Design, revision, and application of ground-water flow models for simulation of selected water-management scenarios in the coastal area of Georgia and adjacent parts of South Carolina and Florida

Water-Resources Investigations Report 00-4084

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

U.S. Department of the Interior
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Cover photograph: Beach area at Jekyll Island, Georgia.
Photograph by Alan M. Cressler

DESIGN, REVISION, AND APPLICATION OF GROUND-WATER FLOW MODELS FOR SIMULATION OF SELECTED WATER-MANAGEMENT SCENARIOS IN THE COASTAL AREA OF GEORGIA AND ADJACENT PARTS OF SOUTH CAROLINA AND FLORIDA

By John S. Clarke and Richard E. Krause

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BRUCE BABBITT, SECRETARY

U.S. GEOLOGICAL SURVEY
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ABSTRACT

Ground-water flow models of the Floridan aquifer system in the coastal area of Georgia and adjacent parts of South Carolina and Florida, were revised and updated to ensure consistency among the various models used, and to facilitate evaluation of the effects of pumping on the ground-water level near areas of saltwater contamination. The revised models, developed as part of regional and areal assessments of ground-water resources in coastal Georgia, are—the Regional Aquifer-System Analysis (RASA) model, the Glynn County area (Glynn) model, and the Savannah area (Savannah) model. Changes were made to hydraulic-property arrays of the RASA and Glynn models to ensure consistency among all of the models; results of theses changes are evidenced in revised water budgets and calibration statistics.

Following revision, the three models were used to simulate 32 scenarios of hypothetical changes in pumpage that ranged from about 82 million gallons per day (Mgal/d) lower to about 438 Mgal/d higher, than the May 1985 pumping rate of 308 Mgal/d. The scenarios were developed by the Georgia Department of Natural Resources, Environmental Protection Division and the Chatham County-Savannah Metropolitan Planning Commission to evaluate water-management alternatives in coastal Georgia. Maps showing simulated ground-water-level decline and diagrams presenting changes in simulated flow rates are presented for each scenario.

Scenarios were grouped on the basis of pumping location—entire 24-county area, central subarea, Glynn-Wayne-Camden County subarea, and Savannah-Hilton Head Island subarea. For those scenarios that simulated decreased pumpage, the water level at both Brunswick and Hilton Head Island rose, decreasing the hydraulic gradient and reducing the potential for saltwater contamination. Conversely, in response to scenarios of increased pumpage, the water level at both locations declined, increasing the hydraulic gradient and increasing the potential for saltwater contamination. Pumpage effects on ground-water levels and related saltwater contamination at Brunswick and Hilton Head Island generally diminish with increased distance from these areas.

Additional development of the Upper Floridan aquifer may be possible in parts of the coastal area without affecting saltwater contamination at Brunswick or Hilton Head Island, due to the presence of two hydrologic boundaries—the Gulf Trough, separating the northern and central subareas; and the hypothesized “Satilla Line,” separating the central and southern subareas. These boundaries diminish pumpage effects across them; and may enable greater ground-water withdrawal in areas north of the Gulf Trough and south of the “Satilla Line” without producing appreciable drawdown at Brunswick or Hilton Head Island.

INTRODUCTION

The Upper Floridan and Lower Floridan aquifers compose the Floridan aquifer system in the 24-county study area (Krause and Randolph, 1989). Nearly all water withdrawn from the Floridan aquifer system in the coastal area (fig. 1) is derived from the Upper Floridan aquifer because of its large areal extent, comparatively shallow depth, good water quality, and high-yield characteristics. Withdrawal from the Upper Floridan aquifer has increased at varying rates since the 1880's, resulting in regional ground-water-level decline and saltwater contamination locally in parts of the coastal area. Seawater encroachment at the northern end of Hilton Head Island, S.C., and saltwater intrusion from deeply buried connate sources in Brunswick, Ga., have occurred and have been documented by Krause and Randolph (1989) and Krause (1997).

The U.S. Geological Survey (USGS), in cooperation with various State, county, and local agencies, conducted extensive studies and developed several ground-water flow models of the Floridan aquifer system during the 1970's and 1980's. These models were used to investigate and evaluate ground-water flow in the Floridan aquifer system in coastal Georgia and adjacent parts of southern South Carolina and northeastern Florida; assist in evaluating and planning for future water-supply demands in the area; and better understand the effects of ground-water withdrawal on saltwater intrusion and seawater encroachment.

This report describes three of the most recent coastal models—the Regional Aquifer-System Analysis (RASA) model (Krause and Randolph, 1989), the Glynn County area model (Randolph and Krause, 1990), and the Savannah area model (Garza and Krause, 1996). The RASA model is regional in scope, covering an area substantially larger than the coastal Georgia study area (fig. 1); whereas, the Glynn County area and Savannah area models are subregions in extent and more detailed in scope, covering areas surrounding Glynn County, Ga., and Savannah, Ga.,–Hilton Head Island, S.C., respectively. The models are referred herein as the RASA, Glynn, and Savannah area models.

A fourth model, the coastal model of Randolph and others (1991), also was developed by the USGS to investigate and evaluate subregional ground-water flow in the Floridan aquifer system and to evaluate the potential of the Floridan for increased development. Because the Savannah and Glynn models are more detailed and cover most of the area of the coastal model, revisions to, and application of, the coastal model are not described in this report, except where revisions impacted use of the other three models. The subregional Glynn, Savannah, and coastal models are all dependent on the functioning of the regional RASA model, in that the RASA model provides lateral boundary fluxes to the subregional models.

Input data for the RASA model were modified during development and calibration of the three subregional models (table 1). This resulted in an iterative process by which calibration of the subregional model necessitated revisions to model input parameters for hydraulic properties; these revisions were subsequently incorporated into the RASA model until calibration of the subregional model was complete. The RASA model was also updated to simulate stresses for the same period as the other three models (May 1985). These changes resulted in the RASA model having input data that were different from that which was originally documented and archived. Similarly, calibration of the Savannah model resulted in changes to the hydraulic-property arrays in the area common to the Savannah and Glynn models; however, these changes were never incorporated into the Glynn model.

During 1995-98, upon requests of the Georgia Department of Natural Resources, Environmental Protection Division (EPD) and the Chatham County–Savannah Metropolitan Planning Commission, the USGS used the RASA, Glynn, and Savannah models to simulate a variety of water-management scenarios to evaluate the potential of the Upper Floridan aquifer to supply additional water without increasing the potential for saltwater contamination. Results of these modeling scenarios have been used by the States of Georgia and South Carolina and other stakeholders in the area to formulate regulatory actions and management plans for the Upper Floridan aquifer. The Georgia EPD uses results of these scenarios to guide regulatory actions and decisions on ground-water-withdrawal permit requests, and has placed various restrictions on further development of the Upper Floridan aquifer in the 24-county area. Georgia EPD has reported on the results of selected USGS model simulations and scenarios, and has used those results to formulate an interim water-management strategy for coastal Georgia (Georgia Environmental Protection Division, 1997).

The Coastal Sound Science Initiative is a series of scientific and feasibility studies proposed by EPD to support development of the State's final strategy to protect the Upper Floridan aquifer from saltwater contamination (Georgia Environmental Protection Division, 1997). Simulation of ground-water flow and solute transport (saltwater contamination) using digital ground-water models is an identified project element of the Coastal Sound Science Initiative.

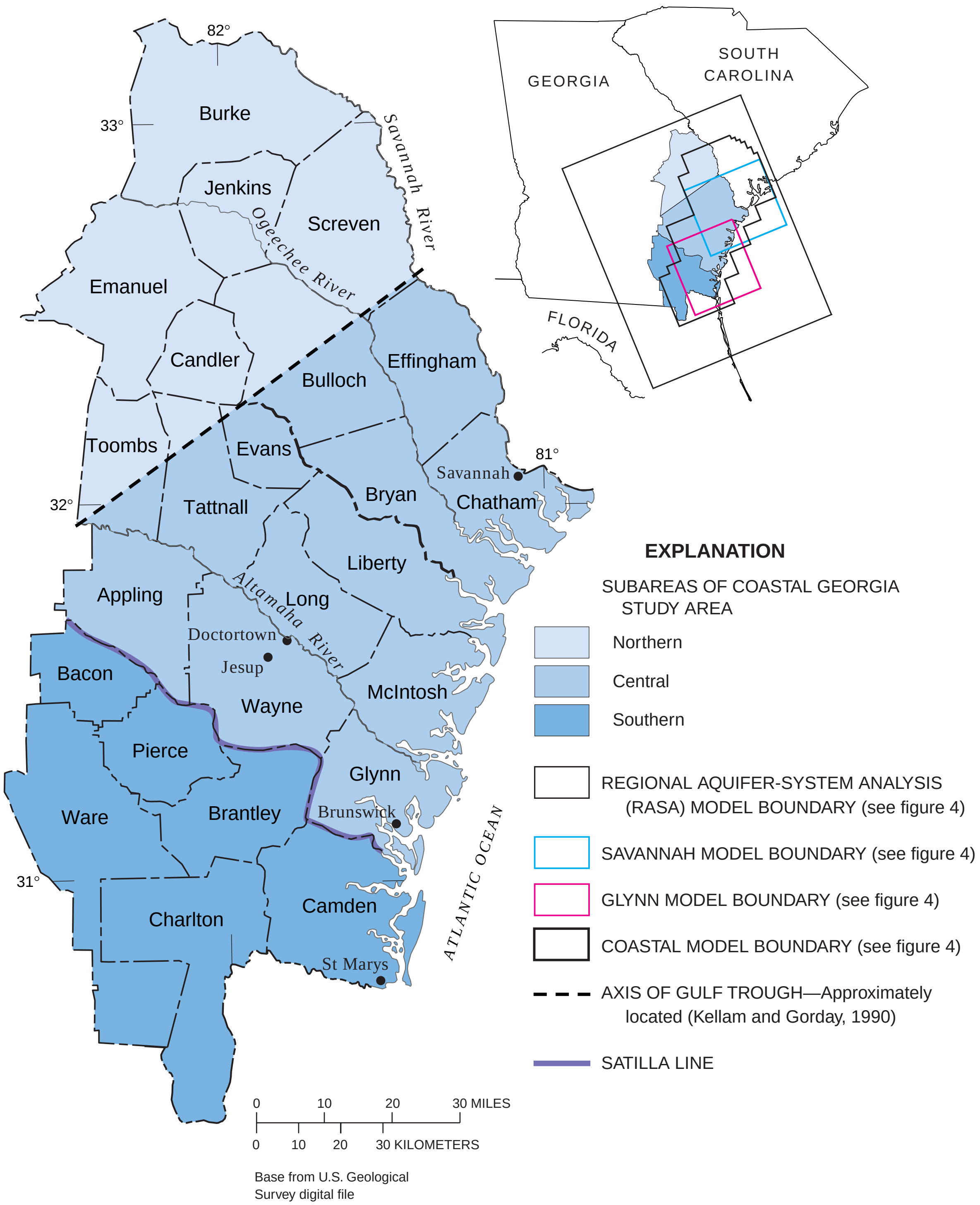


Figure 1. Location of 24-county coastal Georgia study area, and ground-water flow model boundaries.

Table 1. Summary of modifications to coastal area ground-water flow models
[RASA, Regional Aquifer-System Analysis]

Order of calibration	Model being calibrated	Hydraulic properties modified from originally calibrated model				Remarks
		RASA[1]	Glynn[2]	Coastal[3]	Savannah[4]	
1	RASA	yes	no	no	no	RASA was first model developed; no modifications made to other models
2	Glynn	yes	yes	no	no	Changes made to RASA model within and adjacent to the area of the Glynn model. Hydraulic properties were adjusted in the Glynn model first, and then averaged over equivalent model areas to obtain values for RASA model. Pumpage for RASA model updated to May 1985 conditions in area of Glynn model.
3	Coastal	yes	yes	yes	no	Hydraulic properties were adjusted in the coastal and Glynn models first, and then averaged over equivalent model areas to obtain values for RASA model. RASA pumpage in the area of coastal model updated to May 1985 conditions.
4	Savannah	yes	no	no	yes	Hydraulic properties were adjusted in the Savannah model first, and then averaged over equivalent model areas to obtain values for RASA model. Glynn and coastal models were not modified during calibration of Savannah model.

[1]Krause and Randolph (1989)
[2]Randolph and Krause (1990)
[3]Randolph and others (1991)
[4]Garza and Krause (1996)

An element of the modeling task of the Sound Science Initiative calls for "...an independent audit of the existing [USGS] models...by two modeling experts." Georgia EPD contracted with three consulting firms who independently evaluated the RASA, Glynn, coastal, and Savannah models. The three consulting firms concluded that the models (1) were developed according to standard and accepted technical approaches and practices, (2) met the goals and objectives specifically designed for each model, (3) were technically sound, and (4) that their use was appropriate for predicting regional and subregional responses in the Floridan aquifer system and for evaluating pumping alternatives, either as the effects of additional stresses or the relief or relocation of current pumping stresses (Georgia Geologic Survey, 1999). Basically, use of the models for various management objectives was appropriate. The consultants further concluded, that at this time (1999), the coastal model is redundant to the regional RASA model and the subregional Glynn and Savannah models.

Although all the models have been revised and used appropriately since their initial documentation and archival, several items for the RASA and Glynn models have not been fully documented and described, including (1) modifications to the original hydraulic-property and pumpage arrays; (2) changes in simulated water levels and water budget from the originally calibrated models; and (3) revised calibration statistics. In addition, none of the model simulations made by the USGS and results used by EPD and other cooperators and stakeholders, as described above, have been documented or published. Thus, the need for documenting these simulations is fulfilled by this report.

Purpose and Scope

This report documents the revisions, modifications, and updates to the RASA, Glynn, and Savannah models including: (1) changes made to the transmissivity and vertical leakance arrays, (2) changes in the calibration statistics of the revised models, and (3) the water budget of the revised models. Possible effects of the revisions are illustrated by a simulation comparing head and vertical leakance before and after the revisions. The overall design of the three models—unchanged since original development and archival—is briefly described; however, details of model specifications, mathematical basis, design rationale, and sensitivity analyses are not included because these are described in previous reports.

This report also documents the results of 32 computer simulations using the hypothetical scenarios of pumping changes. The scenarios were developed by the Georgia EPD and the Chatham County-Savannah Metropolitan Planning Commission to evaluate water-management alternatives in coastal Georgia. Maps showing simulated ground-water-level decline and diagrams showing changes in simulated flow rates are presented for each scenario.

Description of Study Area

The Georgia EPD defines the coastal area of Georgia to include the 6 coastal counties and adjacent 18 counties (fig. 1), an area of about 12,240 square miles (mi^2). The coastal area has been subdivided by EPD into three subareas—the northern, southern, and central subareas—to facilitate implementation of the State's water-management practices. The northern subarea is northwest of the Gulf Trough, a prominent geologic feature that represents a zone of low permeability in the Floridan aquifer system. The southern subarea lies south of what EPD has called the "Satilla Line," a postulated hydrologic boundary identified by EPD based on a change in the configuration of the potentiometric surface of the Upper Floridan aquifer, and by linear changes depicted on aeromagnetic, aeroradioactivity, gravity, and isopach maps (William H. McLemore, Georgia Environmental Protection Division, Geologic Survey Branch, oral commun., January 6, 2000). The central subarea lies between the northern and southern subareas, and includes the largest concentration of pumping in the coastal area—the Savannah, Brunswick, and Jesup pumping centers (fig. 1).

The coastal Georgia study area is in the Coastal Plain physiographic province. Topographic relief ranges from low in the central and southern subareas to steep in the northern subarea. Altitudes are as high as 100 feet (ft) in the central and southern subareas, and 300 ft in the northern subarea.

Average annual precipitation, based on the period 1941-70, ranges from less than 44 inches per year in Burke County to 54 inches per year in Glynn, Charlton, and Camden Counties (Krause and Randolph, 1989). Rainfall is unevenly distributed throughout the year—maximum rainfall occurs during the summer months of June, July, and August. Estimated evapotranspiration ranges from 31 inches per year in the northern part of the area to over 40 inches per year in Charlton and Ware Counties near the Okefenokee Swamp (Krause and Randolph, 1989). Rainfall as a source of recharge to aquifers is most important during the non-growing season, generally October through March, when evapotranspiration is lowest. Average annual runoff based on the period 1941-70, ranges from 10 to 12 inches per year in the study area (Krause and Randolph, 1989).

Land use is principally urban in industrial areas and in cities such as Savannah and Brunswick. Outside of these areas, land use is a mix of forest, grazed woodland, cropland with pasture, marsh, and swampland.

Hydrogeologic Setting

Coastal Plain strata consist of unconsolidated layers of sand and clay, and semiconsolidated to consolidated layers of limestone and dolomite. These sediments range in age from Late Cretaceous to Holocene, and unconformably overlie igneous, metamophic, and sedimentary rocks of Paleozoic to Mesozoic age. Coastal Plain sedimentary units generally strike southwest-northeast, and dip and thicken to the southeast, where maximum thickness is about 5,500 ft in Camden County (Wait and Davis, 1986).

The principal source of water for all uses in the coastal area is the Floridan aquifer system, consisting of the Upper and Lower Floridan aquifers (Miller, 1986; Krause and Randolph, 1989). Secondary sources of water include the surficial aquifer, and locally, the upper and lower Brunswick aquifers (Clarke and others, 1990), consisting of sand of Miocene to Holocene age. A generalized correlation of geologic and hydrologic units, and corresponding model layers is shown in figure 2.

The surficial aquifer consists of sand of Miocene to Holocene age. The aquifer generally is under water-table conditions; however, locally it is semiconfined to confined.

The upper confining unit underlies the surficial aquifer and consists of clay, silt, and sand of Oligocene to Miocene age. Locally, sand layers within this unit have been identified as sources of water, and were designated by Clarke and others (1990) as the upper and lower Brunswick aquifers. Because these units are present only locally, and for the purpose of simplicity, they were grouped into the upper confining unit for simulation of the Floridan aquifer system.

The Upper Floridan aquifer is highly productive and consists of limestone and dolomite of Eocene to Oligocene age. The aquifer crops out or is near land surface in the northwestern part of the 24-county coastal area where the aquifer is unconfined to semiconfined. Southeast of the outcrop area, the aquifer progressively becomes more deeply buried and confined.

The middle semiconfining unit underlies the Upper Floridan aquifer and separates the Upper Floridan from the underlying Lower Floridan aquifer. The unit consists of dense, low permeability, recrystallized limestone and dolomite of Eocene age. Locally in the Brunswick area, the unit is breached by fractures, which enhances the vertical movement of water between the aquifers (Krause and Randolph, 1989).

GEOLOGIC UNIT			HYDROGEOLOGIC UNIT		
Series	Stage	Formation	Savannah area	Brunswick area	Model layer
Post-Miocene		Undifferentiated	Surficial aquifer	Surficial aquifer	A1
Miocene		Hawthorn Formation	Upper confining unit[1]	Upper confining unit[1]	C1
Oligocene		Suwanee Limestone	Upper Floridan aquifer	Upper Floridan aquifer	A2
Eocene	Upper	Ocala Limestone	Middle semiconfining unit	Upper Floridan aquifer	A2
Eocene	Middle	Avon Park Formation	Middle semiconfining unit	Middle semiconfining unit	C2
Eocene	Middle	Avon Park Formation		Lower Floridan aquifer: Brackish and deep freshwater zones[2]	A3
Eocene	Lower	Oldsmar Formation	Lower confining unit	Lower Floridan aquifer: Lower semi-confining unit	C3
Eocene	Lower	Oldsmar Formation	Lower confining unit	Lower Floridan aquifer: Fernandina permeable zone[3]	A4
Paleocene		Cedar Keys Formation	Lower confining unit	Lower Floridan aquifer: Fernandina permeable zone[3]	A4
Upper Cretaceous		Undifferentiated	Lower confining unit	Lower confining unit	Not simulated

[1]Includes the upper and lower Brunswick aquifers in the Brunswick area (Clarke and other, 1990)
[2]Gregg and Zimmerman (1974)
[3]Krause and Randolph (1989)

Figure 2. Geologic units, hydrogeologic units, and model layers, coastal Georgia (modified from Randolph and others, 1991).

The Lower Floridan aquifer consists of dolomitic limestone of mostly Paleocene and Eocene age. In the Brunswick area, the Lower Floridan aquifer is composed of at least three water-bearing zones—the “brackish water zone”, the “deep freshwater zone” of Gregg and Zimmerman (1974), and the Fernandina permeable zone of Krause and Randolph (1989). The brackish and deep freshwater zones consist of limestone and dolomite of Eocene age. The Fernandina permeable zone consists of pelletal, recrystallized limestone and finely crystallized dolomite of Late Cretaceous to Eocene age. The zone is highly permeable and cavernous, and contains water of high salinity that may be the source of saltwater intrusion in the Brunswick area (Krause and Randolph, 1989).

The lower semiconfining unit separates the Fernandina permeable zone from the overlying brackish and deep freshwater zones of the Lower Floridan aquifer. The unit consists of microcrystalline, locally gypsiferous dolomite and finely pelletal micritic limestone of Eocene age.

For a more complete description of the physiographic, geologic, and hydrogeologic features of the study area, the reader is referred to Krause and Randolph (1989) and Clarke and others (1990).

Ground-Water Flow

Ground-water flow in the Floridan aquifer system is chiefly controlled by rates and distribution of recharge to and discharge from the system, the extent and effects of confinement, and the ability of the aquifers to transmit and store water (Krause and Randolph, 1989). A schematic diagram of the conceptualized predevelopment (no pumping) and modern-day (May 1985) flow systems in coastal Georgia is shown in figure 3. Prior to development, the flow system is considered to have been at dynamic equilibrium and the potentiometric surfaces nearly static from year to year.

The modern-day (May 1985) flow system reflects changes that have occurred as a result of ground-water development (withdrawal). Ground-water withdrawal has lowered water levels, induced additional recharge and reduced natural discharge, and degraded the quality of water in places along the coast. Extensive cones of depression have developed in the potentiometric surface in the Savannah, Brunswick, Jesup, and St Marys, Ga.–Fernandina Beach, Fla. areas. Seawater encroachment on the northern end of Hilton Head Island, S.C., and saltwater intrusion from deeply buried, connate sources at Brunswick, Ga., have occurred and have been documented by Krause and Randolph (1989) and Krause (1997).

Water recharges the aquifers in the northern part of the study area (north of the Gulf Trough) where the aquifers are exposed or near land surface. From these northern areas, water flows mostly southeastward toward the coast and discharges into overlying units and surface-water bodies—major streams, estuaries, and the Atlantic Ocean. As water flows coastward, low-permeability sediments in the vicinity of the Gulf Trough inhibit ground-water flow and produce a steep potentiometric gradient.

Acknowledgments

The authors thank William H. McLemore (Georgia Geologic Survey) for help in developing ground-water management scenarios for simulation. L. Elliott Jones (U.S. Geological Survey) developed model pumping-data arrays and conducted preliminary model simulations. Appreciation is extended to Bonnie J. Turcott and Caryl J. Wipperfurth (U.S. Geological Survey) for preparation of illustrations.

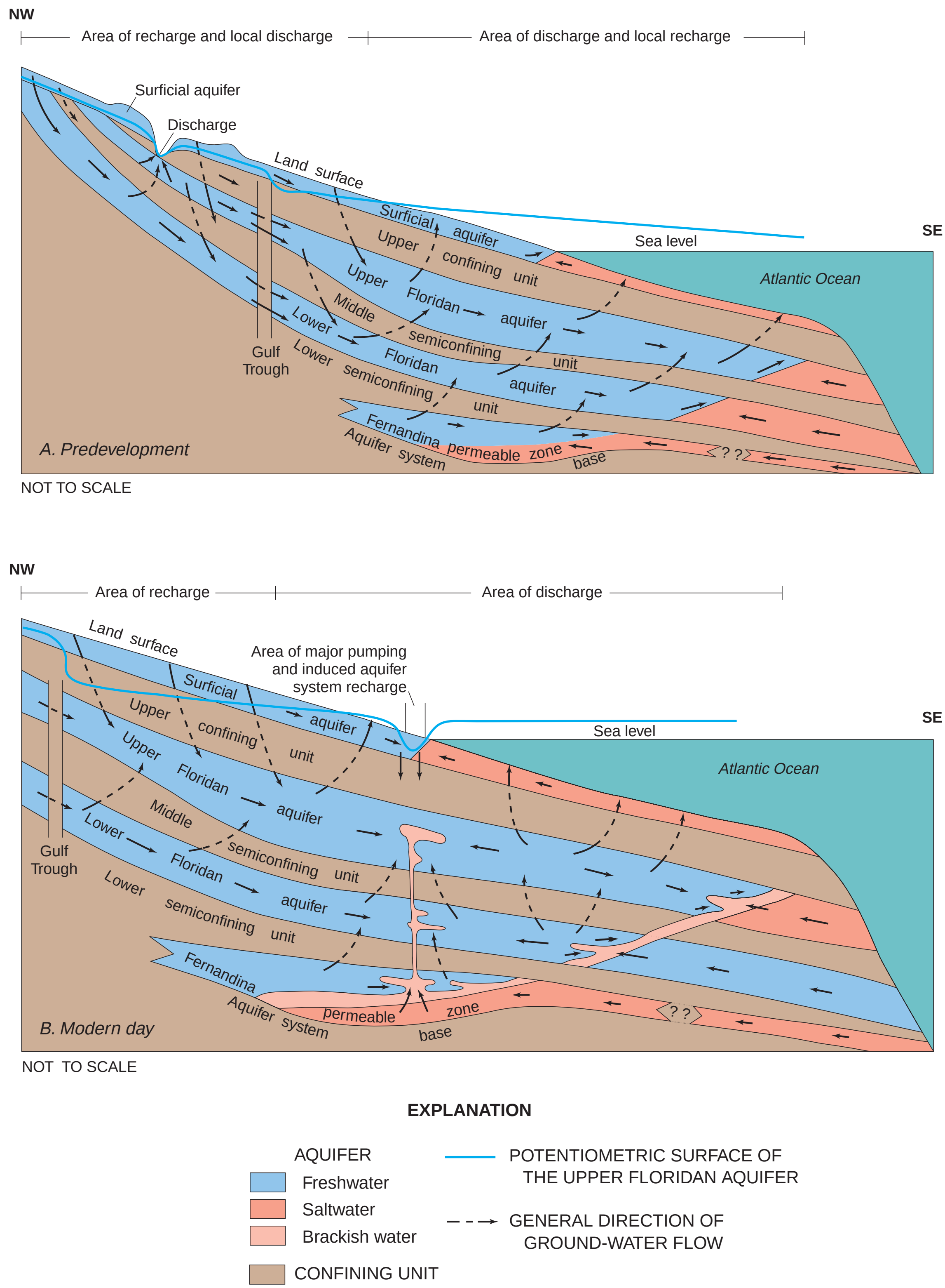


Figure 3. Conceptual models of (*A*) predevelopment and (*B*) modern-day (May 1985) flow systems for Floridan aquifer systems from the outcrop area in the northwest to the offshore area in the southeast (modified from Krause and Randolph, 1989).

DESIGN AND REVISION OF GROUND-WATER FLOW MODELS

During the 1980’s and 1990’s, several ground-water flow models were developed and used to help understand the ground-water flow system in coastal Georgia. The models, developed as part of regional and areal assessments of ground-water resources in coastal Georgia, are—the regional RASA model, and the subregional Glynn, coastal, and Savannah models. The RASA model and each of the subregional models simulate steady-state ground-water flow using the USGS three-dimensional finite-difference ground-water flow-model program, MODFLOW (McDonald and Harbaugh, 1988). All models are designed to actively simulate flow in the Upper and Lower Floridan aquifers, and used the same vertical layering (fig. 2):

- A1—the surficial aquifer, is simulated as a source-sink (specified head) layer;
- C1—the upper confining unit;
- A2—the Upper Floridan aquifer, is actively simulated;
- C2—the middle semiconfining unit;
- A3—the Lower Floridan aquifer, is actively simulated;
- C3—lower semiconfining unit; and
- A4—the Fernandina permeable zone, simulated as a source-sink (specified head) layer.

Regional Aquifer-System Analysis (RASA) Model

The RASA model—covering a 53,250-mi^2 area in the eastern half of the Coastal Plain of Georgia and adjacent parts of southern South Carolina and northeastern Florida (fig. 4)—was constructed in the early 1980’s as part of the USGS RASA program to investigate the entire ground-water flow system in the southeastern Atlantic Coastal Plain (Krause and Randolph, 1989). The RASA model consists of a uniformly spaced grid having 52 rows and 64 columns; cells cover an area of 16 mi^2 (fig. 4). By virtue of its large scale and according to RASA program objectives, the RASA model is regional in scope and generalized.

The RASA model was developed and initially calibrated to simulate predevelopment conditions by Krause (1982), then enhanced and updated to simulate predevelopment and 1980 conditions by Krause and Randolph (1989), then May 1985 conditions in the area of the Glynn model by Randolph and Krause (1990), and May 1985 conditions in the area of the coastal model (Randolph and others, 1991). The model also was used to estimate the potential of the Upper Floridan aquifer to yield additional water without increasing known occurrences of seawater encroachment at Hilton Head Island, S.C., and saltwater intrusion at Brunswick, Ga. (Krause and Randolph, 1989).

Boundary conditions for the RASA model are based largely on natural hydrologic boundaries—a ground-water divide to the west, the updip limit of the Floridan aquifer system to the north, and the freshwater-saltwater interface to the east—were simulated as no-flow boundaries. Artificial boundaries are used in two areas—the southern boundary was simulated using a specified head, and the southwestern boundary was simulated as a general-head boundary.

Subregional Models

Following the development of the regional RASA model, three subregional models were developed to simulate steady-state conditions for the coastal area and to provide higher resolution of simulated head and flow rates. These models are, in order of development:

- the Glynn model (Randolph and Krause, 1990);
- the coastal model (Randolph and others, 1991); and
- the Savannah model (Garza and Krause, 1996).

The subregional models are aligned with the regional RASA model, having the same grid orientation (figs. 4 and 5). Each subregional model is smaller and more detailed than the RASA model, and lies within the area covered by the RASA model. The coastal model encompasses the Glynn and Savannah models. The Glynn and Savannah models also share the common area between Glynn County and Savannah where the models overlap.

The subregional models have artificial boundaries that are determined by using the flow simulated by the RASA model (see section, “Telescoping Model Approach”). Like the RASA model, the subregional models are calibrated to simulate predevelopment conditions. In addition, the Glynn model simulates 1980 and May 1985 conditions; the coastal and Savannah models simulate May 1985 conditions only. The subregional models were used to assess hypothetical changes in pumpage; the coastal and Savannah models also were used to estimate the development potential of the Upper Floridan aquifer.

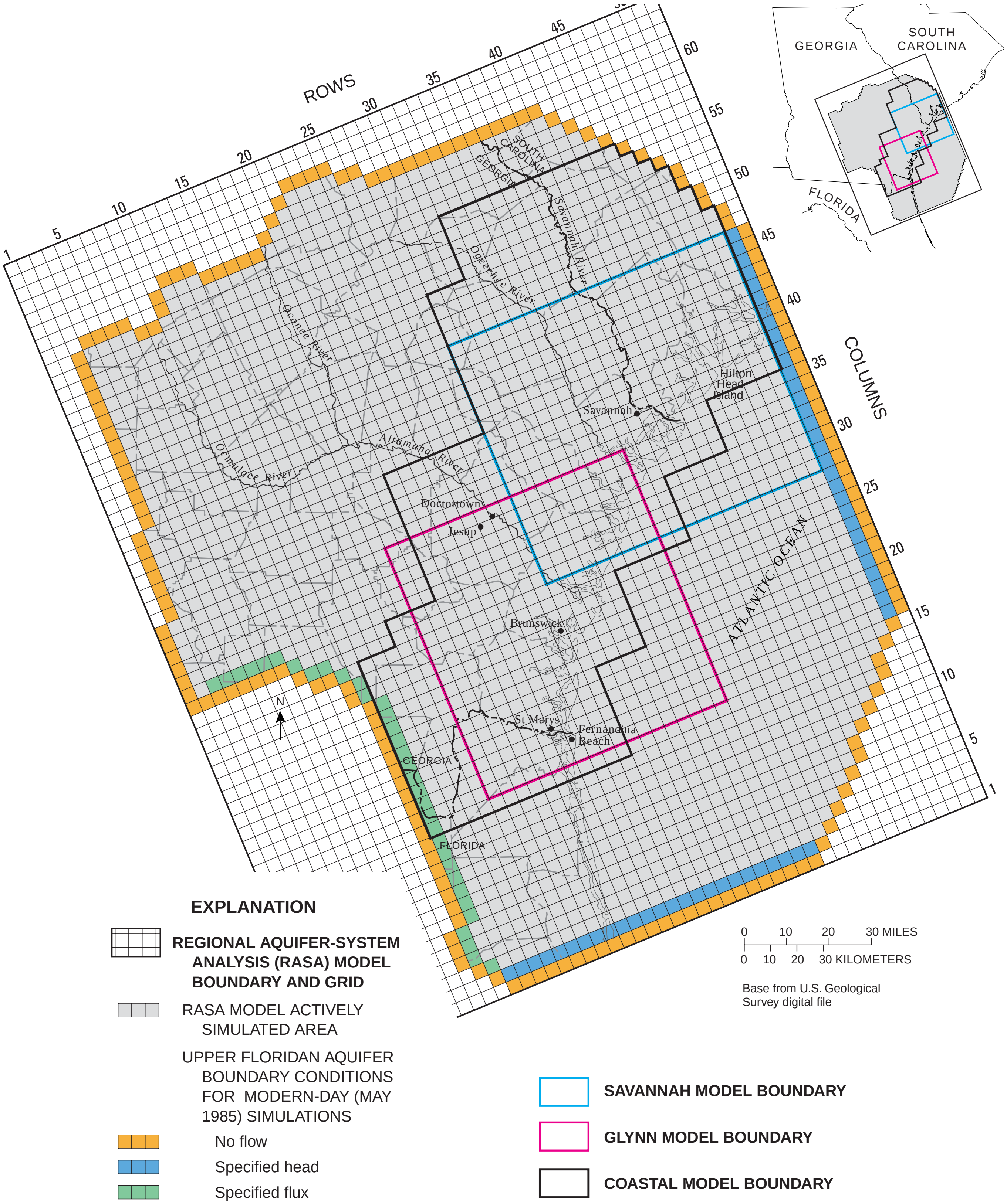


Figure 4. Regional Aquifer-System Analysis (RASA) model grid and boundary conditions for the Upper Floridan aquifer for modern-day (May 1985) simulations and subregional model boundaries.

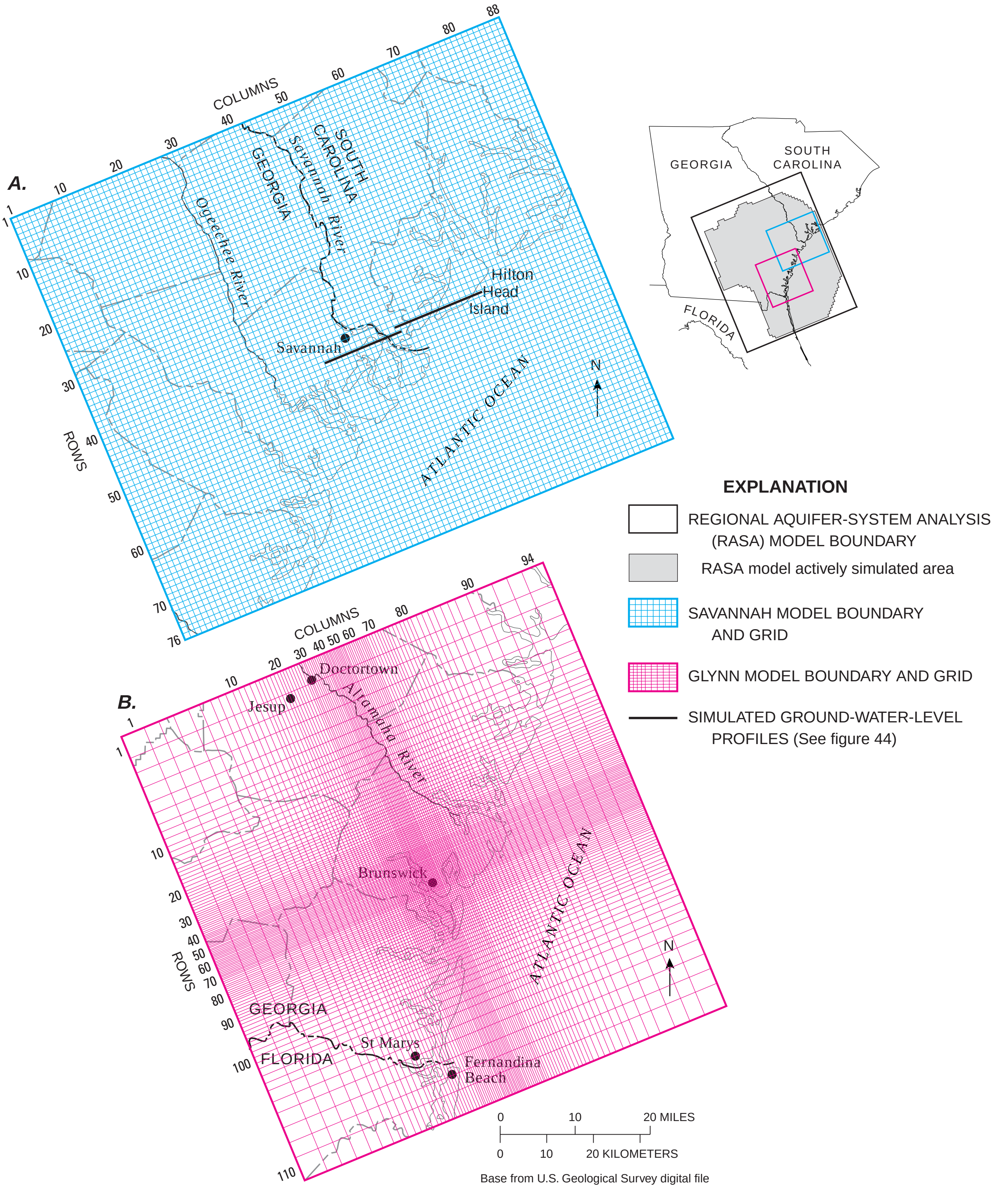


Figure 5. (*A*) Savannah and (*B*) Glynn model grids.

The Glynn model was developed by the USGS during the late 1980's in cooperation with the City of Brunswick, Glynn County, Coastal Area Planning and Development Commission, Georgia EPD, and the U.S. Army Corps of Engineers (Randolph and Krause, 1990). The Glynn model simulates local flow in the Brunswick area and includes surrounding counties in southeastern Georgia and adjacent parts of northeastern Florida (fig. 5). The model covers an area of about 6,100 mi^2 and consists of a variably spaced grid having 110 rows and 94 columns. Cells range in area from 0.0625 mi^2 at the grid center to 16 mi^2 at the grid corners.

The coastal model was developed by USGS during the late 1980's and early 1990's, in cooperation with the Georgia EPD (Randolph and others, 1991). The model covers the 24-county study area and adjacent parts of South Carolina and Florida, and was used to evaluate the water-supply potential of the Floridan aquifer system. The model covers an area of about 14,000 mi^2 and consists of a uniformly spaced grid having 84 rows and 74 columns (fig. 4). Cells have an area of 4 mi^2, or one-fourth the size of a RASA model cell.

The Savannah model was developed by the USGS in the early 1990's, in cooperation with the Chatham County-Savannah Metropolitan Planning Commission (Garza and Krause, 1996). The Savannah model simulates detailed flow in the Savannah, Ga.–Hilton Head Island, S.C., area and includes surrounding counties in eastern Georgia and southern South Carolina (fig. 5). The model covers an area of about 6,700 mi^2 and consists of a uniformly spaced grid having 76 rows and 88 columns. Cells have an area of 1 mi^2, or one-sixteenth the size of a RASA model cell.

Telescoping Model Approach

To provide the lateral boundaries for the subregional models, a telescoping approach was utilized whereby simulated flow values from the larger, regional-scale RASA model were designated along the lateral boundaries for the smaller, detailed, subregional models (Glynn, coastal, and Savannah). The telescoping technique was implemented to increase model-grid resolution for simulating hydrologic conditions in areas where higher resolution and detail was required, while reducing the number of model cells in areas of lesser importance. A secondary consequence and advantage was the reduction of model cells outside the area of interest, which was necessitated in part by the limited data-storage capabilities of computers prior to the late 1980's.

The telescoping technique enables simulation of ground-water flow conditions at a finer resolution than the regional model without having to extend the subregional boundaries to natural hydrologic boundaries (which could be located far from the area of interest). The effects of stresses beyond the boundaries of the subregional models are determined by the regional model, and then the stress effects are transferred through the boundaries to the subregional model. In the case of the coastal Georgia models, boundaries are computed as vector volumes of flow at the boundary between the regional and subregional models. Flow is computed across the regional and subregional boundaries in the regional simulation and is subdivided into as many cells as needed in the subregional simulation. Boundary fluxes are transferred from the regional model to the subregional models using imaginary wells for inflow to (positive flux) and outflow from (negative flux) the subregional model area. For a more complete discussion of the telescoping technique applied to the coastal area models, the reader is referred to Garza and West (1995).

Model Revisions

The coastal area models were calibrated in the following order: RASA, Glynn, coastal, and Savannah. During calibration of each subregional model, hydraulic-property arrays (transmissivity and vertical leakance) of the RASA model were modified to incorporate changes made to the subregional model in areas of model domain overlap. Because subregional model cells are smaller in area than RASA cells, in areas of overlap more than one subregional model cell falls within the area of a single RASA cell. Here, values assigned to the RASA cells are an average of the values of the subregional model cells. Parts of each of the RASA model arrays were adjusted as many as three times from the originally calibrated array during subsequent calibration of the Glynn, coastal, and Savannah models.

Although modifications to hydraulic-property arrays were systematically made to the RASA model during development of each subsequent subregional model, in every instance where modifications were made, corresponding adjustments were not made to other previously developed subregional models. For example, adjustments made during calibration of the Savannah model were incorporated into the RASA model, but were not incorporated into the coastal or Glynn models in the area of model overlap. As a result, a consistent set of data arrays was needed to achieve exact agreement among the models. This report documents changes made to data arrays of the RASA and Glynn models to provide that agreement. Because the coastal model covers an area in common with the Glynn and Savannah models, changes made to the coastal model data arrays are not reported herein.

Changes to Model Input Data

Data arrays of the original models were compared and modified to ensure consistency among the models and resulting simulations. Data arrays for boundary conditions and hydraulic properties (transmissivity and leakance) were compared for all model layers.

Comparison of boundary conditions for the revised RASA model indicates no change to those in the originally calibrated model. For the subregional models, boundary conditions are derived from computed lateral flux from the RASA model (see section, “Telescoping Model Approach”).

Hydraulic-property arrays were modified based on the sequence and resolution of calibration, such that the most recently calibrated model having the finest resolution was given highest precedence over earlier models having coarser discretization and resolution. These modifications allowed incorporation of additional geologic and hydraulic-property data into the hydraulic property arrays. Models were modified according to the following precedence:

- Savannah model: has precedence over all models in areas of overlap because it is the most recently calibrated;
- Glynn model: has precedence over the RASA model in areas of overlap because of its higher resolution and more recent calibration; and
- Coastal model: has precedence over the RASA model in areas of overlap because of its higher resolution.

Differences were expected in hydraulic-property arrays between those used in the original RASA model and those used in the revised RASA model resulting from modifications made during calibration of the subregional models. One of the objectives of developing the subregional models was to identify and replicate small variations in hydraulic properties at a small scale. The local, fine resolution and more widely variable hydraulic properties resulted in greater variation in hydraulic properties in the revised RASA model than in the original. For the Glynn model, hydraulic-property arrays for the revised model differed from the original arrays in the area of overlap with the Savannah model (figs. 6-10).

Sensitivity analyses conducted in previous model investigations (Krause and Randolph, 1989; Randolph and Krause, 1990; Garza and Krause, 1996) indicate that transmissivity was an important hydraulic property in the original calibration of all the models; transmissivity was widely revised during calibration of all models. Ranges of simulated and estimated transmissivity for the Upper and Lower Floridan aquifers are listed in tables 2 and 3. Revised transmissivity arrays for the RASA and Glynn models and original array for the Savannah model are shown in figure 6 for the Upper Floridan aquifer (layer A2), and in figure 7 for the Lower Floridan aquifer (layer A3). Revised transmissivity arrays for the RASA model show the greatest change (greater than ± 10 percent) in the area of the Glynn model; revised transmissivity arrays for the Glynn model show the greatest change in the area of overlap with the Savannah model.

Table 2. Simulated and estimated transmissivity values for the Upper Floridan aquifer (model layer A2)—original and revised models
[—, not applicable]

Model	Transmissivity, in feet squared per day			
	Number of values	Minimum	Maximum	Mean
Estimated based on field data[1]				
—	124	675	1.0×10^6	55,000
RASA model[2]				
Original	2,363	860	4.4×10^6	97,000
Revised	2,363	860	4.4×10^6	97,000
Glynn model				
Original	10,340	8,600	510,000	[3]153,000
Revised	10,340	8,600	510,000	[3]152,000
Savannah model				
Original	6,688	860	205,000	43,400

[1]Determined from aquifer tests and estimated from specific capacity data; Krause and Randolph (1989).

[2]Actively simulated area.

[3]Model-simulated values weighted according to cell areas.

Table 3. Simulated and estimated transmissivity values for the Lower Floridan aquifer (model layer A3)—original and revised models
[—, not applicable]

Model	Transmissivity in feet squared per day			
	Number of values	Minimum	Maximum	Mean
Estimated based on field data[1]				
—	—	2,000	400,000	—
RASA model[2]				
Original	2,053	2,000	320,000	34,000
Revised	2,053	2,000	320,000	34,000
Glynn model				
Original	10,340	4,300	181,000	[3]49,000
Revised	10,340	3,500	181,000	[3]50,000
Savannah model				
Original	6,688	2,000	82,100	8,800
Revised	6,688	2,000	82,100	8,800

[1]Estimated from thickness and qualitative estimates from geophysical logs; Krause and Randolph (1989).

[2]Actively simulated area.

[3]Model-simulated values weighted according to cell areas.

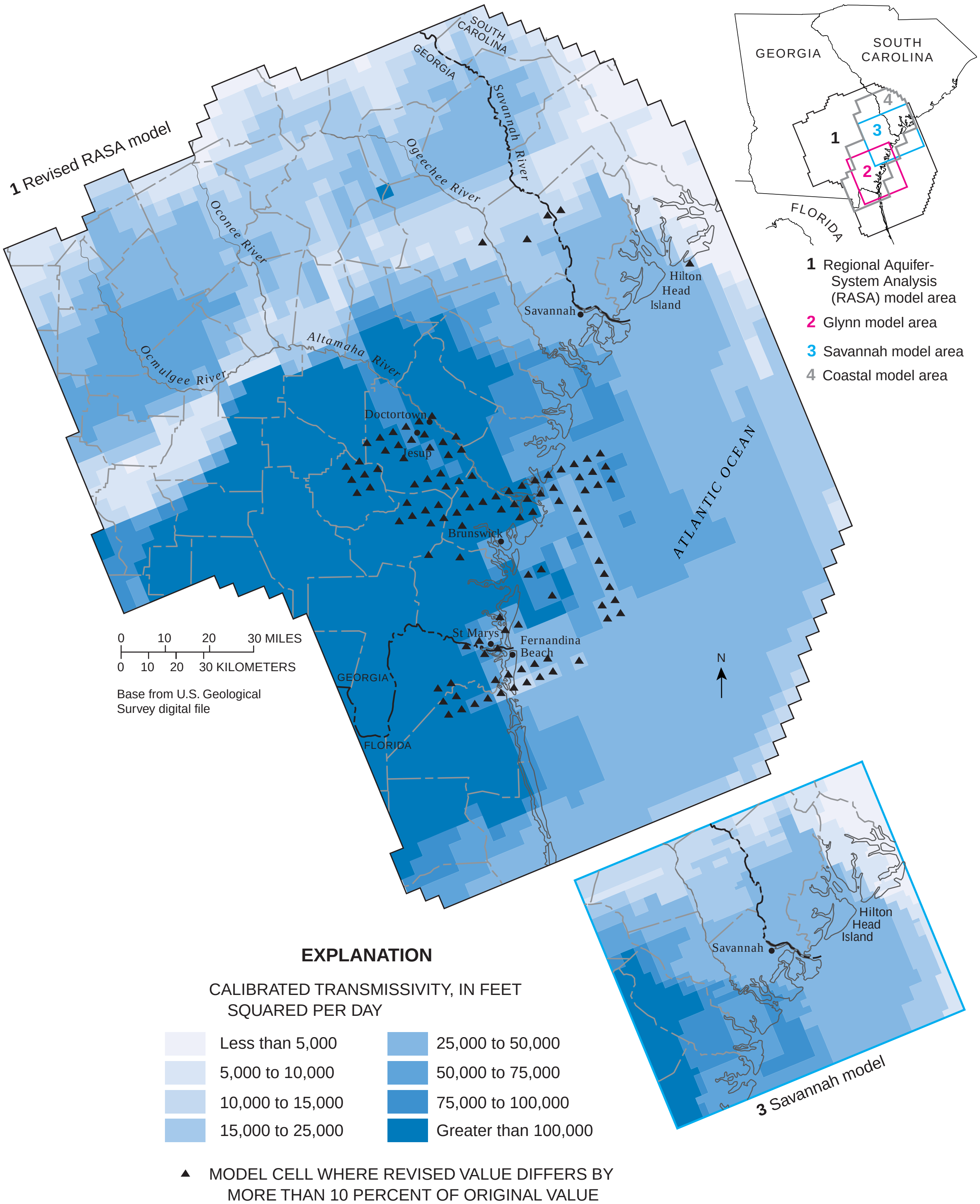
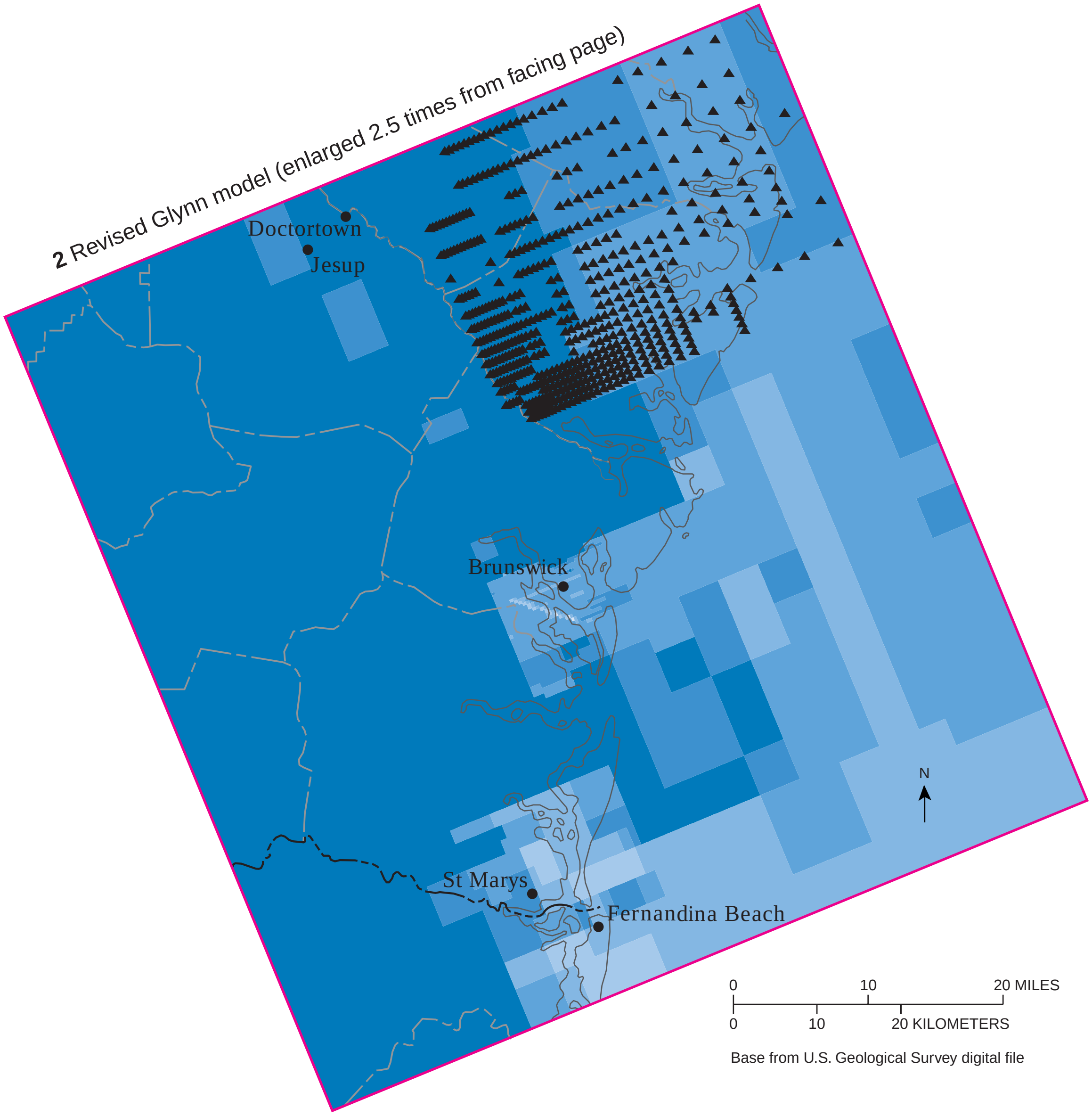


Figure 6. Calibrated transmissivity array for the Upper Floridan aquifer (model layer A2), Savannah models, and revised Glynn and Regional Aquifer-System Analysis (RASA) models.



EXPLANATION

CALIBRATED TRANSMISSIVITY, IN FEET SQUARED PER DAY

- Less than 5,000
- 5,000 to 10,000
- 10,000 to 15,000
- 15,000 to 25,000
- 25,000 to 50,000
- 50,000 to 75,000
- 75,000 to 100,000
- Greater than 100,000

▲ MODEL CELL WHERE REVISED VALUE DIFFERS BY MORE THAN 10 PERCENT OF ORIGINAL VALUE

Figure 6. Calibrated transmissivity array for the Upper Floridan aquifer (model layer A2), Savannah models, and revised Glynn and Regional Aquifer-System Analysis (RASA) models—continued.

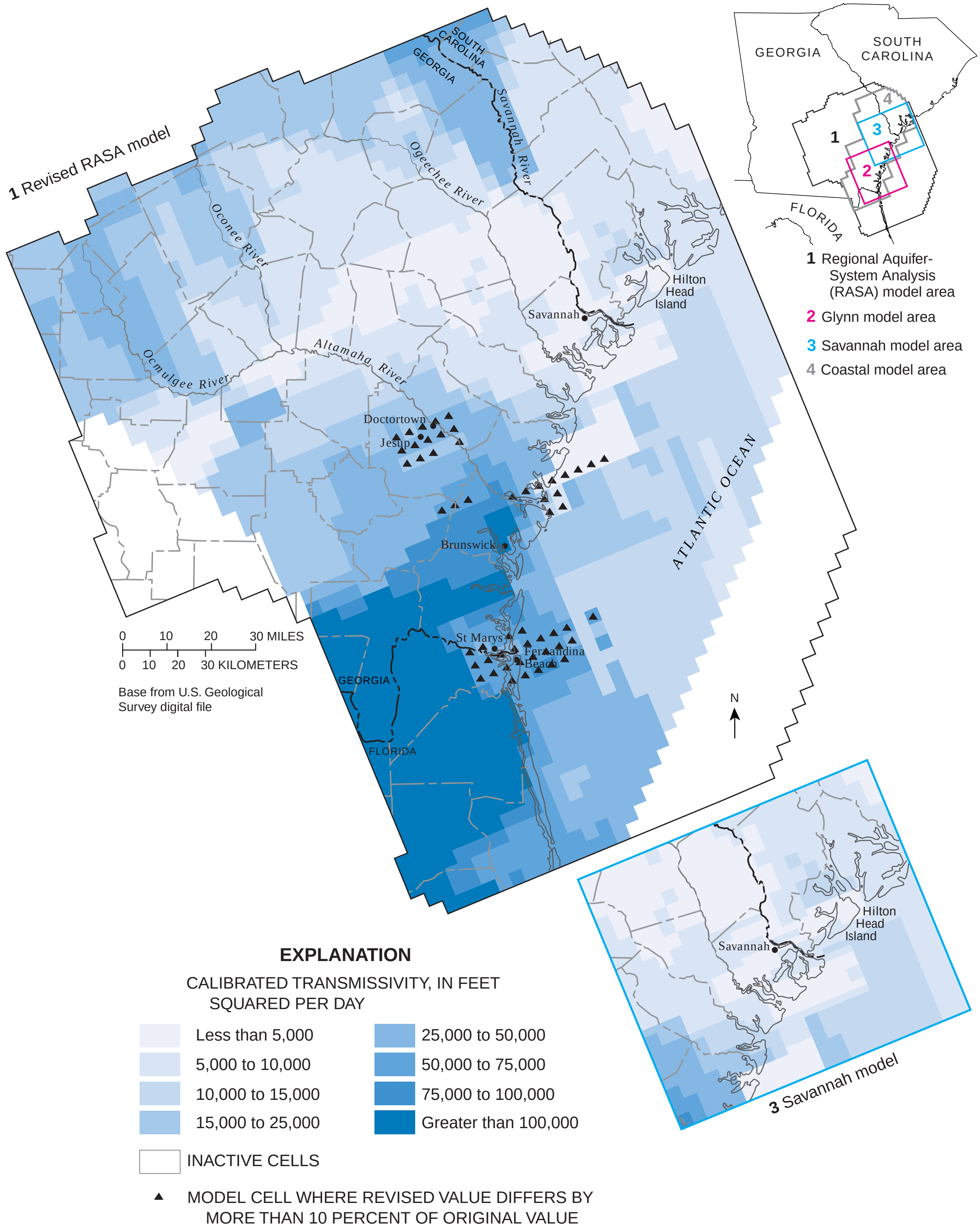


Figure 7. Calibrated transmissivity array for the Lower Floridan aquifer (model layer A3), Savannah model, and revised Glynn and Regional Aquifer-System Analysis (RASA) models.

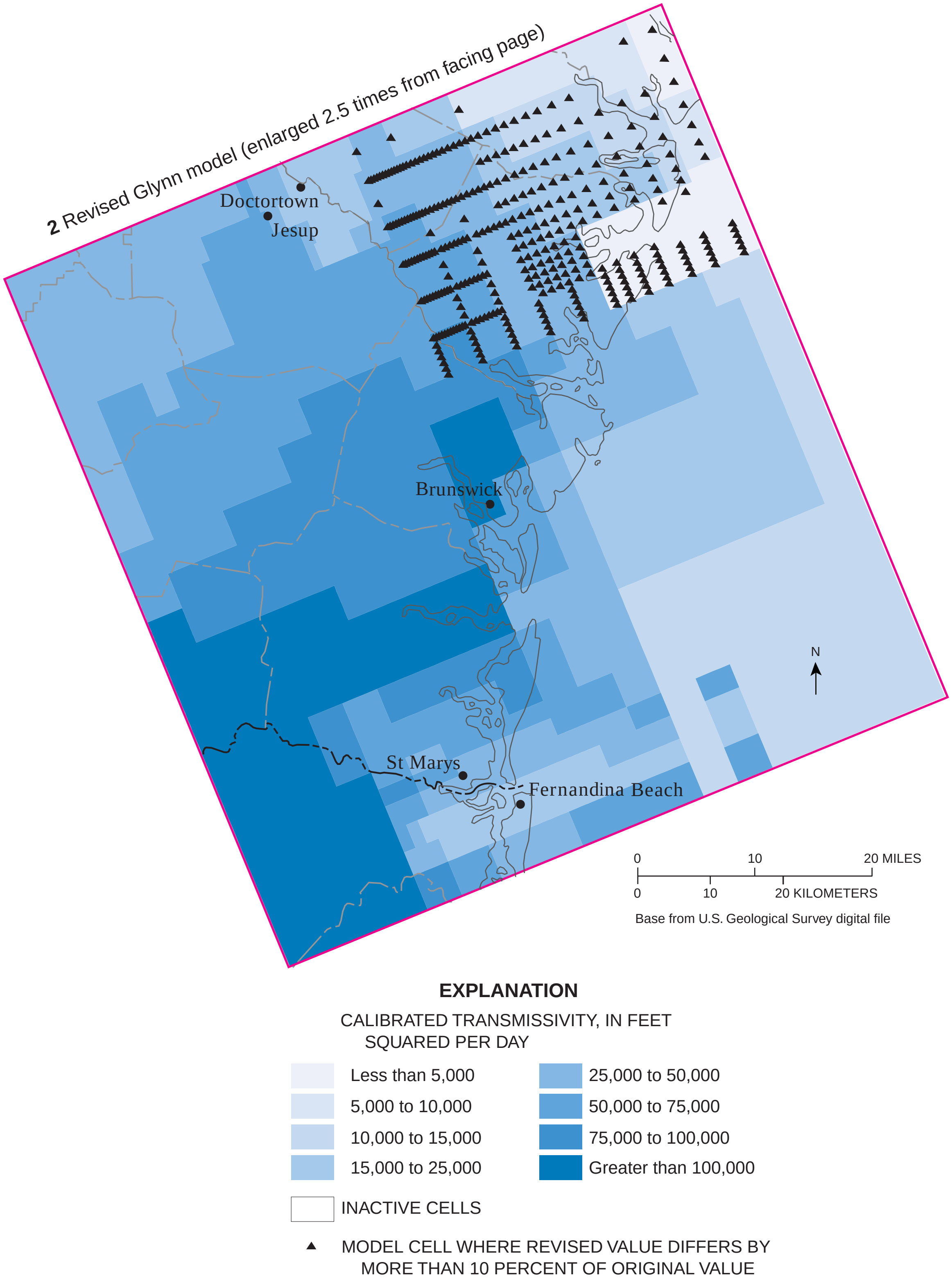


Figure 7. Calibrated transmissivity array for the Lower Floridan aquifer (model layer A3), Savannah model, and revised Glynn and Regional Aquifer-System Analysis (RASA) models—continued.

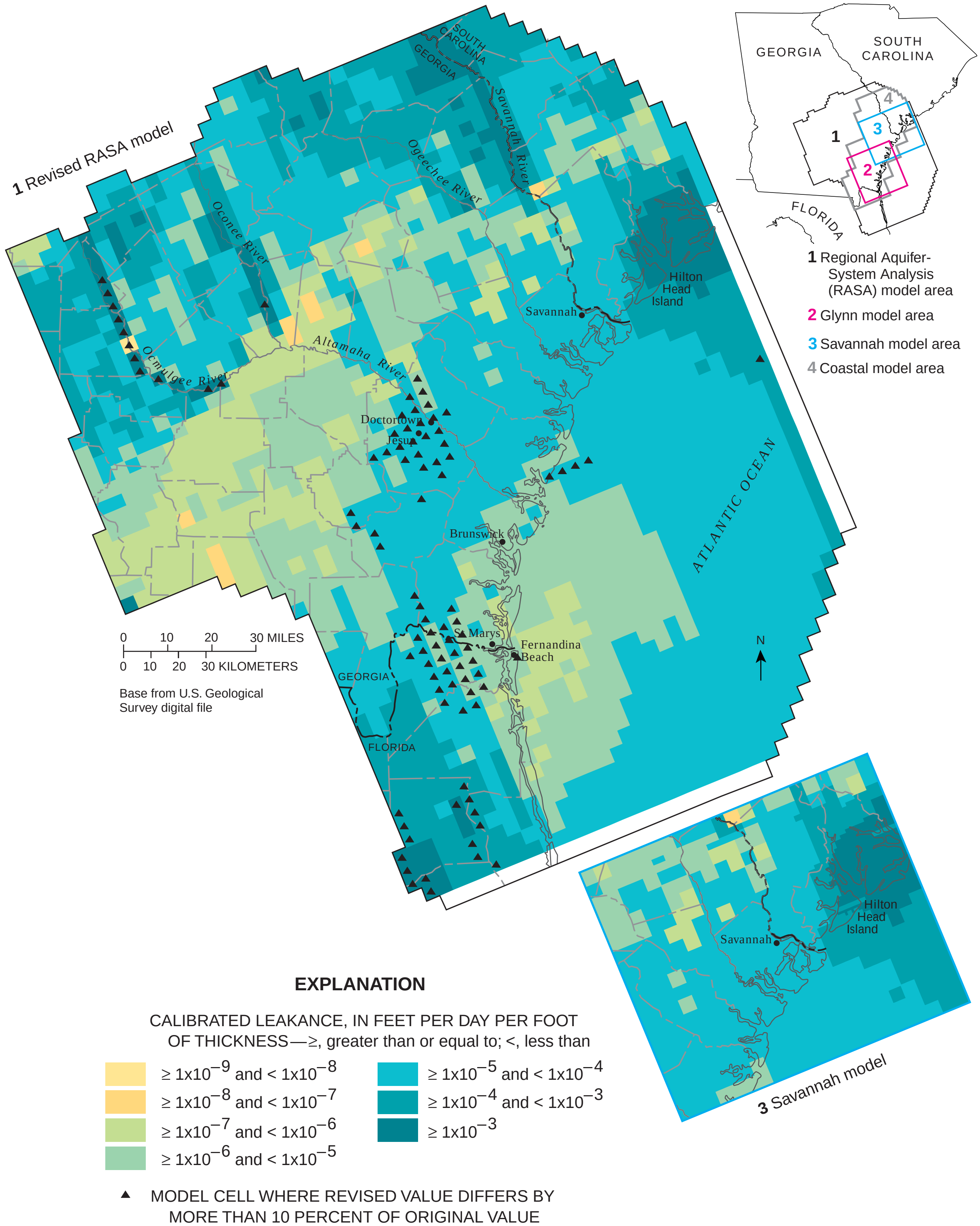
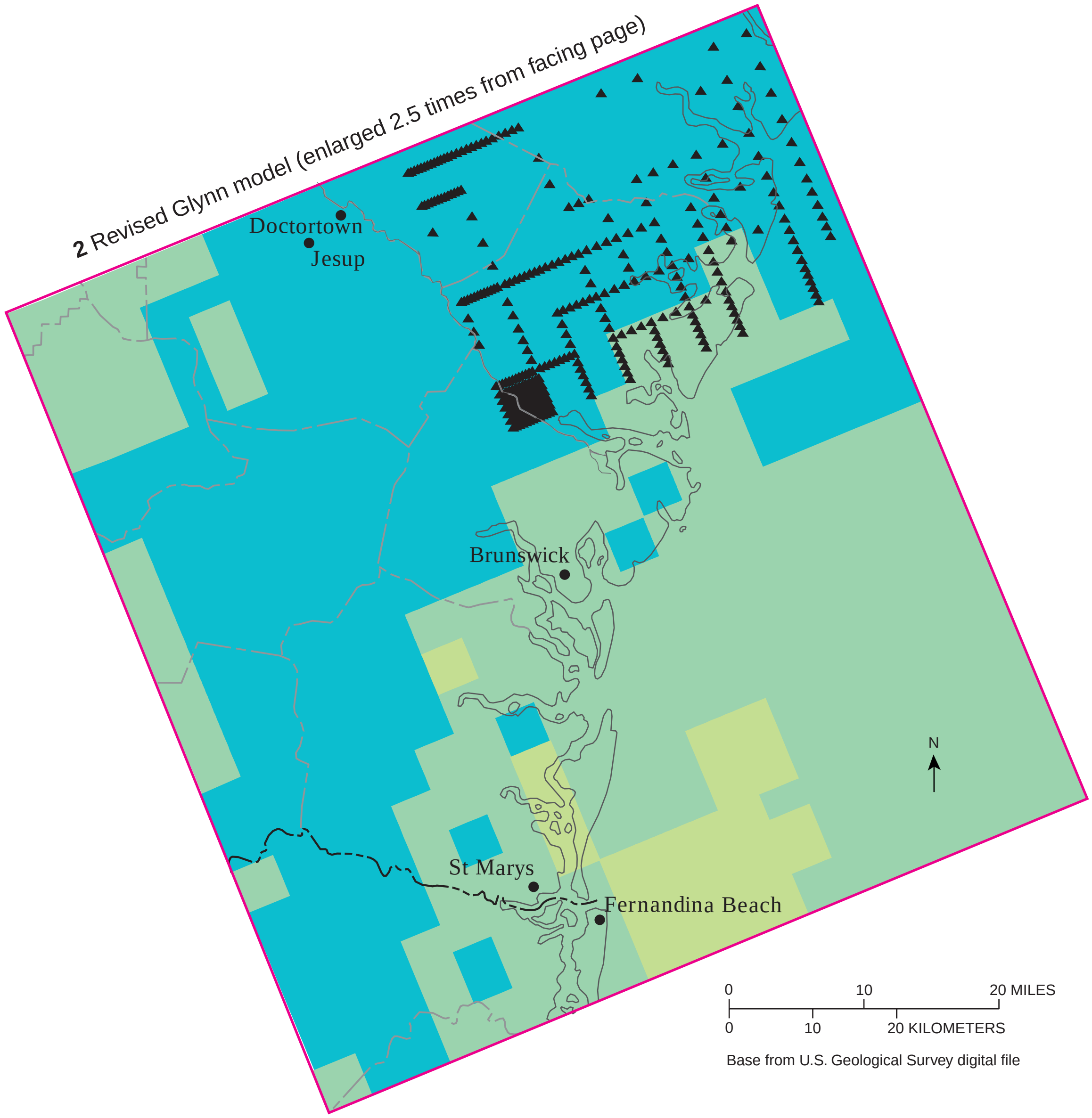


Figure 8. Calibrated leakance array for the upper confining unit (model layer C1), Savannah model, and revised Glynn and Regional Aquifer-System Analysis (RASA) models.



EXPLANATION

CALIBRATED LEAKANCE, IN FEET PER DAY PER FOOT OF THICKNESS—≥, greater than or equal to; <, less than

- $\geq 1\times10^{-9}$ and $< 1\times10^{-8}$
- $\geq 1\times10^{-8}$ and $< 1\times10^{-7}$
- $\geq 1\times10^{-7}$ and $< 1\times10^{-6}$
- $\geq 1\times10^{-6}$ and $< 1\times10^{-5}$
- $\geq 1\times10^{-5}$ and $< 1\times10^{-4}$
- $\geq 1\times10^{-4}$ and $< 1\times10^{-3}$
- $\geq 1\times10^{-3}$

▲ MODEL CELL WHERE REVISED VALUE DIFFERS BY MORE THAN 10 PERCENT OF ORIGINAL VALUE

Figure 8. Calibrated leakance array for the upper confining unit (model layer C1), Savannah model, and revised Glynn and Regional Aquifer-System Analysis (RASA) models—continued.

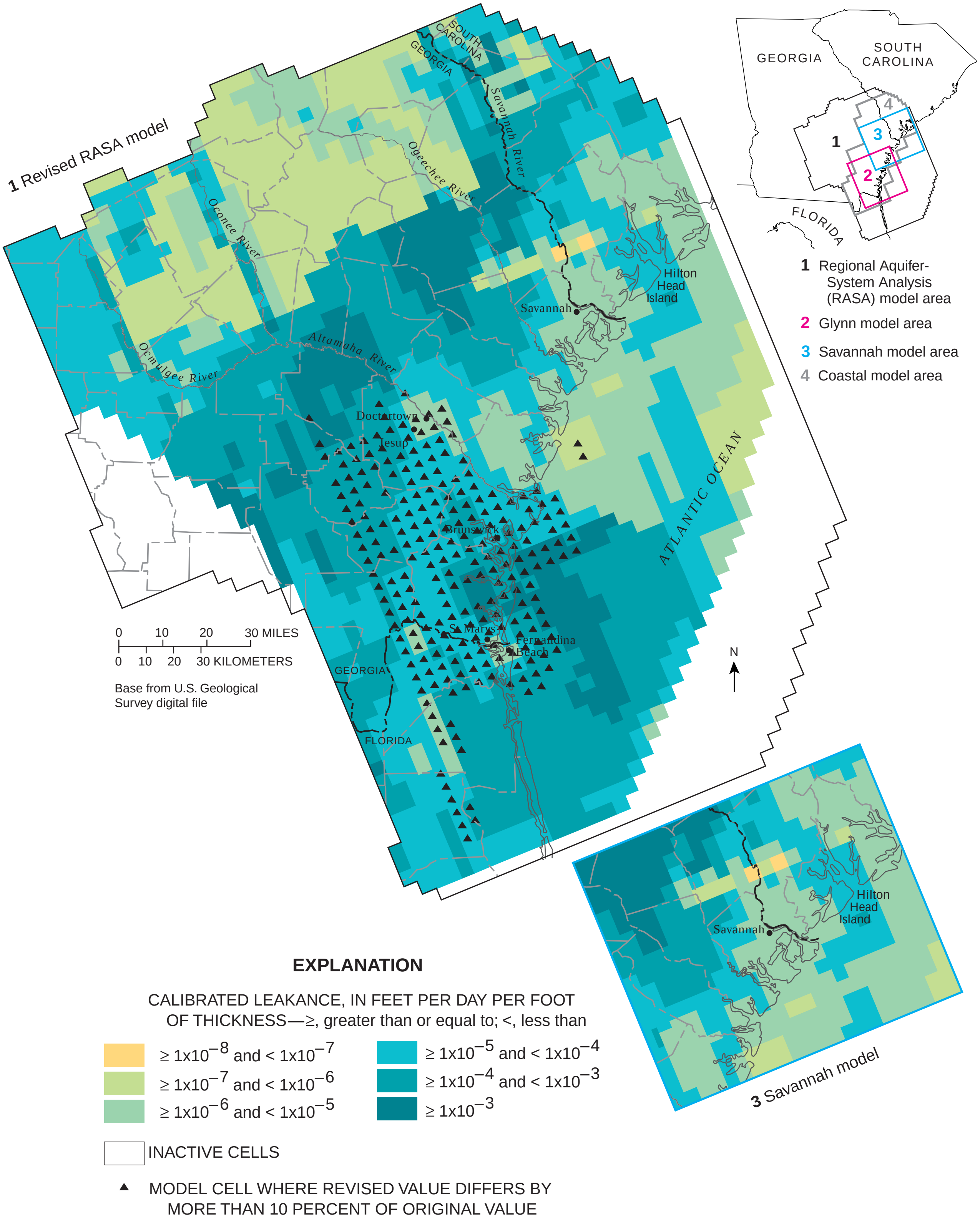
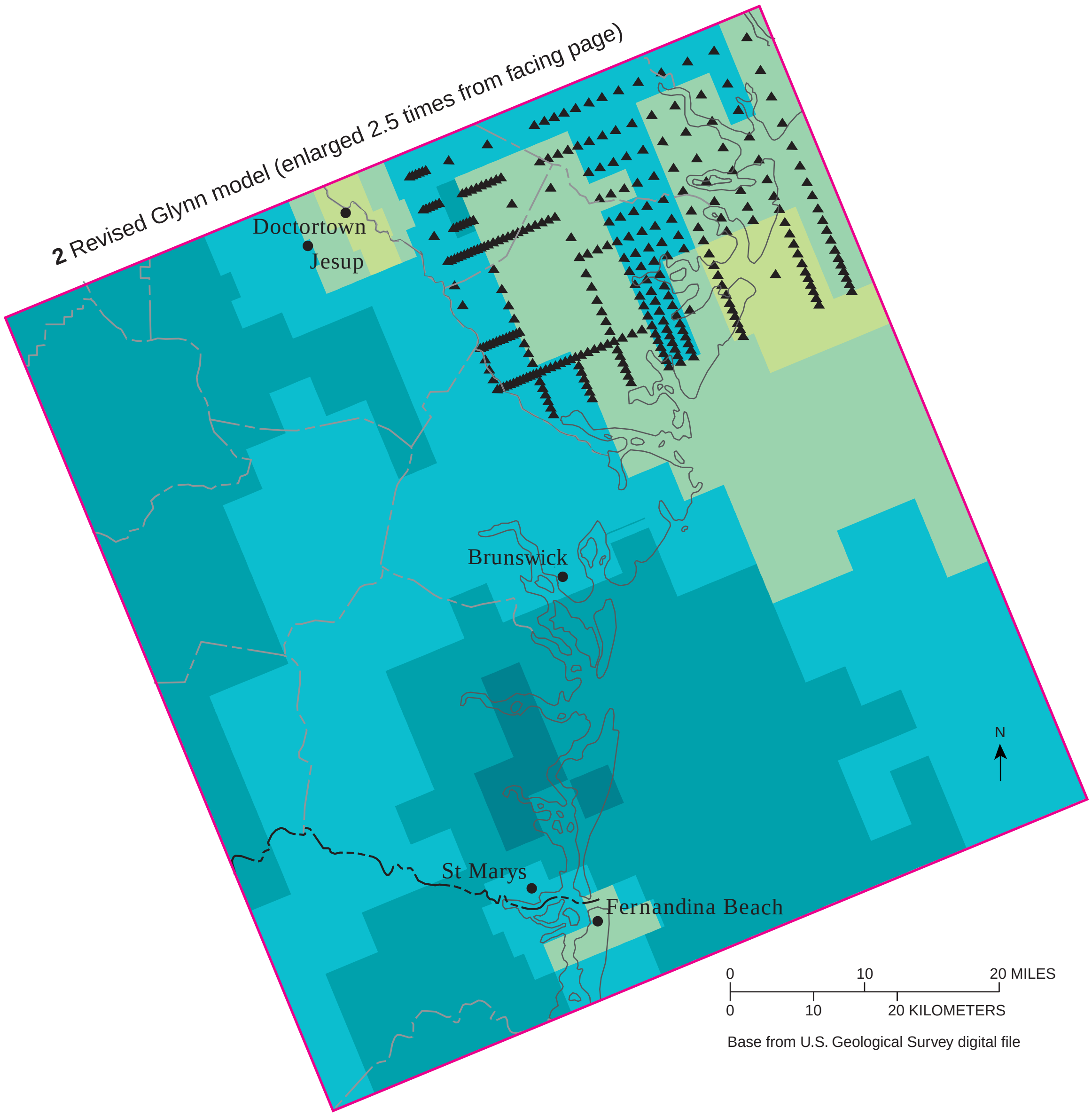


Figure 9. Calibrated leakance array for the middle semiconfining unit (model layer C2), Savannah model, and revised Glynn and Regional Aquifer-System Analysis (RASA) models.



EXPLANATION

CALIBRATED LEAKANCE, IN FEET PER DAY PER FOOT OF THICKNESS—≥, greater than or equal to; <, less than

- ≥ $1x10^{-8}$ and < $1x10^{-7}$
- ≥ $1x10^{-7}$ and < $1x10^{-6}$
- ≥ $1x10^{-6}$ and < $1x10^{-5}$
- ≥ $1x10^{-5}$ and < $1x10^{-4}$
- ≥ $1x10^{-4}$ and < $1x10^{-3}$
- ≥ $1x10^{-3}$

INACTIVE CELLS

▲ MODEL CELL WHERE REVISED VALUE DIFFERS BY MORE THAN 10 PERCENT OF ORIGINAL VALUE

Figure 9. Calibrated leakance array for the middle semiconfining unit (model layer C2), Savannah model, and revised Glynn and Regional Aquifer-System Analysis (RASA) models—continued.

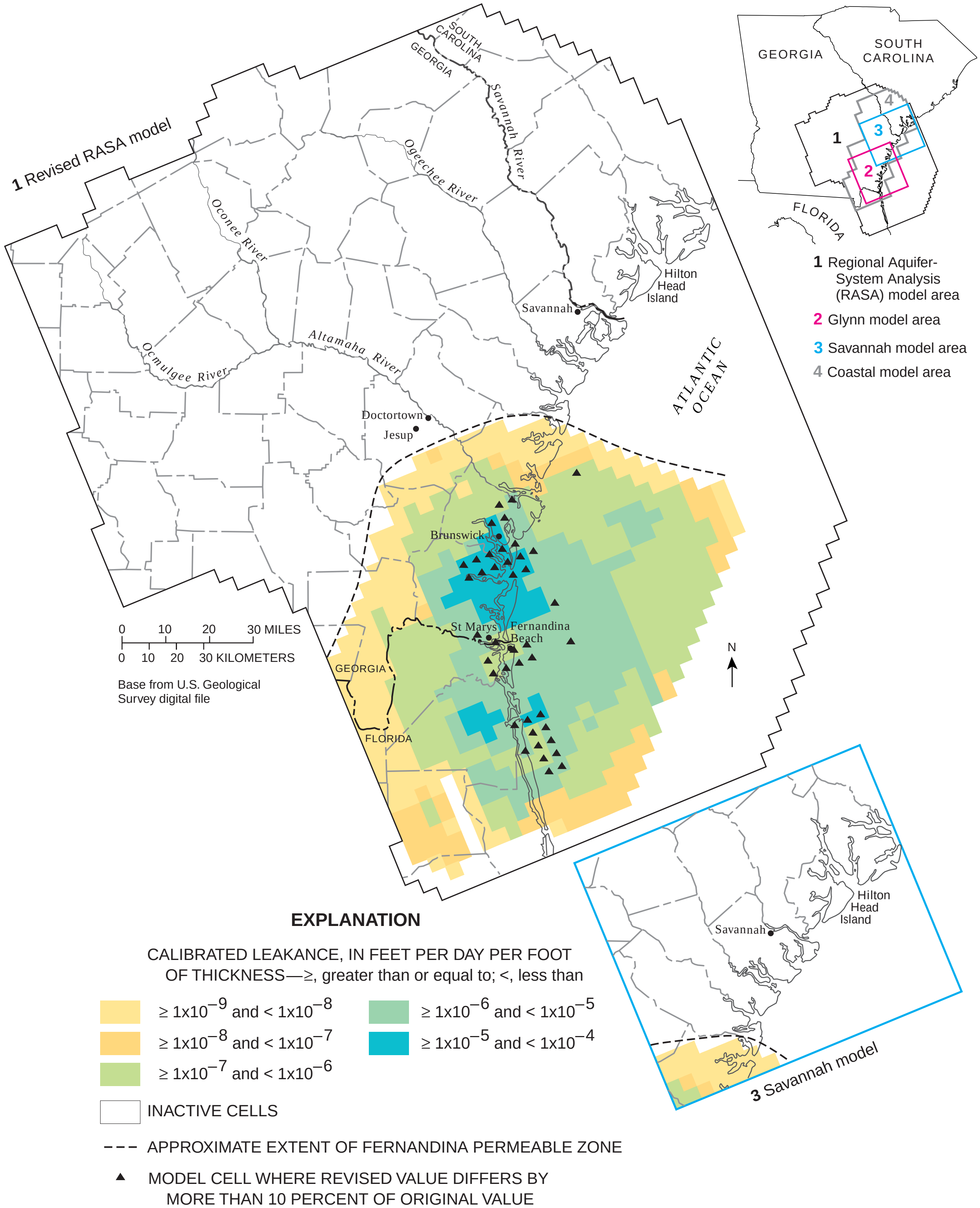


Figure 10. Calibrated leakance array for the lower semiconfining unit (model layer C3), Savannah model, and revised Glynn and Regional Aquifer-System Analysis (RASA) models.

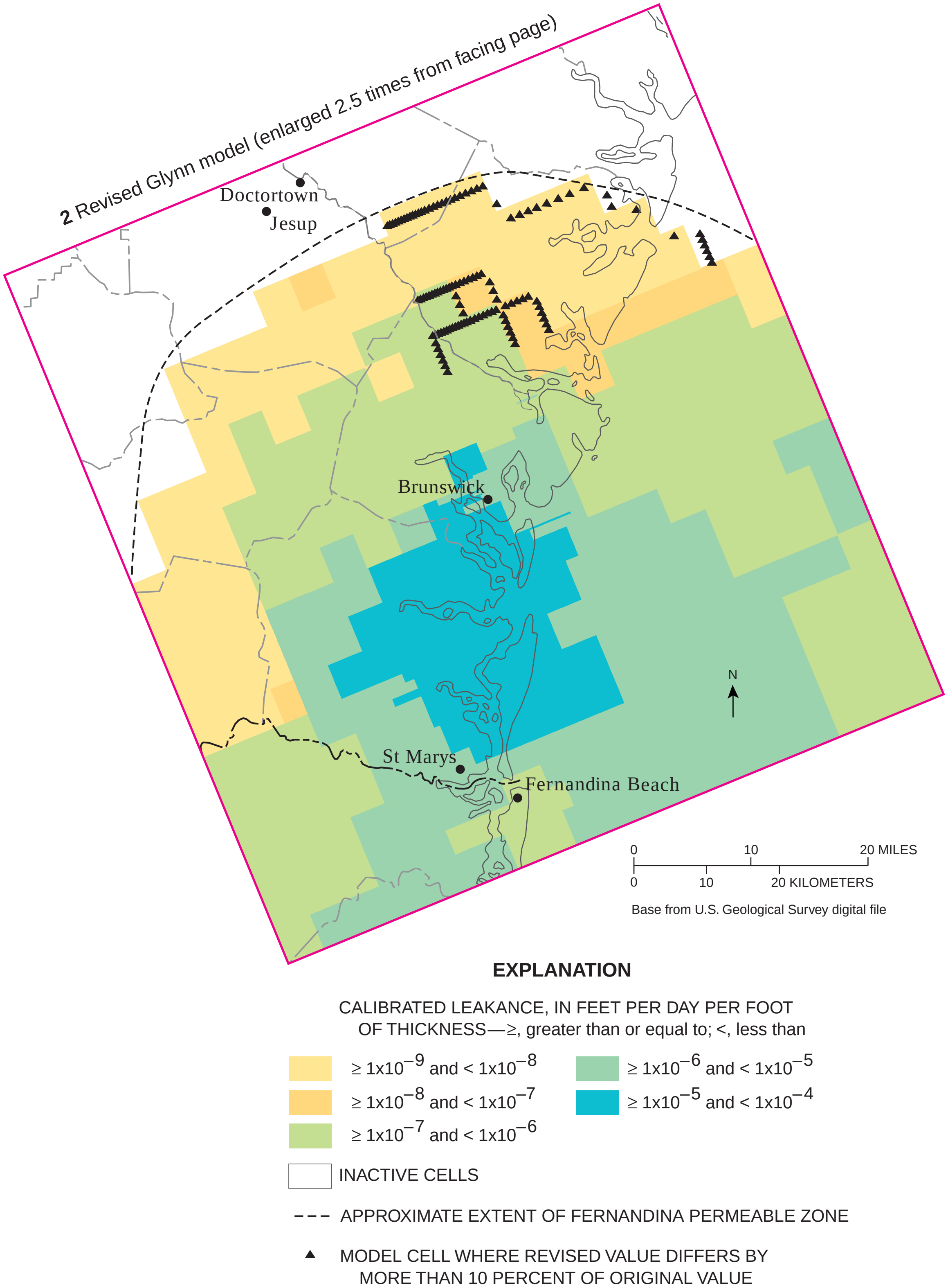


Figure 10. Calibrated leakance array for the lower semiconfining unit (model layer C3), Savannah model, and revised Glynn and Regional Aquifer-System Analysis (RASA) models—continued.

Vertical leakance was revised for all three confining units during calibration of the RASA and subregional models. Revised vertical leakance arrays for the RASA and Glynn models and the original array used in the Savannah model are shown in figure 8 for the upper confining unit (layer C1), figure 9 for the middle semiconfining unit (layer C2), and in figure 10 for the lower semiconfining unit (layer C3). The leakance array for layer C3 covers only part of the area because of the absence of the underlying Fernandina permeable zone (layer A4). Leakance arrays for the revised RASA model show the greatest change (greater than 10 percent) in the area of the Glynn model and near the southern boundary of the RASA model. Changes in the leakance arrays for the revised Glynn model exceed 10 percent in the area of overlap with the Savannah model.

Ranges of simulated and estimated leakance values for the upper confining unit, and middle and lower semiconfining units are listed in tables 4–6. Large discrepancies between field estimates and model input arrays are because core permeameter data measured only the primary porosity of rock samples. Notably, fracture zones in the dense, low permeability, recrystallized limestone and dolomite of the middle semiconfining unit resulted in higher leakance values than in areas where fractures are absent.

Table 4. Simulated and estimated leakance values for the upper confining unit (model layer C1)—original and revised models

[—, not applicable]

Model	Leakance, in feet per day per foot of thickness			
	Number of values	Minimum	Maximum	Mean
	Estimated based on field data[1]			
—	52	—	—	3.2×10^{-5}
	RASA model[2]			
Original	2,313	1.9×10^{-8}	2.5×10^{-2}	2.8×10^{-4}
Revised	2,313	1.9×10^{-9}	5.6×10^{-3}	2.2×10^{-4}
	Glynn model			
Original	10,340	7.2×10^{-7}	7.9×10^{-5}	[3]1.4×10^{-5}
Revised	10,340	7.2×10^{-7}	7.9×10^{-5}	[3]1.4×10^{-5}
	Savannah model			
Original	6,688	9.4×10^{-8}	5.6×10^{-3}	3.9×10^{-4}
Revised	6,688	9.4×10^{-8}	5.6×10^{-3}	3.9×10^{-4}

[1]Estimated from laboratory permeability and unit thickness of core in Chatham County, Ga. No maximum or minimum reported. From Krause and Randolph (1989, p. 28).
[2]Actively simulated area.
[3]Model-simulated values weighted according to cell areas.

Table 5. Simulated and estimated leakance values for the middle semiconfining unit (model layer C2)—original and revised models

[—, not applicable]

Model	Leakance, in feet per day per foot of thickness			
	Number of values	Minimum	Maximum	Mean
	Estimated based on field data[1]			
—	5	—	—	1.0×10^{-7}
	RASA model[2]			
Original	2,021	8.6×10^{-7}	7.8×10^{-3}	4.4×10^{-4}
Revised	2,021	8.6×10^{-8}	7.8×10^{-3}	4.6×10^{-4}
	Glynn model			
Original	10,340	2.8×10^{-7}	3.9×10^{-3}	[3]2.0×10^{-4}
Revised	10,340	2.8×10^{-7}	3.9×10^{-3}	[3]2.0×10^{-4}
	Savannah model			
Original	6,688	8.6×10^{-8}	7.8×10^{-3}	3.1×10^{-4}
Revised	6,688	8.6×10^{-8}	7.8×10^{-3}	3.1×10^{-4}

[1]Estimated from laboratory permeability and unit thickness at two core-holes in Glynn County, Ga. No maximum or minimum reported. From Krause and Randolph (1989, p. 28).
[2]Actively simulated area.
[3]Model-simulated values weighted according to cell areas

Table 6. Simulated and estimated leakance values for the lower semiconfining unit (model layer C3)—original and revised models

[Field data unavailable]

Model	Leakance, in feet per day per foot of thickness			
	Number of values	Minimum	Maximum	Mean
	RASA model[1]			
Original	633	8.6×10^{-9}	3.4×10^{-5}	2.4×10^{-6}
Revised	633	8.6×10^{-9}	2.6×10^{-5}	2.3×10^{-6}
	Glynn model			
Original	9,810	8.6×10^{-9}	4.3×10^{-5}	[2]3.5×10^{-6}
Revised	9,810	8.6×10^{-9}	4.3×10^{-5}	[2]3.5×10^{-6}
	Savannah model			
Original	384	8.6×10^{-9}	2.8×10^{-7}	4.0×10^{-8}
Revised	384	8.6×10^{-9}	2.8×10^{-7}	4.0×10^{-8}

[1]Actively simulated area.
[2]Model-simulated values weighted according to cell areas.

Effects on simulated water levels and water budget

To ensure that the revised models accurately simulate the hydrologic system and evaluate the possible effects of model revisions on simulated water levels and flow rates, a simulation was conducted with the original Savannah and revised RASA and Glynn models using the ground-water withdrawal rates for the period May 1985. The simulated rate of withdrawal is about 591 million gallons per day (Mgal/d) for the RASA model, 197 Mgal/d for the Glynn model, and 102 Mgal/d for the Savannah model. The Glynn and Savannah models have a combined pumpage of 299 Mgal/d; thus, the RASA model simulates an additional 292 Mgal/d in the area outside of the Glynn and Savannah models. Of this amount, 9 Mgal/d is within the coastal Georgia study area, with an additional 283 Mgal/d outside of the study area (recall that the RASA model extends beyond the coastal Georgia study area). Most withdrawals are from the Upper Floridan aquifer (model layer A2).

The simulated potentiometric-surface map produced from the revised models generally is similar to the hand-drawn potentiometric-surface map for May 1985 (Clarke, 1987). The distribution of simulated water levels for the Upper Floridan aquifer produced by the revised models, together with the locations of simulated pumpage, are presented in figure 11. Contours shown in figure 11 are a composite of simulated values for the three models; where data from two or more models overlapped, values from the most recently calibrated model were given precedence.

To assess the effect of model revisions on simulated water levels and flow rates, a comparison was made between simulation results using pumpage data for May 1985 and hydraulic-property arrays for the original and revised RASA and Glynn models. A comparison was not made for the Savannah model because there were no modifications made to data arrays from the original model of Garza and Krause (1996). Simulated water levels showed no change between the original and revised RASA model, and a slight change between the original and revised Glynn model. For the revised Glynn model, 80 percent of the simulated water levels were within 0.5 ft of those simulated by the original model. Larger differences, as much as 9.7 ft, were observed in the southwestern part of the Glynn model area, and likely are the result of revisions to hydraulic-property arrays of the RASA model made during calibration of the coastal model.

Observed water levels in the Upper Floridan aquifer (model layer A2) for May 1985 were compared with simulated water levels generated by the original and revised RASA and Glynn models, and calibration statistics based on water-level residuals were computed for the revised models. Calibration statistics for the revised RASA model are summarized in table 7 and Appendix A, and water-level residuals are plotted in figure 12. For the revised Glynn model, calibration statistics are summarized in table 8 and Appendix B, and water-level residuals are plotted in figure 13.

Simulated water levels for May 1985 for the original RASA and Glynn models showed little change as the result of revisions made to the hydraulic-property arrays (tables 7 and 8). For the revised RASA model, the difference between simulated and observed water levels (residuals) in 252 model cells was the same as the originally calibrated model—a root-mean square of 12.17 ft (table 7). Simulated water levels generally were most accurate in areas along the coast, where differences between simulated and observed water levels were less than 10 ft (Appendix A, fig. 12). Water levels were higher toward the northwest, especially in areas including and north of the Gulf Trough than along the coast, probably the result of steep hydraulic gradients that are not simulated by the model due to the coarse grid resolution. Steep hydraulic gradients are prevalent in the vicinity of the Gulf Trough because of decreased permeability of the Upper Floridan aquifer, and north of the Gulf Trough because of pronounced topographic controls on the flow system due to the shallow depth of the aquifer.

Table 7. Comparison of calibration statistics for water-level residuals for the Upper Floridan aquifer (model layer A2), May 1985, using hydraulic-property arrays from the original and revised Regional Aquifer-System Analysis (RASA) models

Model	Number of observa-tions	Residuals (feet)		
		Mean	Standard deviation	Root-mean square
Original	252	2.28	11.98	12.17
Revised	252	2.28	11.98	12.17

[1]See Appendix A for cell by cell calibration results for revised model.

Table 8. Comparison of calibration statistics for water-level residuals for the Upper Floridan aquifer (model layer A2), May 1985, using hydraulic-property arrays from the original and revised Glynn models[1]

Model	Number of observa-tions	Residuals (feet)		
		Mean	Standard deviation	Root-mean square
Original	145	1.84	7.96	8.14
Revised	145	1.86	7.95	8.13

[1]See Appendix B for cell by cell calibration results for revised model.

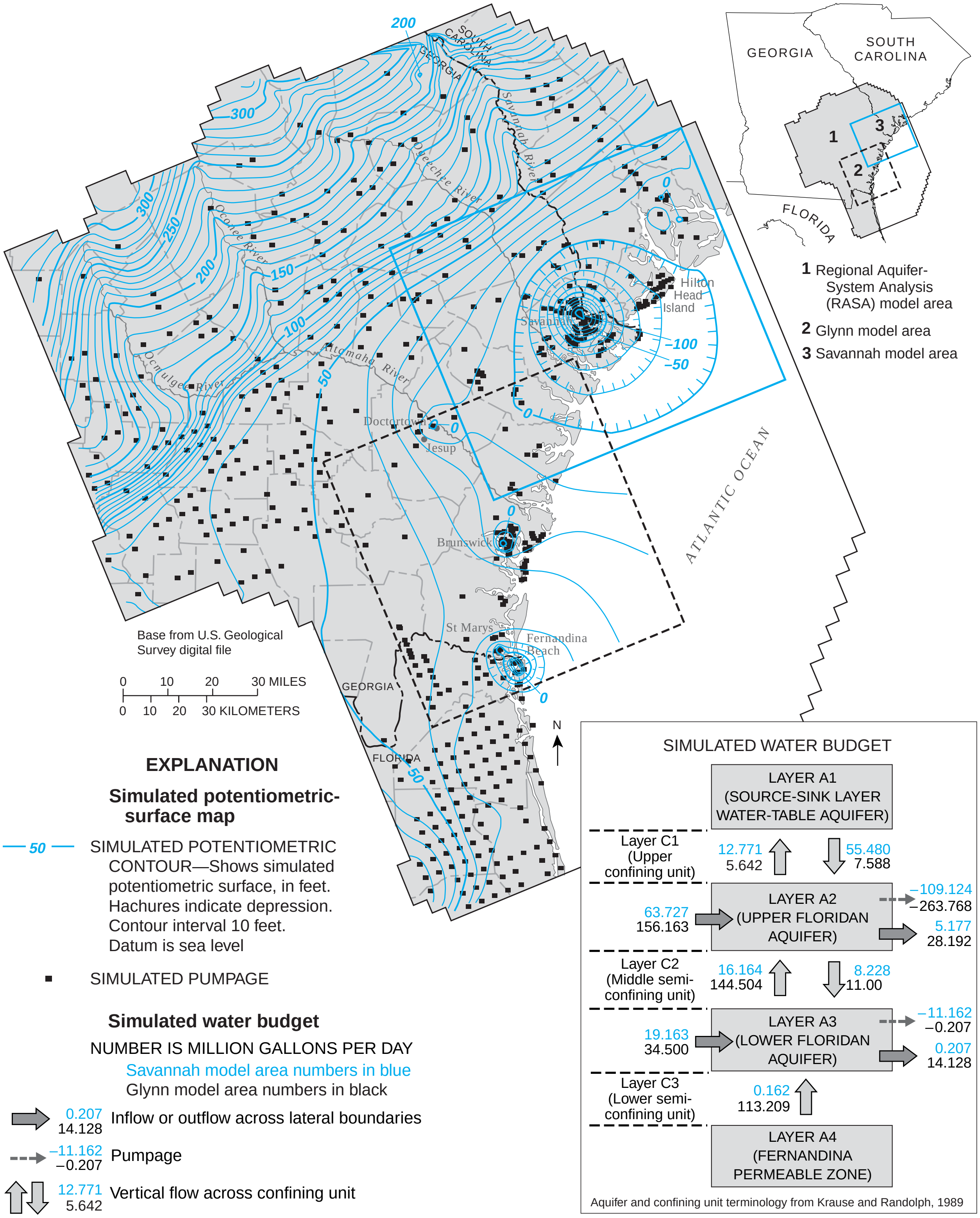


Figure 11. Simulated potentiometric surface of the Upper Floridan aquifer (model layer A2), location of simulated pumpage, and simulated water budget, May 1985, based on the Savannah and revised Glynn and Regional Aquifer-System Analysis (RASA) models.

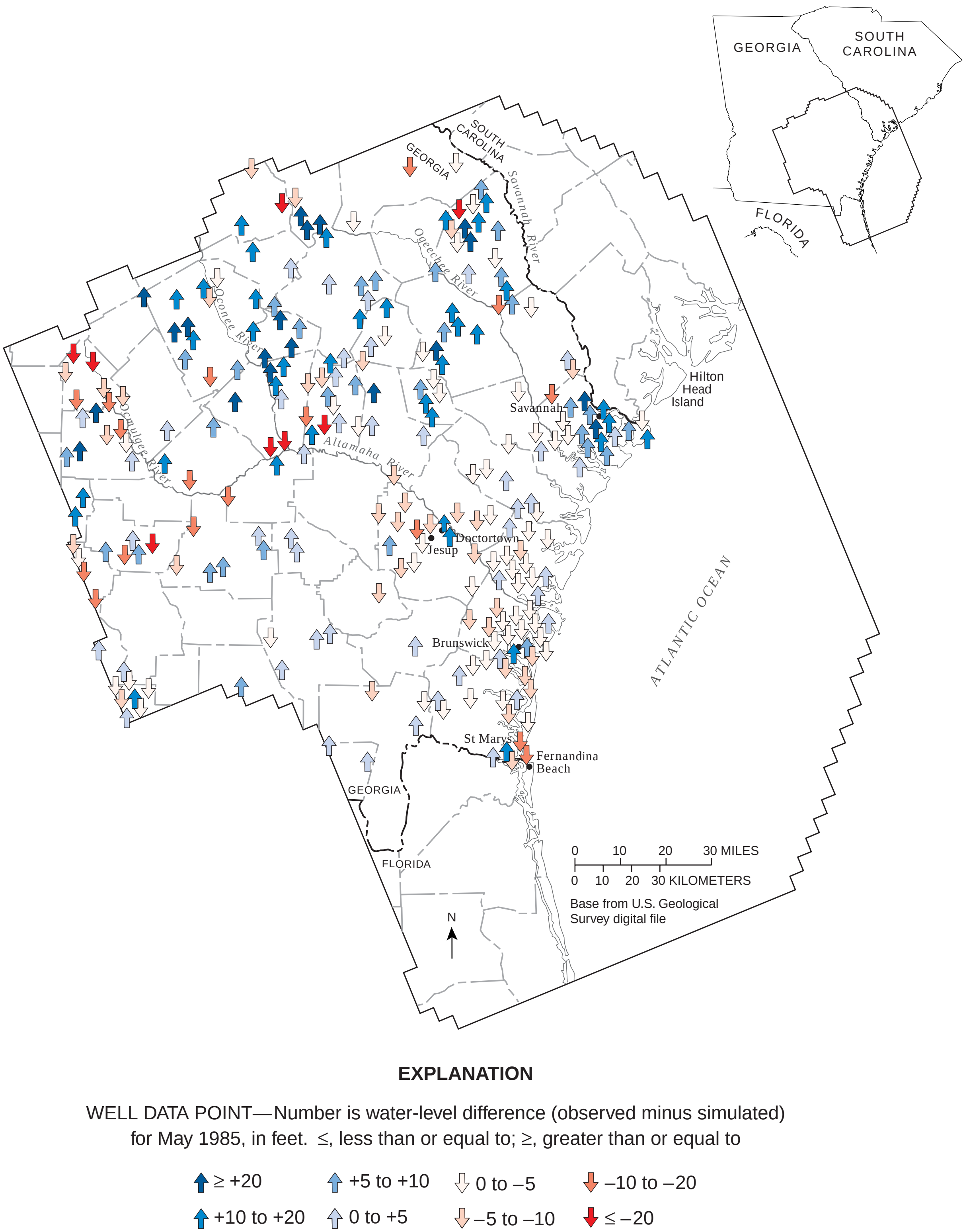


Figure 12. Difference between simulated and observed water levels (residuals) for the Upper Floridan aquifer (model layer A2), May 1985, revised Regional Aquifer-System Analysis (RASA) model.

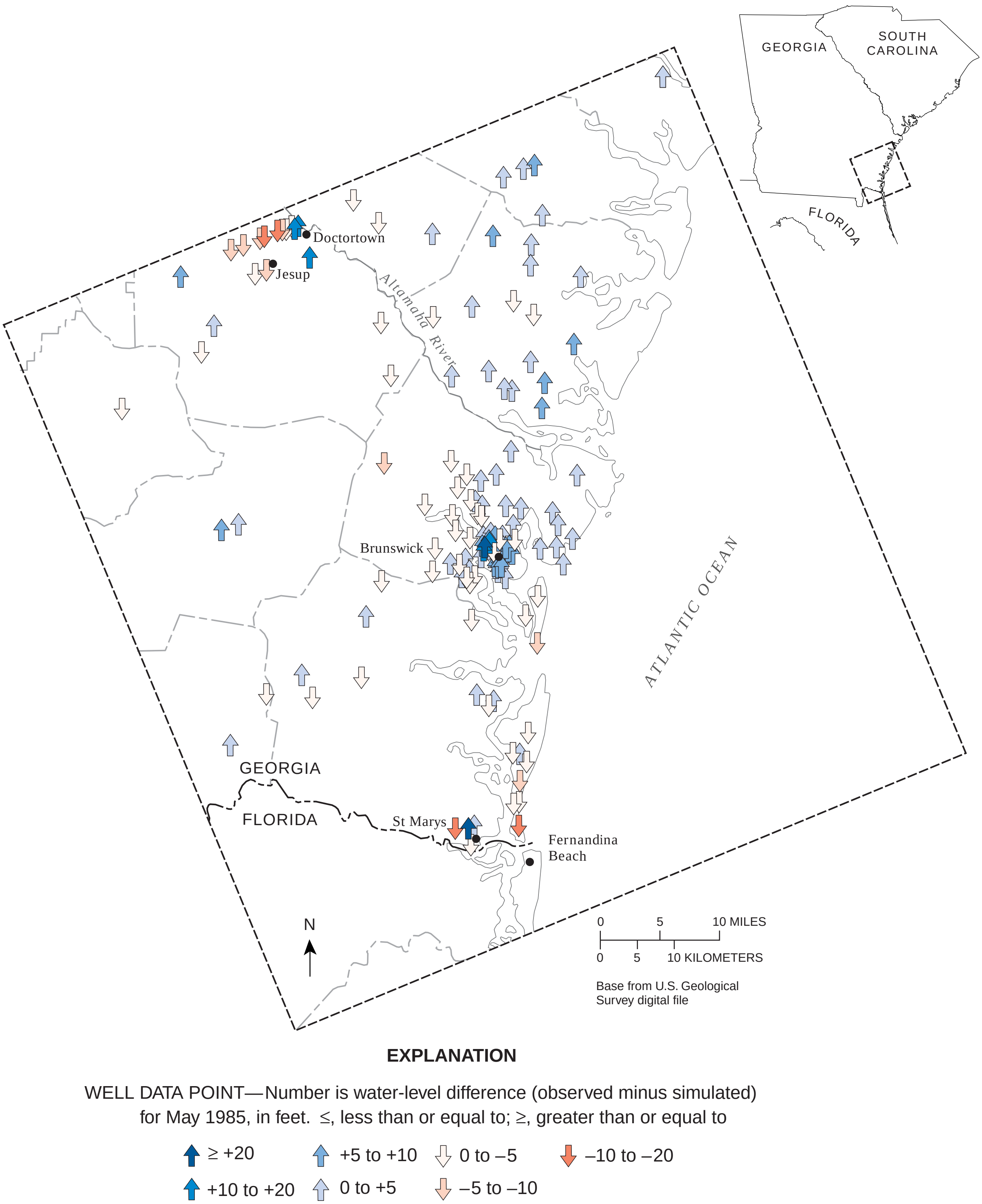


Figure 13. Difference between simulated and observed water levels (residuals) for the Upper Floridan aquifer (model layer A2), May 1985, revised Glynn model.

For the revised Glynn model, water-level residuals generally were less than 5 ft, with scattered residuals greater than 10 ft occurring in the St Marys, Jesup, and Brunswick areas (fig. 13). Higher residuals in these areas may be the result of insufficient grid resolution to simulate steep hydraulic gradients in the vicinity of pumping wells, or a variety of factors influencing accuracy of the simulation, including inaccurate pumping data, insufficient resolution of hydraulic properties, or proximity of the model cell to a lateral model boundary.

The simulated water budget for May 1985 showed no change as the result of revisions made to the hydraulic-property arrays of the RASA model (table 9), and little change as the result of revisions made to the hydraulic-property arrays of the Glynn model (fig. 14). Changes in flow rates for the Glynn model were limited to small changes in vertical leakage between layers, with no change in lateral flow rates (fig. 14). Note that although the net change in flow rates showed little variation, the areal distribution of vertical leakage may have changed as a result of changes to the leakance arrays.

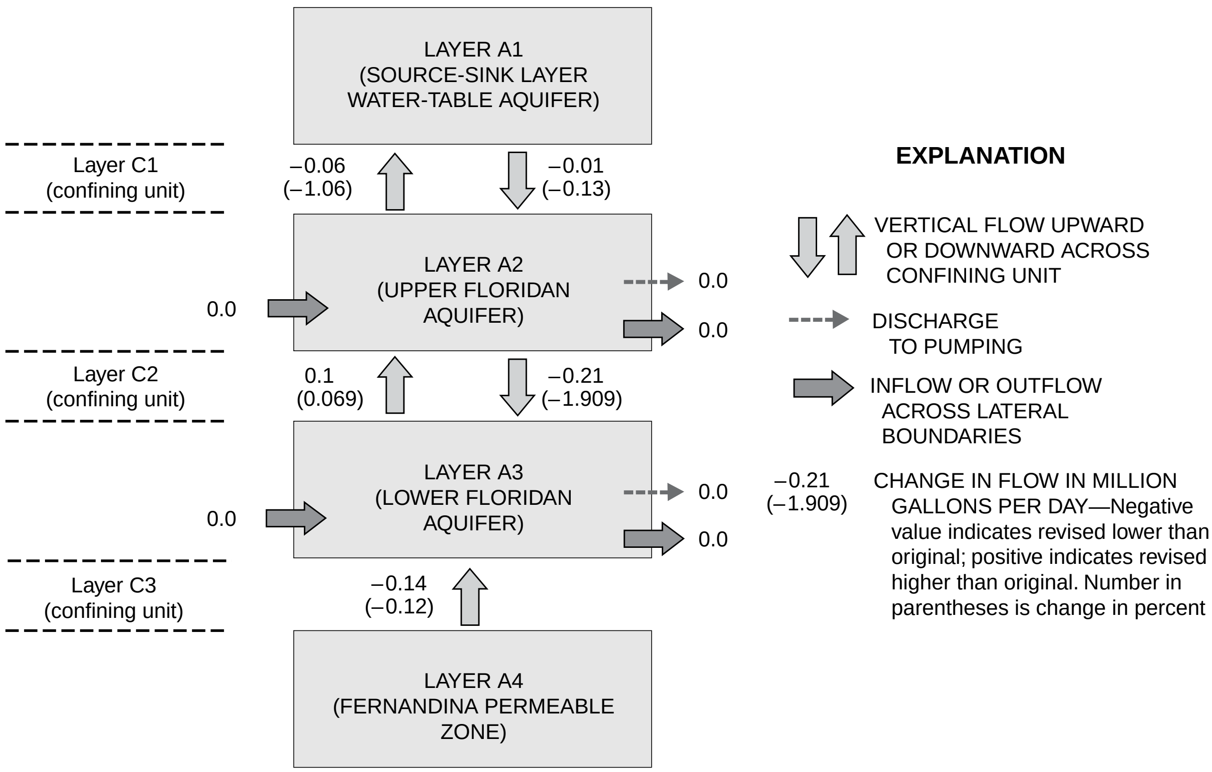


Figure 14. Change in simulated water budget for May 1985 between original and revised Glynn model.

Table 9. Comparison of simulated water budget for May 1985, using hydraulic-property arrays from the original and revised Regional Aquifer-System Analysis (RASA) models

Model	Simulated flow, in million gallons per day						
	Inflow			Outflow			
	Specified head	Head-dependent boundary	Total	Specified head	Head-dependent boundary	Wells	Total
Original	1,161.5	115	1,276.5	682.5	2.7	591.3	1,276.5
Revised	1,161.5	115	1,276.5	682.5	2.7	591.3	1,276.5

SIMULATION OF GROUND-WATER MANAGEMENT SCENARIOS

The revised RASA and Glynn models and the original Savannah model were used to predict the effects of hypothetical changes in the distribution and amount of ground-water withdrawal on the Floridan aquifer system. Results and information from these water-management scenarios were provided to EPD for their use in developing EPD's "Interim Strategy for Managing Saltwater Intrusion in the Upper Floridan Aquifer of Southeast Georgia" (Georgia Environmental Protection Division, 1997). EPD used the results of the various model simulations to evaluate the effects of changes in pumpage on:

- the area affected by saltwater contamination at Brunswick;
- quantity of vertical leakage from the Fernandina permeable zone;
- ground-water levels at Savannah-Hilton Head Island and Brunswick; and
- rate of lateral ground-water movement at Savannah-Hilton Head Island.

EPD's intent for the various scenarios is described in table 10. For each scenario, the three models were used to simulate changes in pumpage and the resultant effects on ground-water levels in the Upper Floridan aquifer and vertical leakage from the Fernandina permeable zone. All aquifer and confining unit properties were unchanged when running the models for each scenario; only pumpage was changed.

Pumpage changes for the various scenarios were developed by EPD based on changes in permitted or actual withdrawal from the Upper Floridan aquifer. Scenarios were grouped according to the following pumping locations:

- 24-county area;
- Central subarea;
- Glynn-Wayne-Camden County subarea; and
- Savannah-Hilton Head Island subarea.

The summary of each scenario described in table 10, includes: (1) pumpage changes from May 1985 rates, (2) EPD scenario identifier, (3) effects of pumpage changes on ground-water levels at Hilton Head Island and Brunswick, and (4) effects of pumpage changes on quantities of vertical leakage from the Fernandina permeable zone in the area of the Glynn model.

To illustrate the effects of pumpage changes for each scenario on the ground-water flow system, comparisons were made between simulated conditions for modern-day (May 1985) conditions and for each scenario having a hypothetical pumping change. Changes are presented on maps showing water-level differences; on diagrams summarizing changes in pumpage, vertical leakage between aquifers, and lateral flow at model boundaries; and in a table summarizing changes in pumpage, water-level changes at cells, and change in vertical leakage from the Fernandina permeable zone. Water-level changes illustrated on the figures may not be as great as changes described in the text because of limitations of figure size and contour intervals.

Water-level changes were tabulated at model cells designated at the locations of saltwater intrusion at Brunswick, Ga., and seawater encroachment at Hilton Head Island, S.C. These locations are important to water-resource managers because they represent areas where water-level declines in the Upper Floridan aquifer would steepen the hydraulic gradient between freshwater and saltwater zones; and thus, increase the potential for saltwater contamination.

The cells at Brunswick represent locations where simulated hydraulic head would affect hydraulic gradient, which, in turn would affect saltwater intrusion into the Upper Floridan aquifer from the underlying Fernandina permeable zone. These cells are located at row 66, column 48, and row 60, column 49 of the Glynn model (fig. 5). Simulated head in the cell at Hilton Head Island can be used to identify changes in hydraulic gradient that could affect lateral encroachment of seawater. This cell is located at row 36 and column 70 of the Savannah model (fig. 5).

The pumpage changes for each scenario resulted in differences in simulated ground-water levels in the Upper and Lower Floridan aquifers, vertical leakage between aquifers, and lateral flow into and out of the model area (fig. 15, table 10). Simulated pumpage changes ranged from about 82 Mgal/d lower to 438 Mgal/d higher than estimated May 1985 rates. These pumpage changes produced a wide range of responses in the ground-water flow system, with pumpage increases generally resulting in increased drawdown at indicator cells, and increased vertical leakage from the Fernandina permeable zone (fig. 15, table 10). For example, in the Brunswick area, a pumpage increase of about 438 Mgal/d for scenario A-6 resulted in an average simulated water-level decline of 37.31 ft at the Brunswick indicator cells, and an associated increase in vertical leakage from the Fernandina permeable zone of 63.05 Mgal/d. Conversely, a pumpage decrease of 57.48 Mgal/d for scenario C-5 resulted in a simulated water-level rise of 13.67 ft at the Brunswick indicator cells, and an associated decrease in vertical leakage from the Fernandina permeable zone of 13.17 Mgal/d.

Table 10. Summary of selected water-management scenarios for coastal Georgia simulated using the Savannah and revised Regional Aquifer-System Analysis (RASA) and Glynn models
[Mgal/d, million gallons per day; ft, feet; EPD, Georgia Environmental Protection Division; <, less than; do., ditto]

Scenario	Georgia Environmental Protection Division Identifier	Simulated pumpage (Mgal/d)		Change from 1985 pumpage (Mgal/d)	Water-level change at indicator cell (ft)		Change in vertical leakage from Fernandina permeable zone[1] (Mgal/d)	Purpose of scenario[2]
		1985	Scenario		Brunswick, Ga.[3]	Hilton Head Island, S.C.[4]		
24-county area								
A-1	9608_04	307.66	276.89	-30.77	4.12	0.28	-5.15	Simulate 10-percent reduction from estimated 1985 pumpage.[5]
A-2	9608_05	307.66	338.43	30.77	-4.42	-0.28	5.94	Same as scenario A-1, except simulate 10-percent increase from estimated 1985 pumpage.
A-3	9608_06	307.66	369.19	61.53	-8.80	-0.57	11.79	Same as scenario A-1, except simulate 20-percent increase from estimated 1985 pumpage.
A-4	9608_08a	307.66	[6]373.00	65.34	4.46	0.34	-0.01	Simulate estimated 1994 ground-water withdrawal.[5,6]
A-5	9608_08g	307.66	672.00	364.34	-10.50	-1.81	23.20	Simulate estimated highest unrestricted pumpage increase for users in the Coastal area.[5,6]
A-6	9608_09a	307.66	746.00	438.34	-37.31	-3.58	63.05	Simulate double estimated 1994 pumpage.[5,6]
Central subarea								
C-1	9611_03a	263.81	256.55	-7.26	4.66	0.11	-2.03	Simulate pumpage decrease for the year 2050[6] whereby projected pumpage for Glynn and Chatham Counties is capped at 1997 levels; pumpage increases outside of Glynn and Chatham Counties represent projected population growth.[5]
C-2	9609_01a	263.81	459.79	195.98	-13.20	-1.68	22.74	Simulate pumpage increase for the year 2050[6] whereby projected pumpage for Glynn County capped at 1997 levels; assumes no restrictions on use outside of Glynn County.
C-3	9512scen01	263.81	250.51	-13.30	0.57	0.29	-0.93	Simulate reduction and redistribution from estimated 1995-96 pumpage. Pumpage represents improved water-conservation measures and allows for general permitting of additional withdrawal from the Upper Floridan aquifer.
C-4	9608_07	263.81	226.61	-37.20	13.21	0.28	-10.13	Simulate reduction and redistribution from estimated 1985 pumpage. Pumpage reductions are largely the result of water conservation measures.[5]
C-5	9512scen02	263.81	206.33	-57.48	13.67	0.56	-13.17	Simulate reduction and redistribution from estimated 1985 pumpage. Pumpage represents implementation of initial version of EPD's Interim Water Management Strategy. Pumpage reductions are largely the result of water conservation.

Table 10. Summary of selected water-management scenarios for coastal Georgia simulated using the Savannah and revised Regional Aquifer-System Analysis (RASA) and Glynn models—Continued

[Mgal/d, million gallons per day; ft, feet; EPD, Georgia Environmental Protection Division; <, less than; do., ditto]

Scenario	Georgia Environmental Protection Division Identifier	Simulated pumpage (Mgal/d)		Change from 1985 pumpage (Mgal/d)	Water-level change at indicator cell (ft)		Change in vertical leakage from Fernandina permeable zone[1] (Mgal/d)	Purpose of scenario[2]
		1985	Scenario		Brunswick, Ga.[3]	Hilton Head Island, S.C.[4]		
Glynn-Wayne-Camden subarea								
G-1	9509glwa01	185.56	175.56	-10.00	2.07	<0.05	-1.64	Simulate pumpage reduction in Glynn and Wayne Counties.
G-2	[7]9509glwa02	185.56	165.66	-20.00	4.46	0.05	-4.07	do.
G-3	9509glwa03	185.56	145.56	-40.00	9.21	0.11	-8.94	do.
G-4	[8]9509itt	185.56	110.89	-74.67	6.25	0.25	-11.16	Simulate pumpage reduction at single isolated location at Doctortown, Wayne County. Pumpage is approximately one-half the difference between actual and permitted use.
G-5	9510everett	185.56	190.56	5.00	-0.78	<0.05	1.18	Simulate effects of pumpage increase north of “Satilla Line” on ground-water levels at Brunswick.
G-6	9510woodbine	185.56	190.56	5.00	-0.42	<0.05	1.46	Simulate effects of pumpage increase south of “Satilla Line” on ground-water levels at Brunswick.
Savannah-Hilton Head Island subarea								
S-1	9509chat01	99.01	89.01	-10.00	0.40	0.27	-0.72	Simulate effects of pumpage reduction in Chatham County. Represents Chatham County –Savannah Metropolitan Planning Commission pumpage reduction plan for year 2005).[1]
S-2	9611_02a	99.01	84.42	-14.59	0.53	0.39	-0.93	Simulate effects of pumpage reduction in Chatham County on the ground-water level at Brunswick and Hilton Head Island. Pumpage represents reduction to be implemented by the year 2005, as specified by Chatham County-Savannah Metropolitan Planning Commission.[5]
S-3	[10]9608_01	99.01	79.01	-20.00	0.66	0.53	-1.10	Simulate effects of pumpage reduction in Chatham County on the ground-water level at Brunswick and Hilton Head Island.[5,10]
S-4	[11]9504sav	99.01	79.38	-19.63	0.65	0.52	-1.09	Simulate effects of pumpage reduction in Chatham County.
S-5	9608_03	99.01	71.66	-27.35	0.94	0.73	-1.54	Simulate effects of pumpage reduction in Chatham County.[5]
S-6	[12]9611_04f	99.01	59.01	-40.00	1.51	1.07	-2.60	Simulate effects of pumpage reduction in Chatham County.[9]
S-7	9611_04g	99.01	49.01	-50.00	1.95	1.34	-3.41	do.[9]
S-8	9611_04d	99.01	44.01	-55.00	2.17	1.47	-3.80	do.[9]
S-9	9611_04e	99.01	39.01	-60.00	2.40	1.61	-4.27	do.[9]
S-10	9611_04b	99.01	34.01	-65.00	2.63	1.74	-4.70	do.[9]

Table 10. Summary of selected water-management scenarios for coastal Georgia simulated using the Savannah and revised Regional Aquifer-System Analysis (RASA) and Glynn models—Continued

[Mgal/d, million gallons per day; ft, feet; EPD, Georgia Environmental Protection Division; <, less than; do., ditto]

Scenario	Georgia Environmental Protection Division Identifier	Simulated pumpage (Mgal/d)		Change from 1985 pumpage (Mgal/d)	Water-level change at indicator cell (ft)		Change in vertical leakage from Fernandina permeable zone[1] (Mgal/d)	Purpose of scenario[2]
		1985	Scenario		Brunswick, Ga.[3]	Hilton Head Island, S.C.[4]		
				Savannah-Hilton Head Island subarea—Continued				
S-11	9611_04c	99.01	29.01	-70.00	2.84	1.88	-5.08	do.[9]
S-12	9610_03a	99.01	17.44	-81.57	3.35	2.19	-6.02	Simulate effects of discontinuation of ground-water pumpage in Chatham County (replaced by surface water) on the ground-water level at Hilton Head Island.[9]
S-13	9610_02a	99.01	149.01	50.00	-1.87	-1.20	3.47	Simulate discontinuation of surface-water withdrawal in western part of Chatham County; replaced by increased ground-water withdrawal.[9]
S-14	9610_01a	99.01	105.39	6.38	-0.06	-0.30	0.12	Simulate effects of pumpage increases in South Carolina on the ground-water level at Hilton Head Island.
S-15	9610_01c	99.01	99.99	0.98	<0.05	-0.22	0.07	do.

[1]Model layer A4, flux difference determined for area of Glynn County model.

[2]William H. McLemore (Georgia Geologic Survey, written commun., January 2, 1998).

[3]Indicator cells at Brunswick, Ga., located at row 66, column 48, and row 60, column 49 of the Glynn model (averaged).

[4]Indicator cell at Hilton Head Island, S.C., located at row 36, column 70 of the Savannah model.

[5]Results used by EPD to estimate time-of-travel of ground water from Hilton Head Island to Savannah, and the area affected by saltwater contamination at Brunswick (Georgia Environmental Protection Division, 1997).

[6]Estimate provided by Pete Terrebonne (Georgia State University, written commun., August 8, 1996).

[7]Also called scenario 9509glwa04.

[8]Also called scenario 9504itt.

[9]Results used in a water-level profile from Hilton Head Island to Savannah.

[10]Also called scenario 9611_04a.

[11]Also called scenario 9509chat02.

[12]Also called scenario 9509chat03.

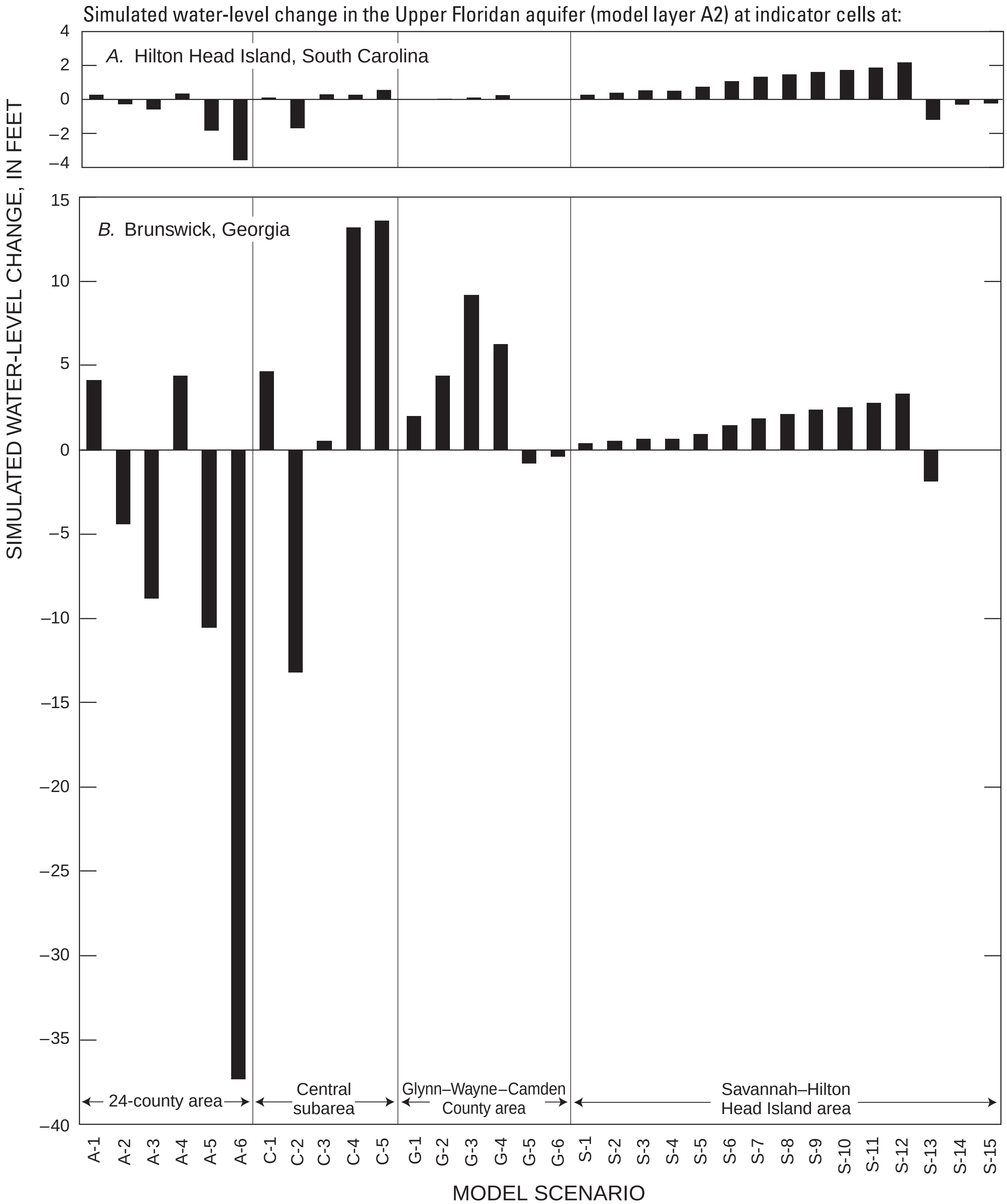


Figure 15. Results of selected water-management scenarios—simulated water-level change in the Upper Floridan aquifer (model layer A2) at indicator cells at (*A*) Hilton Head Island, South Carolina, and (*B*) Brunswick, Georgia; continued next page.

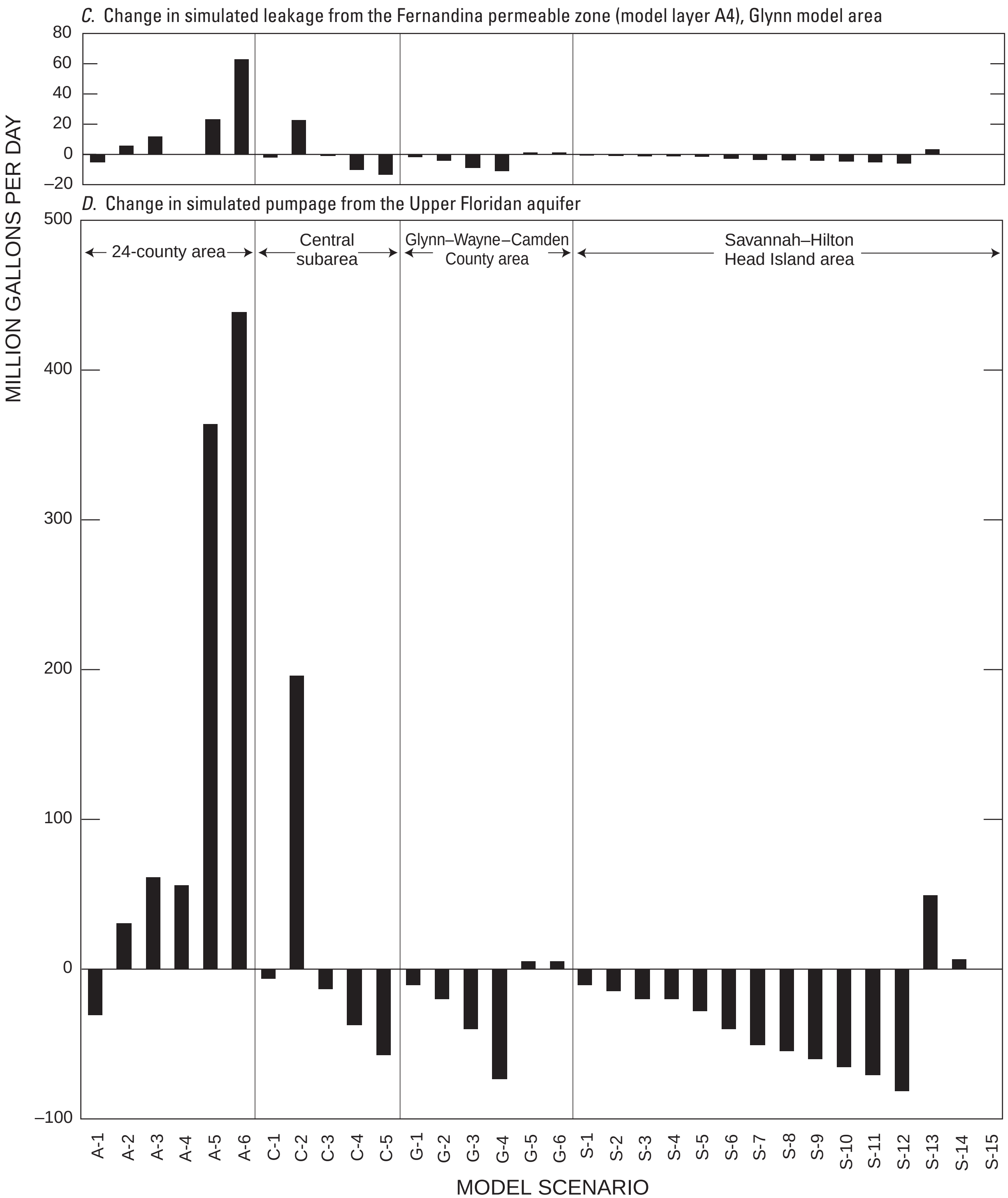


Figure 15—continued. (*C*) changes in simulated vertical leakage from the Fernandina permeable zone (model layer A4) in the Glynn model area; and (*D*) summary of simulated pumpage changes from the Upper Floridan aquifer. The indicator cell for Hilton Head Island is located at row 36 and column 70 of the Savannah model: for Brunswick is located at row 66, column 48 and row 60, column 49 of the Glynn County model. See tables 8–11 for a description of water-management scenarios.

Scenarios for the 24-County Area

Seven hypothetical pumping scenarios were simulated for the entire 24-county coastal area (A-1 through A-7) with changes in pumping rates that ranged from a 30.8 Mgal/d decrease to a 438 Mgal/d increase from May 1985 rates (tables 10, 11; figs. 16-21). (Although a hypothetical scenario (A-7) having a 1,040 Mgal/d increase in pumpage was simulated, results are not shown in a table or illustration, but are discussed herein.)

In scenario A-1, decreasing pumpage from May 1985 rates by 30.8 Mgal/d (10 percent resulted in a water-level rise of as much as 15 ft in the Savannah area, and 2.5 ft or greater that extended through much of the Glynn and Savannah model areas (fig. 16; tables 10, 11). The pumpage decrease resulted in a water-level rise averaging about 4.1 ft at the Brunswick and about 0.3 ft at the Hilton Head Island cells, and about a 5.2 Mgal/d decrease in upward flow of water from the Fernandina permeable zone.

Conversely, scenario A-2 simulated an increase in pumpage from May 1985 rates of 30.8 Mgal/d (fig. 17; tables 10, 11). Because the change in pumpage for scenario A-2 (+30.8 Mgal/d) was the exact opposite of the change in pumpage for scenario A-1 (-30.8 Mgal/d), simulated results for scenario A-2 were nearly the exact opposite of those from scenario A-1. Increased pumpage in scenario A-2 resulted in changes in water level and upward leakage from the Fernandina permeable zone that were about the same magnitude and areal extent as the changes observed in scenario A-1, only opposite in sign (tables 10, 11; fig. 17).

Slight differences in the magnitude of changes in simulated flow rates and head for scenarios A-1 and A-2 may have resulted from computational inaccuracies related to the manner in which lateral flow boundaries are transferred from the regional model to the subregional models. In the telescoping procedure, vector volumes of flow are transferred from the regional model to the subregional model by using imaginary wells that represent inflow (positive flux) and outflow (negative flux) across the subregional model boundaries. Because flow vectors likely will change direction depending on changes in pumping rates (such as scenarios A-1 and A-2), computed flow volumes may not correspond exactly along the subregional flow boundaries. These discrepancies may be the cause of the slight differences in flow rates and water-level changes that were observed between scenarios A-1 and A-2.

Scenario A-3 simulates a 20-percent increase in pumpage, an increase of 61.5 Mgal/d from May 1985 rates (fig.18; tables 10, 11). This increased pumpage resulted in a water-level decline of as much as 25 ft in the Savannah area and a decline of 2.5 ft or greater that extended through much of the Glynn and Savannah model areas (fig. 18). The pumping increase resulted in a water-level decline averaging about 8.8 ft at the Brunswick indicator cells and about 0.6 ft at the Hilton Head Island cell, and an 11.8 Mgal/d increase in leakage from the Fernandina permeable zone.

Four hypothetical scenarios of increased pumpage (A-4 through A-7) were simulated in support of Georgia State University's study, "Management Principles for Ground Water with Salt-Water Intrusion: An Analysis of Alternative Policies for Georgia's Upper Floridan Aquifer" (Cummings and others, 1996). The Georgia State University study employed two management principles: those of "Sustainable Use" and "No Impact on Current Users," to evaluate possible water-resource management alternatives for the Upper Floridan aquifer in the coastal area.

Scenario A-4 uses estimated pumping rates for the 24-county area for 1994 based on information provided by Georgia State University (Peter Terrebonne, Georgia State University, written commun., August 8, 1996). The estimated 1994 pumpage, 373 Mgal/d, is about 18 percent higher than the estimated May 1985 rate of withdrawal (tables 10, 11). Despite this increase, the simulated water level rose an average of about 4.5 ft at the Brunswick and about 0.3 ft at the Hilton Head Island cells, and a slight (0.01 Mgal/d) decrease in leakage from the Fernandina permeable zone (fig. 19).These responses are because of a redistribution of pumpage in the 24-county area away from the coast and known locations of saltwater contamination (table 11). Specifically, pumpage in Glynn County, where saltwater intrusion is occurring at Brunswick, decreased by about 17 Mgal/d from May 1985 rates; and in Chatham County, near the location of seawater encroachment at Hilton Head Island, decreased by about 10.6 Mgal/d. Except for the decrease in pumpage in Glynn and Chatham Counties and a small decrease in pumpage in Wayne County, pumpage was greater in the other 21 counties, a net increase of about 65 Mgal/d from May 1985 rates. These changes in pumpage resulted in water-level rises along the coast—greater than 15 ft in the Savannah area and about 5 ft in the Brunswick area; and in water-level declines of as much as 50 ft about 50 mi inland.

Scenario A-5 uses Georgia State University's projected pumpage for the year 2050, a rate of 672 Mgal/d (Peter Terrebonne, Georgia State University, written commun., August 8, 1996). This pumpage, more than twice the estimated May 1985 rate, resulted in widespread water-level decline in the coastal area, including at the Brunswick (10.5 ft average) and Hilton Head Island (1.8 ft) indicator cells (fig. 20; tables 10, 11). The increased pumpage also resulted in a 23.2 Mgal/d increase in leakage from the Fernandina permeable zone.

Table 11. Summary of simulated pumpage used in water-management scenarios A-1 through A-6, 24-county area
[Reported sums may not agree because of rounding]

County	May 1985 simulated pumpage	Simulated pumpage by scenario and change from May 1985 pumpage, by county (in million gallons per day)						
			A-1	A-2	A-3	A-4[1/,2/]	A-5[2/,3/]	A-6[2/,4/]
Appling	0.75	Scenario	0.67	0.82	0.89	3.00	6.00	7.00
		Difference	-0.07	0.07	0.15	2.25	5.25	6.25
Bacon	0.98	Scenario	0.88	1.07	1.17	5.00	10.00	10.00
		Difference	-0.10	0.10	0.20	4.02	9.02	9.02
Brantley	0.19	Scenario	0.17	0.21	0.23	1.00	7.00	3.00
		Difference	-0.02	0.02	0.04	0.81	6.81	2.81
Bryan	1.69	Scenario	1.52	1.86	2.03	2.00	29.00	5.00
		Difference	-0.17	0.17	0.34	0.31	27.31	3.31
Bulloch (northern part)	4.17	Scenario	3.83	4.68	5.10	13.72	33.00	26.47
		Difference	-0.43	0.43	0.85	9.55	29.16	22.30
Bulloch (southern part)	0.08	Scenario	0.08	0.08	0.08	0.28	0.67	26.47
		Difference	0.00	0.00	0.00	0.19	0.59	22.30
Burke	1.13	Scenario	1.02	1.25	1.36	15.00	29.00	31.00
		Difference	-0.11	0.11	0.23	13.87	27.87	29.87
Camden	32.91	Scenario	29.62	36.20	39.49	38.00	109.00	77.00
		Difference	-3.29	3.29	6.58	5.09	76.09	44.09
Candler	1.66	Scenario	1.49	1.82	1.99	4.00	8.00	8.00
		Difference	-0.17	0.17	0.33	2.34	6.34	6.34
Charlton	0.98	Scenario	0.88	1.08	1.18	2.00	5.90	3.00
		Difference	-0.1	0.10	0.20	1.02	4.92	2.02
Chatham	81.57	Scenario	73.41	89.72	97.88	71.00	94.00	142.00
		Difference	-8.16	8.16	16.31	-10.57	12.43	60.43
Effingham	2.37	Scenario	2.13	2.61	2.84	5.00	33.00	9.00
		Difference	-0.24	0.24	0.47	2.63	30.63	6.63
Emanuel	0.80	Scenario	0.72	0.87	0.95	6.00	10.00	12.00
		Difference	-0.08	0.08	0.16	5.20	9.20	11.20
Evans	1.05	Scenario	0.95	1.16	1.26	3.00	6.00	7.00
		Difference	-0.11	0.11	0.21	1.95	4.95	5.95
Glynn	77.98	Scenario	70.18	85.77	93.57	61.00	74.00	122.00
		Difference	-7.80	7.80	15.60	-16.98	-3.98	44.00
Jenkins	0.62	Scenario	0.56	0.68	0.74	6.00	12.00	13.00
		Difference	-0.06	0.06	0.12	5.38	11.38	12.38
Liberty	15.30	Scenario	13.77	16.83	18.36	17.00	44.01	33.00
		Difference	-1.53	1.53	3.06	1.70	28.70	17.70
Long	0.14	Scenario	0.13	0.15	0.17	1.00	4.00	1.00
		Difference	-0.01	0.01	0.03	0.86	3.86	0.86
McIntosh	0.76	Scenario	0.69	0.84	0.92	1.00	2.00	3.00
		Difference	-0.08	0.08	0.15	0.24	1.24	2.24
Pierce	0.70	Scenario	0.63	0.77	0.85	11.00	23.00	22.00
		Difference	-0.07	0.07	0.15	10.30	22.30	21.30
Screven	1.46	Scenario	1.32	1.61	1.76	13.00	22.00	25.00
		Difference	-0.15	0.15	0.29	11.54	20.54	23.54
Tattnall	0.80	Scenario	0.72	0.88	0.96	7.00	11.00	13.00
		Difference	-0.08	0.08	0.16	6.20	10.20	12.20

Table 11. Summary of simulated pumpage used in water-management scenarios A-1 through A-6, 24-county area—Continued

[Reported sums may not agree because of rounding]

County	May 1985 simulated pumpage	Simulated pumpage by scenario and change from May 1985 pumpage, by county (in million gallons per day)						
			A-1	A-2	A-3	A-4[1,2]	A-5[2,3]	A-6[2,4]
Toombs (northern part)	2.45	Scenario	2.23	2.72	2.97	7.92	14.84	14.84
		Difference	-0.25	0.25	0.50	5.47	12.39	12.39
Toombs (southern part)	0.03	Scenario	0.03	0.03	0.03	0.08	0.16	0.16
		Difference	0.00	0.00	0.00	0.05	0.13	0.13
Ware	2.42	Scenario	2.18	2.66	2.90	7.00	9.00	14.00
		Difference	-0.24	0.24	0.48	4.58	6.58	11.58
Wayne	74.67	Scenario	67.20	82.14	89.61	72.00	76.00	144.00
		Difference	-7.47	7.47	14.93	-2.67	1.33	69.33
TOTAL	**307.66**	**Scenario**	**276.89**	**338.43**	**369.19**	**373.00**	**672.00**	**746.00**
		Difference	**-30.77**	**30.77**	**61.53**	**65.34**	**364.34**	**438.34**

[1]Estimated 1994 pumpage.

[2]Estimated pumpage for scenarios A-4, A-5, and A-6 provided by Pete Terrebonne (Georgia State University, written commun., August 8, 1996).

[3]Projected pumpage for 2050.

[4]Estimated 1994 pumpage multiplied by a factor of 2

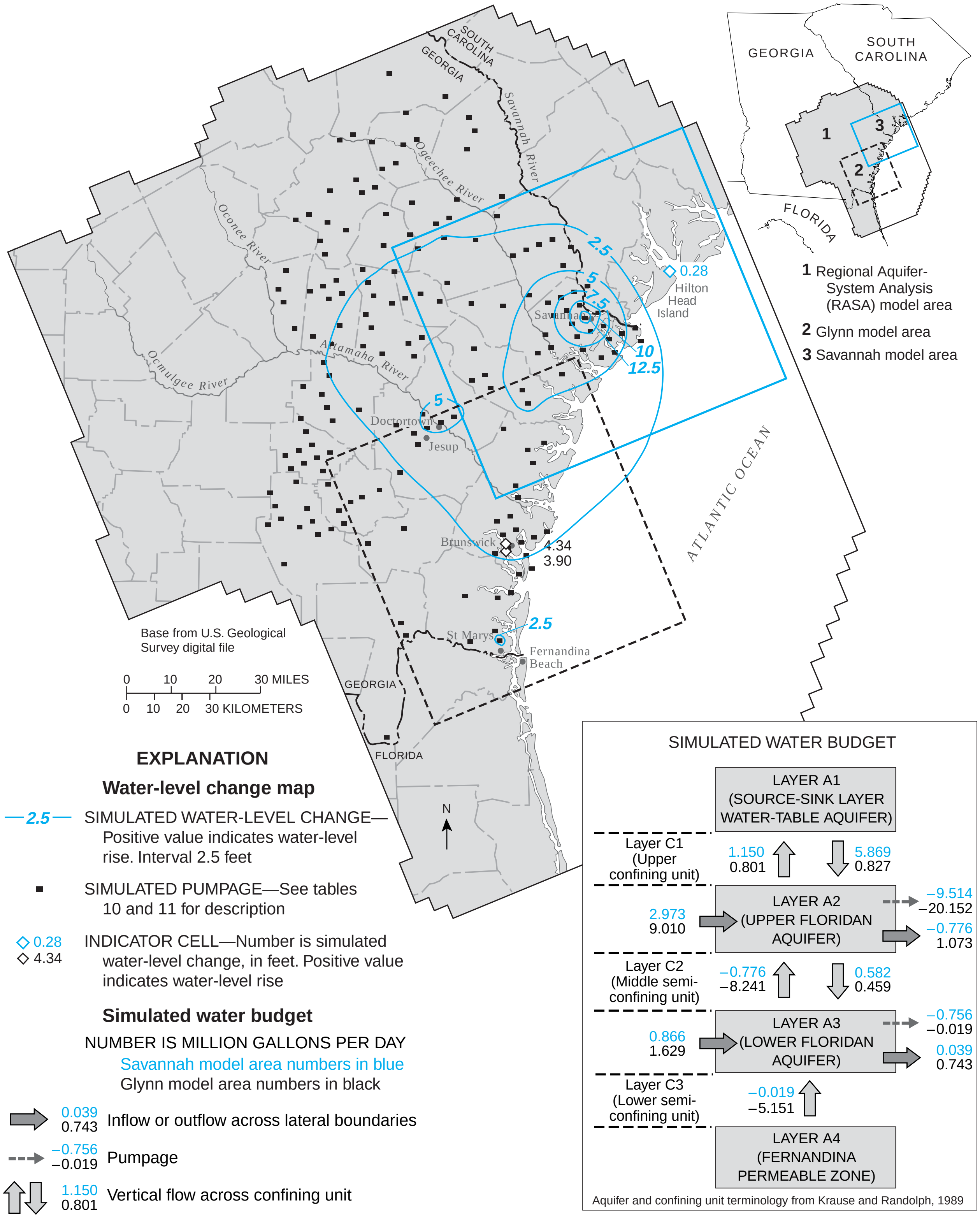


Figure 16. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario A-1, 24-county area.

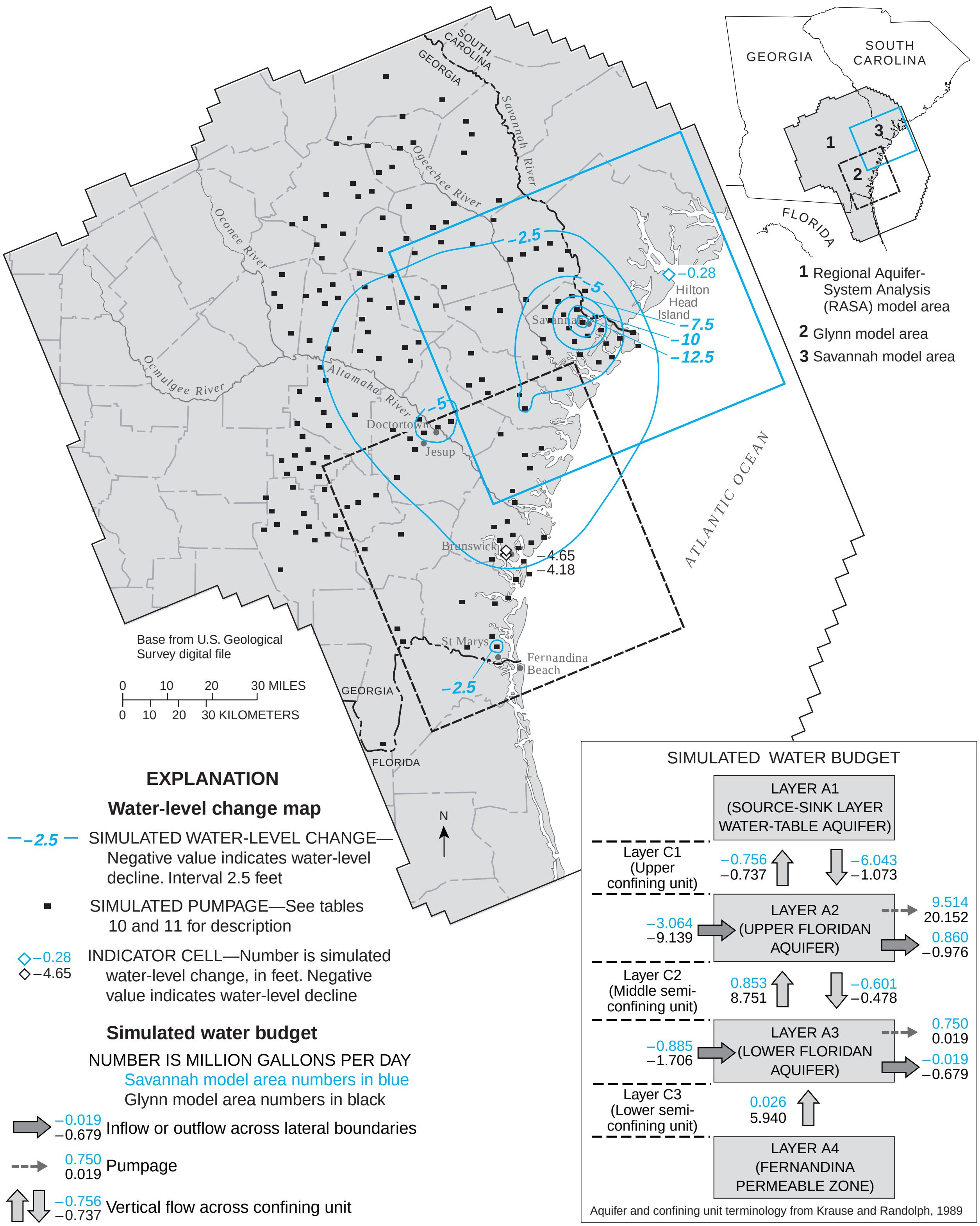


Figure 17. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario A-2, 24-county area.

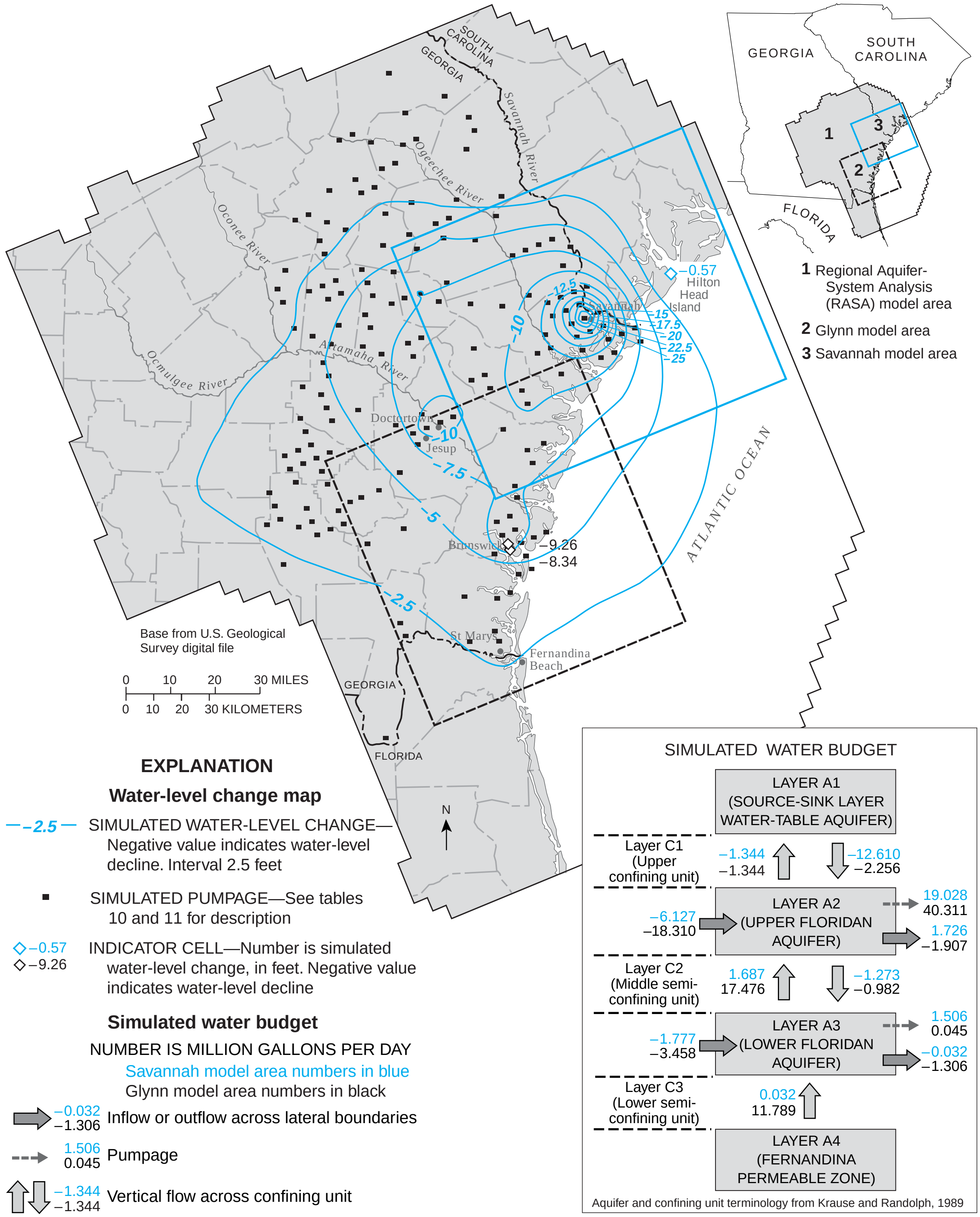


Figure 18. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario A-3, 24-county area.

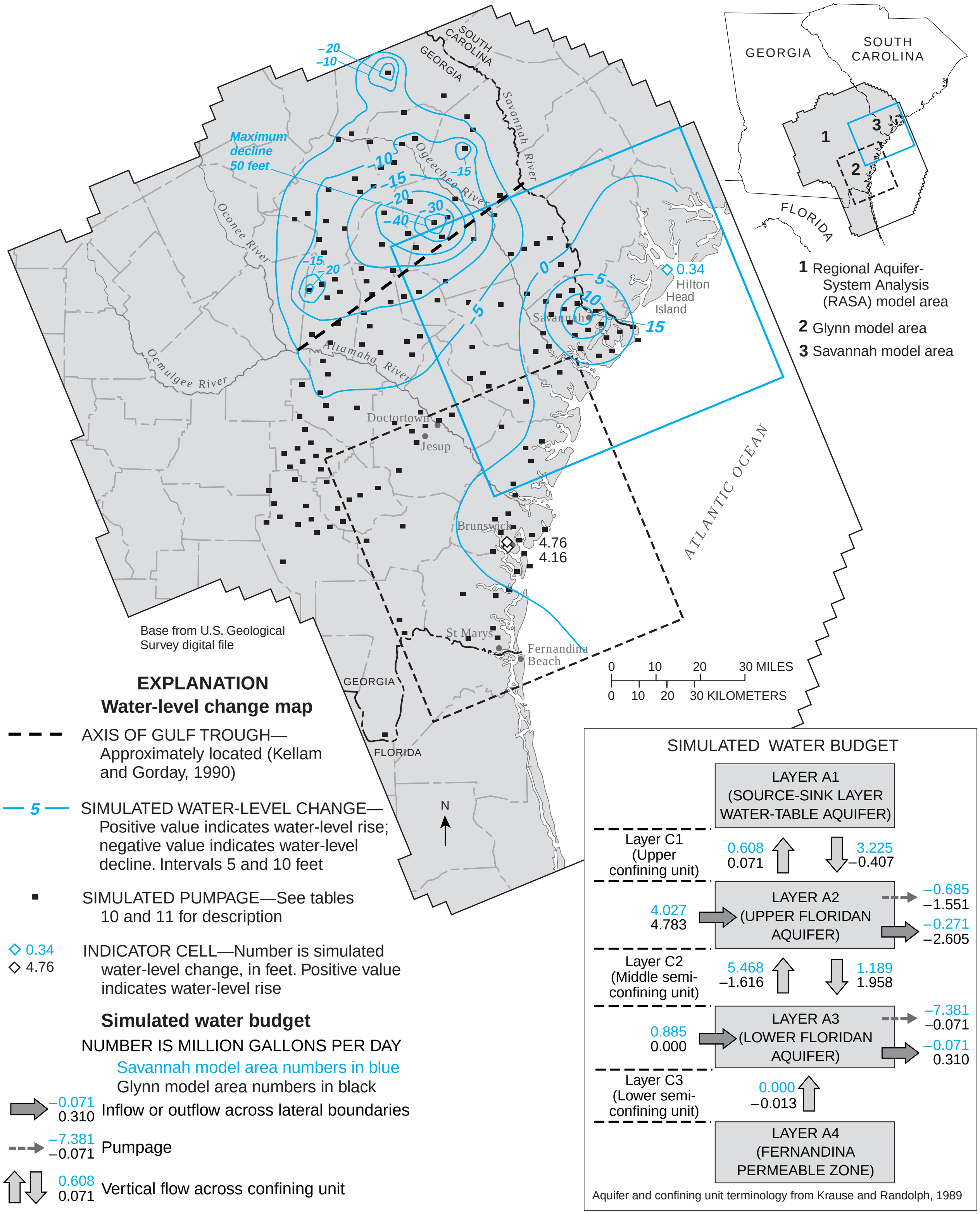


Figure 19. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario A-4, 24-county area.

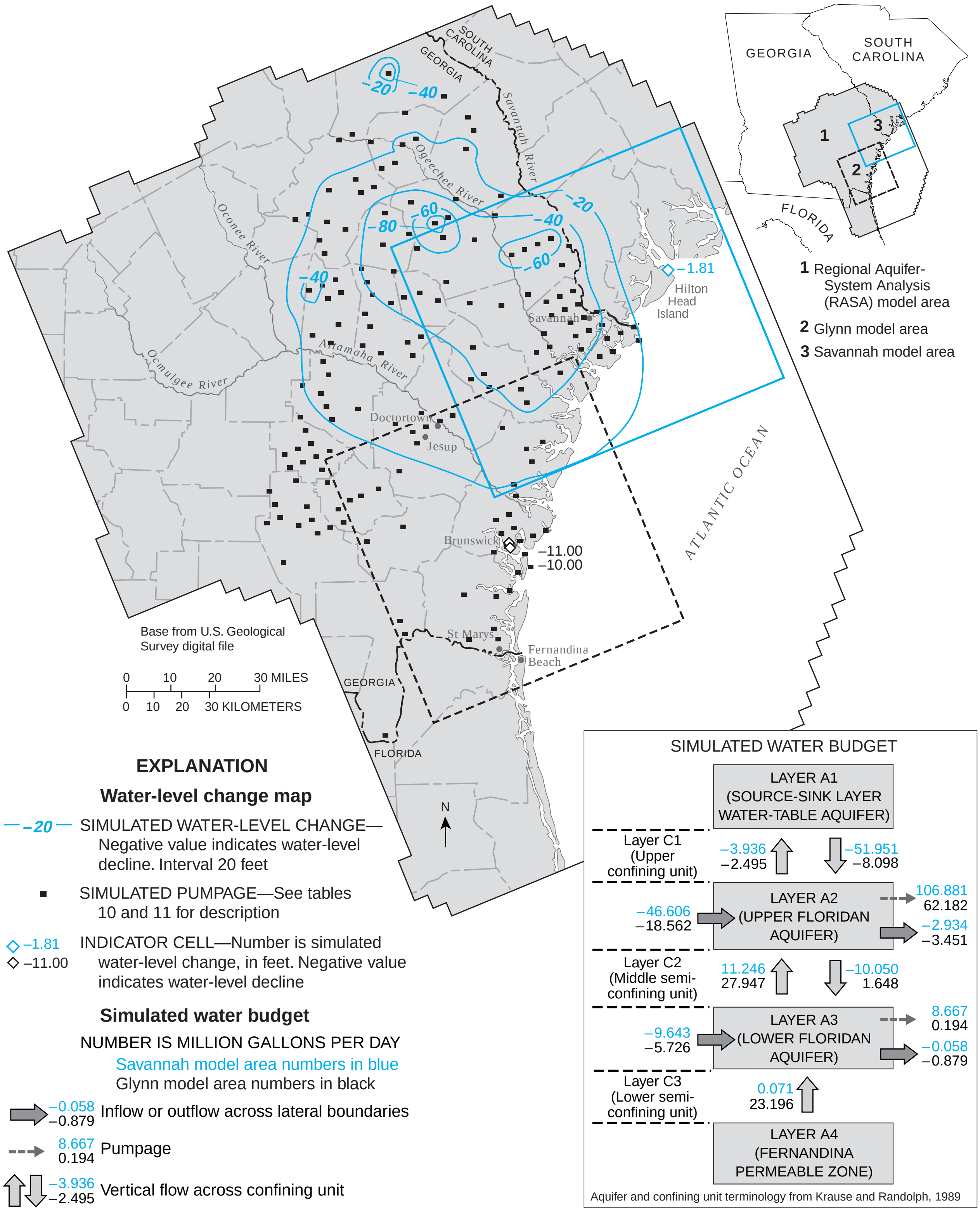


Figure 20. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario A-5, 24-county area.

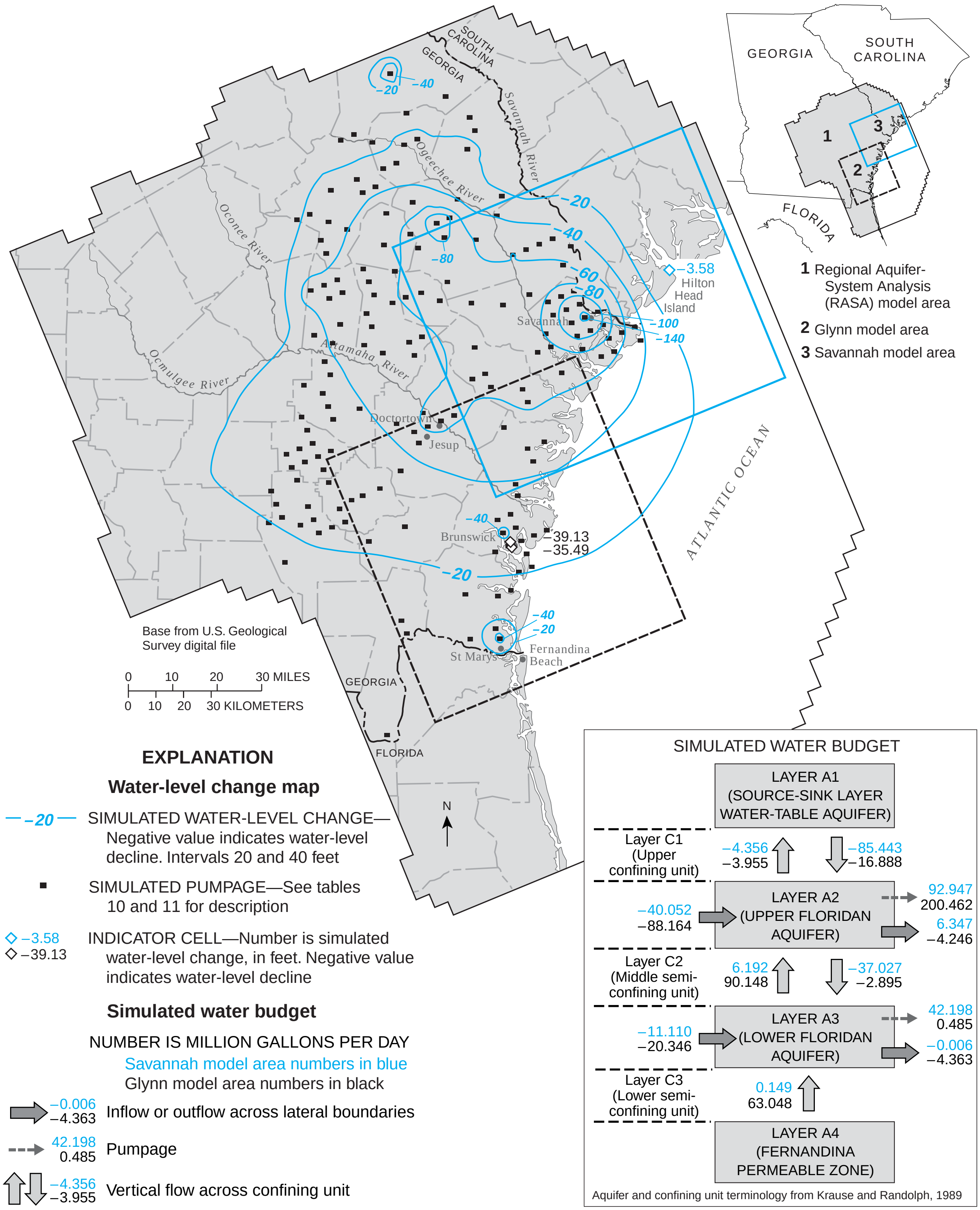


Figure 21. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario A-6, 24-county area.

For scenario A-6, estimated pumpage for 1994 was doubled (746 Mgal/d).The scenario resulted in widespread water-level decline throughout the coastal area; declines of as much as 140 ft were simulated in the Savannah area (tables 10, 11; fig. 21). Water-level declines were an average of about 37.3 ft at the Brunswick and about 3.6 ft at the Hilton Head Island cells, and leakage from the Fernandina permeable zone increased by about 63 Mgal/d.

Pumpage for scenarios A-5 and A-6 (tables 10, 11), and A-7 (results not shown), are more than two to three times the pumping rate used for the model calibration. Model simulations that use pumping rates beyond those that were used for model calibration, are likely to be less accurate than scenarios containing pumpage that is no greater than that used in the calibrated model. Moreover, the greater the pumpage beyond that used for calibration, the less accurate the simulation results. In particular, the pumping rate for scenario A-7(results not shown) is more than three times the pumping rate for May 1985, which resulted in dewatering of the Upper Floridan aquifer in the Savannah area. At Savannah, the top of the Upper Floridan aquifer is about 250 ft below sea level; simulated head in that area for scenario A-7 was -350 ft, or about 100 ft below the top of the aquifer. Such dewatering results in substantial changes in the hydraulic properties and boundary conditions of the model and violates the assumptions on which the model is based. Accordingly, results of scenario A-7 are not included in tables and illustrations.

Scenarios for the Central Subarea

Five hypothetical scenarios (C-1 through C-5) were simulated for the central subarea. These scenarios involved changes in pumpage that ranged from 7.3 Mgal/d lower to 196 Mgal/d higher than May 1985 rates (tables 10, 12; figs. 22-26).

Scenario C-1 simulated a net decrease in pumpage of about 7.3 Mgal/d from May 1985 rates in the central subarea, and includes a reduction in pumpage in the Brunswick and Savannah areas of 10.6 and 17 Mgal/d, respectively (tables 10, 12). Pumpage in the remainder of the central subarea was increased 20.3 Mgal/d. This redistribution of pumpage resulted in a water-level rise along the coast of as much as 10 ft at Savannah and 5 ft at Brunswick, and in water-level decline of as much as 20 ft about 40 mi farther inland (fig. 22). The ground-water level rose an average 4.66 ft at the Brunswick, and 0.1ft at the Hilton Head Island cells, and leakage from the Fernandina permeable zone decreased about 2.03 Mgal/d.

Scenario C-2 simulated an increase in pumpage of 196 Mgal/d from May 1985 rates in the central subarea (tables 10, 12; fig. 23). The scenario includes small pumpage increases in Glynn and Chatham Counties, and larger increases in the other counties in the central subarea. This increased pumpage resulted in widespread water-level decline; the largest decline (160 ft) was in the northwestern part of the Savannah model area.Water levels declined an average 13.2 ft at the Brunswick and 1.68 ft at the Hilton Head Island indicator cells, and leakage from the Fernandina permeable zone increased about 22.7 Mgal/d (fig. 23).

Scenarios C-3, C-4, and C-5, simulated net decreases in pumpage from May 1985 rates in the central subarea of 13.3, 37.2, and 57.5 Mgal/d, respectively (tables 10, 12). Each scenario resulted in water-level rises at the cells and decreased leakage from the Fernandina permeable zone (fig. 15). For scenario C-3, the largest water-level rises were in and northwest of the Savannah area (fig. 24). Water-level rises for scenarios C-4 and C-5 were largest in the Savannah, Brunswick, and Jesup areas (figs. 25, 26).

Scenarios for the Glynn-Wayne-Camden County Area

Six scenarios were simulated for the Glynn-Wayne-Camden County area (G-1 through G-6). Changes in pumpage ranged from a 74.67 Mgal/d decrease to a 5 Mgal/d increase relative to May 1985 pumping rates (tables 10, 13; figs. 27-32).

Scenarios G-1, G-2, and G-3 simulated decreases in pumpage of 10, 20, and 40 Mgal/d, respectively, in Glynn and Wayne Counties (table 13; figs. 27-29). For each scenario, pumpage was reduced equally in both counties, resulting in widespread water-level rise, and a decrease in leakage from the Fernandina permeable zone (fig. 15). At the Brunswick nodes, the average water-level rise ranged from about 2.1 to 9.2 ft, and at the Hilton Head Island node, the water-level rise ranged from less than 0.05 ft to 0.1ft. Leakage from the Fernandina permeable zone decreased about 1.6 to 8.9 Mgal/d.

Scenario G-4 simulated a pumpage decrease of 74.67 Mgal/d, representing the cessation of industrial pumping at Doctortown, Wayne County (table 13; fig. 30). This decrease in pumpage resulted in widespread water-level rise and in a decrease in leakage from the Fernandina permeable zone. At the Brunswick indicator cells, the average water-level rise was about 6.25 ft, and at the Hilton Head Island node, the water-level rise was about 0.25 ft. Leakage from the Fernandina permeable zone decreased about 11.16 Mgal/d.

Table 12. Summary of simulated pumpage used in water-management scenarios C-1 through C-5, central subarea
[Reported sums may not agree because of rounding]

County	May 1985 simulated pumpage	Simulated pumpage by scenario and change from May 1985 pumpage, by county (in million gallons per day)					
			C-1	C-2	C-3	C-4	C-5
Appling	0.75	Scenario	4.10	9.76	1.15	1.65	0.98
		Difference	3.36	9.01	0.40	0.90	0.23
Bryan	1.69	Scenario	5.12	30.82	1.73	3.19	2.53
		Difference	3.43	29.13	0.04	1.50	0.84
Bulloch (northern part)	4.17	Scenario	4.17	4.17	4.17	4.17	4.17
		Difference	0.00	0.00	0.00	0.00	0.00
Bulloch (southern part)	0.08	Scenario	3.78	26.51	0.41	1.08	0.22
		Difference	3.69	26.43	0.33	1.00	-0.14
Chatham	81.57	Scenario	70.96	86.50	71.72	71.57	66.98
		Difference	-10.61	4.93	-9.85	-10.00	-14.59
Effingham	2.37	Scenario	7.24	33.31	0.97	4.27	0.24
		Difference	4.87	30.94	-1.40	1.90	-2.13
Evans	1.05	Scenario	4.86	11.28	1.47	2.95	1.19
		Difference	3.81	10.23	0.42	1.90	0.14
Glynn	77.98	Scenario	60.95	81.09	77.98	46.98	46.95
		Difference	-17.03	3.11	0.00	-31.00	-31.03
Liberty	15.30	Scenario	19.62	53.32	15.16	16.20	12.13
		Difference	4.32	38.02	-0.14	0.90	-3.17
Long	0.14	Scenario	0.77	3.99	0.34	0.54	0.45
		Difference	0.63	3.85	0.20	0.40	0.31
McIntosh	0.76	Scenario	1.43	2.27	0.86	0.56	0.60
		Difference	0.68	1.51	0.10	-0.20	-0.16
Tattnall	0.80	Scenario	8.94	19.63	1.20	2.20	0.20
		Difference	8.14	18.83	0.40	1.40	-0.60
Toombs (northern part)	2.45	Scenario	2.45	2.45	2.45	2.45	2.45
		Difference	0.00	0.00	0.00	0.00	0.00
Toombs (southern part)	0.03	Scenario	3.25	14.12	0.53	1.63	0.07
		Difference	3.22	14.09	0.50	1.60	0.04
Wayne	74.67	Scenario	73.40	88.09	70.34	67.14	67.17
		Difference	-1.24	13.42	-4.30	-7.50	-7.50
TOTAL	**263.81**	**Scenario**	**256.55**	**459.79**	**250.51**	**226.61**	**206.33**
		Difference	**-7.26**	**195.98**	**-13.30**	**-37.20**	**-57.48**

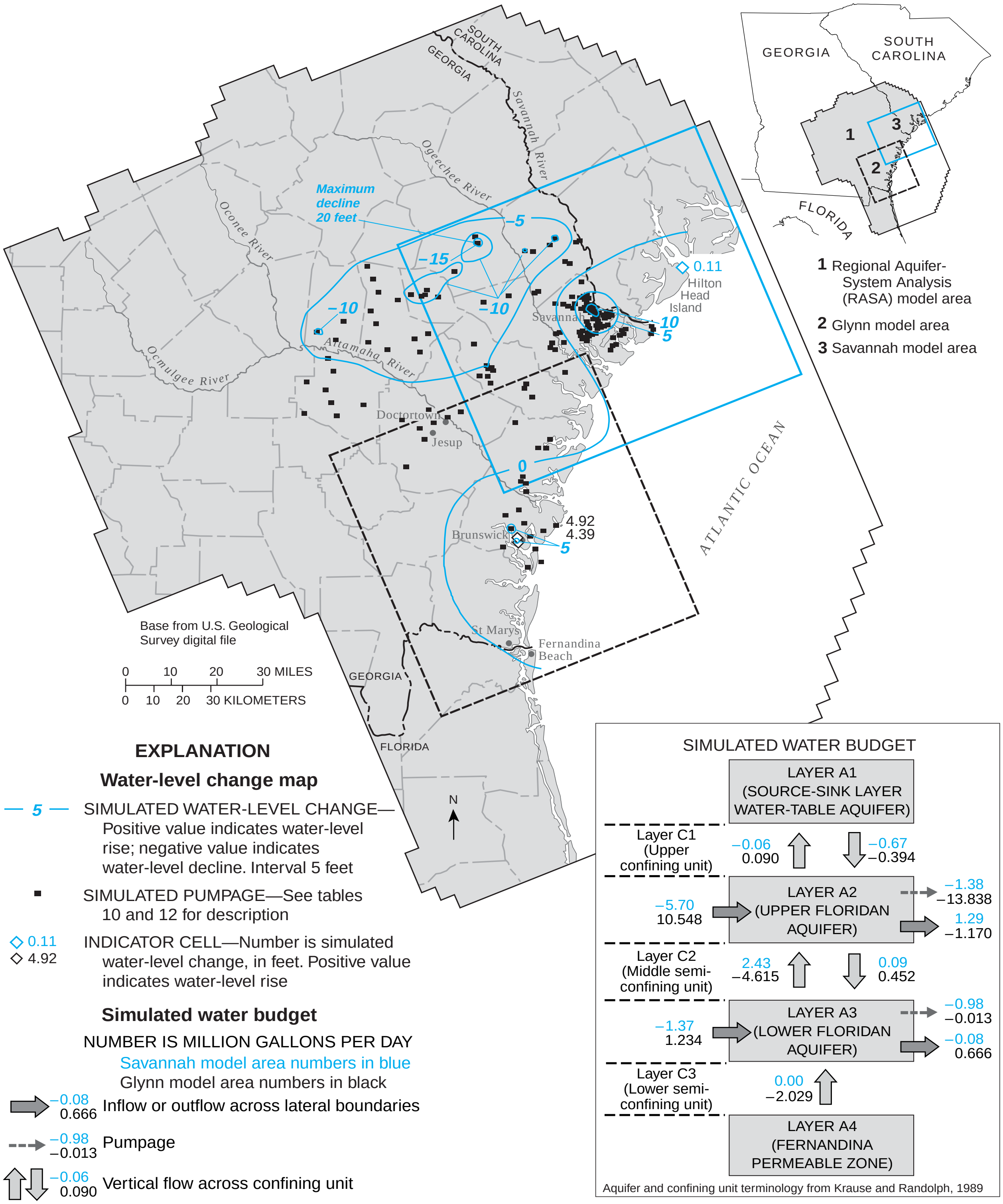


Figure 22. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario C-1, central subarea.

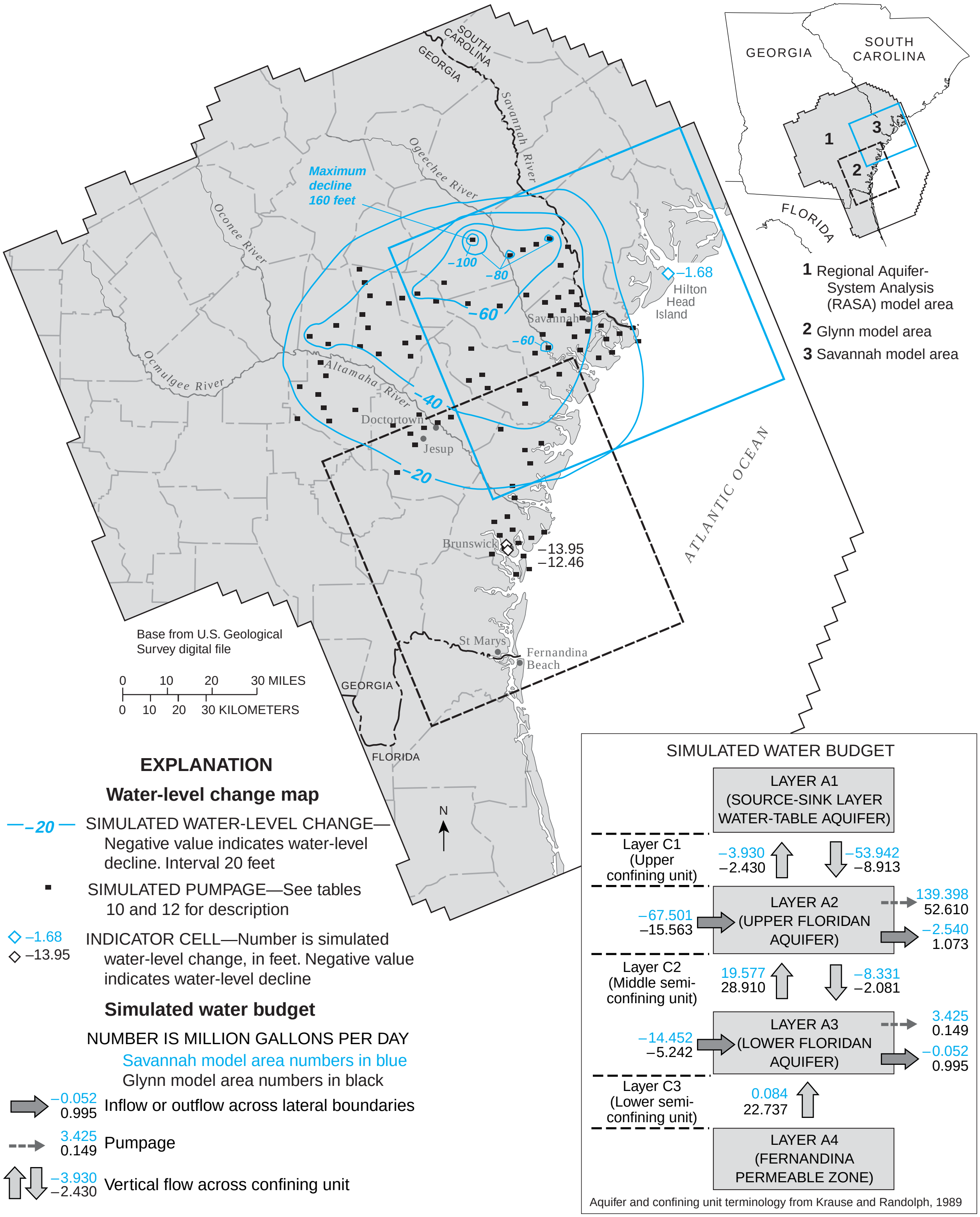


Figure 23. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario C-2, central subarea.

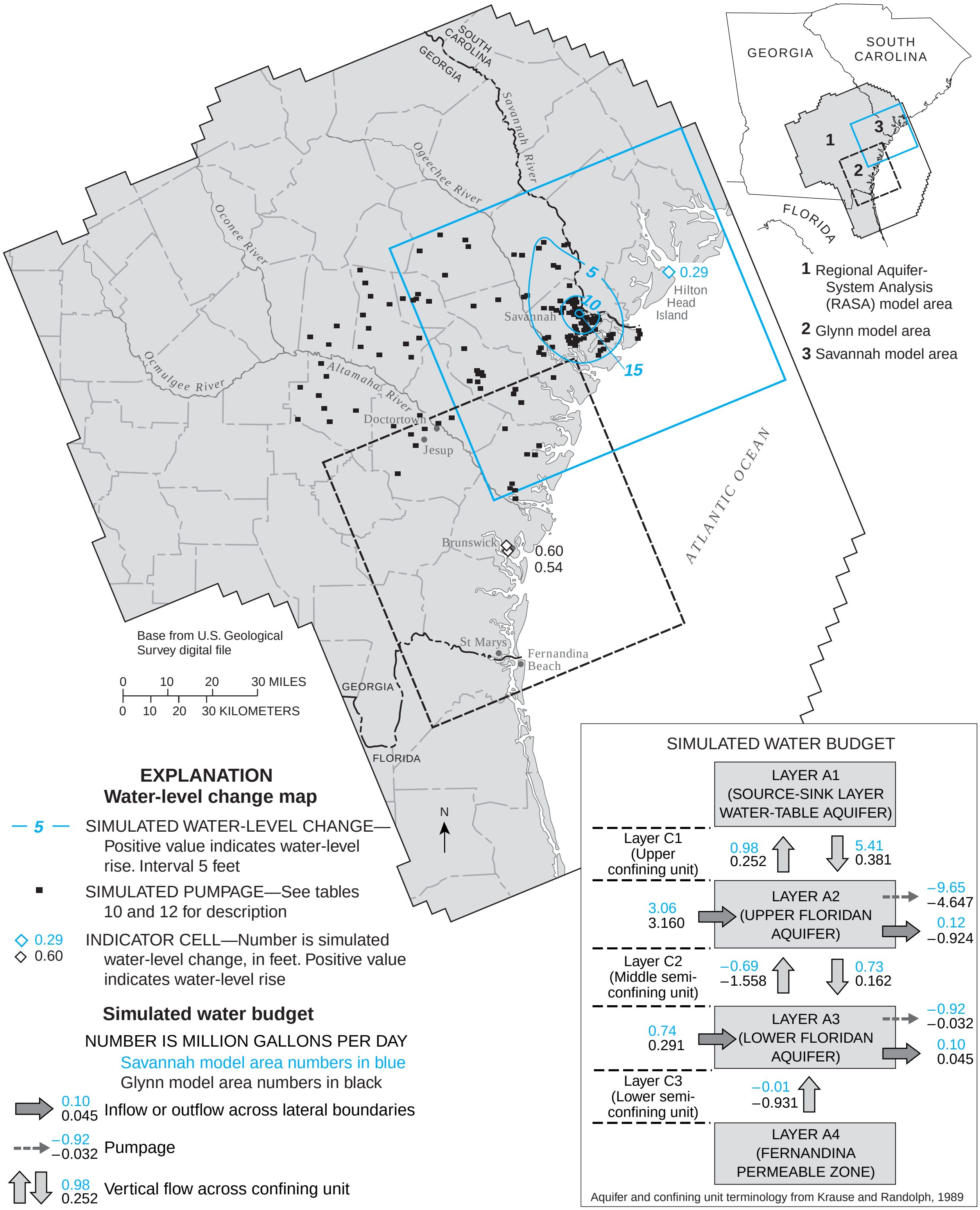


Figure 24. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario C-3, central subarea.

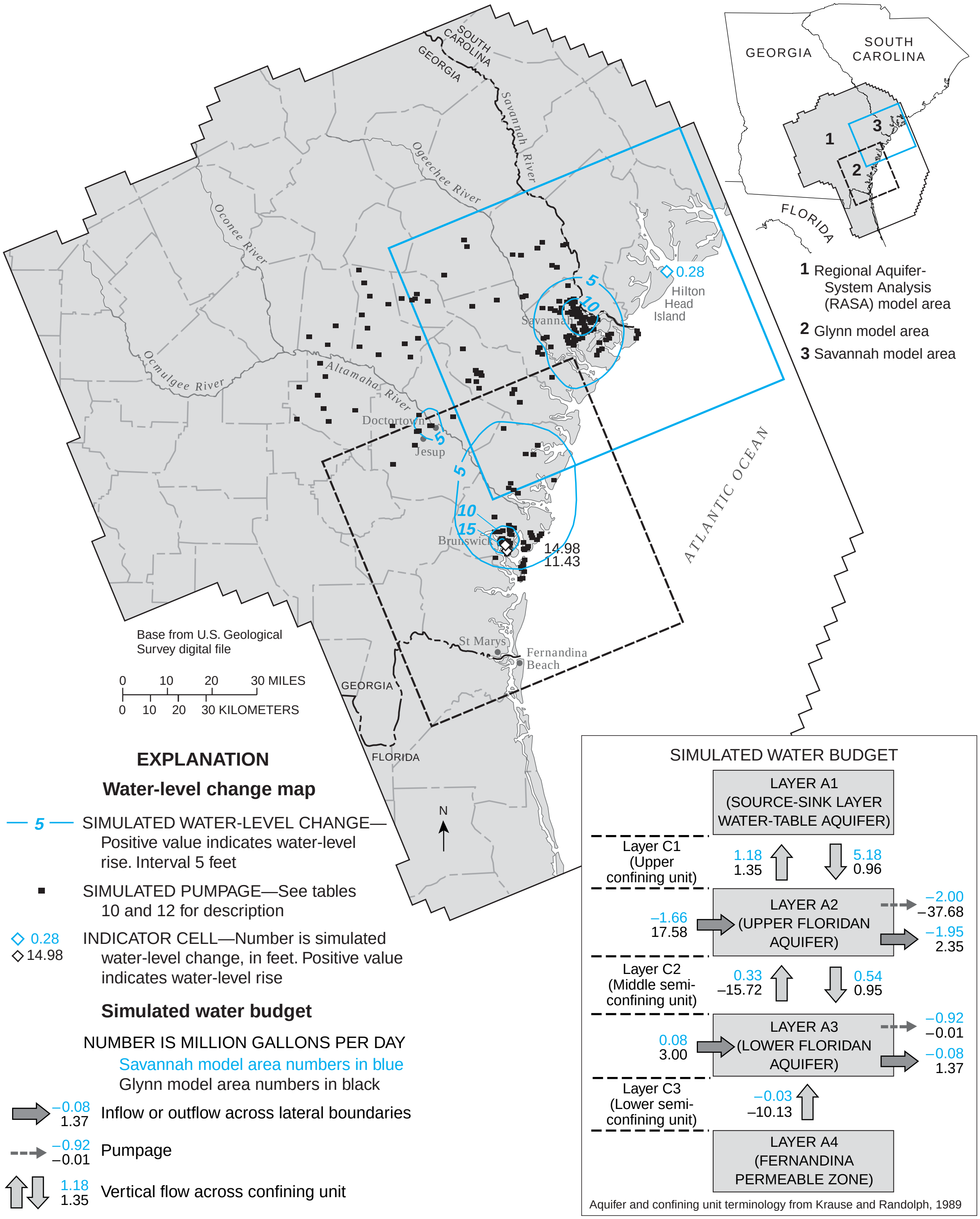


Figure 25. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario C-4, central subarea.

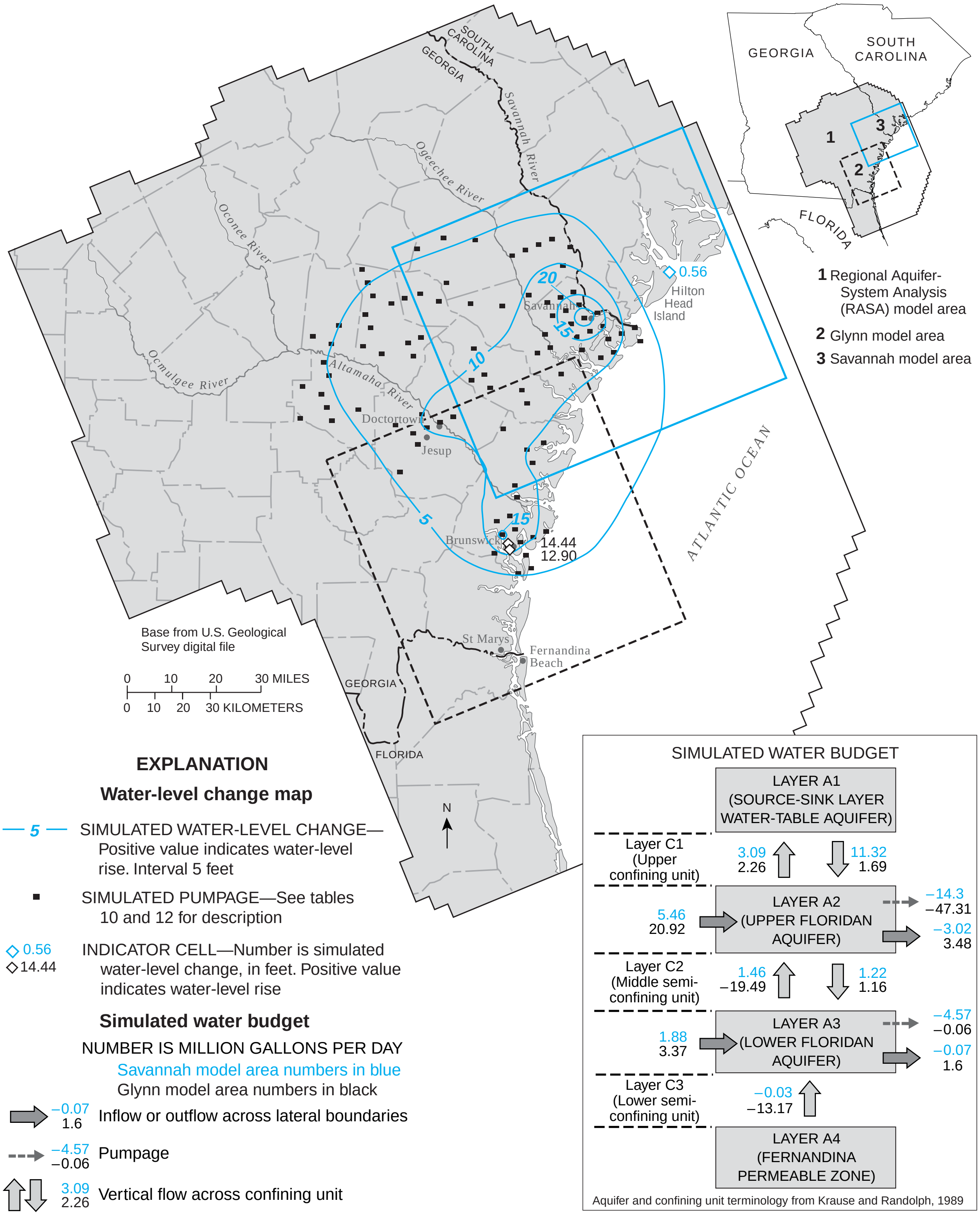


Figure 26. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario C-5, central subarea.

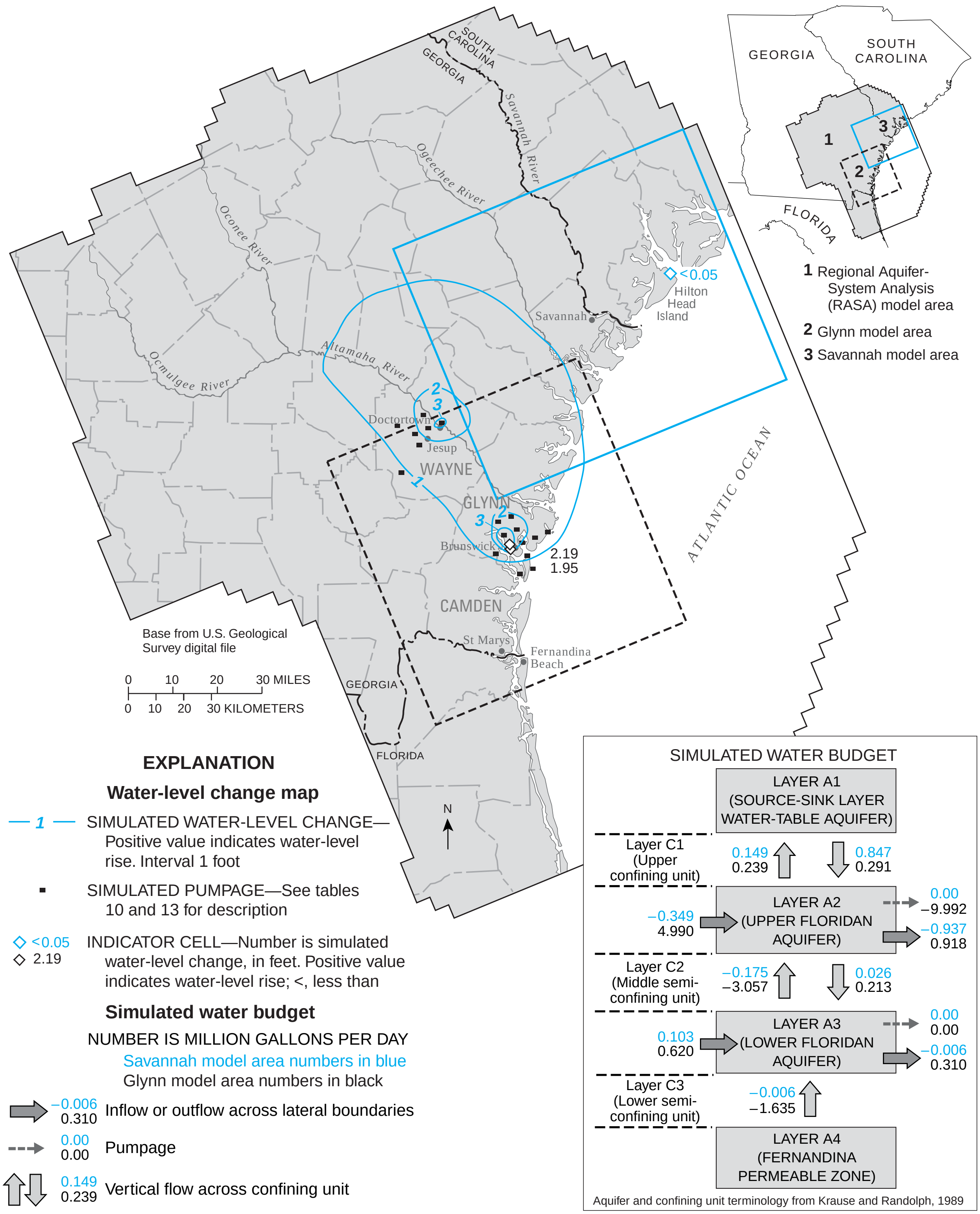


Figure 27. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario G-1, Glynn–Wayne–Camden County area.

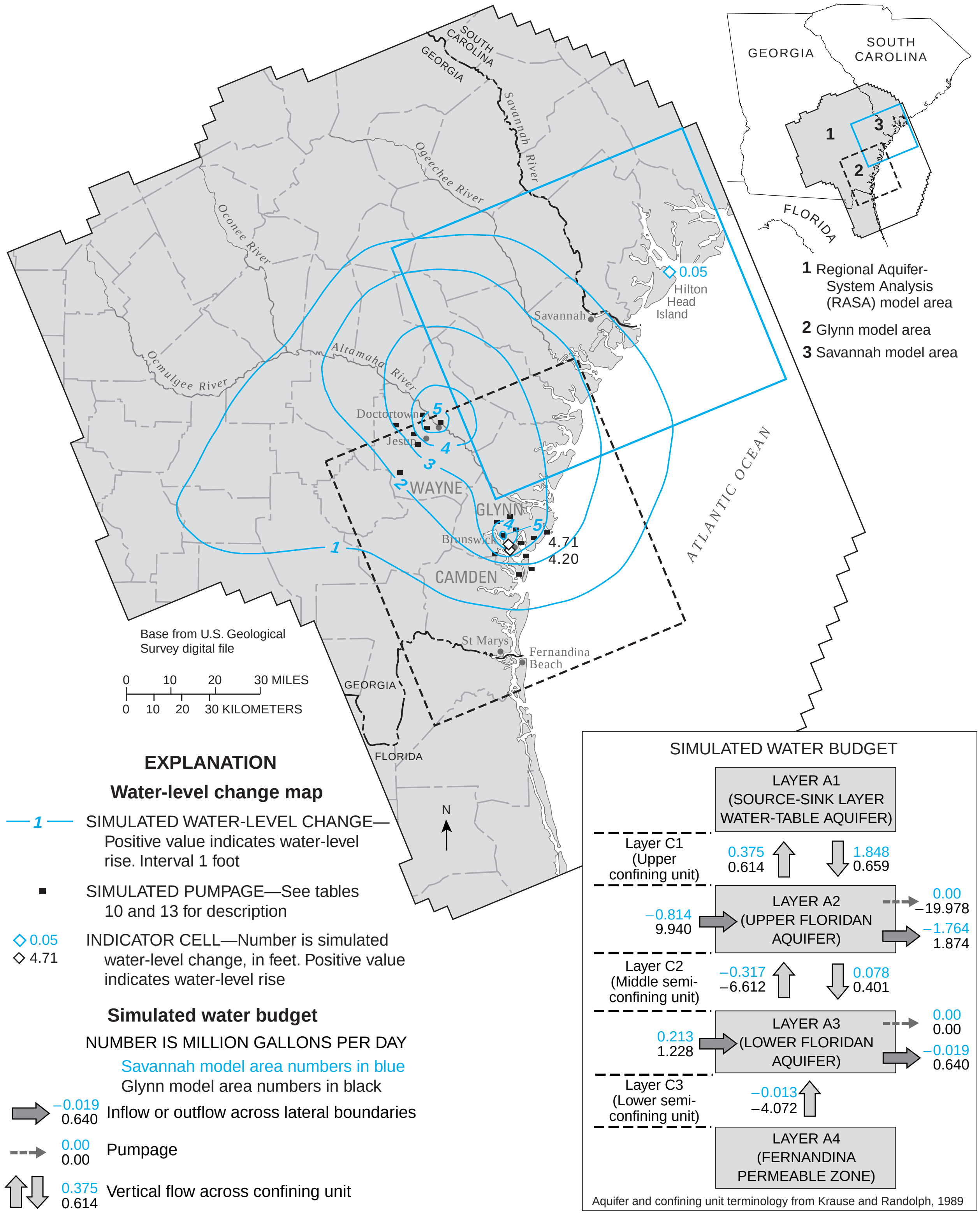


Figure 28. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario G-2, Glynn–Wayne–Camden County area.

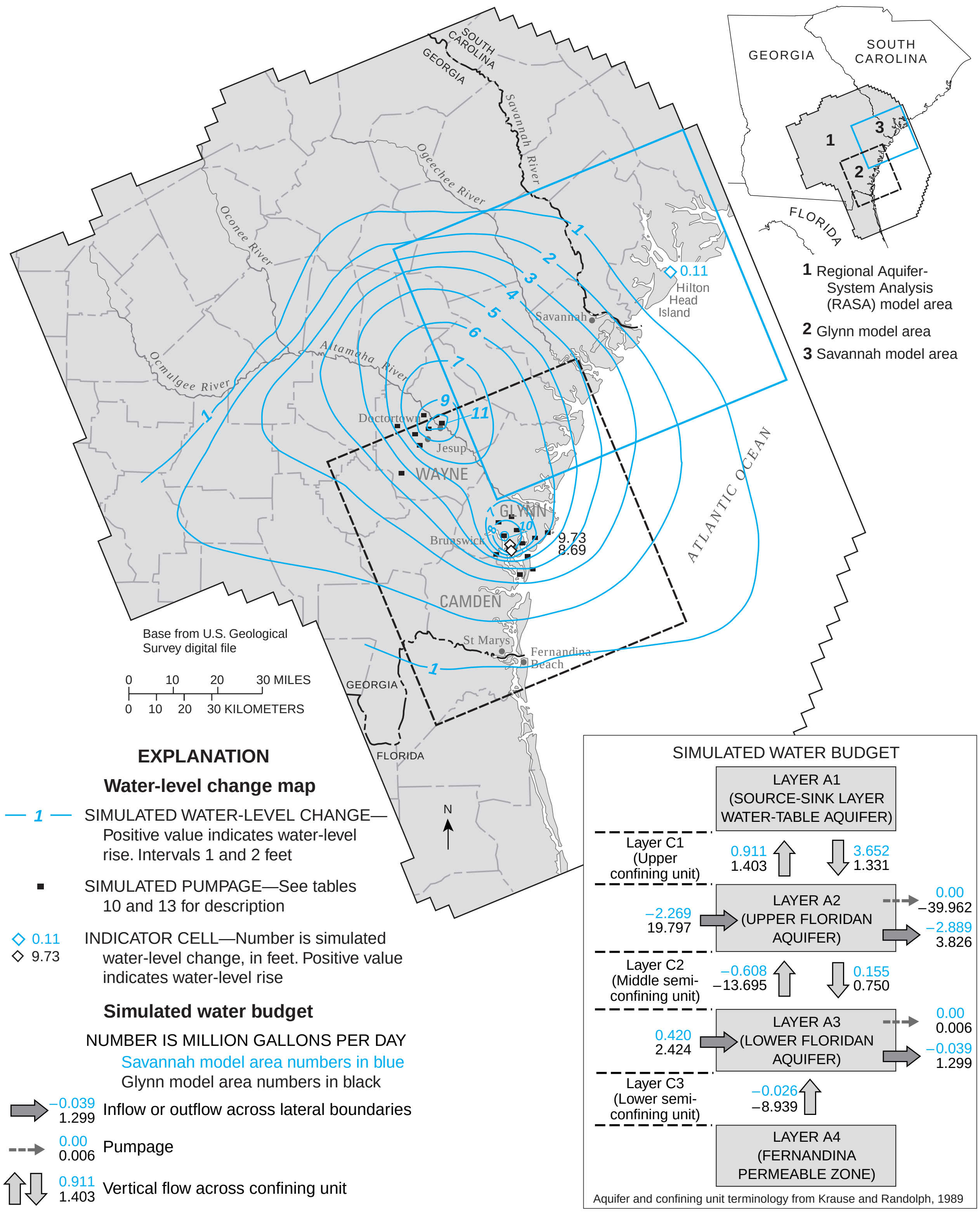
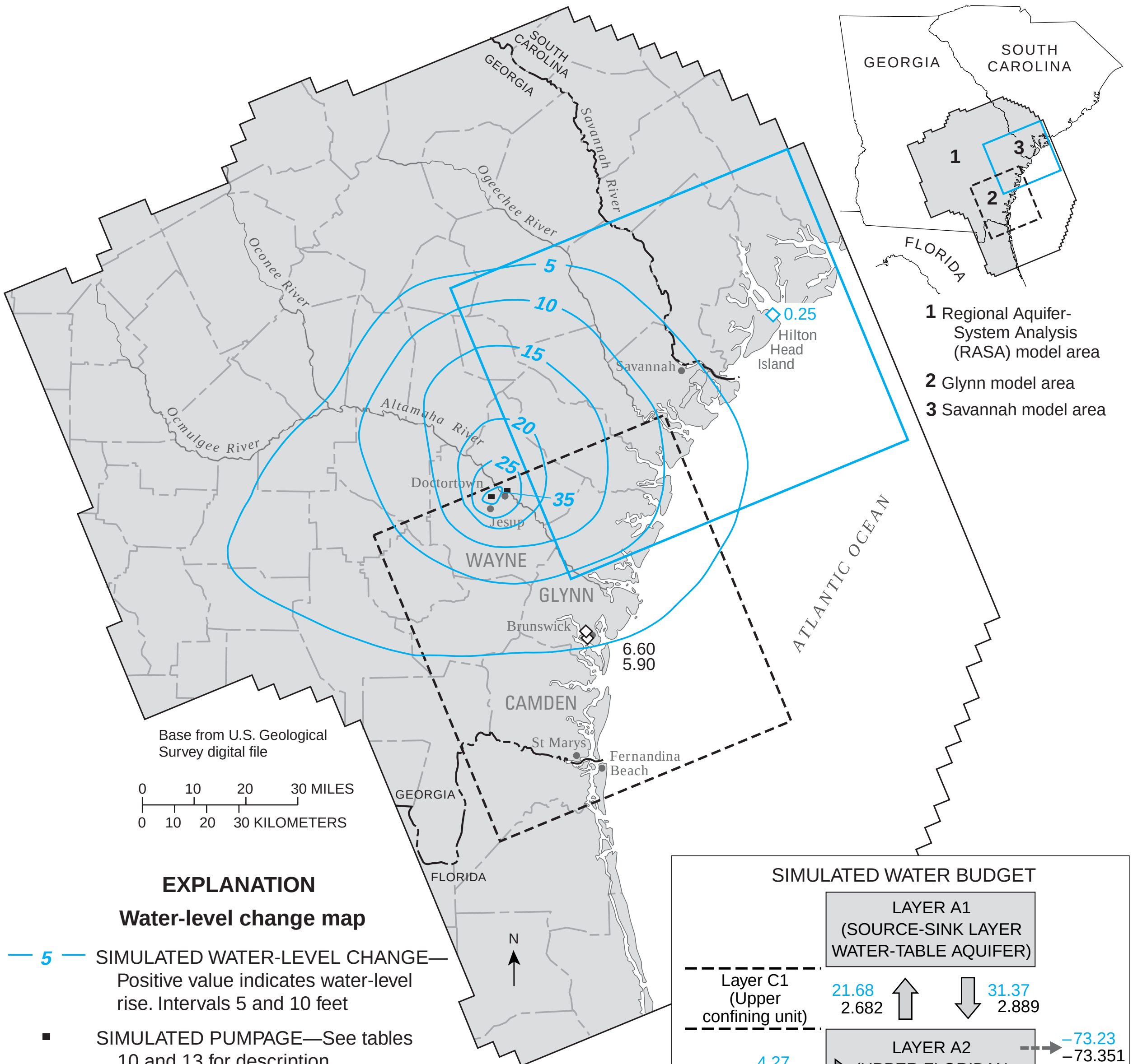


Figure 29. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario G-3, Glynn–Wayne–Camden County area.



EXPLANATION

Water-level change map

— 5 — SIMULATED WATER-LEVEL CHANGE—Positive value indicates water-level rise. Intervals 5 and 10 feet

■ SIMULATED PUMPAGE—See tables 10 and 13 for description

◇ 0.25 ◇ 6.60 INDICATOR CELL—Number is simulated water-level change, in feet. Positive value indicates water-level rise

Simulated water budget

NUMBER IS MILLION GALLONS PER DAY

Savannah model area numbers in blue

Glynn model area numbers in black

2.77 1.907 Inflow or outflow across lateral boundaries

0.05 −0.006 Pumpage

21.68 2.682 Vertical flow across confining unit

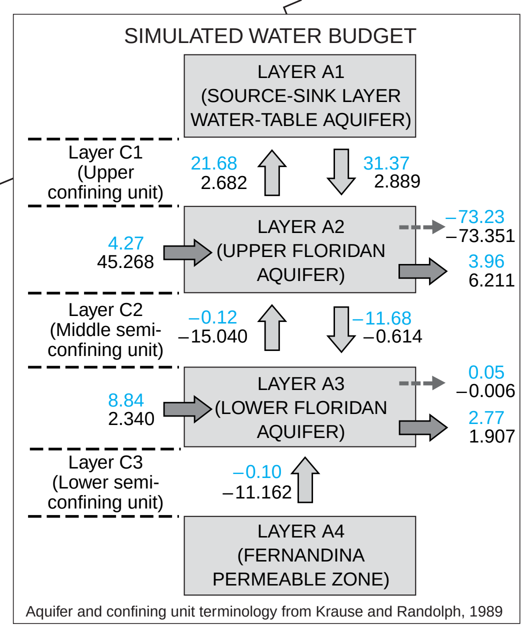


Figure 30. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario G-4, Glynn–Wayne–Camden County area.

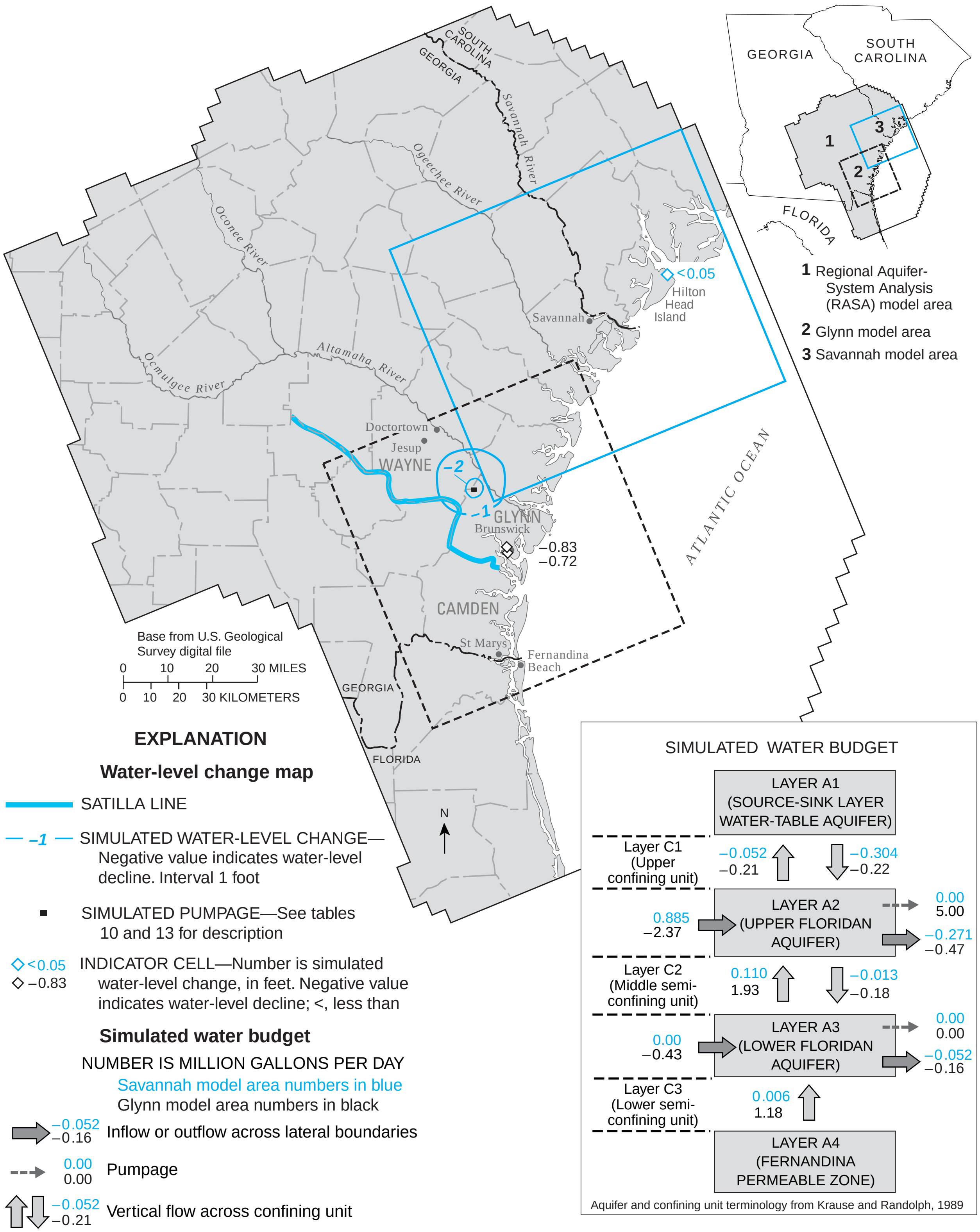


Figure 31. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario G-5, Glynn–Wayne–Camden County area.

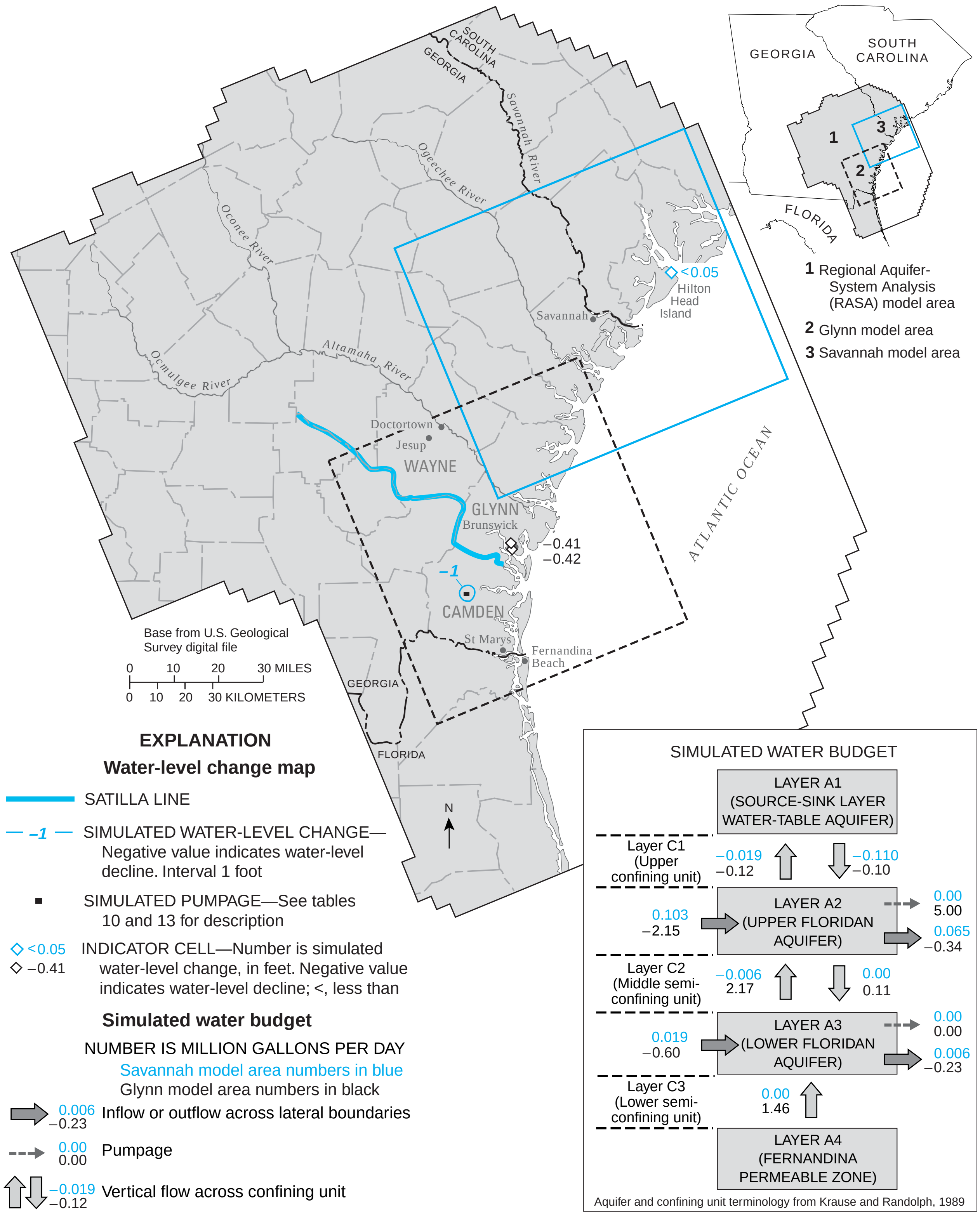


Figure 32. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario G-6, Glynn–Wayne–Camden County area.

Table 13. Summary of simulated pumpage used in water-management scenarios G-1 through G-6, Glynn-Wayne-Camden County area
[Reported sums may not agree because of rounding]

County	May 1985 simulated pumpage (in million gallons per day)	Simulated pumpage by scenario and change from May 1985 pumpage, by county (in million gallons per day)						
			G-1	G-2	G-3	G-4	G-5	G-6
Camden	32.91	Scenario	32.91	32.91	32.91	32.91	32.91	37.91
		Difference	0.00	0.00	0.00	0.00	0.00	5.00
Glynn	77.98	Scenario	72.98	67.98	57.98	77.98	82.98	77.98
		Difference	-5.00	-10.00	-20.00	0.00	5.00	0.00
Wayne	74.67	Scenario	69.67	64.67	54.67	0.00	74.67	74.67
		Difference	-5.00	-10.00	-20.00	-74.67	0.00	0.00
TOTAL	**185.56**	**Scenario**	**175.56**	**165.56**	**145.56**	**110.89**	**190.56**	**190.56**
		Difference	**-10.00**	**-20.00**	**-40.00**	**-74.67**	**5.00**	**5.00**

Scenarios G-5 and G-6 were designed to test effects of the “Satilla Line” on ground-water levels and leakage from the Fernandina permeable zone at Brunswick (tables 10, 13; figs. 31-32). The Satilla Line is a postulated hydrologic feature separating the central and southern subareas that is believed to represent a hydrologic boundary in the Floridan aquifer system (William H. McLemore, Georgia Environmental Protection Division, Geologic Survey Branch, oral commun., January 6, 2000). The feature is manifested in a rise in the potentiometric surface of the Upper Floridan aquifer south of the cone of depression at Brunswick (fig. 11). This change to higher head is simulated in the RASA and Glynn models by assigning higher leakance values to the lower semiconfining unit (layer C3), which allows greater influx of water (and associated higher heads) to the Upper Floridan aquifer (fig. 10).

Each scenario simulated the effect of a 5-Mgal/d increase in pumpage on either side of the Satilla Line—scenario G-5 simulated effects of increased pumpage on the northern side and G-6 simulated effects of increased pumpage on the southern side. As expected, both scenarios resulted in water-level declines at the cells in Brunswick and increased leakage from the Fernandina permeable zone (tables 10, 13; figs. 31-32).

Scenario G-5, having increased pumpage north of the Satilla Line, resulted in greater areal extent and magnitude of water-level decline at the cells in Brunswick than did scenario G-6 (figs. 31-32). However, scenario G-5 resulted in less leakage from the Fernandina permeable zone than scenario G-6, which simulated increased pumpage south of the Satilla Line. This apparent anomaly likely is the result of higher vertical leakance from the lower semiconfining unit and greater extent of the Fernandina permeable zone in the southern part of the Glynn model than in the northern part (see figure 10 for areal extent of Fernandina permeable zone). The differences in water-level decline and leakage response for the two scenarios suggest there may be some minor influence exerted by the Satilla Line on the flow system of the Upper Floridan aquifer.

Scenarios for the Savannah-Hilton Head Island Area

Fifteen scenarios were simulated in the Savannah-Hilton Head Island area. Changes in May 1985 pumpage ranged from an 81.6 Mgal/d decrease to a 50 Mgal/d increase (tables 10, 14; figs. 33-48). Twelve scenarios (S-1 through S-12) simulated the potentiometric gradient between Hilton Head Island and Savannah for a variety of pumping conditions in Chatham County. These simulations were intended to quantify the reduction in pumpage necessary to allow sustainable use of the Upper Floridan aquifer at Savannah. Sustainable, in this case, was defined by EPD to mean that saltwater would not be flowing toward Savannah from the point of encroachment at Port Royal Sound (William H. McLemore, Georgia Geologic Survey, written commun., January 2, 1998).

Scenarios S-1 through S-12 simulated reductions in May 1985 pumpage in Chatham County that ranged from 10 Mgal/d to about 81.6 Mgal/d (a complete cessation of pumpage). All 12 scenarios resulted in water-level rises at the cells, and decreased leakage from the Fernandina permeable zone (figs. 15, 33-44). Results from nine of these scenarios were used to produce profiles of simulated hydraulic head (fig. 45) extending from the point of seawater encroachment on the north end of Hilton Head Island to the center of the cone of depression at Savannah. These simulated profiles, along with the profile for May 1985

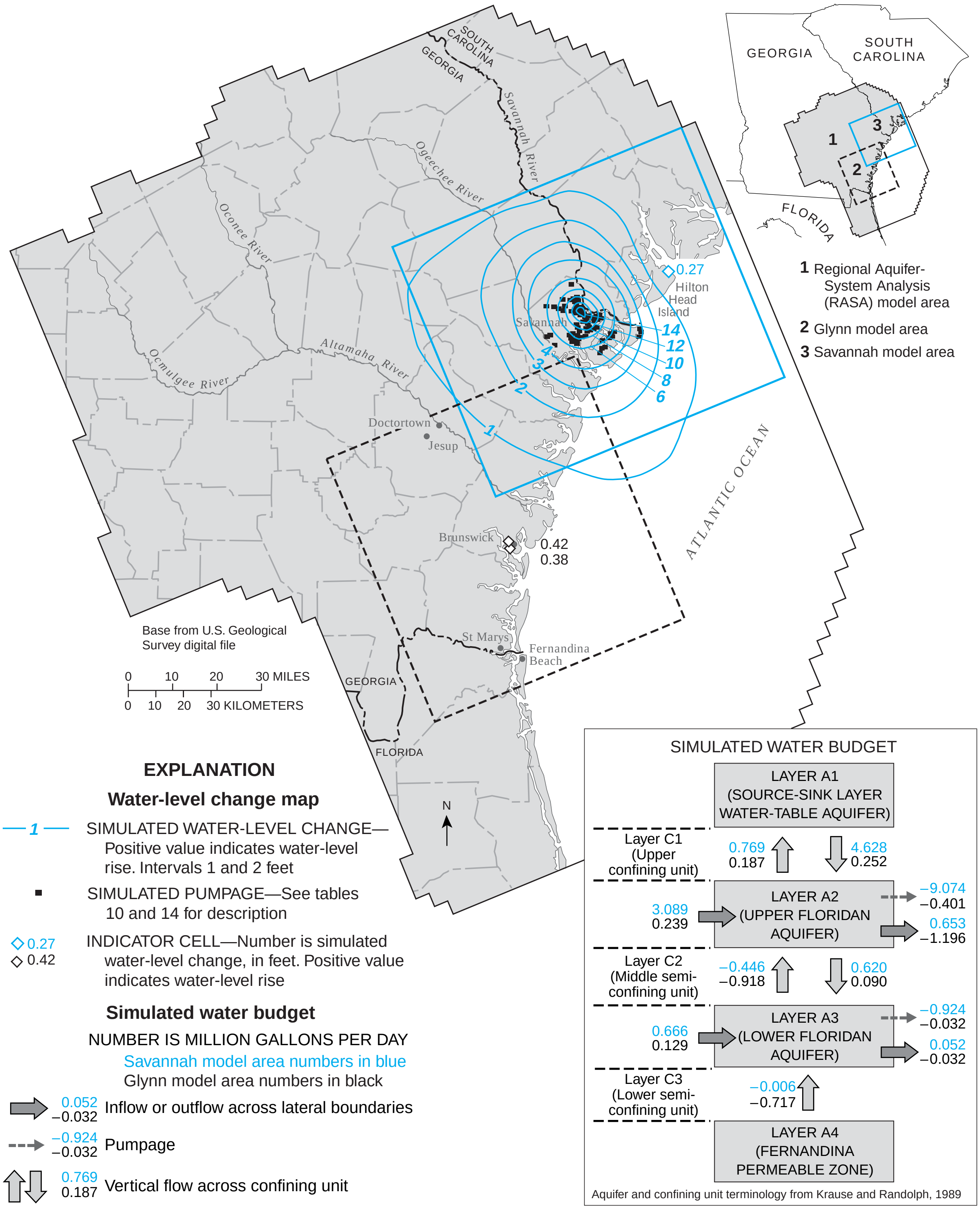


Figure 33. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-1, Savannah–Hilton Head Island area.

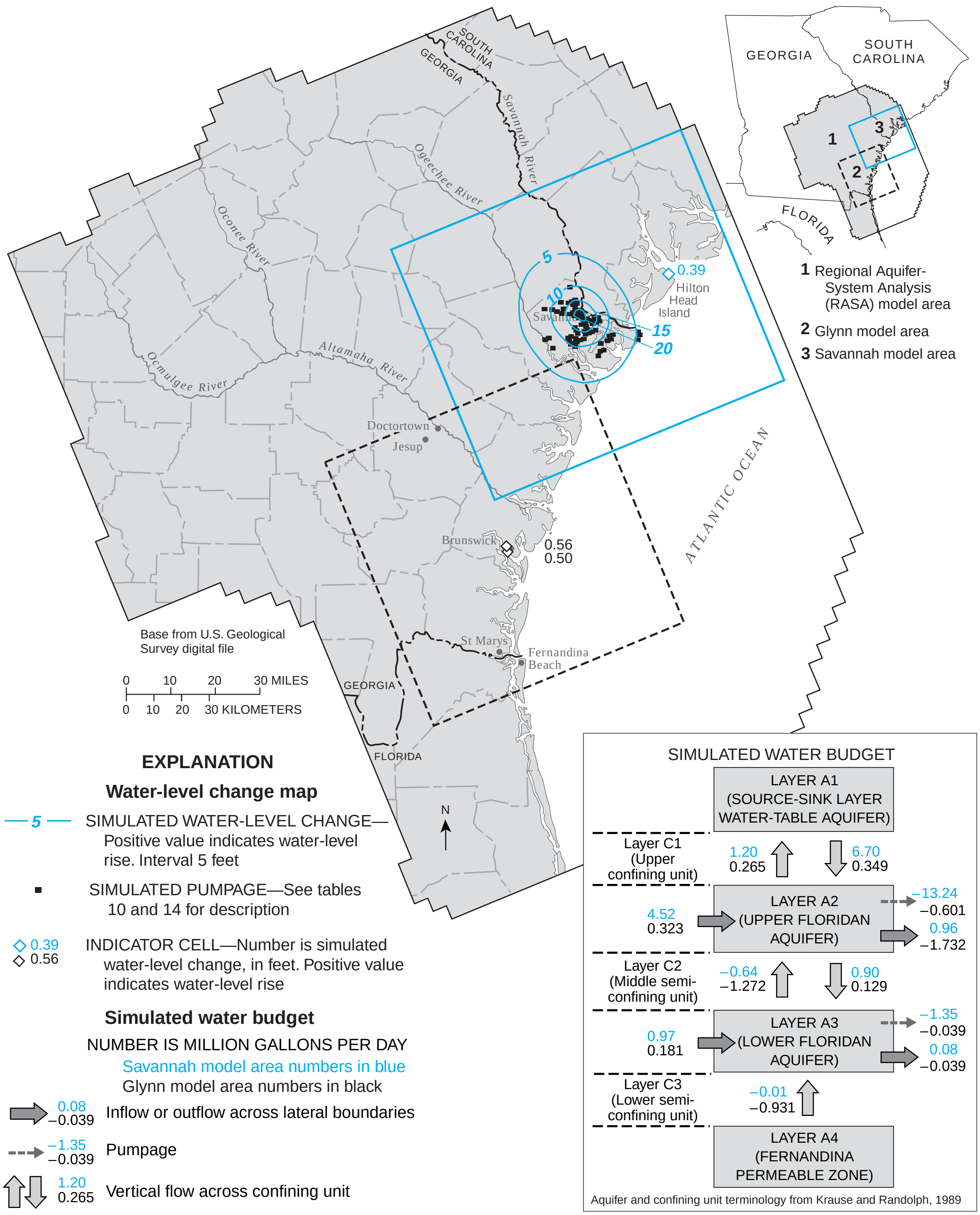


Figure 34. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-2, Savannah–Hilton Head Island area.

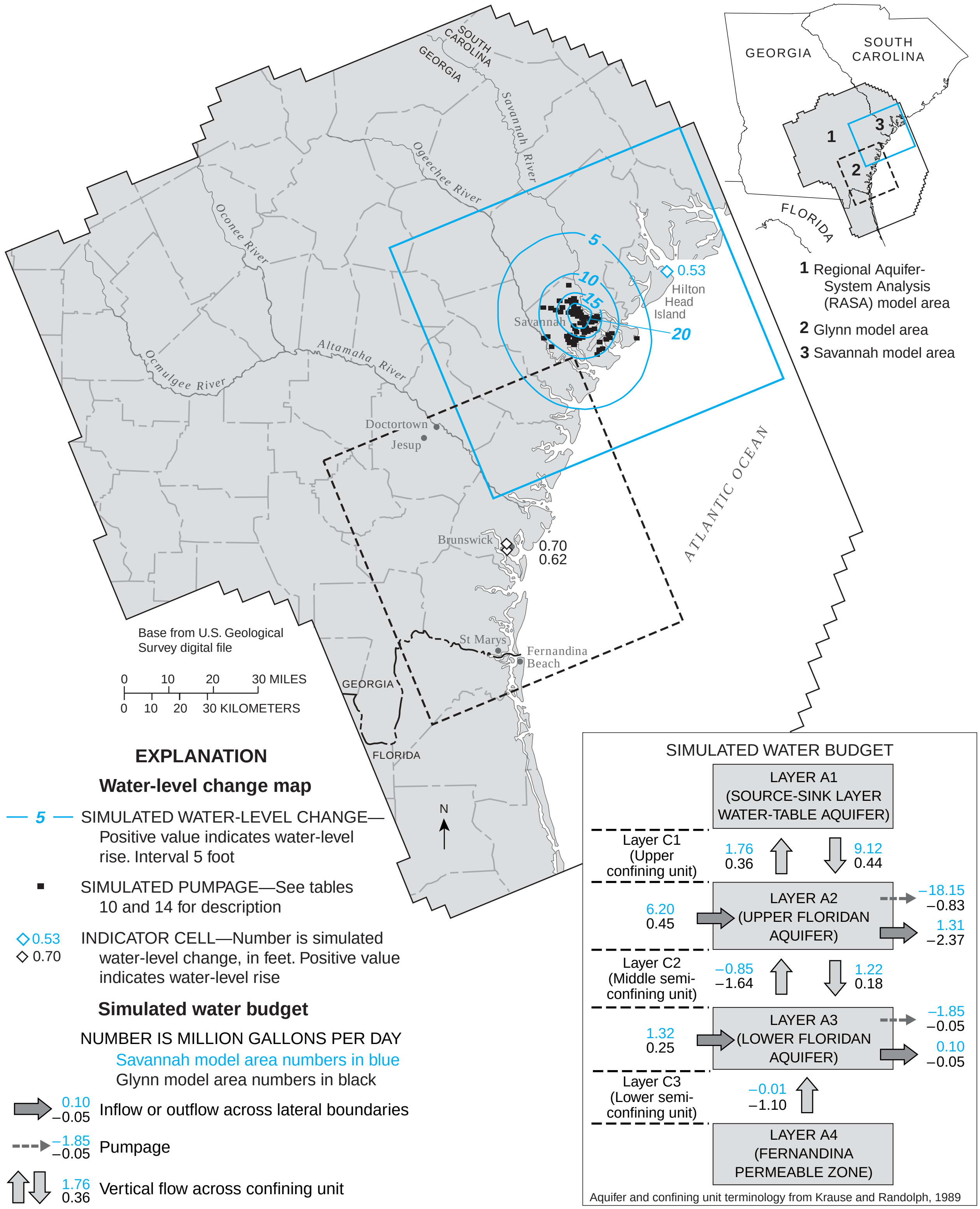


Figure 35. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-3, Savannah–Hilton Head Island area.

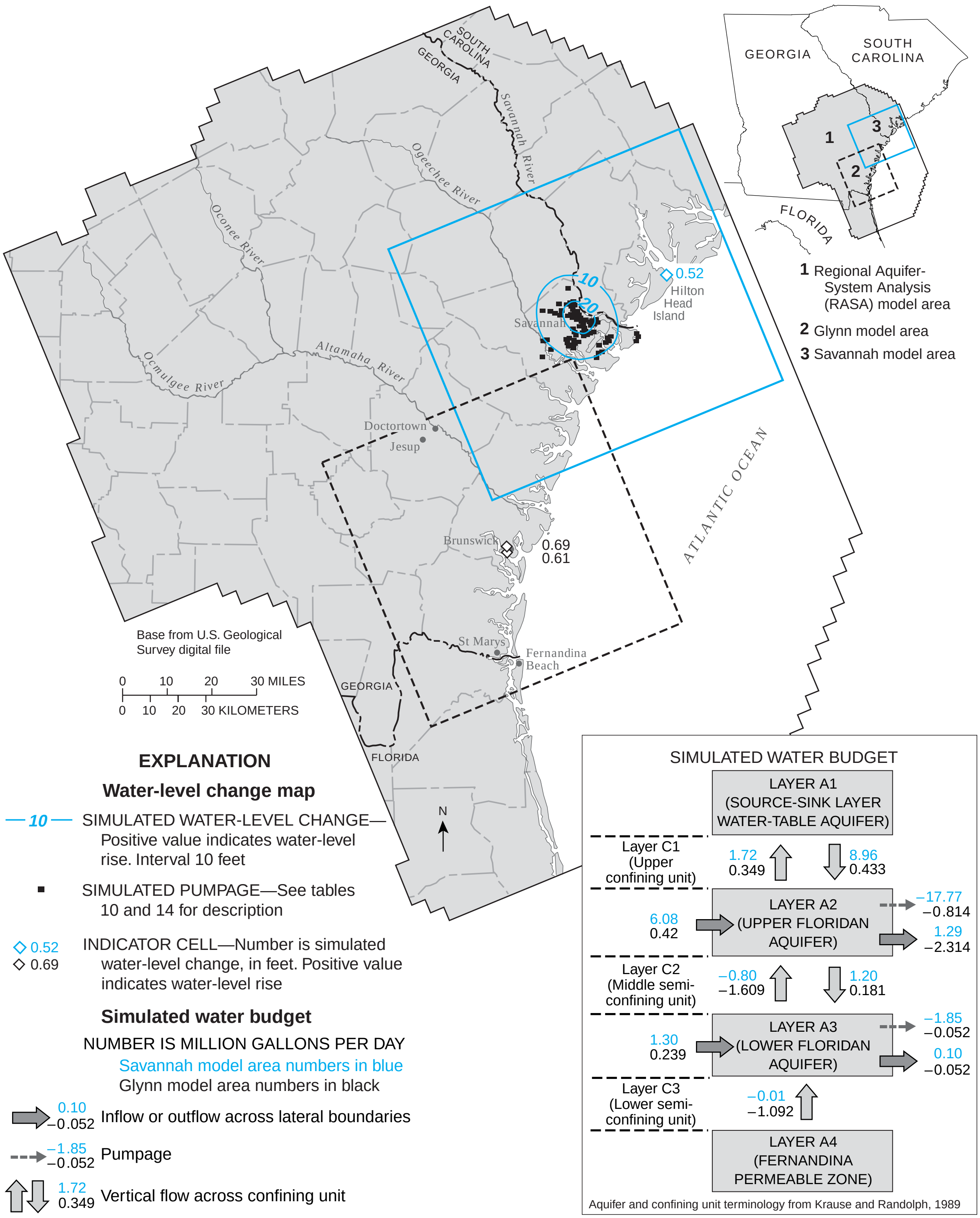


Figure 36. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-4, Savannah–Hilton Head Island area.

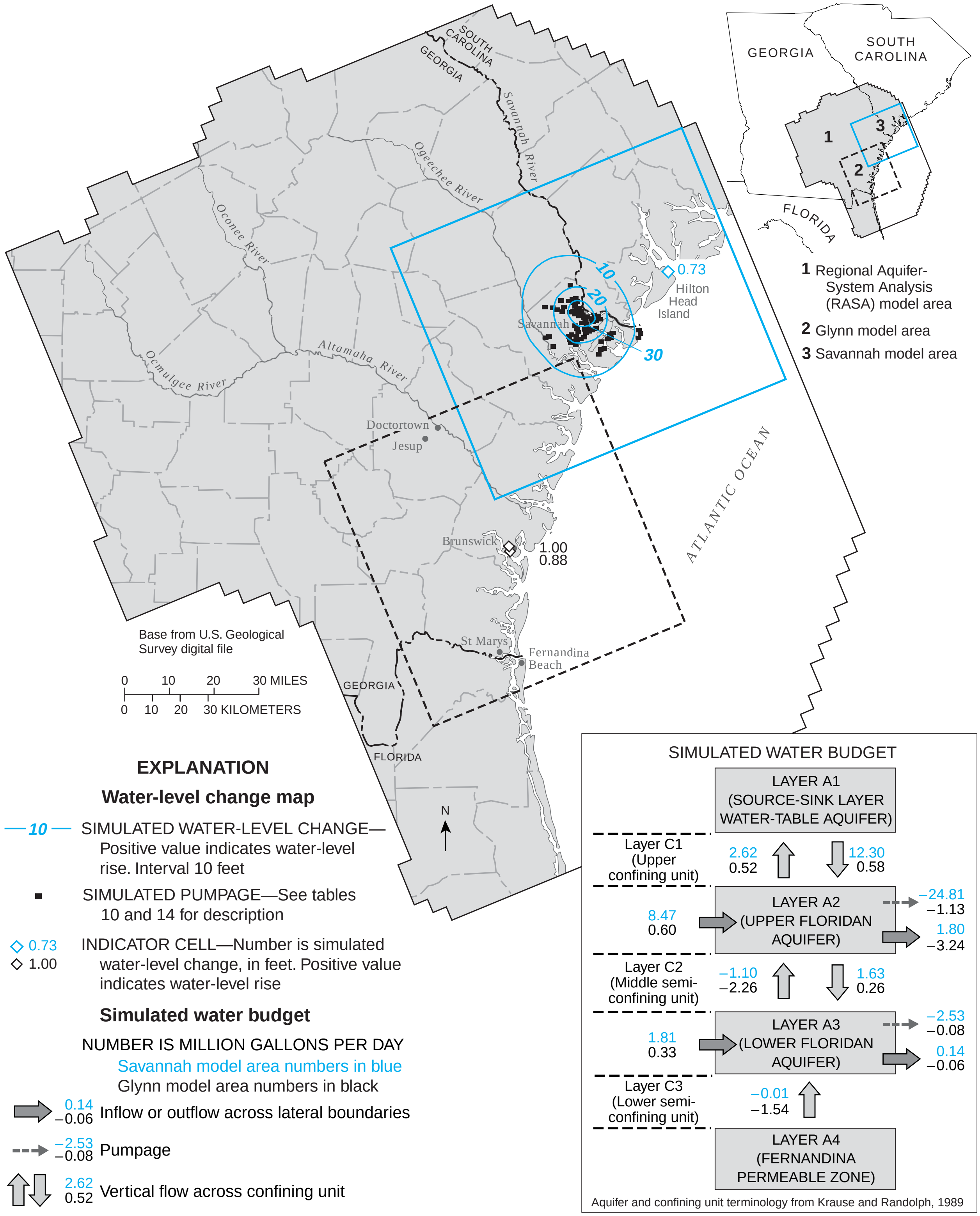


Figure 37. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-5, Savannah–Hilton Head Island area.

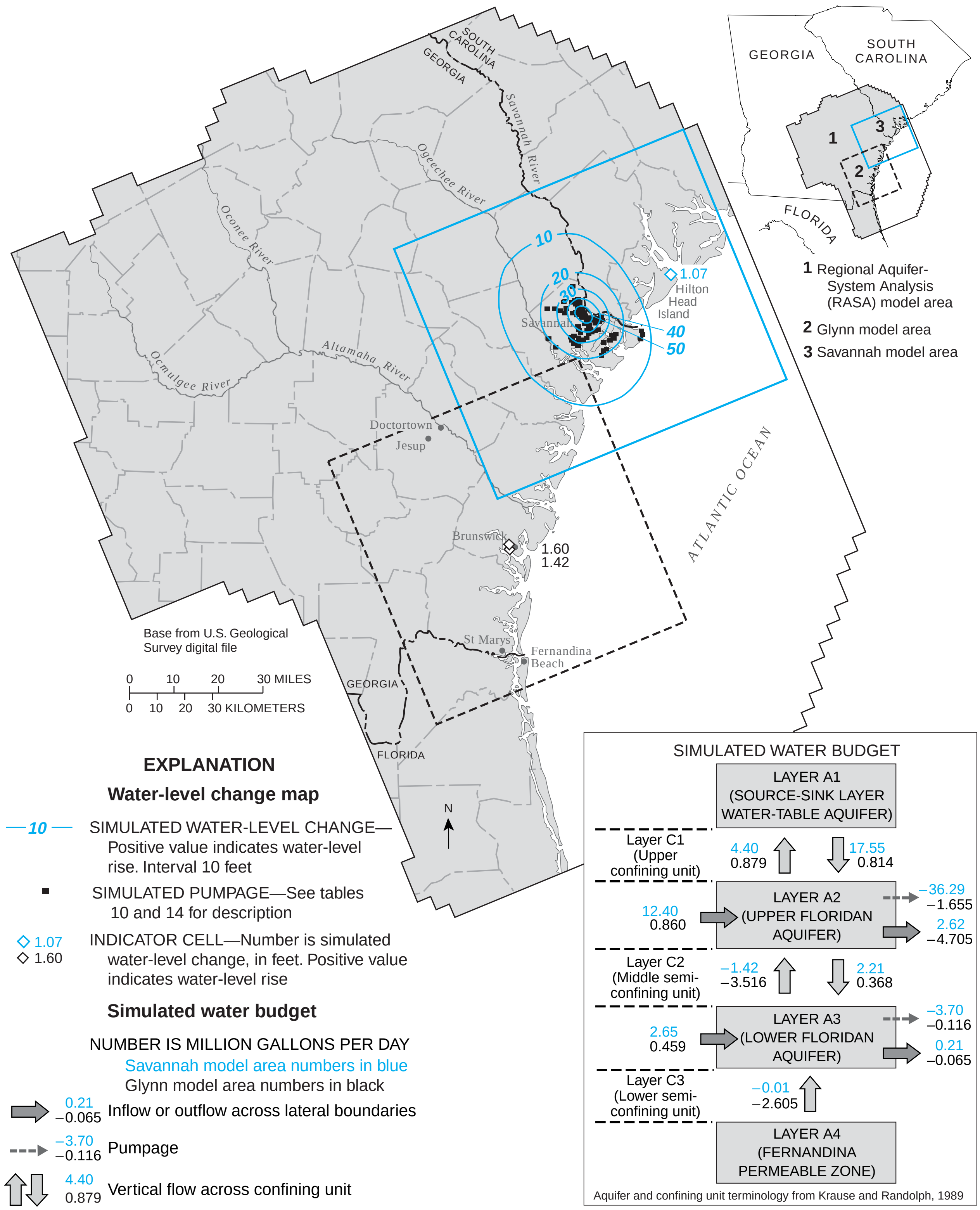


Figure 38. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-6, Savannah–Hilton Head Island area.

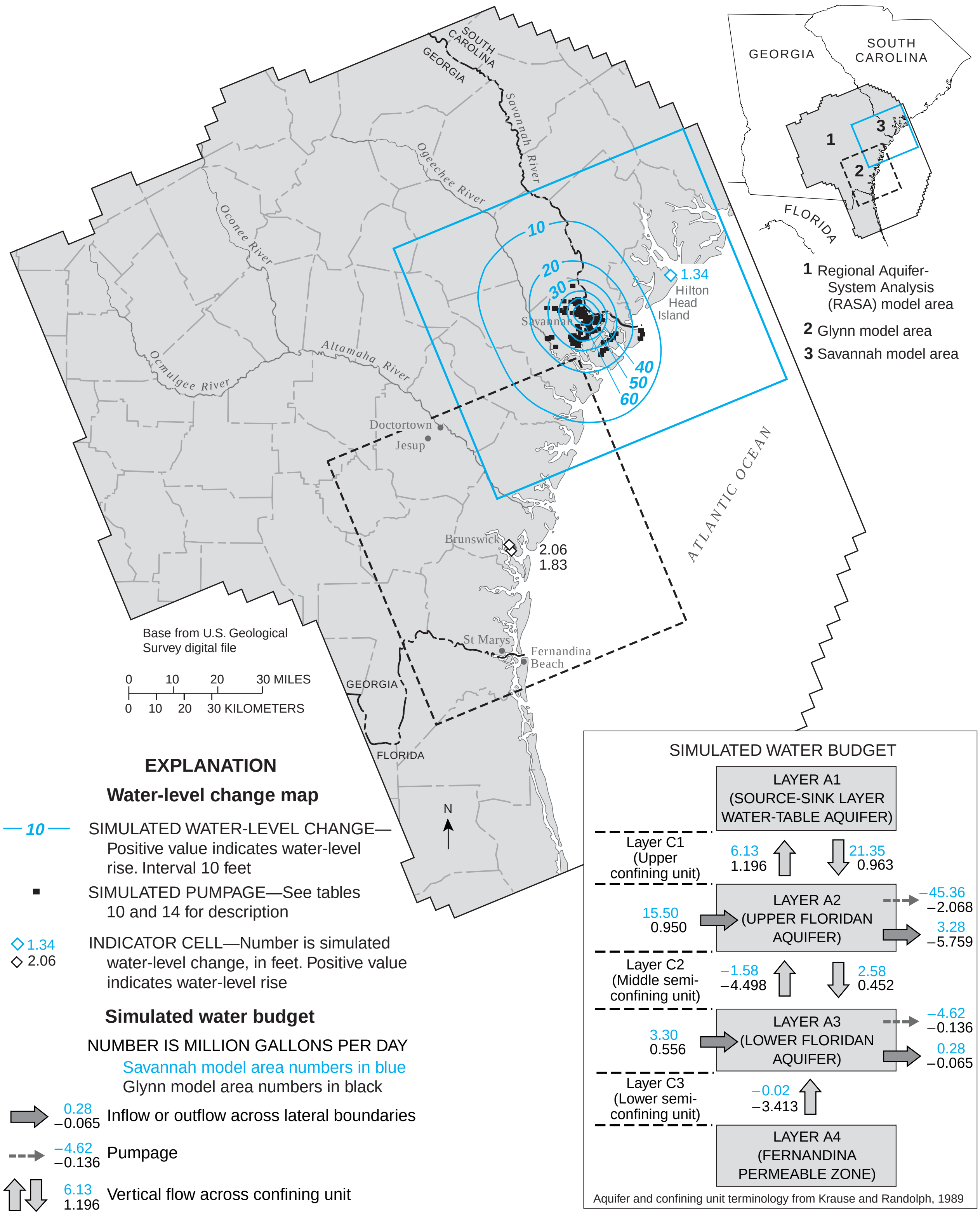


Figure 39. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-7, Savannah–Hilton Head Island area.

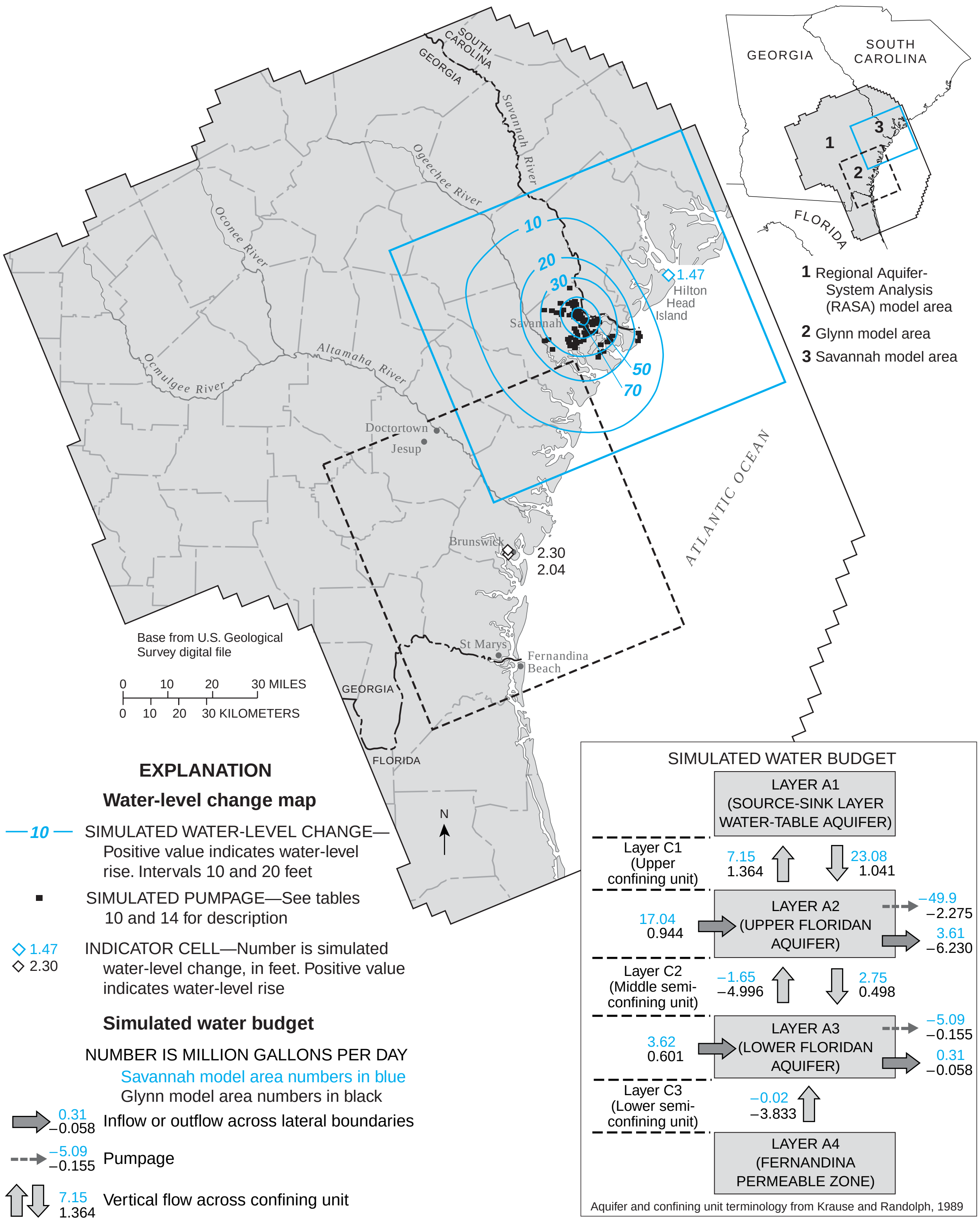


Figure 40. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-8, Savannah–Hilton Head Island area.

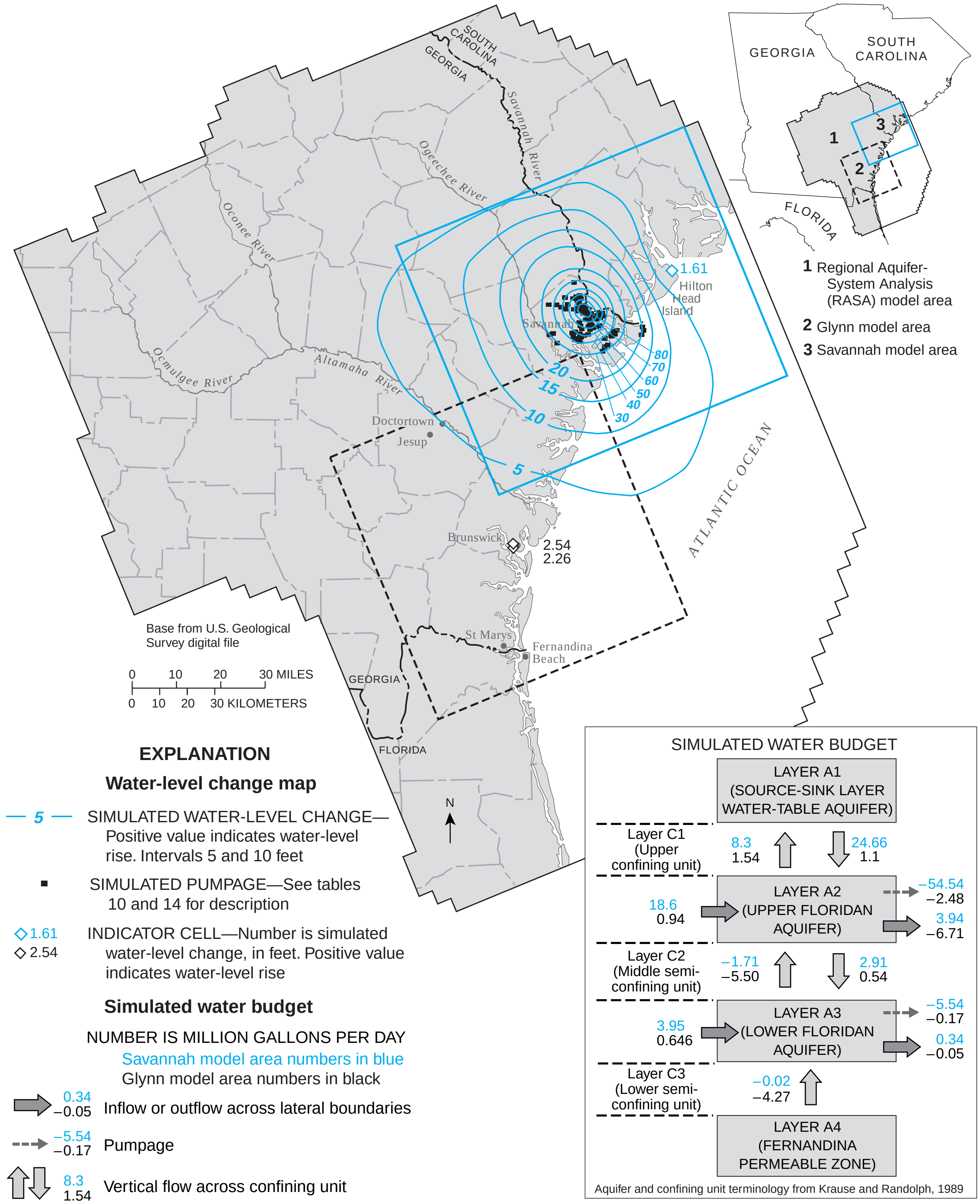


Figure 41. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-9, Savannah–Hilton Head Island area.

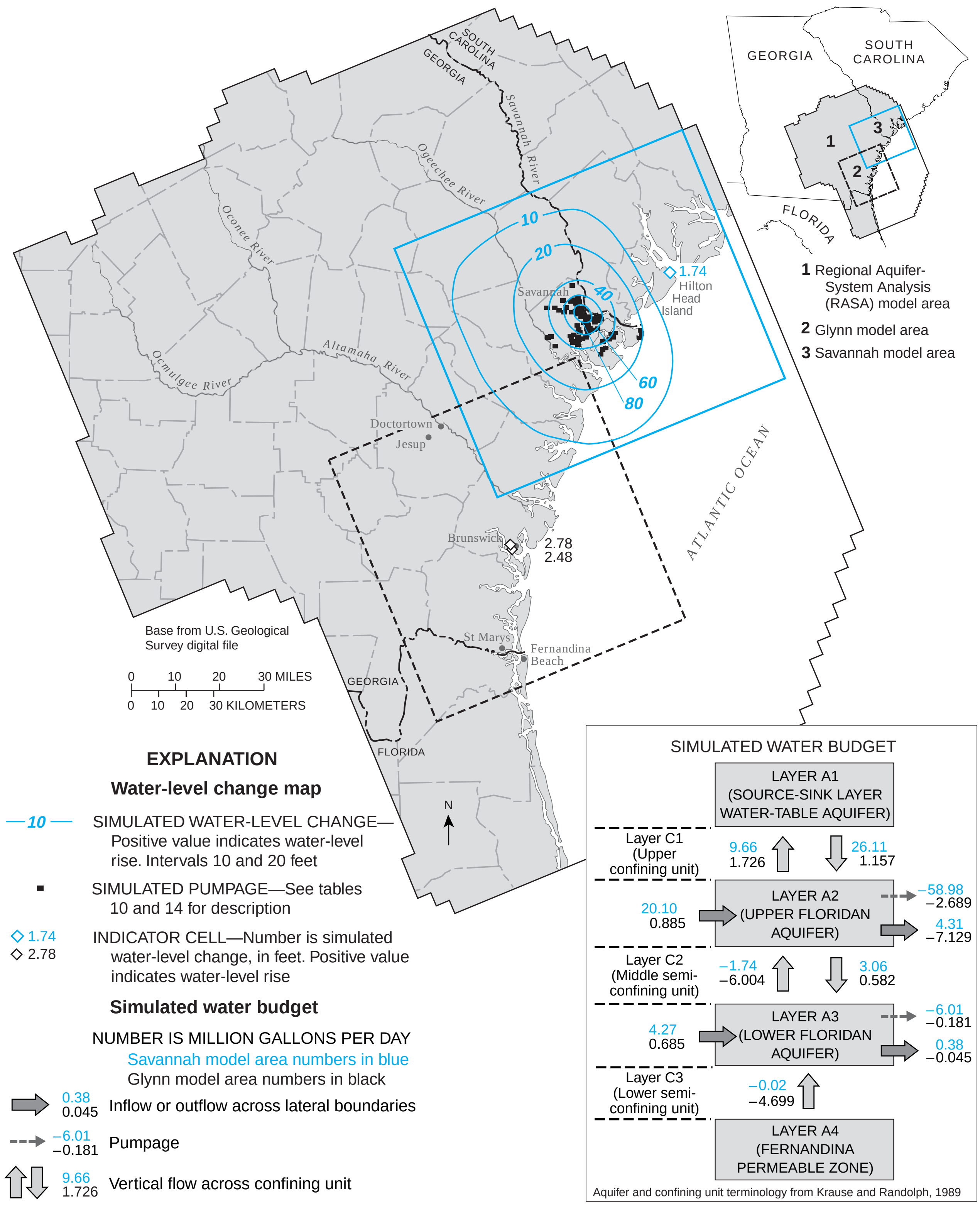
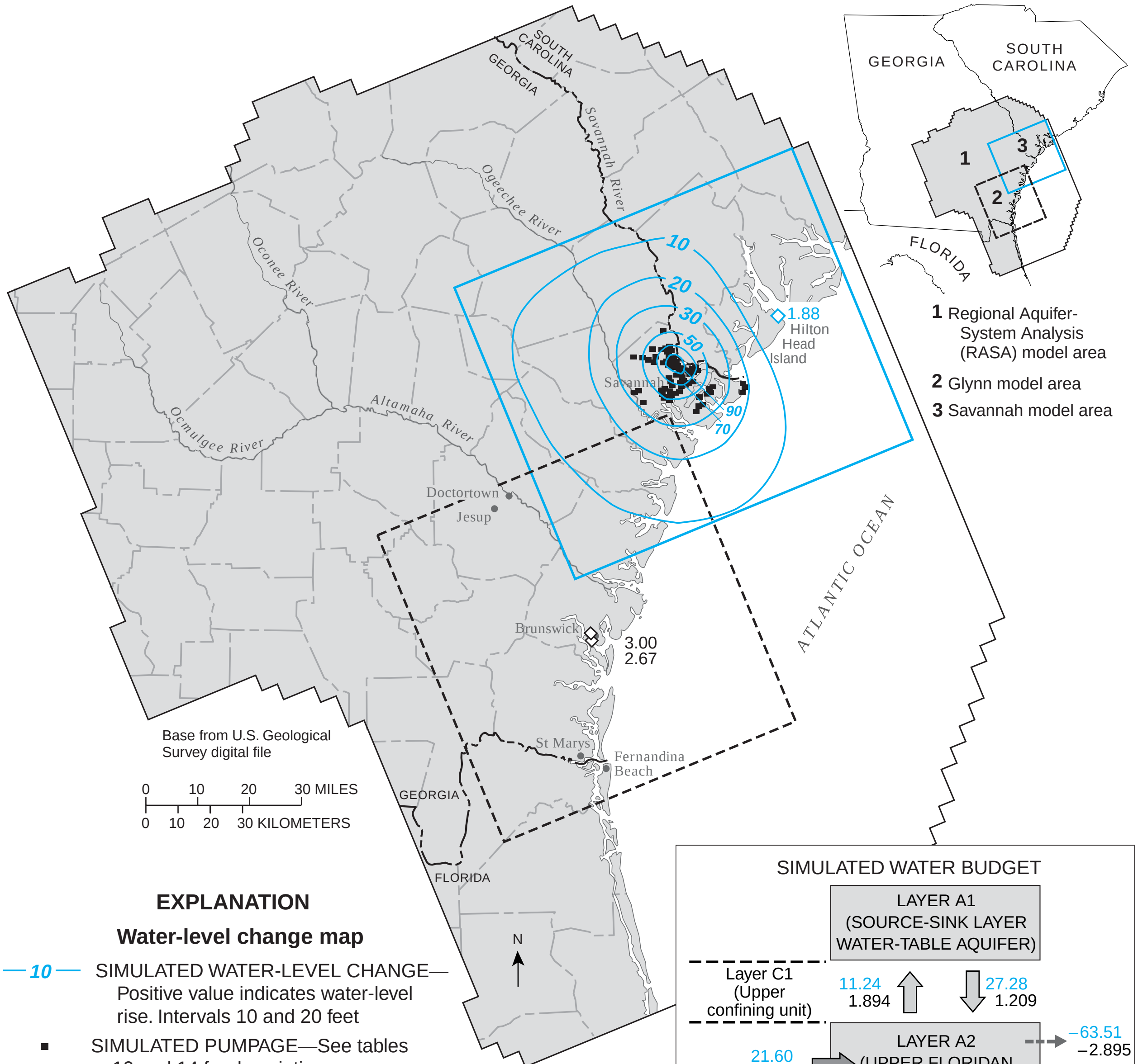


Figure 42. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-10, Savannah–Hilton Head Island area.



EXPLANATION

Water-level change map

— 10 — SIMULATED WATER-LEVEL CHANGE—Positive value indicates water-level rise. Intervals 10 and 20 feet

■ SIMULATED PUMPAGE—See tables 10 and 14 for description

◇ 1.88 / ◇ 3.00 INDICATOR CELL—Number is simulated water-level change, in feet. Positive value indicates water-level rise

Simulated water budget

NUMBER IS MILLION GALLONS PER DAY
Savannah model area numbers in blue
Glynn model area numbers in black

0.41 / 0.032 Inflow or outflow across lateral boundaries

−6.47 / −0.194 Pumpage

11.24 / 1.894 Vertical flow across confining unit

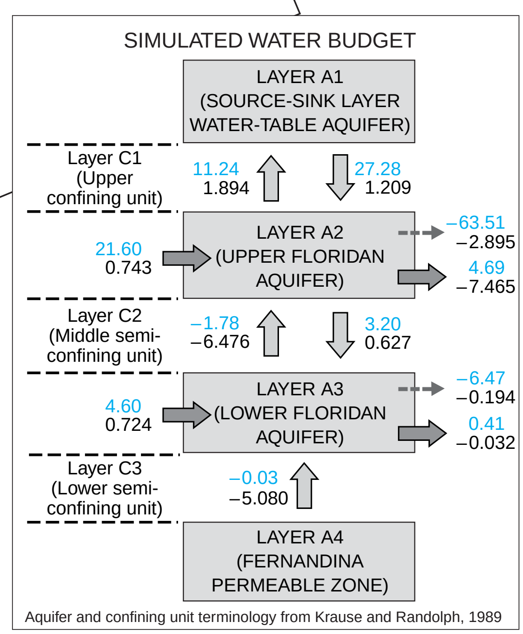


Figure 43. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-11, Savannah–Hilton Head Island area.

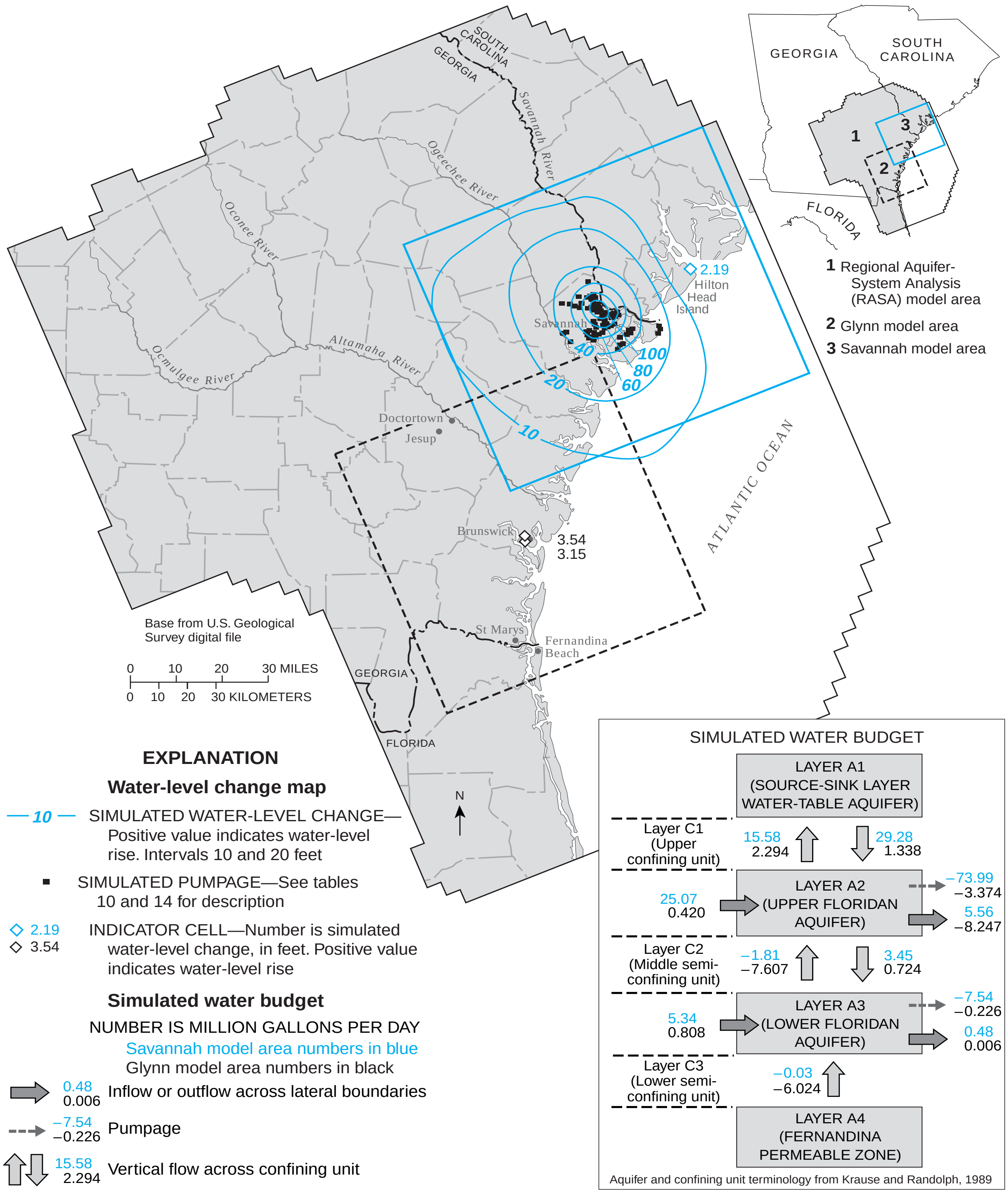


Figure 44. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-12, Savannah–Hilton Head Island area.

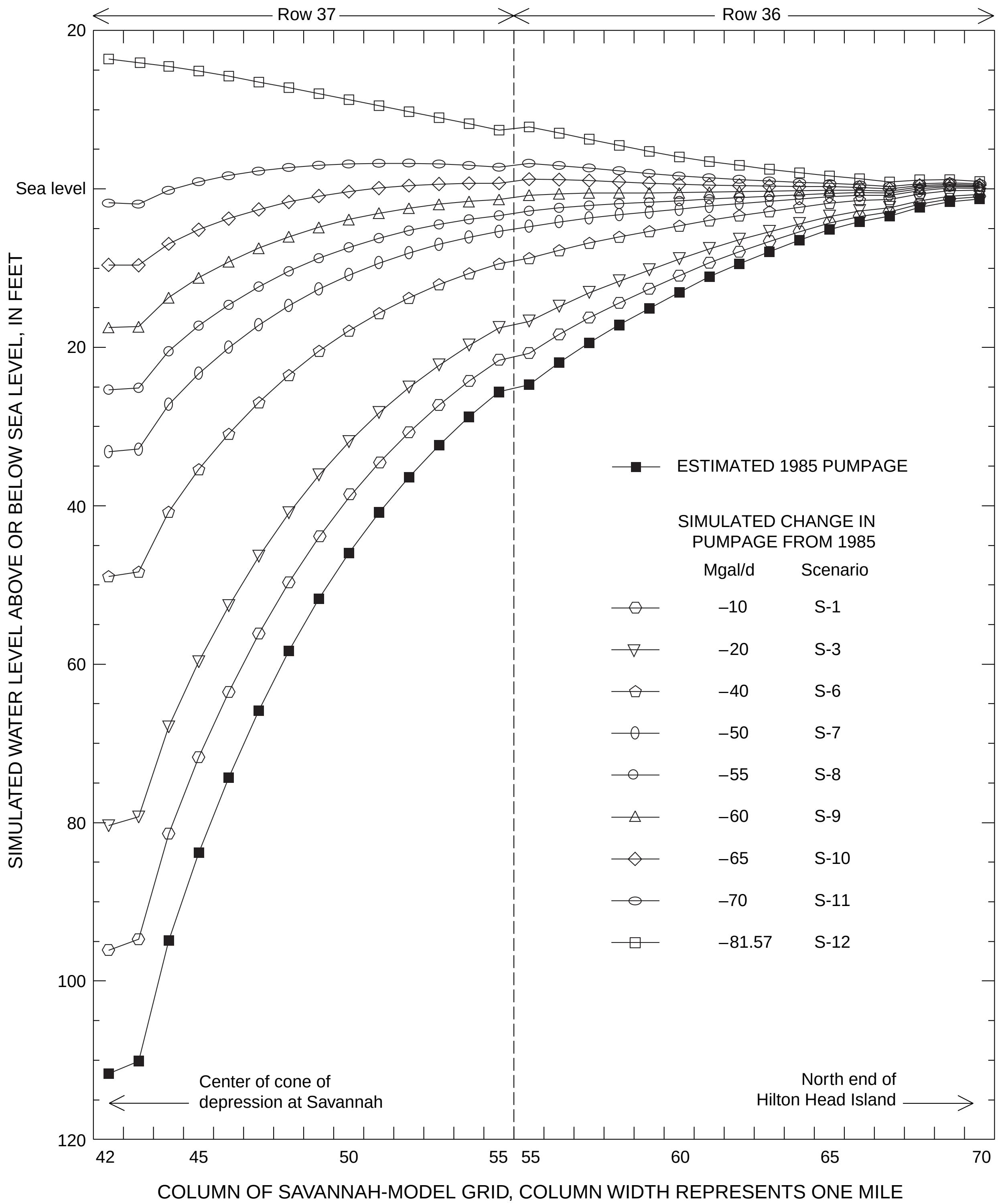


Figure 45. Simulated ground-water-level profiles for the Savannah–Hilton Head Island area for selected water-management scenarios (see figure 4 for location).

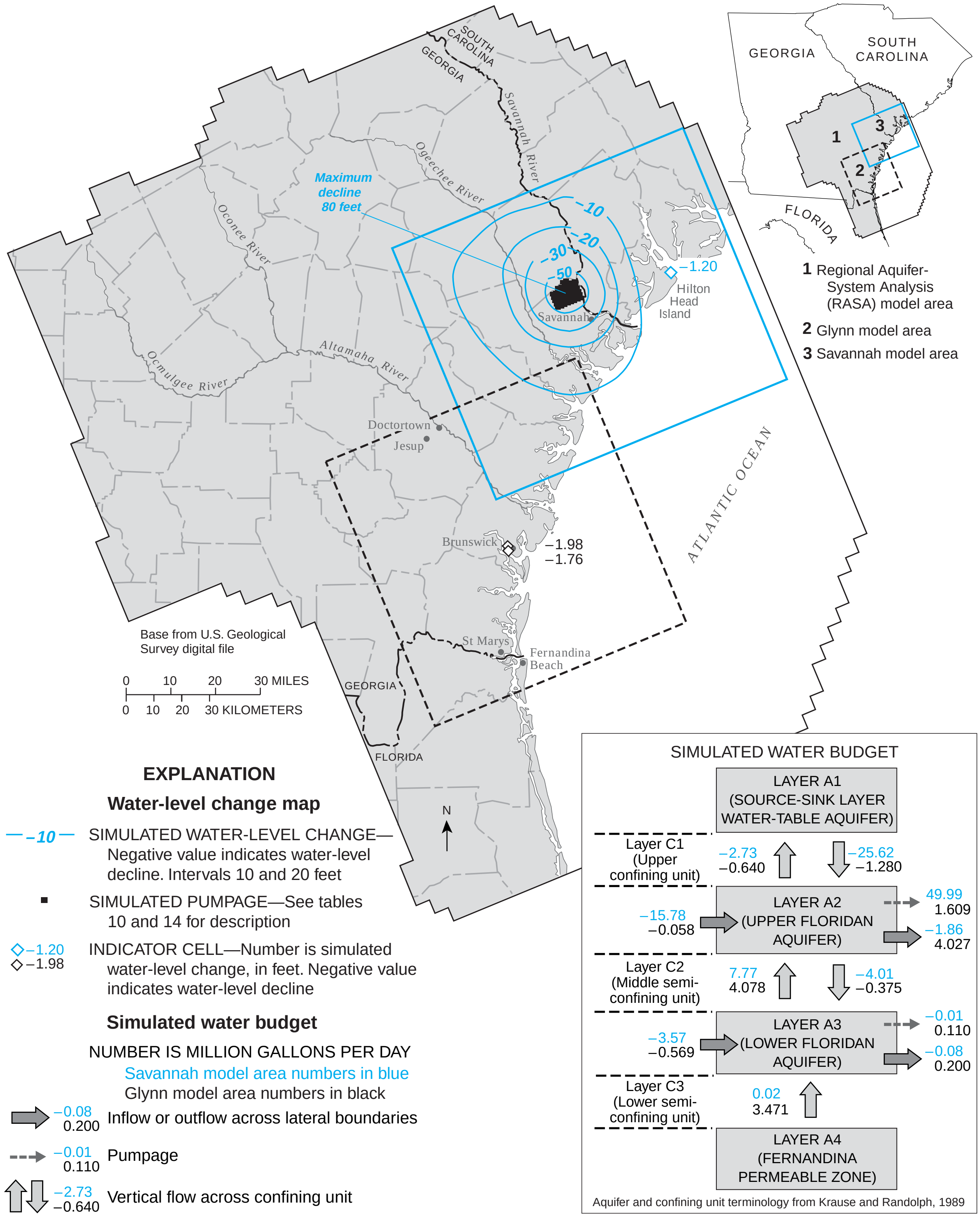


Figure 46. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-13, Savannah–Hilton Head Island area.

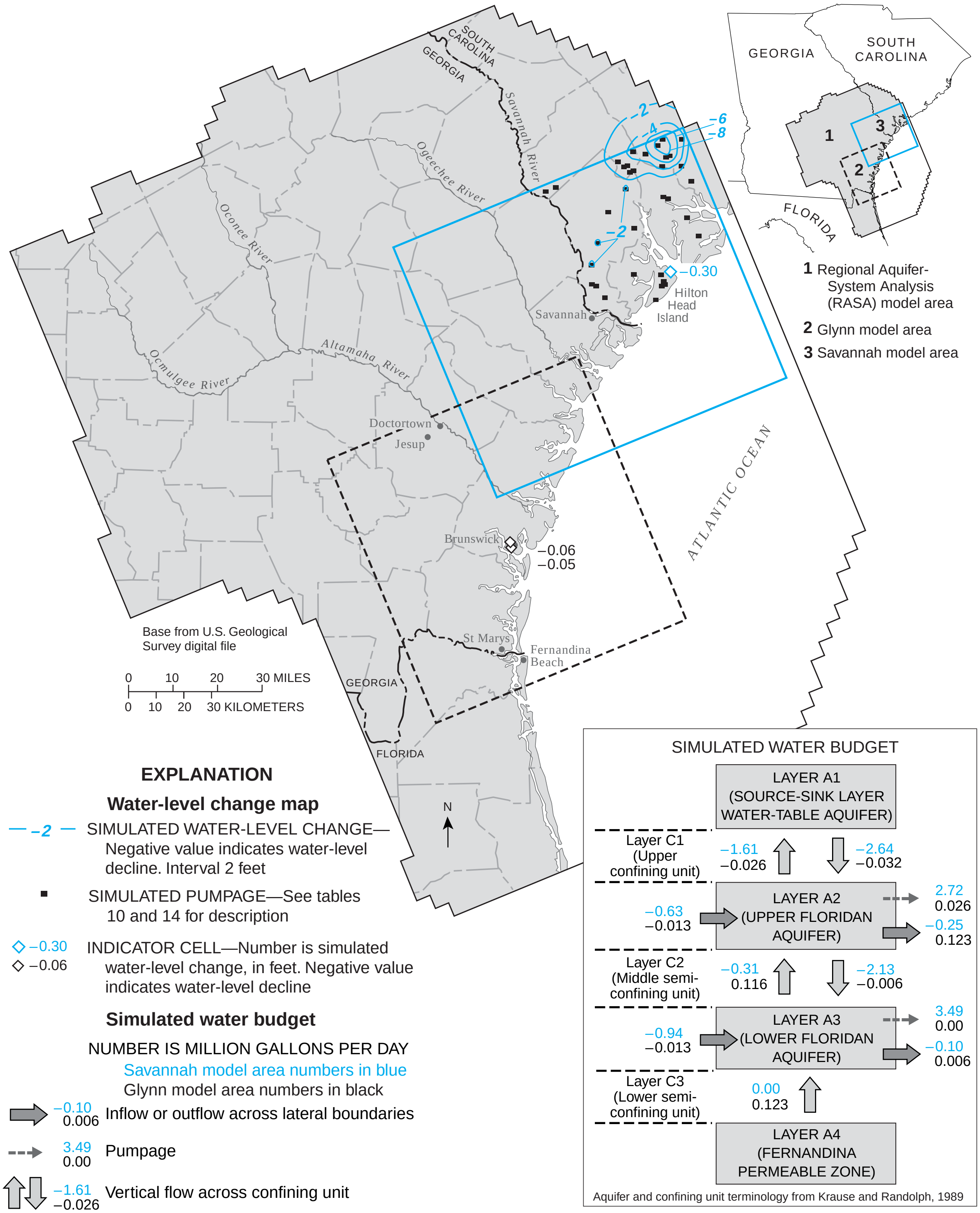


Figure 47. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-14, Savannah–Hilton Head Island area.

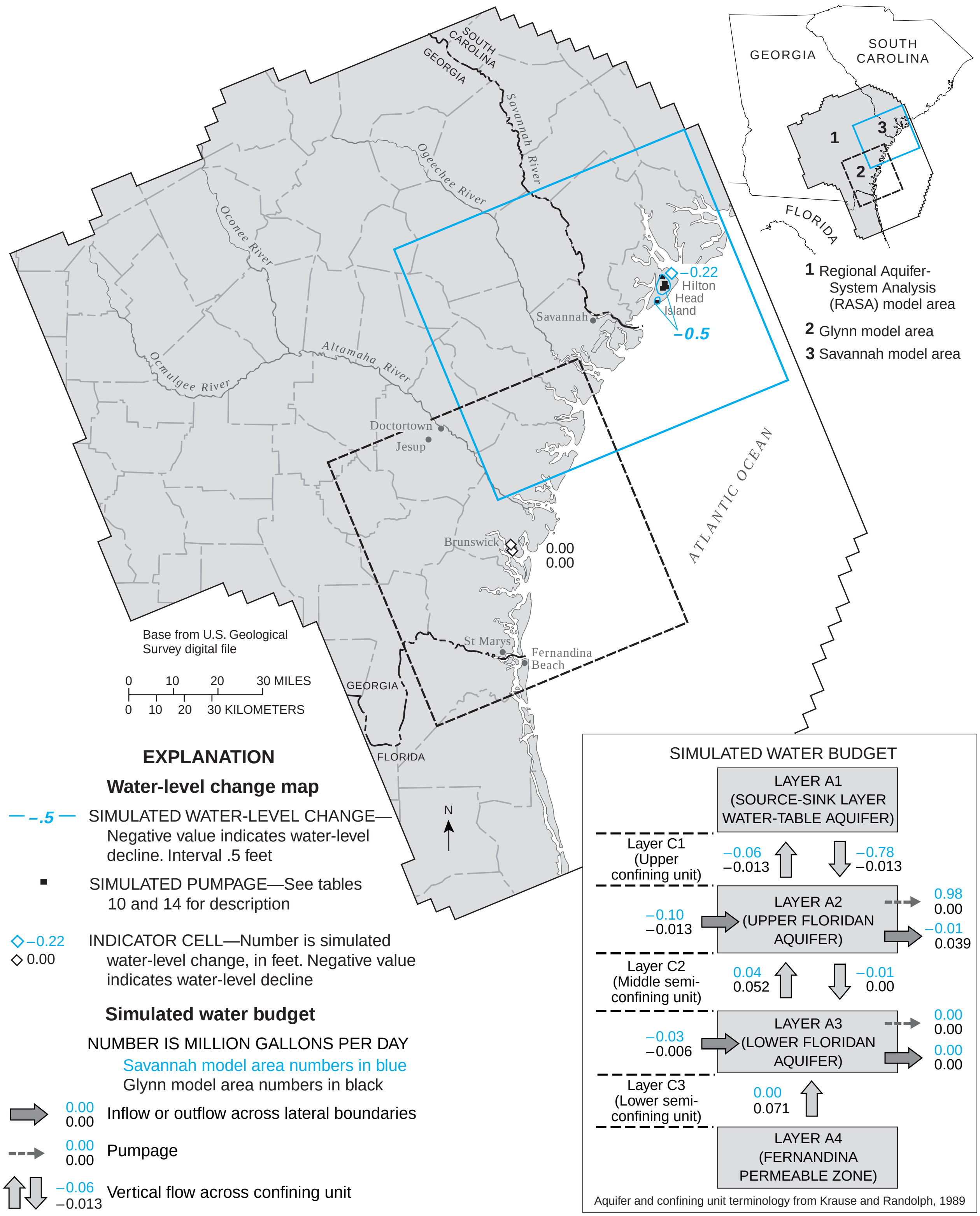


Figure 48. Simulated water-level change from simulated May 1985 conditions for the Upper Floridan aquifer (model layer A2), location of simulated pumpage and indicator cells, and changes in water budget for scenario S-15, Savannah–Hilton Head Island area.

Table 14. Summary of simulated pumpage used in water-management scenarios S-1 through S-15, Savannah-Hilton Head Island area
[Reported sums may not agree because of rounding]

County and state	1985 simulated pumpage	Simulated pumpage by scenario and change from 1985 pumpage, by county (in million gallons per day)															
			S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14	S-15
Chatham, Ga.	81.57	Scenario	77.57	66.98	61.57	61.94	54.22	41.57	31.57	26.57	21.57	16.57	11.57	0.00	131.57	81.57	81.57
		Difference	-10.00	-14.59	-20.00	-19.63	-27.35	-40.00	-50.00	-55.00	-60.00	-65.00	-70.00	-81.57	50.00	0.00	0.00
Beaufort, S.C.	14.95	Scenario	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	17.03	15.93
		Difference	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.08	0.98
Colleton, S.C.	0.35	Scenario	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	2.41	0.35
		Difference	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.06	0.00
Hampton, S.C.	0.12	Scenario	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.91	0.12
		Difference	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.79	0.00
Jasper, S.C.	2.02	Scenario	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	3.47	2.02
		Difference	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.45	0.00
TOTAL	**99.01**	**Scenario**	**89.01**	**84.42**	**79.01**	**79.38**	**71.66**	**59.01**	**49.01**	**44.01**	**39.01**	**34.01**	**29.01**	**17.44**	**149.01**	**105.39**	**99.99**
		Difference	**-10.00**	**-14.59**	**-20.00**	**-19.63**	**-27.35**	**-40.00**	**-50.00**	**-55.00**	**-60.00**	**-65.00**	**-70.00**	**-81.57**	**50.00**	**6.38**	**0.98**

conditions, provide a comparison of changes in hydraulic gradient resulting from the change in pumpage in Chatham County. Smaller lateral hydraulic gradients than those simulated for May 1985 reflect lower ground-water flow velocities and infer slower rates of seawater encroachment into the Upper Floridan aquifer at Hilton Head Island.

As shown in figure 45, progressive reductions in pumpage from May 1985 conditions of as much as 60 Mgal/d in Chatham County produced progressively gentler simulated hydraulic gradients toward the cone of depression at Savannah. With reductions in pumpage greater than 65 Mgal/d, the simulated hydraulic gradient between Hilton Head Island and Savannah becomes reversed, having a component of flow in a northeasterly direction from Chatham County toward Hilton Head Island. Specifically, for scenarios S-10 and S-11—representing reductions in pumpage of 65 Mgal/d and 70 Mgal/d, respectively—a slight ground-water divide developed along the simulated hydraulic-head profile, whereby part of the flow is toward the center of pumping at Savannah, and part of the flow is toward Hilton Head Island. With cessation of pumpage at Chatham County (scenario S-12), the hydraulic gradient along the profile is completely toward Hilton Head Island and probably is similar to pre-pumping conditions that existed in the area.

Scenario S-13 simulates an increase in pumpage of 50 Mgal/d, with a redistribution of pumpage toward the northern part of Chatham County (tables 10, 14; fig. 46). This scenario tested the effect of discontinuing surface-water withdrawal in the western part of Chatham County, and replacing the water supply with wells tapping the Upper Floridan aquifer. This change resulted in a water-level decline at the cells and an increase in leakage from the Fernandina permeable zone (fig. 46). Maximum water-level decline was about 80 ft in the northern part of Chatham County. Water-level decline at cells averaged about 1.9 ft at Brunswick and 1.2 ft at Hilton Head Island. Simulated leakage from the Fernandina permeable zone increased by about 3.5 Mgal/d.

Scenarios S-14 and S-15 simulated changes in pumpage in South Carolina (tables 10, 14; figs. 47-48). Scenario S-14 (table 14, fig. 47) simulated the effects of an increase in pumpage of 6.4 Mgal/d, which resulted in a slight water-level decline at cells (0.06 ft at Brunswick and 0.3 ft at Hilton Head Island) and a slight increase in leakage from the Fernandina permeable zone (0.12 Mgal/d).The largest decline ranged from 2 to 8 ft in the northeastern corner of the Savannah model area.

Scenario S-15 simulated effects of a 0.98 Mgal/d increase in pumpage at Hilton Head Island (table 14, fig. 48). This increase resulted in a slight water-level decline at the Hilton Head Island indicator cell (about 0.2 ft) and no detectable response at the Brunswick cells (less than 0.05 ft). Maximum water-level decline was about 0.5 ft on Hilton Head Island (fig. 48). Leakage from the Fernandina permeable zone increased only slightly (0.07 Mgal/d). These declines resulted in greater lateral hydraulic gradients than those simulated for May 1985, and infer somewhat higher rates of seawater encroachment into the Upper Floridan aquifer at Hilton Head Island.

Potential for Ground-Water Development

The potential for additional development of water from the Upper Floridan aquifer is constrained by water-level decline at known locations of saltwater contamination—Brunswick and the northern end of Hilton Head Island. As previously described, the Savannah and revised RASA and Glynn models were used to predict the effects of 32 hypothetical pumping scenarios on water levels at Brunswick and Hilton Head Island. In general, those scenarios that simulated decreased pumpage resulted in water-level rises at both Brunswick and Hilton Head Island. Conversely, in response to increased pumpage, the water level at each location declined. Generally, the farther that pumping is located away from Brunswick and Hilton Head Island, the smaller the effect on the ground-water level in the Upper Floridan aquifer and on saltwater contamination.

The potential for the Upper Floridan aquifer to supply additional ground-water withdrawal in coastal Georgia without producing a detectable drawdown response at Brunswick or Hilton Head Island may be affected by two hydrologic boundaries—the Gulf Trough, separating the northern and central subareas; and the postulated “Satilla Line”, separating the central and southern subareas (fig. 1).

Additional withdrawal may be possible north of the Gulf Trough without causing detectable drawdown at Brunswick or Hilton Head Island. This is illustrated by the results from scenario A-4, representing a pumpage increase of 18 percent from the estimated May 1985 rate of withdrawal (fig. 19, tables 10, 11). Despite increased pumpage, the simulated water level rose an average of about 4.5 ft at the Brunswick and about 0.3 ft at the Hilton Head Island indicator cells, and leakage from the Fernandina permeable zone decreased slightly (0.01 Mgal/d, fig. 19). These responses are the result of a redistribution of pumpage away from the coast to north of the Gulf Trough. Although greater pumpage may be possible north of the Gulf

Trough, well yields in the area are lower because of low transmissivity. This low transmissivity would produce relatively deep, but areally limited cones of depression, if additional water supplies were developed in the area.

In the southern part of the area, additional withdrawal may be possible south of the hypothesized “Satilla Line” without causing appreciable drawdown at Brunswick or Hilton Head Island. A diminished response to pumpage south of the Satilla Line is demonstrated by comparison of the results from scenarios G-5 and G-6, simulating the effect of a 5-Mgal/d increase in pumpage on either side of the Satilla Line (figs. 31-32; tables 10, 13). Neither scenario produced a drawdown response exceeding 0.05 ft at Hilton Head Island. Scenario G-5, having the increased pumpage north of the Satilla Line, resulted in greater water-level decline at the cells in Brunswick (about 0.8 ft) than did scenario G-6 (about 0.4 ft), suggesting that additional withdrawal may be possible south of the Satilla Line without causing appreciable drawdown north of the feature.

Limitations of Model Application

Each model scenario was based on application of the three ground-water-flow models previously described in this report—the RASA, Glynn, and Savannah models. Limitations of these models are given in detail in the original reports describing their development, calibration, and sensitivity—Krause and Randolph (1989), for the RASA model; Randolph and Krause (1990), for the Glynn model; and Garza and Krause (1996), for the Savannah model.

The three models were calibrated based on hydrologic conditions that existed prior to development (about 1880) and that existed in May 1980 (RASA and Brunswick models only) and May 1985. Although the calibrated models simulate conditions that date back to May 1985 and may seem “out-of-date,” the models are useful for simulating the hydrologic effects of pumping on the Floridan aquifer system. The calibration date of May 1985 corresponds to conditions of nearly maximum pumpage (308 Mgal/d) that were documented with reliable ground-water-level and water-use data that supported the calibration process. Calibration to May 1985 conditions neither implies or indicates that the models are out-of-date or inaccurate. The models simulate steady-state conditions, which are time invariant (independent of time); thus, the cause- and-effect relations of pumpage and water-level change can be applied to any time period that contains the simulated stress conditions.

The scenarios presented in this report simulate pumpage changes that ranged from about 82 Mgal/d lower to about 438 Mgal/d higher than simulated May 1985 pumpage (table 10, fig. 15). The most reliable results from these simulations would correspond with simulated changes in pumpage within the range used during calibration—in the case of these models—0 Mgal/d (predevelopment) to 308 Mgal/d (May 1985 pumpage). Model results would be less reliable for simulations of pumpage outside this range.

Pumping scenarios outside the calibrated range may violate assumptions made regarding boundary conditions and hydraulic properties, and thus, provide unreliable results. For example, errors in simulated ground-water levels in the Upper Floridan and Lower Floridan aquifers may result because of the utilization of source/sink specified-head layers for simulation of the surficial aquifer and Fernandina permeable zone for scenarios in which pumpage is substantially larger than pumpage in the range of calibration. These specified-head layers have the potential to provide an infinite source of water to an aquifer through vertical leakage because the specified head was not allowed to vary through time, or, in response to pumpage in the Upper and Lower Floridan aquifers. Thus, simulated leakage rates and ground-water levels would be higher, and ground-water-level decline lower than expected if head in the surficial aquifer and Fernandina permeable zone were allowed to vary in a natural manner during simulation. Similarly, lateral specified-head boundaries provide an unlimited source of water. Where projected pumpage exceeds the calibrated range, active simulation of the source/sink layers and utilization of alternative lateral boundaries might provide more realistic projections of leakage and ground-water-level change in the Upper and Lower Floridan aquifers.

The three flow models simulate advective ground-water flow and have limited utility to address questions related to solute transport or conditions of variable-density flow, such as seawater encroachment or saltwater intrusion. The models can be used to simulate advective movement of saltwater using a particle-tracking approach similar to that described by Zheng and Bennett (1995, p. 20-23); however, this approach does not account for effects of variable density and dispersion. To account for these effects, models that simulate density-dependent flow and solute transport would be required.

SUMMARY

Water supply in the 24-county coastal area of Georgia is provided mainly by the Upper Floridan aquifer. Pumping from the aquifer has resulted in regional ground-water-level decline and local saltwater contamination in parts of the coastal area. Saltwater intrusion from deeply buried, connate sources in Brunswick, Georgia, and seawater encroachment on the northern end of Hilton Head Island, South Carolina, have occurred and have been documented.

Ground-water flow models of the coastal area of Georgia and in adjacent parts of South Carolina and Florida—developed during the 1970's and 1980's—were revised and updated to ensure consistency among their hydraulic-property arrays and to facilitate simulation of a variety of water-management scenarios. The revised models, developed as part of regional and areal assessments of ground-water resources in coastal Georgia, are—the Regional Aquifer-System Analysis (RASA) model, the Glynn County area (Glynn) model, and the Savannah area (Savannah) model.

Although modifications to hydraulic-property arrays were systematically made to the RASA model during development of each subsequent subregional model, in every instance where modifications were made, corresponding adjustments were not made to other previously developed subregional models. As a result, a consistent set of data arrays was needed to achieve agreement among the models. Changes were made based on the sequence and resolution of calibration, such that the hydraulic properties from the most recently calibrated model having the finest discretization and resolution were given highest precedence for incorporation into the other model arrays. Thus, most modifications were made to hydraulic property arrays for the RASA model, followed by the Glynn model; modifications were not made to the more recently developed Savannah model.

To ensure that the revised models accurately simulate the hydrologic system and to evaluate the possible effects of model revisions on simulated water levels and flow rates, a simulation was conducted using the Savannah and revised RASA and Glynn models; and the ground-water withdrawal rates specified in the original models for the calibration period May 1985. Simulated water levels for May 1985 for both the RASA and Glynn models showed little change as the result of revisions made to the hydraulic-property arrays, and the simulated potentiometric-surface map compares well with the hand-drawn potentiometric-surface map for May 1985.

For the revised RASA model, the difference between simulated and observed water levels (residuals) had a root mean square of 12.17 feet (ft). For the revised Glynn model, water-level residuals were generally less than 5 ft, with scattered residuals greater than 10 ft.

The simulated water budget for May 1985 was unchanged between the original and revised RASA models and was only slightly changed between the original and revised Glynn models. Differences in flow rates for the Glynn model were limited to small changes in vertical leakage between layers, with no change in lateral flow across model boundaries. Although the net difference in flows varied only slightly, the areal distribution of vertical leakage may have shifted as a result of changes to the leakance arrays.

The Savannah and revised RASA and Glynn models were used to predict the effects that hypothetical changes in the distribution and amount of ground-water withdrawal might have on the ground-water levels and flow rates in the Floridan aquifer system. The scenarios were developed by the Georgia Department of Natural Resources, Environmental Protection Division and the Chatham County-Savannah Metropolitan Planning Commission to evaluate water-management alternatives in coastal Georgia. Scenarios were grouped on the basis of pumpage location—entire 24-county area, central subarea, Glynn-Wayne-Camden County subarea, and Savannah-Hilton Head Island subarea.

The scenarios simulated hypothetical pumpage changes that ranged from about 82 million gallons per day (Mgal/d) lower to about 438 Mgal/d higher than May 1985 pumpage (308 Mgal/d) simulated by the models. In general, for those scenarios that simulated decreased pumpage, the water level at both Brunswick and Hilton Head Island rose, decreasing the hydraulic gradient and saltwater contamination. Conversely, in response to increased pumpage, the water level at each location declined, increasing the hydraulic gradient and saltwater contamination.

Profiles of simulated hydraulic head extending from the point of seawater encroachment on the north end of Hilton Head Island to the center of the cone of depression at Savannah indicate that reductions in pumpage in Chatham County flatten the simulated hydraulic gradient from the north end of Hilton Head Island toward the cone of depression at Savannah.With simulated pumpage reductions of 65 Mgal/d or more, the simulated hydraulic gradient between Hilton Head Island and Savannah becomes reversed and has a component of flow in a northeasterly direction from Chatham County toward Hilton Head Island. With cessation of pumpage in Chatham County, the hydraulic gradient along the profile is toward Hilton Head Island, and probably is similar to pre-pumping conditions that existed in the area.

The potential for additional development of water from the Upper Floridan aquifer is constrained by water-level decline at known locations of saltwater

contamination—Brunswick and the northern end of Hilton Head Island. Generally, the farther that pumping is located away from Brunswick and Hilton Head Island, the smaller the effect on the ground-water level in the Upper Floridan aquifer and on saltwater contamination.

The potential for the Upper Floridan aquifer to supply additional ground-water withdrawal in coastal Georgia without producing a detectable drawdown response at Brunswick or Hilton Head Island may be affected by two hydrologic boundaries—the Gulf Trough, separating the northern and central subareas; and the postulated “Satilla Line”, separating the central and southern subareas. Additional withdrawal may be possible in areas north of the Gulf Trough and south of the “Satilla Line”, without producing a detectable drawdown response at Brunswick or Hilton Head Island.

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APPENDIX A—DIFFERENCE IN OBSERVED AND SIMULATED WATER LEVELS FOR THE UPPER FLORIDAN AQUIFER (MODEL LAYER A2), MAY 1985, FOR THE REVISED REGIONAL AQUIFER-SYSTEM (RASA) MODEL

Appendix A. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for the revised Regional Aquifer-System Analysis (RASA) model

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
2	30	86.2	87.9	1.7	19F011, 19F049
2	31	85.2	77.6	-7.6	19F034, 19F046, 19F051
2	32	73.1	72.4	-0.7	19G011
2	35	66.6	70.9	4.2	18H023
3	30	77.8	75.3	-2.5	20F007, 20F009
3	31	61.1	71.9	10.8	20F006
3	32	70.5	69.7	-0.8	19G014
3	33	68.0	69.4	1.4	19G002
3	38	165.9	148.8	-17.0	18K003
3	40	216.2	203.3	-13.0	18K049
3	41	218.9	214.1	-4.8	17K052
3	42	228.6	220.1	-8.4	17L024
4	31	70.2	67.2	-3.0	20G003, 20G013
4	44	220.2	235.1	15.0	17M009
5	41	208.3	214.0	5.7	18L014
5	45	220.5	231.5	11.0	17N001
5	48	244.3	252.0	7.7	17P001, 17P003
6	40	209.4	197.9	-11.5	19L001
6	48	210.4	233.6	23.2	18P001
7	40	183.7	190.6	6.9	20L005
7	41	198.9	203.5	4.7	20L003
7	50	229.0	231.9	2.9	18Q001
7	51	251.8	241.5	-10.4	17R009, 17R010
7	53	275.7	270.5	-5.2	17R007, 17R011
8	40	197.4	176.8	-20.6	20L002
8	48	203.1	197.6	-5.4	18Q002
8	50	190.5	211.7	21.3	18R001
8	54	294.5	271.7	-22.8	17S004
9	38	104.4	97.7	-6.6	21K001
9	46	163.2	167.2	4.0	19P007
9	47	172.8	171.4	-1.4	19P004, 19P005, 19P006
9	48	197.0	179.7	-17.3	19Q001
9	50	205.4	191.7	-13.7	19R001
9	51	213.1	205.7	-7.4	19R003
9	53	269.3	236.8	-32.5	18S008
10	29	53.2	59.6	6.4	23G002

Appendix A. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for the revised Regional Aquifer-System Analysis (RASA) model—Continued

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
10	50	207.1	201.0	-6.1	19R002
11	37	53.9	62.3	8.5	23K001
11	40	142.4	129.7	-12.7	22M003
11	45	150.0	161.5	11.5	21P001
12	37	51.6	58.9	7.3	23L007
12	43	158.5	147.3	-11.2	22N001
12	47	174.0	176.2	2.3	21Q003, 21Q004
13	29	53.4	55.0	1.6	25G001
13	31	57.5	55.5	-2.0	24H001
14	23	46.5	48.8	2.3	27E003, 27E004
14	41	95.6	84.8	-10.8	23N001
14	56	257.6	299.8	42.2	20U008
15	37	46.9	56.2	9.3	24L003
15	38	56.5	57.9	1.4	24L004
15	46	155.8	163.9	8.1	22Q001, 22Q003
15	51	209.0	216.7	7.8	21S002
15	53	216.9	238.2	21.3	21T001, 21T002, 21T005
16	21	43.9	46.3	2.4	28D001
16	30	48.8	50.2	1.4	26H002
16	49	200.6	189.5	-11.1	22R001
16	52	207.0	219.1	12.1	22T001
16	53	166.6	228.2	61.6	22T004, 22T005
16	55	230.1	249.2	19.1	21U006
17	30	46.5	48.8	2.3	27H001
17	36	50.0	52.2	2.2	26L004
17	37	51.1	53.5	2.4	26M003
17	47	140.7	163.8	23.1	23R001
18	25	50.6	45.5	-5.1	29F001
18	42	64.2	75.2	11.0	25P001
18	43	124.1	99.2	-24.9	25P002
18	49	159.2	167.9	8.7	23S002
18	54	219.0	210.1	-8.9	23U008
18	55	209.0	220.2	11.2	22U003
19	43	112.9	89.4	-23.5	25Q003
19	55	232.4	231.4	-1.0	23V001
20	22	40.3	41.4	1.1	30E007

Appendix A. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for the revised Regional Aquifer-System Analysis (RASA) model—Continued

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
20	42	66.3	68.3	2.0	26P001
20	46	125.3	130.0	4.7	25R001
20	47	131.6	142.6	11.1	25R003
20	48	127.0	152.3	25.3	25S002
20	49	139.5	161.6	22.2	24S001
20	51	169.5	186.5	17.0	24T002
21	23	42.0	40.2	-1.8	30F004
21	31	48.3	41.6	-6.7	28K001
21	43	65.7	80.1	14.4	26Q002
21	44	117.6	98.2	-19.5	26Q001
21	48	134.6	152.3	17.8	25S001, 25S003
21	53	204.5	216.7	12.2	24U001
22	22	41.0	38.5	-2.5	31F022
22	23	36.3	38.6	2.3	31F017
22	27	38.1	39.2	1.1	30H003, 30H005
22	43	99.2	74.8	-24.3	27Q003, 27Q004
22	46	126.3	119.1	-7.2	26R002
22	49	135.0	165.1	30.1	25S004
22	51	169.6	191.2	21.6	25T004
22	52	199.9	205.1	5.2	25U003
22	56	238.0	256.7	18.7	24V003
22	58	270.0	284.9	14.9	24W001
23	32	41.1	35.0	-6.1	29K002
23	34	26.7	35.4	8.8	29L005
23	36	47.8	37.9	-9.9	29M002
23	43	66.8	68.0	1.2	27Q002, 27Q005
23	44	88.3	87.8	-0.4	27R004
23	45	99.1	105.5	6.4	27R005, 27R007
23	46	125.6	119.4	-6.1	26R003, 27R006
23	50	173.9	179.3	5.4	26T001
24	18	20.7	21.5	0.8	33E007
24	22	39.5	36.1	-3.4	32F008
24	24	34.8	35.2	0.4	32G004
24	32	31.1	29.9	-1.2	30L011
24	35	39.6	30.4	-9.1	29M001
24	42	52.0	50.5	-1.5	28Q003

Appendix A. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for the revised Regional Aquifer-System Analysis (RASA) model—Continued

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
24	46	114.8	115.9	1.1	27R003
24	47	121.0	133.7	12.7	27S002
24	54	235.0	235.7	0.8	25V001
24	61	329.8	324.3	-5.5	24Y016
25	17	9.0	2.3	-6.6	33D068
25	18	-15.4	-1.1	14.4	33D061, 33D022, 33D058, 33D048
25	24	37.3	32.5	-4.9	32G015
25	33	24.6	20.7	-3.9	30L013, 30L014
25	34	29.7	18.2	-11.5	30L012, 30M011
25	36	32.0	25.1	-7.0	29M004, 30M007, 30N002
25	38	38.4	31.8	-6.6	29N003
25	42	44.6	47.3	2.7	29Q001
25	45	80.7	88.0	7.3	28R001
25	47	125.0	129.7	4.7	27S001
25	58	321.2	285.6	-35.6	25X015
26	17	21.6	2.4	-19.2	34E001
26	18	28.1	16.0	-12.1	34E010, 34E003, 34E014
26	20	37.6	31.9	-5.6	33F002, 33F017
26	21	33.2	33.2	-0.1	33F003
26	24	28.9	28.3	-0.6	33H177
26	27	30.3	23.4	-7.0	32J003
26	34	9.7	4.0	-5.6	30M003, 30M005, 31M006, 31M016, 31M022, 31M024, 31M033, 31M034,
26	44	42.1	64.3	22.2	29R001
26	46	113.7	107.1	-6.6	28S004
26	52	196.2	200.7	4.5	27U005
26	56	221.3	251.4	30.1	26W002
26	57	227.1	260.7	33.7	26X015
26	58	283.1	277.2	-5.9	26X005
27	19	33.1	28.9	-4.2	34E013, 34E012, 34E002, 34F014
27	21	31.8	31.8	0.1	33F004
27	23	35.0	27.8	-7.2	33G005
27	24	19.0	20.4	1.3	33G003, 33G008, 33G002, 33H139, 33H018, 33H013, 33H164, 33H209
27	25	18.5	15.3	-3.2	33H035, 33H038
27	26	24.5	16.8	-7.7	33H193
27	29	21.6	18.8	-2.8	32K014
27	33	-9.7	6.6	16.3	31M032

Appendix A. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for the revised Regional Aquifer-System Analysis (RASA) model—Continued

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
27	34	-17.0	-3.6	13.3	31M009, 31M010, 31M011, 31M012, 31M013, 31M014, 31M030, 31M031
27	47	124.7	124.8	0.1	28S003
27	49	139.0	155.0	15.9	28T001
27	55	215.5	230.6	15.1	27W001
27	56	213.0	235.4	22.4	26W003
28	21	39.8	30.6	-9.2	34G009
28	22	33.6	28.5	-5.1	34G004
28	23	18.7	22.9	4.3	34G002
28	24	-3.0	7.8	10.8	33H120, 33H211, 34H392
28	25	4.2	0.8	-3.4	33H079, 33H100, 33H105, 33H141, 33H174, 33H180, 33H190
28	26	15.5	10.8	-4.7	33H052, 33H149, 33J028, 33J043
28	27	18.9	13.9	-5.0	33J026
28	31	20.0	12.9	-7.1	32L004
28	34	13.2	5.3	-7.9	32M001, 32M002
28	40	28.9	30.6	1.6	30P003
28	47	125.2	121.7	-3.4	29T010
28	50	161.4	163.2	1.8	28U003, 28U004
28	51	165.9	175.3	9.4	28U002
29	23	30.5	20.6	-10.0	34G020
29	24	6.0	13.1	7.0	34H347, 34H062, 34H358, 34H370
29	25	10.2	8.7	-1.5	34H012, 34H357, 34H410
29	26	13.5	11.2	-2.3	33J034, 34J051
29	29	12.7	13.5	0.8	33K027
29	30	17.3	12.6	-4.7	33L027
29	33	13.6	8.2	-5.4	32M009
29	41	20.9	33.4	12.5	31Q002
29	42	26.8	39.1	12.3	30R001
29	43	36.7	45.4	8.7	30R005
29	49	133.4	145.0	11.6	29T009
29	51	162.0	169.8	7.8	29V001
29	55	207.2	203.0	-4.2	28W002
30	23	21.1	19.8	-1.3	35H037
30	24	14.4	13.3	-1.1	34H381, 35H044, 34H383
30	25	12.7	11.6	-1.1	34H328
30	26	14.1	11.9	-2.2	34J029
30	28	13.4	12.3	-1.1	34K073, 34K081

Appendix A. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for the revised Regional Aquifer-System Analysis (RASA) model—Continued

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
30	29	13.3	11.8	-1.5	33K019
30	30	11.4	10.8	-0.6	33L010
30	33	10.6	7.2	-3.4	33M004
30	36	11.0	10.9	-0.1	32N013, 33N085, 33N084
30	42	37.3	37.3	0.0	31R001
30	43	46.0	44.6	-1.4	30R004
30	45	78.0	75.9	-2.0	30S001
31	25	12.8	12.8	0.1	35J004
31	27	9.7	11.7	2.0	34K095
31	28	11.8	11.2	-0.6	34K083, 34K084
31	29	14.1	10.2	-3.9	34L048
31	30	13.9	8.8	-5.0	34L061
31	32	4.6	5.7	1.2	34M070
31	44	41.9	55.8	13.9	31S008
31	45	48.7	74.4	25.7	31S007
32	28	7.1	9.8	2.6	35K069
32	31	5.2	4.4	-0.8	34L060, 34M076
32	33	0.3	1.2	0.9	34M056
32	35	0.2	3.0	2.9	34N091
32	46	87.0	92.4	5.4	31T007, 31T010
33	30	7.4	4.0	-3.4	35L068
33	32	0.6	-1.0	-1.6	34M075
33	33	-6.7	-4.6	2.2	34M049, 34M052
33	37	6.0	3.6	-2.3	33P019
33	46	72.3	89.9	17.7	31T011
33	47	92.2	107.7	15.6	31T023, 32T003
33	50	125.5	133.0	7.6	31V007, 31V018
34	45	57.9	69.8	11.9	32T013
34	57	239.2	226.8	-12.5	30Y001
35	36	-12.5	-11.5	1.1	35P099
35	37	-9.7	-9.9	-0.2	35P078
35	40	8.7	7.9	-0.8	34R039
35	49	117.1	120.0	2.9	32V007
35	51	137.8	134.6	-3.2	32W001
35	52	150.0	144.9	-5.1	31W002
35	53	151.8	162.2	10.4	31W014
36	36	-16.4	-19.8	-3.4	35P100

Appendix A. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for the revised Regional Aquifer-System Analysis (RASA) model—Continued

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
36	46	84.7	73.8	-10.9	33U023
36	51	100.2	126.5	26.3	32W002, 32W014, 32W070
36	52	102.1	135.9	33.8	32W006
36	53	169.6	148.3	-21.4	31X001
37	34	-20.3	-20.2	0.0	36P091, 36P093
37	36	-30.0	-30.5	-0.5	35P085, 36P087, 36Q020
37	37	-30.3	-34.1	-3.8	35Q043, 36Q019
37	39	-8.5	-19.7	-11.2	35R025, 35R026
37	46	62.4	68.4	6.0	34U006
37	47	72.6	84.3	11.7	33U021
37	48	88.3	95.1	6.8	33V020, 33V005
37	49	103.6	101.9	-1.7	33V021
37	52	97.9	112.8	14.9	32W065
37	53	126.1	124.5	-1.6	32X035
37	56	177.4	174.9	-2.4	32Y001
38	35	-40.4	-33.7	6.6	36P094, 36P090
38	36	-52.9	-47.8	5.2	36Q287
38	38	-56.4	-50.0	6.4	36Q013, 36Q014, 36Q283, 36Q300
38	45	46.9	45.6	-1.3	34U008
38	49	84.5	86.5	2.0	33V011
38	51	82.2	91.8	9.6	33W001
38	53	103.1	115.0	11.9	33X013
38	54	123.2	128.6	5.4	33X022
39	34	-35.0	-28.5	6.5	37P086, 37P087
39	35	-50.7	-39.2	11.5	37P005, 37P114, 37P115, 37P083, 38P001, 38P001, 38P012
39	36	-85.0	-62.7	22.3	37Q030, 37Q031
39	37	-101.8	-95.3	6.6	36Q008, 37Q012, 37Q090, 37Q162
39	38	-100.6	-65.9	34.7	36Q005, 36Q007
39	40	-11.6	-20.7	-9.1	36S004
39	41	-7.6	-5.6	2.0	36S022
40	36	-72.7	-53.9	18.8	37Q038, 37Q040, 37Q043, 37Q160
40	37	-84.2	-64.5	19.7	37Q017, 37Q066
41	35	-41.3	-31.3	10.0	38Q190
42	34	-31.8	-20.6	11.2	39P001
42	35	-23.6	-24.6	-1.0	38Q001, 38Q002, 39Q001, 39Q003

[1]For further information on wells used for observation, see the U.S. Geological Survey National Water Information System, Ground-Water Site Inventory System

[2]Average water level of wells located within model cell.

APPENDIX B—DIFFERENCE IN OBSERVED AND SIMULATED WATER LEVELS FOR THE UPPER FLORIDAN AQUIFER (MODEL LAYER A2), MAY 1985, FOR REVISED GLYNN COUNTY MODEL

Appendix B. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for revised Glynn model

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
1	9	26.7	35.2	8.6	29L005
1	15	30.6	24.6	-6.0	30L012
1	17	28.9	19.4	-9.5	30M011
1	20	19.3	11.0	-8.4	30M003
1	21	23.4	9.6	-13.8	30M005
1	24	16.1	4.2	-11.9	31M034
1	25	11.0	1.9	-9.1	31M033
1	26	3.3	-0.7	-4.0	31M022, 31M024
1	27	0.5	-3.6	-4.0	31M016, 31M006
1	28	-18.2	-4.2	14.0	31M030, 31M014, 31M009
1	29	-16.3	-2.5	13.8	31M031, 31M013, 31M012, 31M011, 31M010
1	51	13.2	12.1	-1.2	32M001, 32M002
1	94	-20.3	-17.8	2.5	36P091, 36P093
2	17	22.7	21.6	-1.0	30L013
2	19	26.6	17.3	-9.3	30L014
2	29	-9.7	9.1	18.8	31M032
2	57	13.6	13.0	-0.5	32M009
2	84	0.3	4.7	4.4	34M056
2	86	-2.2	0.9	3.1	34M049
2	87	-11.2	-2.6	8.6	34M052
3	10	31.1	33.8	2.8	30L011
3	70	10.6	12.8	2.1	33M004
4	8	41.1	37.0	-4.1	29K002
4	80	4.6	9.7	5.2	34M070
4	86	0.6	4.9	4.3	34M075
5	3	48.3	44.8	-3.5	28K001
5	84	4.0	7.7	3.7	34M076
6	42	20.0	17.8	-2.2	32L004
6	83	6.4	9.4	3.0	34L060
7	61	17.3	16.4	-0.9	33L027
7	72	11.4	14.6	3.2	33L010
8	79	13.9	12.9	-1.0	34L061
8	87	7.4	7.9	0.5	35L068
10	38	21.6	20.3	-1.3	32K014
10	81	14.1	12.9	-1.3	34L048
12	60	12.7	17.6	4.8	33K027
13	70	13.3	16.3	3.0	33K019
14	78	13.8	14.7	0.9	34K083
14	84	7.1	12.5	5.4	35K069
16	72	11.3	16.0	4.7	34K073
17	73	15.5	15.8	0.3	34K081
18	79	9.8	14.8	5.0	34K084

Appendix B. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for revised Glynn model—Continued

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
20	5	36.5	41.9	5.5	30H003
20	6	39.7	40.8	1.1	30H005
21	26	30.3	24.9	-5.5	32J003
22	77	9.7	15.2	5.5	34K095
26	47	18.9	17.4	-1.6	33J026
28	68	14.1	15.5	1.5	34J029
31	51	19.5	15.7	-3.8	33J043
33	56	14.8	14.9	0.1	33J034
33	61	12.2	14.9	2.6	34J051
34	45	17.0	15.5	-1.5	33J028
35	32	24.5	20.3	-4.2	33H193
38	51	12.9	13.1	0.2	33H149
39	48	12.8	12.8	-0.1	33H052
40	53	11.3	12.1	0.8	33H174
42	39	17.4	13.6	-3.7	33H038
44	60	10.1	11.8	1.7	34H012
44	78	12.8	15.7	3.0	35J004
45	49	9.7	9.0	-0.7	33H190
47	50	10.0	7.6	-2.4	33H079
48	38	16.4	12.1	-4.3	33H035
48	64	11.4	12.7	1.2	34H357
52	30	21.7	21.5	-0.1	33H179
53	42	6.8	4.2	-2.5	33H141
53	48	-2.8	-1.1	1.7	33H105
53	51	-1.4	2.8	4.1	33H100
53	60	9.2	10.3	1.1	34H410
55	52	-4.2	2.4	6.6	33H180
55	71	12.7	15.0	2.2	34H328
56	17	37.3	33.8	-3.5	32G015
56	46	-15.2	-8.1	7.1	33H211
56	49	-8.3	-1.3	7.0	33H120
56	55	1.8	4.9	3.1	34H392
57	47	-36.5	-3.7	32.9	33H214, 33H215
57	48	-9.7	-2.1	7.6	33H216, 33H217, 33H218, 33H130
57	49	-14.7	-0.8	13.8	33H154
58	33	19.0	19.4	0.4	33H164
58	46	-15.7	-2.7	12.9	33H212, 33H213
58	51	-3.4	1.1	4.5	34H469
59	38	12.2	12.4	0.3	33H209
59	49	-1.0	0.6	1.6	33H127, 33H133
59	52	-0.5	1.4	2.0	34H424
59	53	1.5	1.5	0.0	34H412

Appendix B. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for revised Glynn model—Continued

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
60	44	0.3	3.7	3.5	33H207
60	50	-2.7	1.8	4.5	34H374
60	54	0.1	0.9	0.8	34H425
61	27	28.9	27.3	-1.6	33H177
61	50	-0.9	2.9	3.8	34H401, 34H402
61	54	-2.9	2.4	5.3	34H074
61	56	-3.4	6.1	9.5	34H062
61	58	9.5	9.0	-0.5	34H370
61	71	13.4	16.1	2.8	34H383
62	35	19.5	18.7	-0.8	33H013
62	49	4.5	4.4	0.0	34H354, 34H355
62	50	-4.8	4.4	9.2	34H400
62	51	-5.0	4.2	9.3	34H373
62	54	-4.9	4.6	9.5	34H413
62	55	-0.3	5.6	5.9	34H079
63	50	1.3	5.8	4.5	34H128
63	53	1.8	5.6	3.8	34H334, 34H344
63	56	5.2	8.2	3.0	34H347
64	38	14.5	16.2	1.7	33H018
64	50	2.5	7.3	4.8	34H125
65	13	34.8	36.8	2.0	32G004
65	35	18.9	20.2	1.3	33H139
65	48	2.9	9.8	6.9	34H117
65	49	2.9	9.3	6.4	34H345
65	53	4.3	9.1	4.8	34H085
66	49	5.5	11.0	5.5	34H112
66	65	12.9	16.5	3.6	34H358
67	48	9.7	12.7	3.0	34H371, 34H391, 34H403
67	50	4.7	12.1	7.4	34H372
68	36	21.4	21.4	-0.1	33G002
68	73	15.8	18.4	2.6	35H044
69	38	22.2	20.6	-1.6	33G008
69	48	11.8	15.1	3.3	34H097
69	69	13.9	18.4	4.5	34H381
70	36	24.7	24.4	-0.3	33G003
72	50	18.7	18.9	0.3	34G002
75	69	21.1	21.7	0.7	35H037
76	6	36.3	40.4	4.1	31F017
79	4	42.0	41.9	-0.1	30F004
82	32	35.0	33.2	-1.9	33G005
83	58	30.5	27.5	-3.0	34G020
85	6	41.0	40.3	-0.7	31F022

Appendix B. Difference in observed and simulated water levels for the Upper Floridan aquifer (model layer A2), May 1985, for revised Glynn model—Continued

Row	Column	Water level, in feet above (+) or below (-) sea level		Residual (feet)	Well(s) used for observation[1]
		Observed[2]	Simulated		
85	10	39.5	38.7	-0.8	32F008
86	2	40.3	43.6	3.3	30E007
86	51	33.6	31.0	-2.6	34G004
92	51	39.8	33.0	-6.8	34G009
95	26	33.2	35.8	2.6	33F003
97	29	31.8	35.1	3.4	33F004
98	27	37.6	35.1	-2.4	33F002, 33F017
102	35	36.0	33.3	-2.7	34F014
103	28	33.4	31.8	-1.6	34E012
103	30	30.4	32.0	1.6	34E002
104	31	32.4	30.6	-1.8	34E013
105	27	34.1	27.8	-6.3	34E014
106	13	20.7	7.4	-13.3	33E007
106	15	-69.5	-4.1	65.4	33D061, 33D022
106	16	-15.4	-10.9	4.6	33D058, 33D048
106	24	23.6	20.6	-3.0	34E010
106	25	26.5	21.6	-4.9	34E003
107	14	9.0	5.9	-3.1	33D068
107	23	21.6	4.3	-17.3	34E001

[1]For further information on wells used for observation, see the U.S. Geological Survey National Water Information System, Ground-Water Site Inventory System.

[2]Average water level of wells located within model cell.