Water-Supply Potential of Major Streams and the Upper Floridan Aquifer in the Vicinity of Savannah, Georgia

Water-Supply Paper 2411
Prepared in cooperation with
the Chatham County-Savannah Metropolitan
Planning Commission

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

USGS
science for a changing world

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that may be listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" may be no longer available.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Information Services
Box 25286, Federal Center, Denver, CO 80225

Subscriptions to Preliminary Determination of Epicenters can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Information Services
Box 25286, Federal Center, Denver, CO 80225

OVER THE COUNTER

Books and Maps

Books and maps of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey Earth Science Information Centers (ESIC's), all of which are authorized agents of the Superintendent of Documents:

- **ANCHORAGE, Alaska**—Rm. 101, 4230 University Dr.
- **LAKEWOOD, Colorado**—Federal Center, Bldg. 810
- **MENLO PARK, California**—Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**—USGS National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**—Federal Bldg., Rm. 8105, 125 South State St.
- **SPOKANE, Washington**—U.S. Post Office Bldg., Rm. 135, West 904 Riverside Ave.
- **WASHINGTON, D.C.**—Main Interior Bldg., Rm. 2650, 18th and C Sts., NW.

Maps Only

Maps may be purchased over the counter at the following U.S. Geological Survey office:

- **ROLLA, Missouri**—1400 Independence Rd.

Water-Supply Potential of Major Streams and the Upper Floridan Aquifer in the Vicinity of Savannah, Georgia

By REGGINA GARZA and RICHARD E. KRAUSE

Prepared in cooperation with the Chatham County–Savannah Metropolitan
Planning Commission

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2411

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For sale by
U.S. Geological Survey
Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Garza, Reggina

Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia / by Reggina Garza and Richard E. Krause.
p. cm. -- (U.S. Geological Survey water-supply paper 2411)
"Prepared in cooperation with the Chatham County-Savannah Metropolitan Planning Commission."
Includes bibliographical references.
Supt. of Docs. no.: I 19.13:2411
1. Hydrology--Georgia--Savannah Region. 2. Water-supply--Georgia--Savannah Region. 3. Floridan Aquifer. I. Krause, Richard E. II. Chatham County-Savannah Metropolitan Planning Commisision. III. Title. IV. Series.
GB705.G4G37 1996
553.7'09758'724--dc21 96-39311
CIP

ISBN 0-607-86211-4

CONTENTS

PLATES

[Plates are in separate volume]

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS AND ABBREVIATIONS

CONVERSION FACTORS

Multiply inch-pound units	by	to obtain metric units
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
	Flow	
inch per year (in/yr)	25.4	millimeter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
	6.309×10^{-5}	cubic meter per second
gallon per day (gal/d)	0.003785	cubic meter per day
	Transmissivity	
foot squared per day[1] (ft^2/d)	0.0929	meter squared per day
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
	Leakance	
foot per day per foot [(ft/d/ft)]	1.000	meter per day per meter

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

VERTICAL DATUM

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

ACRONYMS AND ABBREVIATIONS

COE	U.S. Army Corps of Engineers
EPA	U.S. Environmental Protection Agency
EPD	Georgia Department of Natural Resources Environmental Protection Division
GWUDS	Georgia Water-Use Data System U.S. Geological Survey, Atlanta, Ga.
NASQAN	National Stream-Quality Accounting Network
MCL	Maximum Contaminant Level
MPC	Chatham County–Savannah Metropolitan Planning Commission
RASA	Regional Aquifer-System Analysis
RMSE	Root Mean Square Error
SCWRC	South Carolina Water Resources Commission
SD	Standard Deviation
SMCL	Secondary Maximum Contaminant Level
SUTRA	Saturated-Unsaturated Transport Model
USGS	U.S. Geological Survey
7Q10	Minimum average discharge for seven consecutive days for 10-year recurrence interval

Water-Supply Potential of Major Streams and the Upper Floridan Aquifer in the Vicinity of Savannah, Georgia

By Reggina Garza *and* Richard E. Krause

Abstract

Long-term pumping from the Upper Floridan aquifer in the Savannah, Georgia, area has lowered ground-water levels, resulting in increased salinity of ground water by seawater encroachment at Hilton Head Island, S.C., and by saltwater intrusion at Brunswick, Ga. Increased pumpage could cause further salinization of the ground-water resources.

The Savannah and Ogeechee Rivers can be considered potential water-supply sources for the Savannah area, on the basis of historic streamflow records and water-quality constituents and properties examined. Analyses of stream-discharge data indicate that the minimum average discharge for seven consecutive days for 10-year recurrence interval (7Q10) was 5,460 cubic feet per second (ft^3/s) at Savannah River near Clyo, Ga., and 192 ft^3/s at Ogeechee River near Eden, Ga. For example, 90 percent of the time, flows in excess of the 7Q10 discharges are about 900 and 200 ft^3/s at these respective localities. However, Georgia Department of Natural Resources, Environmental Protection Division, imposes a nondepletable flow criterion; thus, the actual quantity of water available for withdrawal probably would be less than flows in excess of minimum flow criteria, such as the 7Q10.

A ground-water flow model was developed and used in conjunction with other previously calibrated models in the coastal area to simulate the effects of additional pumping on water levels near sites of seawater encroachment at Hilton Head Island and saltwater intrusion at Brunswick. Based on model simulations and the constraint of preventing water-level declines at locations of encroachment and intrusion, the potential of the Upper Floridan aquifer to supply additional water in the Savannah area is limited under present (1985) hydrologic conditions. The water-supply potential ranges from less than 1 million gallons per day (Mgal/d) in Liberty, McIntosh, most of Bryan, and southern Chatham Counties, Ga., and in southern Beaufort County, S.C., to more than 5 Mgal/d in northern Jasper and northern Beaufort Counties, S.C. Because of the limited water-supply potential, hypothetical alternatives involving redistributions, redistributions and small increases, and decreases in pumpage were simulated to determine the effects on water levels. These simulations indicate that reductions and redistributions of pumping would not adversely affect water levels at locations of encroachment and intrusion. Increased pumping would cause water-level declines, which might increase salinization of the freshwater aquifer.

INTRODUCTION

Increasing water demands in the Savannah, Ga., area have prompted water-resource managers to evaluate the potential for obtaining additional water. The Upper Floridan aquifer is the primary source of freshwater in the coastal area of Georgia. Development of the aquifer as a water supply began in about 1880, and by 1989, water was being pumped from the aquifer at a rate of about 119 million gallons per day (Mgal/d) in the area. Pumping in the area of Savannah and in the adjacent coastal areas in Georgia and South Carolina has resulted in large, regional water-level declines and a reversal in the seaward hydraulic gradient that existed before development (Counts and Donsky, 1963, p. 55–59; Krause and Randolph, 1989, p. D42). The change in hydraulic gradients is causing lateral encroachment of seawater in the Upper Floridan aquifer at the north end of Hilton Head Island, S.C. (Smith, 1988, p. 41), and vertical intrusion of saltwater into the Upper and Lower Floridan aquifers in the Brunswick, Ga., area (Krause and Randolph, 1989, p. D42).

Concerns about future water-supply demands prompted the U.S. Geological Survey (USGS) and the Chatham County–Savannah Metropolitan Planning Commission (MPC) to undertake a cooperative study to evaluate surface-water and ground-water resources in the area (fig. 1). The assessment of surface-water availability was restricted to the Savannah and

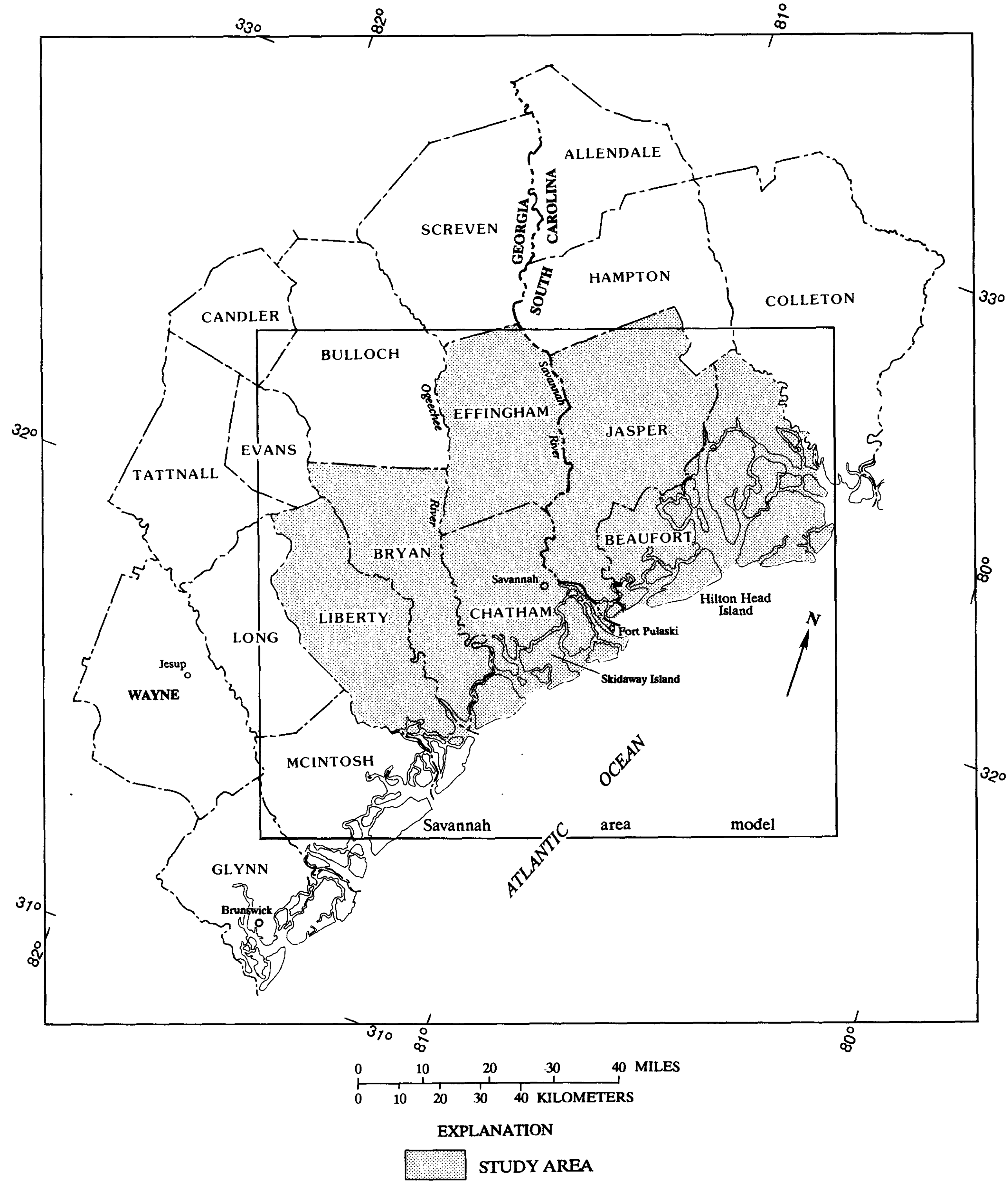


Figure 1.—Study area and areal extent of Savannah area model.

Ogeechee Rivers, because they are considered the only potential surface-water sources in the study area. The availability of ground water was evaluated by using ground-water flow models. Although ground-water flow models were previously developed for the coastal areas of Georgia and South Carolina, these models could not be used to meet the objectives of this study because of outdated hydrologic data, limitations on grid resolution and vertical discretization, or the limited areal extent of the models. Therefore, a model (referred to in this report as the "Savannah area model") was developed to overcome these limitations.

Purpose and Scope

This report describes the results of the evaluation of the water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia, and Hilton Head Island, South Carolina. The water-supply potential of the streams is constrained by the quantity of water available and the quality of the water at potential sites of withdrawal. The water-supply potential of the Upper Floridan aquifer is constrained by ground-water-level declines at known locations of seawater encroachment or saltwater intrusion caused by pumping, not by the availability of ground water or its quality at potential sites of withdrawal. The report has three major parts:

1. *An evaluation of flow and water-quality characteristics at selected gaging stations on the Savannah and Ogeechee Rivers.* The availability of surface water was estimated by determining the discharge that occurs a selected percentage of time in excess of the minimum average discharge for seven consecutive days for a 10-year recurrence interval (7Q10). Water-quality constituents and properties were evaluated on the basis of U.S. Environmental Protection Agency (EPA) "Primary and Secondary Drinking-Water Regulations" (U.S. Environmental Protection Agency, 1986).

2. *A description of the ground-water flow model developed and calibrated for 1985 conditions (the Savannah area model) using the finite-difference technique described by McDonald and Harbaugh (1988).* The Savannah area model was used in conjunction with a ground-water flow model developed for the Glynn County area (Randolph and Krause, 1990) to simulate water-level responses to pumping at various rates from the Upper Floridan aquifer.

3. *An assessment of the water-supply potential of the Upper Floridan aquifer and an evaluation of hypothetical pumping alternatives.* The models were used to determine maximum pumping rates that would not produce water-level decline at selected indicator sites in areas of known seawater encroachment and saltwater intrusion. Hypothetical alternatives involving redistributions, redistributions and small increases, and decreases in pumpage also were simulated to assess the effects of management alternatives on water levels.

Previous Investigations

The hydrogeology and water quality of the Floridan aquifer system have been studied extensively in the coastal area of Georgia and South Carolina. The most recent and comprehensive works on the hydrogeology of the Floridan aquifer system were presented by Clarke and others (1990), Krause and Randolph (1989), and Miller (1986). Studies that evaluated the hydrogeology of the Floridan aquifer system in the Chatham County area include those by Counts and Donsky (1963) and McCollum and Counts (1964); those for South Carolina include Hayes (1979), Hassen (1985), and Spigner and Ransom (1979). Ground-water flow models of the Floridan aquifer system in the study area were developed by Krause and Randolph (1989) and Randolph and others (1991). Ground-water flow models of the Upper Floridan aquifer were developed by Randolph and Krause (1984) and Smith (1988). The model developed by Randolph and Krause (1984) was used to simulate various alternatives for ground-water development as part of a U.S. Army Corps of Engineers (COE) study that evaluated overall water-supply potential for the metropolitan Savannah area (U.S. Army Corps of Engineers, 1984). Bush (1988) described the potential for saltwater encroachment into the Upper Floridan aquifer and simulated ground-water flow beneath the northeast end of Hilton Head Island and Port Royal Sound by using the Saturated-Unsaturated Transport (SUTRA) model developed by Voss (1984). Smith (1991) conducted a similar investigation using additional hydrologic data collected at Port Royal Sound (Burt and others, 1987).

The aforementioned studies by Krause and Randolph (1989) and Randolph and others (1991), and a third study conducted by Randolph and Krause (1990) in the Glynn County area south of the study area, are integral to this study, and are referenced extensively in this report. Descriptions of these studies are discussed in the following paragraphs and in the section "Simulation of the Ground-Water Flow System."

Krause and Randolph's (1989) regional study of the Floridan aquifer system in the eastern half of the Georgia Coastal Plain and adjacent parts of northeastern Florida and southern South Carolina was part of the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA). Objectives of that study were to describe the flow system before development and the changes that occurred as a result of development, describe the quality of water in the aquifer system and its relation to present-day stresses, and determine the potential for additional ground-water development. Because the evaluation of the aquifer system was regional in scope, the assessment of development potential did not address local ground-water-quality concerns in detail, such as those of saltwater intrusion in Brunswick and seawater encroachment at the north end of Hilton Head Island. As such, the potential for ground-water development in the coastal area estimated by Krause and Randolph (1989, fig. 20) was large.

Randolph and Krause (1990) also used simulation to investigate local ground-water flow and ground-water-quality conditions in the vicinity of Brunswick, Ga. The model developed for that study (Glynn County model) was telescoped from the RASA model. "Telescoped," as used in this report, means development of a model having a finer grid spacing than, and embedded within, another model. Therefore, the grid resolution of the Glynn County model was substantially greater than the resolution of the RASA model, thus facilitating the investigation of local flow conditions. The Glynn County model was used to evaluate the response of the aquifer to hypothetical changes in ground-water withdrawals from the Upper Floridan aquifer in the Brunswick area. The development potential of the Upper Floridan aquifer in the Brunswick area was not estimated.

A second subregional ground-water flow model developed for coastal Georgia and adjacent parts of northeastern Florida and southern South Carolina (Randolph and others, 1991) also was telescoped from the RASA model of Krause and Randolph (1989) in a manner similar to that described for the Glynn County model. This model (the coastal model) was used to estimate the ground-water development potential of the Upper Floridan aquifer in coastal Georgia. In the coastal model, the constraint to increased development of the aquifer was the provision of no change in ground-water levels in the areas of saltwater intrusion in Brunswick and seawater encroachment at the northern end of Hilton Head Island. Because of this constraint, estimated ground-water-development potential was less than that estimated by Krause and Randolph (1989).

Well and Surface-Water Station Numbering Systems

In this report, wells in Georgia are numbered using a system based on USGS 7 1/2-minute topographic maps. Topographic maps (quadrangles) in Georgia are assigned a number and letter designation beginning at the southwest corner of the State. Numbers increase eastward through 39, and letters advance alphabetically northward through "Z," then become double-letter designations "AA" through "PP." The letters "I," "O," "II," and "OO" are not used. Wells inventoried in each quadrangle are numbered sequentially beginning with "1." Thus, the second well inventoried in the Garden City quadrangle in Chatham County is designated 36Q002. In South Carolina, wells are identified by letters of the county in which the well is located, and sequentially numbered within the county. For example, well "BFT037" is the 37th well inventoried in Beaufort County.

Surface-water stations are identified by a numbering system used for all USGS reports and publications since October 1, 1950. The station-identification number is assigned according to downstream order, and gaps are left in the series of numbers to allow for new stations that may be established; hence, the numbers are not consecutive. The complete number of each station, such as 02198500, includes the two-digit part number "02" plus the downstream-order number "198500," which can be from 6 to 12 digits (Stokes and others, 1989, p. 8).

Acknowledgments

We thank the Georgia Department of Natural Resources, Environmental Protection Division; the South Carolina Water Resources Commission, and the U.S. Geological Survey, South Carolina District, for assistance, guidance, and cooperation during the course of the investigation. Maribeth Pernik, former-

ly of the U.S. Geological Survey, assisted in early phases of this investigation.

DESCRIPTION OF THE STUDY AREA

The study area lies entirely within the Coastal Plain physiographic province and covers an area of 3,300 square miles (mi^2) including the counties of Chatham, Effingham, Bryan, and Liberty in Georgia and Beaufort and Jasper in South Carolina (fig. 1). The Savannah area model encompasses nearly all the study area and also includes adjacent areas that might affect or be affected by the hydrologic system in the study area; total area within the model boundaries is about 6,700 mi^2. Average precipitation in the study area ranges from about 45 to 52 inches per year (in/yr); runoff ranges from about 10 to 12 in/yr; and average evapotranspiration ranges from about 33 to 35 in/yr (Krause and Randolph, 1989, figs. 4, 5, and 6).

Drainage Features

The two major rivers in the study area are the Savannah and the Ogeechee (fig. 2). The downstream reaches of the rivers are tidally influenced (Clarke and others, 1990, fig. 4). Land use in the river basins, which plays an important role in the quality of the water in the Savannah and Ogeechee Rivers, is a mix of forest, grazed woodland, cropland with pasture, and swampland. Substantial urban development also has taken place in the Savannah River basin.

The Savannah River meanders in a southeasterly direction, and forms the State line between Georgia and South Carolina from North Carolina to the Atlantic Ocean. The length of the Savannah River is approximately 312 miles (mi) from the headwaters to the mouth. The river is regulated by three dams operated by the U.S. Army Corps of Engineers. The dams impound Hartwell Lake, Richard B. Russell Lake, and J. Strom Thurmond Reservoir (formerly Clarks Hill Lake), forming a chain of reservoirs approximately 120 mi long (fig. 3). The Savannah River basin is long and relatively narrow, and has a longer axis in a northwest-southeast direction. The length and maximum width of the basin are about 250 mi and 70 mi, respectively. The total drainage area is approximately 10,580 mi^2; 180 mi^2 in North Carolina, 4,530 mi^2 in South Carolina, and 5,870 mi^2 in Georgia.

The Ogeechee River lies entirely within the State of Georgia, flows approximately 245 mi from its headwaters to the Atlantic Ocean, and is not regulated by dams. The flood plain of the river is largely swampland from just northwest of the study area near the town of Millen in Jenkins County to the Atlantic Ocean. The Ogeechee River drains an area of approximately 5,830 mi^2. The river basin is about 170 mi long and has a maximum width of about 50 mi.

Hydrogeologic Setting

The Savannah area is underlain by several thousand feet of consolidated sedimentary rocks and unconsolidated sediments that range in age from Late Cretaceous to Holocene (Miller, 1986, p. B14-B39). The rocks and sediments dip seaward and generally thicken in that direction. The principal hydrogeologic units in this area are, in descending order, the surficial aquifer, the upper confining unit, and the Floridan aquifer system (fig. 4).

The surficial aquifer consists of interbedded sand, clay, and limestone of Miocene and younger age. Water in the aquifer generally is under water-table conditions (Clarke and others, 1990, p. 9), and is recharged by rainfall. The surficial aquifer is used primarily for domestic lawn irrigation, and is the principal source of drinking water in some rural areas. On Skidaway Island, seasonal pumpage from the upper water-bearing zone of the surficial aquifer ranges from about 20,000 to 230,000 gallons per day (gal/d) for irrigation and ground-water heat pumps (Clarke and others, 1990, p. 21). Wells completed in the surficial aquifer on Skidaway Island yield as much as 40 gallons per minute (gal/min) but on the average are pumped at a rate of about 10 to 20 gal/min (Clarke and others, 1990).

The upper confining unit consists of clay and other clastic sediments of low to moderate permeability (Randolph and others, 1991, p. 20) and lies between the surficial aquifer and the Floridan aquifer system. Although the unit locally includes water-bearing zones (Krause and Randolph, 1989), for the purpose of this report, the unit is considered a confining unit. The thickness of the upper confining unit ranges from about 50 ft in northern Screven County, Ga., and in coastal South Carolina to about 400 ft in the southern part of the study area. The unit is thin or locally absent in sounds and estuaries in the vicinity

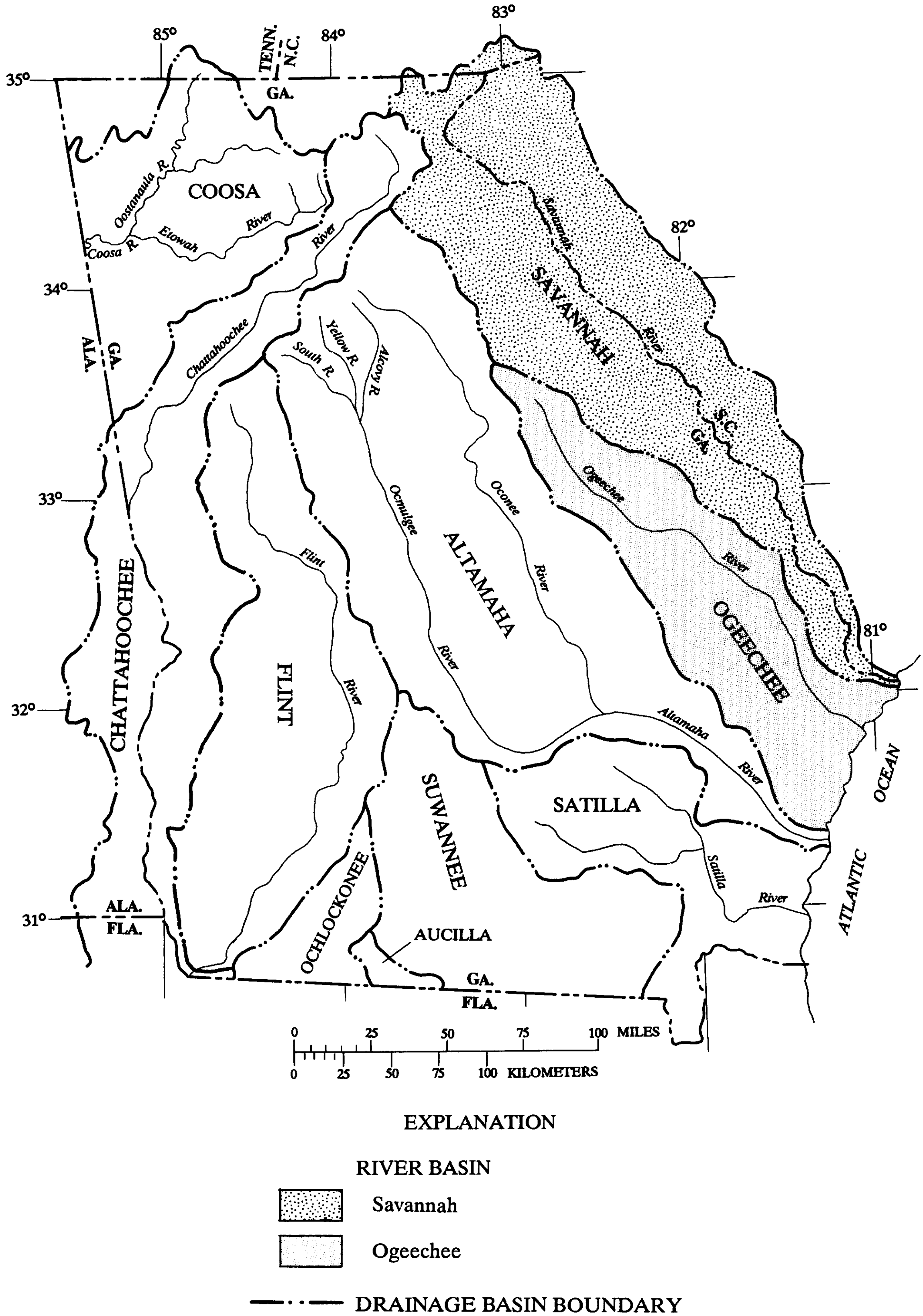


Figure 2.—Savannah and Ogeechee River basins and other major river basins in parts of Georgia and adjacent States. (The Ogeechee River basin includes the coastal drainage and associated waters from the Savannah River basin boundary to the Altamaha River basin boundary (Seaber and others, 1987)).

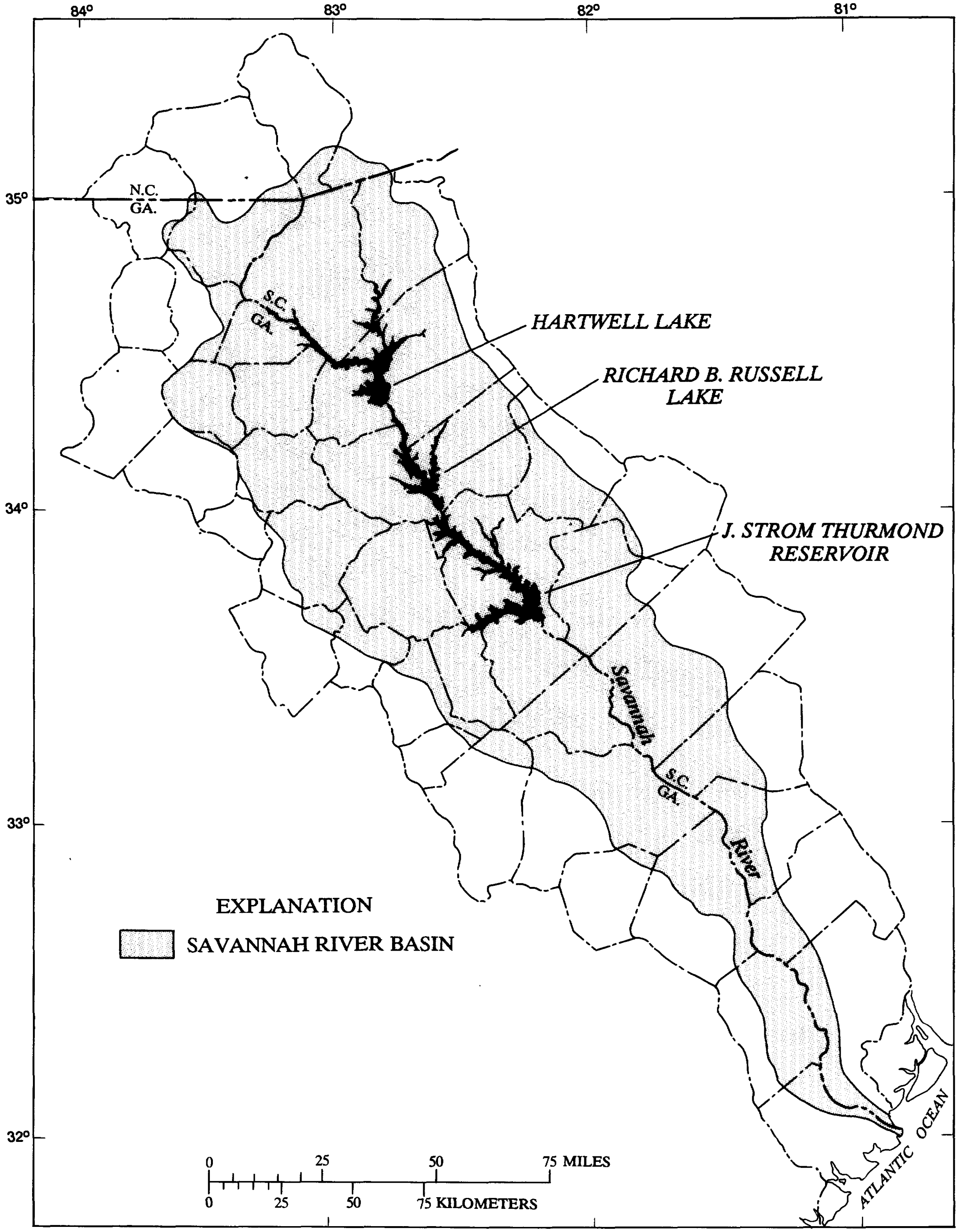


Figure 3.—Savannah River basin in parts of Georgia, South Carolina, and North Carolina.

of Hilton Head Island (Krause and Randolph, 1989, p. D21 and plate 6).

The Floridan aquifer system is composed of the Upper and Lower Floridan aquifers, and consists primarily of carbonate rocks of Oligocene and Eocene age. The Floridan aquifer system is the major source of water in the study area, except where it contains saltwater. Ground-water flow in the Upper Floridan aquifer is a major subject of this report and is discussed in detail in subsequent sections.

Water Use

Water use in the study area for 1989 was estimated to be about 232 Mgal/d, of which about 119 Mgal/d (51 percent) was supplied from ground-water sources, and about 113 Mgal/d (49 percent) was supplied from surface-water sources (table 1). Surface-water withdrawals discussed in this report do not include water withdrawn for thermoelectric plant cooling (about 450 Mgal/d in 1987), because most of that water is returned to the river (Fanning and others, 1991).

In South Carolina, Beaufort and Jasper Counties have been designated "Capacity Use Areas" by the South Carolina Water Resources Commission (Newcome, 1989). Ground-water users in these counties must obtain a permit to withdraw 100,000 gal/d or more (Newcome, 1989, p. 6). In Georgia, ground-water users must obtain a permit from the Georgia Department of Natural Resources, Environmental Protection Division, to withdraw 100,000 gal/d or more (Fanning and others, 1992).

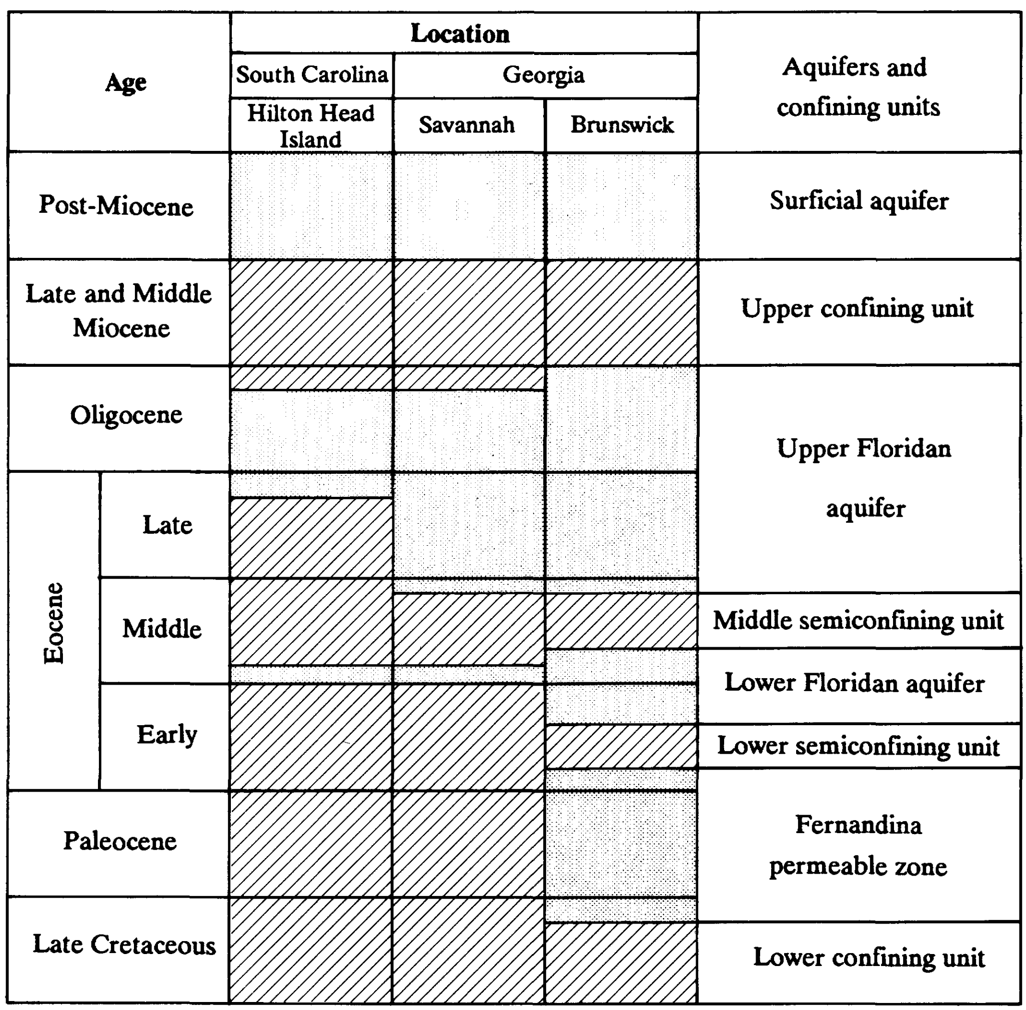


Figure 4.—Aquifers and confining units in the Hilton Head Island, S.C., and Savannah and Brunswick, Ga., areas (modified from Krause and Randolph, 1989).

Data obtained from the Georgia Water-Use Data system (GWUDS) indicate that the Savannah River is the source of supply for about 90 Mgal/d of water used in Chatham County. In Beaufort County, S.C., about 14 Mgal/d (table 1) is supplied by surface-water sources. The Savannah River accounts for less than 1 percent of the total water supplied in southern Beaufort and Jasper Counties (McCready, 1989, p. 3).

The nonpermitted water users in Bryan, Chatham, Effingham, and Liberty Counties during 1989 account for about 10 percent of the total ground water used (table 1) and less than 1 percent of the total surface water withdrawn. Estimates of nonpermitted water use in Georgia are based on population and include water used by mobile homes, parks, and commercial facilities, as well as water used for irrigation and domestic use (rural) (J.L. Fanning, U.S. Geological Survey, written commun., 1991). Estimates of nonpermitted water use in South Carolina were based on the percentages of total water use in Georgia.

WATER-SUPPLY POTENTIAL OF MAJOR STREAMS

Major streams in the study area, the Savannah and Ogeechee Rivers, were considered to be potential sources of additional freshwater to meet future water-supply demands. These rivers were evaluated in terms of discharge and quality of water.

In Georgia, the amendments to the Water Quality Control Act (Georgia Department of Natural Resources, 1990) establish procedures to obtain a permit to withdraw, divert, or impound surface water in the State. The amendments require that instream flow (minimum continuous flow reserved for surface water at or immediately downstream of the withdrawal, diversion, or impoundment) be maintained before a withdrawal permit can be issued. The Act sets instream flow criteria for new or modified permits that are based on either the minimum average discharge for seven consecutive days for a 10-year recurrence interval (7Q10) or the nondepletable flow. The nondepletable flow consists of the 7Q10 plus an additional flow needed to ensure the availability of water to downstream users. The additional flow is determined by the Georgia Department of Natural Resources, Environmental Protection Division, when a withdrawal permit is requested, and depends on the requirements of downstream users and other factors. The factors are particular to each stream and to the expected location of withdrawal from the stream.

In South Carolina, state law does not require permits for withdrawal of surface water. Instead, a policy requires that users report the use or diversion of 100,000 gallons of water per day or more on any day (South Carolina Water Resources Commission, 1982).

The water-supply potential of the streams analyzed in this report was determined on the basis of maintaining the 7Q10. Estimates of the 7Q10 are made using daily mean stream discharge data and differ according to the period of record used. The 7Q10 values used for this study were obtained by using standard statistical methods of the U.S. Geological Survey (Meeks, 1984).

Water Availability

The Savannah and Ogeechee Rivers were considered to be potential sources of additional freshwater supply in the study area. The analysis of surface-water availability included two sites, Savannah River near Clyo (station 02198500) and Ogeechee River near Eden (station 02202500) (fig. 5), where stream-discharge data and water-quality data (discussed in the following section) are available. The period of stream discharge record analyzed for Savannah River near Clyo was 1953–87, subsequent to upstream flow regulation at J. Strom Thurmond Reservoir; and for the unregulated Ogeechee River near Eden, 1938–89.

Flow-duration characteristics are computed using daily stream-discharge data and are useful in assessing availability and variability of flows. For this study, flow-duration values were used to estimate the percentage of time the 7Q10 discharge has been equaled or exceeded. The analysis also was extended to estimate the probability of supplying additional water to meet future water-supply demands.

Flow-duration tables are constructed using classes that represent ranges of stream discharge (tables 2 and 3). Each class is defined by the discharge for the lower limit of the range, and the lower limit for the following class. For example, for Savannah River near Clyo, the lower discharge limit for class 2 is 4,800 cubic feet per second (ft^3/s) (table 2), and the upper limit is less than 5,300 ft^3/s (the lower limit for class 3). "Percent of exceedance" corresponds to the percentage of time that the indicated stream discharge was equaled or exceeded during the period of record.

Table 1.—Permitted and nonpermitted ground- and surface-water use in selected Georgia and South Carolina counties, 1989

[Data furnished by Georgia Water-Use Data System (GWUDS) and South Carolina Water Resources Commission]

County	Ground water, in million gallons per day			Surface water, in million gallons per day			Total
	Permitted	Nonpermitted	Total	Permitted	Nonpermitted	Total	
Bryan, Ga.	0.9	1.3	2.2	0	0	0	2.2
Chatham, Ga.	73.6	6.0	79.6	[1]90.4	0	90.4	170.0
Effingham, Ga.	2.0	1.9	3.9	8.3	.6	8.9	12.8
Liberty, Ga.	14.1	.6	14.7	0	0	0	14.7
Subtotal	90.6	9.8	100.4	98.7	.6	99.3	199.7
Jasper, S.C.	1.1	[2].1	1.2	0	0	0	1.2
Beaufort, S.C.	15.8	[2]1.5	17.3	14.0	[3].1	14.1	31.4
Subtotal	16.9	1.6	18.5	14.0	.1	14.1	32.6
TOTAL	107.5	11.4	118.9	112.7	.7	113.4	232.3

[1]Includes 42 Mgal/d of water purchased from the Savannah Industrial and Domestic plant (city of Savannah, Ga., Water Operation).
[2]Estimated values based on the percentage of nonpermitted ground-water use for Georgia.
[3]Estimated values based on the percentage of nonpermitted surface-water use for Georgia.

For a complete discussion of the flow-duration analysis, the reader is referred to Inman (1971).

A flow-duration curve constructed from the data in table 2 indicates that stream discharge has exceeded the 7Q10 discharge for Savannah River near Clyo (5,460 ft^3/s) about 98 percent of the time (fig. 6). Similarly, the 7Q10 discharge at Ogeechee River near Eden (192 ft^3/s) has been exceeded about 99.4 percent of the time (fig. 7). If the only restriction to water withdrawal were to maintain the 7Q10 discharge in the stream, the flow-duration analysis would provide that information. The flow in excess of the 7Q10 discharge is shown for two percentages (table 4). These percentages were chosen arbitrarily as 90 and 95 percent, to illustrate the analysis. For example, 90 percent of the time, the flow in excess of the 7Q10 discharge is about 910 ft^3/s (588 Mgal/d) for Savannah River near Clyo and 207 ft^3/s (134 Mgal/d) for Ogeechee River near Eden.

Water Quality

Water-quality data were examined to evaluate the suitability of the Savannah River near Clyo and Ogeechee River near Eden as sources of drinking-water supply. These stations are part of the USGS National Stream-Quality Accounting Network (NASQAN), and water-quality data have been collected at the two sites for more than 20 years.

The U.S. Environmental Protection Agency (EPA) developed the "Primary Drinking-Water Regulations" and "Secondary Drinking-Water Regulations" under the Safe Drinking Water Act (U.S. Environmental Protection Agency, 1986) to establish maximum levels for certain constituents. For those constituents that may affect human health, there are maximum contaminant levels (MCL), which are enforceable. For the constituents that affect the aesthetic quality of drinking water, there are nonenforceable secondary maximum contaminant levels (SMCL), which are intended to be used as guidelines for state regulatory agencies.

A statistical analysis was performed for selected water-quality properties and constituents for the Savannah River near Clyo (table 5) and Ogeechee River near Eden (table 6). The selection of properties and constituents analyzed was based on the water-quality data available and established MCL or SMCL standards. The microbiological quality of the water was not evaluated.

Color and turbidity at both stations were higher than the limits established by EPA standards. From the analysis of constituents at Savannah River near Clyo, the maximum values for dissolved iron and dissolved residue concentrations were higher than SMCL standards. At Ogeechee River near Eden, more than

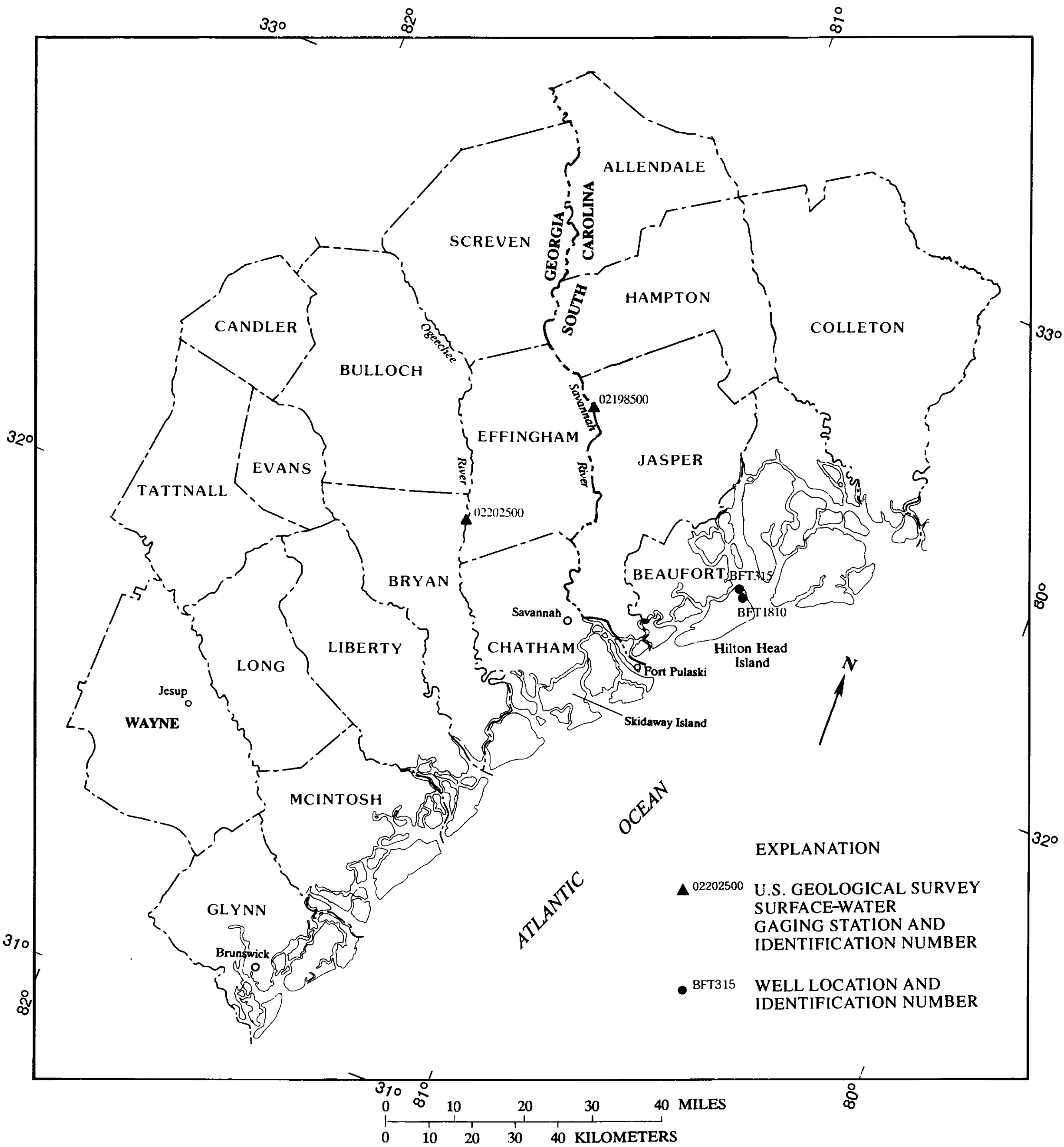


Figure 5.—Locations of selected surface-water stations in study area and wells for which ground-water quality graphs are presented.

Table 2.—Flow duration of daily discharge at Savannah River near Clyo, Ga., station number 02198500, 1953–87

[ft^3/s, cubic feet per second]

Class	Stream discharge (ft^3/s)	Number of days in the class	Cumulative days	Percent of exceedance
1	4,410	47	47	100.00
2	4,800	92	139	99.63
3	5,300	333	472	98.91
4	5,800	696	1,168	96.31
5	6,300	982	2,150	90.86
6	6,900	1,299	3,449	83.18
7	7,500	1,693	5,142	73.02
8	8,200	1,429	6,571	59.77
9	9,000	887	7,458	48.60
10	9,800	815	8,273	41.66
11	11,000	506	8,779	35.28
12	12,000	453	9,232	31.32
13	13,000	364	9,596	27.78
14	14,000	329	9,925	24.93
15	15,000	669	10,594	22.36
16	17,000	236	10,830	17.12
17	18,000	413	11,243	15.28
18	20,000	330	11,573	12.05
19	22,000	299	11,872	9.47
20	24,000	191	12,063	7.13
21	26,000	146	12,209	5.63
22	28,000	179	12,388	4.49
23	31,000	131	12,519	3.09
24	34,000	91	12,610	2.07
25	37,000	67	12,677	1.35
26	41,000	23	12,700	.83
27	44,000	28	12,728	.65
28	48,000	27	12,755	.43
29	53,000	17	12,772	.22
30	58,000	1	12,773	.09
31	63,000	2	12,775	.08
32	69,000	0	12,775	.06
33	75,000	3	12,778	.06
34	82,000	5	12,783	.04

Table 3.—Flow duration of daily discharge at Ogeechee River near Eden, Ga., station number 02202500, 1938–89

[ft^3/s, cubic feet per second]

Class	Stream discharge (ft^3/s)	Number of days in the class	Cumulative days	Percent of exceedance
1	114	17	17	100.00
2	130	40	57	99.91
3	160	57	114	99.70
4	190	133	247	99.40
5	220	246	493	98.70
6	260	470	963	97.40
7	310	494	1,457	94.93
8	360	799	2,256	92.33
9	430	898	3,154	88.12
10	510	956	4,110	83.39
11	600	1,155	5,265	78.36
12	710	1,157	6,422	72.28
13	840	1,132	7,554	66.19
14	990	1,398	8,952	60.23
15	1,200	1,049	10,001	52.87
16	1,400	838	10,839	47.34
17	1,600	1,026	11,865	42.93
18	1,900	1,138	13,003	37.53
19	2,300	980	13,983	31.54
20	2,700	1,018	15,001	26.38
21	3,200	629	15,630	21.02
22	3,700	699	16,329	17.71
23	4,400	550	16,879	14.03
24	5,200	512	17,391	11.13
25	6,100	556	17,947	8.43
26	7,300	339	18,286	5.51
27	8,600	233	18,519	3.72
28	10,000	194	18,713	2.50
29	12,000	131	18,844	1.47
30	14,000	90	18,934	.78
31	17,000	32	18,966	.31
32	20,000	14	18,980	.14
33	23,000	10	18,990	.07
34	27,000	3	18,993	.02

50 percent of the samples contained dissolved iron and dissolved manganese concentrations that were higher than SMCL standards.

Intrusion of seawater from the Atlantic Ocean into the Savannah and Ogeechee Rivers also could affect the use of the rivers as potential sources for drinking water. The presence of seawater increases the chloride concentration and diminishes or precludes the use of the rivers as a water-supply source. At the Savannah River near Clyo and Ogeechee River near Eden, the chloride concentrations range from 3.2 to 13 milligrams per liter (mg/L) (tables 5 and 6), which are below the SMCL limit established by EPA (250 mg/L).

HYDROGEOLOGY OF THE FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system has been described in numerous reports, most recently in the Savannah area by Clarke and others (1990, p. 29–38) and in the area of Savannah and adjacent South Carolina by Krause and Randolph (1989, p. D17–D24). These reports contain detailed descriptions of the aquifer system and regional ground-water flow system.

Geology and Hydraulic Characteristics

The Floridan aquifer system is composed of two water-bearing units, the Upper Floridan aquifer and Lower Floridan aquifer, which, in the extreme southwest part of the model area and southward in the Brunswick area, includes the Fernandina permeable zone (fig. 4). The Upper and Lower Floridan aquifers are separated by a semiconfining unit ("middle semiconfining unit" of Krause and Randolph, 1989, table 3).

The Upper Floridan aquifer consists mainly of carbonate rocks of Oligocene and late Eocene age that crop out northwest of the study area. Depth to the top of the Upper Floridan aquifer in the study area ranges from less than 100 ft to about 450 ft, and increases toward the south (Miller, 1986, pl. 25). The aquifer thickness in the model area ranges from less than 1 ft in the northern part to about 600 ft in the southern part (Miller, 1986, pl. 28).

The transmissivity of the Upper Floridan aquifer in the vicinity of Savannah ranges from about 25,000 to 50,000 ft^2/d (Bush and Johnston, 1988; Krause and Randolph, 1989). Transmissivity in the Hilton Head Island area is about 50,000 ft^2/d (Smith, 1988, fig. 4). The transmissivity ranges from about 5,000 to 10,000 ft^2/d in the northern part of the model area (Krause and Randolph, 1989, pls. 7 and 8) to more than 100,000 ft^2/d in the southern part.

The semiconfining unit separating the Upper and Lower Floridan aquifers consists of low-permeability limestone and dolomite of middle to late Eocene age. Thickness of the semiconfining unit in the model area ranges from less than 100 ft to more than 600 ft (Miller, 1986, fig. 11).

The Lower Floridan aquifer consists of carbonate rocks of early to middle Eocene age that are more dolomitic than rocks composing the Upper Floridan aquifer. Depth to the top of the Lower Floridan

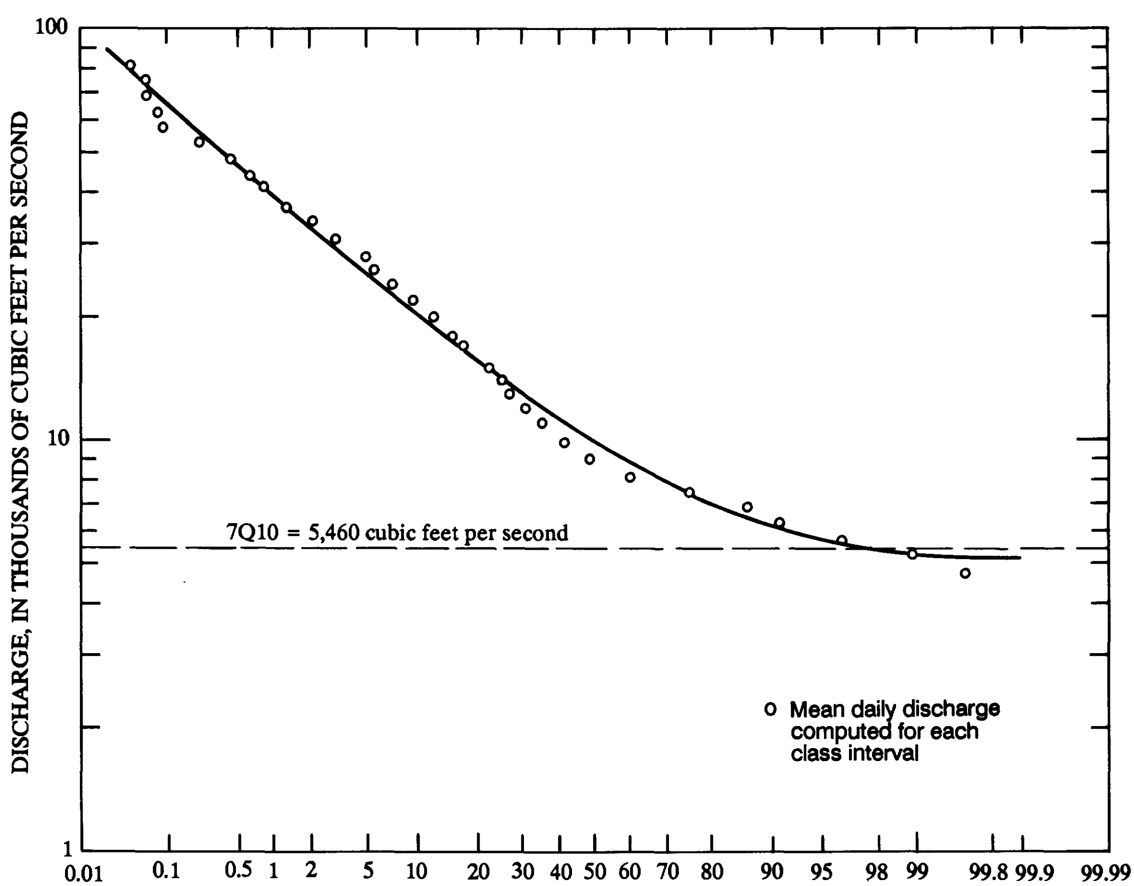


Figure 6.—Flow-duration curve of daily discharges and minimum average discharge for seven consecutive days for 10-year recurrence interval (7Q10) at Savannah River near Clyo, Ga., 1953-87.

aquifer in the model area ranges from about 600 to 1,000 ft (Miller, 1986, pl. 31), and the values used for transmissivity, which were based on simulations by Krause and Randolph (1989), range from about 2,000 to 80,000 ft^2/d.

The Lower Floridan aquifer is not widely used for water supply in coastal Georgia because it is deeply buried and contains saltwater in places. Also, the overlying Upper Floridan aquifer is a major source of freshwater and is the preferred water-supply source in the study area. The Lower Floridan aquifer is a source of freshwater in the Savannah area, where high-yielding wells are completed in the Upper and Lower Floridan aquifers. In the northeastern part of the study area, where the Upper Floridan is thin or absent, the Lower Floridan aquifer is a major source of water supply. Locally, in the extreme southern part of the model area, the Fernandina permeable zone is present in the lower part of the Lower Floridan aquifer (Krause and Randolph, 1989, p. D23). The Lower Floridan aquifer is confined below by low-permeability rocks.

Ground-Water Flow System

The ground-water flow system of the Upper Floridan aquifer has changed substantially since development began in the late 1800's. The most pronounced changes have occurred in the areas of

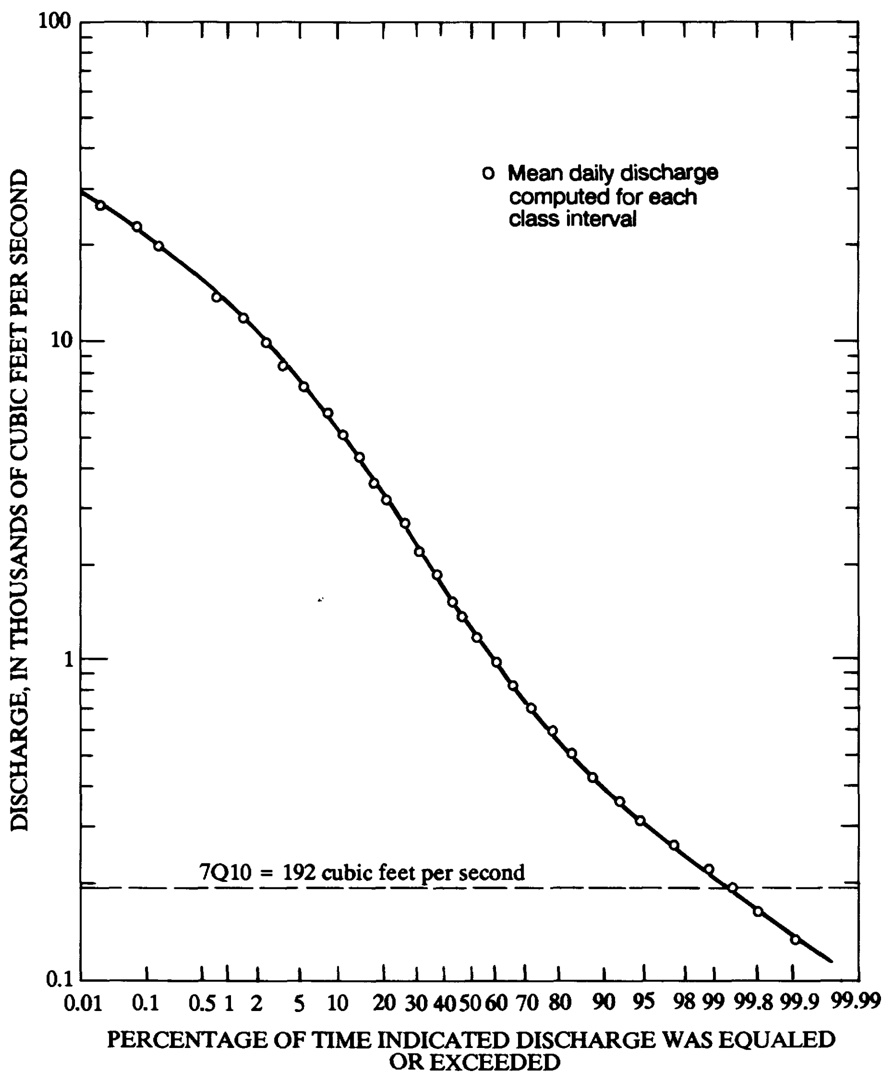


Figure 7.—Flow-duration curve of daily discharges and minimum average discharge for seven concecutive days for 10-year recurrence interval (7Q10) at Ogeechee River near Eden, Ga., 1938-89.

Table 4.—Flow duration, minimum average discharge for seven consecutive days for 10-year recurrence interval (7Q10), and flow in excess of 7Q10, Savannah River near Clyo and Ogeechee River near Eden

Station number (fig. 4)	Station name	Flow, in cubic feet per second, equaled or exceeded, for indicated percentage of time		7Q10, in cubic feet per second	Flow, in cubic feet per second, in excess of the 7Q10 for indicated percentage of time	
		90 percent	95 percent		90 percent	95 percent
02198500	Savannah River near Clyo	6,370	5,920	5,460	910	460
02202500	Ogeechee River near Eden	399	309	192	207	117

greatest ground-water development near Savannah (Krause and Randolph, 1989, p. D2). The changes in ground-water conditions are manifested in the potentiometric surface, the rates and distribution of recharge and discharge, the rates and direction of ground-water flow, and the quality of water in the aquifer.

Predevelopment conditions

Under predevelopment conditions (prior to about 1880), long-term recharge to the Floridan aquifer system was probably equal to discharge, and flow conditions were at steady state. Johnston and others (1980) estimated the potentiometric surface for the Upper Floridan aquifer prior to development. This surface was developed with the intent of showing a general or long-term average condition and might not correspond precisely to historical water-level data at specific sites. In coastal Georgia and adjacent South Carolina, the configuration of the potentiometric surface estimated by Johnston and others (1980) is nearly the same as that of Warren for 1880 (Warren, 1944, fig. 6). Warren's map of the potentiometric surface was based on water-level measurements made in wells open to the Upper Floridan aquifer in coastal Georgia and South Carolina during the late 1800's. The results of these early hydrologic investigations of the aquifer system in the area are published in reports by McCallie (1898, 1908) and Stephenson and Veatch (1915). The estimated predevelopment potentiometric surface (pl. 1) is based largely on the interpretations of Johnston and others (1980), but the potentiometric surface in the area upgradient of the 80-ft potentiometric contour in Georgia is based on the 1942 surface (Warren, 1944, fig. 2) and should be a close approximation of the original surface, because this area was virtually undeveloped at that time.

Before development, recharge generally occurred upgradient, outside the model area as downward leakage, and water flowed downgradient toward the coast, and then northeasterly, toward Port Royal Sound (pl. 1). Thus, ground water in the model area was largely confined and flow was lateral except in the area of Port Royal Island and adjacent islands, where the Upper Floridan aquifer is thinly covered and local recharge occurs. The ground water discharged nearby in deeply scoured reaches of creeks and estuaries near Hilton Head Island (Krause and Randolph, 1989, p. D-33) and by diffuse upward leakage.

Modern-day conditions

The modern-day (1985) ground-water flow system reflects the changes that have occurred as the result of ground-water development (pl. 2). The most noticeable change is the development of a deep cone of depression in the Upper Floridan aquifer beneath the city of Savannah. Hydraulic gradients have reversed, directing flow radially from all directions toward the center of the cone. Local bending in the contours on the flanks of the cone of depression (pl. 2) in the Hilton Head Island, S.C., and Riceboro, Ga., areas is caused by pumping at these locations. Pumping has not eliminated the ground-water mound in the area of Port Royal Island, S.C., and adjacent islands.

Ground-water flow in the Floridan aquifer system was assumed to be under steady-state conditions

Table 5.— Statistical summary of selected water-quality data for Savannah River near Clyo, 1987-89 and 1964-89

[Note: Multiple detection limits during the period of record could result in different values, marked with less than (<) sign; EPA, U.S. Environmental Protection Agency; MCL, maximum contaminant level; SMCL, secondary maximum contaminant level; (2D), turbidity unit (2 consecutive days); mg/L, milligrams per liter; µg/L, micrograms per liter; —, no data; N/A, not applicable; $NO_2 + NO_3$, nitrite plus nitrate, as nitrogen; <, less than. Trace-element concentration above the microgram per liter level should be viewed with caution. Such data may actually represent elevated environmental concentration from natural or human causes; however, these data could reflect contamination introduced during sampling, processing, or analysis. New trace-element protocols were introduced by the U.S. Geological Survey in water year 1994 to confidently produce dissolved trace-element data with insignificant contamination.]

Physical property or constituent	Unit of measure	Period of record	Number of samples	Maximum value	Minimum value	Percentage of samples having units or concentrations equal to or less than indicated value			Reporting level[1]	EPA drinking-water regulations	
						95 percent	50 percent	5 percent		MCL	SMCL
Turbidity	turbidity unit	1987-89	48	23	2.8	21.6	10	3.2			
		1964-89	145	40	.3	23	10	3	0.1	5(2D)	N/A
Color	platinum cobalt unit	1987-89	35	80	10	80	40	14			
		1964-89	225	140	<1	90	35	8	1	N/A	15
pH	standard unit	1987-89	47	7.5	6.7	7.4	7.2	6.8			
		1964-89	383	7.8	5.8	7.3	7	6.3	.1	N/A	6.5-8.5
$NO_2 + NO_3$, dissolved as N	mg/L	1987-89	12	.46	.12	.46	.34	.12			
		1964-89	55	1.2	.10	.53	.38	.13	.1	10	N/A
Sulfate, dissolved	mg/L	1987-89	12	17	9	17	13	9			
		1964-89	166	17	2	12	5.1	2	1	N/A	250
Fluoride, dissolved	mg/L	1987-89	12	.3	<.1	.3	.1	<.1			
		1964-89	134	.6	<.1	.2	.1	<.1	.1	4	N/A
Arsenic, dissolved	µg/L	1987-89	12	1	<1	1	<1	<1			
		1964-89	62	6	<1	1	<1	<1	1	50	N/A
Barium, dissolved	µg/L	1987-89	12	100	<100	100	40	7			
		1964-89	47	300	<100	140	30	<100	100	1,000	N/A
Cadmium, dissolved	µg/L	1987-89	12	2	<1	2	<1	<1			
		1964-89	62	4	<1	2	<1	<1	1	10	N/A
Chromium, dissolved	µg/L	1987-89	12	2	<1	2	<1	<1			
		1964-89	62	30	<1	10	<2	<1	1	50	N/A

in 1985. It is recognized that all hydrologic systems, including the Floridan, function in a transient manner. However, if the quantitative effects of the transient response of the system are small in comparison to the overall flow-system budget, the system can be assumed to be under steady-state conditions and simulation will not introduce significant error. Previous investigations, most of which included simulation, arrived at this same conclusion (Hayes, 1979; Randolph and Krause, 1984, 1990; Smith, 1988, 1993; Krause and Randolph, 1989; and Randolph and others, 1991). The assumption of steady state was tested quantitatively as part of this investigation by using the RASA model, and determining the effects locally in the area of the Savannah area model. Simulations were performed for transient conditions using the RASA mod-

Table 5.— Statistical summary of selected water-quality data for Savannah River near Clyo, 1987–89 and 1964–89—Continued

[Note: Multiple detection limits during the period of record could result in different values, marked with less than (<) sign; EPA, U.S. Environmental Protection Agency; MCL, maximum contaminant level; SMCL, secondary maximum contaminant level; (2D), turbidity unit (2 consecutive days); mg/L, milligrams per liter; µg/L, micrograms per liter; —, no data; N/A, not applicable; $NO_2 + NO_3$, nitrite plus nitrate, as nitrogen; <, less than; Trace-element concentration above the microgram per liter level should be viewed with caution. Such data may actually represent elevated environmental concentration from natural or human causes; however, these data could reflect contamination introduced during sampling, processing, or analysis. New trace-element protocols were introduced by the U.S. Geological Survey in water year 1994 to confidently produce dissolved trace-element data with insignificant contamination]

Physical property or constituent	Unit of measure	Period of record	Number of samples	Maximum value	Minimum value	Percentage of samples having units or concentrations equal to or less than indicated value			Reporting level[1]	EPA drinking-water regulations	
						95 percent	50 percent	5 percent		MCL	SMCL
Chloride, dissolved	mg/L	1987-89	12	11	6.2	11	8.9	6.2			
		1964-89	167	11	3.2	9.1	6	3.7	.1	N/A	250
Copper, dissolved	µg/L	1987-89	12	3	<1	3	2	<1			
		1964-89	65	50	<1	33	2	<1	1	N/A	1,000
Iron, dissolved	µg/L	1987-89	12	400	40	400	205	41			
		1964-89	76	630	10	423	170	20	10	N/A	300
Lead, dissolved	µg/L	1987-89	12	<5	<5	<5	<5	<5			
		1964-89	62	32	<5	13	<5	<5	5	50	N/A
Manganese, dissolved	µg/L	1987-89	12	30	6	32	12	6			
		1964-89	68	30	<10	30	11	<10	10	N/A	50
Zinc, dissolved	µg/L	1987-89	12	30	<10	34	20	<10			
		1964-89	65	200	<10	130	13	<10	10	N/A	5,000
Residue, dissolved at 180° C	mg/L	1987-89	12	86	52	86	68	52			
		1964-89	127	510	34	78	56	41	1	N/A	500

[1]Reporting level: the lowest measured concentration of a constituent that may be reliably reported using a given analytical method.

el, and the contribution of water from storage to the total water budget was evaluated in the area of the Savannah area model. Results from the simulations of the Upper Floridan aquifer indicate that the water released from storage under modern-day conditions represents a minor contribution to the water budget (less than 2 percent) and that the main component of the budget change caused by changes in pumpage is changes in leakage rates through the confining units. Thus, although the system is subjected to changes in pumping stress, storage changes related to this stress are minimal, and for the purpose of this study, the modern ground-water flow system is considered to be under steady-state conditions.

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

Ground-water flow modeling was used to simulate the Floridan aquifer system in the study area. The model developed for this study is based on the larger, coarse-grid model developed as part of the Floridan RASA study (Krause and Randolph, 1989). Two other models were later developed for the coastal area of Georgia: the Glynn County model (Randolph and Krause, 1990) and the coastal model (Randolph and others, 1991). The Savannah area model was developed to estimate the potential for additional ground-water development from the Upper Floridan aquifer in

Table 6.— Statistical summary of selected water-quality data for Ogeechee River near Eden, 1987-89 and 1968-89

[NOTE: multiple detection limits during the period of record could result in different values, marked with less than (<) sign; EPA, U.S. Environmental Protection Agency; MCL, maximum contaminant level; SMCL, secondary maximum contaminant level; (2D), turbidity unit (2 consecutive days); mg/L, milligrams per liter; µg/L, micrograms per liter; —, no data; N/A, not applicable; $NO_2 + NO_3$, nitrite plus nitrate, as nitrogen; <, less than. Trace-element concentration above the microgram per liter level should be viewed with caution. Such data may actually represent elevated environmental concentration from natural or human causes; however, these data could reflect contamination introduced during sampling, processing, or analysis. New trace-element protocols were introduced by the U.S. Geological Survey in water year 1994 to confidently produce dissolved trace-element data with insignificant contamination.]

Physical property or constituent	Unit of measure	Period of record	Number of samples	Maximum value	Minimum value	Percentage of samples having units or concentrations equal to or less than indicated value			Reporting level[1]	EPA drinking-water regulations	
						95 percent	50 percent	5 percent		MCL	SMCL
Turbidity	turbidity unit	1987-89	18	9.4	0.7	9.4	3.8	0.7			
		1968-89	106	25	.4	12.3	3.8	1.2	0.1	5(2D)	N/A
Color	platinum cobalt unit	1987-89	—	—	—	—	—	—			
		1968-89	37	170	15	152	65	15	1	N/A	15
pH	standard unit	1987-89	18	7.8	6.7	7.8	7.2	6.7			
		1968-89	178	8.9	5.1	7.7	7	5.9	.1	N/A	6.5-8.5
$NO_2 + NO_3$, dissolved	mg/L	1987-89	18	.42	<.1	.42	.14	<.1			
		1968-89	70	.42	<.1	.33	.15	<.1	.1	10	N/A
Sulfate, dissolved	mg/L	1987-89	18	20	2.2	20	12	2.2			
		1968-89	148	20	.4	13.6	5	2	1	N/A	250
Fluoride, dissolved	mg/L	1987-89	18	.1	<.1	.1	.1	<.1			
		1968-89	119	.5	<.1	.2	.1	<.1	.1	4	N/A
Arsenic, dissolved	µg/L	1987-89	12	1	<1	1	<1	<1			
		1968-89	62	2	<1	1	<1	<1	1	50	N/A
Barium, dissolved	µg/L	1987-89	12	<100	<100	32	24	20			
		1968-89	48	56	<100	50	28	<100	100	1,000	N/A
Cadmium, dissolved	µg/L	1987-89	12	2	<1	2	<1	<1			
		1968-89	60	6	<1	3	<2	<1	1	10	N/A
Chromium, dissolved	µg/L	1987-89	12	2	<1	2	<1	<1			
		1968-89	62	10	<1	10	<2	<1	1	50	N/A

the Savannah and Hilton Head Island area and to evaluate resource-management alternatives in the Savannah area at a greater resolution than that available with existing models.

Model Design

The RASA, Glynn County, and Savannah area models use a quasi three-dimensional, finite-difference computer code developed by McDonald and Harbaugh (1988) to evaluate the effects of various pumping alternatives under steady-state conditions. The regional (RASA) model and the two subregional (Glynn County and Savannah area) models were interactively used for this study. Because the subregional models are within the boundary of the regional model (fig. 8), each uses the regional model to define boundary conditions, and each model pair (regional-subregional) functions as a telescoped model. Tele-

Table 6.— Statistical summary of selected water-quality data for Ogeechee River near Eden, 1987-89 and 1968-89—Continued

[NOTE: multiple detection limits during the period of record could result in different values, marked with less than (<) sign; EPA, U.S. Environmental Protection Agency; MCL, maximum contaminant level; SMCL, secondary maximum contaminant level; (2D), turbidity unit (2 consecutive days); mg/L, milligrams per liter; µg/L, micrograms per liter; —, no data; N/A, not applicable; $NO_2 + NO_3$, nitrite plus nitrate, as nitrogen; <, less than. Trace-element concentration above the microgram per liter level should be viewed with caution. Such data may actually represent elevated environmental concentration from natural or human causes; however, these data could reflect contamination introduced during sampling, processing, or analysis. New trace-element protocols were introduced by the U.S. Geological Survey in water year 1994 to confidently produce dissolved trace-element data with insignificant contamination.]

Physical property or constituent	Unit of measure	Period of record	Number of samples	Maximum value	Minimum value	Percentage of samples having units or concentrations equal to or less than indicated value			Reporting level[1]	EPA drinking-water regulations	
						95 percent	50 percent	5 percent		MCL	SMCL
Chloride, dissolved	mg/L	1987-89	18	11	4.4	11	8.6	4.4			
		1968-89	147	13	3.7	9.7	6.1	4.1	.1	N/A	250
Copper, dissolved	µg/L	1987-89	12	4	<1	4	1	<1			
		1968-89	59	5	<1	4	2	<1	1	N/A	1,000
Iron, dissolved	µg/L	1987-89	12	1,200	140	1,200	680	140			
		1968-89	64	1,400	90	1,200	545	153	10	N/A	300
Lead, dissolved	µg/L	1987-89	12	<5	<5	<5	<5	<5			
		1968-89	57	17	<5	12	<5	<5	5	50	N/A
Manganese, dissolved	µg/L	1987-89	12	100	20	100	62	22			
		1968-89	62	130	<10	92	38	<10	10	N/A	50
Zinc, dissolved	µg/L	1987-89	12	30	<10	34	<10	<10			
		1968-89	62	120	<10	40	<10	<10	10	N/A	5,000
Residue, dissolved at 180° C	mg/L	1987-89	18	155	42	155	80	42			
		1968-89	118	170	28	107	71	42	1	N/A	500

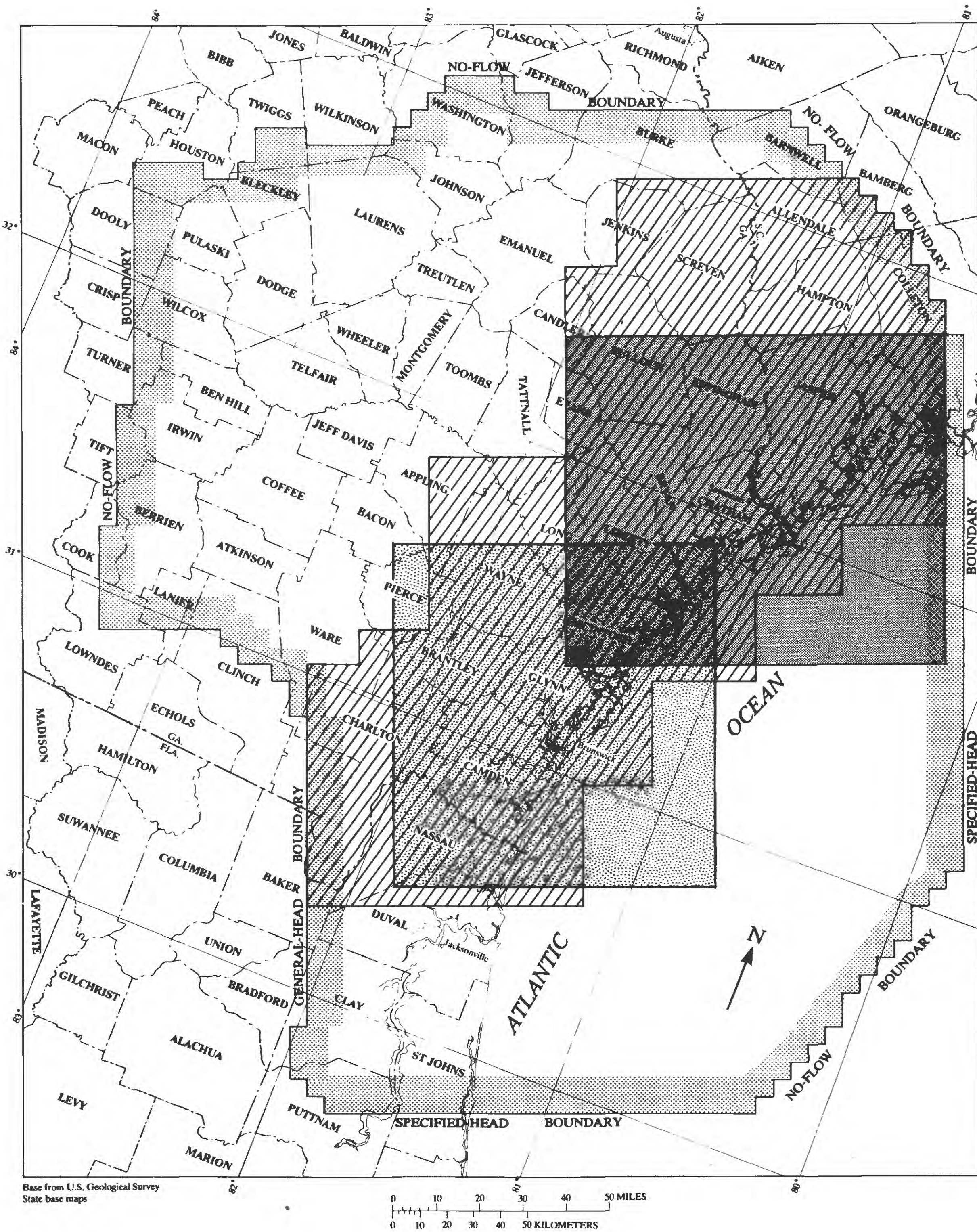
[1]Reporting level: the lowest measured concentration of a constituent that may be reliably reported using a given analytical method.

scoped models are used to evaluate the flow system at a greater resolution than that of the regional model without having to extend the subregional boundaries to natural hydrologic boundaries. The effects of stresses beyond the boundaries of the subregional model are evaluated by the regional model at the subregional boundaries.

Regional flow simulation

The large-scale, regional (RASA) model simulates flow in the northeastern part of the Floridan aquifer system in an area that includes the eastern half of the Coastal Plain of Georgia and adjacent parts of southern South Carolina and northeastern Florida. This model covers an area of approximately 53,250 mi^2. The uniform, finite-difference grid of the RASA model has 52 rows and 64 columns, and each cell is 4 mi on a side and 16 mi^2 in area. The reader is referred to Krause and Randolph (1989) for a complete description of the model.

The RASA model simulates lateral flow and water-level in the Upper and Lower Floridan aquifers. The Upper Floridan aquifer is overlain by the upper confining unit, through which water is simulated as leaking vertically in either direction. The upper confining unit is overlain by the water-table or surficial aquifer in which the water level varies in space, but not in time, and which functions as a source or sink to the Upper Floridan aquifer. Thus, in the RASA



EXPLANATION

MODEL AREA

SAVANNAH AREA (This report)	COASTAL (Randolph and others, 1991)
GLYNN COUNTY (Randolph and Krause, 1990)	REGIONAL AQUIFER-SYSTEM ANALYSIS (Krause and Randolph, 1989)

Figure 8.—Boundaries of Regional Aquifer-System Analysis (RASA), Glynn County, coastal, and Savannah area models.

model, the surficial aquifer is simulated as a specified-head boundary.

The middle semiconfining unit separates the Upper and the Lower Floridan aquifers. Water is simulated as leaking vertically in either direction across the semiconfining unit between the two aquifers as a function of vertical hydraulic conductivity, thickness of the confining unit, and vertical head gradient between the two aquifers.

Where present (in the extreme southern part of the model area), the Fernandina permeable zone functions as a source of water to the Lower Floridan aquifer and is simulated in the RASA model as a specified-head boundary (Krause and Randolph, 1989, p. D23). In the rest of the area, the Floridan aquifer system is underlain by the lower confining unit, which is simulated as an impermeable boundary (Krause and Randolph, 1989, p. D60).

Laterally, the RASA model extends to the outcrop area of the Floridan aquifer system in South Carolina and to the estimated offshore extent of the freshwater flow system to the east (Krause and Randolph, 1989, pls. 3 and 4). The Upper Floridan aquifer is thought to pinch out northeast of the Combahee River in South Carolina (Krause and Randolph, 1989, p. D21) and is simulated in this vicinity by using low values of transmissivity. The southern boundary was simulated by using a specified-head boundary, and the southwestern boundary was simulated as a general-head boundary. A general-head boundary calculates the flow into the RASA model based on (1) the hydraulic gradient from an arbitrary distance outside the model to the first active cell inside the boundary and (2) the average transmissivity over that distance. The influence of these artificial lateral boundaries on simulation results is considered minimal relative to the Savannah area model because of the great distance from the boundaries to the centers of pumping.

Subregional flow simulation

The Glynn County model (Randolph and Krause, 1990) was designed to improve resolution in the areas of greatest pumping and saltwater intrusion in Brunswick, Glynn County, Ga. The model grid is variable, having finer discretization in the Brunswick area to facilitate simulation of local flow. The grid is divided into 110 rows and 94 columns and the total model area is 6,080 mi^2. The grid of the Glynn County model is aligned with that for the RASA model so that each cell is a fraction of the original 4-mi side of a RASA cell. The cells of the Glynn County model range in area from 16 mi^2 on the four corners of the grid to 0.00391 mi^2 in the center of the grid in Brunswick (330 ft on a side). The lateral boundaries of the Glynn County model are completely within RASA model boundaries (fig. 8) and rely on the RASA model simulations for boundary flow. The vertical boundaries are the same as those of the RASA model. A detailed description of the Glynn County model design and development is given by Randolph and Krause (1990).

The Savannah area model was developed for this study to gain greater resolution than the coastal model (Randolph and others, 1991) in the Savannah–Hilton Head Island area where the largest ground-water withdrawal from the Upper Floridan aquifer occurs. The Savannah area model includes the coastal counties in Georgia and South Carolina that surround Chatham County (fig. 1) and simulates an area of 6,680 mi^2. The uniform, finite-difference grid of the model has 76 rows and 88 columns (pl. 3). Each cell is 1 mi on a side, one-sixteenth the size of a RASA model cell, and one-fourth the size of a coastal model cell.

Lateral boundaries for the Savannah area model are derived from simulations of the RASA model (fig. 8). The RASA model provides flow across the calculated-flow boundary, which is then input to the Savannah area model. The vertical boundaries of the Savannah area model are identical to those of the RASA model (Krause and Randolph, 1989).

Input data for Savannah area model

Transmissivity values input to the Savannah area model were based on values from the RASA model (Krause and Randolph, 1989). For the Upper Floridan aquifer, transmissivity values were assigned to specific cells based on results from multi-well aquifer tests and specific-capacity data. In addition, transmissivity in the northeastern part of the model area in South Carolina was adjusted to more closely agree with that used by Smith (1988). Transmissivity of the Upper Floridan aquifer from the calibrated Savannah area model and selected field values of transmissivity derived from multi-well aquifer tests are shown on plate 4. This illustration, and those showing other "input" data (except pumping rate), depict data arrays that resulted from the calibrated model. (See section, "Model Calibration".) Transmissivity data for the study area were reported by Bush and Johnston (1988, p. C8, table 2), Hayes (1979, p. 32, table 9), Krause and Randolph (1989, p. D24, pl. 7), Counts and Donsky (1963, p. 40, table 3), and Dyar and others (1972, p. 13, table 1). Transmissivity values assigned to the lower Floridan aquifer were based on the calibrated RASA model array. Transmissivity of the Lower Floridan aquifer from the calibrated Savannah area model is shown on plate 5.

Values of leakance for the upper confining unit and for the middle semiconfining unit were taken from the RASA model and input to the Savannah area model. Estimates of leakance were originally derived from estimates of vertical hydraulic conductivity and thickness of the confining unit (Krause and Randolph, 1989). Ranges in leakance for the upper and middle confining units used in the calibrated Savannah area model are shown on plates 6 and 7, respectively.

Values of head for the surficial aquifer were estimated from land-surface and water-surface altitudes from USGS 7 1/2-minute topographic maps. The water levels for the surficial aquifer were contoured (pl. 8) from the input data set of surficial aquifer head, which has a uniform data density at one-mile centers. As such, contours are approximately located and are not intended to show exact water-level data at specified sites. The values of specified head representing the Fernandina Permeable zone range from 58 to 67 ft and were based on the RASA model (Krause and Randolph, 1989).

Rates and location of pumping for May 1985 were identified and input into the Savannah area model. Pumpage data for the Upper Floridan aquifer used in the calibrated Savannah area model are shown on plate 9, and pumpage data for the Lower Floridan are listed in table 7.

Table 7.—1985 pumpage data used in the Savannah area model, Lower Floridan aquifer

Location of pumping site (row, column)	Pumpage, in million gallons per day
2,80	0.10
4,70	.03
6,81	.44
6,71	.04
7,72	.30
10,72	.05
12,73	.20
16,78	.40
16,76	1.07
16,75	.13
17,77	2.20
20,74	.03
24,80	.41
25,73	.05
28,77	.06
33,43	[1].33
34,43	[1].34
37,41	[1]1.02
37,43	[1]6.44
38,43	[1]1.63
39,44	[1].42
40,43	[1].81
42,43	[1].09
44,40	[1].61

[1]Based on estimates of percentage of contribution from Lower Floridan aquifer to total pumpage from both Upper and Lower Floridan aquifers.

Model Calibration

The Savannah area model was calibrated for modern-day (1985) conditions and tested for acceptance for predevelopment (1880) conditions. The calibration procedure was based on comparing heads simulated by the model with ground-water-level measurements made in wells completed in the Upper Floridan aquifer in May 1985 (pl. 10). Calibration was an iterative process in which adjustments were made to the hydraulic properties for the Savannah area model. Adjustments were subsequently translated to input arrays for the RASA model. The RASA model was then executed to simulate the new boundary flow for the Savannah area model. This process was repeated until calibration. Although the adjustments to the Savannah area model input data sets altered the input arrays for the RASA model, those adjustments did not affect the calibration of the RASA model.

Some differences in measured and simulated water levels are expected because measured water levels are based on the altitude of land surface estimated from USGS 7 1/2-minute topographic maps. In addition, the simulated head represents the head value at the center of a cell and the measured ground-water level represents head at the actual location of a well, which may be located anywhere within the cell. The comparison between simulated and measured heads becomes more significant as the model resolution becomes greater. The possibility of geographic coincidence becomes greater as cell size becomes smaller and the comparison is more meaningful, particularly in areas of steep hydraulic gradients.

The differences between simulated and measured ground-water levels are called "residuals." The residuals for the calibrated Savannah area model are listed in table 8. Statistics of mean, root-mean-square error (RMSE), and standard deviation (SD) of water-level residuals were computed for each simulation to help determine the ability of the model to represent the 1985 ground-water conditions. The mean of residuals is the average of all water-level residuals. The RMSE is the square root of the average sum of squares of the residuals. The SD is the measure of the dispersion of the water-level residuals about the mean. The following formulas were used to compute the statistics:

$$\text{Mean of residuals} \quad \bar{h} = \frac{1}{n} \sum_{i=1}^{n} (h_s - h_m), \qquad (1)$$

where n = the number of measured water levels within the model area;

h_s = the simulated water level at the center of the cell in which a water level was measured; and

h_m = the measured water level in wells completed in the Upper Floridan aquifer.

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (h_s - h_m)^2} \qquad (2)$$

$$\text{SD} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (h_s - \bar{h}_m)^2} \qquad (3)$$

Statistics for the water-level residuals for the calibrated model are

Mean of residuals	=	1.3 ft
Root-mean-square error	=	4.0 ft
Standard deviation	=	3.8 ft

The frequency distribution of water-level residuals illustrates the degree of calibration for the Savannah area model (fig. 9). Of the water levels measured (n=136), 82 percent of the simulated values match the observed measurements within 5 ft. In addition, water-level residuals are well distributed throughout the model area (pl. 10). Several of the large residuals are within the cone of depression, where the hydraulic gradient is steep, and the likelihood of having large residuals is greatest. For the Beaufort County area of South Carolina, the RMSE is 3.2 ft, based on 33 comparisons. For Hilton Head Island and other near-shore islands, the RMSE is 2.2 ft, based on 22 comparisons.

The test for acceptance of the calibration consisted of comparing the estimated predevelopment potentiometric surface (Johnston and others, 1980) with the surface simulated by using the Savannah area model without pumpage (pl. 1). Visual comparison of the surfaces indicates that the model simulated the approximate predevelopment potentiometric surface of the Upper Floridan aquifer with a high degree of replication. Although not a rigorous test of acceptance or accuracy, a statistical analysis was made of the residuals from the calibrated model for conditions prior to development. Unlike the analysis for 1985 conditions in which residuals were computed only for cells in which measurements were available, in the test for acceptance, values of head were interpolated for all model cells from the estimated potentiometric surface and used as "measured" water levels in the computations of the residuals. Thus, the number of "measured" water levels, and hence residuals, is the number of cells (6,688) representing the Upper Floridan aquifer in the model. The RMSE of the residuals is about 4.0 ft. The model also simulated an area of local recharge from the surficial aquifer to the Upper Floridan aquifer, a ground-water mound in the Upper Floridan aquifer, on St. Helena Island, S.C. This mound was not included on the generalized map constructed by Johnston and others (1980).

Simulated Water Budget

Flow through the Floridan aquifer system under predevelopment conditions in the model area is about 132 ft^3/s, based on simulations using the Savannah area model. About 107 ft^3/s flows through the Upper Floridan aquifer (table 9) and about 25 ft^3/s flows through the Lower Floridan aquifer (table 10). Thus, approximately 82 percent of the flow in the model is within the Upper Floridan aquifer. Before development, the net contribution of leakage was from the Upper Floridan aquifer to the surficial aquifer, and from the Lower to the Upper Floridan aquifer.

The overall water budget and rates and direction of flow also have changed with development. Total flow in the model area is about 258 ft^3/s for 1985. Of this total, about 210 ft^3/s is through the Upper Floridan aquifer (table 9) and about 48 ft^3/s through the Lower Floridan aquifer (table 10). The

Table 8.—Water-level residuals, Upper Floridan aquifer, for calibrated (1985) Savannah area model

Well location (row, column)	Water level, in feet above or below (–) sea level		Residual; difference between simulated and measured water level, in feet
	Simulated	Measured	
2,15	85.6	84.5	1.1
2,36	63.5	62.4	1.1
5,6	82.0	77.9	4.1
5,36	51.7	46.9	4.8
8,20	57.1	57.9	–.8
12,12	46.1	41.9	4.2
12,73	7.9	–1.8	9.7
13,5	45.8	46.0	–.2
16,3	40.9	39.7	1.2
16,60	7.5	3.0	4.5
17,7	37.4	37.3	.1
17,73	8.0	1.9	6.1
21,70	9.4	1.5	7.9
21,73	18.8	20.2	–1.4
22,73	18.3	18.8	–.5
23,4	30.5	25.5	5.0
23,41	–9.1	–7.6	–1.5
23,78	10.5	7.8	2.7
24,28	8.2	8.7	–.5
24,73	13.6	2.1	11.5
24,79	10.7	12.4	–1.7
25,41	–16.0	–11.6	–4.4
25,79	8.9	4.3	4.6
26,64	–.3	–1.8	1.5
26,71	4.6	2.4	2.2
27,64	–.9	–7.1	6.2
28,80	4.3	1.9	2.4
28,83	5.0	2.8	2.2
30,49	–30.5	–29.2	–1.3
30,72	2.0	2.1	–.1
30,82	7.6	3.0	4.6
30,86	4.1	2.5	1.6
31,53	–22.4	–23.7	1.3
31,82	7.4	3.8	3.6
32,34	–25.3	–25.1	–.2
32,50	–34.1	–39.3	5.2
32,76	3.1	–.5	3.6
32,80	5.6	2.5	3.1
32,84	3.3	.5	2.8
33,36	–37.2	–31.9	–5.3
33,42	–65.4	–67.0	1.6
34,39	–62.4	–71.0	8.6
34,60	–12.1	–14.9	2.8
34,61	–9.9	–12.1	2.2
34,74	1.1	1.3	–.2
35,42	–85.2	–94.5	9.3
35,69	–1.2	–3.7	2.5

Table 8.—Water-level residuals, Upper Floridan aquifer, for calibrated (1985) Savannah area model—Continued

Well location (row, column)	Water level, in feet above or below (–) sea level		Residual; difference between simulated and measured water level, in feet
	Simulated	Measured	
36,38	–59.9	–52.1	–7.8
36,43	–96.9	–107.0	10.1
36,60	–13.1	–14.5	1.4
36,63	–8.0	–6.1	–1.9
36,84	.5	1.9	–1.4
37,50	–46.1	–49.8	3.7
37,51	–41.0	–43.9	2.9
37,52	–36.5	–32.2	–4.3
38,43	–104.2	–115.9	11.7
38,68	–4.2	–4.9	.7
39,18	5.4	6.0	–.6
39,24	–3.6	–1.8	–1.8
39,26	–7.9	–9.6	1.7
39,34	–35.4	–27.5	–7.9
39,43	–101.1	–103.3	2.2
39,44	–94.6	–98.3	3.7
39,65	–7.9	–9.2	1.3
39,69	–4.0	–4.5	.5
40,35	–40.0	–33.1	–6.9
40,41	–80.4	–89.9	9.5
40,43	–93.3	–98.6	5.3
40,45	–85.5	–90.4	4.9
40,46	–78.2	–82.9	4.7
40,47	–71.7	–73.8	2.1
41,33	–29.7	–22.5	–7.1
41,35	–38.8	–35.3	–3.5
41,43	–83.4	–82.3	–1.1
41,45	–81.3	–87.1	5.8
41,65	–10.2	–7.8	–2.4
42,5	12.8	11.0	1.8
42,29	–16.1	–16.4	.3
42,35	–37.3	–29.6	–7.7
42,42	–73.5	–85.5	12.0
42,60	–17.8	–19.3	1.5
42,61	–16.5	–14.2	–2.3
42,62	–14.6	–14.0	–.6
42,65	–10.1	–10.0	–.1
43,11	7.6	6.9	.7
43,28	–13.4	–12.5	–.9
43,39	–55.6	–52.9	–2.7
43,45	–63.4	–60.4	–3.0
43,47	–55.0	–56.2	1.2
44,7	10.1	16.2	–6.1
44,9	8.6	8.2	.4
45,25	–7.2	–6.8	–.4
45,38	–43.9	–50.9	7.0

total pumpage from the Floridan aquifer system in 1985, input to the Savannah area model, is 186 ft^3/s, from which 91 percent, or 169 ft^3/s, is withdrawn from the Upper Floridan aquifer. Direction of net leakage through the upper semiconfining unit has been reversed to downward as a result of head decline in the Upper Floridan aquifer. Thus, under modern-day conditions, net leakage is from the surficial aqui-

Table 8.—Water-level residuals, Upper Floridan aquifer, for calibrated (1985) Savannah area model—Continued

Well location (row, column)	Water level, in feet above or below (–) sea level		Residual; difference between simulated and measured water level,in feet
	Simulated	Measured	
46,41	–44.9	–50.7	5.8
46,44	–46.5	–47.3	.8
46,48	–40.9	–41.3	.4
46,53	–28.6	–28.8	.2
47,14	4.4	4.0	.4
47,37	–31.3	–29.8	-1.5
47,45	–41.1	–43.7	2.6
47,47	–39.1	–40.0	1.0
47,48	–37.6	–38.2	.6
48,7	8.3	7.3	.9
48,15	3.2	.2	3.0
48,56	–21.2	–22.0	.8
49,33	-19.1	–20.1	1.0
49,41	–30.8	–31.0	.2
49,44	–33.3	–39.1	5.8
49,56	–20.3	–20.9	.6
50,34	–19.5	–20.5	1.0
52,15	1.6	.3	1.3
53,12	4.7	1.3	3.4
54,16	–.3	–2.2	1.9
54,18	–6.6	–11.2	4.6
54,28	–8.2	–9.8	1.6
56,5	8.6	10.6	–2.0
58,27	–4.7	–7.7	3.0
59,11	6.5	4.6	1.9
60,16	3.2	.6	2.6
61,15	4.4	4.0	.4
63,14	5.9	6.4	–.5
64,6	10.9	11.4	–.5
65,2	12.8	17.3	–4.5
67,11	9.5	13.9	–4.4
67,16	6.5	2.6	3.9
67,18	5.4	7.4	–2.0
68,12	9.4	14.1	–4.7
70,4	13.3	11.7	1.6
70,7	12.2	13.3	-1.1
70,9	11.4	11.8	–.4
72,5	13.2	13.3	–.1
72,10	11.4	13.8	–2.4
72,15	9.2	7.1	2.1
73,6	13.0	11.3	1.7
74,7	12.7	15.5	–2.8
75,10	12.0	9.8	2.2

fer to the Upper Floridan aquifer and from the Lower to the Upper Floridan.

Model Sensitivity

The response of simulated water levels in the Savannah area model to changes in aquifer and confining-unit properties was evaluated by performing sensitivity analyses. The relative sensitivity of the model to changes in these properties indicates (1) the degree of importance of individual properties to the simulation of ground-water flow and (2) the location and type of additional data collection that would be beneficial to further refinement of the Savannah area model. A model is considered to be sensitive to a property when a small change in that property results in a comparatively large change in the residuals. Similarly, a model is considered to be less sensitive to a property when a substantial change in that property results in little or no change in the residuals. To maintain continuity across the subregional model boundaries, aquifer and confining units properties were changed in the RASA model by the same factor used to test the sensitivity of the Savannah area model.

For the Savannah area model, the sensitivity analysis was conducted on transmissivities of the Upper and Lower Floridan aquifers, independently, and on vertical leakance between the surficial and Upper Floridan aquifers and between the Upper and Lower Floridan aquifers. The sensitivity of the Savannah area model was evaluated by comparing the measured water levels with those simulated during the sensitivity analysis for the Upper Floridan aquifer. The direction of water-level changes caused by an increase or decrease in the value of a particular property is determined by the mean. Negative values for the mean indicate that, on the average, under the conditions

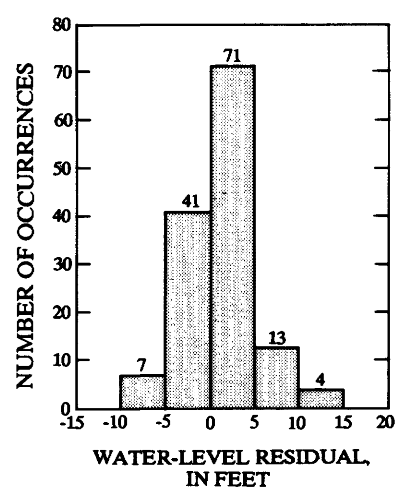


Figure 9.—Histogram of water-level residuals, computed using results from calibrated (1985) Savannah area model.

Table 9.—Simulated water budget for predevelopment (1880) and 1985 conditions for Upper Floridan aquifer, from Savannah area model

	Flow, in cubic feet per second	
	Predevelopment	**1985**
INFLOW		
Leakage through confining units:		
Surficial aquifer to Upper Floridan aquifer	24	87
Lower Floridan aquifer to Upper Floridan aquifer	23	30
Total leakage	47	117
Lateral inflow	60	93
TOTAL INFLOW	107	210
OUTFLOW		
Pumpage	0	169
Leakage through confining units:		
Upper Floridan aquifer to surficial aquifer	99	18
Upper Floridan aquifer to Lower Floridan aquifer	5	12
Total leakage	104	30
Lateral outflow	3	11
TOTAL OUTFLOW	107	210

tested, the model simulates water levels that are higher than those measured in 1985. The sensitivity was determined quantitatively in terms of the mean of the residuals, SD, and RMSE. The formulas for these statistics are the same as those given in the section "Model Calibration," and the results of the sensitivity analysis are listed in table 11.

Comparison of the statistics (table 11) indicates that simulated water levels in the Upper Floridan aquifer are most sensitive to (1) changes in the transmissivity of the Upper Floridan aquifer and (2) changes in the leakance between the surficial and the Upper Floridan aquifers. For example, a decrease in the transmissivity of the Upper Floridan aquifer by half of its calibrated value results in an increase of the RMSE from about 4.0 to 35.3 ft, indicating the strong sensitivity to changes in this property. For a similar change applied to the transmissivity of the Lower Floridan aquifer, the RMSE increases to about 6.3 ft.

Results of the sensitivity analysis indicate an increased confidence that the calibrated values of transmissivity for the Upper Floridan aquifer and vertical leakance for the upper confining unit represent the physical system more closely than do values of the other aquifer and confining-unit properties tested in the sensitivity analysis. Therefore, accurate estimates of transmissivity of the Upper Floridan aquifer and vertical leakance of the upper confining unit, or obtaining data for those properties, are important to reliable simulation of water levels in the aquifer.

Table 10.—Simulated water budget for predevelopment (1880) and 1985 conditions for Lower Floridan aquifer, from Savannah area model

	Flow, in cubic feet per second	
	Predevelopment	1985
INFLOW		
Leakage through confining units:		
Upper Floridan aquifer to Lower Floridan aquifer	5	12
Fernandina permeable zone to Lower Floridan aquifer	0	0
Total leakage	5	12
Lateral inflow	20	36
TOTAL INFLOW	25	48
OUTFLOW		
Pumpage	0	17
Leakage through confining units:		
Lower Floridan aquifer to Upper Floridan aquifer	23	31
Lower Floridan aquifer to Fernandina permeable zone	0	0
Total leakage	23	31
Lateral outflow	2	0
TOTAL OUTFLOW	25	48

WATER-SUPPLY POTENTIAL OF THE UPPER FLORIDAN AQUIFER

The potential of the Upper Floridan aquifer to supply additional water was estimated on the basis of water-level constraints. The Glynn County and Savannah area models were used to estimate maximum rates of pumpage that could occur without lowering head at the locations of existing seawater encroachment and saltwater intrusion. Because results of simulations indicated that the potential for increased development was limited, the effects of small increases, decreases, and redistribution in pumpage were estimated in the model.

Ground-Water Quality

The water-supply potential of the Upper Floridan aquifer is constrained by salinity of the water in the aquifer. Seawater encroachment and saltwater intrusion, caused by ground-water pumping and resulting water-level declines, limit additional development of the Upper Floridan aquifer for water supply. The

Table 11.—Results of sensitivity analysis for 1985 conditions

Property	Multiplier	Upper Floridan aquifer water level, in feet		
		Mean	Standard deviation	Root-mean-square error
Transmissivity of Upper Floridan aquifer	0.5	27.3	22.4	35.3
	2.0	-21.3	14.4	25.7
Transmissivity of Lower Floridan aquifer	.5	4.1	4.8	6.3
	2.0	-5.2	4.9	7.2
Vertical leakance between surficial and Upper Floridan aquifers	.1	20.1	6.3	21.0
	10.0	-18.4	12.2	22.0
Vertical leakance between Upper and Lower Floridan aquifers	.1	2.0	5.0	5.4
	10.0	-.1	4.5	4.5

encroachment and instrusion of saltwater into freshwater zones of the Upper Floridan aquifer have been documented on the basis of specific conductance and chloride concentration in ground water. Therefore, specific conductance and chloride concentration are the water-quality characteristics that were of interest in evaluating the water-supply potential of the Upper Floridan aquifer.

Lateral migration of seawater (seawater encroachment) is occurring at the north end of Hilton Head Island (Smith, 1988; Bush, 1988; Krause and Randolph, 1989, p. D50). The chloride concentration in water from well BFT315 (fig. 5), which is completed in the lower part of the Upper Floridan aquifer, increased from about 100 mg/L in 1978 to about 600 mg/L in 1983 (fig. 10). In addition, the specific conductance (an indicator of dissolved solids concentrations, including chloride) of water from well BFT1810, also on Hilton Head Island (fig. 5), increased from about 750 to more than 7,500 microsiemens per centimeter at 25°C (μS/cm) during the period 1987–90 (fig. 11). This increase in specific conductance probably is a result of an increase in chloride concentration related to seawater encroachment.

Saltwater intrusion also is occurring in Brunswick, Ga., 65 mi south of Savannah, where saltwater from the Fernandina permeable zone has intruded upward into parts of the Lower Floridan and Upper Floridan aquifers. Chloride concentration in water from the Upper Floridan aquifer mixed with vertically intruded saltwater exceeds 2,000 mg/L at two areas in Brunswick (Krause and Randolph, 1989, p. D51).

Potential for Ground-Water Development

Because additional water-level declines caused by pumping can accelerate rates of encroachment or intrusion, the analysis of the potential for additional development of water from the Upper Floridan aquifer was constrained by water-level declines at the known locations of encroachment and intrusion. Encroachment or intrusion in the aquifer has been identified at three sites; one at the north end of Hilton Head Island and two at Brunswick. Cells assigned to these sites in the Savannah area and Glynn County models are called indicator sites. The indicator site in the Savannah area model for seawater encroachment is cell (36,70). The indicator sites in the Glynn County model for saltwater intrusion at Brunswick are cells (60,49) and (66,48) (fig. 12) (Randolph and Krause, 1990, pl. 3). The development potential of the Lower Floridan aquifer was beyond the scope of this study and was not evaluated.

Any increase in pumpage that causes water-level decline at any of the three indicator sites was considered unacceptable. Simulation of "no change," or absolute zero, is not practical because of computational accuracy. Thus, a simulated value of ground-water-level decline of 0.05 ft was adopted to represent no-change, or zero decline. However, stabilizing potentiometric heads at indicator sites at current levels might not prevent future lateral encroachment of seawater. Landward encroachment will continue to occur along previously established head and concentration gradients. The Savannah area model simulates lateral flow of water of constant density and cannot address conditions of variable-density flow, such as landward encroachment of seawater into freshwater aquifers.

To estimate the development potential of the Upper Floridan aquifer, hypothetical pumpage increases were simulated independently at 24 cells randomly distributed and areally dispersed throughout the study area (table 12, pl. 11). A selected pumping rate, at each of the 24 sites, was considered acceptable if the simulated water-level decline was less than 0.05 ft (no change) at each of the three indicator sites. If the simulation resulted in no change at all three indicator sites, the pumping rate at the pumping site was increased, another simulation was performed, and the results were analyzed using the same criteron.

After the maximum pumping rate was determined for each of the 24 cells, a map was constructed showing lines of equal rates of ground-water-

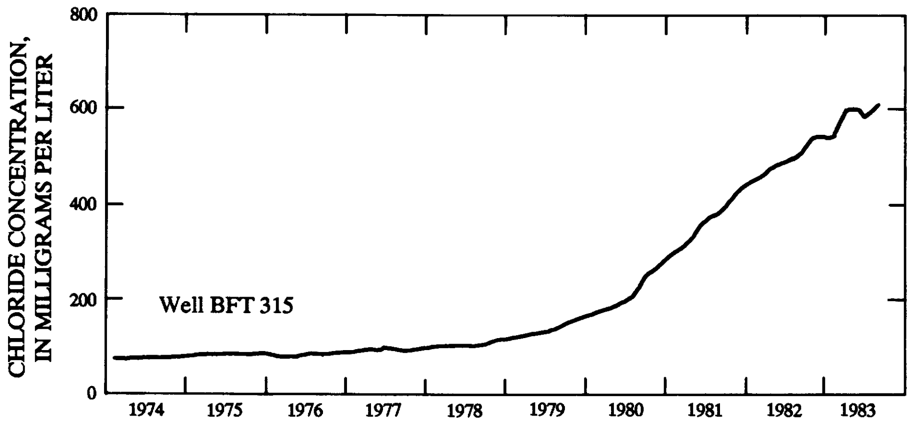


Figure 10.—Chloride concentration in water from well BFT315, Hilton Head Island, 1974-83.

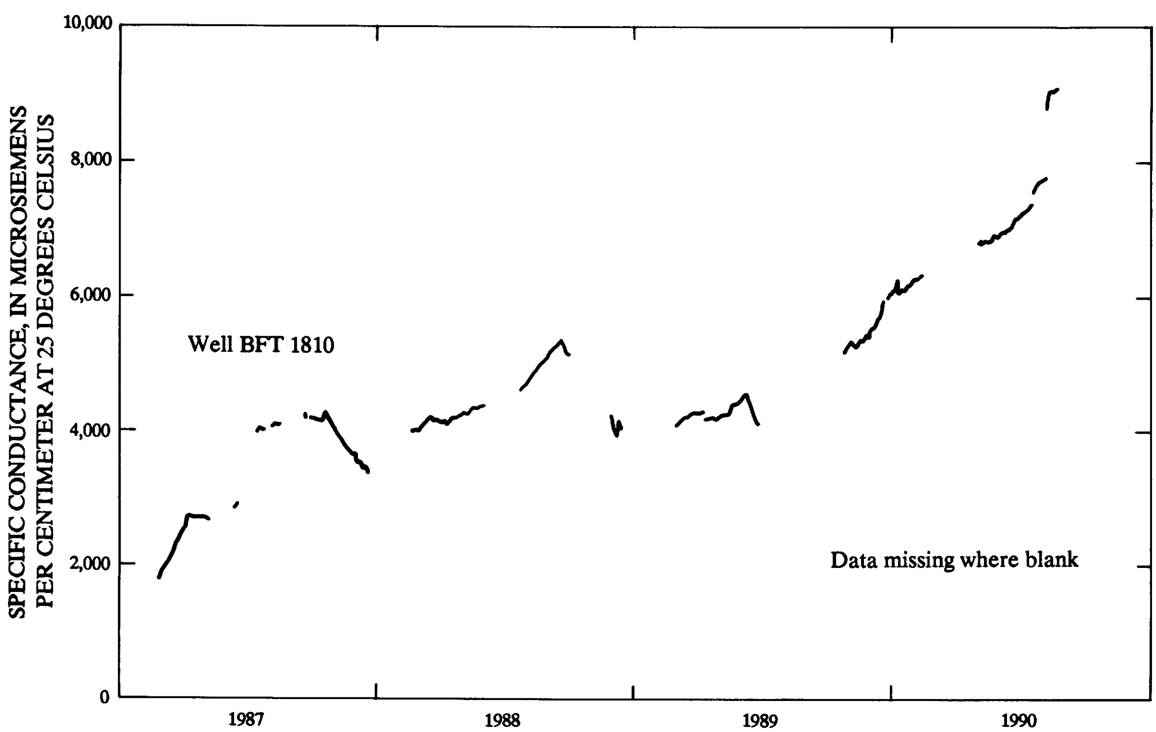


Figure 11.—Specific conductance of water from well BFT1810, Hilton Head Island, 1987-90.

development potential (pl. 11). The map shows the estimated rate of additional ground-water withdrawal that the Upper Floridan aquifer may support without causing water-level decline at the indicator sites. The potential rates indicate the total increase in pumpage allowable from one or more wells at a single cell (pl. 11). The analysis considers that additional pumping can occur in only one cell. If additional pumpage occurs in more than one cell, the effects on the water levels at the indicator sites are cumulative, and depending on their location, the no-change constraints may be violated. For example, the development po-

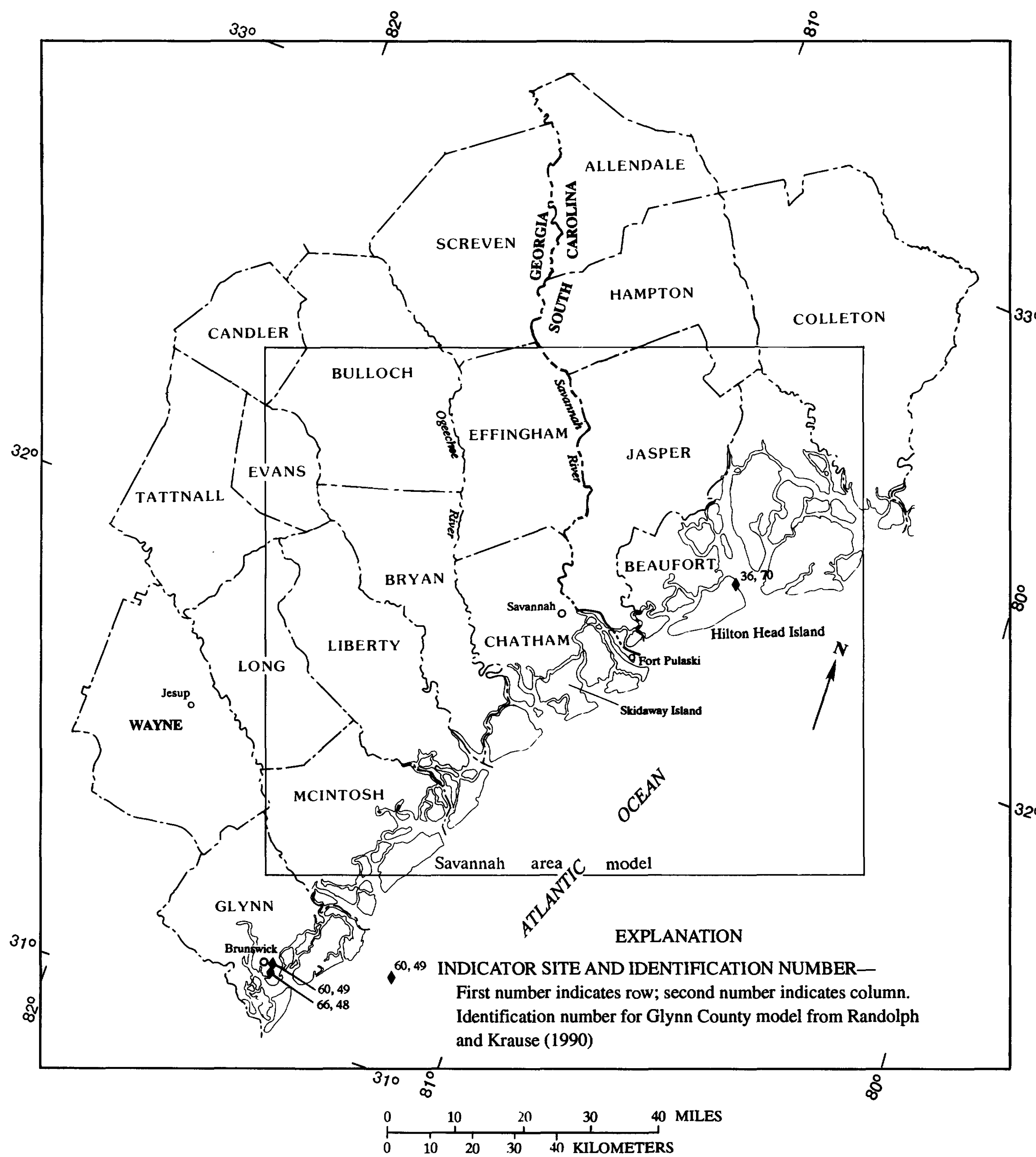


Figure 12.—Indicator sites of seawater encroachment at Hilton Head Island, and saltwater intrusion at Brunswick.

tential at Savannah Beach, in eastern Chatham County, is about 1 Mgal/d (pl. 11). However, if that additional pumpage occurred there, pumpage at a second location along the 1 Mgal/d development potential line would have to be relatively small because the cumulative effect of additional pumpage in excess of 1 Mgal/d may violate the no-change constraint at the indicator sites.

The potential for additional ground-water development under the no-change constraints increases with distance from the indicator sites. The area where the potential for ground-water development is greater than 5 Mgal/d is in the northeastern part of the study area, away from the areas of known encroachment and intrusion, and in an area where the Upper Floridan aquifer has comparatively low transmissivity (pl. 11). Although development potential in the northern part of the study area is comparatively large, well yields may be small because of low transmissivity. If additional water supplies were developed in that area, pumping could produce relatively deep, but areally limited, cones of depression.

In the Beaufort County, S.C., area, the estimate of development potential was based only on the constraints of water-level change at the indicator sites, primarily at Hilton Head Island. However, coastal areas in the rest of Beaufort County, east of the Broad River, also may be subject to local seawater encroachment (Hassen, 1985, p. 14). The development potential map and the hypothetical alternatives simulated and discussed in this report do not consider such constraints for that area, only that at the north end of Hilton Head Island. Thus, the potential for additional ground-water development in the Beaufort County area probably is less than that shown on plate 11 if additional constraints were applied.

Although the Upper Floridan aquifer may pinch out northeast of the Combahee River (Krause and Randolph, 1989, p. D21), the aquifer is simulated in that part of the area by using low values of transmissivity. Because of the uncertainty regarding the hydrogeology of the area, development potential of the Upper Floridan aquifer in that area is not addressed (pl. 11).

The simulated ground-water-development potential in the area of Hilton Head Island is less than 1 Mgal/d. The area includes the southern part of Beaufort County and all of Hilton Head Island. Additional ground-water withdrawal greater than 1 Mgal/d in this area probably would lower ground-water levels and accelerate the rate of seawater encroachment at the north end of Hilton Head Island. Simulated ground-water-development potential also is less than 1 Mgal/d in the southwestern part of the model area (pl. 11), because of the no-change constraints at the indicator sites near Brunswick.

The ground-water-development potential in the Georgia part of the Savannah area model is different than that estimated for the corresponding area by Randolph and others (1991). The difference can be attributed to changes (refinements) made to the RASA and Glynn County models during calibration and acceptance testing of the Savannah area model. Differences in estimated development potential mainly are (1) an increase in potential in the immediate Chatham County area of from 1 Mgal/d or less, to about 2 Mgal/d and (2) a decrease in potential in the southwestern part of the model areas, which in Randolph and others (1991) had a potential of less than 3 Mgal/d, to less than 1 Mgal/d. Although the differences in estimated ground-water-development potential seem to be substantial (compare potential reported by Randolph and others (1991, fig. 3) with those given in this report, plate 11), the pumping rates are comparatively small. The drawdown at the northernmost indicator site (60,49) in Brunswick is about 0.07 ft, when pumping 1 Mgal/d at cell (45,30) in Bryan County, and about 0.13 ft, when pumping the same quantity at cell (68,12) in McIntosh County. The difference in drawdown at the indicator site in Brunswick resulting from these pumping rates at the two locations is only 0.06 ft, even though the pumping locations are nearly 30 mi apart. The estimated development potential at these two locations is about 0.8 Mgal/d at cell (45,30) and about 0.4 Mgal/d at cell (68,12), a difference of only 0.4 Mgal/d.

The development potential map (pl. 11) indicates that the potential of the Upper Floridan aquifer to supply additional water is limited. Additional supplies can be developed without lowering heads at the indicator sites by the redistribution of current pumping. In order to reduce heads at the indicator sites, overall reductions in pumpage from the Upper Floridan aquifer may be required. Hypothetical alternatives of redistribution and decreases in pumpage were evaluated using the models. In addition, an alternative of redistribution in pumpage combined with an increase in pumpage was simulated and evaluated. Results of these alternatives are discussed in the following section.

Table 12.—Hypothetical pumping sites, selected pumping rates, and resulting simulated water-level changes in Upper Floridan aquifer at indicator sites

[Mgal/d, million gallons per day]

Location of pumping site[1] (row, column)	Pumping rate[2] (Mgal/d)	Simulated water-level decline, in feet, at indicator sites designated by row and column		
		[3]36,70	[4]60,49	[4]66,48
4,45	5	0.03	0.03	0.03
7,69	4	.03	.01	.01
8,56	3	.04	.02	.02
9,17	5	.02	.18	.17
10,65	2	.03	.01	.01
12,36	4	.04	.09	.08
15,58	1	.02	.01	.01
17,64	1	.02	.01	.01
22,11	1	.00	.06	.05
25,44	2	.05	.06	.05
25,73	2	.02	.00	.00
26,61	1	.05	.01	.01
28,21	3	.02	.16	.14
36,49	1	.04	.02	.02
39,59	1	.09	.02	.01
40,8	3	.01	.24	.22
41,43	2	.05	.09	.08
45,30	2	.02	.13	.12
45,54	1	.05	.03	.02
50,45	1	.02	.05	.04
52,35	4	.05	.26	.24
56,10	2	.01	.19	.17
57,24	2	.01	.18	.16
68,12	1	.00	.13	.11

[1]Location on plate 11.

[2]Pumping rates selected are examples and do not necessarily correspond to estimated development potential. Development potential at pumping sites shown on plate 11 may be less or greater than that shown here.

[3]Indicator site in Savannah area model.

[4]Indicator site in Glynn County model (Randolph and Krause, 1990, pl. 3).

Hypothetical Ground-Water-Development Alternatives

Eight hypothetical ground-water development alternatives tested as part of this study are discussed in this section. All the alternatives were simulated by using the Savannah area and Glynn County models, and were evaluated on the basis of the water-level change criteria at the indicator sites described previously.

For the following alternatives, pumping rates and locations were arbitrarily chosen. A redistribution of pumpage involves a decrease in pumpage at an existing location or locations and the assignment of that pumpage to a new location or locations. All alternatives are restricted to pumping from the Upper Floridan aquifer, except for those involving a decrease in or a redistribution of pumpage in Savannah, in which a small proportion of the pumpage change is in the Lower Floridan aquifer. The changes in pumpage for all alternatives discussed in this report are summarized in table 13 and the effects of those changes on water levels at the indicator sites are presented in table 14 and in the section "Evaluation of alternatives." Although water-level changes are discussed for both models, the maps (pls. 12-19) presented are exclusively for the area of the Savannah area model.

Table 13.—Hypothetical alternatives of changes in pumpage

[+, increase in pumpage; -, decrease in pumpage; –, not applicable]

Location of pumpage change (row, column)	Pumpage change for indicated hypothetical pumping alternative, in million gallons per day							
	1	2	3	4	5	6	7	8
31,41	—	—	—	—	+5.0	+5.0	—	—
36,36	+14.0	—	—	—	—	—	—	—
36,38	—	—	—	+5.0	—	—	—	—
36,67	-.1	—	—	—	—	—	—	-0.1
36,68	-.1	—	—	—	—	—	—	-.1
37,42	-4.6	-3.6	-9.1	-9.1	—	—	-5.5	—
37,43	-5.4	-3.0	-7.6	-7.6	-6.0	-6.0	-4.5	—
37,57	+2.3	—	—	—	—	—	—	—
38,42	—	-.2	-.6	-.6	—	—	-.4	—
38,68	—	—	—	—	—	—	—	-.1
38,69	-.1	—	—	—	—	—	—	-.1
38,70	-.1	—	—	—	—	—	—	-.1
39,32	—	—	—	—	—	+5.0	—	—
39,43	—	-1.3	-3.3	-3.3	-4.0	-4.0	-2.0	—
39,66	-.1	—	—	—	—	—	—	-.2
39,67	-.3	—	—	—	—	—	—	-.3
40,42	—	-.2	-.4	-.4	—	—	-.2	—
40,43	—	-1.0	-2.5	-2.5	—	—	-1.5	—
40,46	—	-.3	-.7	-.7	—	—	-.4	—
40,69	-.1	—	—	—	—	—	—	-.1
41,10	—	-.3	—	—	—	—	—	—
41,45	—	-.9	-2.2	-2.2	—	—	-1.4	—
41,61	-.2	—	—	—	—	—	—	-.2
41,65	-.1	—	—	—	—	—	—	-.1
41,66	-.4	—	—	—	—	—	—	-.5
42,10	—	-.6	—	—	—	—	—	—
42,11	—	-.3	—	—	—	—	—	—
42,42	—	-.5	-1.1	-1.1	—	—	-.7	—
42,43	—	-.1	-.1	-.1	—	—	-.1	—
42,60	-.1	—	—	—	—	—	—	-.1
42,61	-.2	—	—	—	—	—	—	-.2
42,63	-.4	—	—	—	—	—	—	-.4
43,34	—	—	—	+5.0	—	—	—	—
43,42	—	—	-.1	-.1	—	—	-.1	—
43,43	—	-.6	-1.4	-1.4	—	—	-.9	—
44,38	—	-.4	-1.0	-1.0	—	—	-.6	—
44,39	—	-.3	-.8	-.8	—	—	-.5	—
44,40	—	-.4	-.9	-.9	—	—	-.6	—
45,37	—	—	—	—	+5.0	—	—	—
45,38	—	-.3	-.7	-.7	—	—	-.4	—
54,18	—	-2.6	—	—	—	—	—	—
NET	+4.0	-16.9	-32.5	-22.5	0	0	-19.8	-2.6

Table 14.—Water-level changes at indicator sites resulting from hypothetical pumping alternatives

[–, decrease in water level; +, increase in water level]

Location of indicator site (row, column)	Water-level change, for indicated hypothetical pumping alternative, in feet							
	1	2	3	4	5	6	7	8
36,70	+0.29	+0.37	+0.86	+0.68	+0.07	+0.08	+0.53	+0.49
[1]60,49	–.28	+.13	+1.45	+.94	–.03	–.04	+.90	+.02
[1]66,48	–.25	+.10	+1.35	+.86	–.03	–.03	+.82	+.02

[1]Location of indicator site in Glynn County model (Randolph and Krause, 1990, pl. 3). Water-level changes simulated using the Glynn County model.

Alternative 1: Redistributed and increased pumpage in Beaufort County, South Carolina, and Chatham County, Georgia

This alternative combines a decrease in pumpage of 2.3 Mgal/d at Hilton Head Island and increase in pumpage of 2.3 Mgal/d at a site west of Hilton Head Island, in Beaufort County, with a decrease in pumpage of 10 Mgal/d at Savannah and increase in pumpage of 14 Mgal/d at a site 10 mi west of the city (table 13, alternative 1). Results of the simulations indicate that a water-level rise of about 0.3 ft would occur at the north end of Hilton Head Island, and a water-level decline of about 0.3 ft would occur at Brunswick (table 14, alternative 1). The water-level changes resulting from simulation of alternative 1 for the Savannah area model are shown on plate 12.

Alternative 2: Decrease in pumpage in Chatham and Liberty Counties, Georgia

This alternative involves a reduction in current pumpage by 16.9 Mgal/d (table 13, alternative 2) in the area of largest ground-water withdrawal. Simulation of this pumping alternative indicates a general water-level rise in the study area. The largest water-level change occurs near Savannah, where water-level rises of about 20 ft are simulated (pl. 13). A rise of about 0.4 ft was simulated at the indicator site at Hilton Head Island and a rise of about 0.1 ft at the indicator sites at Brunswick (table 14, alternative 2).

Alternative 3: Decrease in pumpage in Chatham County

This alternative involves a reduction in ground-water pumpage in Chatham County by 32.5 Mgal/d (table 13, alternative 3). Simulation of this pumping alternative indicates a ground-water level rise of about 0.9 ft at the north end of Hilton Head Island and a rise of about 1.4 ft at the indicator sites at Brunswick (table 14, alternative 3). A water-level rise of about 50 ft is indicated in the Savannah area (pl. 14).

Alternative 4: Decrease in pumpage and development of new pumping centers in Chatham County

This alternative involves a reduction in pumpage and the development of new pumping centers in Chatham County. Ground-water pumpage was reduced by 32.5 Mgal/d, and two pumping centers, pumping 5 Mgal/d each, were established in Chatham County (table 13, alternative 4). One new pumping center was located near the intersection of Highways I-95 and I-16, west of Savannah, and the second southwest of the city. Simulation of this pumping alternative indicates ground-water level rises of about 0.7 ft at the north end of Hilton Head Island and about 0.9 ft at the indicator sites in Brunswick (table 14, alternative 4). A water-level rise of about 40 ft in the Savannah area is also indicated (pl. 15).

Alternative 5: Redistribution of pumpage from Savannah to two locations northwest and southwest of the city in Chatham County

This alternative involves redistribution of pumpage totaling 10 Mgal/d in Chatham County. Pumpage was decreased by 10 Mgal/d near the center of the cone of depression in Savannah and increased by 5 Mgal/d at each of two locations in Chatham County, one northwest and the other southwest of Savannah (table 13, alternative 5). Simulation of this alternative indicates a water-level rise of about 0.06 ft at the indicator site on Hilton Head Island (pl. 16) and a water-level decline of about 0.03 ft at the indicator sites in Brunswick (table 14, alternative 5).

Alternative 6: Redistribution of pumpage from Savannah to two locations northwest and west of the city in Chatham County

This alternative is similar to that of alternative 5 except in the location of one of the two pumping sites. The 5 Mgal/d increase in pumpage occurs at the site northwest of Savannah (same location as in alternative 5), and at a second location west of the city of Savannah (table 13, alternative 6). Simulation of this alternative indicates water-level rise at the indicator site on Hilton Head Island of about 0.08 ft (pl. 17) and water-level declines of about 0.03 and 0.04 ft at the indicator sites in Brunswick (table 14, alternative 6).

Alternative 7: Decrease in pumpage in the vicinity of Savannah

This alternative involves reduced pumpage at various locations in Chatham County (table 13, alternative 7) totaling 19.8 Mgal/d. Simulation of this pumping alternative indicates a general water-level rise (pl. 18). Water-level rises of about 0.5 ft at the indicator site on Hilton Head Island and about 0.9 ft and 0.8 ft at the indicator sites in Brunswick were simulated (table 14, alternative 7).

Alternative 8: Decrease in pumpage on Hilton Head Island, South Carolina

This alternative involves a reduction in pumpage of 2.6 Mgal/d, distributed throughout Hilton Head Island (table 13, alternative 8). Simulation of this alternative indicates a general water-level rise, mainly in the area of the island (pl. 19). Water-level rises of about 0.5 ft at the indicator site on the north end of Hilton Head Island and 0.02 ft at the indicator sites in Brunswick were simulated (table 14, alternative 8).

Evaluation of alternatives

Analysis of the results of eight hypothetical ground-water development alternatives confirms that the potential for withdrawing additional water from the Upper Floridan aquifer is limited. The alternative that involved 4 Mgal/d net increase in pumpage (alternative 1) did not adversely affect the water level at the indicator site at Hilton Head Island as a result of the redistribution of pumpage in that immediate area. However, ground-water levels declined at the indicator sites in Brunswick, even though redistribution was included in the alternative.

Simulation of ground-water levels for management alternatives involving redistributions of pumpage with no net change in overall pumping rates in the model area (alternatives 5 and 6) satisfy the constraint of not increasing water-level decline at the sites of high salinity. Simulation of the two alternatives indicated water-level rises at the indicator site on Hilton Head Island and water-level declines of less than 0.05 ft at the indicator sites in Brunswick. These ground-water management alternatives would involve decreases in pumpage in the area of the cone of depression and increases in pumpage in other areas (pls. 16 and 17). These alternatives may allow ground-water development in areas where access to distributed sources of water might be limited.

Results of the simulation of the alternative that involves a 32.5 Mgal/d decrease in pumpage in the Savannah area and the redistribution of 10 Mgal/d of that decrease to two locations west and southwest of the city (alternative 4) also satisfy the constraints of not increasing water-level decline at the sites of high salinity. Simulation of this alternative indicates water-level rises at all indicator sites (table 14) as a result of the comparatively large net reduction in pumpage of 22.5 Mgal/d. This alternative also would allow ground-water development in areas where access to distributed sources of water might be limited.

Results of the alternatives involving only decreases in pumpage (16.9, 32.5, 19.8, and 2.6 Mgal/d; alternatives 2, 3, 7, and 8, respectively) are expectably favorable in terms of ground-water level rise at the indicator sites. However, these alternatives and alternative 4 reduce the quantity of water supplied by the Upper Floridan aquifer to users in the area. If water-supply demands increase, water from other sources would be needed to meet these demands.

SUMMARY

The water-supply potential of major surface-water sources and the Upper Floridan aquifer were evaluated in the Savannah area. The analyses include assessing surface-water availability, estimating the potential for additional ground-water development, and

evaluating hypothetical ground-water development alternatives.

The Savannah and Ogeechee Rivers were evaluated as potential surface-water sources by conducting a statistical analysis of stream-discharge data and examination of stream water-quality data. Surface-water availability was limited by the constraint of maintaining the minimum average flow for seven consecutive days for 10-year recurrence interval (7Q10).

Results from the surface-water analysis indicate that 90 percent of the time the flows exceed the 7Q10 by about 900 cubic feet per second (ft^3/s) at Savannah River near Clyo, Ga., and by about 200 ft^3/s at Ogeechee River near Eden, Ga., and these rivers could support additional withdrawal. However, Georgia Department of Natural Resources, Environmental Protection Division, imposes a nondepletable flow criterion; thus, the actual quantity of water available for withdrawal would be less than flows in excess of minimum flow criteria, such as the 7Q10. On the basis of the properties and constituents analyzed, the quality of water at the sites is within the U.S. Environmental Protection Agency Primary and Secondary Drinking-Water Standards. Therefore, Savannah River near Clyo and Ogeechee River near Eden could be considered as potential sources of supply.

Salinity of water from the Upper Floridan aquifer has been reported in coastal Georgia and South Carolina as a result of pumping and consequent ground-water-level decline. Seawater encroachment is occurring at Hilton Head Island, and saltwater intrusion is occurring at Brunswick. Although Brunswick is not in the study area, it is affected by ground-water pumping in the study area.

Three ground-water flow models have been developed in the coastal area of Georgia and South Carolina and were used to estimate the potential for additional ground-water development. The models are the RASA, Glynn County, and Savannah area models. The Savannah area model was developed as part of this study to simulate the ground-water flow system at a greater resolution than previous models in the Savannah area. The Glynn and Savannah area models are subregional models that are within the area of the regional (RASA) model and utilize the RASA model to determine boundary conditions. The Savannah area model simulates the effects that increased pumpage could have on ground-water levels at the location of seawater encroachment at Hilton Head Island, and the Glynn County model simulates the effect that such pumpage could have on water levels at the location of saltwater intrusion at Brunswick. Based on model simulations and the constraint of preventing water-level declines at locations of encroachment and intrusion, the potential of the Upper Floridan aquifer to supply additional water in the Savannah area is limited under present (1985) hydrologic conditions. The water-supply potential ranges from less than 1 million gallons per day (Mgal/d) in Liberty, McIntosh, most of Bryan, and southern Chatham Counties, Ga., and in southern Beaufort County, S.C., to more than 5 Mgal/d in northern Jasper and northern Beaufort Counties, S.C.

The Glynn County and Savannah area models also were used to evaluate the effects that hypothetical pumping alternatives might have at the sites of seawater encroachment and saltwater intrusion. Eight hypothetical alternatives were simulated to consider redistribution, redistribution and small increases, and decreases in pumpage. Simulation of these hypothetical ground-water alternatives indicates that reduction and redistribution in pumpage would not adversely affect water levels in the areas where salinity has been reported and that additional development of the Upper Floridan aquifer is limited, even with pumping redistribution.

REFERENCES CITED

Burt, R.A., Belval, D.L., Crouch, Michael, and Hughes, W.B., 1987, Geohydrologic data form Port Royal Sound, Beaufort County, South Carolina: U.S. Geological Survey, Open-File Report 86-497, 67 p.

Bush, P.W., 1988, Simulation of saltwater movement in the Floridan aquifer system, Hilton Head Island, South Carolina: U.S. Geological Survey Water-Supply Paper 2331, 19 p.

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida, and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–C, 80 p.

Clarke, J.S., Hacke, C.M., and Peck, M.F., 1990, Geology and ground-water resources of the coastal area of Georgia: Georgia Geologic Survey Bulletin 113, 106 p.

Counts, H.B., and Donsky, Ellis, 1963, Salt-water encroachment, geology, and ground-water resources of Savannah area, Georgia and South Carolina: U.S. Geological Survey Water-Supply Paper 1611, 100 p.

Dyar, T.R., Tasker, G.D., and Wait, R.L., 1972, Hydrology of the Riceboro area, coastal Georgia: Georgia Water Quality Control Board, Final Report, 74 p.

Fanning, J.L., Doonan, G.A., and Montgomery, L.T., 1992, Water use in Georgia, by county for 1990: Georgia Geologic Survey Information Circular 90, 98 p.

Fanning, J.L., Doonan, G.A., Trent, V.P., and McFarlane, R.D., 1991, Power generation and related water use in Georgia: Georgia Geologic Survey Information Circular 87, 37 p.

Garza, Reggina, and Krause, R.E., 1992, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia: U.S. Geological Survey Open-File Report 92-629, 49 p.

Georgia Department of Natural Resources, 1990, Surface-water withdrawals, *in* Water-Quality Control Act, 1988-89: Atlanta, Environmental Protection Division, Chap. 391-3-6-.07.

Hassen, J.A., 1985, Ground-water conditions in the Ladies and St. Helena Islands area, South Carolina: South Carolina Water Resources Commission Report 147, 56 p.

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

Inman, E.J., 1971, Flow characteristics of Georgia streams: U.S. Geological Survey Open-File Report, 262 p.

Johnston, R.H., Krause, R.E., Meyer, F.W., Ryder, P.D., Tibbals, C.H., and Hunn, J.D., 1980, Estimated potentiometric surface for the Tertiary limestone aquifer system, southeastern United States, prior to development: U.S. Geological Survey Open-File Report 80-406, 1 sheet, scale 1:1,000,000.

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

McCallie, S.W., 1898, A preliminary report on the artesian-well system of Georgia: Georgia Geologic Survey Bulletin 7, 214 p.

———1908, A preliminary report on the underground waters of Georgia: Georgia Geologic Survey Bulletin 15, 376 p.

McCollum, M.J., and Counts, H.B., 1964, Relation of salt-water encroachment to the major aquifer zones, Savannah area, Georgia and South Carolina: U.S. Geological Survey Water-Supply Paper 1613–D, 26 p.

McCready, R.W., 1989, Water use and future requirements Hilton Head Island and vicinity South Carolina: South Carolina Water Resources Commission Report 168, 54 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Meeks, W.C., 1984, Daily values statistics (programs A969 and A193) in National Water Data Storage and Retrieval System (WATSTORE), *revised by* G.R. Dempster, Jr.: U.S. Geological Survey WATSTORE User's Guide, v. 1, chap. 4, p. G1-G38.

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

Newcome, Roy, Jr., 1989, Ground-water resources of South Carolina's Coastal Plain–1988, an overview: South Carolina Water Resource Commission Report 167, 127 p.

Randolph, R.B., and Krause, R.E., 1984, Analysis of the effects of proposed pumping from the principal artesian aquifer, Savannah, Georgia, area: U.S. Geological Survey Water-Resources Investigations Report 84-4064, 26 p.

———1990, Analysis of the effects of hypothetical changes in ground-water withdrawal from the Floridan aquifer system in the area of Glynn County, Georgia: U.S. Geological Survey Water-Resources Investigations Report 90-4027, 32 p.

Randolph, R.B., Pernik, Maribeth, and Garza, Reggina, 1991, Water-supply potential of the Floridan aquifer system in coastal Georgia—a digital model approach: Georgia Geologic Survey Bulletin 116, 30 p.

Seaber, P.R., Kapinos, F.P., and Knapp, G.L., 1987, Hydrologic Unit Maps: U.S. Geological Survey Water-Supply Paper 2294, 63 p.

Smith, B.S., 1988, Ground-water flow and saltwater encroachment in the Upper Floridan aquifer, Beaufort and Jasper Counties, South Carolina: U.S. Geological Survey Water-Resources Investigations Report 87-4285, 61 p.

———1993, Saltwater movement in the Upper Floridan aquifer beneath Port Royal Sound, South Carolina: U.S. Geological Survey Open-File Report 91-483. 64 p.

South Carolina Water Resources Commission, 1982, South Carolina Water Use Reporting and Coordinating Act: Columbia, February 1982, no. 282, sec. 49, chap. 4.

Spigner, B.C., and Ransom, Camille, III, 1979, Report on ground-water conditions in the Low Country area, South Carolina: South Carolina Water Resources Commission Report 132, 144 p.

Stephenson, L.W., and Veatch, J.O., 1915, Underground waters of the Coastal Plain of Georgia: U.S. Geological Survey Water-Supply Paper 341, 539 p.

Stokes, W.R., III, McFarlane, R.D., and Buell, G.R., 1989, Water-resources data, Georgia, water year 1988: U.S. Geological Survey Water-Data Report GA-88-1, 448 p.

U.S. Army Corps of Engineers, 1984, Metropolitan Savannah water-resource management study: Savannah, U.S. Army Corps of Engineers, Savannah District, Final Report, 83 p.

U.S. Environmental Protection Agency, 1986, Water-quality criteria summary, *in* Quality criteria for water: Washington, D.C., Office of Water, Regulation and Standards, EPA 440/5-86-001.

U.S. Geological Survey, 1975, Hydrologic unit map—1974, state of Georgia: U.S. Geological Survey, map series, scale 1:500,000, 1 sheet.

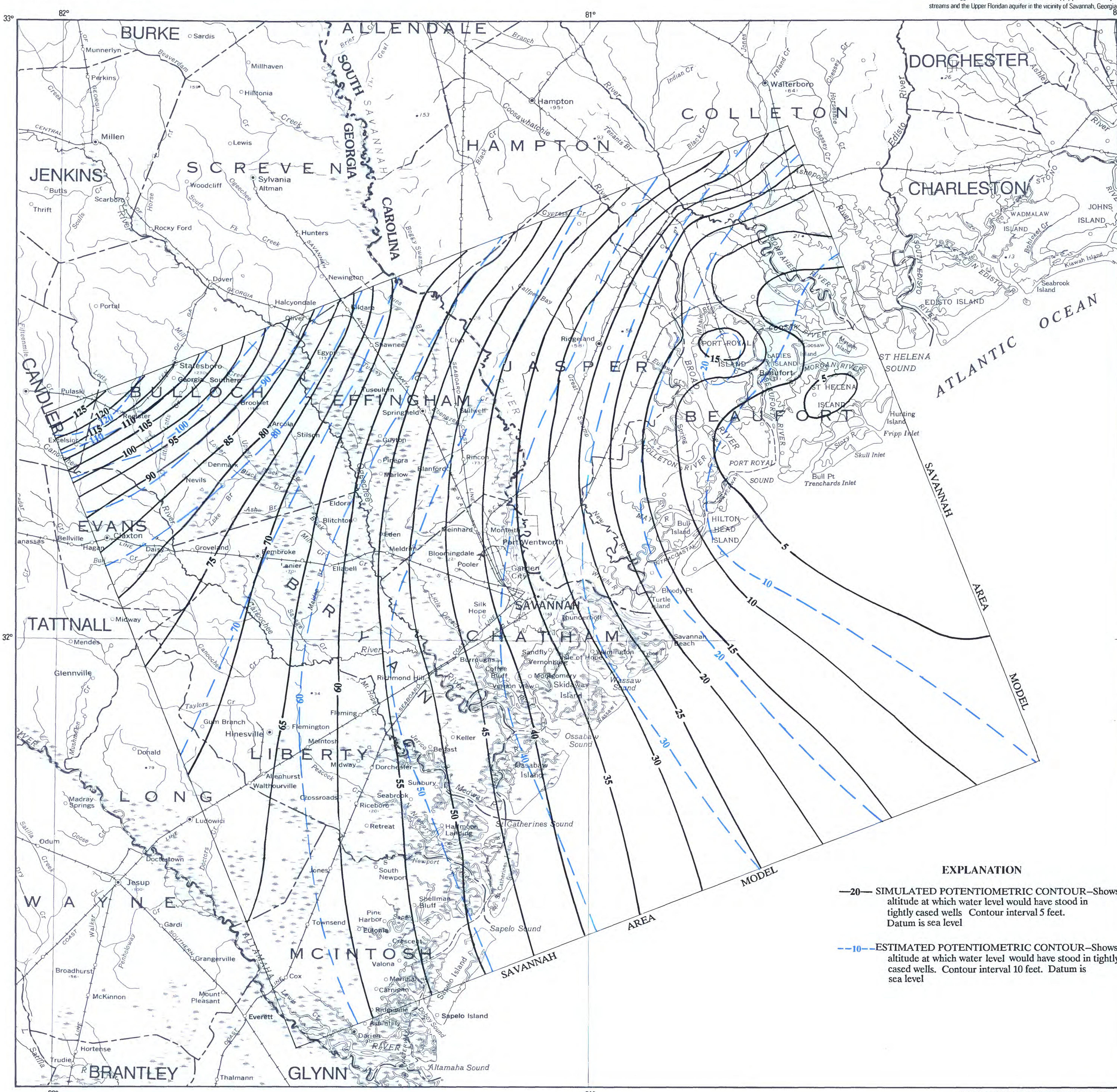
Voss, C.I., 1984, A finite-element simulation model for saturated, unsaturated, fluid density-dependent ground-water flow with energy transport or chemically-reactive single-species solute transport: U.S. Geological Survey Water-Resources Investigations Report 84-4369, 409 p.

Warren, M.A., 1944, Artesian water in southeastern Georgia with special reference to the coastal area: Georgia Geologic Survey Bulletin 49, 140 p.

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
CHATHAM COUNTY-SAVANNAH METROPOLITAN PLANNING COMMISSION

WATER-SUPPLY PAPER 2411
Configuration of potentiometric surface—Predevelopment—PLATE 1
Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

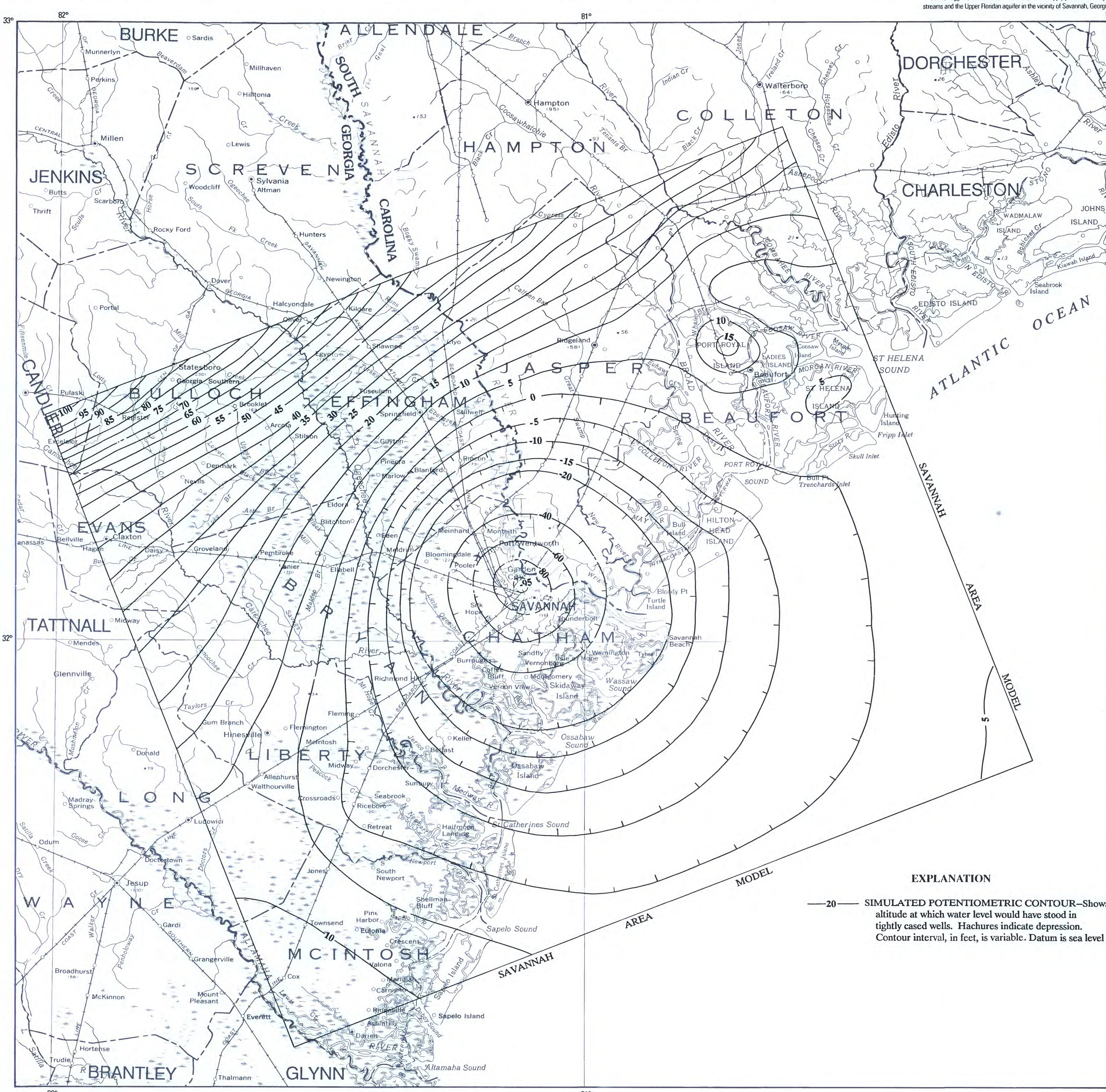
Estimated potentiometric contours from Johnston and others (1980)

MAP SHOWING SIMULATED AND ESTIMATED CONFIGURATION OF THE POTENTIOMETRIC SURFACE OF THE UPPER FLORIDAN AQUIFER FOR PREDEVELOPMENT (1880) CONDITIONS

By
Reggina Garza and Richard E. Krause

1997

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000

10 0 10 20 30 MILES

10 0 10 20 30 40 KILOMETERS

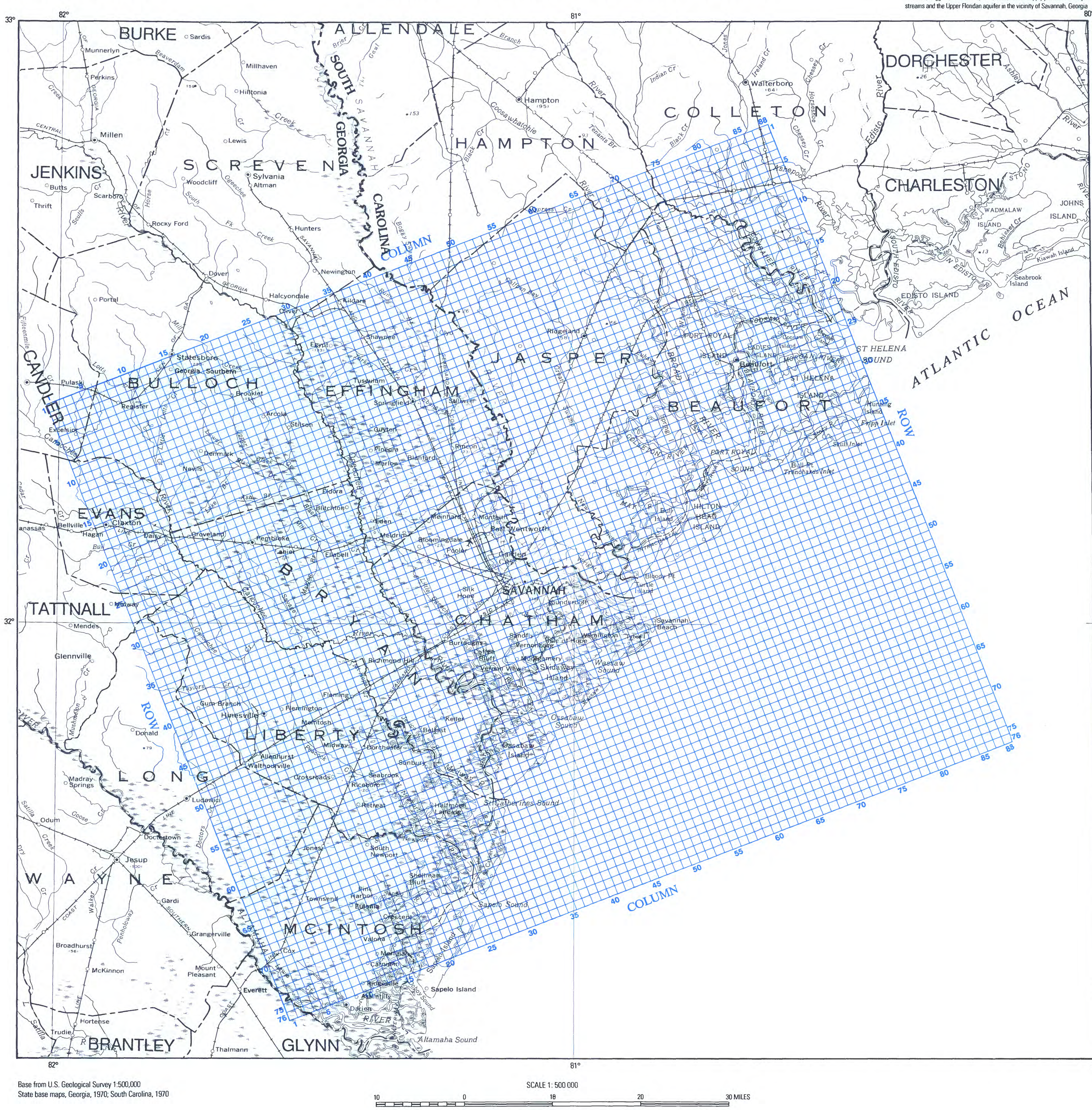
MAP SHOWING SIMULATED CONFIGURATION OF THE POTENTIOMETRIC SURFACE OF THE UPPER FLORIDAN AQUIFER, 1985

By

Reggina Garza and Richard E. Krause

1997

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

MAP SHOWING GRID FOR THE SAVANNAH AREA MODEL

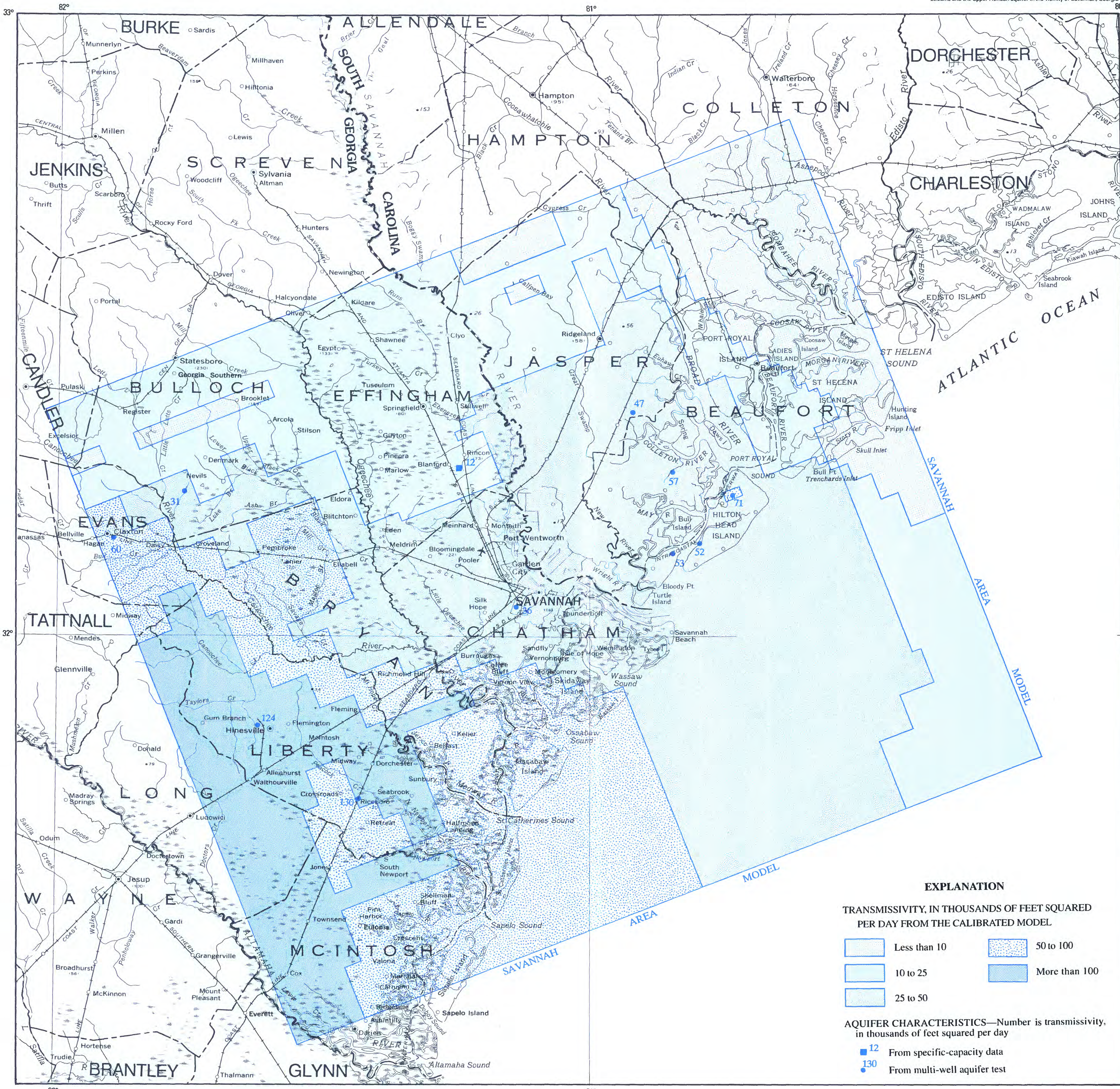
By
Reggina Garza and Richard E. Krause

1997

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION

WATER-SUPPLY PAPER 2411
Calibrated transmissivity distribution and calculated site values, Upper Floridan aquifer—PLATE 4
Garza, Reggina, and Krause, R.E., 1997, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

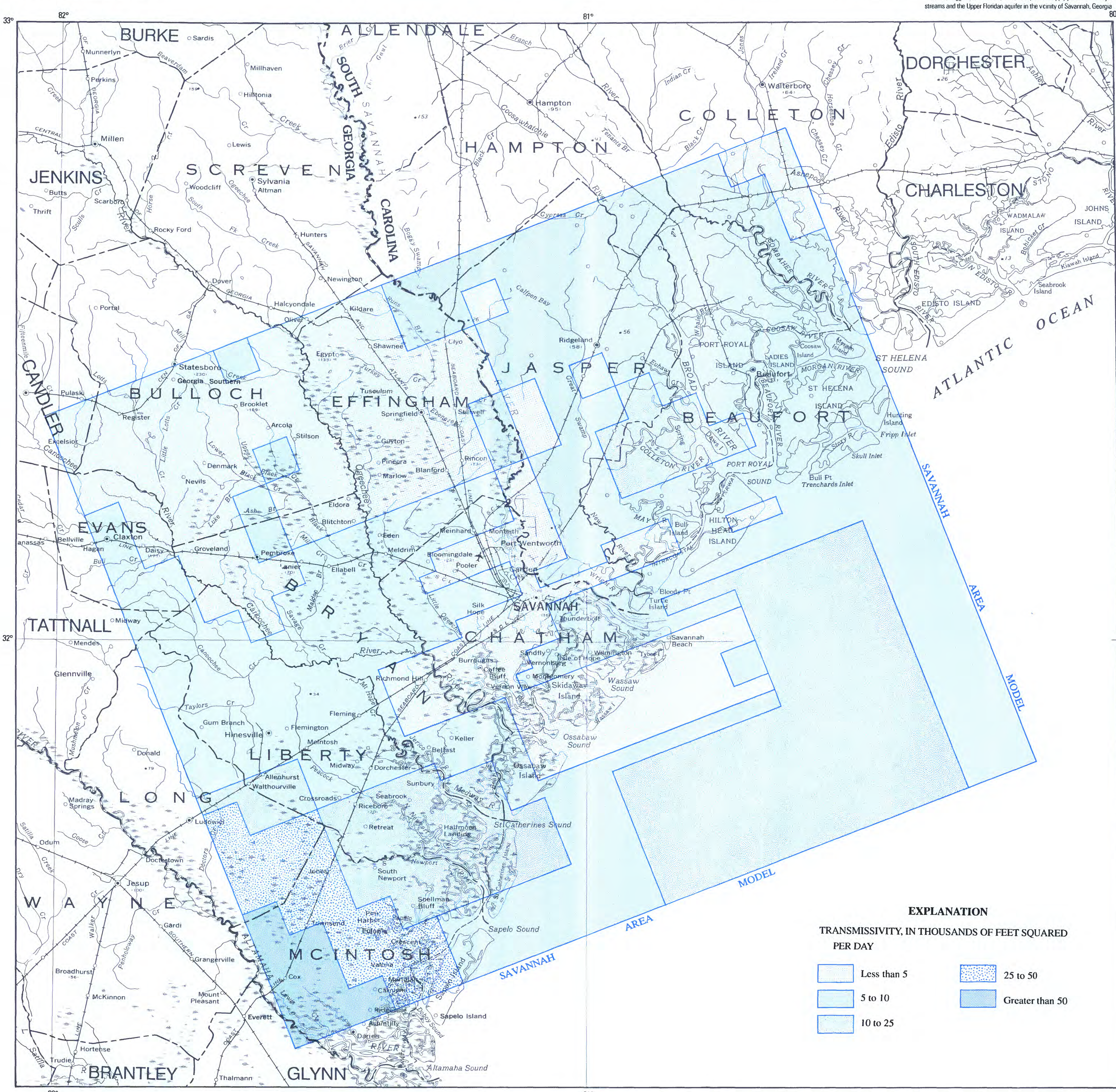
MAP SHOWING CALIBRATED TRANSMISSIVITY DISTRIBUTION AND SITE TRANSMISSIVITY VALUES CALCULATED FROM SPECIFIC-CAPACITY DATA AND MULTI-WELL AQUIFER TESTS, UPPER FLORIDAN AQUIFER

By
Reggina Garza and Richard E. Krause

1997

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

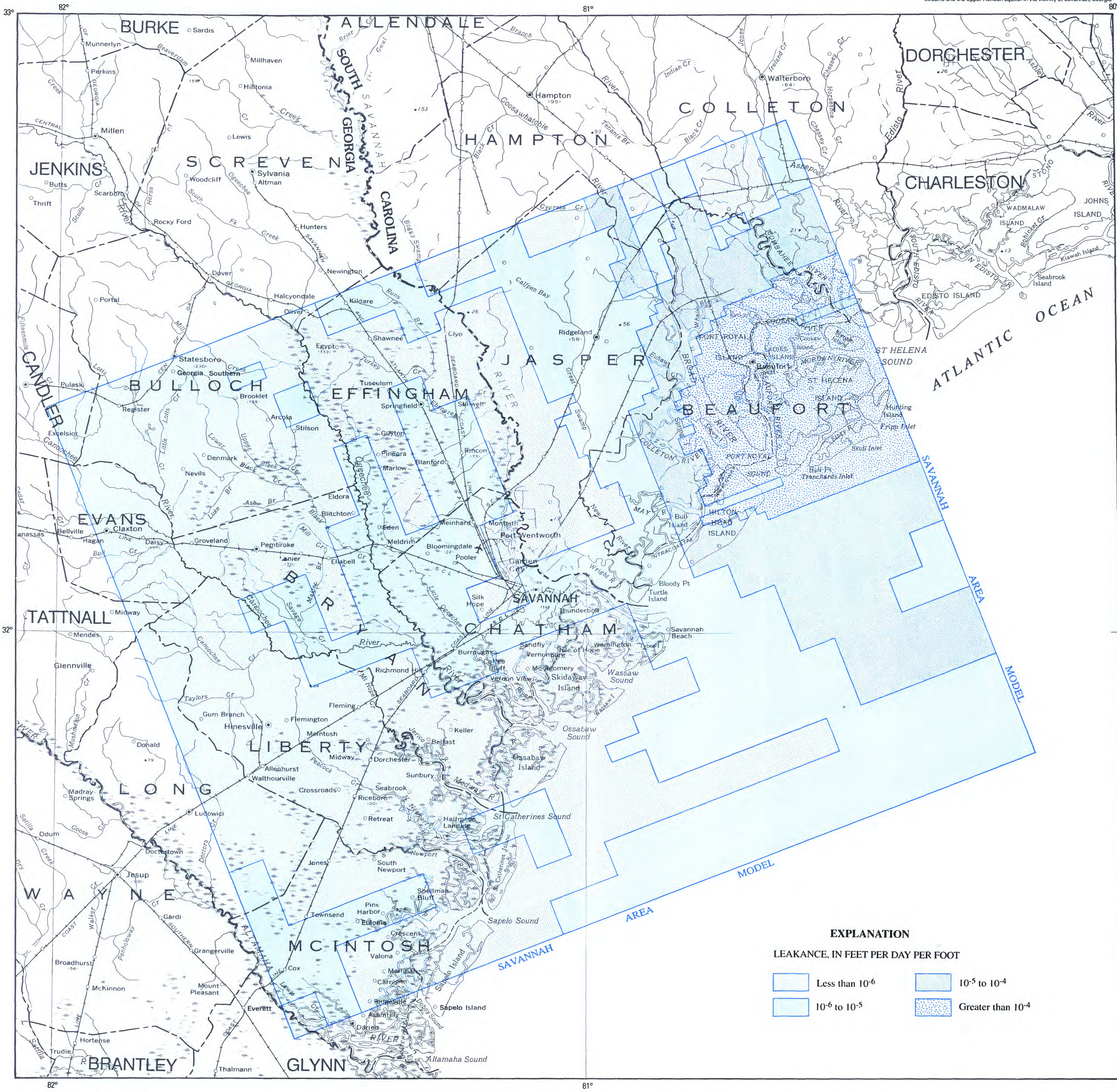
SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

MAP SHOWING CALIBRATED TRANSMISSIVITY DISTRIBUTION, LOWER FLORIDAN AQUIFER

By
Reggina Garza and Richard E. Krause

1997

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000

10 0 10 20 30 MILES

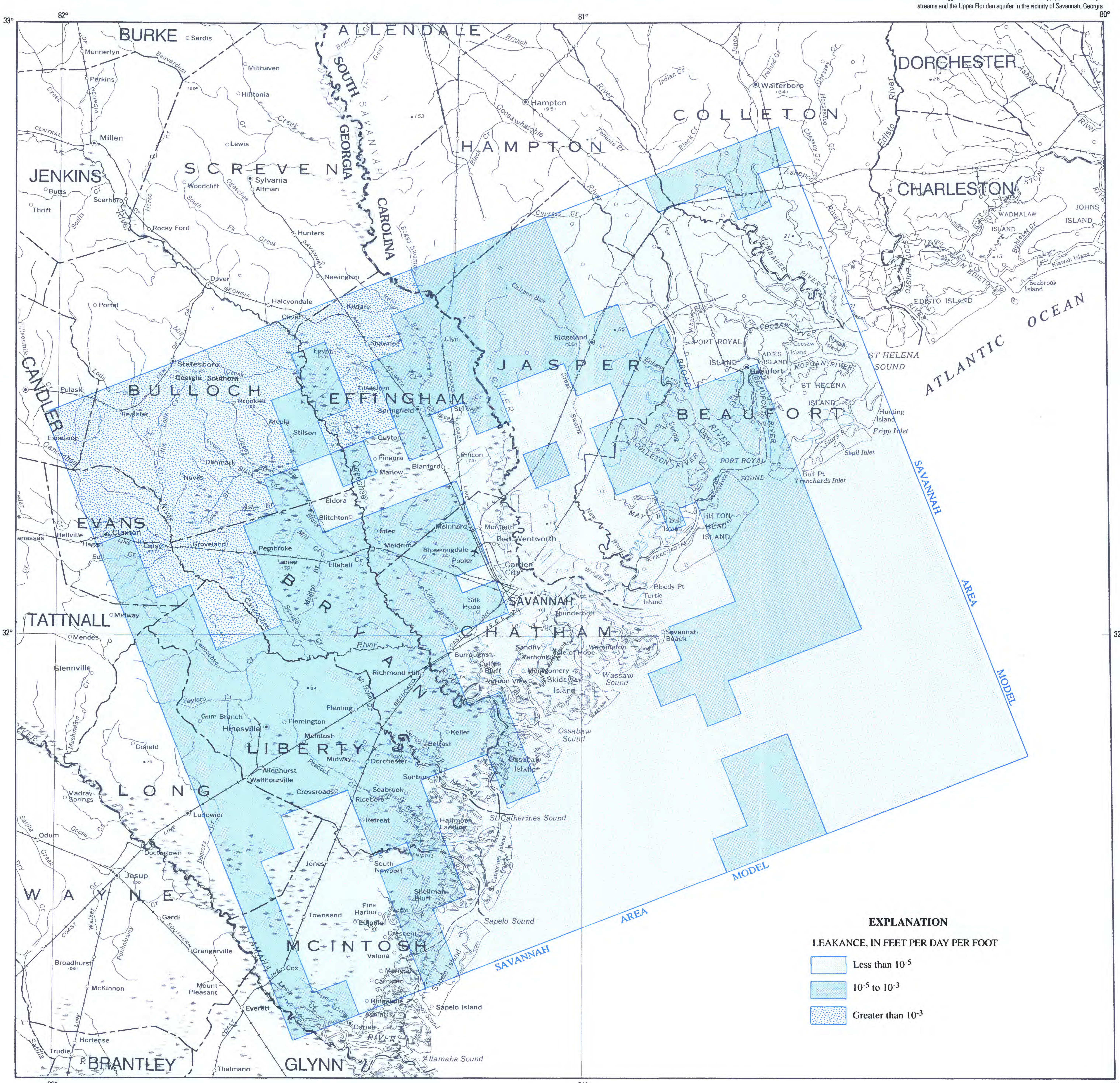
10 0 10 20 30 40 KILOMETERS

MAP SHOWING CALIBRATED LEAKANCE DISTRIBUTION, UPPER CONFINING UNIT

By
Reggina Garza and Richard E. Krause
1997

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



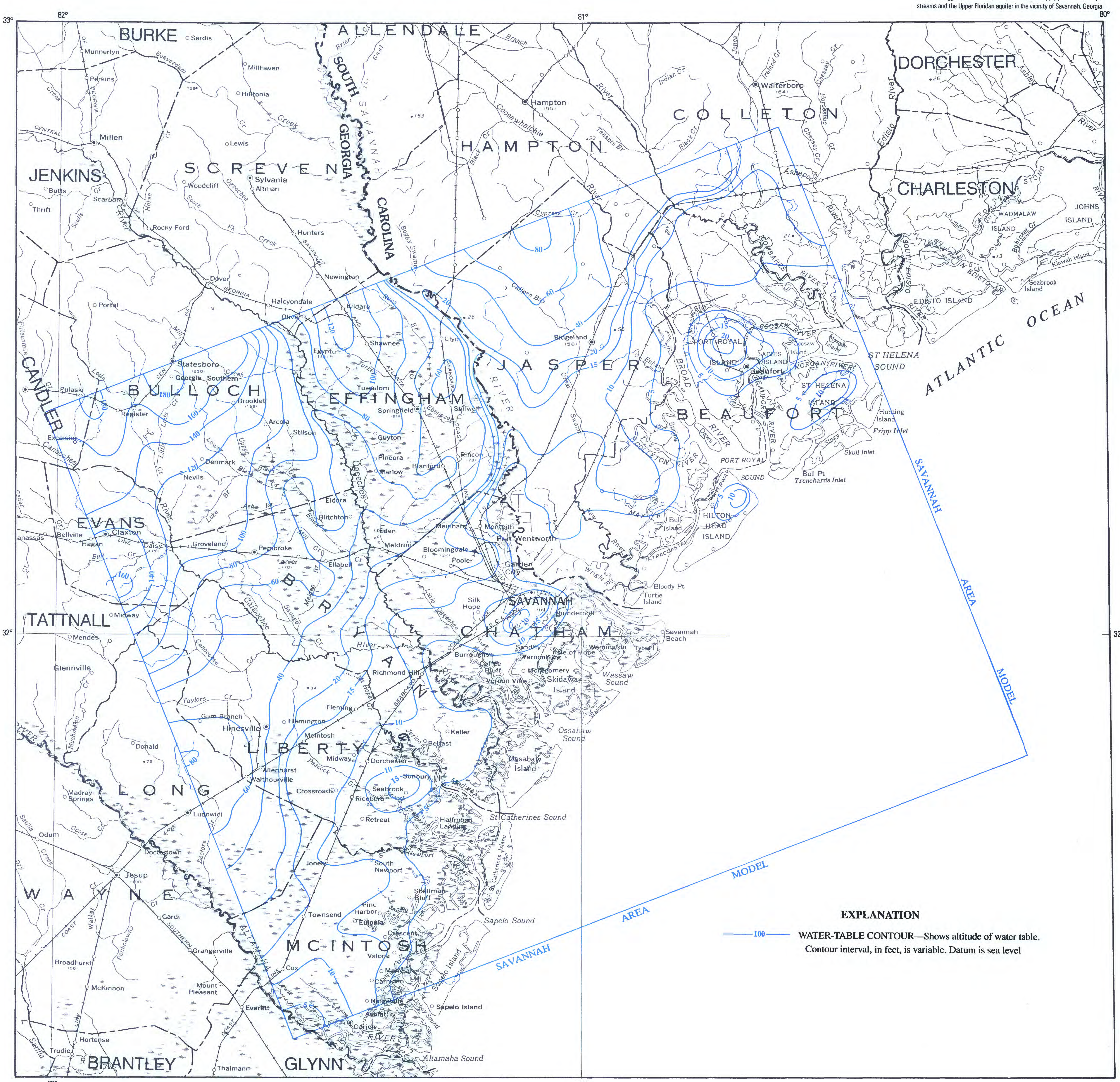
Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

MAP SHOWING CALIBRATED LEAKANCE DISTRIBUTION, MIDDLE SEMICONFINING UNIT

By
Reggina Garza and Richard E. Krause
1997

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

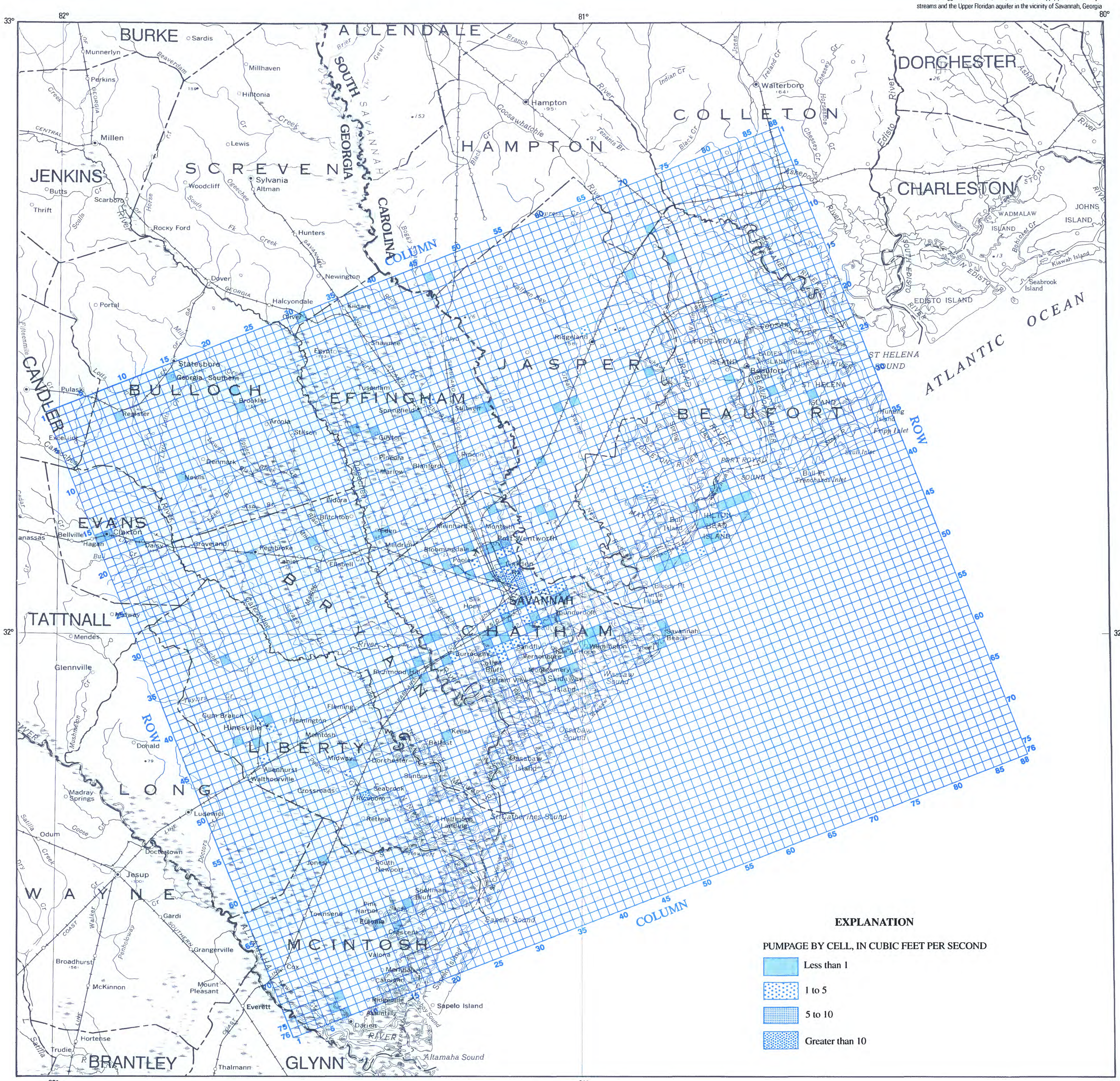
MAP SHOWING ESTIMATED WATER-TABLE SURFACE, SURFICIAL AQUIFER, 1985

By
Reggina Garza and Richard E. Krause

1997

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

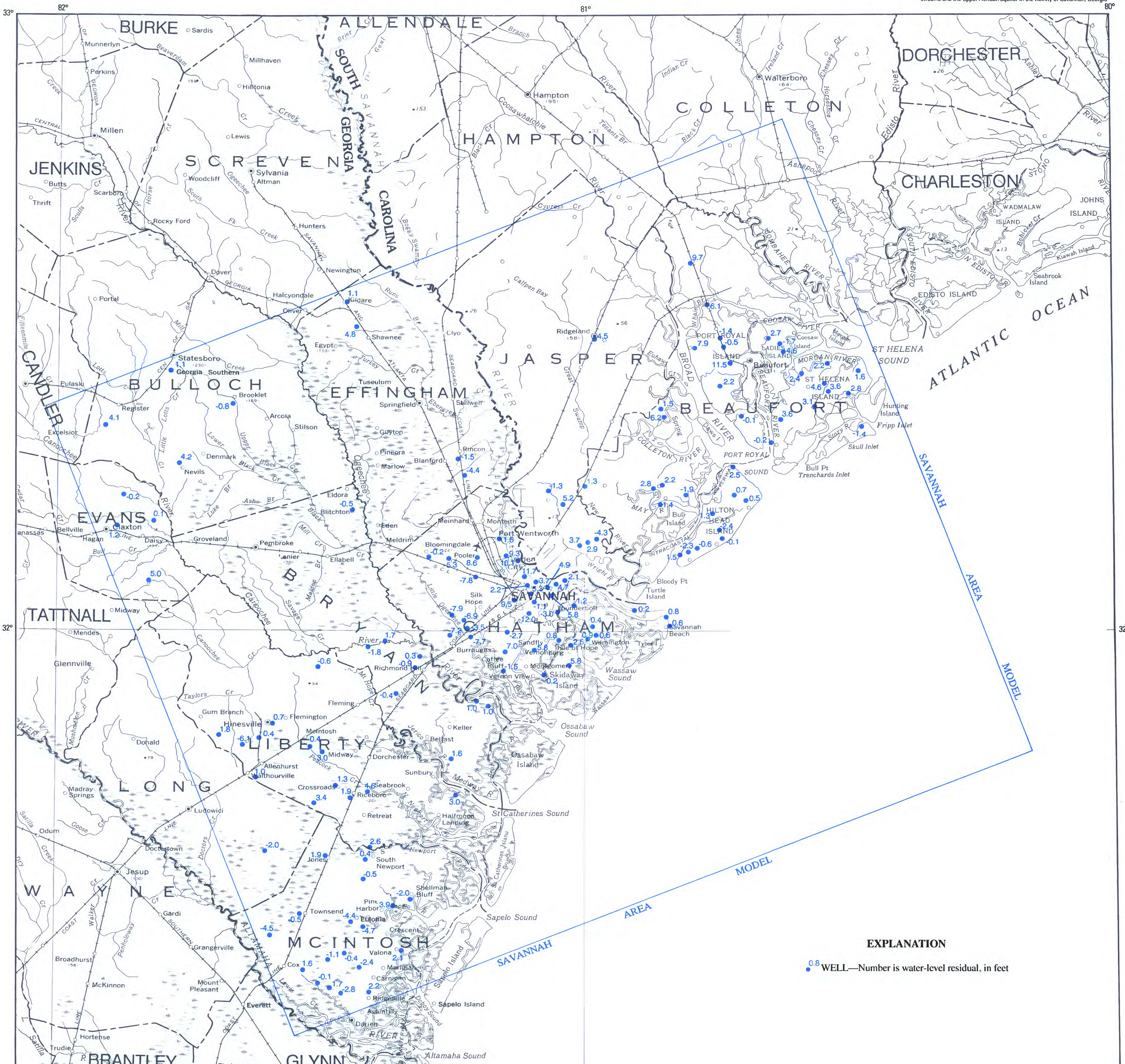
SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

MAP SHOWING DISTRIBUTION OF 1985 PUMPAGE USED FOR MODEL CALIBRATION, UPPER FLORIDAN AQUIFER

By
Reggina Garza and Richard E. Krause

1997

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000

10 0 10 20 30 MILES

10 0 10 20 30 40 KILOMETERS

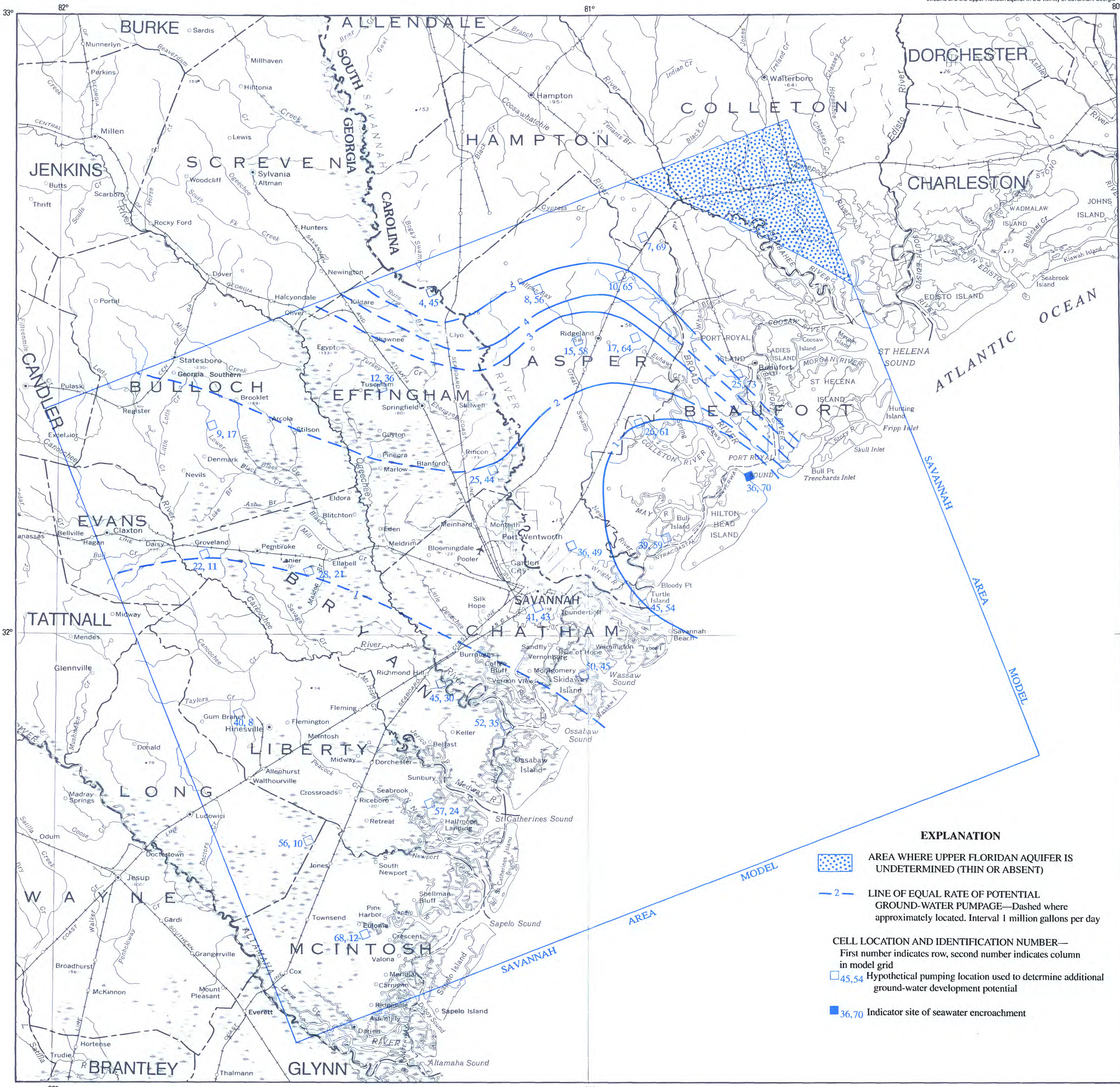
MAP SHOWING WATER-LEVEL RESIDUALS IN THE UPPER FLORIDAN AQUIFER COMPUTED USING RESULTS FROM THE CALIBRATED (1985) SAVANNAH AREA MODEL

By

Reggina Garza and Richard E. Krause

1997

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000

10 0 10 20 30 MILES

10 0 10 20 30 40 KILOMETERS

MAP SHOWING ESTIMATED GROUND-WATER DEVELOPMENT POTENTIAL OF THE UPPER FLORIDAN AQUIFER

By

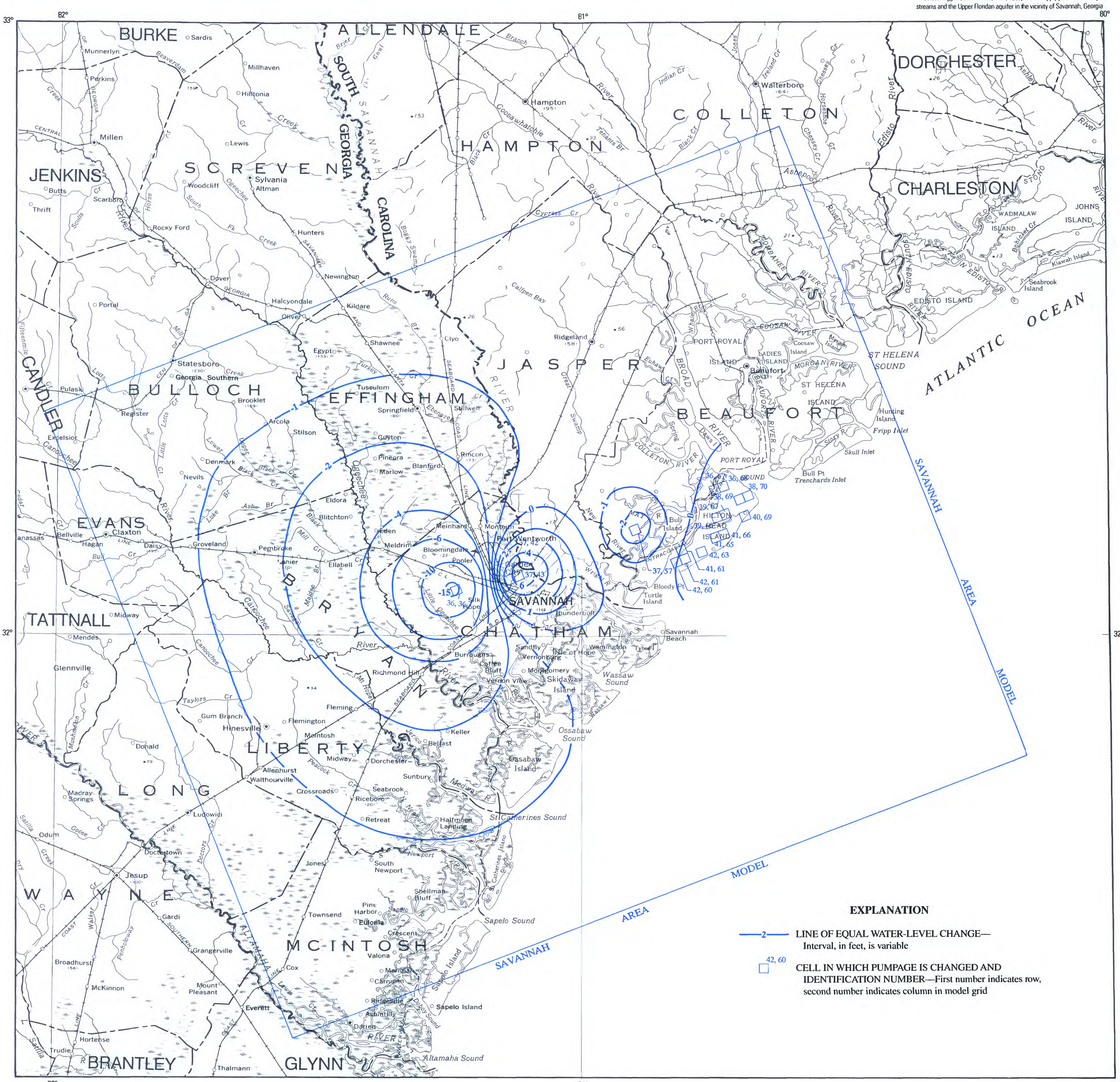
Reggina Garza and Richard E. Krause

1997

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION

WATER-SUPPLY PAPER 2411
Simulated water-level change (alternative 1)—PLATE 12
Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1:500 000

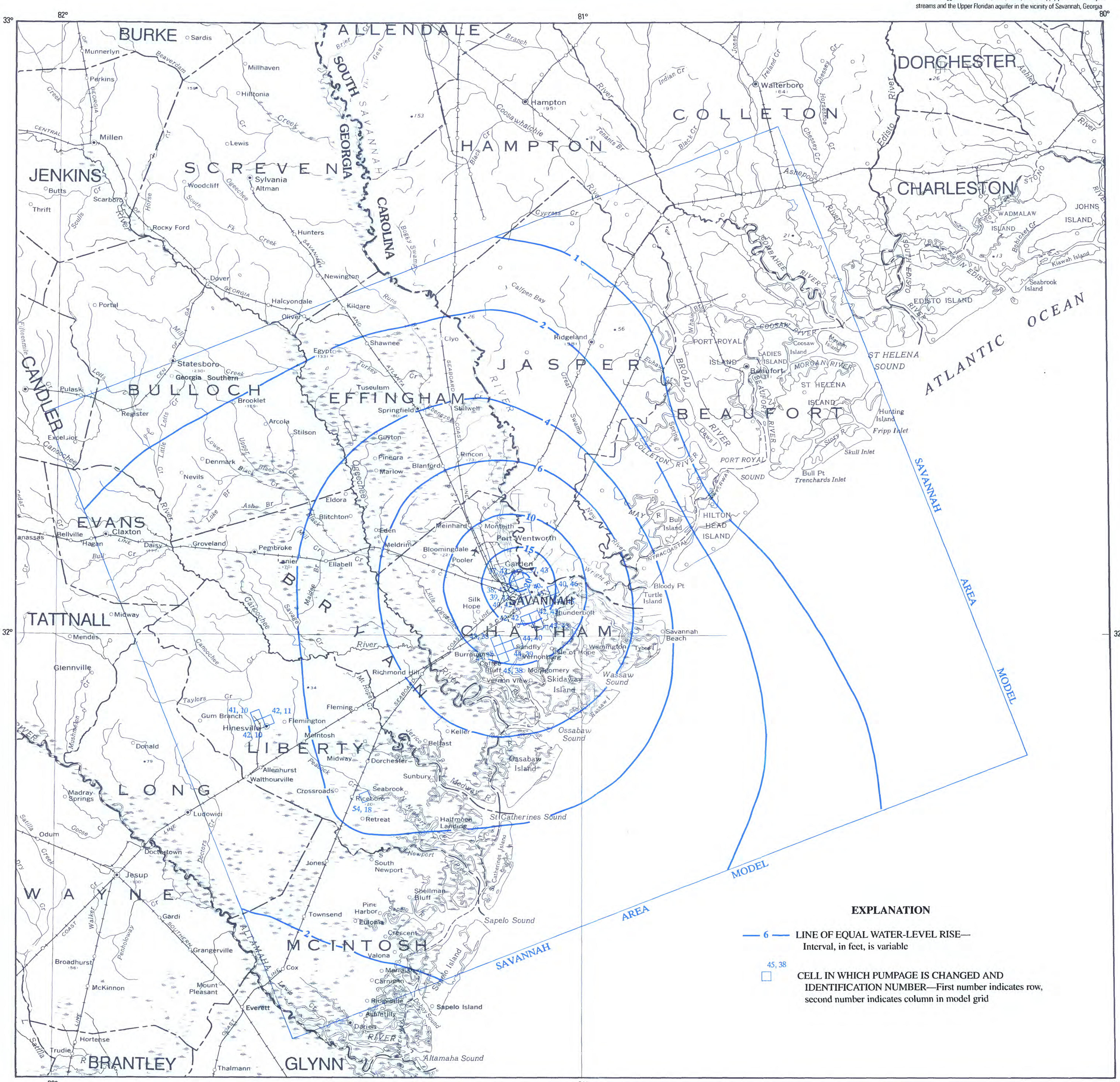
MAP SHOWING SIMULATED WATER-LEVEL CHANGE CAUSED BY A REDISTRIBUTION IN PUMPAGE OF 2.3 MILLION GALLONS PER DAY FROM HILTON HEAD ISLAND, SOUTH CAROLINA, TO WESTERN BEAUFORT COUNTY, SOUTH CAROLINA, AND A DECREASE IN PUMPAGE OF 10 MILLION GALLONS PER DAY IN SAVANNAH, GEORGIA, AND AN INCREASE IN PUMPAGE OF 14 MILLION GALLONS PER DAY IN WESTERN CHATHAM COUNTY, GEORGIA, UPPER FLORIDAN AQUIFER (ALTERNATIVE 1)

By

Reggina Garza and Richard E. Krause

1997

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000

10 0 10 20 30 MILES

10 0 10 20 30 40 KILOMETERS

MAP SHOWING SIMULATED WATER-LEVEL CHANGE CAUSED BY A DECREASE IN PUMPAGE OF 16.9 MILLION GALLONS PER DAY IN THE AREAS OF CHATHAM AND LIBERTY COUNTIES, GEORGIA, UPPER FLORIDAN AQUIFER (ALTERNATIVE 2)

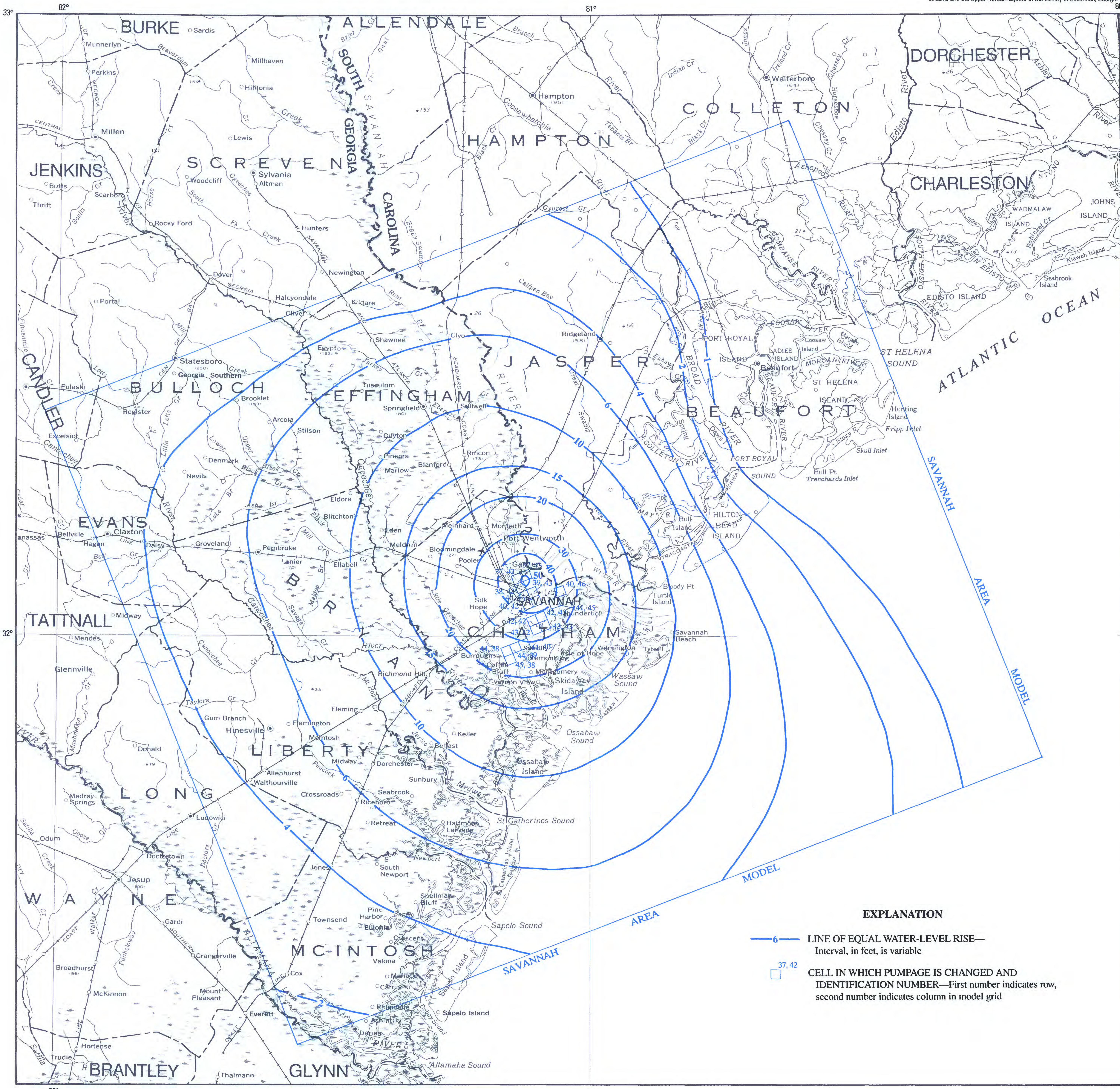
By
Reggina Garza and Richard E. Krause

1997

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION

WATER-SUPPLY PAPER 2411
Simulated water-level change (alternative 3)—PLATE 14
Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

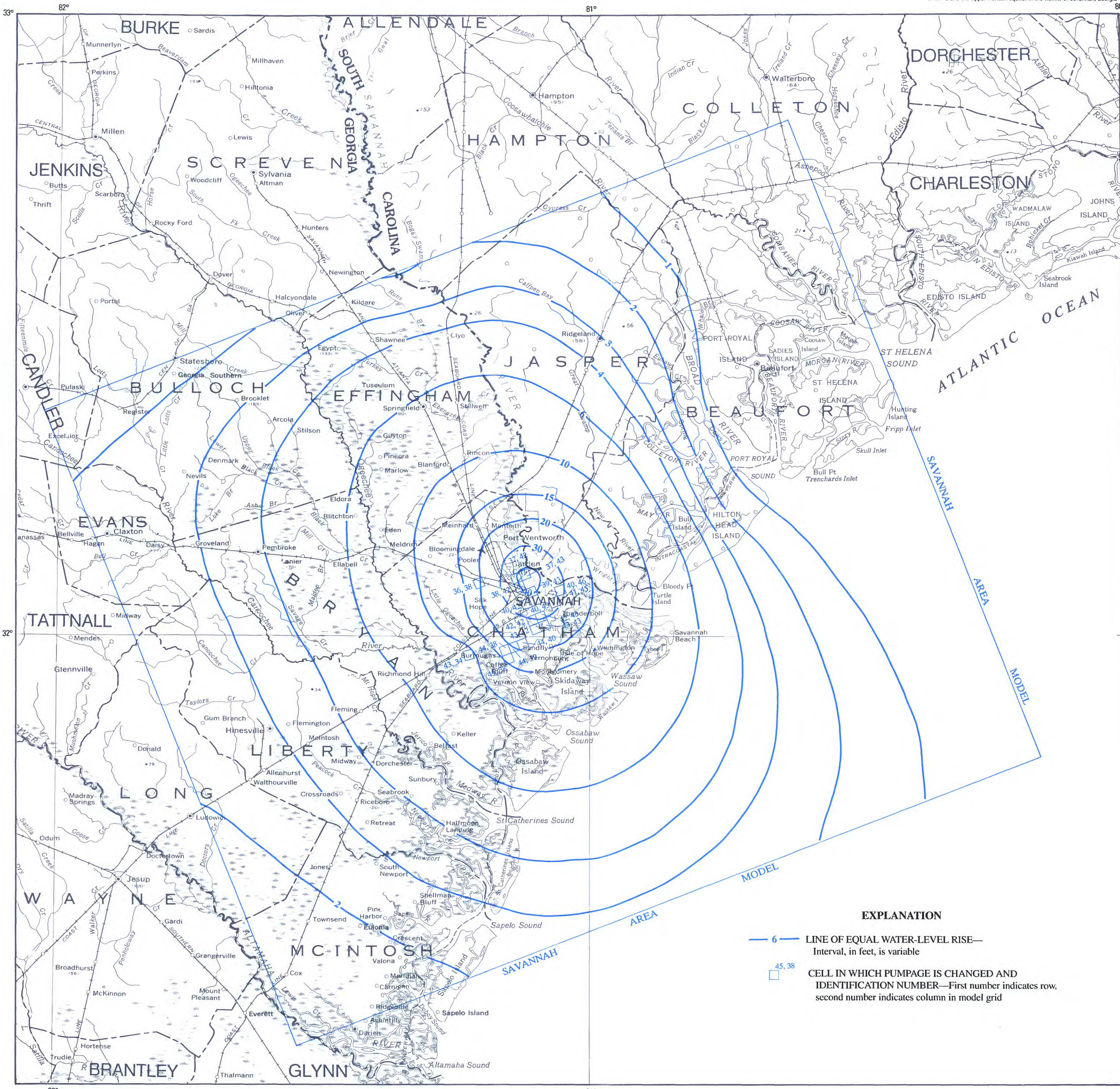
SCALE 1:500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

MAP SHOWING SIMULATED WATER-LEVEL CHANGE CAUSED BY A DECREASE IN PUMPAGE OF 32.5 MILLION GALLONS PER DAY IN THE AREA OF CHATHAM COUNTY, GEORGIA, UPPER FLORIDAN AQUIFER (ALTERNATIVE 3)

By
Reggina Garza and Richard E. Krause
1997

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

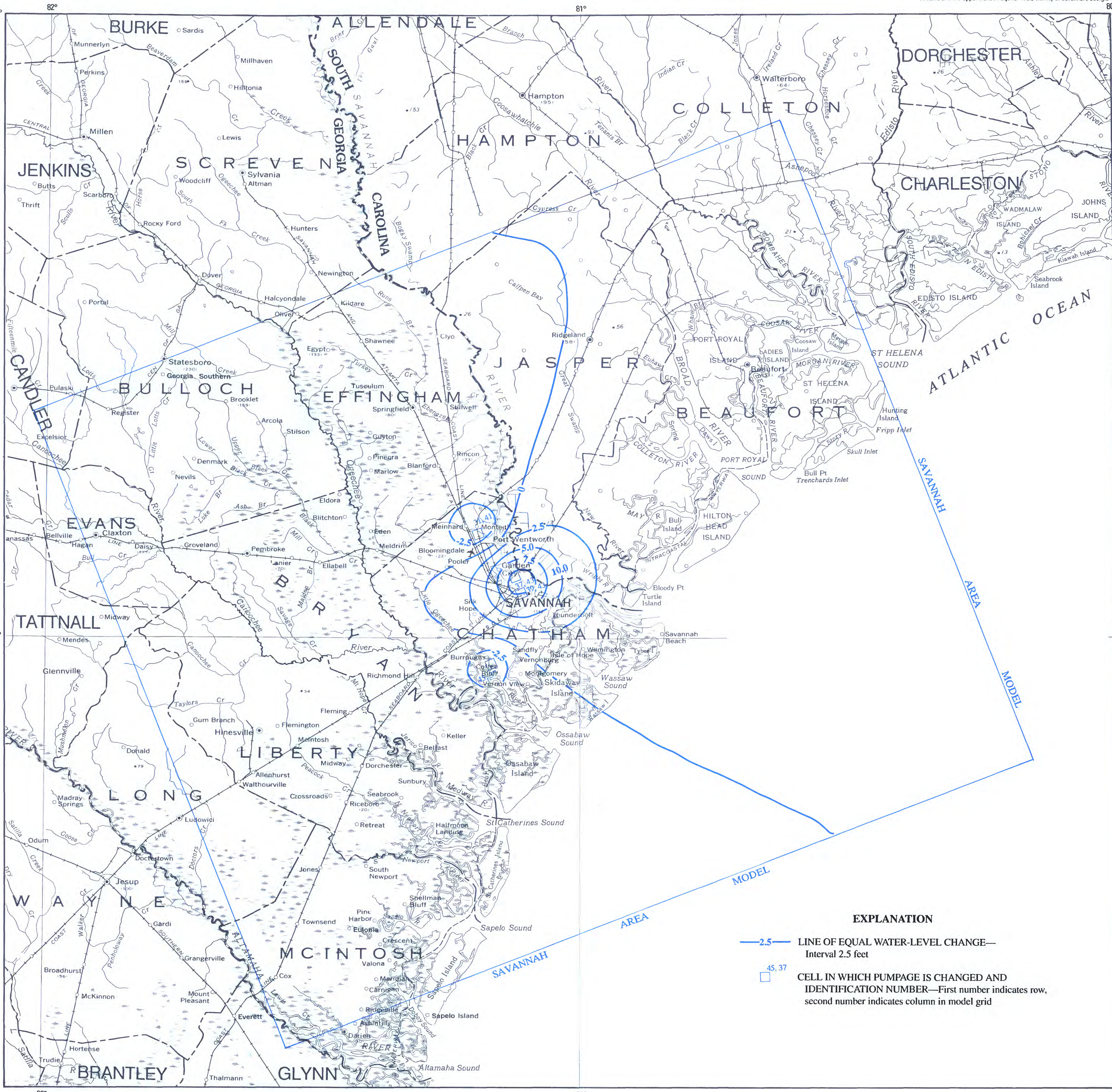
MAP SHOWING SIMULATED WATER-LEVEL CHANGE CAUSED BY A DECREASE IN PUMPAGE OF 32.5 MILLION GALLONS PER DAY IN THE AREA OF CHATHAM COUNTY, GEORGIA, AND AN INCREASE IN PUMPAGE OF 5 MILLION GALLONS PER DAY EACH AT LOCATIONS WEST AND SOUTHWEST OF SAVANNAH, GEORGIA, UPPER FLORIDAN AQUIFER (ALTERNATIVE 4)

By
Reggina Garza and Richard E. Krause
1997

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

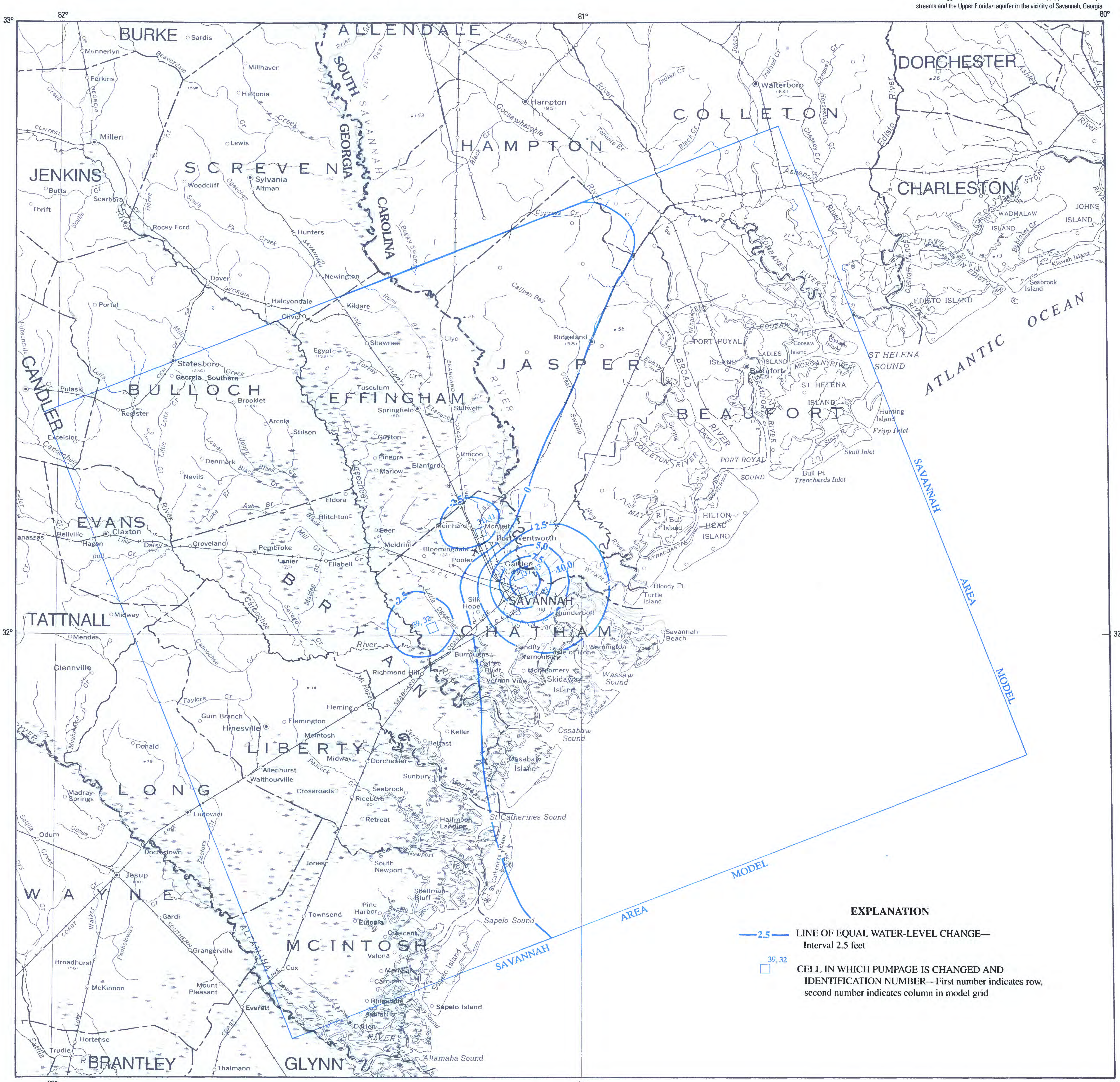
SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

MAP SHOWING SIMULATED WATER-LEVEL CHANGE CAUSED BY A REDISTRIBUTION OF PUMPAGE OF 10 MILLION GALLONS PER DAY FROM SAVANNAH, GEORGIA, TO LOCATIONS NORTHWEST AND SOUTHWEST OF SAVANNAH, GEORGIA, EACH PUMPING 5 MILLION GALLONS PER DAY, UPPER FLORIDAN AQUIFER (ALTERNATIVE 5)

By
Reggina Garza and Richard E. Krause

1997

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000

10 0 10 20 30 MILES

10 0 10 20 30 40 KILOMETERS

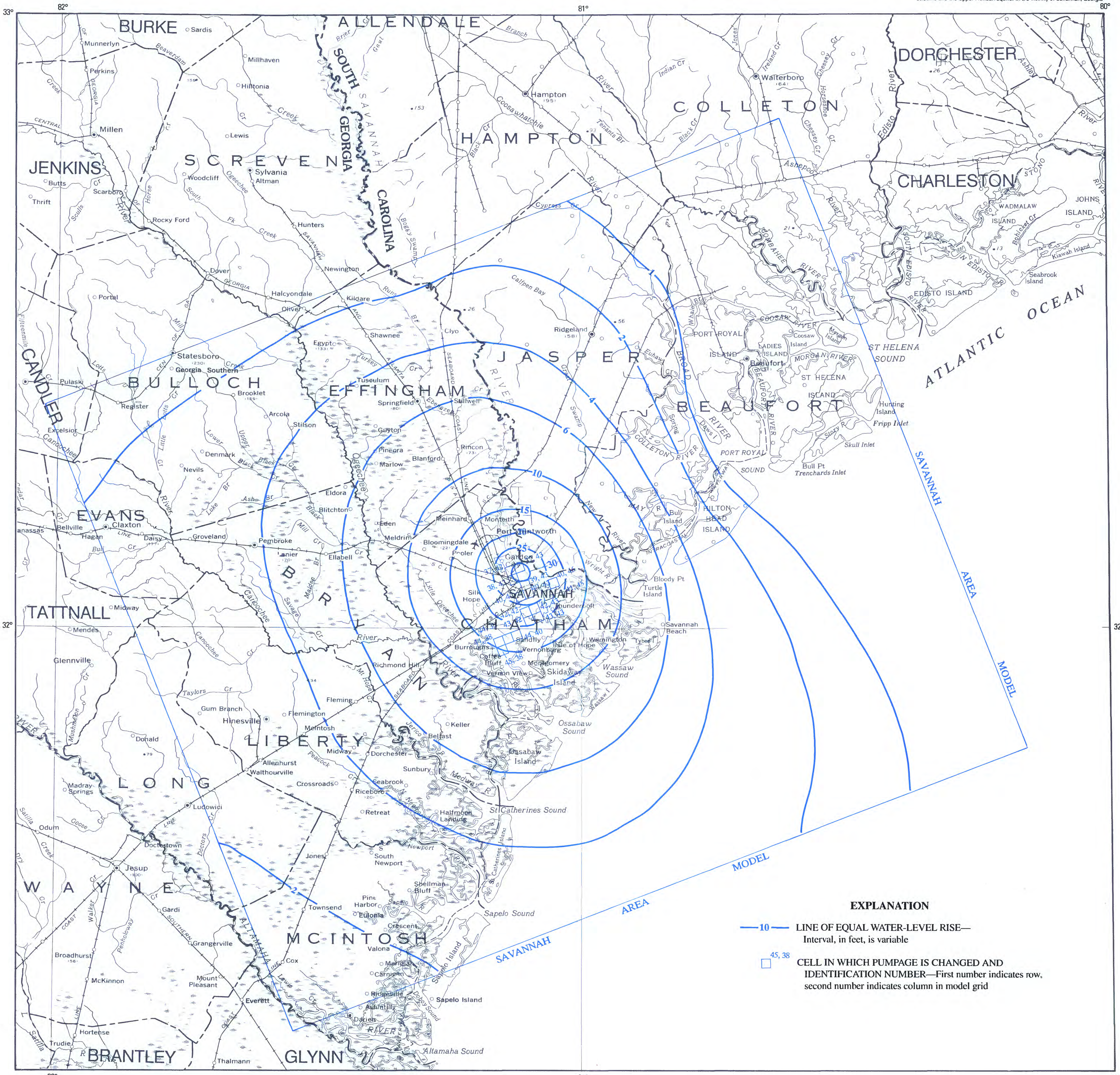
MAP SHOWING SIMULATED WATER-LEVEL CHANGE CAUSED BY A REDISTRIBUTION OF PUMPAGE OF 10 MILLION GALLONS PER DAY FROM SAVANNAH, GEORGIA, TO LOCATIONS NORTHWEST AND WEST OF SAVANNAH, GEORGIA, EACH PUMPING 5 MILLION GALLONS PER DAY, UPPER FLORIDAN AQUIFER (ALTERNATIVE 6)

By
Reggina Garza and Richard E. Krause

1997

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

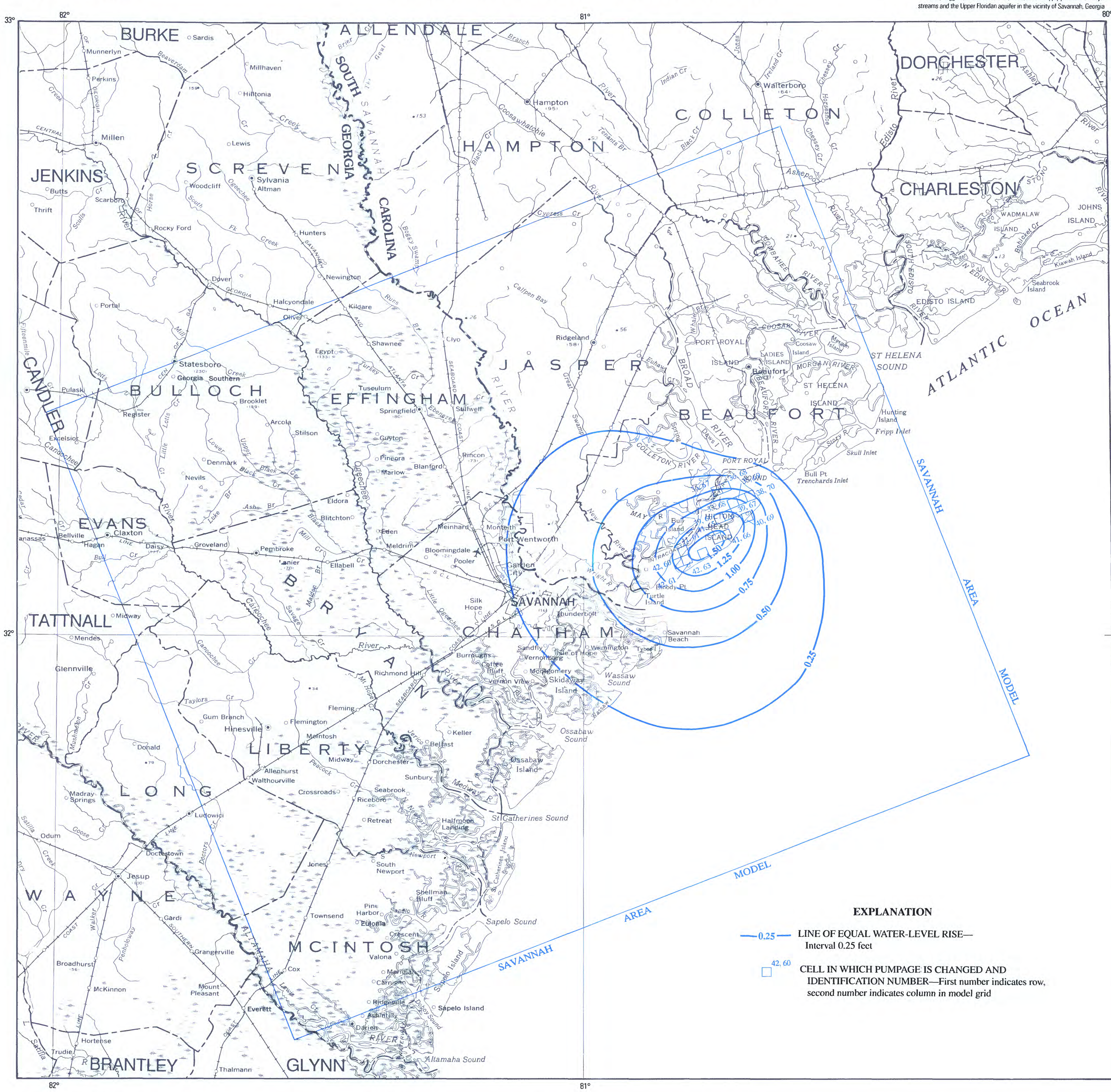
MAP SHOWING SIMULATED WATER-LEVEL CHANGE CAUSED BY A DECREASE IN PUMPAGE OF 19.8 MILLION GALLONS PER DAY AT SAVANNAH, GEORGIA, UPPER FLORIDAN AQUIFER (ALTERNATIVE 7)

By
Reggina Garza and Richard E. Krause

1997

Prepared in cooperation with the
CHATHAM COUNTY–SAVANNAH METROPOLITAN PLANNING COMMISSION

Garza, Reggina, and Krause, R.E., 1996, Water-supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia



Base from U.S. Geological Survey 1:500,000
State base maps, Georgia, 1970; South Carolina, 1970

SCALE 1: 500 000
10 0 10 20 30 MILES
10 0 10 20 30 40 KILOMETERS

MAP SHOWING SIMULATED WATER-LEVEL CHANGE CAUSED BY A DECREASE IN PUMPAGE OF 2.6 MILLION GALLONS PER DAY ON HILTON HEAD ISLAND, SOUTH CAROLINA, UPPER FLORIDAN AQUIFER (ALTERNATIVE 8)

By
Reggina Garza and Richard E. Krause

1997