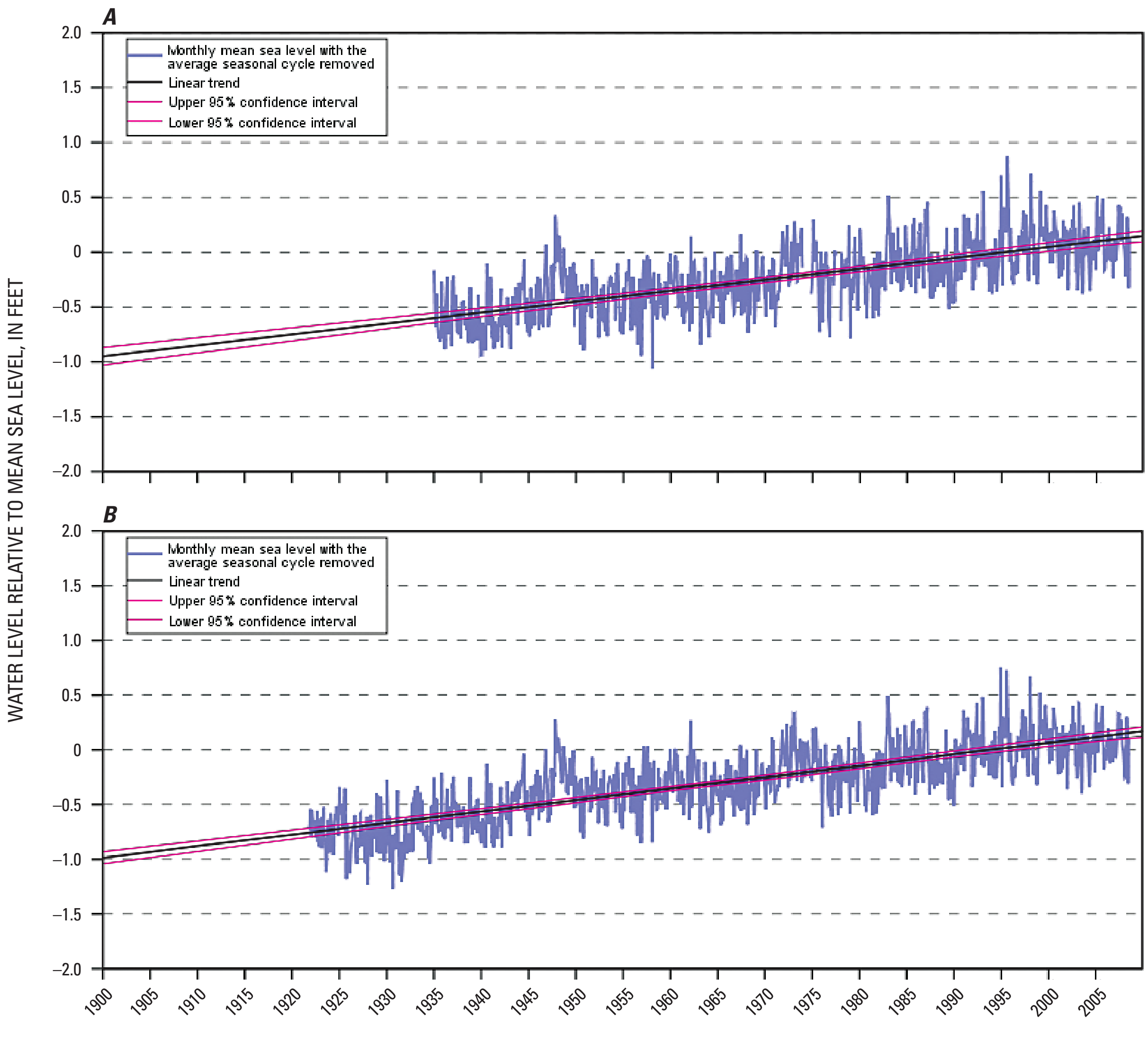


Figure 11. Mean sea-level trends at *(A)* Fort Pulaski, Georgia, from 1935 to 1999 and *(B)* Charleston, South Carolina, from 1921 to 1999 (National Ocean and Atmospheric Administration; datum [0] is National Tidal Datum Epoch 1983–2001; –, below datum; Fort Pulaski graph accessed on October 30, 2008, at *http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8670870*, Charleston graph accessed on October 30, 2008, at *http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8665530*).

Layering (Framework)

The hydrologic unit layering is the same as used in the original SUTRA model (Provost and others, 2006). The seven simulated aquifer and confining units in the SUTRA model (fig. 12) are

- hydrogeologic unit 1, the confined upper and lower water-bearing zones of the surficial aquifer system grouped together,
- hydrogeologic unit 2, the Brunswick aquifer system confining unit,
- hydrogeologic unit 3, the upper and lower Brunswick aquifers grouped together to form the Brunswick aquifer system,
- hydrogeologic unit 4, the Upper Floridan aquifer confining unit,
- hydrogeologic unit 5, the Upper Floridan aquifer,
- hydrogeologic unit 6, the Lower Floridan aquifer confining unit, and
- hydrogeologic unit 7, the Lower Floridan aquifer.

Unit 1 comprises the confined upper and lower water-bearing zones of the surficial aquifer system. The SUTRA model does not specifically address the unconfined portion of the surficial aquifer system because the spatial discretization of the model is generally insufficient to simulate accurately unconfined flow-system characteristics. Simulated flow in the confined surficial aquifer system is used primarily as a means to move water into and out of the deeper confined aquifers, and not to provide detailed characterization of flow in the unit. The top surfaces of each hydrologic unit are the same as in the original SUTRA model, except that the top of unit 1 has been modified to reflect a refined and improved discretization of the land-surface altitude and bathymetry, as described in Appendix 2.

Spatial Discretization

The revised SUTRA model has the same dimensions and resolution as the original model. It encompasses 42,155 mi^2 and is constructed with 4,093 elements and 4,126 nodes in the horizontal dimensions, and 24 elements and 25 nodes in the vertical dimension. In the study area, the finite-element mesh is refined laterally to allow more detailed representation of the pumping and head distributions, and is coarsened elsewhere to minimize the number of elements and nodes, and thus the computational demands of the SUTRA model (fig. 13). The lateral discretization is further refined in selected areas where saltwater intrusion into the Upper Floridan aquifer is observed. 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 hydrogeologic unit. Horizontal element sizes range from about 0.003 mi^2 to 774 mi^2. The mesh was generated and modified using graphical grid-generation tools from the graphical user interface SutraGUI (Winston and Voss, 2004).

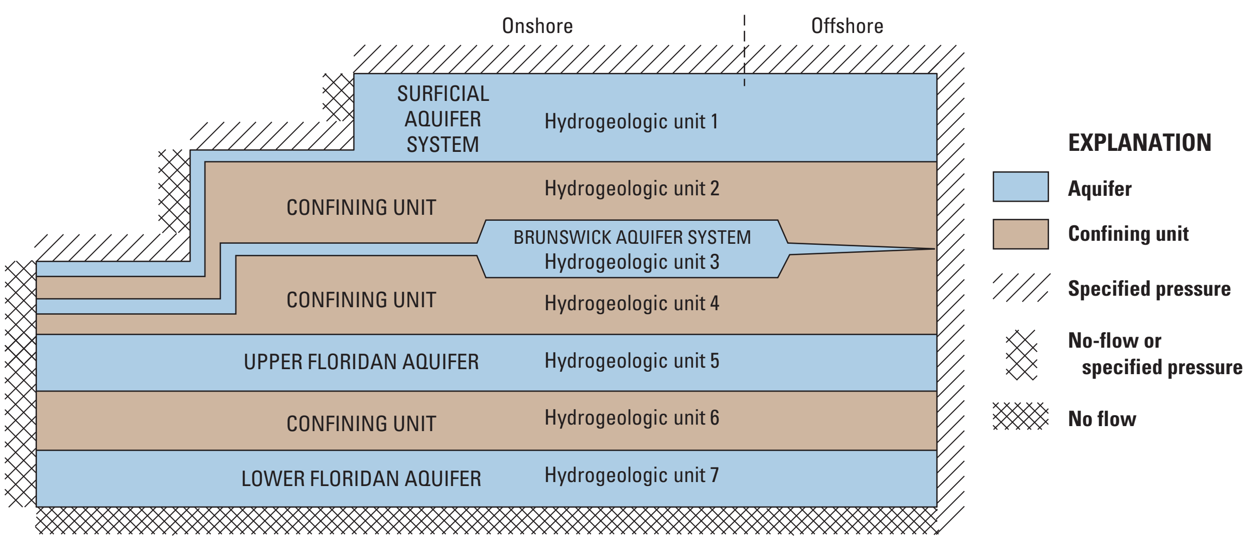


Figure 12. Schematic diagram showing layering of simulated hydrogeologic units and boundary conditions (modified from Provost and others, 2006).

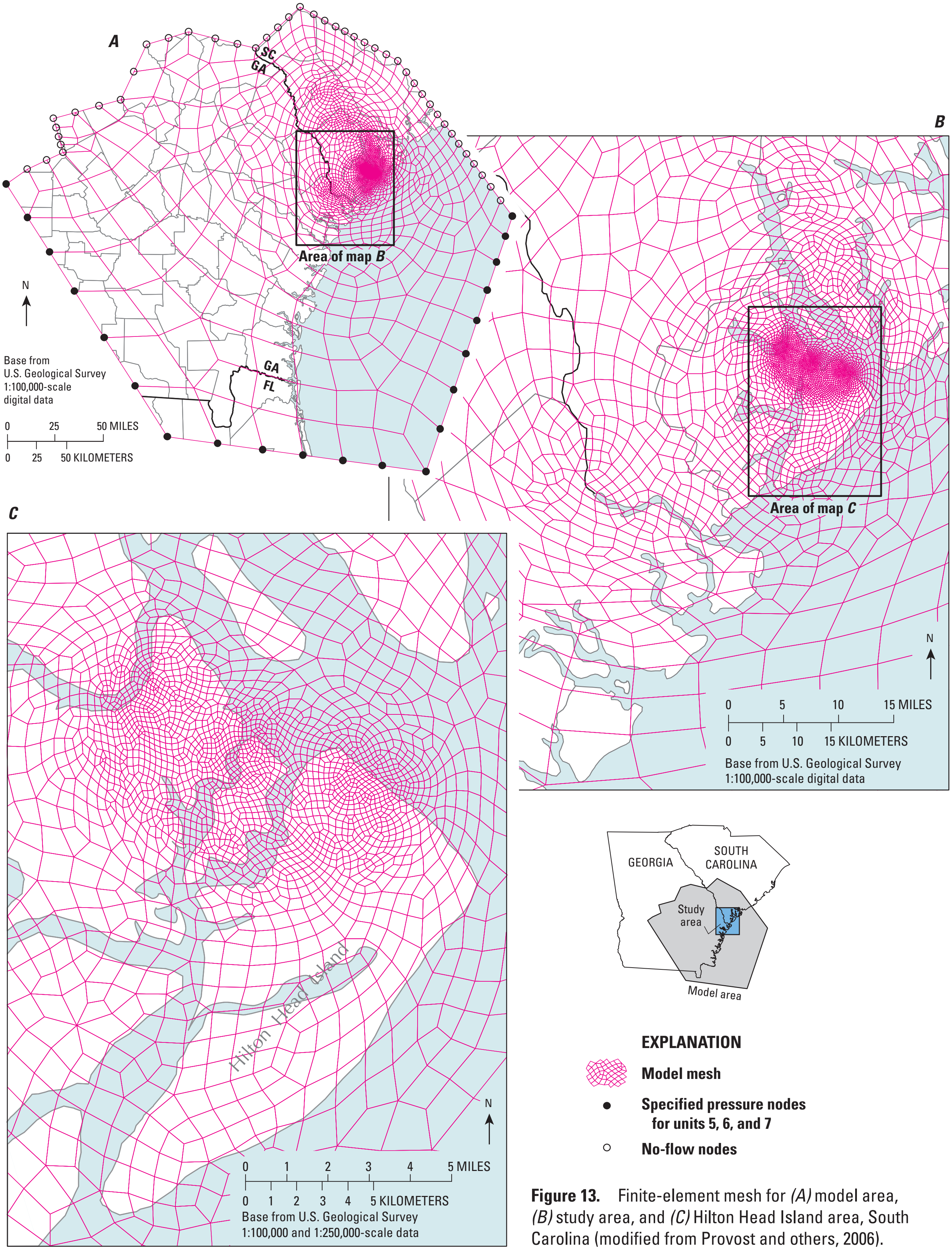


Figure 13. Finite-element mesh for *(A)* model area, *(B)* study area, and *(C)* Hilton Head Island area, South Carolina (modified from Provost and others, 2006).

Hydraulic and Transport Properties

To meet the objectives of this study, permeability values and zones were modified from the original SUTRA model (Provost and others, 2006). Permeability within each layer was assumed to be isotropic. In hydrogeologic units 1, 6, and 7, the permeability of each was assumed to be homogenous because of limited data for the surficial aquifer system, Lower Floridan confining unit, and Lower Floridan aquifer, respectively. The permeabilities for hydrogeologic units 2, 3, and 4 (representing the overlying confining unit) and unit 5 (representing the Upper Floridan aquifer) were distributed into zones. During calibration, zone geometries were modified, new zones were added, and permeability values were adjusted manually to achieve a better match with observed heads and estimated chloride concentrations in the study area. The resulting permeability distribution is shown in figure 14, and values of permeability zones are listed in table 1. The calibrated values are within the wide range observed for carbonate rock types (Freeze and Cherry, 1979, table 2.2).

The rate at which a solute is transported is approximately inversely proportional to the effective porosity of the porous medium. In the original SUTRA model, effective porosity values were assigned based on published laboratory analyses (Counts and Donsky, 1963; Burt and others, 1987)—0.33 for the surficial and Brunswick aquifer systems, 0.33 for the Upper Floridan and Lower Floridan aquifers, and 0.44 for the confining units. Because these values are based on laboratory measurements performed on core samples, they do not necessarily reflect the fraction of pore space through which most of the solute transport occurs at the field scale. Specific yield values of representative rock types, for example, 0.005–0.05 for limestone and 0.01–0.10 for clay (Driscoll, 1986), indicate effective porosity values may be lower than those used in the original SUTRA model. In a carbonate aquifer, if most of the solute transport occurs through preferential flow channels (which are not necessarily discernible in laboratory samples) that compose a small fraction of the total pore space, the effective porosity that is relevant to simulating solute transport in a carbonate aquifer can be significantly less than the porosity measured from cores in the laboratory. At the field scale, however, it is difficult to know how most of the solute is being transported. For modeling purposes, field data that show concentration over time at specific locations along a flow path may be used to estimate effective porosity; however, such data are not available to sufficiently constrain transport rates. Therefore, values of effective porosity intermediate between those from laboratory analyses and rock-type representatives were assigned by multiplying values in the original model by one-half. The resulting values of effective porosity are 0.165 for aquifer units (surficial aquifer system, Brunswick aquifer system, Upper Floridan aquifer, and Lower Floridan aquifer) and 0.22 for all confining units. Sensitivity of the model results to the value of the effective porosity is considered in this study, although sensitivity testing did not result in modification of selected input values.

Diffusion and dispersion are chemical and physical processes by which a solute moves through fluids as a function of the concentration and flow gradients, respectively. In dynamic systems, such as those described by this model, mechanical dispersion is much more effective at transporting solute than diffusion. For details regarding the relation between molecular diffusivity and dispersion in the mass balance equation, see equation 2.31 of the SUTRA manual (Voss and Provost, 2008). For this model, the molecular diffusion value used is arguably too high because it represents diffusion in free water, and ignores the effects of adsorption and more complex transport pathways in a solid matrix (Freeze and Cherry, 1979). The dispersion and diffusivity values used for this model, however, result in a predominance of dispersive transport. Testing of the calibrated model by reducing the molecular diffusivity by an order of magnitude did not affect the resulting simulated concentration distribution.

The concentration of seawater, expressed as the mass fraction of TDS, was set to a representative value of 0.0357 kilogram (kg)-TDS/kg-fluid (Voss and Provost, 2002), or 35.7 parts per thousand (ppt), which falls within the range 33 to 36 ppt reported by von Arx (1962). Freshwater was assigned a density of 1,000 kilograms per cubic meter (kg/m^3). The density of seawater was assumed to vary linearly with solute concentration at a rate of 700 kg/m^3 per unit increase in solute mass fraction (Voss and Provost, 2002), giving a seawater density of 1,024.99 kg/m^3. It was assumed that the dissolved solids in seawater are 55.04 percent by weight chloride (von Arx, 1962). Mass fraction of total dissolved solids, C, was converted to chloride concentration in mg/L, $\hat{C}_{Cl}$, using the formula

$$\hat{C}_{Cl} = (550.4)\,(1000 + 700\,C)\,C, \qquad (1)$$

which takes into account the variation of fluid density with concentration.

Other hydraulic and transport properties are the same as those used in the original SUTRA model and are explained in more detail in Provost and others (2006). These properties are listed in table 2.

Table 1. Assigned permeability values by zone, as shown in figure 14.

Hydrologic unit	Permeability zone (see fig. 14 for location)	Permeability (square meter)
1	N/A	2.5×10^{-11}
2, 4	c1	7.08×10^{-17}
	c2	7.19×10^{-16}
	c3	3.60×10^{-18}
	c4	3.60×10^{-17}
	c5	3.60×10^{-17}
	c6	1.00×10^{-16}
	c7	1.00×10^{-16}
	c8	1.00×10^{-15}
	c9	5.00×10^{-16}
	c10	1.00×10^{-16}
	c11	1.00×10^{-16}
	c12	1.00×10^{-16}
	c13	1.00×10^{-16}
	c14	1.79×10^{-17}
	c15	1.79×10^{-17}
	c16	1.00×10^{-16}
	c17	1.00×10^{-16}
	c18	1.00×10^{-16}
	c19	1.00×10^{-17}
	c20	1.00×10^{-16}
	c21	1.00×10^{-16}
	c22	1.00×10^{-16}
	c23	1.00×10^{-16}
	c24	1.00×10^{-16}
	c25	1.00×10^{-16}
	c26	1.00×10^{-16}
	c27	1.00×10^{-16}
	c28	1.00×10^{-16}
	c31	1.00×10^{-16}
	c32	1.00×10^{-16}
	c33	5.00×10^{-15}
	c34	1.00×10^{-13}
	c35	1.00×10^{-13}
	c36	1.00×10^{-16}
	c37	1.00×10^{-16}
	c38	1.00×10^{-16}
	c39	1.00×10^{-16}
	c51	1.00×10^{-16}
	c52	1.00×10^{-10}
	c53	5.00×10^{-13}
	c54	5.00×10^{-14}
	c55	1.00×10^{-16}
	c56	1.00×10^{-16}
	c57	1.00×10^{-16}
	c58	1.00×10^{-16}
	c81	1.00×10^{-16}
	c82	1.00×10^{-16}
	c83	1.00×10^{-16}
	c84	1.00×10^{-16}
	c85	1.00×10^{-16}
	c86	1.00×10^{-16}
	c87	1.00×10^{-16}
	c88	1.00×10^{-16}
	c89	5.00×10^{-14}
	c90	1.00×10^{-16}
	c91	5.00×10^{-13}
	c92	1.00×10^{-16}
3	b1	1.80×10^{-11}
	c1	7.08×10^{-17}
	c2	7.19×10^{-16}
	c3	3.60×10^{-18}
	c4	3.60×10^{-17}
	c5	3.60×10^{-17}
	c6	1.00×10^{-16}
	c7	1.00×10^{-16}
	c8	1.00×10^{-15}
	c9	5.00×10^{-16}
	c10	1.00×10^{-16}
	c11	1.00×10^{-16}
	c12	1.00×10^{-16}
	c13	1.00×10^{-16}
	c14	1.79×10^{-17}
	c15	1.79×10^{-17}
	c16	1.00×10^{-16}
	c17	1.00×10^{-16}
	c18	1.00×10^{-16}
	c19	1.00×10^{-17}
	c20	1.00×10^{-16}
	c21	1.00×10^{-16}
	c22	1.00×10^{-16}
	c23	1.00×10^{-16}
	c24	1.00×10^{-16}
	c25	1.00×10^{-16}
	c26	1.00×10^{-16}
	c27	1.00×10^{-16}
	c28	1.00×10^{-16}
	c31	1.00×10^{-16}
	c32	1.00×10^{-16}
	c33	5.00×10^{-15}
	c34	1.00×10^{-13}
	c35	1.00×10^{-13}
	c36	1.00×10^{-16}
	c37	1.00×10^{-16}
	c38	1.00×10^{-16}
	c39	1.00×10^{-16}
	c51	1.00×10^{-16}
	c52	1.00×10^{-10}
	c53	5.00×10^{-13}
	c54	5.00×10^{-14}
	c55	1.00×10^{-16}
	c56	1.00×10^{-16}
	c57	1.00×10^{-16}
	c58	1.00×10^{-16}
	c81	1.00×10^{-16}
	c82	1.00×10^{-16}
	c83	1.00×10^{-16}
	c84	1.00×10^{-16}
	c85	1.00×10^{-16}
	c86	1.00×10^{-16}
	c87	1.00×10^{-16}
	c88	1.00×10^{-16}
	c89	5.00×10^{-14}
	c90	1.00×10^{-16}
	c91	5.00×10^{-13}
	c92	1.00×10^{-16}
5	uf1	4.03×10^{-12}
	uf2	7.19×10^{-13}
	uf3	3.60×10^{-11}
	uf4	2.75×10^{-11}
	uf5	1.42×10^{-10}
	uf6	1.01×10^{-9}
	uf7	6.13×10^{-11}
	uf8	9.81×10^{-10}
	uf9	3.60×10^{-11}
	uf10	2.01×10^{-11}
	uf11	3.38×10^{-11}
	uf12	1.00×10^{-11}
	uf13	2.00×10^{-11}
	uf14	1.50×10^{-10}
	uf15	6.00×10^{-11}
	uf16	6.00×10^{-11}
	uf17	1.60×10^{-11}
	uf18	6.00×10^{-11}
	uf19	6.00×10^{-12}
	uf20	6.00×10^{-13}
	uf21	2.00×10^{-12}
	uf22	2.00×10^{-13}
	uf23	8.00×10^{-11}
6	N/A	7.19×10^{-15}
7	N/A	3.60×10^{-12}

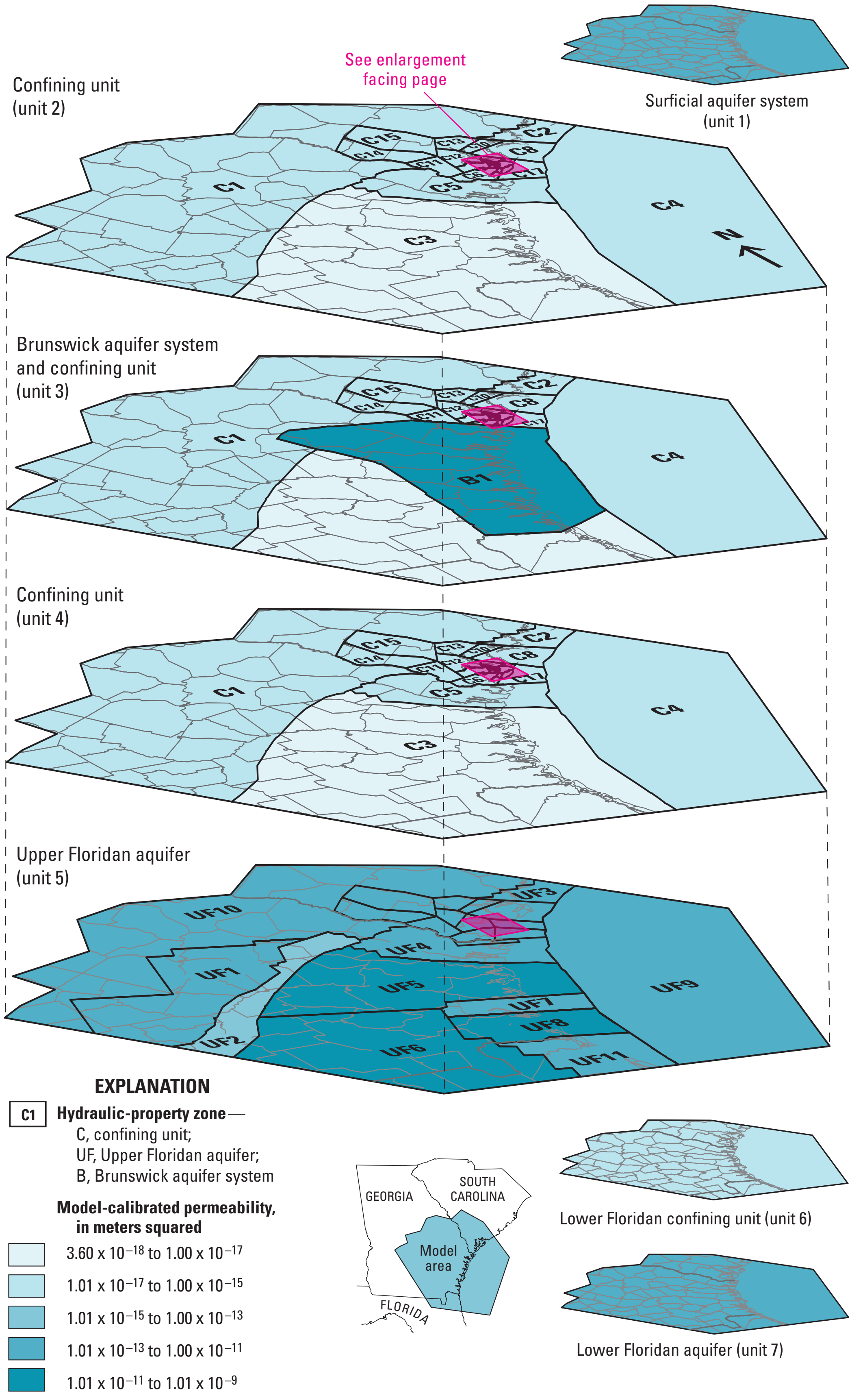


Figure 14. Distribution of permeability for model units (see table 1).

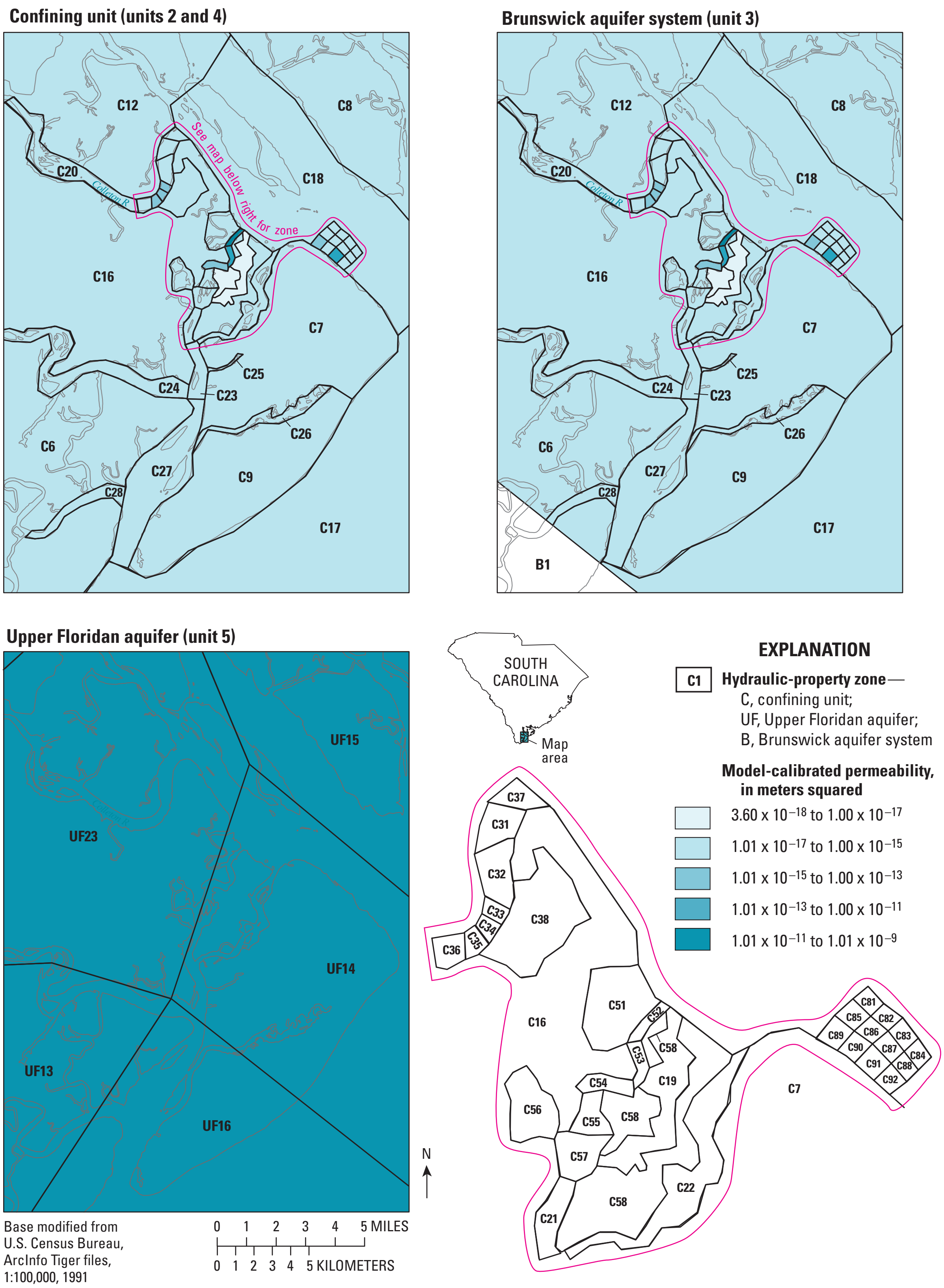


Figure 14. Distribution of permeability for model units (see table 1).—Continued

Table 2. Selected SUTRA input physical properties.

[m, meter; m^2/s, square meter per second; kg, kilogram; s^2, square second; s, second; kg/m^3, kilogram per cubic meter]

Physical property	Value in calibrated model
Porosity, all aquifer units	0.165 (dimensionless)
Porosity, all confining units	0.22 (dimensionless)
Longitudinal dispersivity, horizontal directions (varies with element size)	135–15,000 m
Longitudinal dispersivity, vertical direction (varies with element size)	0.04–158 m
Transverse dispersivity, horizontal directions (one-tenth of longitudinal dispersivity, horizontal directions)	13. –1,500 m
Transverse dispersivity, vertical direction (one-tenth of longitudinal dispersivity, vertical direction)	0.004–15.8 m
Molecular diffusivity	1.0×10^{-9} m^2/s
Fluid compressibility	4.47×10^{-10} $[kg/(m \times s^2)]^{-1}$
Solid-matrix compressibility	2.0×10^{-10} $[kg/(m \times s^2)]^{-1}$
Fluid viscosity	0.001 $kg/(m \times s)$
Freshwater density	1,000 kg/m^3
Rate of change in fluid density with solute-mass fraction	700 kg/m^3
Solute-mass (dissolved solids) fraction in seawater	0.0357 (dimensionless)

Boundary Conditions

Boundary conditions are similar to those in the original model, and are based on natural hydrologic boundaries where available; where unavailable, appropriate artificial boundary conditions were applied. Most of the differences between the original and revised boundary conditions are for the top boundary.

Top and Bottom Boundary Condition

For all top nodes of the model, pressure and concentration values were specified as a function of sea-level altitude, and sea-level altitude varies with time with each time step, relative to the reference altitude of sea level in 2004. The top nodes of the grid represent the land surface and sea floor. For each time step, if the altitude of a top node is below sea level at that time step (offshore nodes), the pressure of the overlying column of sea water was applied, assuming a corresponding density, and the concentration of inflow was set to the estimated chloride concentration of seawater (fig. 15):

$$P_{sf} = \rho_{sw} g H_{sw} , \tag{2}$$

where

P_{sf} is specified pressure at a seafloor node,
ρ_{sw} is the density of seawater,
g is the gravitational constant, and
H_{sw} is the height of the column of seawater.

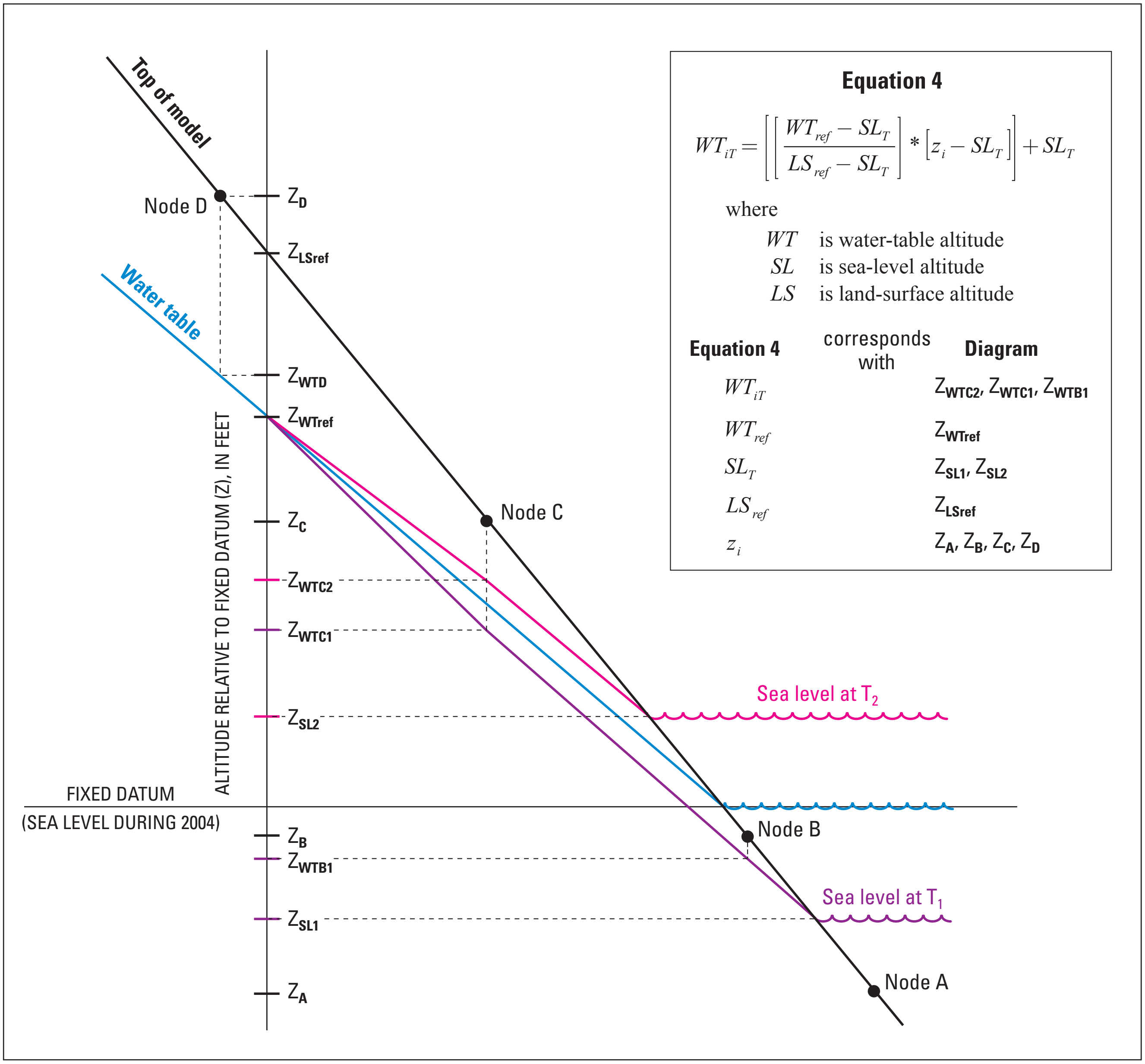


Figure 15. Schematic diagram showing how specified pressures are assigned to top nodes, for example, at nodes A, B, C, and D. At times T_1 and T_2, the altitude of node A (Z_A) is below sea level (Z_{SL1} and Z_{SL2}), and the specified pressures are functions of $Z_{SL1} - Z_A$ and $Z_{SL2} - Z_A$, respectively. Altitudes of nodes C (Z_C) and D (Z_D) are above sea level at times T_1 and T_2, so specified pressures are a function of calculated water-table altitude. The altitude of node D is above the reference land-surface altitude (Z_{LSref}), so the water-table altitude (Z_{WTD}) is a function of land-surface altitude, independent of time as described in equation 4. The altitude of node C is below the reference land-surface altitude and above sea levels at times T_1 and T_2, so water-table altitudes (Z_{WTC1} and Z_{WTC2}) are calculated according to equation 4 at each time, as a function of Z_{WTref} (reference water-table altitude, see Appendix 3) and Z_{SL1} and Z_{SL2}, respectively. At time T_1, the altitude of node B (Z_B) is below the reference land-surface altitude and above sea level, so specified pressure is calculated as a function of the water-table altitude (Z_{WTB1}), which is calculated according to equation 4. At time T_2, the altitude of node B is below sea level, and specified pressure is calculated as a function of $Z_{SL2} - Z_B$, similar to node A.

If the altitude of a top node is above sea level at that time step (onshore nodes), the pressure is set assuming zero pressure at the estimated water-table altitude and a hydrostatic freshwater gradient between the water-table and land-surface (node) altitudes:

$$P_{ls} = P_{wt} - (\rho_{fw} g D_{wt}), \quad (3)$$

where

- P_{ls} is the specified pressure at a land-surface node,
- P_{wt} is the pressure at the water table (zero),
- ρ_{fw} is the density of freshwater, and
- D_{wt} is the depth of the water table below land-surface altitude.

Equation 3 results in a negative value for the specified pressure at the top node when the water table is below land-surface altitude. For these onshore nodes, the concentration is specified as freshwater.

Water-table altitude is estimated as a function of land-surface altitude as described in Appendix 3. At sea level and below, surficial water-bearing units are assumed to be fully saturated, and they are assumed to be partially unsaturated above sea level. As sea level changes, there is a corresponding transitional altitude between saturated and unsaturated conditions. Sea-level changes are assumed to have a greater effect on the altitude of the water table for land-surface altitudes closer to sea level than those further from sea level. In order to account for this in the model, the onshore specified pressure during each time step was assigned by recalculating the water-table altitude based on a simple linear approximation of water-table altitude as a function of land-surface altitude (Appendix 3, method 1), as follows:

- assume a fixed datum of sea level in 2004, a reference land-surface altitude of 30 ft above the fixed datum (because the water-table data diverge from the linear trend below about 30 ft), and a reference water-table altitude calculated at the reference land-surface altitude using the simple linear function in appendix 3;
- for any node altitude above the reference altitude, water-table altitude is calculated using the simple linear function in appendix 3;
- for any node altitude between the reference altitude and the relative sea level at time T, water-table altitude is calculated as a linear function between the reference water-table altitude and a value of 0 at the relative sea level:

$$WT_{iT} = \left[\left[\frac{WT_{ref} - SL_T}{LS_{ref} - SL_T} \right] * [z_i - SL_T] \right] + SL_T, \quad (4)$$

where

- WT_{iT} is the water-table altitude at node i at time T,
- WT_{ref} is the reference water-table altitude,
- SL_T is sea-level altitude at time T relative to the fixed datum,
- LS_{ref} is the reference land-surface altitude, and
- z_i is the altitude of node i relative to the fixed datum (fig. 15);

for any node altitude below the relative sea level at time T, the surficial units are assumed to be saturated, and the specified pressure is calculated as a function of the depth of seawater, not as a function of water-table altitude.

The boundary condition at the bottom of the model represents an impermeable boundary across which there is no flow and no solute transport. Throughout the model area, this boundary corresponds to the contact between the Lower Floridan aquifer and underlying low-permeability sediments of Paleocene and older age.

Lateral Boundaries

Lateral boundary conditions were selected to coincide as closely as possible with assumed natural no-flow boundaries or groundwater divides. With the exception of the offshore boundary at the Florida–Hatteras slope, lateral boundary conditions are formulated exactly as in the original SUTRA model (Provost and others, 2006). Lateral boundaries are generally far from the study area; thus, their effects on the flow system are subdued by distance.

The northwestern boundary follows the updip extent of the Floridan aquifer system or its equivalent, as defined by Miller (1986), and is defined as a no-flow boundary (indicated by the no-flow nodes in fig. 13). The onshore part of the northeastern boundary was assigned a no-flow boundary because it is parallel to estimated flow lines as shown on the potentiometric surface of the Upper Floridan aquifer (Ransom and White, 1999). This boundary was projected offshore and connected to the easternmost offshore boundary.

To the southwest and south of the model area, there are no proximal natural hydrologic boundaries for the Floridan aquifer system because it extends west across Georgia and Alabama and south across Florida. For each node at the top of unit 5 along this boundary, a pressure was calculated from the Upper Floridan aquifer head value estimated from predevelopment, May 1980, May 1998, and September 2000 potentiometric maps (Johnston and others, 1980, 1981; Peck and others, 1999; Peck and McFadden, 2004). A hydrostatic pressure gradient was assumed for each vertical column of nodes, and the corresponding time-independent pressure was calculated for, and specified at, each of the nodes under the top node in unit 5 along that boundary (figs. 12 and 13).

The offshore boundary at the Florida–Hatteras slope is set using a specified pressure representing a hydrostatic gradient along each vertical column of nodes. The specified pressure at the top node is determined by the height of the overlying column of seawater. In the original SUTRA model, this boundary was a no-flow boundary. Changing this boundary has a negligible effect on simulated pressures and chloride concentrations in the study area, yet it creates a saltwater wedge emanating from the boundary, which is an arguably realistic feature.

Pumpage

The pumpage distribution used for the model was modified from that used in Provost and others (2006) and is the same as used in Payne (2007). Provost and others (2006) processed pumpage data for predevelopment through 2000; Payne (2007) extended the model input by processing the pumpage data to 2004. The pumpage history was modified to include an updated estimate for Upper Floridan aquifer pumpage in 2004. The primary intent of including an estimate of 2004 pumpage was to represent the changes in pumpage in the Savannah-Hilton Head Island area after 2000. Estimates for the Upper Floridan aquifer pumpage in the 24-county coastal Georgia area were provided by the GaEPD (Vicky Trent, written commun., 2006). Upper Floridan aquifer pumpage estimates for Beaufort, Colleton, and Jasper Counties in South Carolina were provided by the South Carolina Department of Health and Environmental Control (Jack Childress, written commun., 2006). Values for all other pumpage, including that for all other aquifers and the nonsite-specific pumpage, compose a small fraction of the pumpage in the study area and were assigned the same values used for 2000 pumpage (Provost and others, 2006). Thus the changes in stress distribution between 2000 and 2004 are indicated for only the Upper Floridan aquifer in the counties shown in table 4–1 (Appendix 4).

The methods used to distribute pumpage are described in detail Provost and others (2006) and Taylor and others (2003). Average daily pumpage for a given year or month was distributed spatially for periods for which (1) the model was calibrated, (2) substantial data coverage was available, or (3) pumpage changed substantially. These periods include 1915, 1920, 1930, 1937, 1940, 1955, 1970, 1980, 1985, 1990, 1997, September 1998, 2000, and 2004. See Provost and others (2006) and Payne and others (2005) for a detailed description of the processing of pumpage data.

Initial Conditions

To provide an initial representation of estimated predevelopment conditions in 1885, the model was run to establish a near steady-state condition based on sea level at that time. The following procedure was used: (1) initial concentrations everywhere in the system were set to freshwater; (2) sea level was set at the level estimated for 1885, which is about 1 ft lower than present-day sea level, and all other boundary conditions were set as previously described; (3) for these conditions, the model was run for a period of about 5,000 years (simulation results showed that the model closely approached a steady state within 5,000 years). The resulting simulated pressure and concentration distributions were used as the initial conditions for the 1885–2004 simulation.

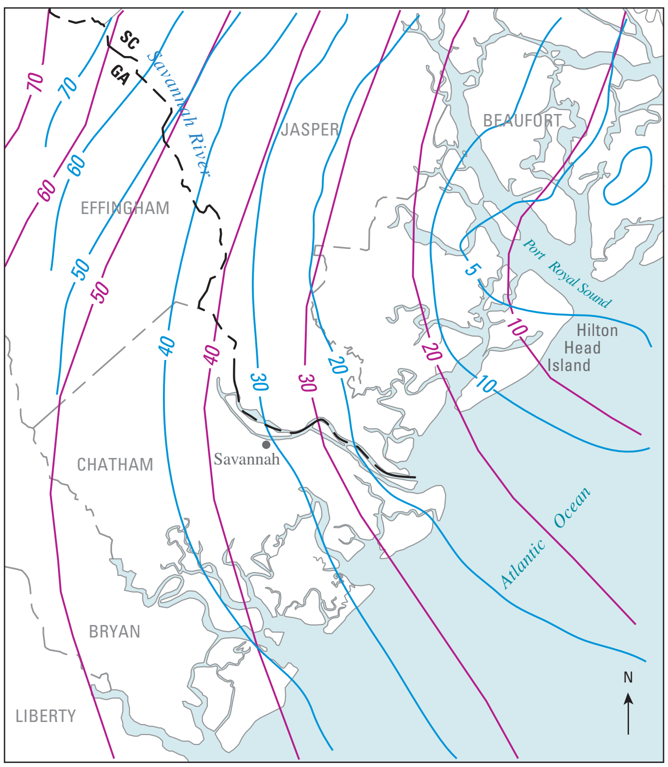
Model Calibration

The model was calibrated using a manual parameter estimation approach whereby permeability values were adjusted to obtain a reasonable match of selected Upper Floridan aquifer water-level and water-quality data for 2004. Initial predevelopment conditions were simulated, followed by a transient simulation for the period 1885–2004 using half-year time steps. For each time step, the pressure at each node was computed using the density (calculated from concentration at each node) from the previous time step. The resulting calibration likely represents just one of many possible realizations of physical properties and boundary conditions that would result in a comparable overall match to field conditions for this configuration and conceptual model.

Simulated Predevelopment Conditions

Simulated pressure heads after 5,000 simulated years under 1885 conditions (no pumping, estimated 1885 sea level) were used to generate an Upper Floridan aquifer predevelopment potentiometric map (fig. 16). The results indicate that the model generally simulates similar features as estimated by Johnston and others (1980), including flow toward the Port Royal Sound area. In the Hilton Head Island and Port Royal Sound area, the model generally calculates lower heads than previously estimated.

The simulated predevelopment chloride distribution shows the development of a saltwater wedge from the offshore boundary and concentrations in the study area of less than 100 mg/L (fig. 17). No predevelopment data exist for comparison, although theoretically this is a reasonable distribution because anecdotal evidence indicates freshwater was discharging in the area, as previously described. For the predevelopment simulation, sea level was set at estimated 1885 levels. Sea level has probably risen, however, between tens and several hundred feet over the last 5,000 years (Meisler and others, 1985; Colquhoun and Brooks, 1986); therefore, a simulated chloride concentration using a rising sea level over 5,000 years would likely result in a less advanced saltwater wedge. The blocky nature of the contours in the offshore area is a result of the very coarse model discretization in that area.



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

0 5 10 15 MILES
0 5 10 15 KILOMETERS

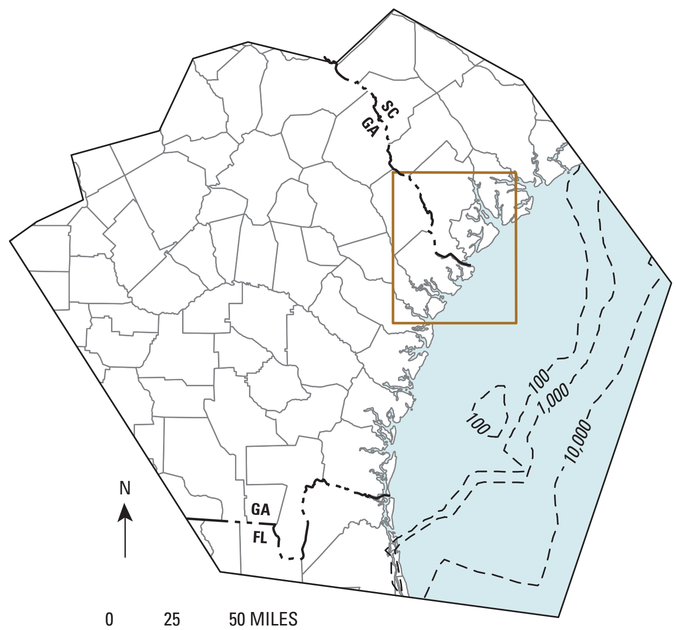
EXPLANATION

Potentiometric contour—Shows potentiometric surface of the Upper Floridan aquifer during predevelopment. Contour intervals 5 and 10 feet

—30— Simulated (datum is NAVD 88)

—30— Estimated (Johnston and others, 1980; datum is NGVD 29)

Figure 16. Potentiometric surface of the Upper Floridan aquifer for the calibrated model in the study area during predevelopment.



0 25 50 MILES
0 25 50 KILOMETERS

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

EXPLANATION

Model boundary

Study-area boundary

— — 100 — — **Simulated chloride-concentration contour**—Shows simulated chloride concentration, in milligrams per liter, in groundwater in the Upper Floridan aquifer during 1885

Figure 17. Simulated chloride concentration in groundwater in the Upper Floridan aquifer for the calibrated model in the model area during 1885.

Simulated Heads and Residuals, 2004

The model was calibrated by comparing observed water levels and simulated pressures in the model, and by minimizing the differences between the two; however, these two values cannot be compared directly. Observed water levels represent a composite pressure head over the open interval of a well, whereas SUTRA computes an exact pressure at the nodes of the model mesh, interpolating between the nodes within the model elements, and the pressure varies considerably with depth. Comparison of model calculations with field observations thus requires that the model-calculated pressures at an observation well location in the model domain be converted to an equivalent water level in a hypothetical well within a stack of elements corresponding to the open interval of the observation well. For this study, an observed water level is assumed to represent the entire thickness of the Upper Floridan aquifer, and many of the wells for which construction data are available indicate this assumption is valid. An approximate pressure head is calculated using the simulated pressure value in the middle of a column elements representing the Upper Floridan aquifer at an observation site. Assuming a freshwater density may result in an overestimated pressure head if the simulated concentration is substantially elevated over the assumed open interval. Calculations at a few observation locations, however, where the simulated concentrations were elevated, indicate that the estimated pressure head is only, at most, a few feet higher than if the pressure head were calculated using the resulting density and integrated over the open interval, and that the resulting difference is within the error associated with water-level measurements.

Observed water levels used in the calibration are located in the Upper Floridan aquifer in the study area and were measured, with a few exceptions, in October 2004. Observations used were limited to the study area because outside of the study area, the grid resolution becomes very coarse and, in some areas, particularly north of the study area, the Upper Floridan aquifer is likely less confined (Hockensmith, 2001) and the model is not designed to represent these conditions. Calibration to observed water levels was done to attempt to minimize residuals and spatial bias and achieve a simulated pressure head within 10 ft of an observed water level. Payne and others (2005) established a calibration head target of 9–10 ft for the coastal MODFLOW model based on the standard deviation of altitude accuracy at well sites and seasonal water-level variation. Although the areal extent and range of altitudes for well sites in this model is smaller, the same error criteria were applied because, for wells close to the coast (e.g. well BFT-1810), tidal fluctuations as high as 3 ft may occur. An additional small source of error could be introduced by the variable density of water in areas of highest chloride concentration, as discussed previously.

Water-level residuals are calculated as simulated pressure head minus observed water level; positive residuals indicate that the simulated value is higher than the observed value, and negative residuals indicate the simulated value is lower than observed. The overall match to observed water levels is indicated in table 3 and figure 18. The majority of residuals fall within the ±10-ft error criterion, and the root mean square error (RMSE) is just under 7 ft. Dividing the standard deviation of the residuals for the Upper Floridan aquifer by the range of observed water levels gives a calibration fit of 0.07, which is less than 0.1, indicating a good fit of the data (Kuniansky and others, 2003). The resulting simulated potentiometric surface shows the general features observed in the area, including the cone of depression centered at Savannah and the low gradient at the northern end of Hilton Head Island (fig. 19).

Table 3. Water-level and chloride-concentration calibration statistics.

[ft, foot; mg/L, milligram per liter; RMSE, root mean square error]

Water-level calibration statistics	
Number of observation sites	97
Average water-level residual, ft	1.6
Average absolute value of residual, ft	4.6
Median water-level residual, ft	0.1
Median absolute value of residual, ft	2.8
Maximum residual, ft	23.8
Minimum residual, ft	–17.4
Percent residuals within 10-ft error criterion	88
Standard deviation of residuals	6.8
RMSE	6.9
RMSE/range of observed values	0.07
Chloride concentration calibration statistics	
Number of observations	59
Average residual of log concentration (log mg/L)	–0.6
Average absolute value of residual of log concentration (log mg/L)	0.9
Median residual of log concentration (log mg/L)	–0.3
Median absolute value of residual (log mg/L)	0.6
Maximum residual of log concentration (log mg/L)	2.2
Minimum residual of log concentration (log mg/L)	–3.4
Percent residuals within one order of magnitude	61
Standard deviation of log residuals	1.2
RMSE	1.3

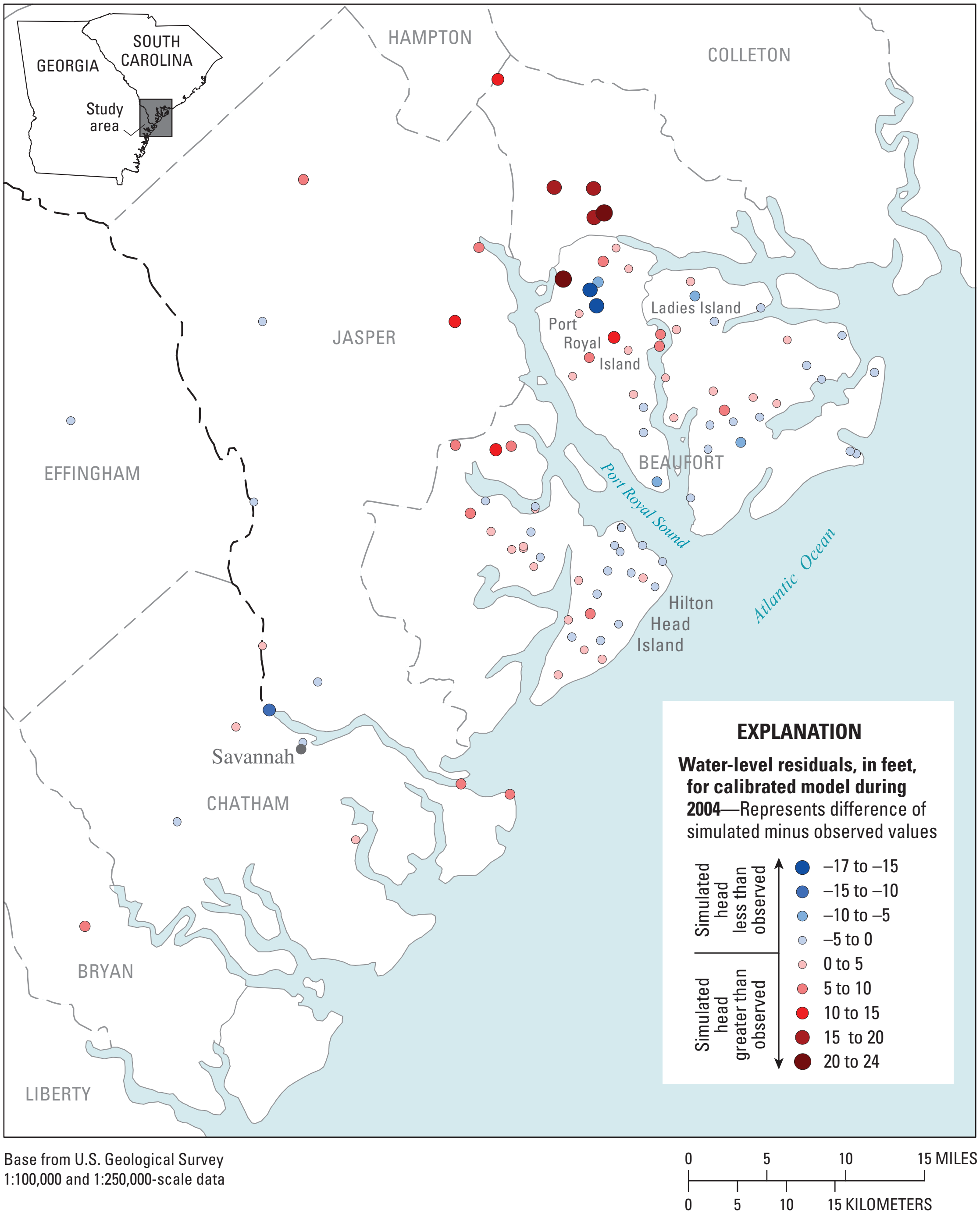


Figure 18. Difference between simulated pressure heads and observed water levels (residuals) for the calibrated model in the study area during 2004. (See Appendix 1 for well locations and data.)

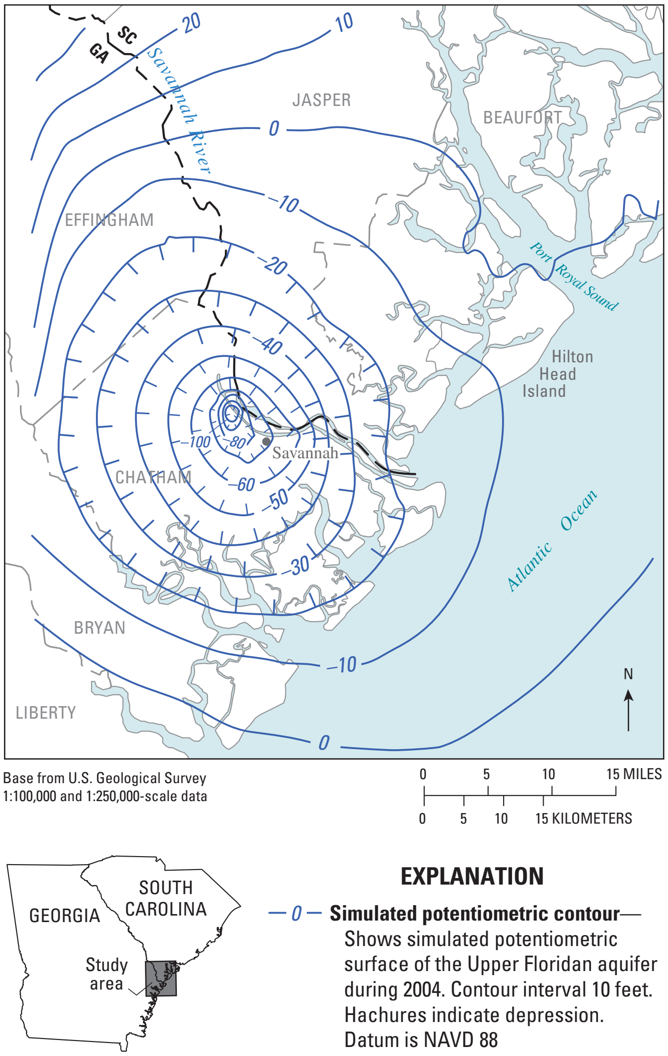


Figure 19. Simulated potentiometric surface of the Upper Floridan aquifer for the calibrated model in the study area during 2004.

Water-level residuals (fig. 18) indicate no obvious spatial bias in the residuals, except that the northernmost residuals tend to be positive. At the northern part and north of Port Royal Island and Ladies Island, the magnitudes of the residuals are high. In one area, there is a potentiometric mound (Provost and others, 2006), and water levels vary over a range of almost 40 ft (fig. 20). To achieve a closer calibration in this area would require more refined permeability zones, and possibly an increased mesh density. Rather than refine the model to try to capture this local variability, efforts were focused on matching water levels in wells in the areas closer to the area of saltwater intrusion at and near Hilton Head Island.

Simulated Chloride Distribution, 2004

The model was calibrated to estimate chloride distribution using specific conductance data for 2004 in the Upper Floridan aquifer in the Hilton Head Island area, primarily in southern Beaufort County. Salinity data for other areas of the model were not used because the model is designed to simulate saltwater intrusion by a specific mechanism in the study area, and not elevated salinities in other aquifers, or other areas. For the assumed conceptual model, the calibration was targeted at capturing the general pattern of chloride concentration in the Upper Floridan aquifer inferred from the specific conductance logs. The estimated maximum chloride concentration during 2004 from specific conductance logs (table 1–3, Appendix 1; Childress and Ransom, 2005) was compared to the simulated chloride concentration at the middle node layer of the hydrologic unit representing the Upper Floridan aquifer. Generally, in areas of elevated chloride concentration, the simulated chloride concentration was highest near the middle of the Upper Floridan aquifer (fig. 21). For this reason, the spatial distribution of chloride concentration in figure 18 was compared to values simulated at the middle node. The extent of the simulated area was too large, and the vertical discretization was of insufficient resolution to provide a closer match to the observed vertical salinity distribution.

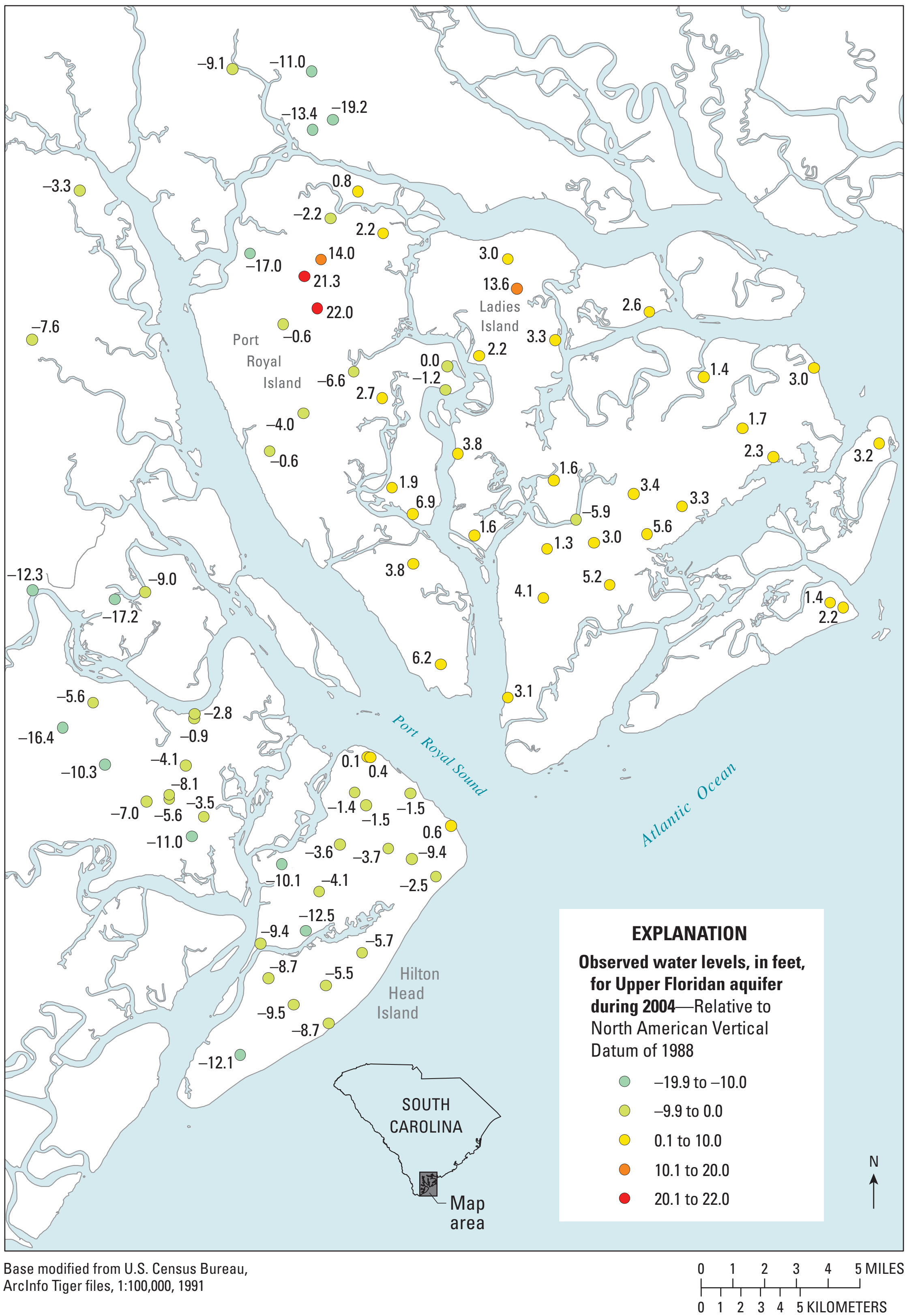


Figure 20. Observed water levels in the Upper Floridan aquifer in the Hilton Head Island area, South Carolina, during October 2004.

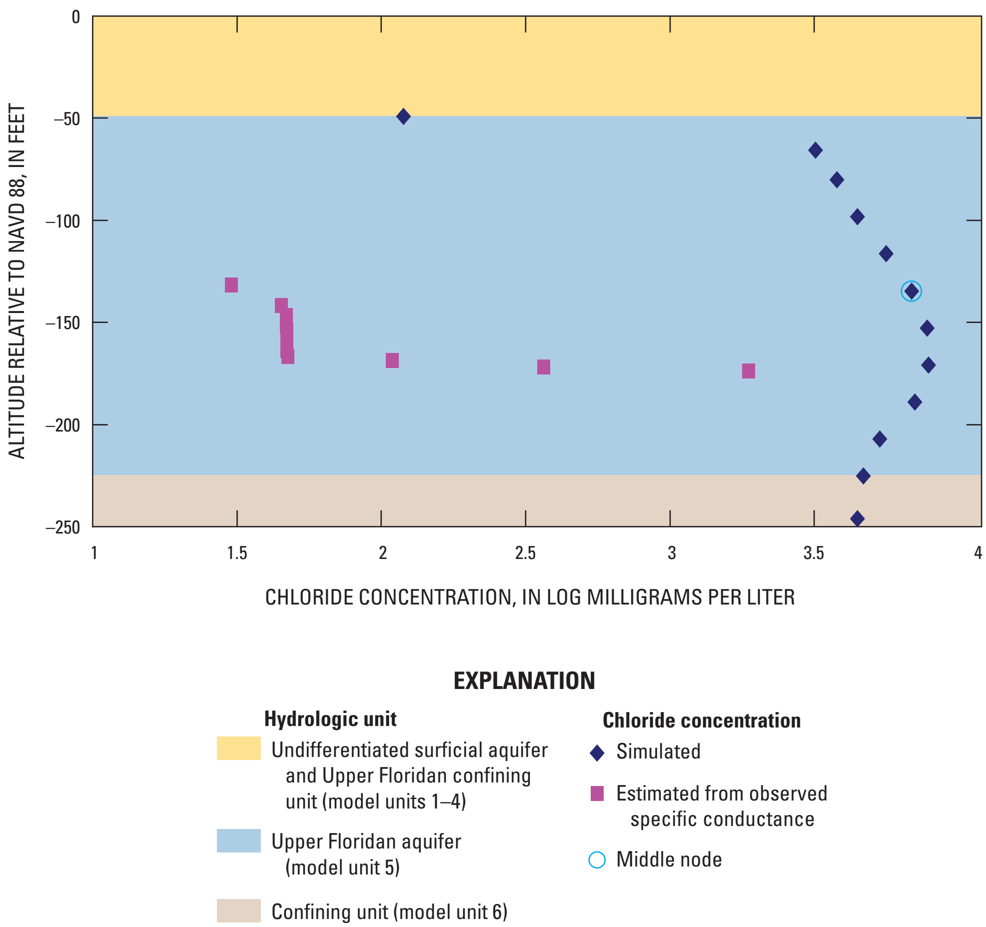


Figure 21. Vertical profile of simulated chloride concentration and chloride concentration estimated from observed specific conductance at well BFT-0315. (See Appendix 1, figure 1–2 for location.)

The model simulates saltwater plumes in the Upper Floridan aquifer emanating from four postulated source areas (based on seismic and specific conductance data). One source area is at the northern end of Hilton Head Island, one is near the mouth of the Colleton River, and two are at Pinckney Island (fig. 22). For the plumes at the four postulated source areas, saltwater enters through designated areas—permeability zones in the Upper Floridan confining unit intentionally set with higher permeability values than surrounding zones. The plume at the northern end of Pinckney Island and under Port Royal Sound develops outside of the designated source area. In this particular area, the confining unit is thin, and the bathymetry indicates a small trough-like feature resulting in a higher specified pressure relative to surrounding areas (Appendix 2, fig. 2–1). Generally, the simulated plumes capture areas of high salinity on the northern end of Hilton

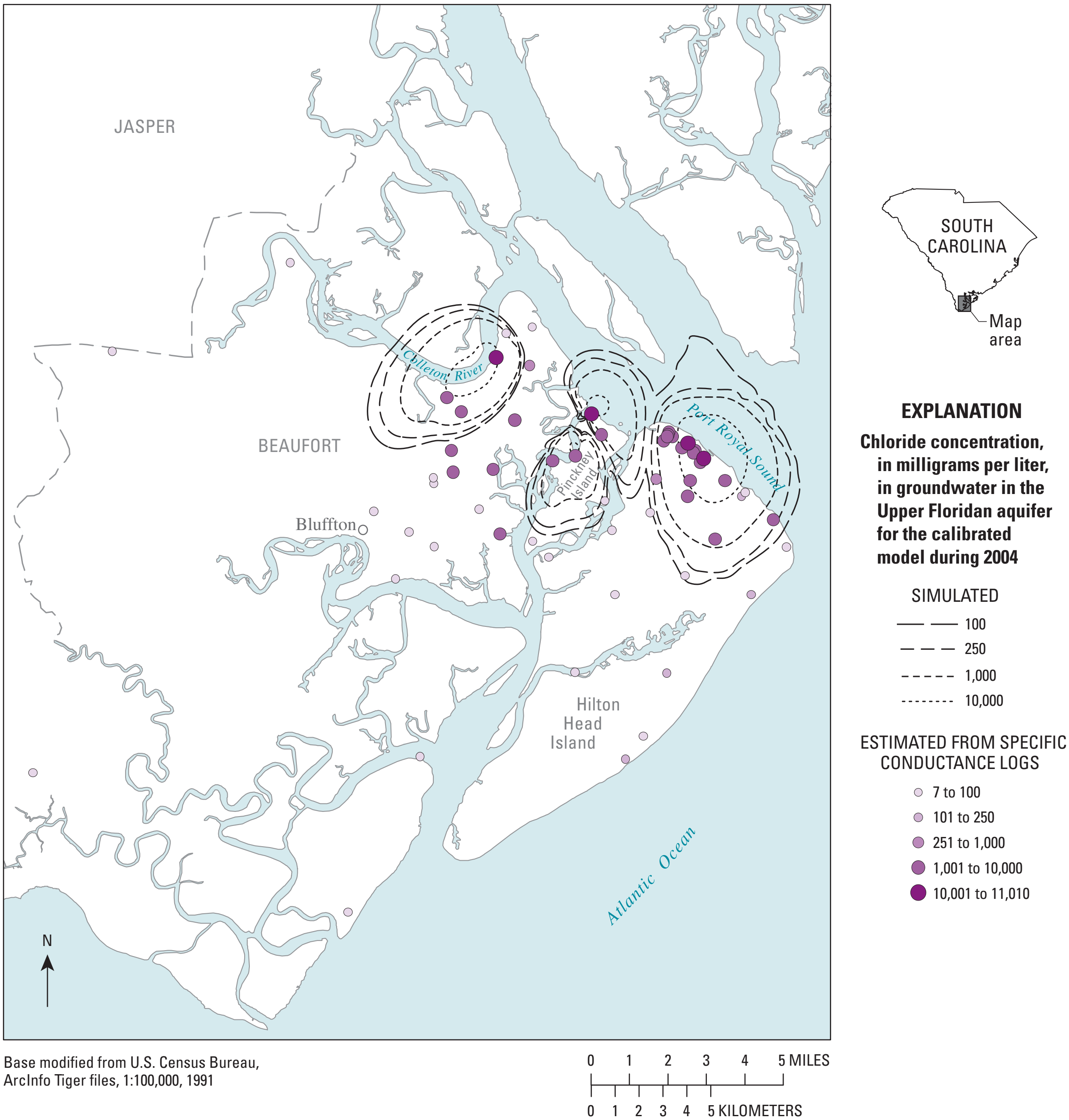


Figure 22. Simulated and observed chloride concentration in groundwater in the Upper Floridan aquifer for the calibrated model in the Hilton Head Island area, South Carolina, during 2004. (See Appendix 1, table 1–3 and figure 1–2, for well-site information.)

Head Island, at Pinckney Island, and near the Colleton River. The highest simulated concentrations coincide with the highest observed values at these locations. Observed elevated salinity between Calibogue Sound and the Colleton River northeast of Bluffton (fig. 23) are not matched by the simulation. In areas that were difficult to match, the conceptual model or model configuration may have been unable to explain the observed salinity distribution, and no attempts were made to force the model to fit by adjusting the physical properties or boundary conditions to unreasonable values or configurations.

In the plume areas, the simulated and observed chloride concentrations at many sites are within an order of magnitude (fig. 23). The most notable exception is the area northeast of Bluffton, where the simulated values are several orders of magnitude lower than observed. At the northern end of Hilton Head Island, the residuals are mostly positive, and simulated

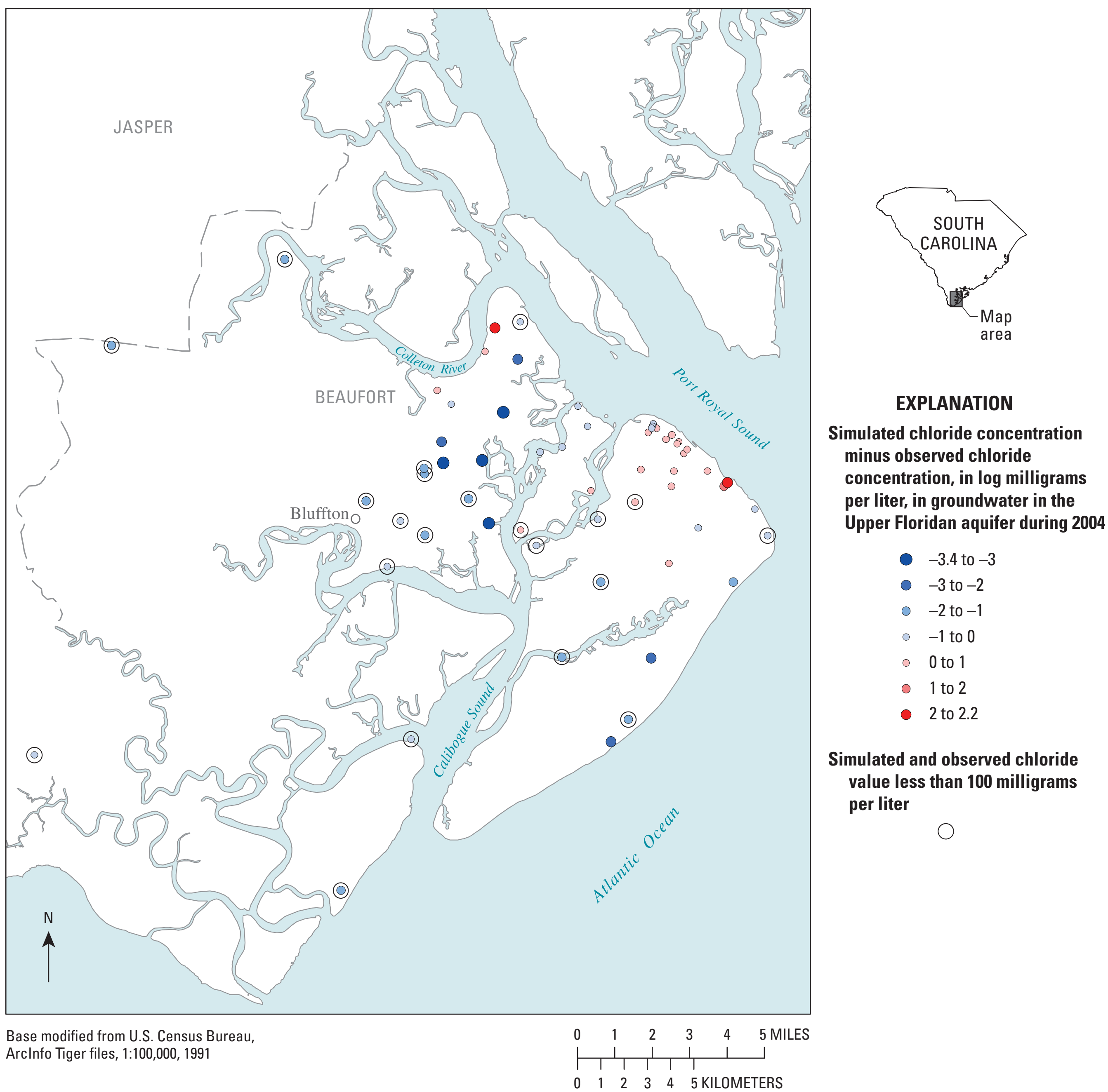


Figure 23. Concentration residuals (simulated minus observed chloride concentration, in log milligrams per liter) in groundwater in the Upper Floridan aquifer for the calibrated model in the Hilton Head Island area, South Carolina, during 2004.

values, though small, are greater than observed. In order to allow enough saltwater into the system to match chloride concentrations away from the source area, permeability was increased in the source area, resulting in more positive residuals. Some of the negative residuals south and west of the plume areas are of apparently large magnitude, but the observed and simulated values are less than 100 mg/L and do not indicate a poor model match (Appendix 1, table 1–3). For lower specific conductance values, the model matches observations more poorly than at higher values for log-transformed values (fig. 24). Overall match statistics are listed in table 3.

Changes in Groundwater Levels and Chloride Concentrations at the Northern End of Hilton Head Island, 1960–2004

Few data exist to constrain the rate of saltwater movement in the Hilton Head Island area. The history of saltwater intrusion at the northern end of Hilton Head Island is known primarily through chloride and specific conductance monitoring at two observation sites. Chloride concentrations were monitored at well BFT-0315 (Appendix 1, fig. 1–2) from the early 1960s through the early 1980s, and show a marked increase starting in the late 1970s (fig. 25). The model results show similar values and a similar rate of increase just after 1975. Before the mid-1970s, the simulated chloride concentration values diverge from the observed values. Monitoring data indicate that the background chloride concentration is just under 100 mg/L, but the model assumes a freshwater background concentration of 0 mg/L. Specific conductance was monitored at well BFT-1810 (Appendix 1, fig. 1–2) since about 1990, and the data indicate elevated (greater than 1,000 mg/L) and increasing chloride concentrations (fig. 26). Simulated chloride concentrations match these values well although the salinity was already elevated by 1990, so the data are not sufficient to constrain timing of saltwater intrusion or rates of saltwater movement.

Water levels also were monitored at wells BFT-0315 and BFT-1810 (figs. 27 and 28). Simulated pressure-head values at BFT-0315 are below or at the bottom of the range of observed water levels from the mid-1960s to the mid-1980s. Simulated pressure-head values at BFT-1810 are within, or close to the middle of, the range of observed water levels from the late 1980s through 2004. The two sites are proximal to each other, so that adjusting the model to better match results at one site would result in a poorer match at the other site. Mesh and permeability distribution refinement in the local area would likely be required to match simulated to observed water levels better at both sites.

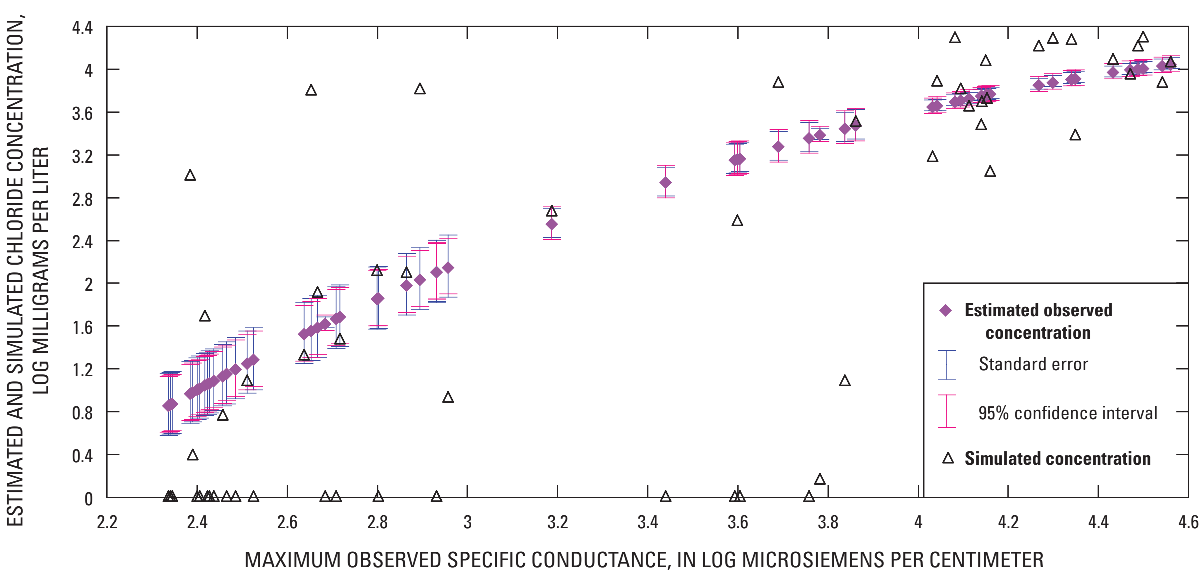


Figure 24. Simulated and estimated observed chloride concentration at each observation well and observed specific conductance.

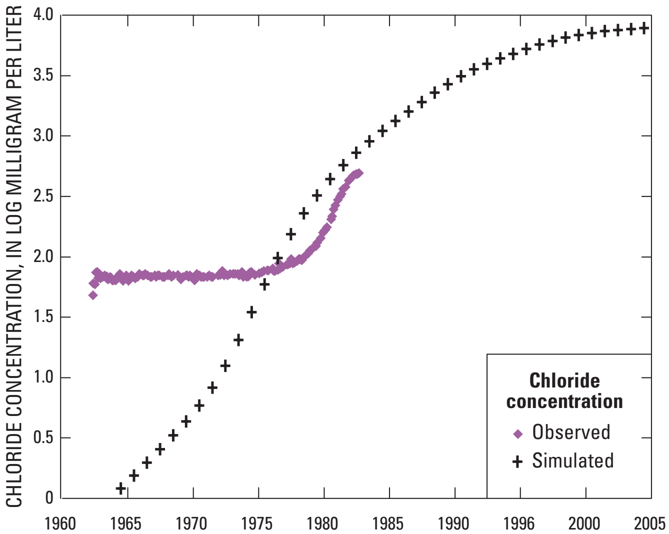


Figure 25. Observed and simulated chloride concentration at well BFT-0315 from 1960 to 2005. (See Appendix 1, figure 1–2 for location.)

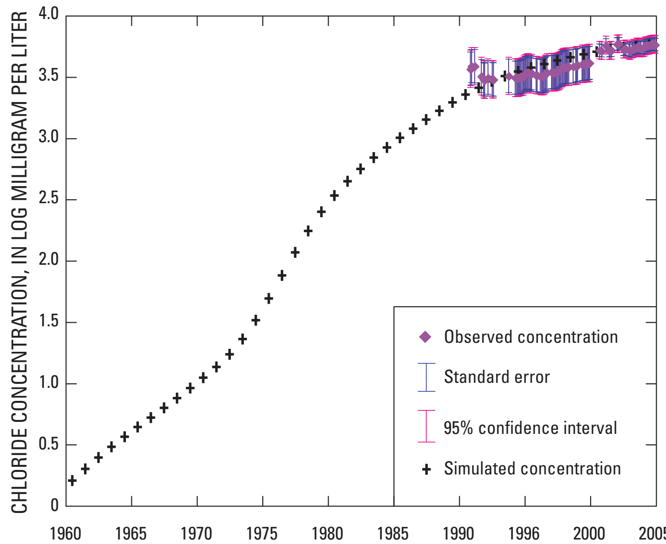


Figure 26. Estimated chloride concentration from observed specific conductance and simulated chloride concentration at well BFT-1810 from 1960 to 2005. (See Appendix 1, figure 1–2 for location.)

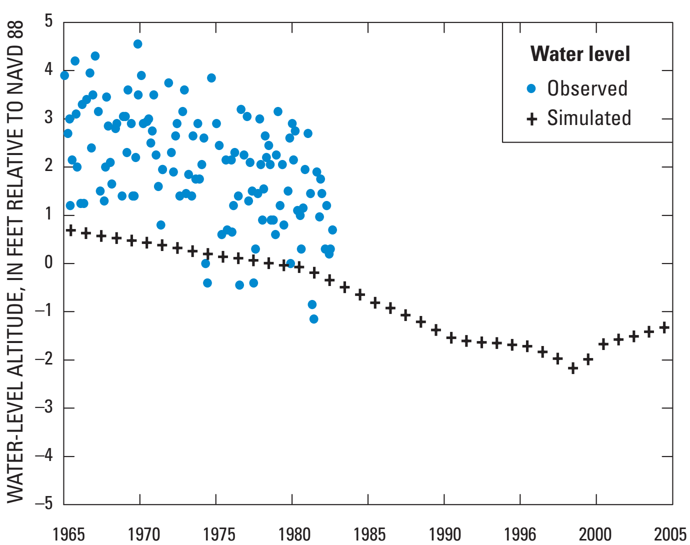


Figure 27. Observed and simulated water levels at well BFT-0315 from 1965 to 2005. (See Appendix 1, figure 1–2 for location.)

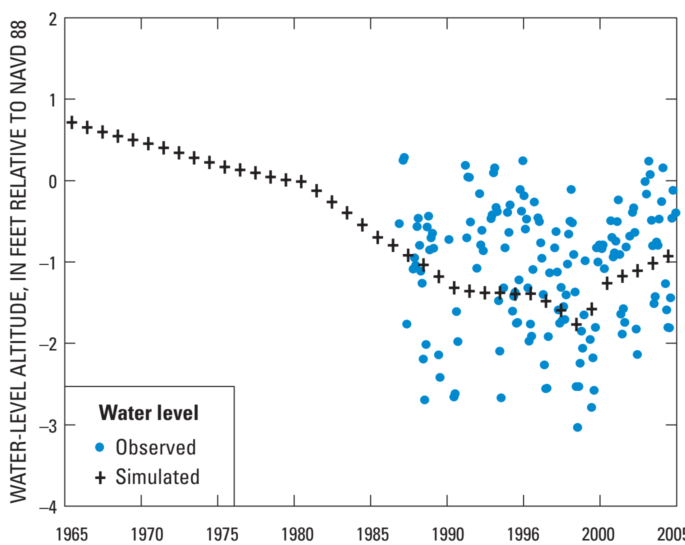


Figure 28. Observed and simulated water levels at well BFT-1810 from 1965 to 2005. (See Appendix 1, figure 1–2 for location.)

Comparison of Results to Original Model Results

One of the most substantial changes from the original model was the rediscretization of the top node altitude in order to make the top boundary condition self-consistent in the low altitude and offshore areas near the plumes. In the original model, a substantial amount of saltwater enters the Upper Floridan aquifer, even under no-stress conditions. By refining the top node altitude with refined land-surface altitude and bathymetry data, saltwater leakage through the confining unit and into the Upper Floridan aquifer beneath Port Royal Sound was limited such that, under predevelopment conditions, extensive saltwater plumes do not develop in the Upper Floridan aquifer. This is a more acceptable initial condition than that used in the original model because, although no data exist, it is not expected that saltwater intrusion would occur under predevelopment conditions when higher heads are expected to prevent downward leakage of saltwater.

Another change in model boundary conditions from the original model was the implementation of a specified pressure boundary at the offshore lateral boundary. This boundary is intended to represent the edge of the continental shelf and can be conceptualized as an escarpment that exposes the Floridan aquifer system directly to seawater. In the original model, this boundary was implemented as no-flow, so that saltwater enters only as downward leakage from the top model nodes. Although testing during model development indicated that the nature of this boundary does not affect simulated heads or chloride concentration perceptibly in the study area, implementation of a specified pressure boundary allows for the development of a saltwater wedge emanating from this boundary, which is a classic feature of seawater intrusion theory.

Other changes in model boundaries and hydraulic property distribution in the plume area resulted in changes in model fit. The original model showed a spatial bias in simulated head residuals in the plume area, where simulated values of head were almost all too low. Modifications for this model resulted in elimination of most of the spatial bias (except in the northern part of Beaufort County, where local hydrologic features are not specifically accounted for), without compromising the overall fit. The simulated chloride concentration for this model fits better at Hilton Head Island and the southern end of Pinckney Island, but fits more poorly in the marshy area between Pinckney Island and the Colleton River. Overall fit is thus improved by these model modifications.

Model Sensitivity

Sensitivity of the model results to selected boundary conditions and physical properties was evaluated using perturbations of the calibrated model. For each model run, input was modified, and initial conditions were generated using a 5,000-year predevelopment simulation. Then the model was run from 1885–2004, and results were compared with the results of the calibrated model during 2004. Sensitivity testing of the original model included perturbation of permeability values, effective porosity, dispersion, source-water concentration, spatial and temporal discretization, nonlinearity iterations, and matrix-solver-convergence tolerances, and indicated that the model was most sensitive to effective porosity. For this model, sensitivity testing included perturbation of specified pressure at the top boundary, permeability values and distribution, effective porosity, and dispersion.

Top Boundary Condition—Water-Table Configuration

The specified pressure at the top boundary for onshore areas is set as a function of the water-table altitude. The pressure at the water table is always zero, so the specified pressure at the top boundary will vary depending upon the depth to the water table. Because the top boundary is above the water table, the specified pressure will be negative. The higher the water-table altitude is, the larger, or less negative, the specified pressure; the lower the water-table altitude is, the smaller, or more negative the specified pressure. Two alternative water-table-altitude functions were used to test the sensitivity of the model to onshore specified pressure. To simulate a high specified pressure at the top boundary, water-table altitude was set to land-surface altitude. To simulate a low specified pressure, a more complex water-table function was used (method 2, Appendix 3) that accounts for water-table values nearest the coast that are below the linear trend estimated for the water table at higher altitudes. These depressed water-table altitudes near the coast may occur as a result of local conditions, such as pumpage or man-made drainage features.

Setting the water table to land-surface altitude resulted in slightly higher simulated pressure heads and a slightly smaller extent of the chloride plumes than in the calibrated model (fig. 29). By increasing the water-table altitude, more freshwater recharge to the Upper Floridan aquifer is simulated, resulting in higher heads that reduce the amount of saltwater that can enter the system and dilution of the saltwater plumes. The difference in simulated plume extent is greater near Pinckney Island and the Colleton River than at the northern end of Hilton Head Island. At Pinckney Island, the confining unit is thin, and south and east of the Colleton River, land-surface altitude is relatively high compared to the rest of the plume area. At the northern end of Hilton Head Island, the land-surface altitude is also relatively high with respect to the rest of the plume area, but the thickness of the confining unit there is more effective in preventing recharge to the Upper Floridan aquifer.

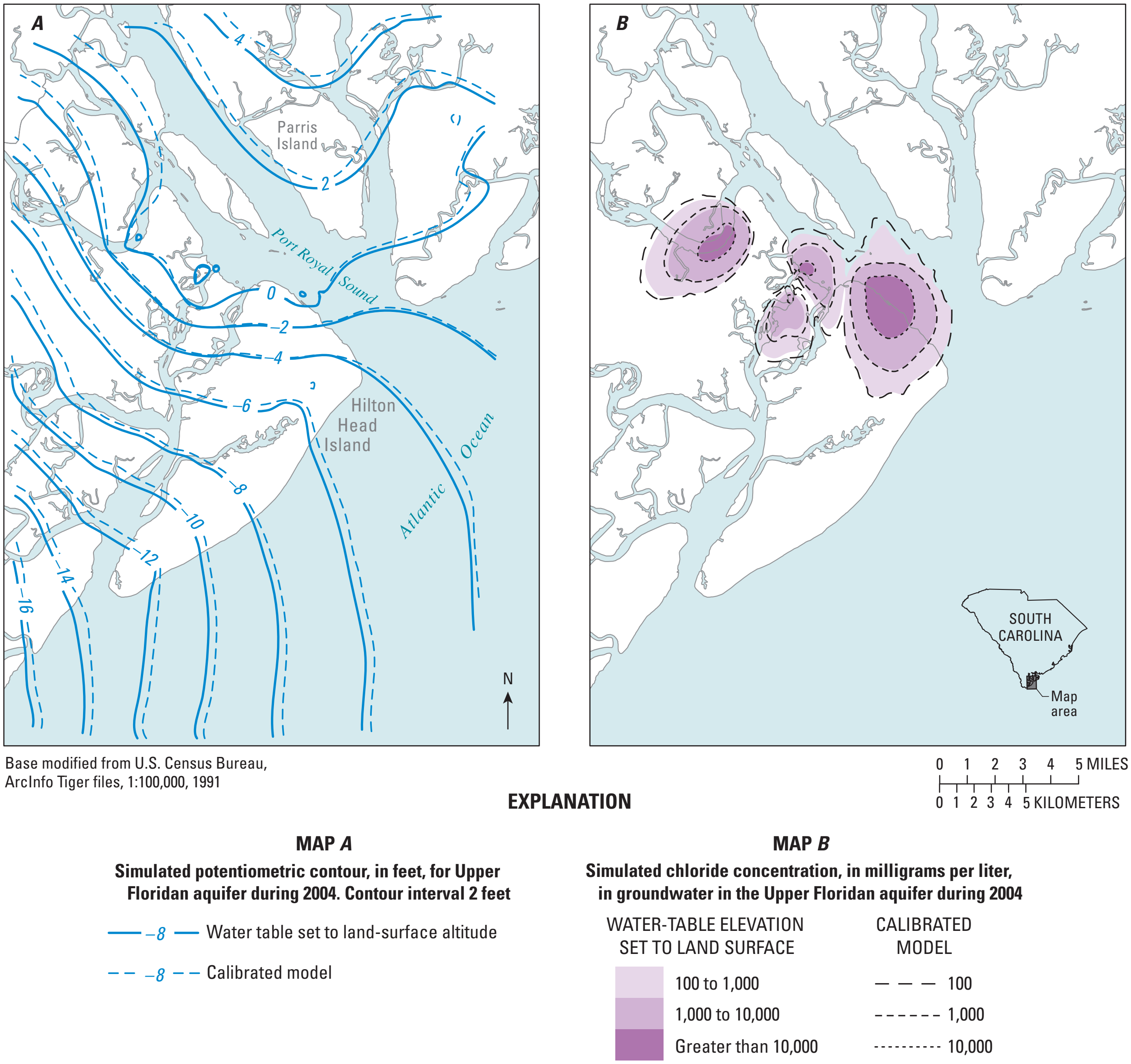
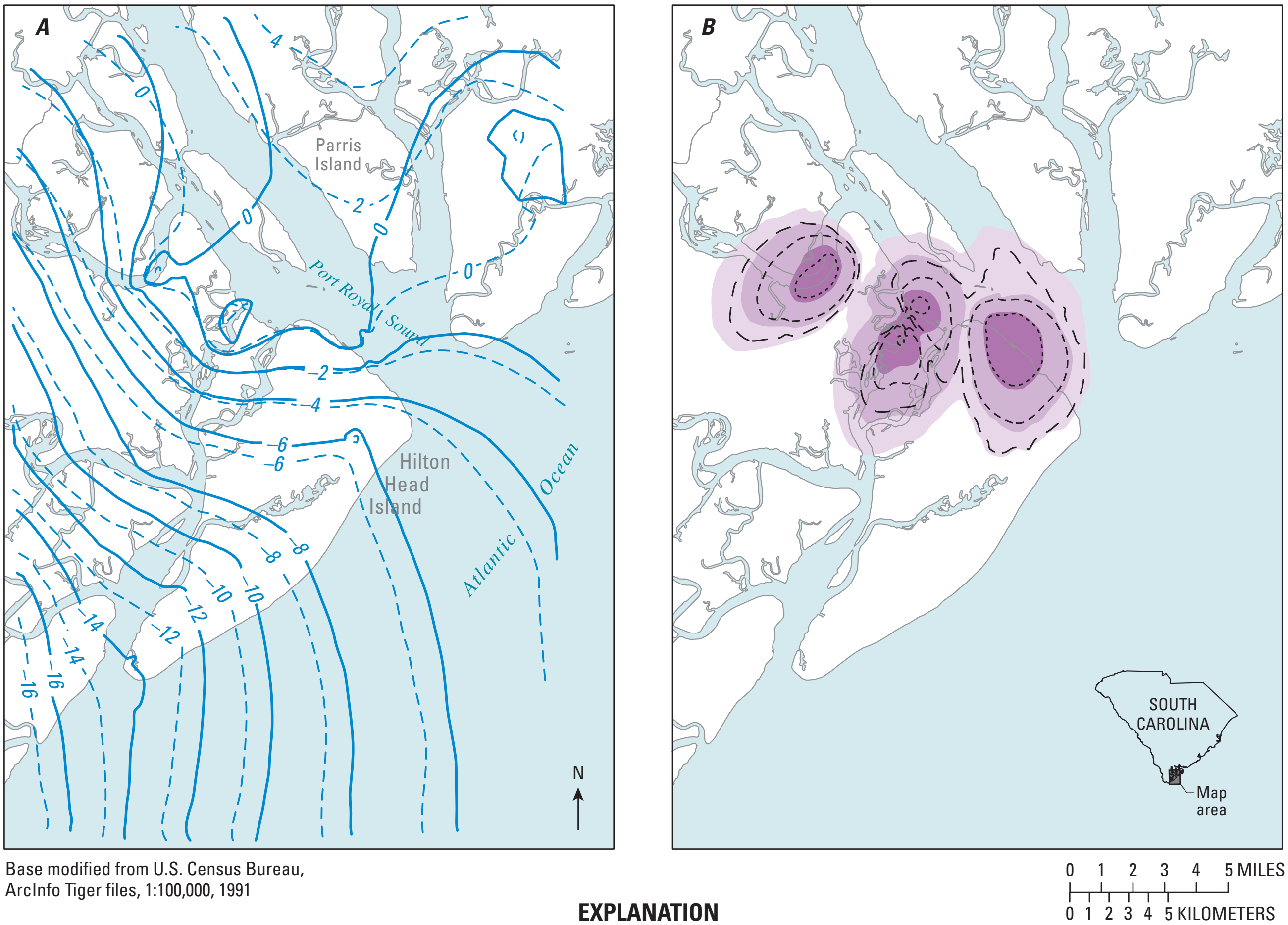


Figure 29. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model and for water table set to land-surface altitude in the Hilton Head Island area, South Carolina, during 2004.

Setting the water-table altitude lower at low land-surface altitudes (method 2 in Appendix 3) resulted in lower simulated pressure heads and a greater extent of the chloride plumes, particularly south of Pinckney Island, southwest of the Colleton River, and under Port Royal Sound, than in the calibrated model (fig. 30). Lowering the water-table altitude reduces the freshwater recharge, resulting in lower pressures that allow more saltwater to enter the system and reducing dilution of saltwater in the Upper Floridan aquifer. The simulated plume extent at the northern end of Hilton Head Island is relatively unaffected by the water-table configuration. In general, though, reducing the freshwater head has a greater apparent effect on model results than increasing it.



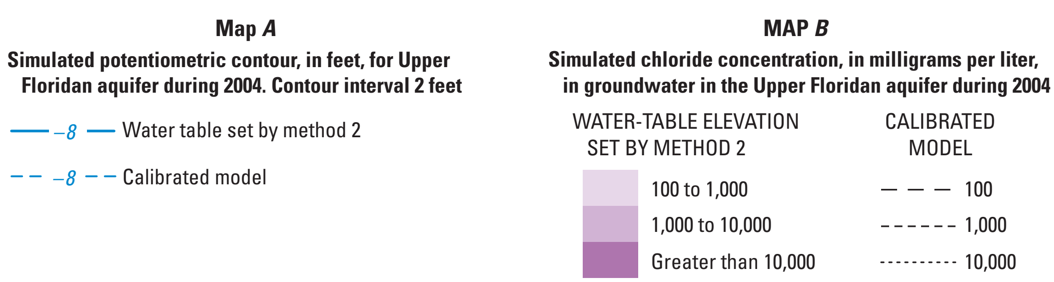


Figure 30. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model and for water table set by method 2 (Appendix 3) in the Hilton Head Island area, South Carolina, during 2004.

Overlying Confining-Unit Permeability

The sensitivity of the model to permeability of the overlying confining unit was tested separately in the saltwater-source areas and in freshwater-recharge areas closest to the coast. In the first case, the test effectively allows more or less saltwater to enter the system. In the second case, the test effectively allows more or less freshwater recharge to the system in the areas affected by saltwater contamination.

Saltwater-Source Areas

In the saltwater-source areas, permeability values were first increased by an order of magnitude. This increase resulted in higher simulated pressure heads, by 1–2 ft in some areas, and an increased extent of most of the chloride plumes (fig. 31). The exception is the plume that developed north of Pinckney Island in Port Royal Sound because saltwater enters the Upper Floridan aquifer there from outside of the designated source areas. As more saltwater is allowed to enter at the designated source areas, less saltwater is drawn in outside of those designated areas, for example, in the area just north of Pinckney Island, resulting in a smaller plume there.

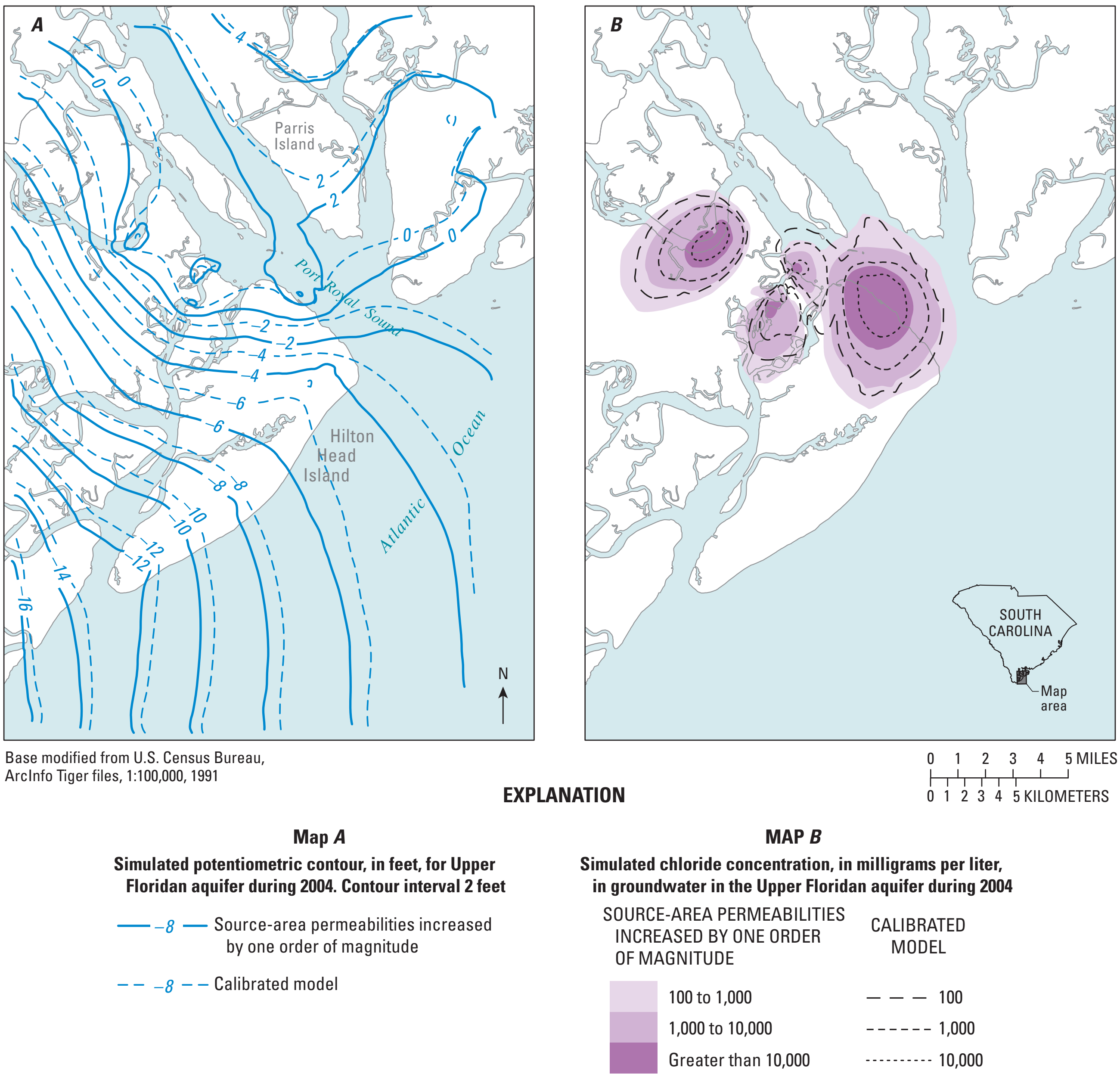
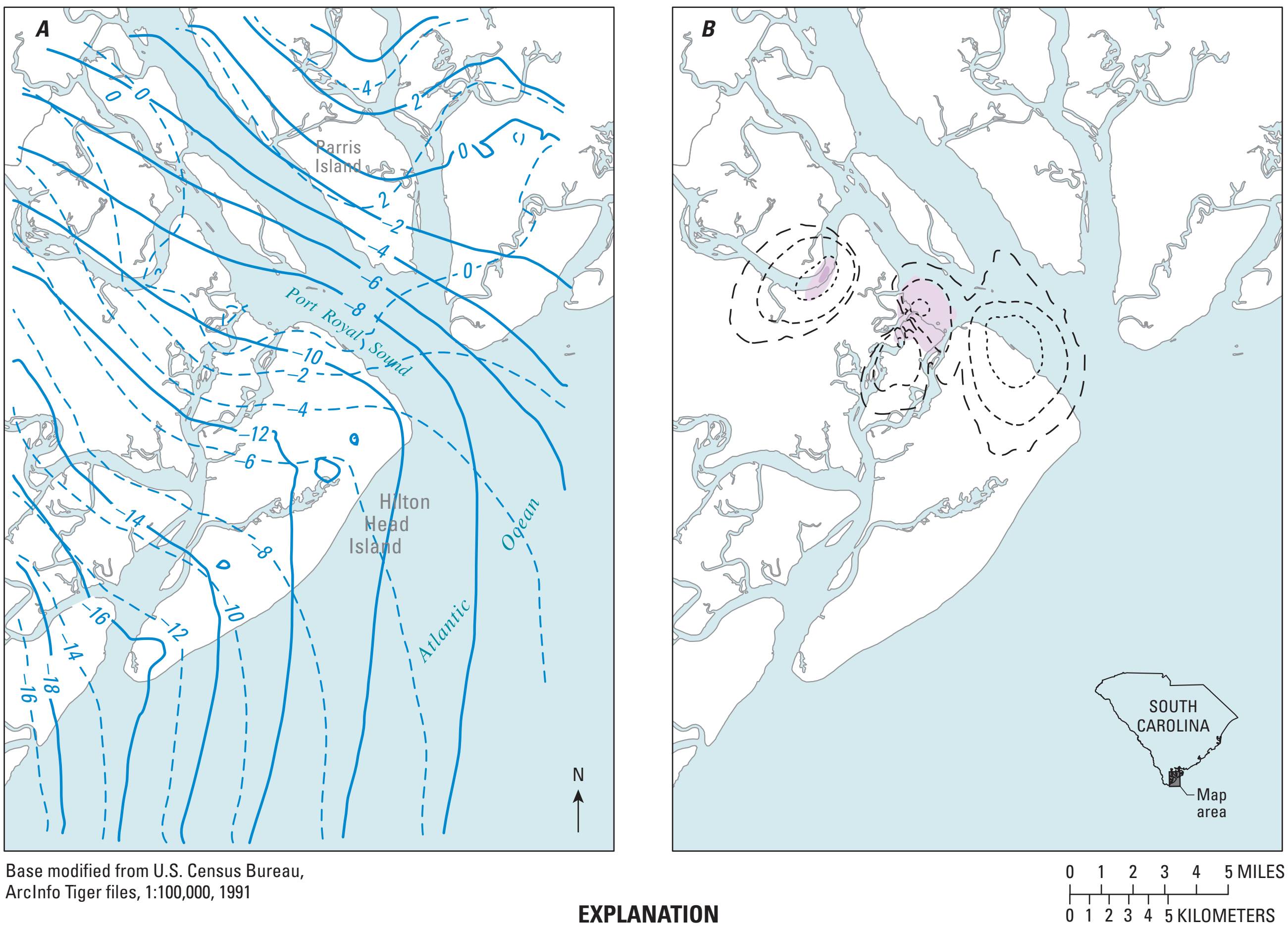


Figure 31. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model and for source-area permeabilities increased by one order of magnitude in the Hilton Head Island area, South Carolina, during 2004.

Permeability values in the designated source areas were reduced by setting them to the values of the adjacent permeability zones, which are at least an order of magnitude lower. For example, permeability in zones C89 and C91 were changed to match the values in zone C18 (fig. 14). This reduction effectively removes the high permeability zones designated as source areas. Results show substantially reduced heads, by up to 10 ft from northern Hilton Head Island, across northern Pinckney Island, to the Colleton River (fig. 32*A*). Small plumes develop at the Colleton River and northern end of Pinckney Island (fig. 32*B*) because the confining unit is thin and specified pressure at the top saltwater boundary is high enough to allow saltwater to enter the Upper Floridan aquifer at those locations, even without imposing zones of relatively increased permeability. Plumes do not develop at the northern end of Hilton Head Island or southern Pinckney Island when designated source areas of increased permeability are removed. These results indicate that for this model configuration and scale, the increase in permeability in the source areas is required in order to allow enough saltwater into the system to simulate observed conditions.



Base modified from U.S. Census Bureau, ArcInfo Tiger files, 1:100,000, 1991

EXPLANATION

Map *A*

Simulated potentiometric contour, in feet, for Upper Floridan aquifer during 2004. Contour interval 2 feet

—–8— Source-area permeabilities set to surrounding lower permeability values

– – –8 – – Calibrated model

MAP *B*

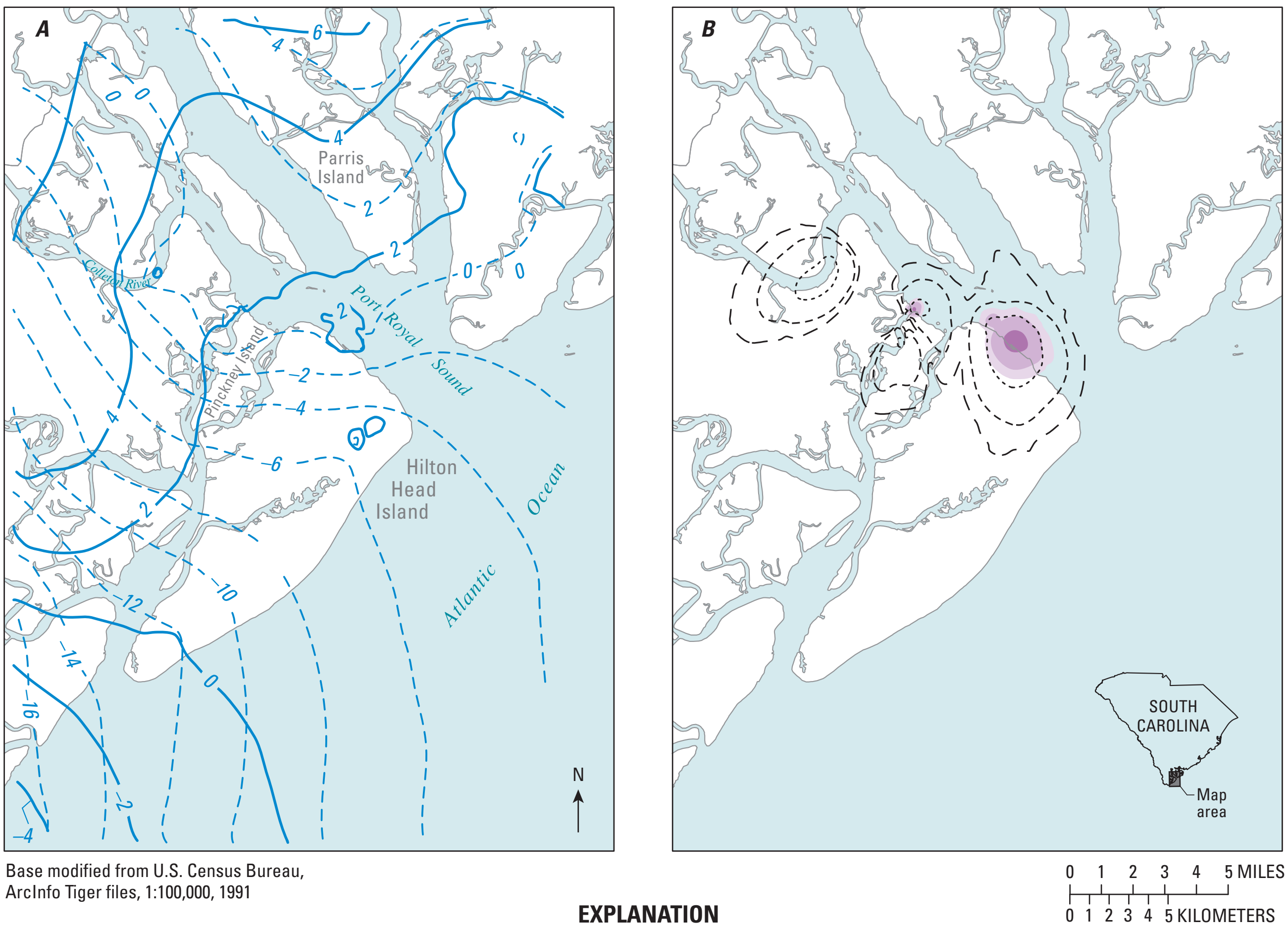
Simulated chloride concentration, in milligrams per liter, in groundwater in the Upper Floridan aquifer during 2004

SOURCE-AREA PERMEABILITIES SET TO SURROUNDING LOWER PERMEABILITY VALUES	CALIBRATED MODEL
100 to 1,000	— — — 100
1,000 to 10,000	- - - - - - 1,000
	---------- 10,000

Figure 32. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model and for source-area permeabilities set to surrounding lower permeability values in the Hilton Head Island area, South Carolina, during 2004.

Freshwater-Recharge Areas

In the areas where the top boundary conditions were set to approximate the water table, model sensitivity to permeability of the confining unit in the study area was tested by increasing and decreasing by one order of magnitude the permeability of the confining unit. Increasing the permeability of the confining unit resulted in substantially higher simulated heads from about 2 ft higher at the northern end of Hilton Head Island to about 12 ft higher at the southern end of Hilton Head Island (fig. 33*A*), and much smaller gradients across Hilton Head Island. The resulting simulated plumes are much smaller in extent, and the plumes at the Colleton River and southern Pinckney Island do not develop (fig. 33*B*). Increasing the confining-unit permeability reduced the vertical gradient between the specified pressure and the simulated pressure in the Upper Floridan aquifer, resulting in a higher pressure head that reduced saltwater transport into the aquifer and diluted saltwater that may have entered the Upper Floridan aquifer.



EXPLANATION

Map *A*

Simulated potentiometric contour, in feet, for Upper Floridan aquifer during 2004. Contour interval 2 feet

— 2 — Confining-unit permeabilities increased by one order of magnitude

– – –8 – – Calibrated model

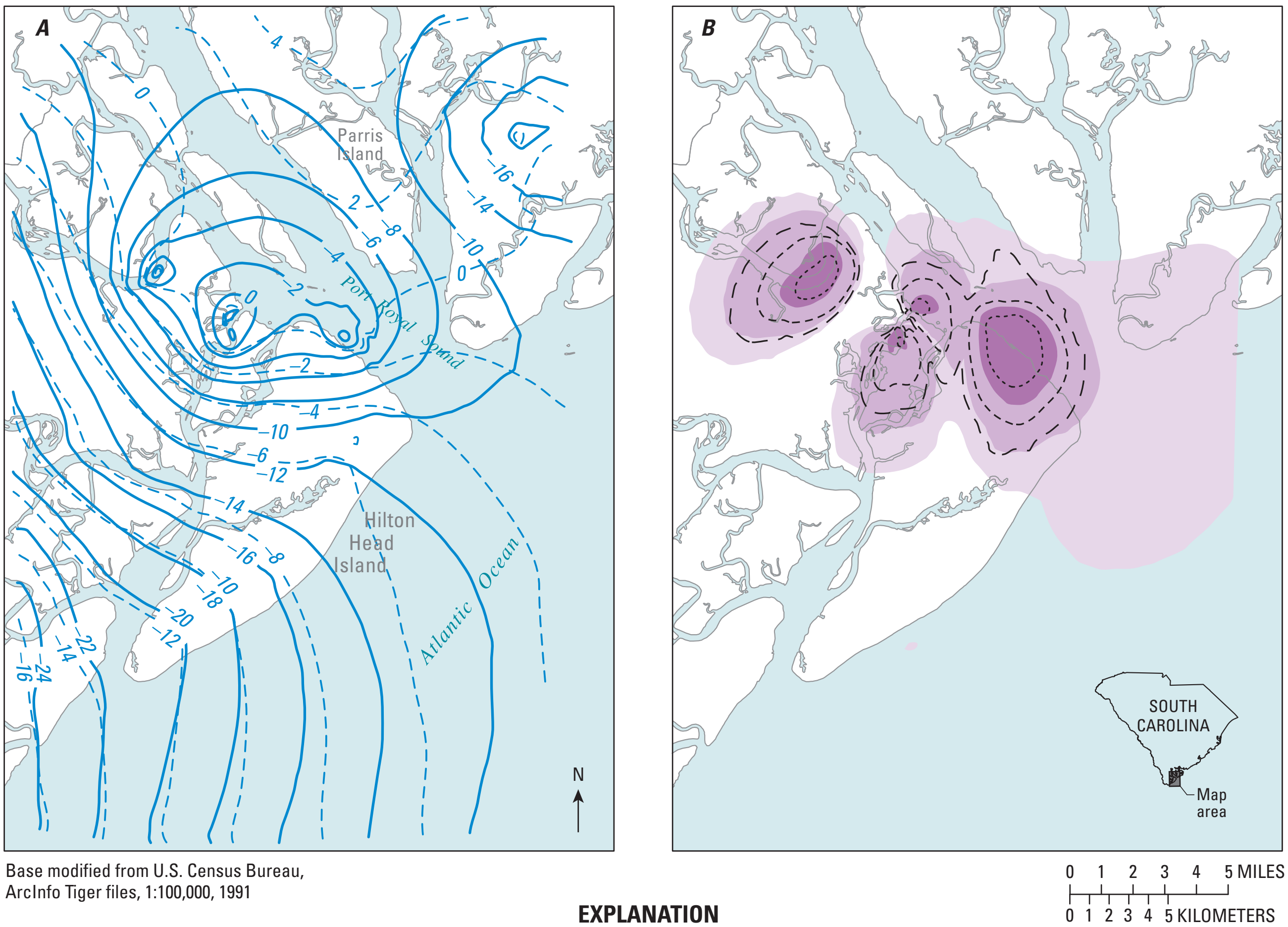
MAP *B*

Simulated chloride concentration, in milligrams per liter, in groundwater in the Upper Floridan aquifer during 2004

CONFINING-UNIT PERMEABILITIES INCREASED BY ONE ORDER OF MAGNITUDE	CALIBRATED MODEL
100 to 1,000	— — — 100
1,000 to 10,000	------ 1,000
Greater than 10,000	--------- 10,000

Figure 33. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model and for confining-unit permeabilities (except for source-area permeabilities) increased by one order of magnitude in the Hilton Head Island area, South Carolina, during 2004.

Reducing the permeability of the confining unit increased the vertical gradient between the specified pressure and the simulated pressure in the Upper Floridan aquifer and resulted in substantially lower heads in the study area (fig. 34*A*), from about 2 ft lower at the northern end of Hilton Head Island to about 8 ft lower at the southern end of Hilton Head Island. The lower simulated pressure head results in a greater extent of the simulated plume (fig. 34*B*), particularly offshore of Hilton Head Island. These results indicate the model is rather sensitive to the permeability assigned to the confining unit.



EXPLANATION

Map *A*

Simulated potentiometric contour, in feet, for Upper Floridan aquifer during 2004. Contour interval 2 feet

—–8— Confining-unit permeabilities reduced by one order of magnitude

– – –8 – – Calibrated model

MAP *B*

Simulated chloride concentration, in milligrams per liter, in groundwater in the Upper Floridan aquifer during 2004

CONFINING-UNIT PERMEABILITIES REDUCED BY ONE ORDER OF MAGNITUDE	CALIBRATED MODEL
100 to 1,000	100
1,000 to 10,000	1,000
Greater than 10,000	10,000

Figure 34. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model and for confining-unit permeabilities (except for source-area permeabilities) reduced by one order of magnitude in the Hilton Head Island area, South Carolina, during 2004.

Upper Floridan Aquifer Permeability

Model sensitivity to the Upper Floridan aquifer permeability was tested by increasing and decreasing values in the study area by one half order of magnitude (or, by a factor of 5). Increasing the Upper Floridan aquifer permeability resulted in notably higher simulated heads in the Hilton Head Island area, relative to the calibrated model, from about 2 ft higher at the northern end of Hilton Head Island and Pinckney Island, to about 10 ft higher at the southern end of Hilton Head Island (fig. 35*A*). The extent of the resulting simulated plumes are slightly enlarged relative to the calibrated model, with the exception of the area to the west of Pinckney Island, which is notably larger (fig. 35*B*). Increasing the Upper Floridan permeability results in higher simulated pressures in the Pinckney Island and Colleton River source areas, driving more saltwater into the aquifer.

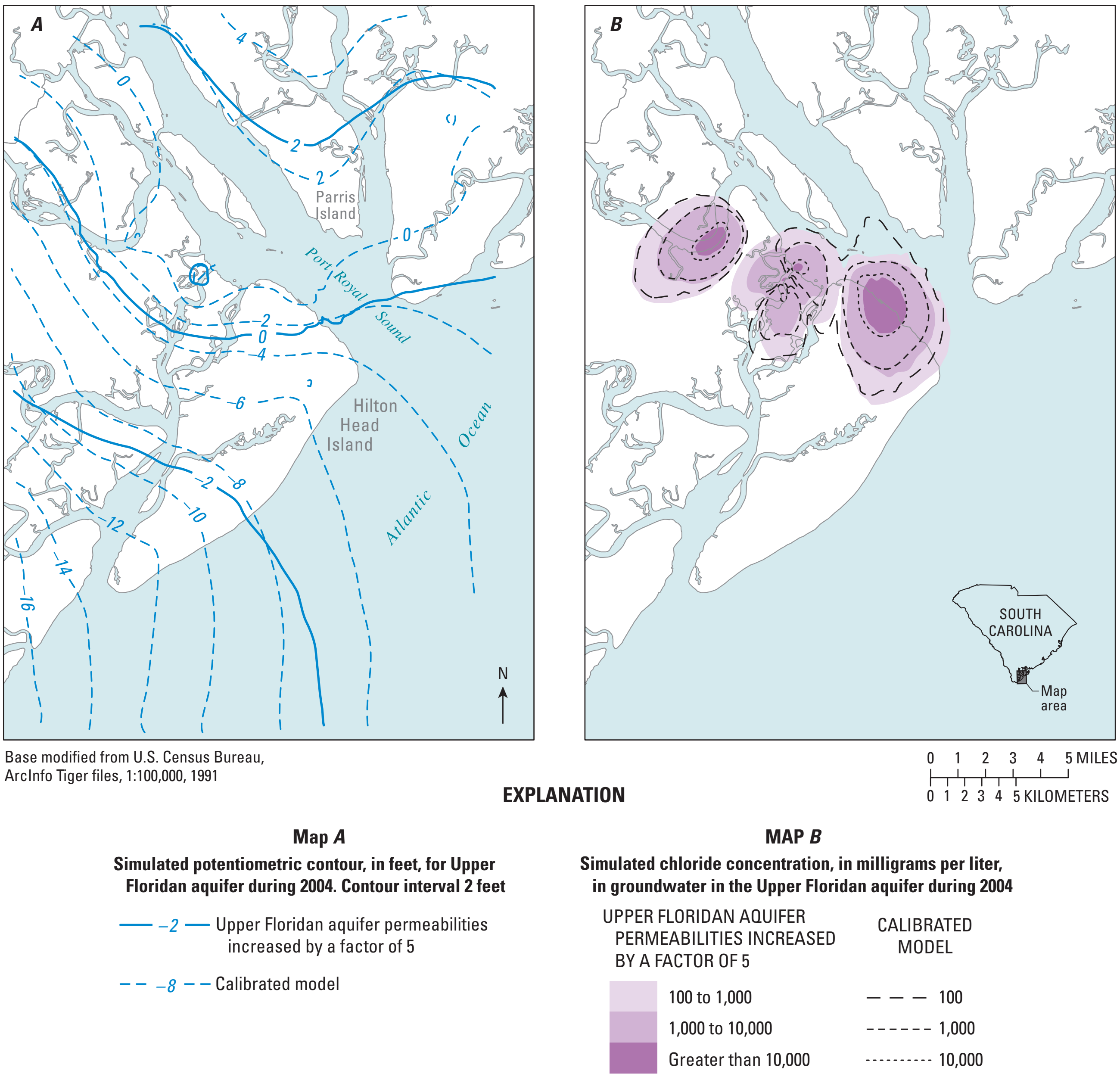
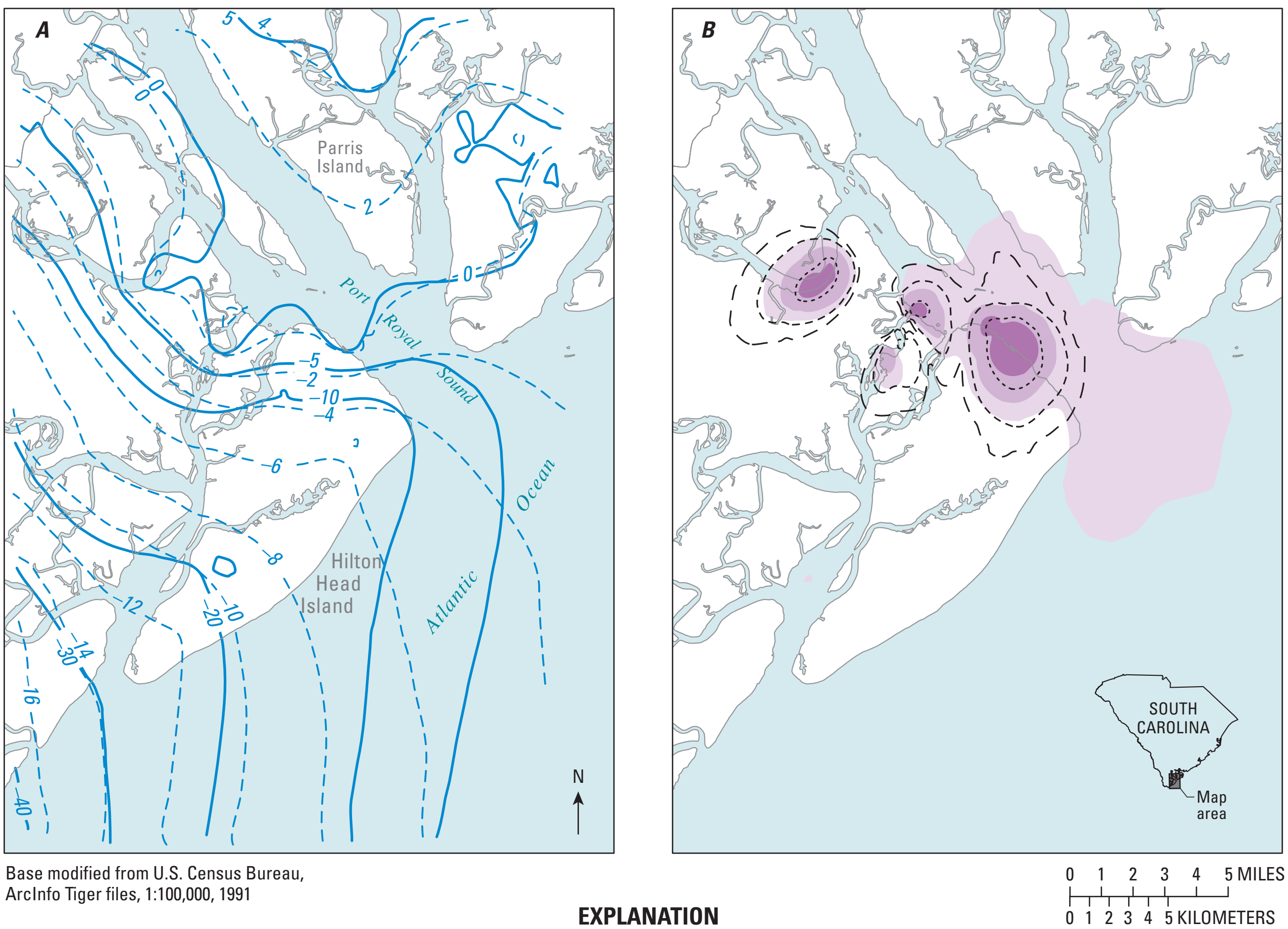


Figure 35. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model and for Upper Floridan aquifer permeabilities increased by a factor of 5 in the Hilton Head Island area, South Carolina, during 2004.

Reducing the Upper Floridan aquifer permeability in the study area results in much lower simulated heads, relative to the calibrated model, by as much as 3 ft at the northern end of Hilton Head Island and 10 ft at the southern end (fig. 36*A*). The resulting simulated chloride plumes are generally substantially smaller, except under Port Royal Sound, where a relatively large, low-concentration plume has developed (fig. 36*B*). For this sensitivity simulation, the offshore plume develops under simulated predevelopment conditions, probably because the resulting heads in the Upper Floridan aquifer are too low to flush out any saltwater that enters or to prevent it from entering the aquifer there. The smaller plumes that emanate from the designated source areas at Pinckney Island and the northern end of Hilton Head Island merge with the Port Royal Sound plume between 1885 and 2004.



EXPLANATION

Map *A*

Simulated potentiometric contour, in feet, for Upper Floridan aquifer during 2004. Contour interval, in feet, is variable

—— −5 —— Upper Floridan aquifer permeabilities reduced by a factor of 5

– – −8 – – Calibrated model

MAP *B*

Simulated chloride concentration, in milligrams per liter, in groundwater in the Upper Floridan aquifer during 2004

UPPER FLORIDAN AQUIFER PERMEABILITIES REDUCED BY A FACTOR OF 5	CALIBRATED MODEL
100 to 1,000	100
1,000 to 10,000	1,000
Greater than 10,000	10,000

Figure 36. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model and for Upper Floridan aquifer permeabilities reduced by a factor of 5 in the Hilton Head Island area, South Carolina, during 2004.

Effective Porosity

The effective porosity values used for the calibrated model represent intermediate values within a range between higher laboratory-derived values from samples from beneath Port Royal Sound (Burt and others, 1987), and lower published values for specified rock-aquifer types (Driscoll, 1986). To test model sensitivity to effective porosity, simulations were run using these upper and lower values. The upper values used were 0.33 for all aquifer units and 0.44 for all confining units, and the lower values used were 0.05 for all aquifer units and 0.10 for all confining units. Varying effective porosity had little effect on simulated heads, showing a slight decrease in head with increased effective porosity and a slight increase in head with decreased effective porosity. This is because the influence of porosity is limited to effects caused by changes in dissolved solute, specifically changes in fluid density and thus the calculated pressure field (figs. 37*A*, 38*A*).

In contrast, varying effective porosity substantially affects the simulated saltwater distribution. Effective porosity and

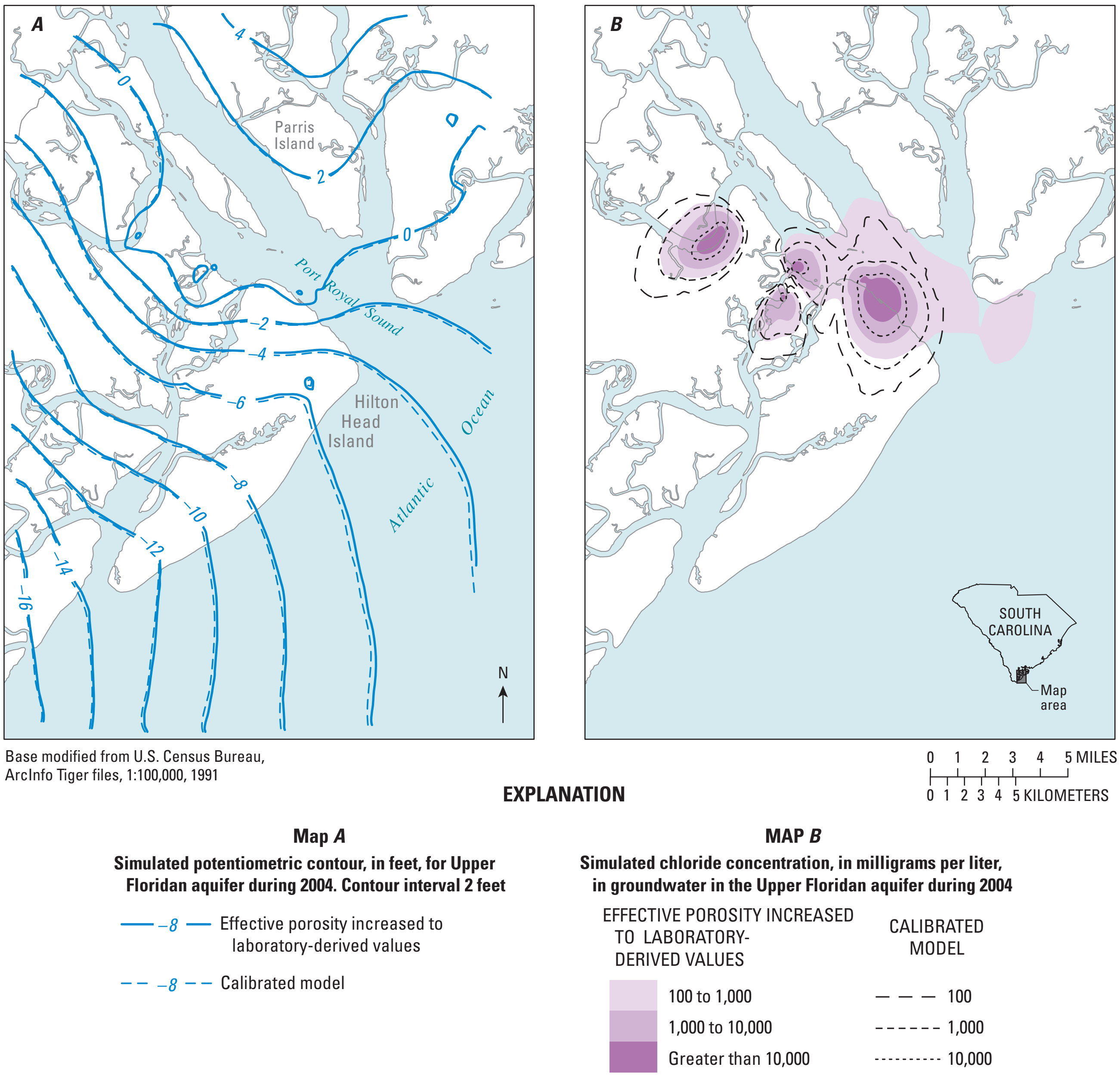


Figure 37. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model and for effective porosity increased to laboratory-derived values in the Hilton Head Island area, South Carolina, during 2004.

solute-transport rates are inversely related: increasing effective porosity leads to slower rates of solute transport, and reducing effective porosity increases rates of solute transport. The extent of simulated chloride plumes in the Upper Floridan aquifer is generally smaller for the effective porosity as set to laboratory-derived values (fig. 37*B*). The exception is under Port Royal Sound, where a larger area is composed of low chloride concentrations (100–1,000 mg/L) than for the calibrated model. For the predevelopment simulation for this sensitivity test, some saltwater entered the aquifer under Port Royal Sound, and remained there, because reduced transport rates caused by increased effective porosity prevented saltwater from being flushed away under predevelopment conditions.

Reducing effective porosity results in a substantially larger extent of simulated saltwater plumes in the Upper Floridan aquifer (fig. 38*B*), particularly in the southwestern direction of flow, for plumes emanating from the northern end of Hilton Head Island, southern Pinckney Island, and the Colleton River. In addition, several low-concentration plumes have developed in other areas—offshore of Hilton Head Island and in the southern part of Calibogue Sound—that do not occur under higher-effective porosity conditions. These

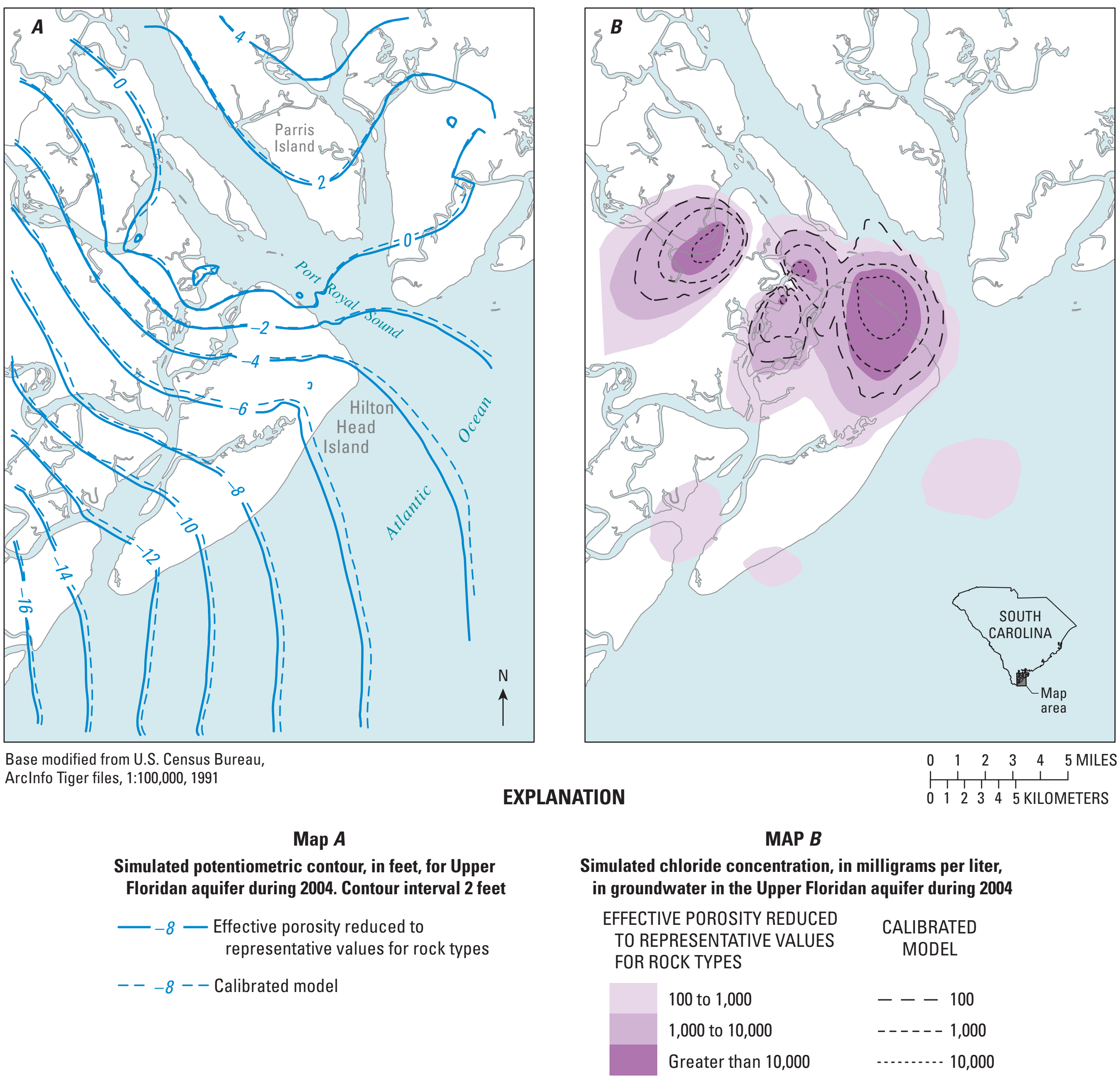


Figure 38. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model and for effective porosity reduced to representative values for rock types in the Hilton Head Island area, South Carolina, during 2004.

additional plumes occur in areas where the confining unit is observed and is represented in the model as thin. In the case of the offshore plume, sampling of the Upper Floridan aquifer in 2000 in that area indicated elevated salinity (Falls and others, 2005). Sampling of the Upper Floridan aquifer beneath Calibogue Sound, however, did not indicate elevated salinity in the aquifer, possibly because the sediments that were deposited in the area of eroded confining unit were of low enough permeability to prevent leakage of saltwater. These results indicate that, although effective porosity values are unknown, they could be parameterized to calibrate the model. Because of the high degree of uncertainty, using inverse methods to estimate reasonable effective porosity values would be a better approach than the deterministic approach used for this model.

Dispersion

The simulated longitudinal and transverse dispersivities were increased and decreased by a factor of 2 relative to the calibrated model. Simulated potentiometric contours (not shown) under either condition were virtually indistinguishable from those simulated for the calibrated model, as shown in figure 19. Dispersion controls the attenuation of the plume away from the source areas: increasing the dispersion resulted in a larger plume extent with slightly reduced concentration gradients (greater distance between contours). Reducing the dispersion decreased the plume extent and resulted in slightly increased gradients (less distance between contours) relative to the calibrated model (fig. 39).

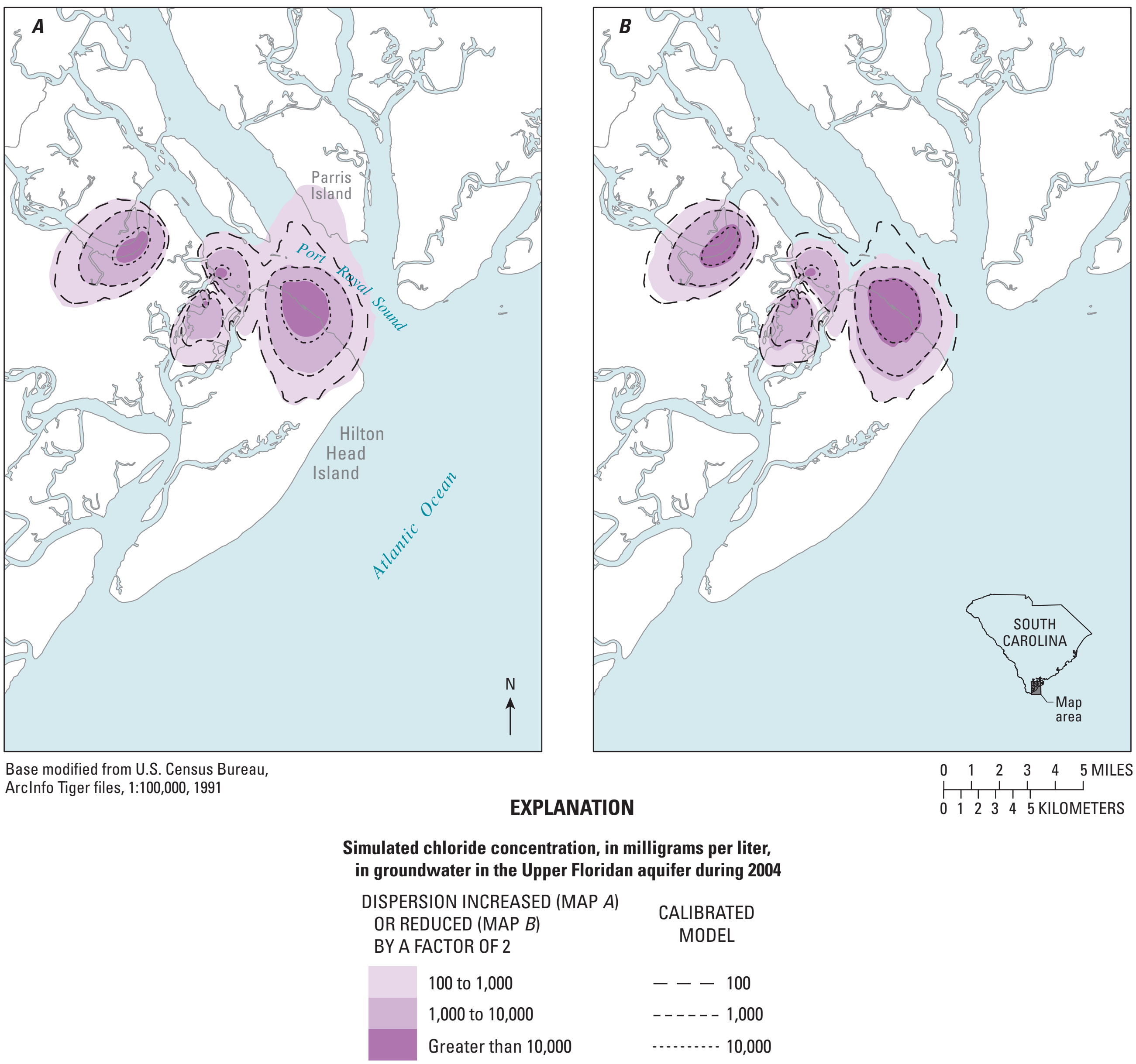


Figure 39. Simulated chloride concentration in groundwater for the calibrated model and for dispersion *(A)* increased and *(B)* reduced by a factor of 2 in the Hilton Head Island area, South Carolina, during 2004.

Simulation of Sea-level Rise and Pumpage Elimination, 2004–2104

Using the calibrated model results for 2004 as initial conditions, four scenarios were simulated for the 100-year period of 2004–2104. The four scenarios represent: (1) continuation of the estimated sea-level-rise rate of 1 ft/century from 1885–2004; (2) an increase in the sea-level-rise rate to 2 ft/century; (3) a cessation of sea-level rise (rate decreases to 0 ft/century); and (4) continuation of the 1-ft/century rate with an elimination of all pumpage in the model. Results illustrate the relative response of the model to projected rates of sea-level rise, and the relative influence of pumpage and sea-level rise on simulated saltwater intrusion in the Upper Floridan aquifer in the Hilton Head Island area.

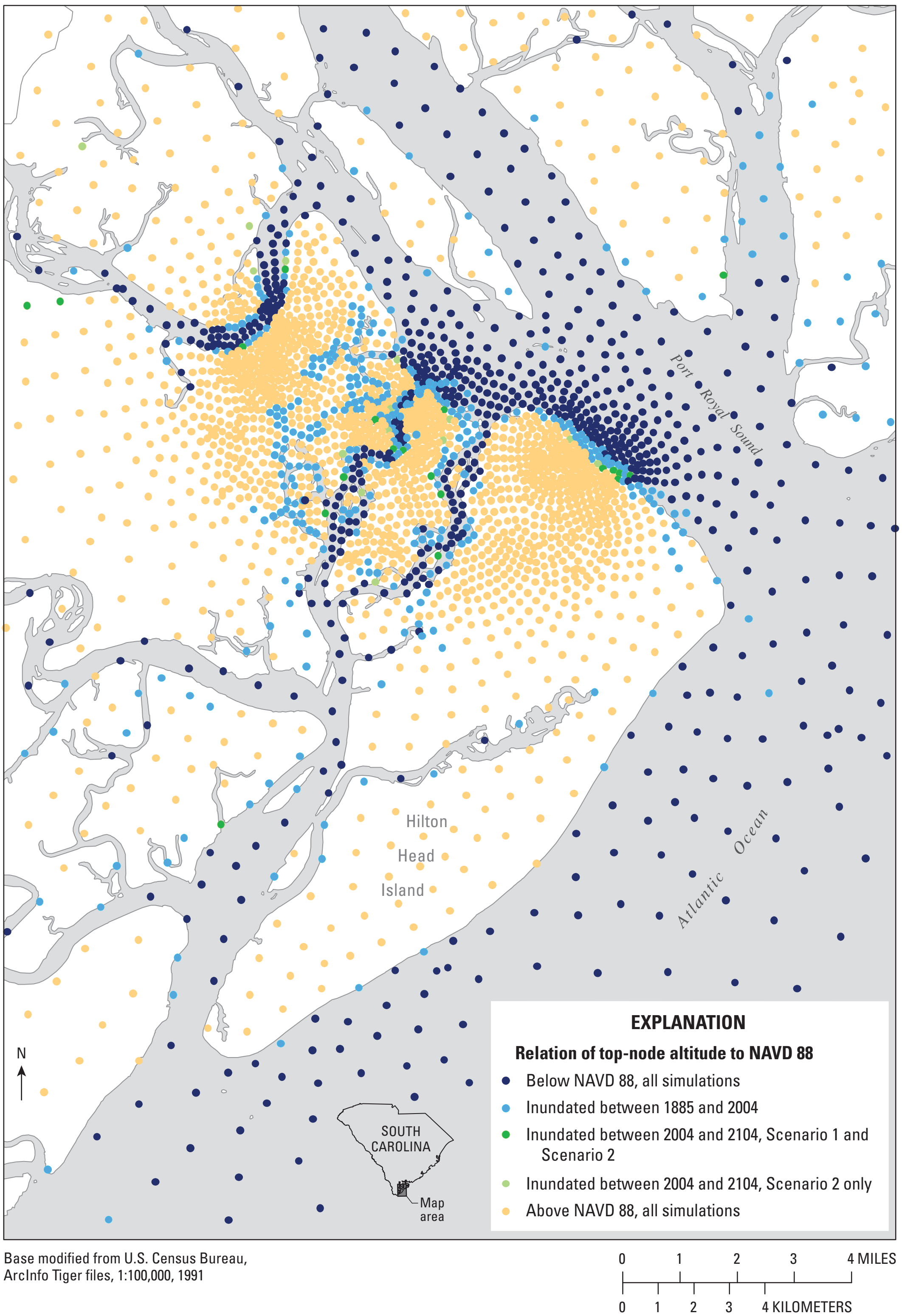
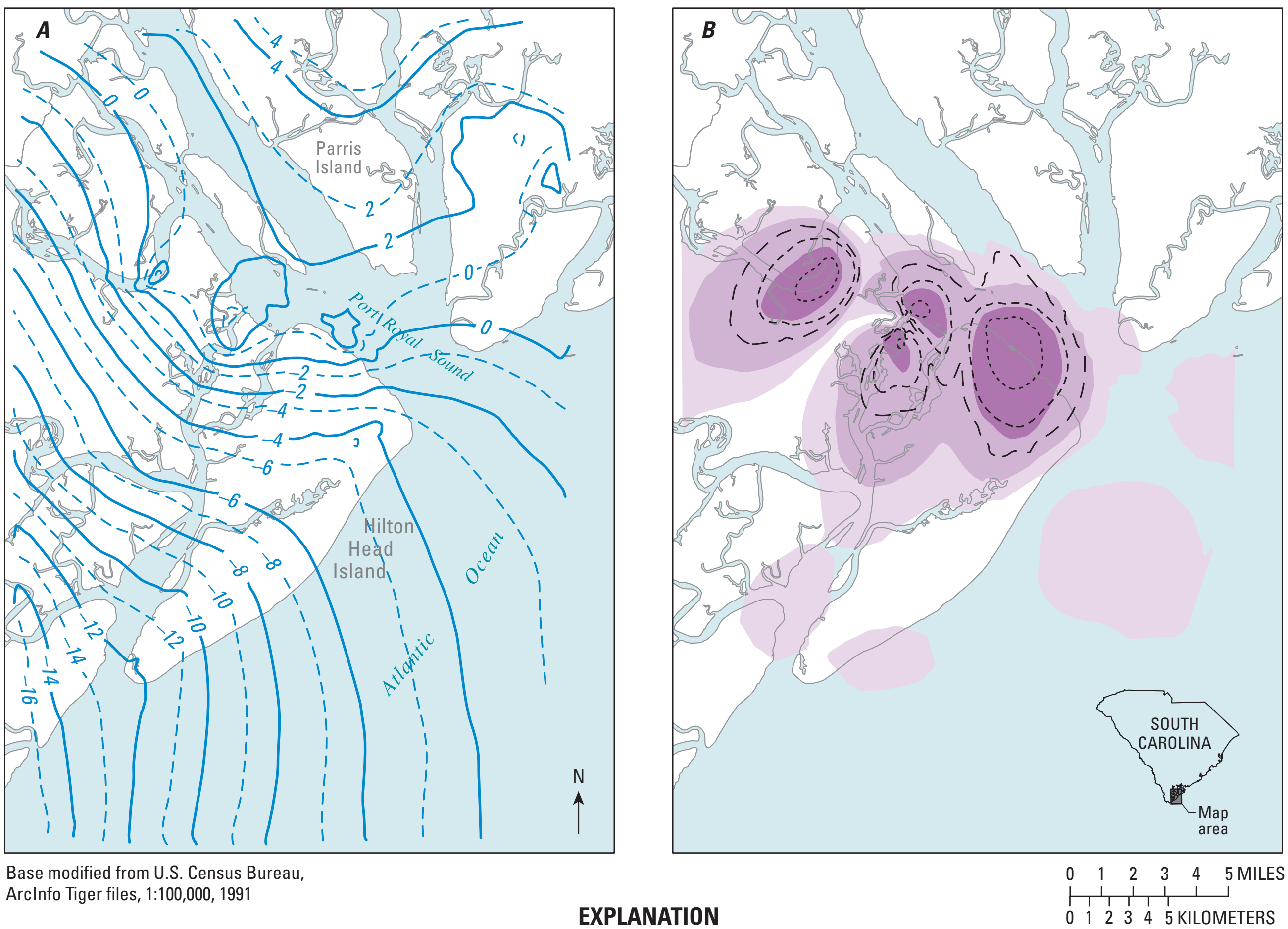


Figure 40. Relation of top-node altitude to North American Vertical Datum of 1988 (NAVD 88) in the Hilton Head Island area, South Carolina.

Scenario 1: Sea Level Continues to Rise at Current Estimated Rate

For Scenario 1, sea level continues to rise at the rate used in the calibrated model, about 1 ft/century, during 2004–2104, and the number of top model nodes representing saltwater inundation increases (fig. 40). Pumpage is maintained at the 2004 rate and distribution. During 2104, simulated water levels in the Upper Floridan aquifer are about 1 ft higher throughout the study area than during 2004 (fig. 41*A*). The simulated extent of the chloride plumes in the Upper Floridan aquifer and the extent of the highest concentrations have expanded substantially (fig. 41*B*). The increase in plume size may be affected by the continually rising sea level and the resulting increasing pressure, but it is more likely because the system is far from steady state even with no change in the stresses, as will be shown from other scenario results. In addition, several additional low-concentration plumes have developed offshore of Hilton Head Island and at the southern end of Hilton Head Island and Calibogue Sound.



Base modified from U.S. Census Bureau,
ArcInfo Tiger files, 1:100,000, 1991

EXPLANATION

Map *A*

Simulated potentiometric contour, in feet, for Upper Floridan aquifer. Contour interval 2 feet

—— –8 —— Scenario 1 during 2104

– – –8 – – Calibrated model during 2004

MAP *B*

Simulated chloride concentration, in milligrams per liter, in groundwater in the Upper Floridan aquifer

SCENARIO 1 DURING 2104	CALIBRATED MODEL DURING 2004
100 to 1,000	— — — 100
1,000 to 10,000	- - - - - - 1,000
Greater than 10,000	---------- 10,000

Figure 41. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model during 2004 and for Scenario 1 during 2104 in the Hilton Head Island area, South Carolina.

Scenario 2: Sea-Level-Rise Rate Doubles

For Scenario 2, the sea-level-rise rate of 2 ft/century during 2004–2104 represents a doubling of the 1885–2004 rate, and the inundated area is shown in figure 40. Pumpage is maintained at the 2004 rates and distribution. During 2104, simulated water levels in the Upper Floridan aquifer are about 2 ft higher in the study area than during 2004 (fig. 42*A*). The simulated extent of the chloride plumes in the Upper Floridan aquifer during 2104 and the extent of the highest concentrations are similar to those simulated for Scenario 1; however, the extent of chloride plumes is substantially increased relative to the 2004 results (fig. 42*B*). In the Pinckney Island area, the simulated extents of the 1,000- and 10,000-mg/L chloride contours for Scenario 2 during 2104 are greater than for Scenario 1 (fig. 43), indicating more saltwater has entered the Upper Floridan aquifer as a response to higher sea levels. Because a large part of southern Pinckney Island is very low altitude, rising sea level exposes more nodes in critical areas to saltwater, providing a greater source area for saltwater to enter the Upper Floridan aquifer, especially where the upper confining unit is thin.

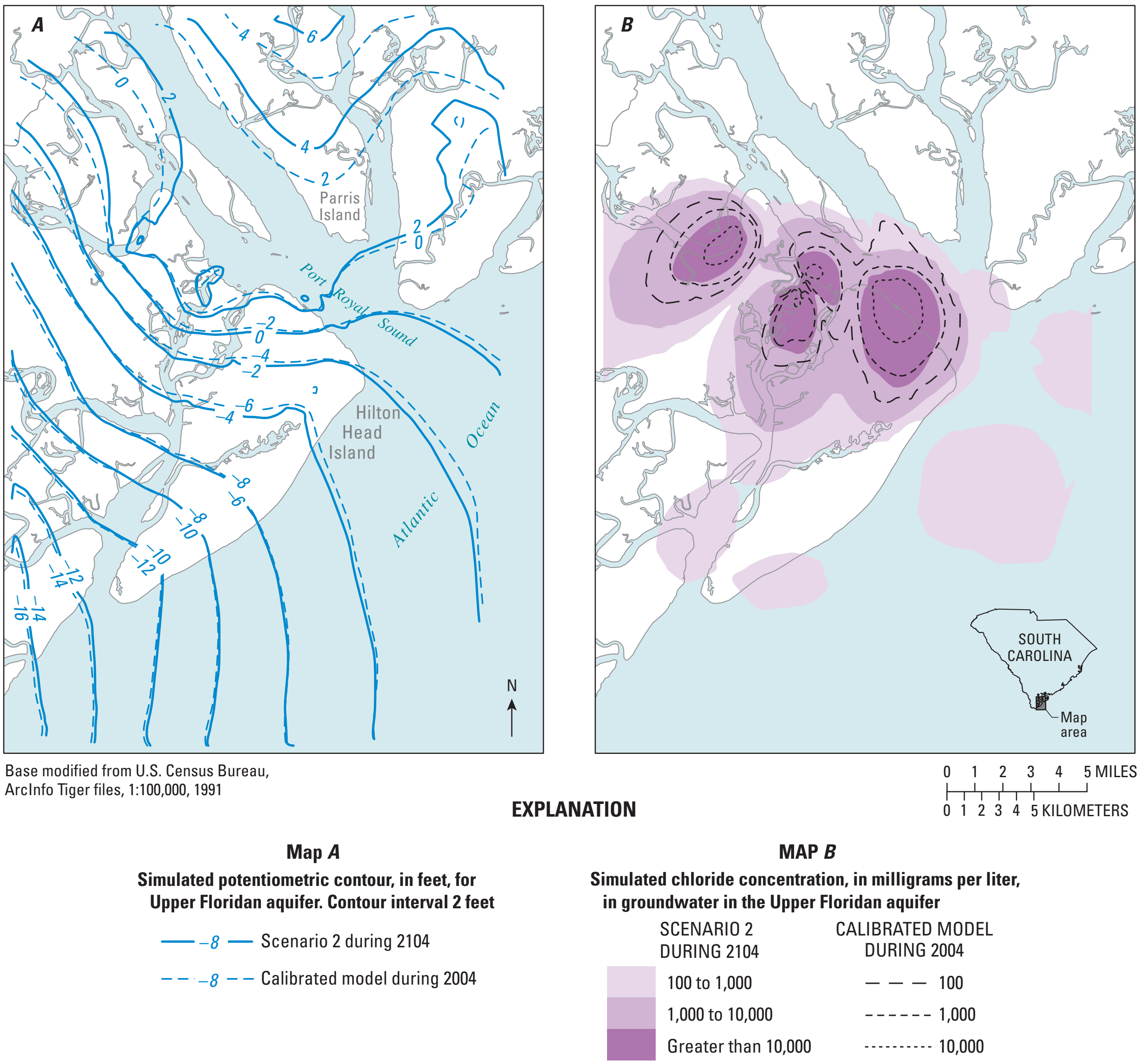


Figure 42. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model during 2004 and for Scenario 2 during 2104 in the Hilton Head Island area, South Carolina.

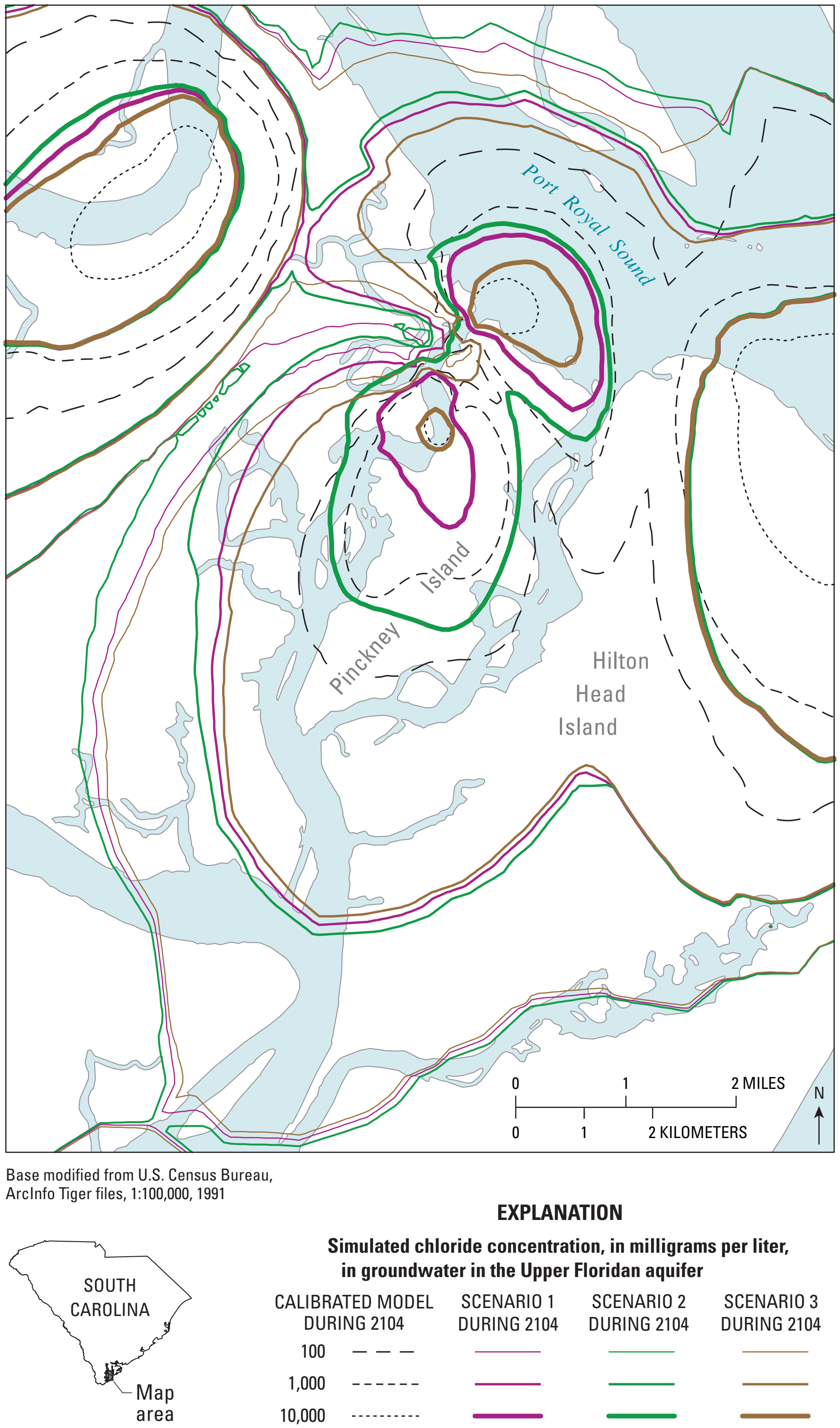


Figure 43. Simulated chloride concentration contours in groundwater during 2104 and Scenario 1, Scenario 2, and Scenario 3 during 2104, near Pinckney Island, South Carolina.

Scenario 3: Sea-Level Rise Ceases at the 2004 Sea Level

For Scenario 3, sea-level rise ceases and is maintained at the 2004 sea level, and pumpage is maintained at the 2004 rate and distribution. During 2104, simulated water levels in the Upper Floridan aquifer are a fraction of a foot higher in the study area than during 2004 (fig. 44*A*). The slight apparent difference in potentiometric contours is a result of the conversion to pressure head from simulated pressure assuming freshwater density, rather than integrating for each column of nodes to estimate a pressure head. By assuming freshwater density, the estimated pressure head is slightly higher than would be otherwise. The simulated extent of the chloride plumes in the Upper Floridan aquifer in 2104 has expanded substantially relative to the 2004 distribution (fig. 44*B*), and is similar to Scenario 1 and Scenario 2. The simulated extent of the 10,000-mg/L chloride contours at Pinckney Island for Scenario 3 is smaller than that for Scenarios 1 and 2, and is only slightly larger than that during 2004 (fig. 43). This result indicates that saltwater intrusion at Pinckney Island is especially responsive to sea-level rise, and in the absence of a rising sea level, saltwater intrusion is less likely to occur there.

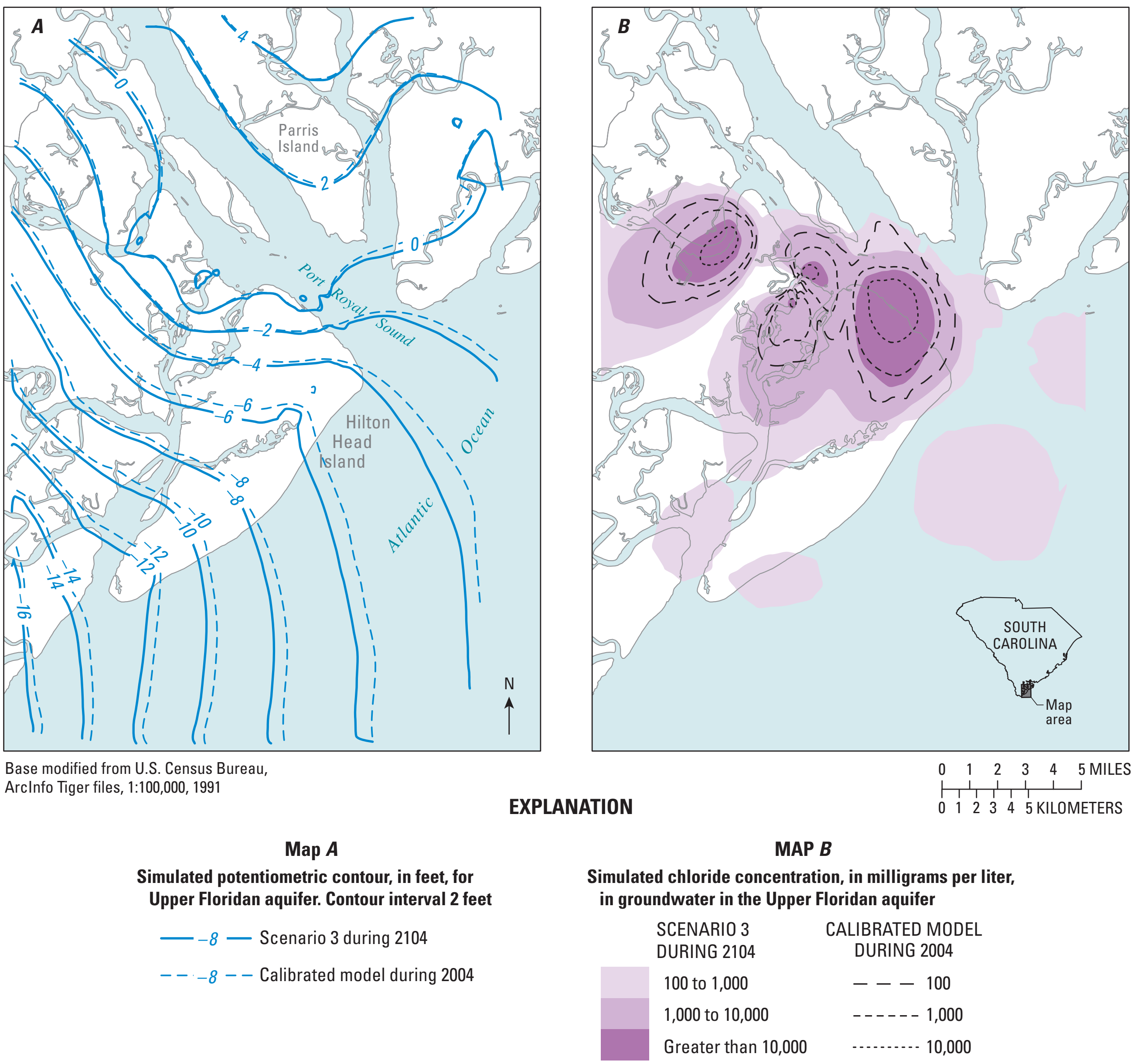


Figure 44. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model during 2004 and for Scenario 3 during 2104 in the Hilton Head Island area, South Carolina.

Scenario 4: Pumpage is Eliminated while Sea Level Continues to Rise at Current Estimated Rate

For Scenario 4, all pumpage in the model is eliminated during 2004–2104 while sea level continues to rise at 1 ft/century. By 2104, simulated water levels in the Upper Floridan aquifer rise to about 2 ft higher than predevelopment water levels because the sea level is about 2 ft higher in 2104 than in 1885 (fig. 45*A*). The simulated plumes in 2104 are smaller than those simulated in 2004, and the maximum concentration is less (fig. 45*B*). In particular, the southernmost extent of each plume is most affected by the reduction in pumpage because the greatest pumping stresses occur to the south and southwest of the plumes and because groundwater flow on Hilton Head Island has been restored to predevelopment directions, eastward or offshore (compared to the 2004 southwestward direction toward Savannah). At southern Pinckney Island, the plume almost disappears.

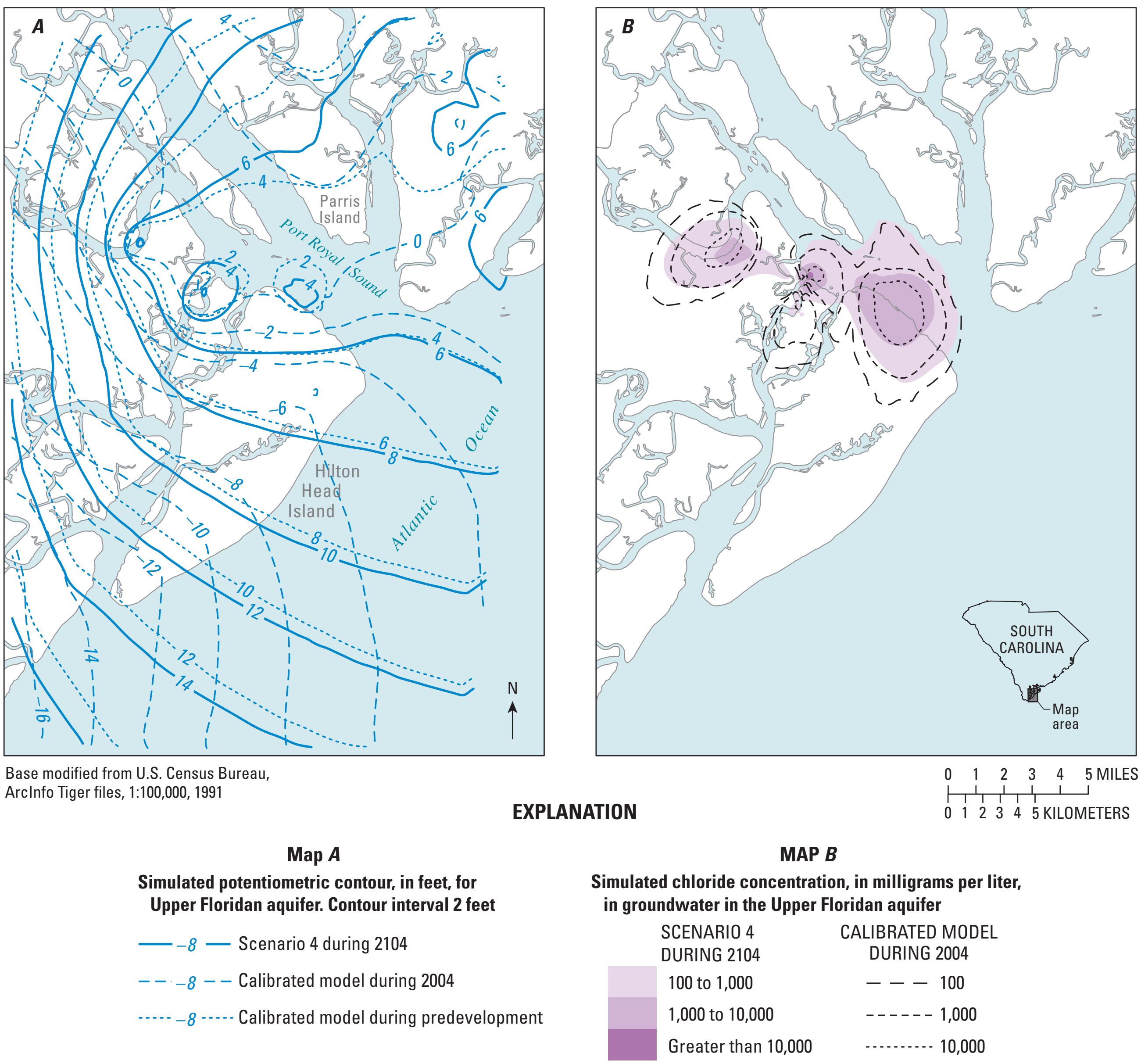


Figure 45. Simulated *(A)* potentiometric contours and *(B)* chloride concentration in groundwater for the calibrated model during predevelopment and 2004, and for Scenario 4 during 2104 in the Hilton Head Island area, South Carolina.

Relative Effects of Sea-Level Rise and Pumpage Elimination

Results for each scenario are subject to considerable uncertainty and should be interpreted with caution, as will be discussed in more detail in the Model Limitations section. Because the uncertainty in the fundamental components of the model is the same for each scenario, the relative differences in responses among the scenarios will be dominated by the differences in the boundary conditions between the scenarios. Comparison of results for Scenarios 1, 2, and 3 indicates that the rate of sea-level change has little effect on overall plume development, except in the Pinckney Island area. Pinckney Island is particularly prone to increased saltwater intrusion with change in sea level because it is a relatively large area of low land-surface altitude and confining unit thickness. Comparison of Scenarios 1 and 4 indicates that pumpage elimination has the opposite effect of sea-level rise by reducing saltwater intrusion and plume expansion, and that some incremental amount of pumpage reduction, although not simulated, may offset effects of sea-level rise. It must be noted, however, that Scenario 3 indicates that, even without changes in pumpage and with a static sea level, saltwater plumes continue to expand because the system is still approaching a steady-state distribution of saltwater.

Model Limitations

Model results must be interpreted in light of uncertainties and assumptions inherent in model construction, and in consideration of how the model is intended to be used. Some limitations are manifested in poor model fit. For example, the underestimation of chloride concentrations at a cluster of sites between Pinckney Island and the Colleton River, and at two sites along the east central part of the coast of Hilton Head Island (figs. 22 and 23) indicates that data may be insufficient to develop an accurate conceptual model to explain all of the observed elevated salinity. The model also does not capture the spatial variability and steep concentration gradients at the northern end of Hilton Head Island and at the Colleton River, which may be the result of insufficient model discretization or an inaccurate conceptual model. Simulated water levels at the northern part of Port Royal Island and north (fig. 18) also show a poor fit to observed water levels. In this area, observed water levels are quite variable, with more than a 40-ft range within small areas (fig. 20) indicating some local heterogeneity is not accounted for by the model. There are many reasons for a poor model fit; some possible reasons are described below.

The model is designed to consider relative effects of sea-level change and pumpage modifications in a general way. The model was calibrated by a manual parameter estimation method to match observed water levels and estimated chloride concentrations. Thus, the calibration represents a qualitative degree of fit. Though the sensitivity analysis represents effects of reasonable ranges of model inputs on simulated results, it does not attempt a rigorous quantification of model sensitivity or predictive uncertainty of model results.

This model represents one realization of the hydrologic system, and an infinite number of such realizations are possible, many of which would likely fit the observations as well as or better than this one. Potential sources of error and uncertainty in the model are discussed in this section, and ways to improve our understanding of the hydrologic system and predictive capabilities of the model are suggested.

Conceptual Model

This model is designed to represent the conceptual model as described in a previous section, and is limited by the availability of data to define that model. The conceptual model of saltwater entering the Upper Floridan aquifer from downward leakage through localized areas where the confining unit is thin or eroded is supported by (1) the observation that highest chloride concentrations are localized in three areas, and concentrations generally decrease away from those areas, and (2) seismic data that indicate a thin or eroded confining unit in at least two of those areas (Colleton River and Pinckney Island). This does not preclude the possibility that other processes may contribute to the observed saltwater distribution. For example, the model simulates downward leakage through the confining unit in areas away from the designated saltwater-source areas, such as the southern part of Pinckney Island and under Port Royal Sound. In the area between the Colleton River and Pinckney Island, saltwater may be leaking downward from the overlying emergent wetlands in a similar manner. At the northern end of Hilton Head Island, elevated chloride concentrations do not appear to be related to thinning of the overlying confining unit as suggested by seismic data. Elevated concentrations in this area may be related to higher concentrations observed beneath Port Royal Sound (Landmeyer and Belval, 1996), which may originate in a more distal source area. An alternative possibility is that some of the elevated chloride concentrations may occur from upconing of water from the underlying confining unit. This alternative is suggested by specific conductance data that indicate a steep vertical concentration gradient at the inferred bottom of the Upper Floridan aquifer, and by elevated specific conductance in the underlying confining unit. Also, chloride concentrations in samples taken from the middle Floridan aquifer at well BFT-0315 were elevated several years in advance of elevated values found in the Upper Floridan aquifer.

Regional Flow System

The model area was taken from the original model and a precursory regional flow model (Payne and others, 2005) and is substantially larger than the study area. The model area and grid were designed to set model boundaries at natural hydrologic boundaries where possible, and otherwise to set model boundaries far from the study area to subdue any potential boundary effects on the study area (Provost and others, 2006). The simulated potentiometric surface for the Upper Floridan aquifer in 2000 has regional-scale features and altitudes similar to an estimated potentiometric surface for September 2000 (Peck and McFadden, 2004; fig. 46). Similarities include the cone of depression around Savannah, the high hydraulic gradient in the Gulf Trough area, and low hydraulic gradient area in the south-central part of the model area. Differences in details, for example the location of contours, may result from interpretation or interpolation, model discretization, or lack of model refinement to specifically match the regional water-level data. Localized pumping may affect nearby observed water levels, hence the interpretation of the potentiometric contours. These local-scale features are not likely to be reflected in a model with extremely coarse node spacing (generally on the order of miles to tens of miles), where pumpage is distributed to the nearest node. Adjustment of hydraulic properties or boundary conditions in areas away from the study area may have resulted in a better match of simulated to observed water levels outside of the study area. This adjustment should not have affected the results in the study area substantially because flow patterns indicate that the model generally reflects the regional flow system, and thus the flow from the greater model area into the study area. There are some salinity data for the Floridan aquifer system in the southern part of the model area, in Glynn and Camden Counties, and in the Lower Floridan aquifer in the study area, but the model is not designed to simulate chloride concentrations that likely are the result of different processes or a different conceptual model than those which are presented here (for example, movement of saline connate waters at greater depths in the hydrologic system), and should not be expected to do so.

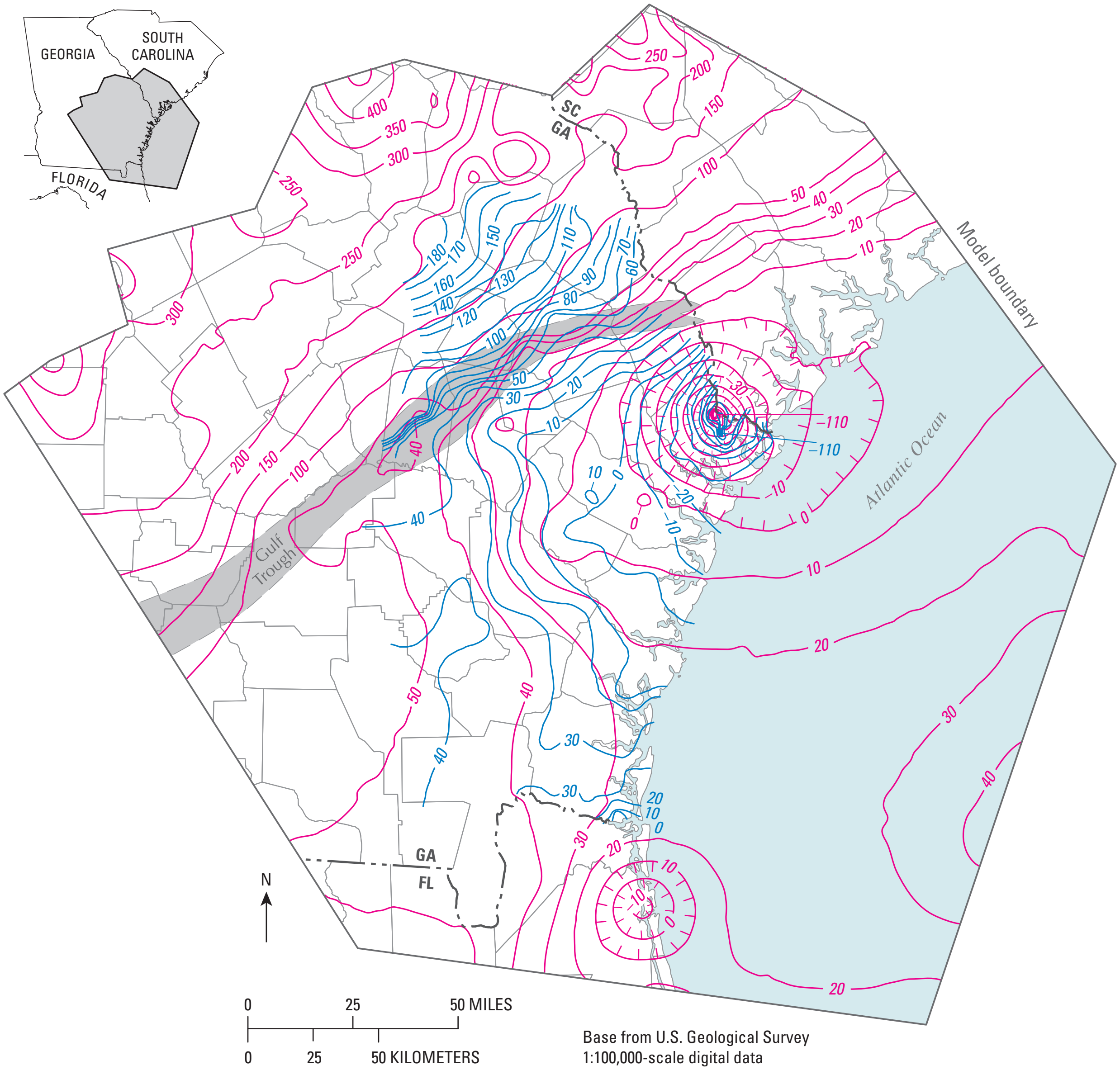
Field Data and Physical Properties

The model was calibrated to October 2004 water-level measurements made in wells completed in the Upper Floridan aquifer. Water levels fluctuate temporally in response to local pumping, and, to a lesser extent, tides. Because the pumping history is not known in sufficient detail to model all of these fluctuations, the ability of the model to fit the water-level data is inherently limited. Quantifiable components of water-level-observation accuracy include land-surface altitude, accuracy of measurement, and temporal variations in water level. At well BFT-1810 on Hilton Head Island, water levels fluctuate up to 5 ft annually and even up to 2–3 ft within a single month based on a 20-year continuous record (USGS Automated Data Processing System database).

Calibration was performed by matching simulated chloride values to values estimated from specific-conductance logs in wells inferred to be open to the Upper Floridan aquifer. Error associated with estimating chloride concentration from specific conductance is discussed in Appendix 1. Although absolute error is greater for the larger values of specific conductance, measures of relative error, as indicated by the log-transformed values, are generally greater at low specific conductance values. If any of the wells penetrate the underlying confining unit, some of the interpreted salinity may be due to connate saltwater present beneath the Upper Floridan aquifer entering the borehole, and connate water may not represent a mix of seawater and fresh groundwater, unlike the composition simulated by the model. Also, vertical flow may be occurring within the boreholes, causing mixing of waters from different depths and making it difficult to interpret the measured vertical profiles of specific conductance. Finally, available water-quality data are not sufficient to constrain saltwater-transport rates because consistent data collection has only been occurring since about 1997, and transport rates are likely too slow to indicate any appreciable changes during the short monitoring period since then.

During calibration, permeability values were adjusted to match water-level and estimated chloride values. The original source of permeability values are from available aquifer-test data (Clarke and others, 2004). These values were modified through calibration of the regional MODFLOW model (Payne and others, 2005), modified through calibration of the original SUTRA model (Provost and others, 2006), and then used as initial values for the calibration of this model. For calibration of this model, permeability values and permeability-zone geometries for the Upper Floridan aquifer and the overlying confining unit were adjusted manually to minimize residuals. Sensitivity testing indicates simulated water levels and chloride distribution are very sensitive to confining-unit permeability in particular. Although parameter-uncertainty measures of the final permeability values are not made, the calibrated values are within the wide range observed for carbonate rock types (Freeze and Cherry, 1979, table 2.2). The configuration of the discrete permeability zones and the final permeability values reflect informed judgments made by the modeler and may not represent the only way to fit the observed data.

Effective porosity of the porous medium is a major control on the rate at which solute is transported, but it is poorly characterized in the study area. In the original SUTRA model, porosity values were derived from laboratory measurements performed on core samples and, therefore, may be at the high end of the expected range of effective porosity (Provost and others, 2006). Alternatively, field-scale effective porosities may be arguably lower if the bulk of solute is transported through smaller, more localized pathways (for example, values of specific yield for representative rock types [Driscoll, 1986]). Porosity likely occurs at multiple scales in aquifers, with transport occurring through both small and large pore spaces. If transport is occurring through the smaller pore spaces, such as primary porosity or intergranular secondary porosity, then larger values of effective porosity may be more appropriate; if most of the transport is occurring through larger secondary porosity such as open fractures, or vuggy material, then smaller values may be more appropriate. For this model, intermediate porosity values were applied throughout the



EXPLANATION

Potentiometric contour—Shows potentiometric surface of Upper Floridan aquifer, 2000. Contour interval 10 and 50 feet. Hachures indicate depression. Datum is NAVD 88

— 30 — Estimated (Peck and McFadden, 2004)

— 30 — Simulated

Figure 46. Potentiometric surface of the Upper Floridan aquifer for the calibrated model in the model area during 2000, and estimated during September 2000 (Gulf Trough modified from Kellam and Gorday, 1990).

model domain because data indicating rate of transport are not available. Sensitivity testing indicates that the simulated chloride distribution is sensitive to effective porosity, indicating substantial predictive uncertainty of chloride distribution in the model.

In the original SUTRA model, dispersivities (parameters that control the rates and directions of spreading) were adjusted, along with selected permeabilities, to fit the general trends in the observed chloride distribution. Dispersivities were linked to element size, which generally increases with distance from the source areas, to help ensure a stable numerical solution. Thus, as the simulated solute moves away from the source areas, the solute is apparently subject to greater dispersion. Qualitatively, this agrees with what is typically observed in the field—as a rule, dispersion increases as the transport reach increases. However, the dispersivity values that best characterize the future spreading of the solute plumes into unaffected areas are subject to considerable uncertainty.

Land-surface altitude and bathymetry data are used to determine the pressure and concentration boundary condition at the top of the model. Land-surface altitude and bathymetry data are acquired and processed separately, so some uncertainty exists in the geometry of where the onshore pressure boundary condition should be applied compared with the offshore pressure boundary condition. This uncertainty pertaining to boundary condition adds uncertainty to model results because the altitude of a large part of the area is very close to mean sea level, particularly the emergent wetlands. Uncertainty also is introduced by error within the land-surface altitude and bathymetry data. For nodes at locations above mean sea level, the top node altitudes were assigned primarily from 30-m digital elevation model (DEM) data and were modified where comparisons with 7.5-minute topographic quadrangle maps indicated errors in the digital data.

Boundary and Initial Conditions

The top boundary condition in onshore areas is constructed under the assumption that freshwater recharge to the confined aquifer system occurs as downward leakage from the water table. The method of estimating the water-table altitude contributes uncertainty because there are few data with which to constrain it. For this model, the water-table altitude is estimated as a function of land-surface altitude, the data for which are derived from DEMs and contribute to the uncertainty. Furthermore, the water-table surface likely has declined historically with the construction of drainage features, particularly in areas closest to the coast, but those specific changes are unknown (Drennan Park, South Carolina Department of Natural Resources, oral commun., 2007).

Although estimates of recharge from stream base-flow data exist for the model area (Priest, 2004), model-independent estimates (from precipitation, evapotranspiration, stream discharge, and other data) specific to the study area apparently do not exist. Furthermore, because of the large area covered by the model and the coarse discretization outside of the study area, the model was not designed to simulate specifically the shallow unconfined flow system and the stream–aquifer interactions. Thus, the model cannot be used to directly estimate recharge that is comparable to measureable parameters such as average stream base flow. To estimate recharge from model results, an average regional rate of flux into the Upper Floridan aquifer was calculated as follows and compared against independently estimated regional recharge rates. SUTRA calculates a flow vector at each element centroid. Element layer 9 represents the top-most elements for hydrologic unit 5, the Upper Floridan aquifer. For those elements that are onshore, the flux was calculated by multiplying the vertical component of the velocity vector by the porosity (0.165). The flux was areally averaged for that subset of elements. Estimated in this way, the recharge to the Upper Floridan aquifer for the model area is 3.2 inches per year (in/yr). This value compares reasonably well with estimates from drought base flow for coastal Georgia of 0–2.4 in/yr during 1971–2001 (Priest, 2004) and 3 in/yr for 1980 for the easternmost Gulf Coast Coastal Plain region (Williamson and others, 1990). However, this estimation is not rigorous, and it should be emphasized that this model is not specifically suited to estimate recharge.

The specified concentration at the top boundary is set such that when the altitude of a top model node is above mean sea level, the chloride concentration of inflow is zero; below mean sea level, the chloride concentration of inflow is set to the estimated seawater concentration. Thus the distribution of the chloride source is dependent on the geometry of the zero-foot land-surface altitude contour. Salinity monitoring in the area indicates that the salinity in the tidal creeks and in Port Royal Sound is less than salinity in seawater (Van Dolah others, 2002, 2004). More importantly, low-lying areas that are inundated under high tide (emergent wetlands) are likely more saline than the freshwater condition that is applied in the model. Where the confining unit is thin, there could be a potential source of saltwater in the Upper Floridan aquifer that is not accounted for in this model.

The bottom boundary of the model, the base of the Floridan aquifer system, is simulated as a no-flow boundary; therefore, flow and transport across that boundary are precluded. Effectively, this would increase the transport rates because none of the solute can be lost across that boundary (Provost and others, 2006). The boundary of this model is removed from the base of the Upper Floridan aquifer, however, and likely has little effect on transport rates in the Upper Floridan aquifer.

Drawdown due to pumping provides much of the driving force for groundwater flow in the study area. Although the pumping history incorporated into the model is believed to take into account most of the major pumping centers, parts of the history have been constructed on the basis of incomplete records, particularly prior to the 1980s (Provost and others, 2006). Furthermore, the pumping rates are annualized, whereas the water-level calibration data represent a much shorter period of time and may be responding to localized and short-term, temporally variable pumpage.

The predevelopment potentiometric surface and salinity in the Upper Floridan aquifer are unknown. Estimates have been made assuming that the aquifer discharges into streams at some locations, that onshore water levels are above sea level, and that there is some offshore discharge of freshwater (Counts and Donsky, 1963; Johnston and others, 1980; Landmeyer and Belval, 1996). Because simulated water levels respond quickly to changes in pumpage, any difference between the simulated and the actual predevelopment potentiometric surface is unlikely to have much effect on the simulated present-day surface. The predevelopment distribution of chloride in the Upper Floridan aquifer also is unknown, although shortly after the initiation of pumpage at Parris Island, salinity levels in the Upper Floridan aquifer increased to an unacceptable level (Hayes, 1979). This finding suggests that salinity of the Upper Floridan aquifer may have been elevated in parts of the study area under predevelopment conditions.

Calibration Approach

This model was calibrated deterministically, by trial-and-error adjustment primarily of the permeability distribution. The resulting model represents only one realization of physical parameters that results in a satisfactory fit of observed water levels and chloride concentrations. Instead, calibrating the model for a range of reasonable values for several physical parameters, including effective porosity and dispersion, and for a variety of boundary condition configurations, such as recharge at the top boundary, would likely result in multiple realizations that fit observed data equivalently. Different working realizations of the model could result in different predictions for the same scenarios. Automated parameter estimation would provide an expeditious way to generate multiple working model realizations; however, time constraints precluded this kind of approach for this model.

Future Predictions

Results of these scenarios should be interpreted with caution because they are predicated on a particular conceptual model that may not describe the system sufficiently to explain its behavior and current state. Even if a model does accurately reproduce the past or present state of a system, it may not be unique in its ability to describe field observations and may not take into account all sources of future saltwater intrusion. Model predictions can be no more certain, and are likely far more uncertain, than the degree to which the past or present state of the system can be simulated. Furthermore, the scenarios are based on an assumed range of possible future sea-level-rise rates, assumed changes in the water-table surface with sea-level rise, and an assumed future pumping distribution, all of which are sources of substantial uncertainty.

Discussion

A numerical model will produce the most reliable results in areas in which the physical system is most accurately characterized and for the period for which the model is calibrated. With increasing spatial distance and time from the best characterized calibration conditions, model accuracy will decrease. Despite the limitations of the model, one of its most appropriate uses is as a tool to better understand the flow system and guide efforts to refine the conceptual model. Refinement of the conceptual model will result in a more useful numerical model and will ultimately reduce the uncertainty in results.

The conceptual model accounts for saltwater intrusion in the Upper Floridan aquifer occurring primarily as a result of downward leakage of seawater or brackish water through the confining unit in areas where the confining unit is thin or eroded. Although the model generally reproduces the observed salinity trends, the simulation results indicate that this conceptual model is not refined enough, or cannot by itself explain all details of the present-day saltwater distribution in the Upper Floridan aquifer in the study area. Uncertainty could be reduced by considering alternative or refined conceptual models, and with continued data collection, monitoring, and analysis.

Saltwater may be transported to the study area from more distal sources. For example, saltwater could have leaked into the Upper Floridan aquifer beneath Port Royal Sound or locations north thereof, or offshore of Hilton Head Island, and subsequently spread south to the northern end of Hilton Head Island or west to the eastern edge of the Island. Saltwater that has been present in units below the Upper Floridan aquifer before observed occurrence in the Upper Floridan aquifer, for example in the middle Floridan aquifer at well BFT-0315, may have been drawn upward by increasing stresses in the Upper Floridan aquifer. Saltwater may be leaking downward through the confining unit in more places than indicated by the specific conductance data, for example from brackish water sources in emergent wetlands between Calibogue Sound and the Colleton River. Testing these alternative conceptual models and configurations could be worthwhile because they might produce different results for predictive scenarios.

The conceptual model could be refined with continued and additional data collection and analysis. To gain a better understanding of the possible pervasiveness of saltwater leakage through the confining unit, pore-water sampling and(or) geophysical-data collection (for example resistivity surveys of tidal creeks, rivers, and sounds) could help better define hydraulic properties of units overlying and underlying the Upper Floridan aquifer. The model could be improved with better constraints on the rate of saltwater transport, such as through consistently collected, long-term, continuous specific conductance monitoring integrated with a targeted water-quality sampling program. Resampling or additional geophysical surveying of the Upper Floridan aquifer beneath Port Royal Sound could provide insight on the saltwater intrusion that occurs on the northern end of Hilton Head Island because no obvious area of leakage is indicated in the seismic data.

Even without additional data-collection programs, our understanding of the nature and causes of saltwater intrusion in the Hilton Head Island area could be expanded by testing alternative conceptual models, or model configurations, to create different reasonable models that represent the observations to an equivalent degree of accuracy. A more rigorous quantification of error in model input and model sensitivity to input parameters may illustrate the predictive uncertainty in the model and could be used to optimize efforts to collect additional data.

Summary and Conclusions

A major concern associated with climate change is the increased potential for saltwater intrusion in coastal aquifers as a result of rising sea level. In the Hilton Head Island, South Carolina, area, saltwater intrusion has been observed in the Upper Floridan aquifer since the late 1970s. The Upper Floridan aquifer in the Hilton Head Island area is particularly prone to saltwater intrusion where the confining unit is thin or eroded in places that are inundated by salty or brackish water. During the last century, groundwater pumpage increased because of population growth, increased tourism, and sustained industrial activity in the coastal area of Georgia and South Carolina. This increased groundwater pumpage has resulted in water-level declines, which likely have contributed to the occurrence of saltwater in the Upper Floridan aquifer. Long-term tidal records indicate that sea level has been rising at a rate of about 0.3 meter (m) per century (approximately 1 foot per century) along the South Carolina and Georgia coast during the 1900s, and geologic data indicate that sea level has been rising for the past several thousand years. Low-lying areas, such as emergent wetlands, are subject to more sustained inundation, and an increasing area will be inundated if sea level continues to rise during this century.

Numerical modeling was used to examine the potential effects of future sea-level rise on saltwater intrusion in the Upper Floridan aquifer in the Hilton Head Island area. The model was revised from a previously developed saltwater-transport model of the study area. The numerical model represents a conceptual model in which saline surface water intrudes vertically into the Upper Floridan aquifer through localized “source areas,” which represent areas where the confining units overlying the aquifer are thin or absent. As sea level rises, an increasing area will be covered by a source of saltwater that may leak downward into the aquifer.

Modeling results indicate that the conceptual model and(or) model configuration may explain some, but not all, of the observed salinity in the Upper Floridan aquifer. Inferred saltwater plumes at the northern end of Hilton Head Island, at Pinckney Island, and at the Colleton River are simulated by the model, but salinities between Calibogue Sound and the Colleton River are underestimated by the model. The model configuration does not account for saline water in the overlying emergent wetlands, which may be a source of saltwater that leaks downward in a more diffuse way than the conceptual model that is implemented can simulate. Furthermore, land-surface altitude values from the 30-m digital elevation model are probably inaccurate in some areas, as indicated by comparison with 7.5-minute topographic maps. Alternatively, there may be additional localized areas of high permeability, or source areas, in the confining unit that are not accounted for or are unknown. The model results do not preclude the possibility that other mechanisms, such as upward flow from below the Upper Floridan aquifer or lateral flow from more distal, offshore sources, may contribute to the observed salinity distribution.

The model was tested for sensitivity to various parameters and boundary conditions. Although relative parameter sensitivities were not rigorously quantified, the results indicate that the evolution of the chloride plumes was found to be particularly sensitive to the confining-unit permeability of the localized designated source areas and the overall unit. Reducing source-area confining-unit permeability values and increasing the overall confining-unit permeability resulted in a reduction of plume extent. Reducing the permeability of the source-area confining-unit permeability limits the amount of saltwater that enters the Upper Floridan aquifer. Increasing the overall confining-unit permeability allows more freshwater to recharge the Upper Floridan aquifer, keeping water levels high and preventing saltwater from entering the aquifer. The evolution of chloride plumes also is sensitive to Upper Floridan aquifer permeability, effective porosity, and the water-table altitude. Simulated water levels are particularly sensitive to the overall confining-unit permeability and to the Upper Floridan aquifer permeability.

Scenario simulation results indicate that, if present-day (year 2004) pumping conditions are maintained, the extent of saltwater in the Upper Floridan aquifer will increase, whether or not sea level continues to rise. The rate at which sea level rises primarily affects the simulated plume extent in the Pinckney Island area. Because of low land-surface altitudes there, a larger area changes from a freshwater to a saltwater boundary condition with rising sea level than in other areas. It is possible that with more accurate land-surface altitude data and more refined discretization and boundary conditions, simulated saltwater transport will be affected by sea-level rise in other low-lying areas, such as between Calibogue Sound and the Colleton River. Model results indicate that if all pumpage is eliminated and sea level continues to rise, the simulated saltwater extent in the Upper Floridan aquifer is reduced, particularly in the Pinckney Island area. These results indicate that pumpage is a strong driving force for saltwater intrusion, more so than sea-level rise. There is likely an optimal overall pumpage reduction from the 2004 distribution that would result in a minimally changed saltwater distribution for a given sea-level-rise rate.

The model provides estimates of the future evolution of the observed chloride distribution and water levels in the Upper Floridan aquifer with changing sea level and with pumpage elimination. However, uncertainty in field data, the conceptual model, the physical properties and representation of the hydrogeologic framework, and boundary and initial conditions limits the accuracy and applicability of the model, particularly for simulations projected far into the future. The conceptual model could be refined with data-collection programs aimed at identifying the pervasiveness of saltwater leakage through the confining unit, such as collection of pore-water samples or use of remote geophysical techniques like resistivity surveys. Continuous or consistent regular monitoring of Upper Floridan aquifer salinity and water levels at key locations could help to constrain estimations of saltwater transport rates. Resampling of the Upper Floridan aquifer under Port Royal Sound in locations sampled in the 1980s and analyzing for chloride concentration could improve the understanding of the conceptual model. Finally, a more quantitative sensitivity analysis of hydraulic properties could provide information for calibration and predictive uncertainties, and also could help focus additional data-collection programs.

In general, the accuracy with which the model can be expected to reproduce field measurements and predict the future evolution of chloride distribution in the Upper Floridan aquifer in the study area is limited by the sources of uncertainty in the model. Taking these uncertainties into account, it is reasonable to interpret the model results presented in this report as reproducing, in a general way, the observed chloride distribution and trends in the Upper Floridan aquifer. Further, the model results provide an indication of the relative effects of different sea-level-rise rates for conservative pumping rates (2004 pumping levels maintained after 2004) for the given conceptual model.

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Appendix 1. Relation Between Specific Conductance and Chloride Concentration

Water-quality data for samples collected from the Upper Floridan aquifer offshore of Hilton Head Island and onshore at and near Hilton Head Island (table 1–1) were used to determine a relation between specific conductance and concentration in the study area. Data from Landmeyer and Belval (1996) and Falls and others (2005) were plotted with specific conductance as an independent variable and chloride concentration as a dependent variable. Specific conductance (in microsiemens per centimeter at 25 degrees Celsius) and chloride concentration (in milligrams per liter) values were log transformed, and a binomial regression resulted in the following relation:

$$y = -0.4057x^2 + 4.2301x - 6.8116\ , \qquad (1\text{–}1)$$

where

y is the log of chloride concentration in milligrams per liter, and

x is the log of specific conductance in microsiemens per centimeter at 25 degrees Celsius.

For this regression, $R^2 = 0.94$.

The fit of these data to this function is estimated using standard error and the 95-percent confidence interval. There is more scatter in the log-transformed data at lower values than at higher values. In consideration of this scale-dependent error, the data were segregated into three groups; for log specific conductance values 2–3, 3–4, and greater than 4 (or, for normalized specific conductance values, 100–1,000, 1,000–10,000, and greater than 10,000). Standard error and 95-percent confidence interval for the log transformed values were determined for each bin (table 1–2). Figure 1–1 shows the data, the predicted function relating chloride concentration to specific conductance, and standard error and 95-percent confidence intervals around the function.

To provide estimates for model calibration, the maximum chloride concentration was estimated from the maximum specific conductance value observed in vertical profiles at observation sites in the Hilton Head Island area (Childress and Ransom, 2005; Rob Devlin, South Carolina Department of Health and Environmental Control, written commun., December 21, 2007; fig. 1–2). Most of the data used for calibration were collected in 2004, but data for well BFT-2310 from 2003 were included to provide relevant spatial information regarding the distribution of chloride in the Upper Floridan aquifer west of Hilton Head Island and Calibogue Sound. Estimates of maximum chloride concentration, as well as the standard error brackets and 95-percent confidence interval, are listed in table 1–3.

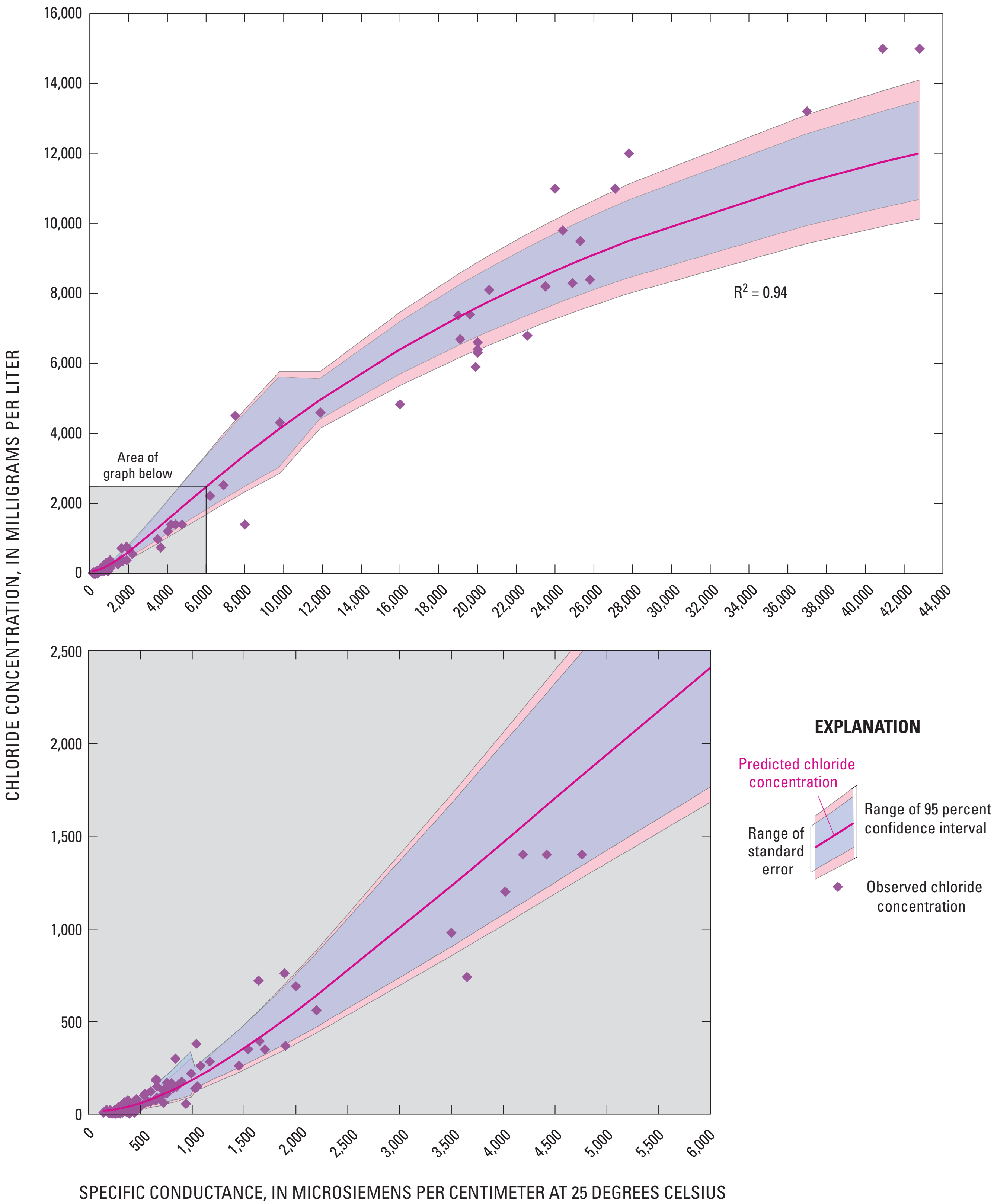

Figure 1–1. Relation between specific conductance and chloride concentration for sites beneath Port Royal Sound, onshore at and near Hilton Head Island, and offshore of Hilton Head Island, South Carolina.

Figure 1–2. Specific conductance observation sites in the Hilton Head Island area, South Carolina, during 2004.

Table 1–1. Observed specific conductance and chloride concentrations of groundwater in the Upper Floridan aquifer in the Hilton Head Island and Port Royal Sound area, South Carolina.

[Source of data: 1, Landmeyer and Belval, 1996; 2, Falls and others, 2005; ft, feet; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; —, no data]

Well identification	Sample date	Source of data	Depth to top of open interval, ft	Depth to bottom of open interval, ft	Specific conductance, µS/cm	Chloride concentration, mg/L
39Q025	8/19/1997	2	115	135	265	13
BFT-0018	7/26/1956	1	—	—	297	7.5
BFT-0022	1/27/1956	1	—	84	371	9
BFT-0029	7/11/1956	1	—	87	533	56
BFT-0100	10/21/1953	1	—	200–235	243	3.5
BFT-0102	8/27/1954	1	—	300	939	56
BFT-0102	4/21/1955	1	—	300	1,170	282
BFT-0103	8/27/1954	1	—	96	4,130	22
BFT-0104	10/20/1954	1	—	100	216	6.2
BFT-0106	3/25/1955	1	—	81	274	24
BFT-0114	4/21/1955	1	—	100	256	8.5
BFT-0117	3/30/1957	1	—	95	328	7.2
BFT-0121	1/14/1977	1	—	105	240	7.2
BFT-0121	2/27/1985	1	84	100	241	5.7
BFT-0124	4/6/1966	1	97	107	297	6.4
BFT-0131	3/28/1956	1	—	113	305	7.8
BFT-0132	00/00/1956	1	—	103	305	7
BFT-0133	3/15/1956	1	—	110	353	38
BFT-0138	7/11/1956	1	—	400–600	444	9.5
BFT-0146	7/20/1956	1	—	265	329	20
BFT-0159	1/24/1984	1	—	50	195	9
BFT-0181	12/20/1984	1	93	117	4,760	1,400
BFT-0182	7/11/1956	1	—	50	349	18
BFT-0182	9/10/1958	1	—	52	339	17
BFT-0184	7/11/1956	1	—	50	241	12
BFT-0210	5/21/1985	1	130	160	325	17
BFT-0287	4/5/1966	1	90	195	445	31
BFT-0314	4/13/1965	1	125	230	145	7.6
BFT-0315	4/13/1965	1	—	190	573	70
BFT-0317	4/5/1966	1	86	196	399	33
BFT-0343	4/5/1966	1	124	200	356	34
BFT-0401	4/4/1966	1	140	214	756	112
BFT-0430	3/22/1984	1	—	92	6,200	2,218
BFT-0439	7/23/1985	1	182	195	332	29
BFT-0439	7/23/1985	1	182	195	332	49
BFT-0441	1/10/1985	1	187	216	500	43
BFT-0452	3/22/1984	1	—	78	37,000	13,210
BFT-0453	4/16/1985	1	85	105	289	38
BFT-0453	6/4/1986	1	85	105	303	6.6
BFT-0455	3/22/1984	1	—	98	16,000	4,839

Table 1–1. Observed specific conductance and chloride concentrations of groundwater in the Upper Floridan aquifer in the Hilton Head Island and Port Royal Sound area, South Carolina.—Continued

[Source of data: 1, Landmeyer and Belval, 1996; 2, Falls and others, 2005; ft, feet; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; —, no data]

Well identification	Sample date	Source of data	Depth to top of open interval, ft	Depth to bottom of open interval, ft	Specific conductance, µS/cm	Chloride concentration, mg/L
BFT-0456	4/11/1984	1	—	75	19,000	7,373
BFT-0458	10/21/1974	1	—	71	272	5.1
BFT-0459	11/15/1976	1	—	106	24,000	11,000
BFT-0459	2/26/1985	1	85	100	4,020	1,200
BFT-0468	4/11/1984	1	—	63	340	17.5
BFT-0470	3/22/1984	1	—	62	370	16.3
BFT-0472	4/11/1984	1	—	99	575	67.5
BFT-0488	4/11/1984	1	—	100	500	44.9
BFT-0506	4/11/1984	1	—	75	170	22.7
BFT-0510	4/11/1984	1	—	60	650	74
BFT-0519	4/11/1984	1	—	60	385	17.5
BFT-0530	3/26/1984	1	—	190	720	126.9
BFT-0534	3/22/1984	1	—	110	350	20.2
BFT-0549	4/11/1984	1	—	30	370	39.5
BFT-0556	2/23/1977	1	—	35	2200	560
BFT-0562	11/24/1975	1	—	120	20,000	6,600
BFT-0562	3/22/1984	1	—	92	20,000	6,308
BFT-0563	11/25/1975	1	—	100	350	25
BFT-0565	11/25/1975	1	—	170	8,000	1,400
BFT-0565	5/22/1985	1	89	207	11,900	4,600
BFT-0565	5/22/1985	1	89	207	11,900	4,600
BFT-0566	2/25/1985	1	184	232	42,800	15,000
BFT-0569	11/25/1975	1	—	70	7,500	4,500
BFT-0569	4/11/1984	1	—	40	6,900	2,524
BFT-0591	4/11/1984	1	—	60	192	9.5
BFT-0599	1/24/1984	1	—	100	410	20.5
BFT-0782	1/11/1984	1	—	90	295	16.8
BFT-0786	1/14/1977	1	—	524	1,700	350
BFT-0787	1/14/1977	1	—	239	600	67
BFT-0787	4/23/1985	1	126	239	479	63
BFT-0791	3/6/1985	1	81	102	436	28
BFT-0795	1/16/1985	1	77	91	40,900	15,000
BFT-0825	2/23/1977	1	—	150	220	5.7
BFT-0966	3/26/1984	1	—	911	850	147
BFT-0969	3/26/1984	1	—	105	455	28.6
BFT-0970	3/26/1984	1	—	159	390	18.6
BFT-0989	4/11/1984	1	—	91	470	31
BFT-1043	1/24/1984	1	—	99	345	63
BFT-1253	1/24/1984	1	—	70	320	17
BFT-1260	3/22/1984	1	—	92	340	18.2

Table 1–1. Observed specific conductance and chloride concentrations of groundwater in the Upper Floridan aquifer in the Hilton Head Island and Port Royal Sound area, South Carolina.—Continued

[Source of data: 1, Landmeyer and Belval, 1996; 2, Falls and others, 2005; ft, feet; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; —, no data]

Well identification	Sample date	Source of data	Depth to top of open interval, ft	Depth to bottom of open interval, ft	Specific conductance, µS/cm	Chloride concentration, mg/L
BFT-1270	1/11/1984	1	—	70	275	12.5
BFT-1288	3/22/1984	1	—	94	364	18.2
BFT-1288	1/4/1985	1	60	115	208	22
BFT-1404	3/22/1984	1	—	40	295	15.3
BFT-1421	1/24/1984	1	—	90	490	50
BFT-1428	3/22/1984	1	—	82	342	23.4
BFT-1458	4/11/1984	1	—	45	750	144
BFT-1459	4/11/1984	1	—	63	725	61
BFT-1504	4/11/1984	1	—	50	900	173.9
BFT-1509	1/24/1984	1	—	200	182	19
BFT-1514	1/24/1984	1	—	90	250	14
BFT-1520	3/22/1984	1	—	50	1,650	395
BFT-1537	1/24/1984	1	—	70	990	217.9
BFT-1545	1/11/1984	1	—	60	600	122
BFT-1549	3/22/1984	1	—	81	175	16.3
BFT-1557	3/22/1984	1	—	75	400	19
BFT-1560	4/11/1984	1	—	52	400	39
BFT-1578	1/11/1984	1	—	70	277	12
BFT-1579	1/11/1984	1	—	100	250	11.5
BFT-1580	1/11/1984	1	—	50	260	8.2
BFT-1581	1/11/1984	1	—	63	318	13.9
BFT-1582	1/11/1984	1	—	80	255	12
BFT-1584	1/11/1984	1	—	130	220	11.5
BFT-1587	3/22/1984	1	—	85	465	77.3
BFT-1593	1/24/1984	1	—	70	2,000	690
BFT-1594	1/24/1984	1	—	100	440	68
BFT-1598	3/22/1984	1	—	65	260	7.5
BFT-1603	2/21/1984	1	—	43	1,040	378.7
BFT-1604	2/21/1984	1	—	105	460	80.3
BFT-1610	2/21/1984	1	—	57	250	22.6
BFT-1610	2/21/1984	1	—	63	263	23.1
BFT-1610	2/21/1984	1	—	66	320	27.4
BFT-1610	2/21/1984	1	—	66	348	33.2
BFT-1612	4/11/1984	1	—	75	430	49
BFT-1613	4/11/1984	1	—	70	405	22
BFT-1614	4/11/1984	1	—	70	800	165.9
BFT-1615	4/11/1984	1	—	65	342	16.5
BFT-1616	4/11/1984	1	—	75	420	21
BFT-1617	4/11/1984	1	—	45	380	50
BFT-1618	4/11/1984	1	—	45	9,800	4,308

Table 1–1. Observed specific conductance and chloride concentrations of groundwater in the Upper Floridan aquifer in the Hilton Head Island and Port Royal Sound area, South Carolina.—Continued

[Source of data: 1, Landmeyer and Belval, 1996; 2, Falls and others, 2005; ft, feet; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; —, no data]

Well identification	Sample date	Source of data	Depth to top of open interval, ft	Depth to bottom of open interval, ft	Specific conductance, µS/cm	Chloride concentration, mg/L
BFT-1619	4/11/1984	1	—	70	390	59
BFT-1672	7/23/1984	1	75	107	1,080	260
BFT-1672	7/23/1984	1	174	211	24,400	9,800
BFT-1672	7/23/1984	1	174	211	23,500	8,200
BFT-1673	8/2/1984	1	85	101	652	190
BFT-1673	8/3/1984	1	170	208	20,000	6,400
BFT-1673	8/3/1984	1	170	208	23,500	8,200
BFT-1673	8/2/1994	1	85	101	652	180
BFT-1674	8/9/1984	1	101	113	660	150
BFT-1674	8/9/1984	1	101	113	705	98
BFT-1674	8/10/1984	1	170	174	27,800	12,000
BFT-1674	8/10/1984	1	170	174	27,100	11,000
BFT-1675	8/23/1984	1	89	103	536	100
BFT-1675	8/24/1984	1	89	103	544	110
BFT-1675	8/24/1984	1	186	212	871	160
BFT-1675	8/24/1984	1	186	212	838	300
BFT-1676	8/30/1984	1	97	110	380	74
BFT-1676	8/30/1984	1	97	110	354	54
BFT-1676	8/31/1984	1	178	182	1,640	720
BFT-1676	8/31/1984	1	178	182	1,890	760
BFT-1677	9/7/1984	1	92	99	4,420	1,400
BFT-1677	9/7/1984	1	92	99	4,190	1,400
BFT-1677	9/8/1984	1	159	176	19,100	6,700
BFT-1677	9/8/1984	1	159	176	19,600	7,400
BFT-1678	9/20/1984	1	76	86	757	170
BFT-1678	9/20/1984	1	76	86	789	150
BFT-1678	9/21/1984	1	151	155	1,050	150
BFT-1678	9/21/1984	1	151	155	1,030	140
BFT-1679	9/27/1984	1	108	120	1,450	260
BFT-1679	9/27/1984	1	108	120	1,450	260
BFT-1680	10/5/1984	1	103	117	20,600	8,100
BFT-1680	10/5/1984	1	103	117	19,900	5,900
BFT-1680	10/5/1984	1	173	218	25,300	9,500
BFT-1680	10/5/1984	1	173	218	24,900	8,300
BFT-1689	1/11/1985	1	91	203	246	3.9
BFT-1754	4/22/1985	1	66	75	2,390	5.8
BFT-1810	1/28/1987	1	175	202	1,540	350
BFT-1810	1/29/1987	1	102	125	266	20
BFT-1814	1/13/1987	1	175	220	816	140
BFT-1814	1/15/1987	1	102	150	658	90

Table 1–1. Observed specific conductance and chloride concentrations of groundwater in the Upper Floridan aquifer in the Hilton Head Island and Port Royal Sound area, South Carolina.—Continued

[Source of data: 1, Landmeyer and Belval, 1996; 2, Falls and others, 2005; ft, feet; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; —, no data]

Well identification	Sample date	Source of data	Depth to top of open interval, ft	Depth to bottom of open interval, ft	Specific conductance, µS/cm	Chloride concentration, mg/L
BFT-1841	2/3/1987	1	96	100	3,500	980
BFT-2249	6/13/2000	2	78	135	1,900	370
BFT-2251	6/25/2000	2	198	220	472	25
BFT-2251	6/28/2000	2	93	698	3,650	740
BFT-2258	9/10/1999	2	91	154	22,570	6,800
BFT-2295	6/4/2001	2	95.5	107	25,800	8,400
BFT-2297	7/20/2001	2	103	121	231	9.3
HAM-0073	2/23/1977	1	—	200	260	3.7
HAM-0122	6/25/1985	1	82	174	285	5.2
HAM-0122	6/25/1985	1	82	174	285	3.3
HAMPTON	1/3/1956	1	—	667	395	3.4
Hardeeville	10/11/1956	1	—		229	4
JAS-0018	1/24/1958	1	—		305	6
JAS-0101	10/11/1956	1	—	450	305	4
JAS-0104	4/14/1957	1	—	330	254	4.2
JAS-0104	5/2/1957	1	—	330	265	2.5
JAS-0104	5/3/1957	1	—	330	271	6.5
JAS-0136	6/26/1985	1	200	245	200	5.1
JAS-0136	6/26/1985	1	200	245	200	4.3
Ridgeland	10/11/1956	1	—	459	307	5.8
Ridgeland Well #102	6/18/1954	1	—	210	309	5.2

Table 1–2. Standard error and 95 percent confidence interval for chloride concentration calculated as a function of specific conductance for each group of specific conductance values.

[µS/cm, microsiemen per centimeter; mg/L, milligram per liter]

Range of specific conductance values, log µS/cm	Standard error, log mg/L chloride	95 percent confidence interval, log mg/L chloride
2 to 3	0.28	0.031
3 to 4	0.14	0.035
Greater than 4	0.051	0.015

Table 1–3. Observed specific conductance and estimated chloride concentration and simulated chloride concentration during 2004 for sites in the Hilton Head Island area used for model calibration.

[ft, foot; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; <, less than; —, no data]

Well identifier	Altitude of sampling interval, ft	Date	Maximum recorded value of specific conductance, µS/cm	Estimated chloride concentration, mg/L	Estimated chloride concentration, log mg/L	Simulated chloride concentration, log mg/L	Simulated minus estimated chloride concentration, log mg/L (residual)
BFT-0250	–133.1 to –183.1	3/16/2004	279	12	1.09	$< 3.7 \times 10^{-6}$	–1.09
		7/13/2004	268	—	—	—	—
BFT-0315	–157.2 to –172.2	3/15/2004	4,900	1,878	3.27	3.87	0.59
BFT-0321	–124.7 to –215.7	3/14/2004	929	141	2.15	0.93	–1.22
		8/2/2004	880	—	—	—	—
BFT-0358	–81 to –360	3/3/2004	265	12	1.07	$< 3.7 \times 10^{-6}$	–1.07
		10/4/2004	270	—	—	—	—
BFT-0429	–99 to –280	3/4/2004	6,640	2,794	3.45	1.08	–2.37
		7/19/2004	6,850	—	—	—	—
		10/4/2004	7,100	—	—	—	—
BFT-0436	–126.8 to –188.8	3/10/2004	887	127	2.1	$< 3.7 \times 10^{-6}$	–2.1
		8/2/2004	824	—	—	—	—
BFT-0437	–130 to –192	3/16/2004	635	72	1.86	$< 3.7 \times 10^{-6}$	–1.86
		8/2/2004	635	—	—	—	—
BFT-0441	–114.8 to –207.8	3/15/2004	1,363	361	2.55	2.67	0.12
		7/26/2004	1,560	—	—	—	—
		10/24/2004	1,740	—	—	—	—
BFT-0444	–129.4 to –195.4	3/14/2004	875	127	2.1	$< 3.7 \times 10^{-6}$	–2.1
		8/2/2004	832	—	—	—	—
BFT-0500	–80 to –330	3/3/2004	292	14	1.15	$< 3.7 \times 10^{-6}$	–1.15
BFT-0502	–69.7 to –212.7	3/3/2004	12,720	5,600	3.75	3.47	–0.27
		6/17/2004	14,880	—	—	—	—
		10/9/2004	14,990	—	—	—	—
BFT-0570	–64.8 to –351.8	7/13/2004	255	10	1.02	$< 3.7 \times 10^{-6}$	–1.02
BFT-0787	–115 to –229	1/28/2004	18,100	7,106	3.85	4.21	0.36
		7/14/2004	18,900	—	—	—	—
BFT-1326	–116.5 to –176.5	1/16/2004	3,840	1,460	3.16	$< 3.7 \times 10^{-6}$	–3.16
		6/11/2004	4,200	—	—	—	—
BFT-1591	–114.1 to –239.1	10/14/2004	10,750	4,448	3.65	3.18	–0.47
BFT-1689	–81.57 to –195.57	1/11/2004	241	10	0.98	0.39	–0.59
		6/23/2004	250	—	—	—	—
BFT-1810	–93.4 to –189.4	3/16/2004	16,200	5,746	3.76	3.72	–0.04
		7/30/2004	12,430	—	—	—	—
BFT-1814	–108.3 to –198.3	2/5/2004	3,890	1,437	3.16	2.58	–0.58
		7/14/2004	4,050	—	—	—	—
BFT-1822	–80.1 to –249.1	2/3/2003	484	42	1.62	$< 3.7 \times 10^{-6}$	–1.62
BFT-1846	–71.6 to –166.6	1/16/2004	10,340	4,560	3.66	3.88	0.22
		6/8/2004	11,750	—	—	—	—
		10/8/2004	10,800	—	—	—	—

Table 1–3. Observed specific conductance and estimated chloride concentration and simulated chloride concentration during 2004 for sites in the Hilton Head Island area used for model calibration.—Continued

[ft, foot; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; <, less than; —, no data]

Well identifier	Altitude of sampling interval, ft	Date	Maximum recorded value of specific conductance, µS/cm	Estimated chloride concentration, mg/L	Estimated chloride concentration, log mg/L	Simulated chloride concentration, log mg/L	Simulated minus estimated chloride concentration, log mg/L (residual)
BFT-2162	–107.2 to –206.2	3/10/2004	720	109	2.03	3.81	1.77
		6/25/2004	855	—	—	—	—
BFT-2163	–109 to –207	3/10/2004	449	36	1.56	3.79	2.24
		6/25/2004	452	—	—	—	—
BFT-2164	–94.2 to –198.2	2/10/2004	7,170	2,973	3.47	3.5	0.03
		7/29/2004	7,360	—	—	—	—
BFT-2165	–106.5 to –186.5	1/11/2004	259	11	1.04	1.69	0.64
		7/12/2004	264	—	—	—	—
BFT-2166	–66.4 to –200.4	3/2/2004	30,000	9,795	3.99	3.94	–0.05
		7/29/2004	29,100	—	—	—	—
BFT-2187	–103.4 to –201.4	2/11/2004	19,600	7,509	3.88	4.28	0.4
		7/31/2004	20,200	—	—	—	—
BFT-2188	-97.9 to -198.9	2/1/2004	26,600	9,285	3.97	4.08	0.11
		7/29/2004	27,600	—	—	—	—
BFT-2189	–78.6 to –176.6	2/27/2004	14,110	5,813	3.76	3.04	–0.73
		7/21/2004	14,780	—	—	—	—
BFT-2190	–80.4 to –180.4	2/27/2004	700	95	1.98	2.09	0.12
		7/21/2004	768	—	—	—	—
BFT-2196	–84.7 to –194.7	2/10/2004	13,860	5,611	3.75	3.69	–0.06
BFT-2197	–86.1 to –196.1	2/10/2004	12,980	5,296	3.72	3.65	–0.08
BFT-2198	–104.7 to –190.7	2/11/2004	9,510	5,024	3.7	4.29	0.59
		7/31/2004	15,300	—	—	—	—
BFT-2199	–103.3 to –208.3	2/11/2004	27,000	8,086	3.91	4.27	0.36
		4/21/2004	27,700	—	—	—	—
		7/31/2004	17,340	—	—	—	—
BFT-2200	–104 to –189	3/4/2004	32,300	10,181	4.01	4.29	0.29
		7/31/2004	30,800	—	—	—	—
BFT-2201	–87.6 to –203.6	2/11/2004	30,700	10,021	4	4.21	0.21
BFT-2245	–138.9 to –238.9	3/5/2004	286	14	1.13	0.76	–0.37
BFT-2247	–129.9 to –165.9	3/5/2004	251	10	1	$< 3.7 \times 10^{-6}$	–1.00
BFT-2299	–64.3 to –153.3	1/16/2004	2,540	875	2.94	$< 3.7 \times 10^{-6}$	–2.94
		6/23/2004	2,990	—	—	—	—
BFT-2300	–68.8 to –150.8	1/11/2004	3,590	1,418	3.15	$< 3.7 \times 10^{-6}$	–3.15
		6/23/2004	4,270	—	—	—	—
BFT-2301	–69.6 to –146.6	1/16/2004	33,600	11,010	4.04	4.06	0.01
		6/21/2004	39,300	—	—	—	—
BFT-2302	–62 to –163	1/16/2004	238	9	0.97	3	2.03
		6/23/2004	247	—	—	—	—

Table 1–3. Observed specific conductance and estimated chloride concentration and simulated chloride concentration during 2004 for sites in the Hilton Head Island area used for model calibration.—Continued

[ft, foot; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; <, less than; —, no data]

Well identifier	Altitude of sampling interval, ft	Date	Maximum recorded value of specific conductance, µS/cm	Estimated chloride concentration, mg/L	Estimated chloride concentration, log mg/L	Simulated chloride concentration, log mg/L	Simulated minus estimated chloride concentration, log mg/L (residual)
BFT-2303	–81.8 to –179.8	1/20/2004	342	19	1.28	$< 3.7 \times 10^{-6}$	–1.28
		6/11/2004	328	—	—	—	—
		10/11/2004	328	—	—	—	—
BFT-2304	–80.2 to –183.2	1/20/2004	5,270	2,272	3.35	$< 3.7 \times 10^{-6}$	–3.35
		6/11/2004	6,210	—	—	—	—
		10/11/2004	5,600	—	—	—	—
BFT-2305	–67.2 to –189.2	3/2/2004	270	11	1.06	$< 3.7 \times 10^{-6}$	–1.06
		7/9/2004	260	—	—	—	—
BFT-2306	–70.4 to –193.4	7/9/2004	221	8	0.88	$< 3.7 \times 10^{-6}$	–0.88
BFT-2307	–68.6 to –206.6	2/25/2004	306	16	1.2	$< 3.7 \times 10^{-6}$	–1.2
BFT-2308	–106.1 to –204.1	2/5/2004	510	48	1.69	1.47	–0.21
		7/14/2004	531	—	—	—	—
BFT-2309	–134 to –238	2/22/2004	521	47	1.67	$< 3.7 \times 10^{-6}$	–1.67
		7/16/2004	500	—	—	—	—
BFT-2310	–75.2 to –186.2	2/1/2003	6,240	2,418	3.38	0.16	–3.22
		8/28/2003	5,990	—	—	—	—
		12/22/2003	5,860	—	—	—	—
BFT-2311	–82.5 to –228.5	1/9/2004	199	7	0.86	$< 3.7 \times 10^{-6}$	–0.86
		1/11/2004	236	—	—	—	—
		7/9/2004	210	—	—	—	—
BFT-2312	–91 to –207	3/2/2004	22,400	8,165	3.91	3.38	–0.54
		7/29/2004	22,300	—	—	—	—
BFT-2313	–85 to –192	2/27/2004	35,100	10,768	4.03	3.87	–0.17
		7/29/2004	34,600	—	—	—	—
BFT-2314	–90.7 to –216.7	1/20/2004	441	33	1.52	1.32	–0.2
		7/12/2004	427	—	—	—	—
BFT-2315	–87.4 to –201.4	2/25/2004	326	18	1.25	1.08	–0.17
		7/13/2004	322	—	—	—	—
BFT-2401	–81.3 to –209.3	2/3/2004	15,500	5,719	3.76	4.07	0.31
		3/4/2004	16,300	—	—	—	—
		7/31/2004	12,200	—	—	—	—
BFT-2402	–84.7 to –234.7	2/3/2004	12,220	5,087	3.71	3.81	0.1
		3/4/2004	12,610	—	—	—	—
		7/31/2004	12,580	—	—	—	—
BFT-2404	–80.6 to –243.6	10/14/2004	630	71	1.85	2.11	0.26
BFT-2405	–81.1 to –231.1	10/14/2004	464	38	1.58	1.91	0.32
JAS-0134	–189.8 to –241.8	3/24/2004	219	7	0.87	$< 3.7 \times 10^{-6}$	–0.87

Appendix 2. Land-Surface Altitude-Bathymetry Discretization

The altitude of the top layer of nodes in the model was refined from the original SUTRA model (Provost and others, 2006) to more accurately represent land-surface altitude and bathymetry in the study area. In the original model, the top altitude was interpolated from a more coarsely discretized regional flow model (Payne and others, 2005), which sampled the 30-meter (m) digital elevation model (DEM) onshore and bathymetric data offshore. For this model, the 30-m DEM and bathymetric data were sampled directly at the locations of each node, following these steps:

1. For the entire onshore part of the model domain, the 30-m DEM (National Elevation Dataset, 2008) was sampled at the model mesh nodes;
2. For a subset of the model (fig. 2–1), nodes in the offshore area sampled the nearest bathymetry point value (National Oceanic and Atmospheric Administration, 2008);
3. The resulting land surface and bathymetric altitudes at the model node locations were then checked against 7-1/2-minute series topographic quadrangle maps (Spring Island, SC; Bluffton, SC; Parris Island, SC; Hilton Head, SC), and manually corrected where the 30-m DEM or bathymetric data were notably inconsistent with the topographic maps.

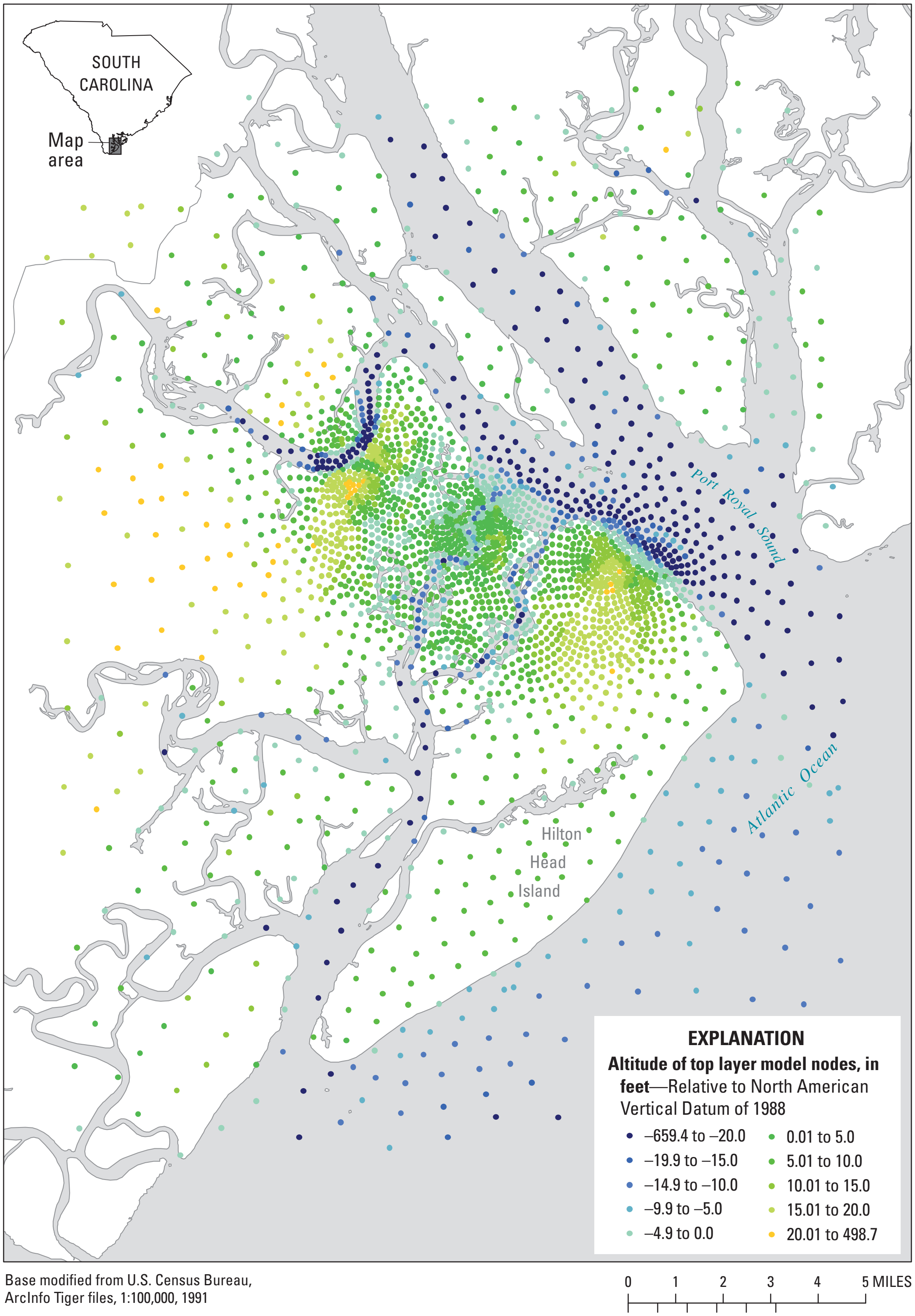

Figure 2–1. Altitude of top layer model nodes that were modified from original SUTRA model in the Hilton Head Island area, South Carolina.

Appendix 3. Estimation of Water-Table Altitude for Calculating Top Pressure Boundary Condition

The water-table altitude used to calculate the specified pressure at onshore nodes at the top boundary of the model was estimated using groundwater-level altitudes stored in the U.S. Geological Survey National Water Information System and land-surface altitudes derived from a digital-elevation model. The data used are described in Peck and Payne (2003). Data from 295 wells 100 feet or less in depth and distributed throughout the model area were used for the analysis. In order to achieve a relatively even spatial distribution, the data were temporally unconstrained, but were manually spatially culled to remove bias resulting from data clusters. Two methods were used to generate the land-surface altitude–water-table altitude relation.

Method 1: Simple Linear Function

A linear regression was used to determine a relation between land-surface altitude as the independent variable, and water-table altitude as the dependent variable. The function was constrained to intersect the x and y axes at zero, to result in a smooth transition between the onshore and offshore specified pressure at neighboring nodes:

$$y = 0.9295x \quad , \qquad (3–1)$$

where

y is the water-table altitude, and

x is the land-surface altitude at a specified location (fig. 3–1).

with an R^2 (also commonly known as the coefficient of determination) value of 0.99.

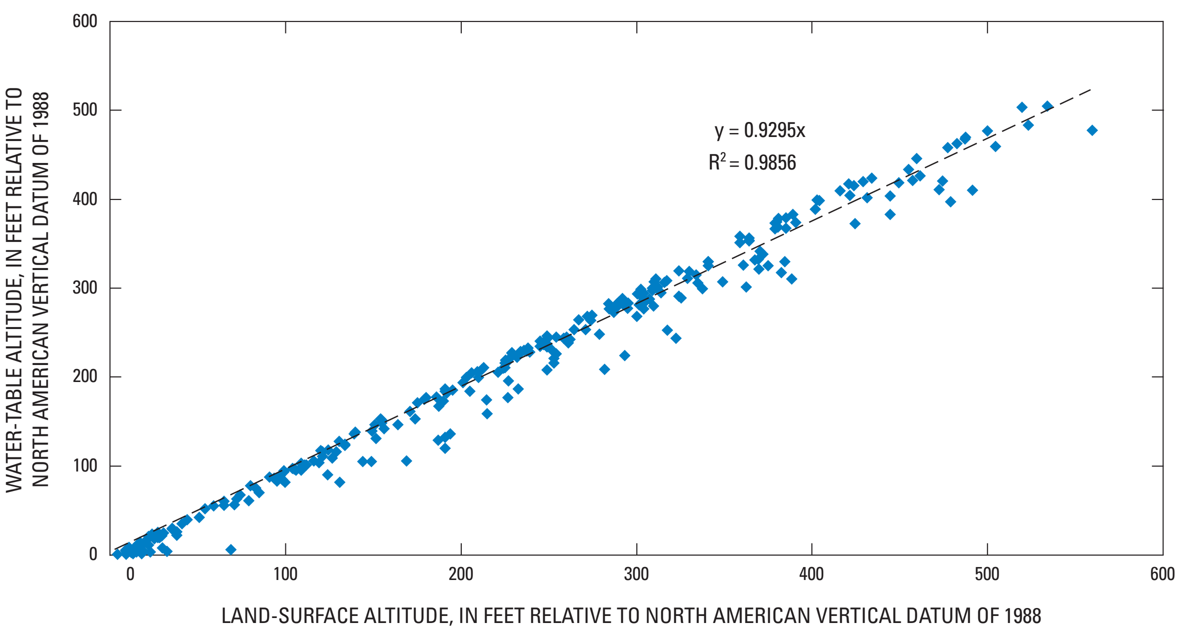

Figure 3–1. Linear relation between land-surface altitude and water-table altitude, method 1.

Method 2: Two-Piece Linear and Binomial Function

1. For method 1, the estimated water-table altitude tends to be too high for land-surface altitudes below about 30 feet (ft) (fig. 3–1). So, for land-surface altitudes below 30 ft relative to the North American Vertical Datum of 1988 (NAVD 88), a binomial regression, constrained to intersect the x and y axes at zero, was used to estimate water-table altitude:

$$y = 0.0141x^2 + 0.3119x \quad , \tag{3–2}$$

   with an R^2 value of 0.65 (fig. 3–2).

2. The intersection between these functions is at a land-surface altitude of about 44 ft. So for land-surface altitude above 44 ft, equation 3–1 is used to estimate the water-table altitude, and for land-surface altitude less than or equal to 44 ft, equation 3–2 is used.

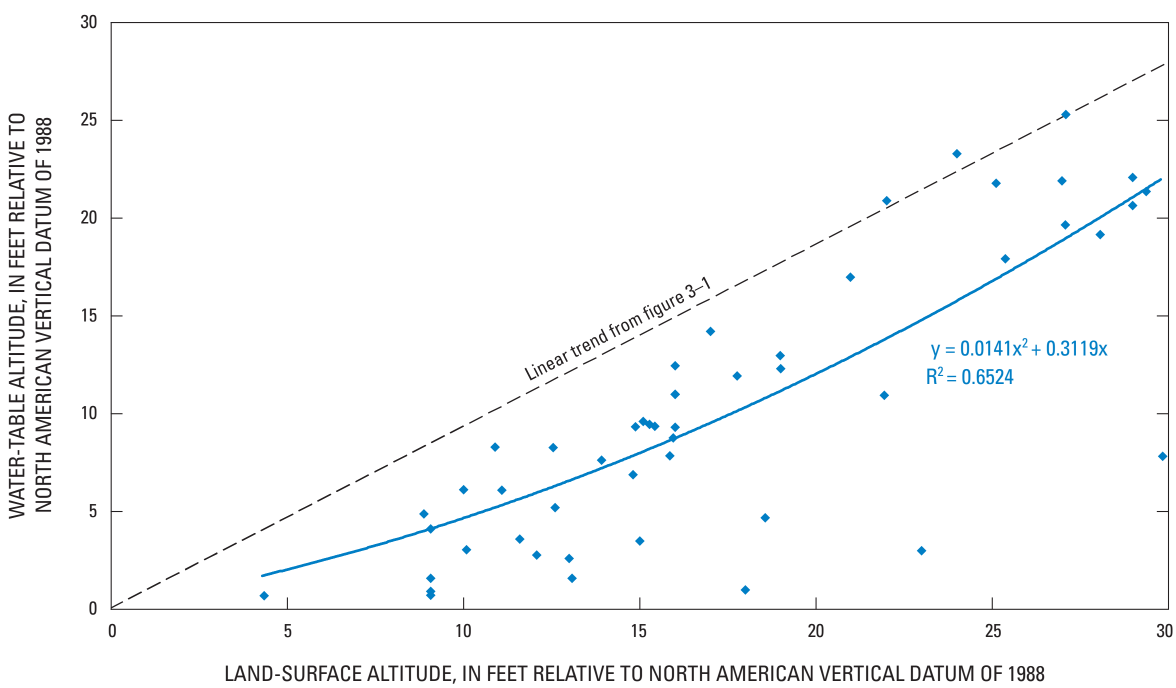

Figure 3–2. Binomial relation between land-surface and water-table altitudes for land-surface altitudes less than 30 feet, used in method 2.

Appendix 4. 2000 and 2004 Pumpage

Table 4–1. Upper Floridan aquifer pumpage in 2000 and 2004 for counties in model area.

State	County	Upper Floridan aquifer pumpage, in million gallons per day	
		2000	2004
Georgia	Appling	4.17	4.06
Georgia	Bacon	4.04	3.62
Georgia	Brantley	1.30	0.94
Georgia	Bryan	1.60	2.07
Georgia	Bulloch	5.70	5.64
Georgia	Burke	22.34	18.61
Georgia	Camden	50.55	6.30
Georgia	Candler	2.79	2.59
Georgia	Charlton	1.25	1.29
Georgia	Chatham	68.15	67.00
Georgia	Effingham	4.62	6.85
Georgia	Emanuel	4.22	3.57
Georgia	Evans	0.70	0.70
Georgia	Glynn	61.14	57.80
Georgia	Jenkins	4.03	3.92
Georgia	Liberty	15.69	15.78
Georgia	Long	0.69	0.98
Georgia	McIntosh	0.85	0.94
Georgia	Pierce	6.22	6.18
Georgia	Screven	16.24	14.25
Georgia	Tattnall	3.66	2.76
Georgia	Toombs	6.30	6.64
Georgia	Ware	8.45	5.82
Georgia	Wayne	63.47	63.12
South Carolina	Beaufort	21.44	19.74
South Carolina	Colleton	0.00	0.17
South Carolina	Jasper	3.34	2.65
Totals		**382.97**	**323.99**

Appendix 5. Water-Level Data and Simulated Water Levels

Table 5–1. Observed, simulated, and residual (simulated minus measured) water levels in 2004 in the study area.

[Longitude and latitude in decimal degrees (NAD 83); ft, foot]

State	County	Well identifier	Longitude	Latitude	Date measured, 2004	Land-surface altitude, ft	Measured water-level altitude, ft	Simulated water level altitude, assuming freshwater density, ft	Residual
Georgia	Bryan	35P110	–81.31639	31.91194	10/26	10.47	–17.76	–9.78	7.97
Georgia	Effingham	35T003	–81.31928	32.37686	10/26	40.00	3.14	–0.36	–3.50
Georgia	Chatham	36Q008	–81.14706	32.09187	10/26	9.91	–77.53	–73.88	3.64
		36Q020	–81.21317	32.00604	10/26	13.00	–35.57	–39.92	–4.35
		37P114	–81.01983	31.98521	10/26	10.00	–39.35	–37.18	2.16
		37Q016	–81.07400	32.07604	10/26	4.70	–71.06	–73.01	–1.95
		37Q185	–81.11011	32.10632	11/5	6.00	–78.09	–91.10	–13.01
		38Q002	–80.90317	32.03410	10/26	8.00	–24.43	–18.31	6.12
		39Q003	–80.85039	32.02299	10/26	7.00	–22.10	–15.42	6.69
South Carolina	Beaufort	BFT–0118	–80.75011	32.42218	10/27	15.00	–3.98	4.62	8.60
		BFT–0133	–80.71705	32.52242	10/28	12.12	0.76	3.67	2.91
		BFT–0145	–80.74066	32.55098	10/29	22.00	–13.36	4.66	18.02
		BFT–0181	–80.67983	32.30655	10/27	11.23	6.20	1.06	–5.14
		BFT–0198	–80.67150	32.44184	10/28	17.41	–0.03	5.10	5.13
		BFT–0301	–80.89928	32.34543	10/25	19.07	–12.25	–5.05	7.20
		BFT–0315	–80.72095	32.26551	10/25	16.06	0.13	0.02	–0.11
		BFT–0358	–80.82844	32.24883	10/26	20.00	–6.96	–5.68	1.28
		BFT–0374	–80.81705	32.23158	10/27	10.08	–10.99	–6.08	4.91
		BFT–0392	–80.77649	32.49548	10/27	15.38	–17.00	4.13	21.13
		BFT–0420	–80.72955	32.55520	10/28	17.49	–19.16	4.62	23.78
		BFT–0429	–80.81928	32.26406	11/24	22.00	–4.10	–4.21	–0.11
		BFT–0430	–80.64400	32.29048	10/29	5.53	3.08	0.01	–3.07
		BFT–0436	–80.74595	32.14494	10/26	11.00	–8.72	–8.60	0.12
		BFT–0441	–80.72816	32.24938	10/25	10.65	–1.36	–1.84	–0.48
		BFT–0444	–80.72678	32.17657	10/26	16.60	–5.74	–6.93	–1.19
		BFT–0449	–80.46094	32.32682	10/29	6.21	2.16	0.43	–1.73
		BFT–0452	–80.43871	32.40079	10/29	6.00	3.16	0.40	–2.76
		BFT–0455	–80.46816	32.32911	10/29	6.00	1.40	0.34	–1.06
		BFT–0461	–80.84150	32.68042	10/28	16.00	4.24	17.87	13.63
		BFT–0470	–80.60399	32.37047	10/28	–0.08	–5.93	1.68	7.61
		BFT–0471	–80.66705	32.40187	10/28	14.38	3.81	4.53	0.72
		BFT–0486	–80.83844	32.34330	10/25	15.00	–9.03	–2.26	6.77
		BFT–0488	–80.51261	32.40940	10/28	10.00	1.68	1.21	–0.47
		BFT–0493	–80.81400	32.28517	10/26	19.50	–2.80	–1.66	1.14
		BFT–0497	–80.49650	32.39607	10/28	6.02	2.34	0.81	–1.53
		BFT–0500	–80.82845	32.25072	10/26	21.00	–5.56	–5.54	0.02
		BFT–0501	–80.81372	32.28715	10/26	20.00	–0.90	–1.02	–0.12
		BFT–0559	–80.67288	32.43102	10/27	7.00	–1.21	5.51	6.72
		BFT–0563	–80.54649	32.37488	10/28	17.38	3.27	3.33	0.06
		BFT–0564	–80.62317	32.33517	10/28	19.17	4.13	0.90	–3.23
		BFT–0566	–80.69316	32.35241	10/28	13.06	3.81	3.09	–0.72
		BFT–0600	–80.56594	32.36295	10/28	10.00	5.58	2.36	–3.22
		BFT–0652	–80.71094	32.22354	10/25	17.14	–3.69	–4.85	–1.16
		BFT–0668	–80.75678	32.18719	10/25	10.00	–12.49	–7.21	5.28
		BFT–0676	–80.76872	32.21797	10/25	9.08	–10.05	–5.59	4.46
		BFT–0697	–80.72233	32.24350	10/25	18.32	–1.54	–2.55	–1.01
		BFT–0704	–80.76455	32.15382	10/26	9.08	–9.48	–9.35	0.13
		BFT–0709	–80.79400	32.13186	10/26	8.60	–12.08	–11.50	0.58
		BFT–0744	–80.77789	32.16629	10/26	9.08	–8.65	–9.38	–0.73

Table 5–1. Observed, simulated, and residual (simulated minus measured) water levels in 2004 in the study area.—Continued

[Longitude and latitude in decimal degrees (NAD 83); ft, foot]

State	County	Well identifier	Longitude	Latitude	Date measured, 2004	Land-surface altitude, ft	Measured water-level altitude, ft	Simulated water level altitude, assuming freshwater density, ft	Residual
South Carolina	Beaufort	BFT–0771	–80.69844	32.21854	10/26	10.07	–9.44	–5.85	3.59
Continued		BFT–0777	–80.68566	32.21021	10/26	10.00	–2.49	–5.30	–2.81
		BFT–0779	–80.73705	32.22603	10/26	16.00	–3.56	–4.62	–1.06
		BFT–0782	–80.63678	32.48965	10/28	17.44	3.01	3.56	0.55
		BFT–0787	–80.69816	32.24822	10/26	12.00	–1.52	–1.77	–0.25
		BFT–0798	–80.73816	32.49189	10/27	36.00	14.04	4.21	–9.83
		BFT–0805	–80.78150	32.18218	10/26	13.00	–9.35	–8.14	1.21
		BFT–0844	–80.85511	32.34016	10/25	1.07	–17.24	–3.30	13.94
		BFT–0976	–80.58705	32.34020	10/28	10.00	5.20	–0.68	–5.88
		BFT–0982	–80.65956	32.36468	10/28	9.14	1.58	2.58	1.00
		BFT–1212	–80.74011	32.57741	10/28	21.55	–10.98	7.13	18.11
		BFT–1239	–80.74678	32.16218	10/26	10.00	–5.53	–8.05	–2.52
		BFT–1292	–80.62038	32.35744	10/28	10.00	1.28	1.10	–0.18
		BFT–1306	–80.75955	32.46297	10/27	29.48	–0.56	4.29	4.85
		BFT–1311	–80.70399	32.50300	10/29	8.97	2.22	3.76	1.54
		BFT–1330	–80.81011	32.24050	10/27	15.02	–3.46	–5.16	–1.70
		BFT–1417	–80.61566	32.38855	10/27	10.00	1.60	2.30	0.70
		BFT–1418	–80.88511	32.28272	10/26	24.69	–16.44	–7.94	8.50
		BFT–1452	–80.86816	32.29353	10/26	19.50	–5.56	–6.35	–0.79
		BFT–1540	–80.53261	32.43329	10/29	10.00	1.36	1.50	0.14
		BFT–1548	–80.57260	32.38129	10/28	26.50	3.38	4.23	0.85
		BFT–1583	–80.65399	32.44604	10/28	15.00	2.24	4.89	2.65
		BFT–1592	–80.59482	32.35962	10/28	23.79	3.00	0.92	–2.08
		BFT–1599	–80.63233	32.47602	10/29	21.50	13.56	3.80	–9.76
		BFT–1604	–80.47289	32.43576	10/29	14.00	2.97	0.56	–2.41
		BFT–1605	–80.61260	32.45214	10/29	18.20	3.26	3.23	–0.03
		BFT–1609	–80.56094	32.46352	10/29	6.46	2.58	1.29	–1.29
		BFT–1701	–80.70317	32.38744	10/28	18.12	1.86	4.36	2.50
		BFT–1714	–80.70705	32.42822	10/27	20.18	2.70	5.74	3.04
		BFT–1717	–80.72205	32.44043	10/27	21.23	–6.59	5.51	12.10
		BFT–1732	–80.74733	32.48433	10/29	40.33	21.30	4.13	–17.17
		BFT–1733	–80.73233	32.51046	10/27	9.39	–2.18	4.04	6.22
		BFT–1736	–80.76900	32.40543	10/27	18.00	–0.59	2.54	3.13
		BFT–1800	–80.86288	32.26547	10/26	30.00	–10.27	–7.32	2.95
		BFT–1806	–80.78316	32.57966	10/28	24.00	–9.08	8.04	17.12
		BFT–1810	–80.72011	32.26520	10/26	14.00	0.35	0.06	–0.29
		BFT–1814	–80.67677	32.23302	10/26	12.00	0.61	–3.70	–4.31
		BFT–1822	–80.74899	32.20494	10/25	10.00	–4.12	–6.07	–1.95
		BFT–1870	–80.84094	32.24821	10/26	23.50	–8.05	–6.66	1.39
		BFT–1925	–80.74094	32.46988	10/27	38.76	21.96	4.51	–17.45
		BFT–1970	–80.69261	32.37523	10/29	12.78	6.88	3.96	–2.92
South Carolina	Jasper	JAS–0112	–81.11567	32.16571	10/26	10.00	–52.49	–51.40	1.09
		JAS–0298	–80.89594	32.45937	10/26	15.00	–7.63	2.49	10.12
		JAS–0397	–80.86789	32.52628	10/27	13.20	–3.30	5.78	9.08
		JAS–0402	–81.10677	32.46379	10/26	55.00	5.01	3.57	–1.44
		JAS–0406	–81.05788	32.59327	10/27	90.00	11.77	19.92	8.15
		JAS–0420	–81.12095	32.29824	10/26	21.00	–16.09	–20.07	–3.98
		JAS–0421	–81.05650	32.13129	10/26	10.00	–52.20	–52.60	–0.40

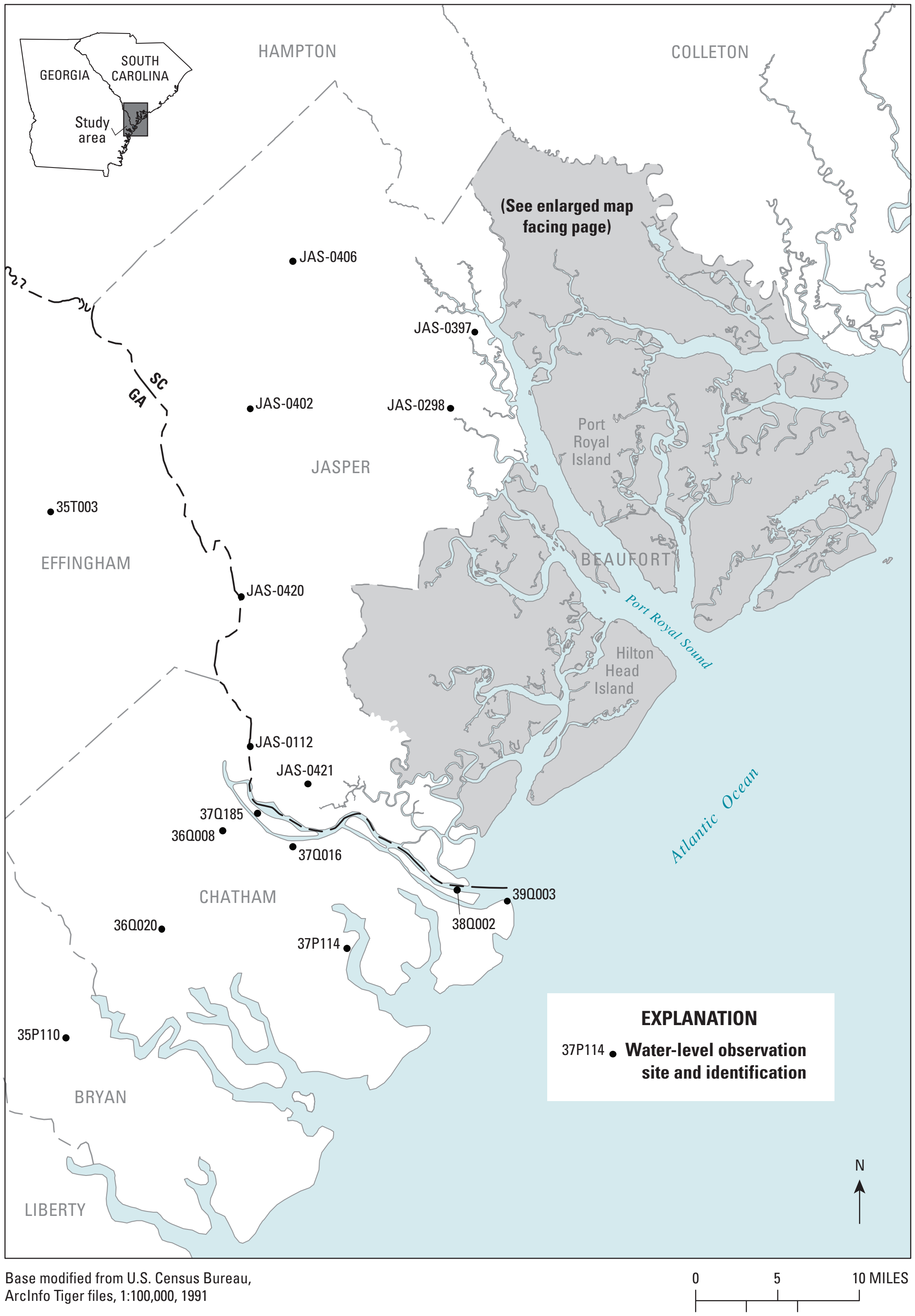

Figure 5–1. Water-level-observation sites in the Hilton Head Island area, South Carolina, during 2004.

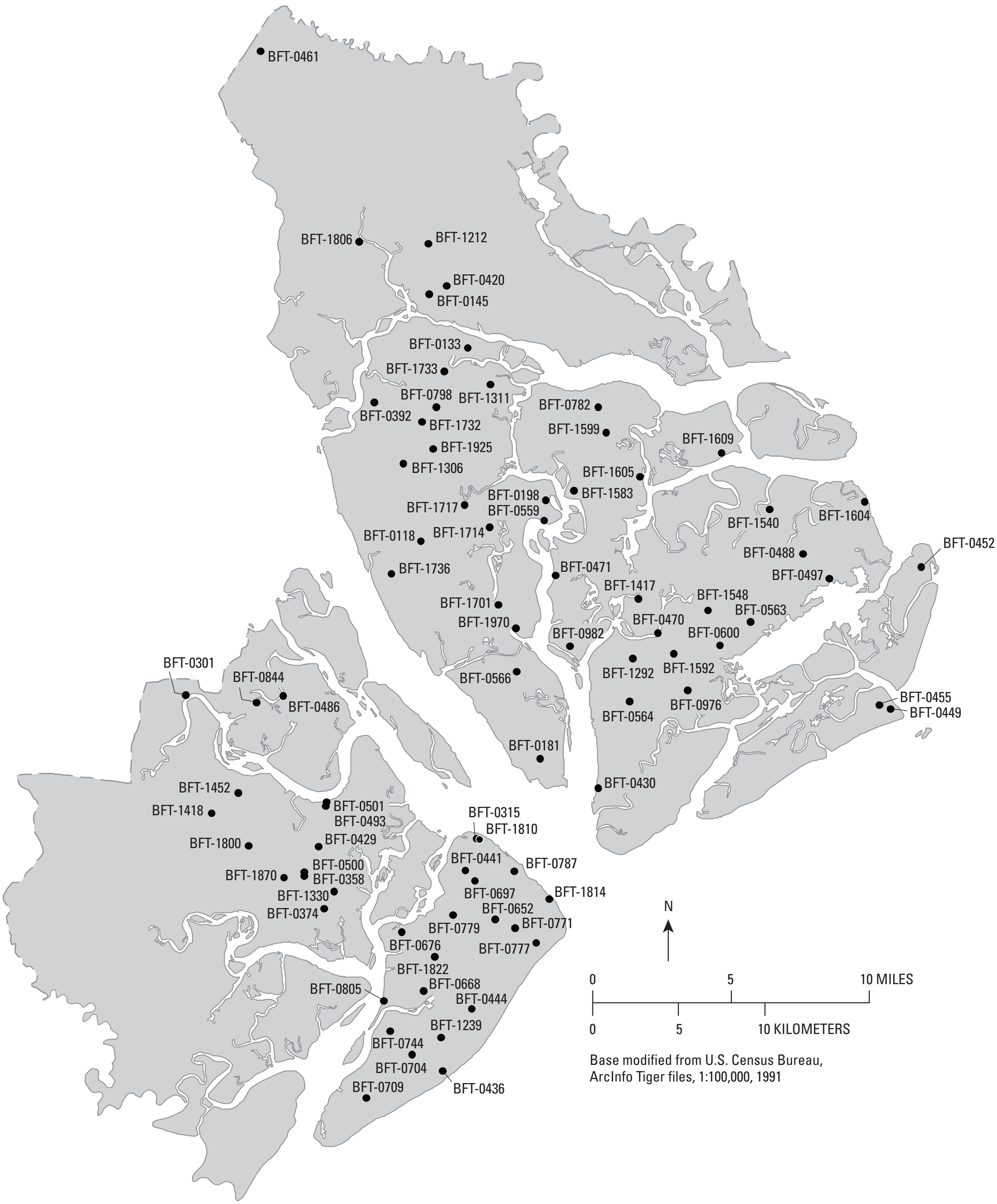

Figure 5–1. Water-level-observation sites in the Hilton Head Island area, South Carolina, during 2004.—Continued

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For more information about this publication, contact:
USGS Georgia Water Science Center
3039 Amwiler Road
Atlanta, GA 30360
telephone: 770-903-9100

http://ga.water.usgs.gov/

Edited by Kimberly A. Waltenbaugh

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