Saltwater Movement in the Upper Floridan Aquifer Beneath Port Royal Sound, South Carolina

United States Geological Survey Water-Supply Paper 2421

Prepared in cooperation with the South Carolina Water Resources Commission

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.

Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

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 Earthquakes & Volcanoes, 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, Map Distribution
Box 25286, MS 306, Federal Center
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and 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, Map Distribution
Box 25286, Bldg. 810, Federal Center
Denver, CO 80225

Residents of Alaska may order maps from

U.S. Geological Survey, Earth Science Information Center
101 Twelfth Ave. - Box 12
Fairbanks, AK 99701

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 offices, 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 offices:

- **FAIRBANKS, Alaska**—New Federal Bldg., 101 Twelfth Ave.
- **ROLLA, Missouri**—1400 Independence Rd.
- **STENNIS SPACE CENTER, Mississippi**—Bldg. 3101

Saltwater Movement in the Upper Floridan Aquifer Beneath Port Royal Sound, South Carolina

By BARRY S. SMITH

Prepared in cooperation with the South Carolina
Water Resources Commission

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2421

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

Printed in the Eastern Region, Reston, Va.

UNITED STATES GOVERNMENT PRINTING OFFICE : 1994

For sale by the
U.S. Geological Survey, Map Distribution
Box 25286, MS 306, Federal Center
Denver, CO 80225

Library of Congress Cataloging In Publication Data

Smith, Barry S.
Saltwater movement in the upper Floridan aquifer beneath Port Royal Sound, South Carolina / by Barry S. Smith ; prepared in cooperation with the South Carolina Water Resources Commission.
p. cm. — (U.S. Geological Survey water-supply paper ; 2421)
Includes bibliographical references.
Supt. of Docs. no.: I19.13: 2421
1. Saltwater encroachment—South Carolina—Port Royal Sound. 2. Floridan Aquifer. I. South Carolina Water Resources Commission. II. Title. III. Series.
GB1197.83.S6S65 1994
628.1'14—dc20 93-32580
CIP

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
cubic meter per second (m^3/s)	35.31	cubic foot per second
cubic meter per second (m^3/s)	22.83	million gallons per day
gram (g)	0.03527	ounce, avoirdupois
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
meter per day (m/d)	3.281	foot per day
meter per day (m/d)	24.5	gallon per day per square foot
meter per year (m/yr)	3.281	foot per year
centimeter per year (cm/yr)	0.3937	inch per year
kilogram per second (kg/s)	2.2	pound per second
square kilometer (km^2)	0.3861	square mile
square meter (m^2)	10.76	square foot
square meter per day (m^2/d)	10.76	square foot per day
cubic meter (m^3)	35.31	cubic foot
cubic meter per day (m^3/d)	264.2	gallon per day
centimeter per second squared (cm/s^2)	0.03281	foot per second squared
kilogram per cubic meter (kg/m^3)	0.0624	pound per cubic foot

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

$$°F=(1.8\times°C)+32$$

Additional Abbreviation

milligram per liter=mg/L

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.

Hydraulic conductivity and transmissivity: In this report, hydraulic conductivity is reported in meters per day (m/d), a mathematical reduction of the unit cubic meter per day per square meter [$(m^3/d)/m^2$]. Transmissivity is reported in meters square per day (m^2/d), a mathematical reduction of the unit cubic meter per day per square meter times meter of aquifer thickness ([$(m^3/d)/m^2$]m).

Saltwater Movement in the Upper Floridan Aquifer Beneath Port Royal Sound, South Carolina

By Barry S. Smith

Abstract

Freshwater for Hilton Head Island, South Carolina, is supplied by withdrawals from the Upper Floridan aquifer. Freshwater for the nearby city of Savannah, Georgia, and for the industry that has grown adjacent to the city, has also been supplied, in part, by withdrawal from the Upper Floridan aquifer since 1885. The withdrawal of ground water has caused water levels in the Upper Floridan aquifer to decline over a broad area, forming a cone of depression in the potentiometric surface of the aquifer centered near Savannah. In 1984, the cone of depression extended beneath Hilton Head Island as far as Port Royal Sound. Flow in the aquifer, which had previously been toward Port Royal Sound, has been reversed, and, as a result, saltwater in the aquifer beneath Port Royal Sound has begun to move toward Hilton Head Island.

The Saturated-Unsaturated Transport (SUTRA) model of the U.S. Geological Survey was used for the simulation of density-dependent ground-water flow and solute transport for a vertical section of the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound. The model simulated a dynamic equilibrium between the flow of seawater and freshwater in the aquifer near the Gyben-Herzberg position estimated for the period before withdrawals began in 1885; it simulated reasonable movements of brackish water and saltwater from that position to the position determined by chemical analyses of samples withdrawn from the aquifer in 1984, and it approximated hydraulic heads measured in the aquifer in 1976 and 1984.

The solute-transport simulations indicate that the transition zone would continue to move toward Hilton Head Island even if pumping ceased on the island. Increases in existing withdrawals or additional withdrawals on or near Hilton Head Island would accelerate movement of the transition zone toward the island, but reduction in withdrawals or the injection of freshwater would slow movement toward the island, according to the simulations.

Future movements of the transition zone toward Hilton Head Island will depend on hydraulic gradients in the aquifer beneath the island and the sound. Hydraulic gradients in the Upper Floridan aquifer beneath Hilton Head Island and Port Royal Sound are strongly influenced by withdrawals on the island and near Savannah. Since 1984, withdrawals on Hilton Head Island have increased.

INTRODUCTION

Hilton Head Island is a large resort community in Beaufort County, S.C. (fig. 1). Freshwater for the island is supplied by wells withdrawing water from the Upper Floridan aquifer, which is part of the Floridan aquifer system. The Upper Floridan aquifer has been a major source of water for the nearby city of Savannah, Ga., since 1885 and for the commerce and industry adjacent to the city (Warren, 1944, p. 80). The withdrawal of ground water has caused water levels in the Upper Floridan aquifer to decline over a broad area forming a cone of depression in the potentiometric surface of the aquifer centered near Savannah (Clarke and others, 1985, p. 97, fig. 2.7.4.101). In 1984, the

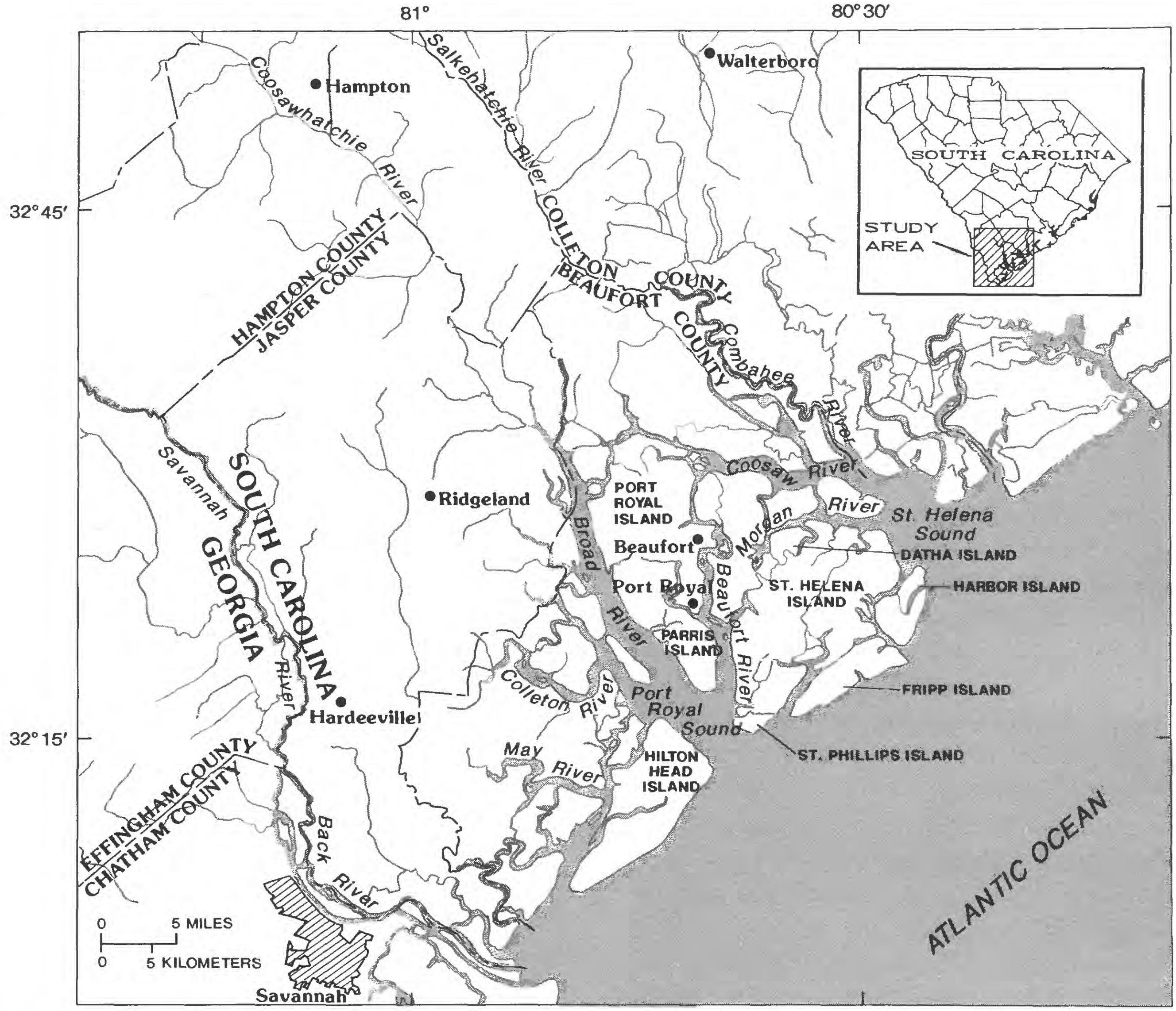

Figure 1. Location of Hilton Head Island and Port Royal Sound.

cone of depression extended beneath Hilton Head Island as far as Port Royal Sound (fig. 2).

Before the ground-water withdrawals, freshwater moved through the aquifer from the Savannah area toward Hilton Head Island to Port Royal Sound (Counts and Donsky, 1963, p. 54, 56, and pl. 5B). Because of increased withdrawals, however, flow in the aquifer has been reversed beneath Hilton Head Island, and saltwater in the aquifer beneath Port Royal Sound is moving slowly toward the island (Warren, 1944, p. 119; and Counts and Donsky, 1963, p. 56).

The U.S. Geological Survey (USGS), in cooperation with the South Carolina Water Resources Commission, began a comprehensive study in 1983 to investigate saltwater encroachment in the Upper Floridan aquifer in Beaufort and Jasper Counties. The geology, hydrology, water quality, geochemistry, and ground-water flow characteristics of the Upper Floridan aquifer were studied.

Purpose and Scope

The principal objectives of the study were to determine

1. the location and chemical character of the transition zone between saltwater and freshwater near Hilton Head Island;
2. the rate of saltwater movement toward Hilton Head Island;

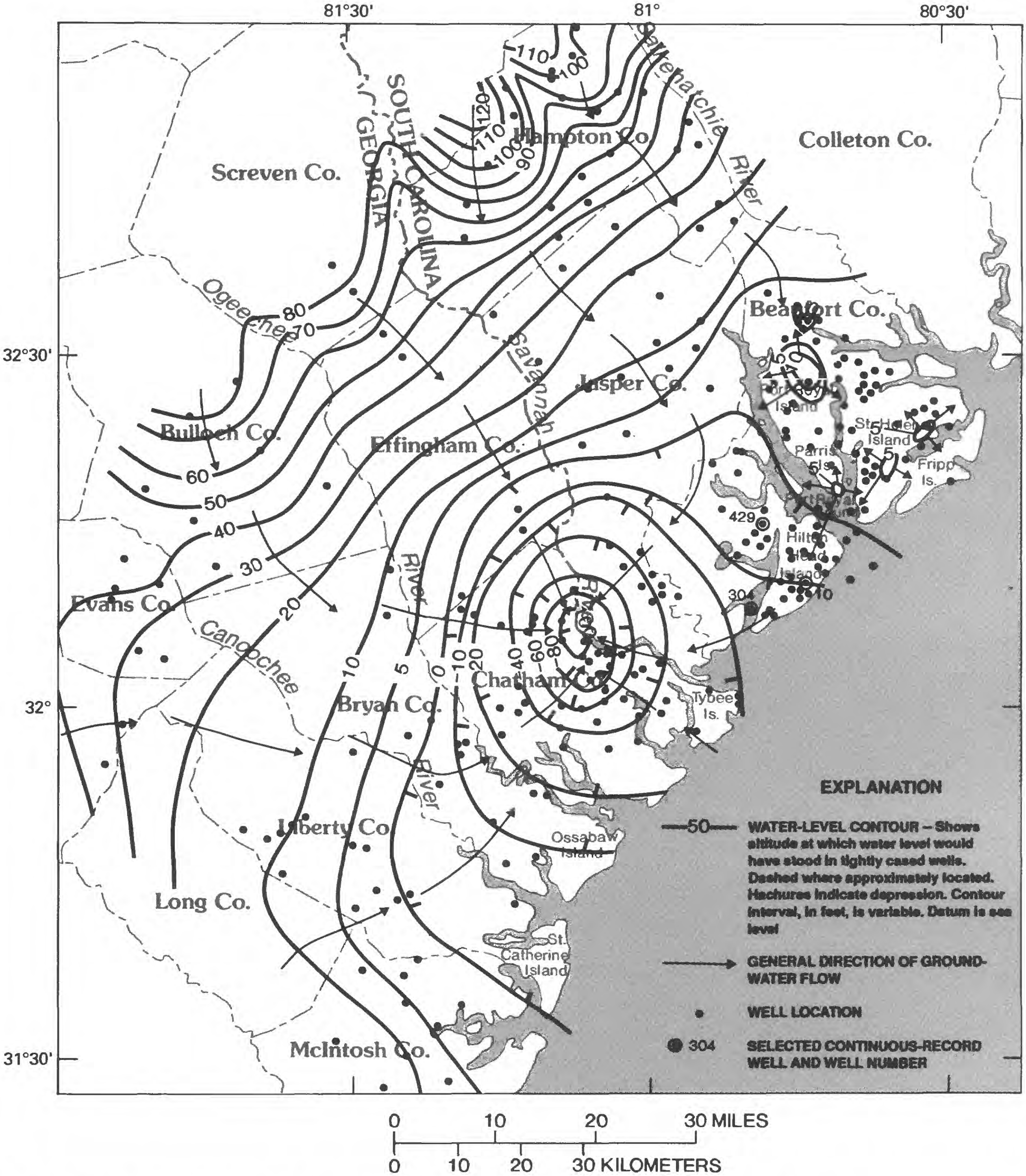

Figure 2. Potentiometric surface of the Upper Floridan aquifer in 1984 (from Smith, 1988, p. 19, fig. 8).

3. the length of time before saltwater encroaches into the aquifer beneath Hilton Head Island under different pumping situations; and
4. the possibility of slowing saltwater movement by injecting freshwater on Hilton Head Island.

These objectives were addressed by use of an areal ground-water flow model of the Upper Floridan aquifer (assuming uniform water density) as described in a previous report of this study (Smith, 1988). In conjunction with the areal flow model, a density-dependent ground-water flow and solute-transport model was applied to an 8-km by 60-m vertical section of the Upper Floridan aquifer and upper confining units. Saltwater movement along this 8-km section of the Upper Floridan aquifer beneath northeastern Hilton Head Island and Port Royal Sound is the subject of this report (fig. 3).

Approach

The location and character of the transition zone between freshwater and saltwater in the Upper Floridan aquifer beneath Port Royal Sound and the Atlantic Ocean near Hilton Head Island were investigated by test drilling and sampling from a self-elevating platform ship in 1984. Chemical analyses indicated that the transition zone is in the top 30 m of the aquifer in this area.

Simulation of the movement of the transition zone in response to changes in pumping and injection required a density-dependent ground-water flow and solute-transport model. The Saturated-Unsaturated Transport (SUTRA) model of the USGS was chosen for simulation of density-dependent ground-water flow and solute transport in a vertical section (Voss, 1984). Geohydrologic data, water chemistry, and flow characteristics used in the solute-transport model were measured in the field or obtained from previous studies.

A hydrogeologic section through the Port Royal Sound area was chosen and a simple, rectangular finite-element mesh with appropriate boundaries was designed for simulating movement of the transition zone in the aquifer and the upper confining unit of the section. First, the solute-transport model was used to simulate the dissolved-solids concentrations of the transition zone under steady-state conditions prior to the first withdrawal of ground water in 1885. Next, movement of the transition zone from 1884 to 1984 was simulated. Finally, potential movement of the transition zone beneath Port Royal Sound toward Hilton Head Island from 1984 through 2032 was simulated for five hypothetical schemes: (1) no changes in ground-water withdrawals, (2) additional ground-water withdrawals on Hilton Head Island beginning in the year 2000, (3) additional ground-water withdrawals on the mainland beginning in the year 2000, (4) elimination of ground-water withdrawals on Hilton Head Island beginning in the year 2000, and (5) freshwater injection near shore beginning in 2000.

Previous Studies

In an unpublished memorandum to the Navy Department in 1944, M.J. Mundorff of the USGS described saltwater contamination of the limestone aquifer (Upper Floridan aquifer) caused by withdrawals at Parris Island. The aquifer was contaminated by seawater from the tidal creeks adjacent to Parris Island, according to Mundorff, when an appreciable amount of water was withdrawn, water levels were lowered, and the natural flow of ground water from the island to the surrounding tidal flats and creeks was reversed. Areas where fresh ground water had previously discharged became sources of saltwater recharge. The potential for further encroachment of saltwater in the aquifer from the Parris Island area because of water level declines and pumping near Savannah was described by Warren (1944, p. 125 and 127).

In an unpublished memorandum to the Department of the Navy in 1957, G.E. Siple of the USGS described four possible ways in which the limestone (Upper Floridan) aquifer in the Parris Island area could be further contaminated: (1) downward seepage of salty or brackish water from surficial or overlying sources, (2) lateral migration through the limestone, (3) upward movement of salty water from sources below, and (4) leakage through defective wells. In a separate unpublished report to the Navy, Siple, in 1960, described contamination of wells in the Beaufort, S.C., area caused by downward seepage and lateral encroachment of saltwater from nearby tidal creeks and by leaks in poorly constructed wells.

Counts and Donsky (1959, p. 12–13 and table 2) reported salty water with chloride concentrations as high as 2,000 mg/L at a depth of 693 ft (211 m) in the limestone beneath the middle of Hilton Head Island, which is now considered the middle confining unit of the Floridan aquifer system or possibly the Lower Floridan aquifer. They believed, however, that lateral migration of saltwater in the upper parts of the aquifer from the Atlantic Ocean and estuaries in the Hilton Head Island area was the most likely potential source of saltwater contamination because the thick clayey-silt confining units above and below the aquifer would retard vertical leakage.

In a comprehensive report, Counts and Donsky (1963, p. 56 and 58 and pls. 3 and 5) described the regional flow of ground water prior to pumping in the Savannah area and the changes in flow patterns caused by pumping as of 1957. They also estimated the

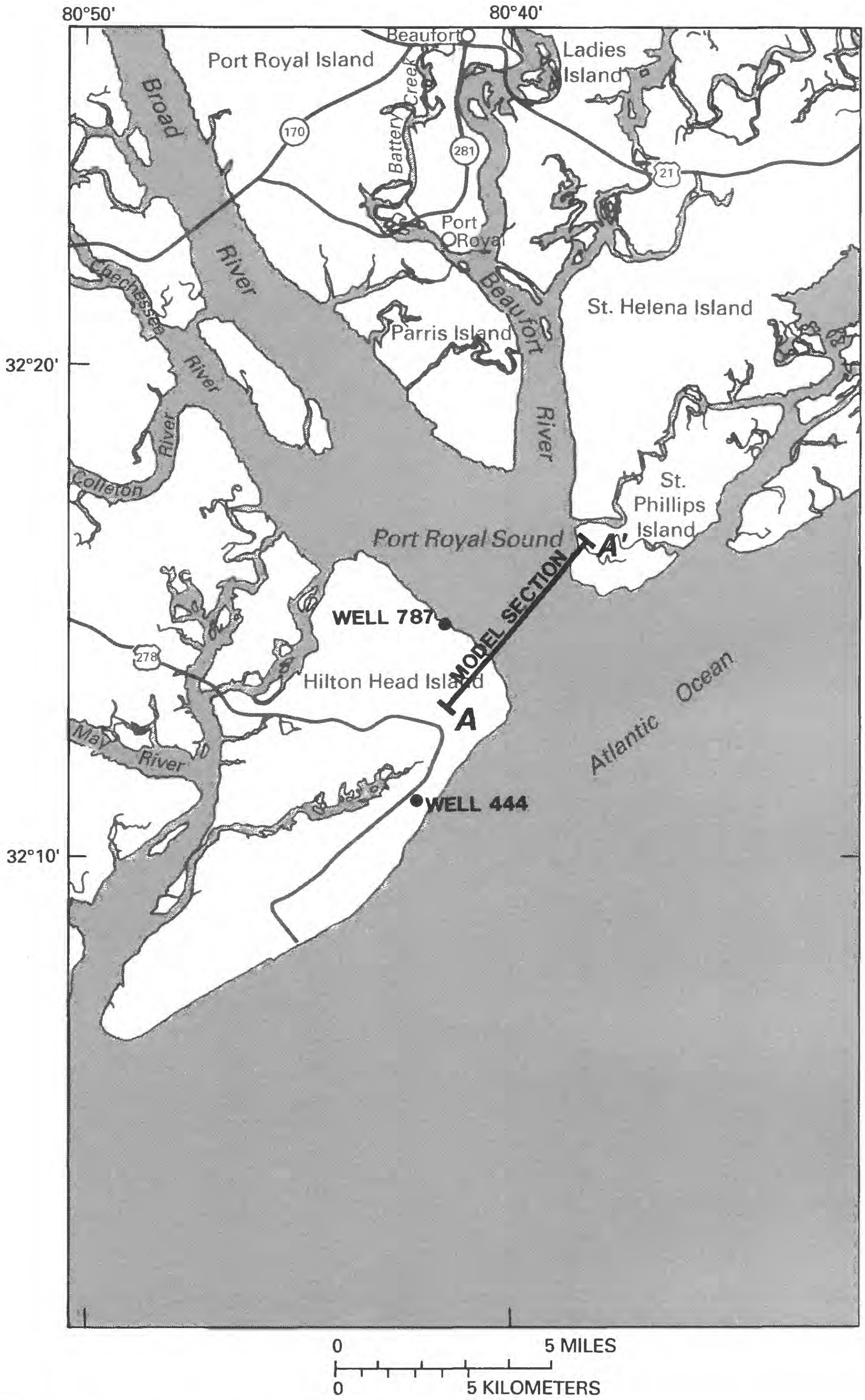

Figure 3. Section location in the Port Royal Sound area.

potential movement of saltwater into the upper part of the limestone (Upper Floridan) aquifer from the Hilton Head Island and Port Royal Sound area toward pumped wells near Savannah (p. 86).

Back and others (1970, p. 2334 and fig. 8) used geochemistry and carbon-14 dating to show that freshwater was leaking downward to recharge the Upper Floridan aquifer on Hilton Head and Port Royal Islands. They also indicated that high-chloride water in the deeper limestone beneath Hilton Head Island was relatively old, that modern saltwater was leaking downward toward the aquifer from Port Royal Sound, and that the saltwater beneath Parris Island was relatively young (Back and others, 1970, p. 2335, figs. 7 and 8).

Hayes (1979, p. 63, 66, 69, and 70 and fig. 26) described local contamination of wells by salty water and attributed it to seawater entering the aquifer east of Parris Island and moving along the regional hydraulic gradient toward northern Hilton Head Island. He implied that a transition zone between seawater and freshwater existed beneath Port Royal Sound and that the aquifer was connected to the sea bottom southeast of Hilton Head Island. Hayes also recognized that a slight ground-water divide near the northeastern shore of Hilton Head Island in 1976 would inhibit, but would not prevent, saltwater encroachment (p. 67 and fig. 25). In a more recent report, Hassen (1985, p. 14 and 29 and fig. 20) described freshwater zones surrounded by brackish water in the limestone (Upper Floridan) aquifer beneath Ladies and St. Helena Islands just east of Port Royal Sound.

Bush (1988) simulated saltwater movement in the Upper and Lower Floridan aquifers in a vertical section from Port Royal Sound through the northeastern half of Hilton Head Island. He concluded that the transition zone between saltwater and freshwater had not moved far from its prepumping position, and he reiterated the conclusion of previous investigators that lateral migration of saltwater in the Upper Floridan aquifer rather than vertical migration of saltwater from lower permeable zones in the aquifer posed the greatest threat to freshwater supplies. He also indicated that if hydraulic heads on Hilton Head Island remained at 1983 levels for 45 to 50 years, there would be no significant threat of saltwater intrusion; but, if heads continued to decline at rates similar to the long-term historic trend, considerably more landward movement of salty water would occur. Bush indicated that the precision of saltwater simulations for the Hilton Head Island area could be improved by better definition of lateral and vertical permeabilities in the Upper Floridan aquifer and by better definition of the distribution of dissolved-solids concentrations in ground water.

The USGS, in cooperation with the South Carolina Water Resources Commission, presented hydrologic, geologic, and chemical data including dissolved-solids concentrations from drilling and sampling the Upper Floridan aquifer beneath Port Royal Sound and the adjacent Atlantic Ocean (Burt and others, 1987). Smith (1988) estimated the location of the interface of seawater and freshwater in the Upper Floridan aquifer prior to pumping on the basis of simulated water levels and the Gyben-Herzberg principle, a special case of the Hubbert interface equation (Hubbert, 1940, p. 864). Smith estimated the average velocity of saltwater encroachment in the aquifer in 1984 to be 15 to 24 m/yr beneath Port Royal Sound between Parris and Hilton Head Islands. He also inferred that saltwater encroachment toward Hilton Head Island could be slowed by reduction or rearrangement of ground-water withdrawals on and near the island or by injection of freshwater through wells along the northeastern shore of the island.

Hughes and others (1989, p. 37) described the geology, hydrology, and mechanisms for saltwater contamination in Beaufort and Jasper Counties. Hughes and others also estimated saltwater encroachment of 30 m/yr using slightly different estimates of aquifer properties and hydraulic gradients than did Smith.

Acknowledgments

Some of the hydrologic and geologic data used in this report were collected by Michael Crouch and W. Brian Hughes, formerly of the South Carolina Water Resources Commission. Clifford Voss of the USGS advised the author in the design of the finite-element mesh and use of the solute-transport model.

GROUND-WATER HYDROLOGY

The Upper Floridan aquifer is the uppermost aquifer of the Floridan aquifer system. In Beaufort and Jasper Counties, S.C., the upper permeable zone of the Upper Floridan aquifer is the principal aquifer for virtually all large-capacity wells and is referred to in this report as the Upper Floridan aquifer (fig. 4). The upper

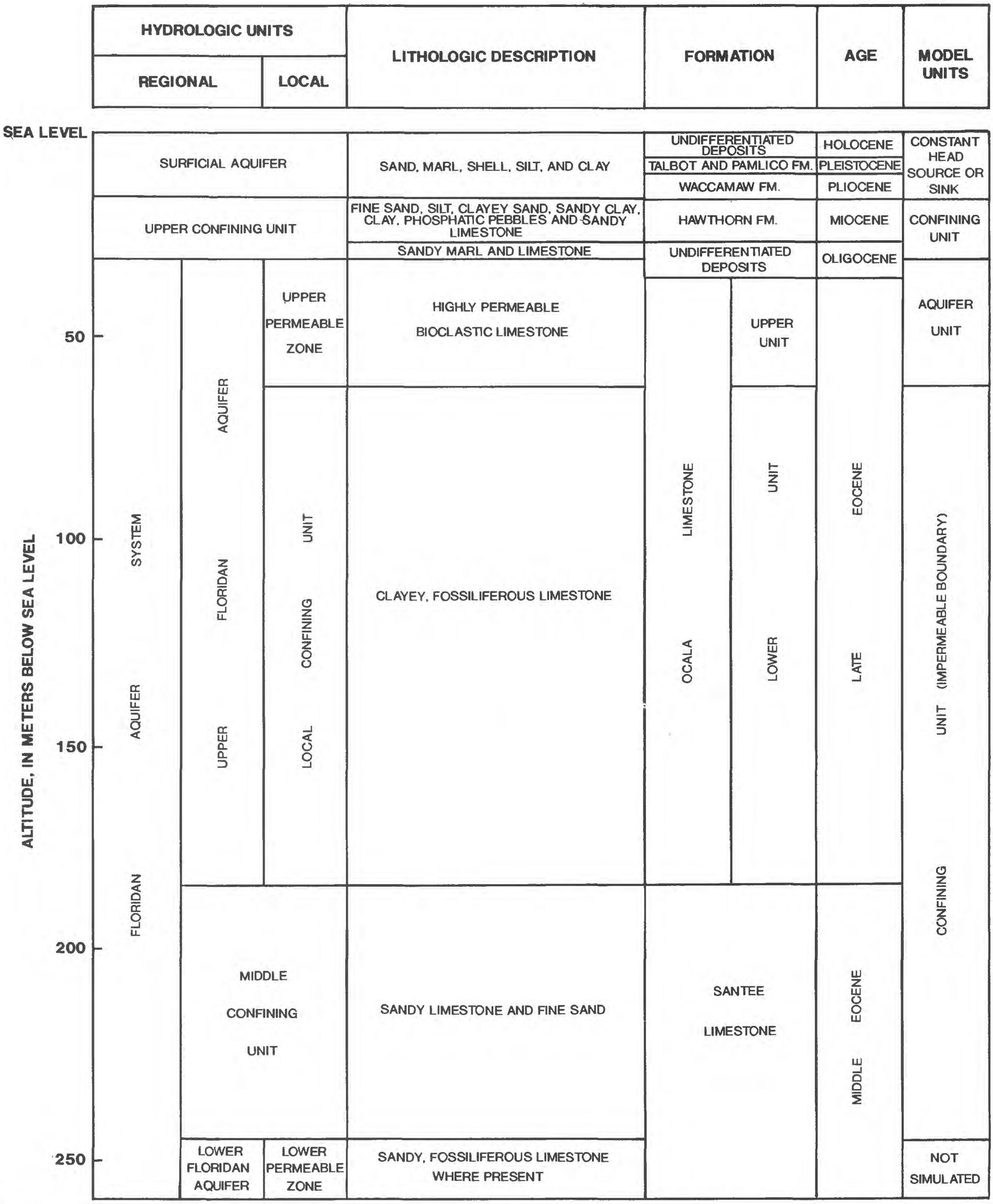

Figure 4. Framework, lithology, stratigraphy, and model units of the Floridan aquifer system in South Carolina.

permeable zone is a highly permeable bioclastic limestone of late Eocene age in South Carolina and late Eocene and Oligocene age in southeastern Georgia. The Upper Floridan aquifer is the principal ground-water resource of the region, and is continuous throughout Beaufort and Jasper Counties in South Carolina as well as the adjacent counties in Georgia. Additional information on the geometry of the aquifer system in Beaufort and Jasper Counties, S.C. is presented by Hughes and others (1989), Hassen (1985), Hayes (1979), Spigner and Ransom (1979), and Counts and Donsky (1963).

The Upper Floridan aquifer is confined by the Miocene Hawthorn Formation above and, in places, by unnamed Oligocene deposits. These deposits are called the upper confining unit. The upper confining unit is a marine deposit composed mostly of fine sand, silt, clayey sand, sandy clay, and clay (Counts and Donsky, 1963, p. 30; Hayes, 1979, p. 30). Phosphatic pebble zones and sandy dolomitic limestone are present in places in the Hawthorn Formation and the sandy dolomitic limestone is sometimes pumped for domestic water supplies (Hayes, 1979, p. 30). The Hawthorn deposits are, however, less permeable than the Upper Floridan aquifer and water quality in the Hawthorn Formation varies areally (Counts and Donsky, 1963, p. 30).

Pliocene, Pleistocene, and Holocene sand interspersed with marl, shell, silt, and clay deposits form the surficial aquifer of which the top is generally the water table. Siple, in an unpublished report to the Navy in 1960, described the following formations above the Miocene deposits: the Waccamaw Formation of Pliocene age, which consists of sandy marl and clay; the Pamlico Formation of Pleistocene age, which consists of plastic clay and shell; the Talbot Formation of Pleistocene age, which consists of thin-bedded sand and clay but is present only at high elevations in the area; and unnamed deposits of Holocene age, which consist of fine sand, silt, and marl.

The surficial sand aquifer generally is discontinuous and variable in grain size, thickness, and hydraulic conductivity. Water quality for the surficial sand aquifer in the Beaufort area also varies, but the aquifer is pumped in places for domestic water supplies.

The upper permeable zone of the Upper Floridan aquifer is confined below by a thick sequence of clayey fossiliferous limestone of late Eocene age (fig. 4). Some discontinuous permeable zones exist in places in this sequence, but the permeability of the unit is usually much lower than that of the upper permeable zone. Thus, the upper permeable zone is referred to as the Upper Floridan aquifer in this report. The clayey limestone beneath the upper permeable zone is called a local confining unit, because the Upper Floridan aquifer generally is much thicker in parts of Georgia and Florida than it is in the study area as indicated in figure 4. Sandy limestone and fine sand of middle Eocene age occur beneath the late Eocene rocks and are equivalent to the middle confining unit of Miller (1986, p. B56).

A deeper aquifer called the Lower Floridan aquifer by Miller (1986, p. B10 and B63) and the lower permeable zone by Hayes (1979, p. 31 and 32) occurs in some places in South Carolina. The Lower Floridan aquifer is a sandy fossiliferous limestone of middle Eocene age. The Lower Floridan aquifer is not as permeable or extensive as the Upper Floridan aquifer. Limestone at a depth of 211 m (middle confining unit or possibly the Lower Floridan aquifer) contains salty (brackish) water in some places in the study area, particularly beneath Hilton Head Island (Counts and Donsky, 1959, p. 12–13, table 2).

Aquifer Properties

Transmissivity of the Upper Floridan aquifer has been determined from aquifer tests at several sites in and around Port Royal Sound (Counts and Donsky, 1963, p. 40–41 and table 3; Hayes, 1979, p. 34–35 and fig. 11; and Krause, 1982, pl. 1). The areal distribution of aquifer transmissivity was contoured, tested, and slightly adjusted in an areal ground-water flow model of the Upper Floridan aquifer that encompassed 18,855 km^2 in and offshore of Georgia and South Carolina (Smith, 1988, fig. 4).

The transmissivity map of Smith (1988, fig. 4) was used in this study and is reproduced, in part, in figure 5. The transmissivity of the Upper Floridan aquifer varies in the Port Royal Sound area from 6,600 m^2/d beneath northern Hilton Head Island to less than 500 m^2/d beneath St. Helena Island (fig. 5). The variation in transmissivity of the Upper Floridan aquifer is caused in part by a thinning of the aquifer toward the northeast. The transmissivity approaches zero about 35 km northeast of Hilton Head, where the limestone grades into and is interbedded with clastic rocks of low permeability (Smith, 1988, fig. 4).

High transmissivity beneath Hilton Head Island is probably not entirely the result of a thicker aquifer.

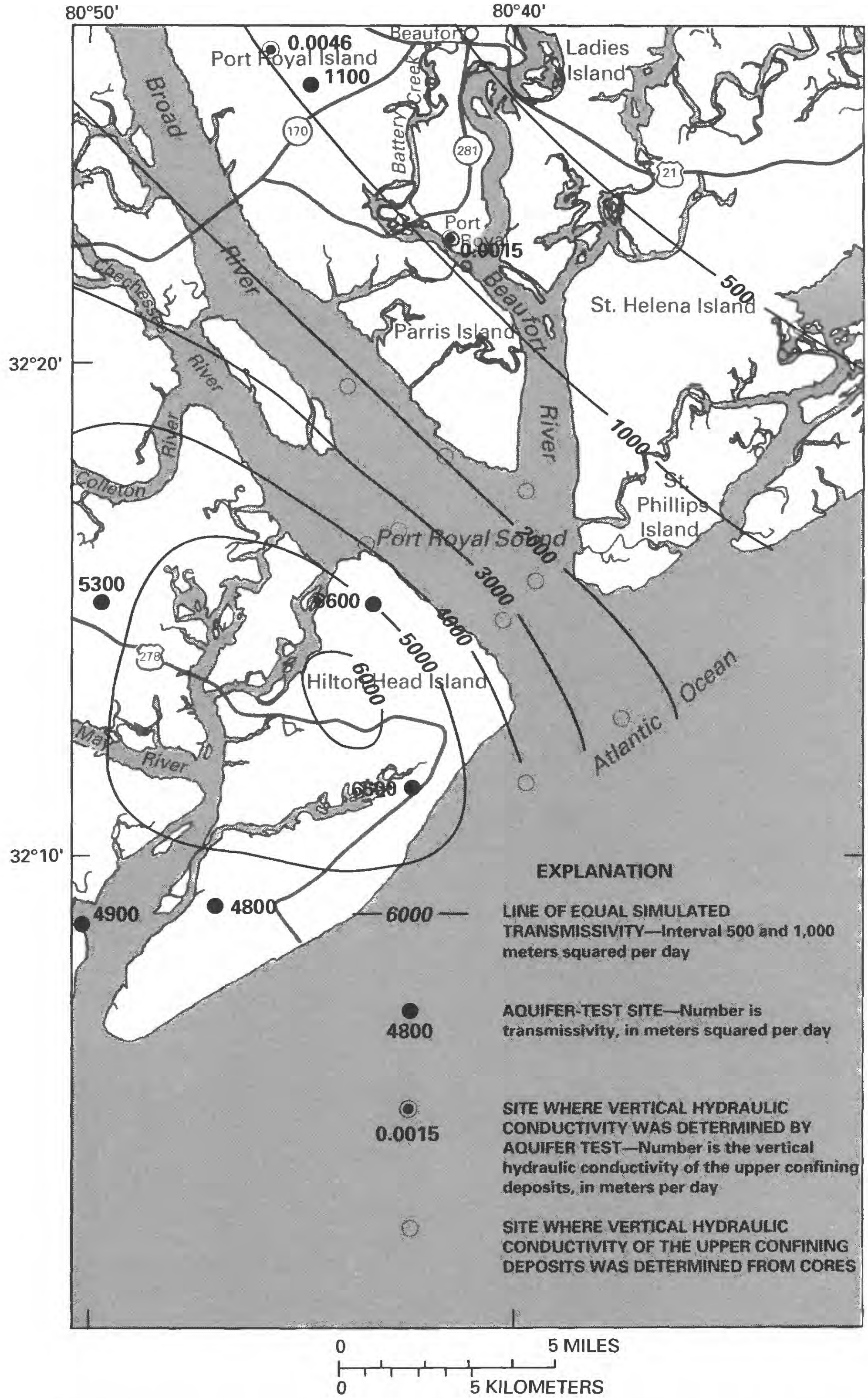

Figure 5. Aquifer transmissivity, aquifer-test sites, and core-sample sites in the Port Royal Sound area.

In the Port Royal Sound area, hydraulic conductivity of the aquifer as well as aquifer thickness varies areally.

Porosities of limestone samples cored from various depths of the Floridan aquifer system in and near Port Royal Sound have been determined in the laboratory. Counts and Donsky (1963, p. 42, 43, 60, and table 4) estimated the porosity of the limestone of the principal artesian aquifer (Floridan aquifer system) to be 35 percent using data from 10 samples at 3 sites. The median of the 10 samples is 33 percent and the mean is 34 percent. Porosities of the Upper Floridan aquifer, particularly of the most permeable zones, are more difficult to determine because poorly to moderately indurated bioclastic limestone like that of the study area is difficult to recover undisturbed.

Bush (1988, fig. 5) used a porosity of 30 percent in a solute-transport model of the Upper and Lower Floridan aquifers beneath Hilton Head Island. He derived that porosity from the six samples from the Daufuskie Island site, the site nearest Hilton Head Island, reported by Counts and Donsky (1963, p. 43 and table 4). He found that solute concentrations simulated in his model were changed very little when porosity was increased or decreased by 50 percent (Bush, 1988, table 2).

Storage coefficients for the Upper Floridan aquifer range from 0.0001 to 0.0005 at 14 of 18 aquifer-test sites in and near Savannah, Hilton Head Island, and Beaufort (Counts and Donsky, 1963, p. 41, table 3; and Hayes, 1979, p. 34, table 9, and p. 35, fig. 11). The storage coefficient at eight of the sites is 0.0003. Very little water, however, is derived from storage in the Upper Floridan aquifer. Using an average storage coefficient of 0.0003, Randolf and Krause (1984, p. 15) calculated the amount of water contributed from storage in a 12,950 km^2 area around Savannah to be approximately 0.04 m^3/s or less than 1 percent of the total water withdrawn from the system in 1980.

Properties of Confining Deposits

Vertical hydraulic conductivities of the confining deposits above the Upper Floridan aquifer were determined previously from aquifer tests at two sites on Port Royal Island (fig. 5). Hayes (1979, p. 50) calculated a vertical hydraulic conductivity of 0.0015 m/d at one aquifer-test site at Port Royal, S.C., and 0.0046 m/d at another west of Beaufort, S.C. using the Hantush-Jacob method.

Table 1. Vertical hydraulic conductivities and porosities of cores from the upper confining unit beneath Hilton Head Island and Port Royal Sound

[m/d, meters per day; dashes indicate no data]

Beaufort County, well number	Vertical Hydraulic conductivity m/d	Logarithmic (base 10) vertical hydraulic conductivity m/d	Porosity (percent)
1672	0.0017	−2.77	41
	.0017	−2.77	39
	.0043	−2.37	—
	.022	−1.66	—
1674	.0033	−2.47	44
	.0026	−2.59	43
	.070	−1.15	38
	.00017	−3.77	64
1675	.00085	−3.07	72
	.0017	−2.77	47
1676	.00085	−3.07	45
	.94	−0.02	41
	.010	−2.00	48
	.0017	−2.77	66
1677	.0026	−2.59	45
1678	.00037	−3.44	—
1679	.00013	−3.88	—
	.13	−0.89	50
	.019	−1.72	44
1680	.00085	−3.07	—
	.026	−1.59	45
	.061	−1.21	44
	.061	−1.21	35
1809	[1].00094	−3.02	21
	[1].0012	−2.91	33

[1]Average of two tests with cores of different diameters.

Vertical hydraulic conductivities of sediments from the upper confining unit were also determined from permeameter tests of 23 samples cored from 8 sites beneath Port Royal Sound (Burt and others, 1987, table 5, p. 56) and from 2 samples cored from a site on northern Hilton Head Island (fig. 5 and table 1). Values of vertical hydraulic conductivity from the aquifer tests and from the permeameter tests were converted to square meters per day, transformed to a base ten log scale, and plotted to show the frequency distribution (fig. 6). The distribution of hydraulic conductivity in a given geologic unit may approximate the log-normal distribution (Davis, 1969, p. 76).

Vertical hydraulic conductivities of the upper confining unit vary over four orders of magnitude on the basis of the permeameter tests, but the largest number of samples per $\log_{10}$ cycle are between 10^{-3} and 10^{-2} m/d. The mode of the distribution from the

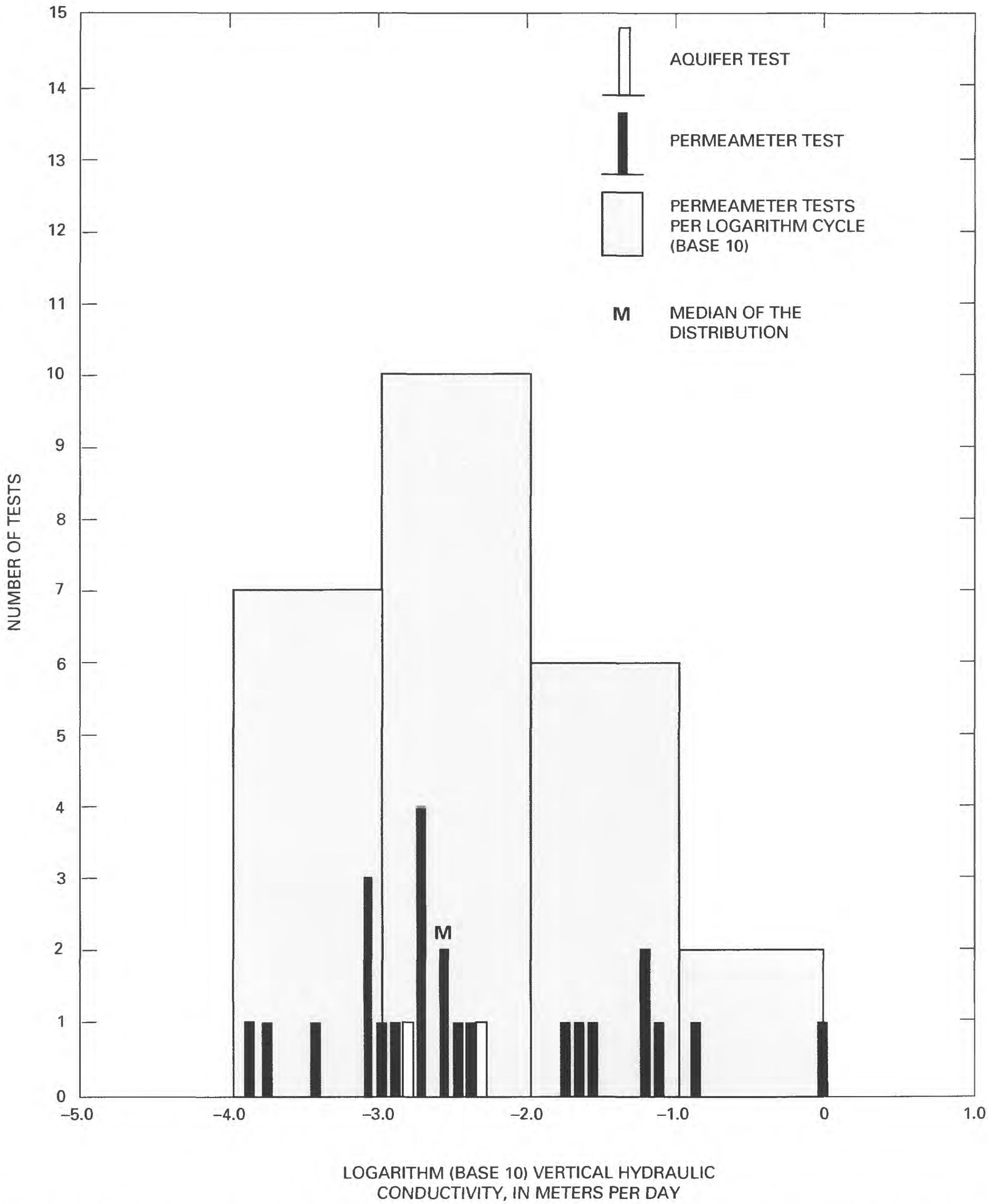

Figure 6. Frequency distribution of logarithmic (base 10) vertical hydraulic conductivities of the upper confining unit in the Port Royal Sound area.

permeameter test (0.0017) and the median (0.0026 m/d) are also in that log cycle and are between the values calculated from the aquifer tests by Hayes (1979, p. 50).

Porosities of the upper confining sediments were also determined by gravimetric method from 18 samples cored beneath Port Royal Sound and 2 samples from northern Hilton Head Island (table 1). Individual values of porosity varied from 21 to 72 percent (fig. 7). The median of the porosity tests was 44 percent and the mean was 45 percent. The median, mean, mode, and values for 11 of the 18 samples were between 40 and 50 percent. Porosity values from a single formation have normal rather than log-normal distributions (Domenico and Schwartz, 1990, p. 67).

Limited data are available from the clayey limestones beneath the upper permeable zone of the Upper Floridan aquifer in or near the study area. Interconnection between water-yielding zones of the principal artesian aquifer (Upper Floridan aquifer) is poor because the material between them is relatively impermeable and, as a result, the chemical quality of water varies in different permeable zones (McCollum and Counts, 1964, p. D13). Laboratory analyses of two limestone samples, one cored from a depth of about 130 m and the other from about 220 m in the Savannah area, show vertical hydraulic conductivities of 2.4 and 0.00082 m/d, respectively (Counts and Donsky, 1963, p. 43, table 4). Thus, the combination of low permeability and thickness inhibits leakage between the upper permeable zone of the Upper Floridan aquifer and less permeable zones that could exist at depth.

Ground-Water Flow Before 1885

As part of this investigation, an areal ground-water flow model was used to simulate hydraulic heads for the Upper Floridan aquifer during the steady-state period before ground-water withdrawals began in 1885 (Smith, 1988). Simulated hydraulic heads of the areal model, which encompassed 7,280 mi^2 in and offshore of South Carolina and Georgia, were converted to meters and contoured so that they would show in detail the patterns of flow before ground-water withdrawals began in the Port Royal Sound area (fig. 8).

Before 1885, regional ground-water flow converged on Port Royal Sound from the southwest and west. Flow from the north and northeast was of local origin. Fresh ground water discharged to Port Royal Sound and the Atlantic Ocean by upward leakage through the confining deposits above the aquifer. The ground water mixed with saltwater in the aquifer and formed a transition zone between freshwater and saltwater beneath the sound and the ocean.

The upper confining unit is thinner in the Port Royal Sound and Beaufort areas than elsewhere and, consequently, the aquifer is less confined in this area than to the south or west. The Port Royal Sound area was a place of regional discharge for the aquifer because of this reduced confinement.

Patterns of flow on Parris and St. Helena Islands to the north and northeast of Port Royal Sound indicate that ground water also diverged from the high ground of the sea islands. Freshwater from precipitation on the high ground leaked downward through the confining deposits to recharge the aquifer, and ground water flowed from the islands to discharge by upward leakage to the sound and adjacent tidal creeks and flats.

Recharge to the Upper Floridan aquifer by downward vertical leakage was calculated by the areal ground-water flow model for 1-mile-square increments (Smith, 1988, figs. 17 and 18). On Port Royal Island, recharge before withdrawals began was estimated to range from 0 cm/yr at the shoreline to about 15 cm/yr on higher ground. On the other islands north and northeast of Port Royal Sound, recharge ranged from 0 cm/yr at the shorelines to about 8 cm/yr on higher ground. Recharge to the aquifer by downward vertical leakage also occurred on northern Hilton Head Island before withdrawal began ranging from 0 to 10 cm/yr.

The theoretical location of the steady-state interface of seawater and freshwater before ground-water withdrawals began (fig. 8) was simulated in the areal model as a no-flow boundary. The location of the interface was estimated and adjusted by trial and error until simulated hydraulic heads at the middle of the aquifer approximated those expected from the Gyben-Herzberg principle, a special case of the Hubbert interface equation (Hubbert, 1940, p. 925). The concept of a sharp interface is a simplification, however, because diffuse zones of brackish water and saltwater would have existed in the aquifer. A diffuse zone results from the mixing of seawater and freshwater. This zone is caused by the reciprocative motion of ocean tides and seasonal fluctuations in water evels, which are brought about by variations in

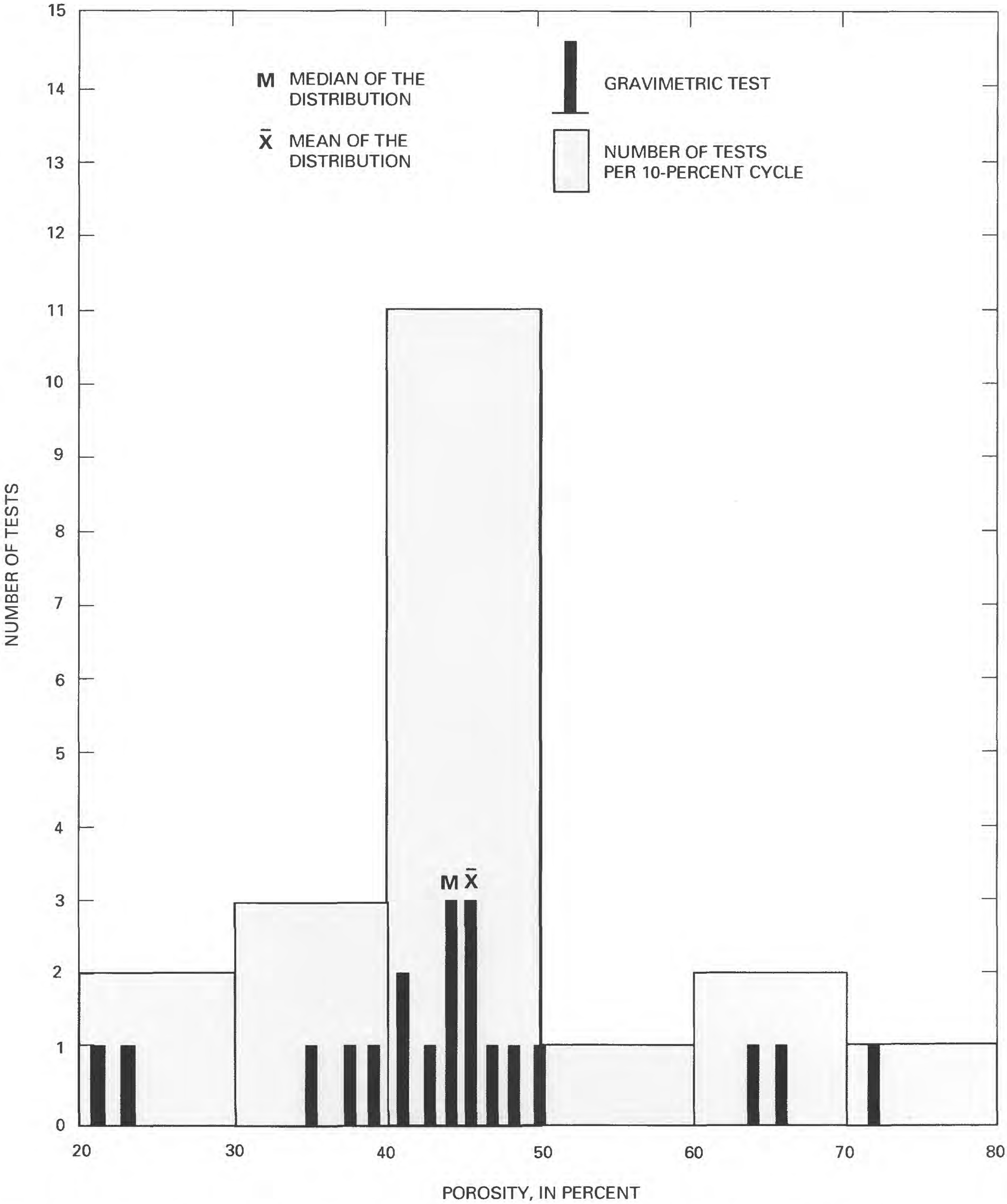

Figure 7. Frequency distribution of porosities of the upper confining unit in the Port Royal Sound area.

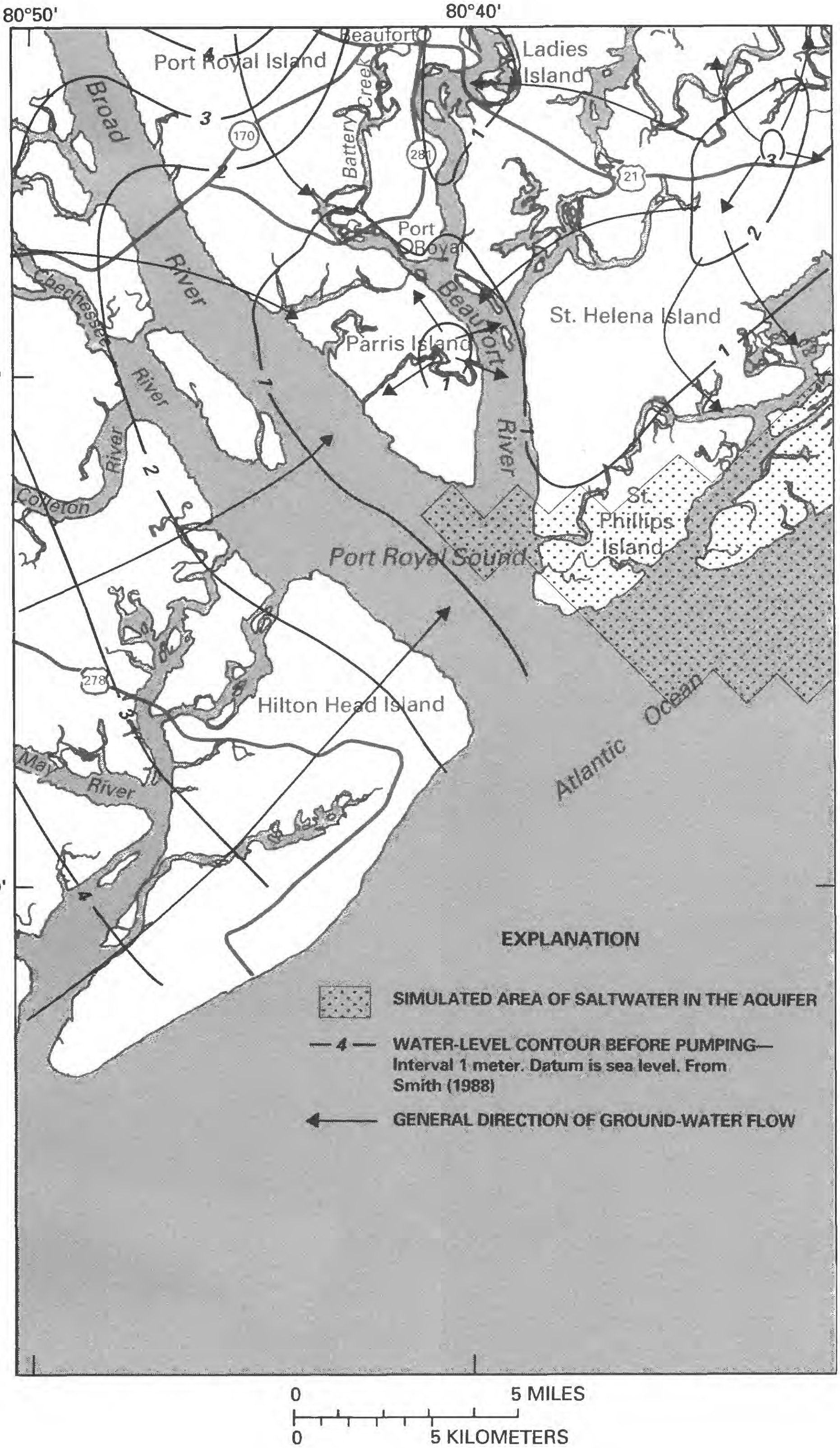

Figure 8. Patterns of flow in the Upper Floridan aquifer in the Port Royal Sound area before withdrawals of ground water began in 1885.

recharge and other forces, including pumping (Cooper, 1964, p. C8).

Use of Ground Water

Water was first withdrawn from the limestone aquifer at Savannah in 1885 through flowing wells (Warren, 1944, p. 80). Use of ground water in and around Savannah increased slowly from 1885 to the mid-1930's. Counts and Donsky (1963, p. 46, fig. 3) estimated ground-water withdrawals in the Savannah area of less 1 m^3/s during the 50 yr before 1935.

Use of ground water increased substantially in the late 1930's and early 1940's in the Savannah area, leveled off during the late 1940's and early 1950's at about 1.8 m^3/s, and then increased again in the 1950's, reaching about 2.6 m^3/s near the end of the decade (Counts and Donsky, 1963, p. 46, fig. 3). Withdrawals continued to increase in the 1960's and 1970's in the Savannah area, and, in 1980, about 3.2 m^3/s of water was withdrawn from the aquifer (Krause and others, 1984, p. 9, table 4).

A slight reduction in withdrawals from the aquifer occurred from 1981 through 1983 in the Savannah area because of industrial shutdowns (Stiles and Matthews, 1983, p. 90; and Clarke and others, 1985, p. 90). About 3.0 m^3/s of water were withdrawn in 1983 (Smith, 1988, p. 15). In 1984, withdrawals increased slightly to 3.1 m^3/s (Clarke and others, 1985, p. 96).

In South Carolina, withdrawals from the Upper Floridan aquifer were relatively minor before the 1960's. The largest wells were for military bases, farms, and small communities. Various wells had been drilled and abandoned on or near Parris Island around the late 1800's and early 1900's, during World War I, and during World War II; however, withdrawals were limited because of saltwater contamination (Burnette, 1952; and Hayes, 1979, p. 55 and fig. 21*A*).

In the late 1950's, the largest withdrawals from the Upper Floridan aquifer in South Carolina were from several sites on Port Royal Island in and near Beaufort, where a total of about 0.13 m^3/s was withdrawn. The city of Beaufort and the military installations on Port Royal and Parris Islands began using water transported by canal and pipelines from the Savannah River in 1965 and remained relatively minor users of ground water.

With economic expansion and real-estate development in the 1960's, Hilton Head Island became the predominant user of water from the Upper Floridan aquifer in South Carolina. By 1976, about 0.38 m^3/s was being withdrawn from the aquifer on Hilton Head Island (Hayes, 1979, p. 52 and fig. 20). By 1982, withdrawals on the island had increased to 0.42 m^3/s (U.S. Army Corps of Engineers, 1984, p. 6), and in 1984, about 0.42 m^3/s was being withdrawn (Smith, 1988, p. 15). Withdrawals on Hilton Head have increased since 1984.

Ground-Water Levels

Water levels in observation wells open to the Upper Floridan aquifer respond readily to changes in withdrawals. Up to 1981, a slow, steady decline in aquifer water levels was observed in southern South Carolina (Smith, 1988, fig. 7). In southeastern Georgia, a similar decline, up to 1981, has been attributed to a continuous increase in withdrawal of ground water for municipal and industrial use near Savannah (Matthews and others, 1982, p. 22). From 1981 to 1984, water levels recovered and remained essentially steady in observation wells in southern South Carolina and southeastern Georgia because of reductions in industrial withdrawals near Savannah (Clarke and others, 1985, p. 90).

Continuous-record wells open to the Upper Floridan aquifer on northeastern Hilton Head Island also showed a long-term decline in water levels until 1981 (fig. 9). From 1981 to 1984, steady water levels were recorded in the aquifer on northeastern Hilton Head Island, although seasonal variations in water levels were superimposed on the long-term trend. From 1984 to 1986, water levels resumed a slow, steady decline, probably because of increases in withdrawals.

Seasonal changes in aquifer water levels on Hilton Head Island are caused by natural variations in recharge and seasonal variations in ground-water withdrawal. Beaufort County well 444, located near production wells on Hilton Head Island, shows such seasonal changes in the aquifer water levels. Withdrawals are typically greatest from May to September when increased water consumption is caused by an influx of tourists and by irrigation of golf courses and lawns. Water levels normally rise each year from late fall to early spring, when tourism, irrigation, and evapotranspiration are least.

Beaufort County well 787 is very close to the northeastern shore of Hilton Head Island, near Port Royal Sound. Water levels in well 787 generally have been below sea level since early 1979 (fig. 9). Water

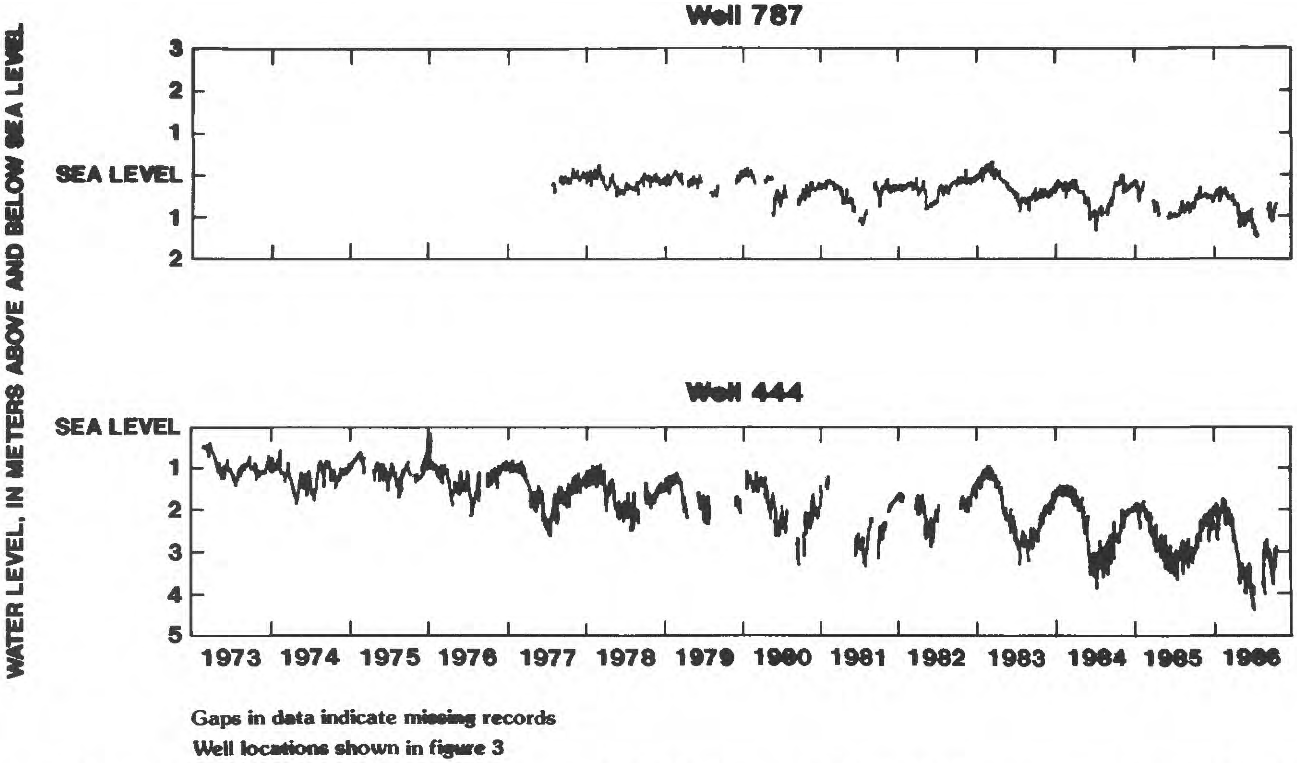

Figure 9. Water levels in continuous-record wells open to the Upper Floridan aquifer on northeastern Hilton Head Island.

levels, however, did rise above sea level in the first months of 1983 during the general recovery attributed to industrial shutdowns in Georgia, and water levels were briefly above sea level in autumn 1984. Water levels above sea level on the northern end of the island indicate ground-water flow toward Port Royal Sound, which would inhibit saltwater encroachment.

Ground-Water Flow in 1984

Water levels were measured in observation wells on Hilton Head and St. Helena Islands during March 1984 (fig. 10) and on Hilton Head Island during August 1984. Hydraulic heads in the aquifer beneath Port Royal Sound and the Atlantic Ocean were measured in wells open to the aquifer during test drilling and sampling from July to October 1984 (fig. 11). The heads in the aquifer beneath Port Royal Sound and the Atlantic Ocean were corrected for variations in ocean tides (Burt and others, 1987, figs. 11–19) and, where necessary, for variations in density (Kohout, 1964, p. C28) caused by the occurrence of brackish water and saltwater.

Water levels were not measured in the pumped wells. The locations of pumped wells are shown in figures 10 and 11 to indicate the effect of pumping on the patterns of ground-water flow.

Water levels in the Upper Floridan aquifer beneath Hilton Head Island were slightly higher in March than in August 1984. Patterns of ground-water flow, however, were similar throughout the year.

Ground-water flow in the Upper Floridan aquifer beneath Hilton Head Island is affected by withdrawals on the island, as well as those near Savannah. The largest withdrawals on Hilton Head Island, which range from 2,000 to 4,000 m^3/d, generally are located in the eastern and southern parts of the island (figs. 10 and 11). Flow in the aquifer beneath the island is generally southwestward, but some water is diverted locally toward the wells. From Hilton Head Island, ground water flows in a curved path southwestward toward wells near Savannah (fig. 2).

Precipitation falling on Hilton Head Island leaks downward to the water table and some of that water migrates through the surficial and upper confining deposits to recharge the Upper Floridan aquifer. Beneath Port Royal Sound and the Atlantic Ocean, saltwater leaks downward through the surficial and upper confining deposits toward the aquifer. The downward leakage of freshwater beneath Hilton Head

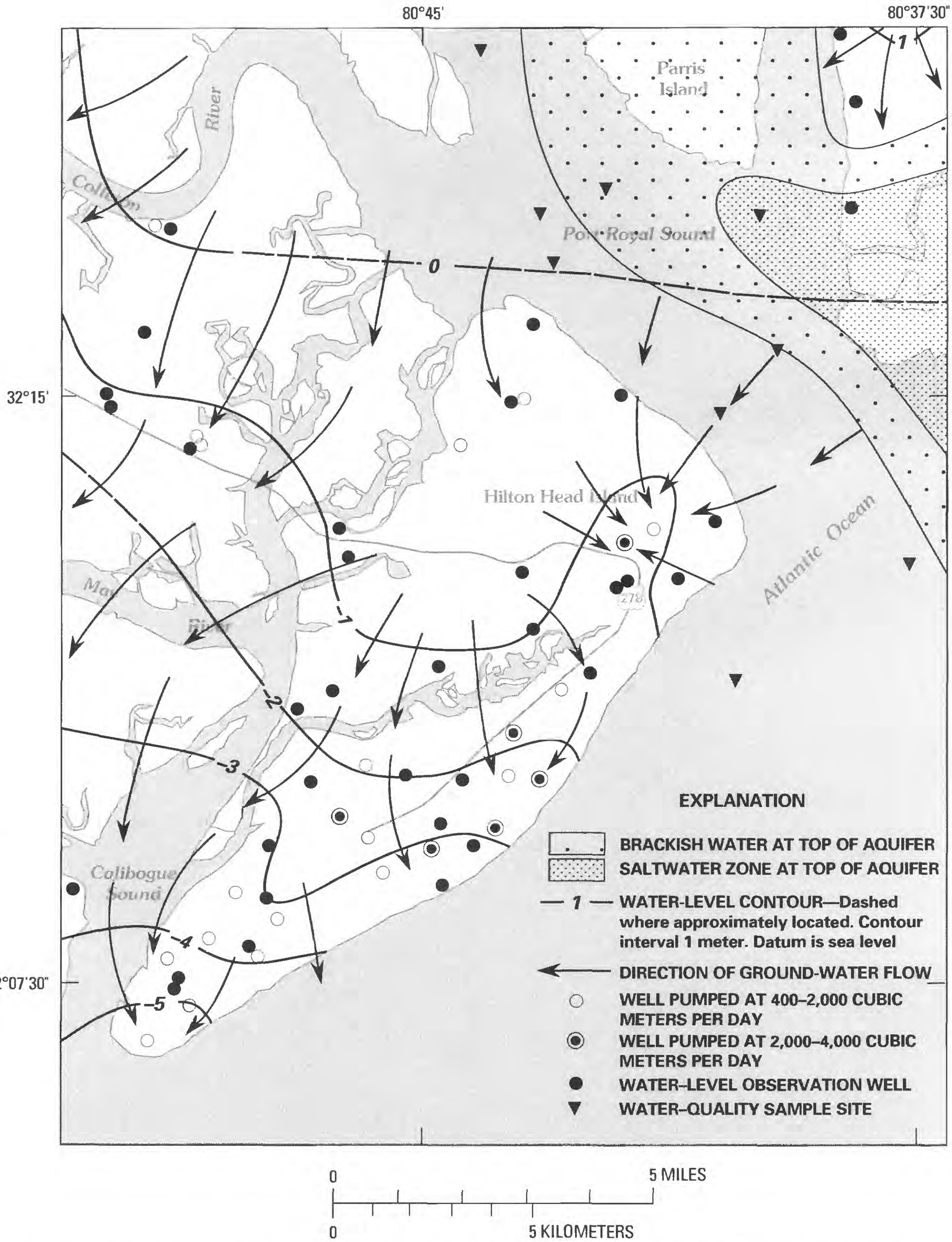

Figure 10. Patterns of flow in the Upper Floridan aquifer in March 1984 and zones of brackish water and saltwater in the top of the aquifer in the summer and fall of 1984 in the Port Royal Sound area.

Island and of saltwater beneath Port Royal Sound were indicated previously by geochemical interpretations (Back and others, 1970, p. 2335, figs. 7–8).

Using a ground-water flow and solute-transport model of a vertical section of the Upper and Lower Floridan aquifer, Bush (1988, p. 13) simulated a net

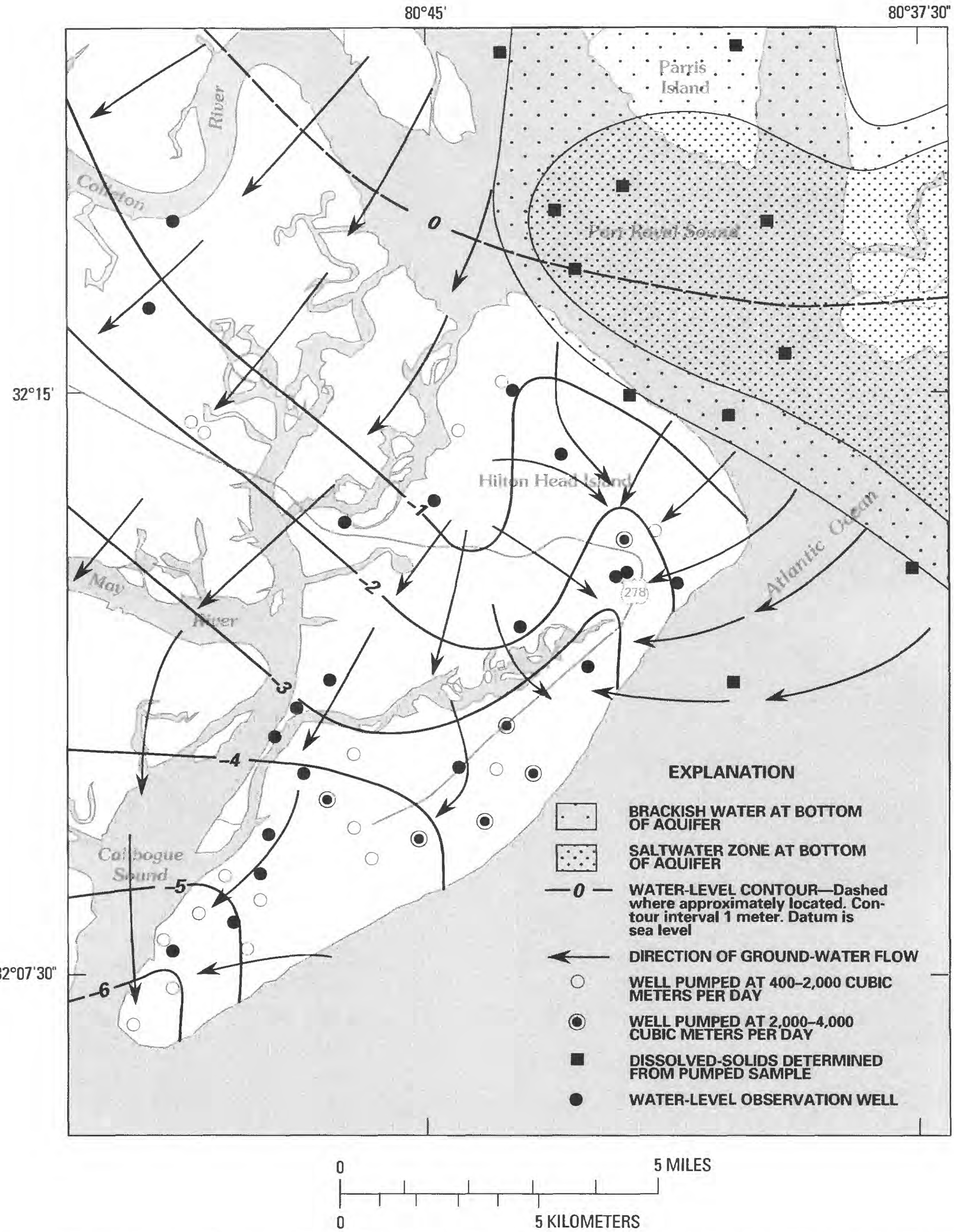

Figure 11. Patterns of flow in the Upper Floridan aquifer in August 1984 and zones of brackish water and saltwater in the bottom of the aquifer in the summer and fall of 1984 in the Port Royal Sound area.

rate of recharge of 9.7 cm/yr beneath northeastern Hilton Head Island for 1983. Recharge by downward vertical leakage for 1984 was estimated previously in this study by using an areal uniform-density model of ground-water flow. Estimated leakages, based on areal simulation, ranged from 8 to 20 cm/yr beneath northern Hilton Head Island, depending on location (Smith, 1988, fig. 17). Water levels and vertical leakages on the sea islands north and east of Port Royal Sound remained unchanged from those before withdrawals began in 1885, according to the areal model.

SALTWATER MOVEMENT

Freshwater flow in the Upper Floridan aquifer beneath Hilton Head Island was previously toward Port Royal Sound, but flow has been reversed because of the decline in aquifer heads caused by withdrawals. Areas beneath Port Royal Sound and the Atlantic Ocean, where freshwater had discharged by upward leakage before the withdrawals, are now areas where saltwater is leaking downward toward the aquifer.

Transition Zone

The nature and location of the transition zone between saltwater and freshwater in the Upper Floridan aquifer beneath Port Royal Sound and the Atlantic Ocean near Hilton Head was investigated in the late summer and early autumn of 1984 by drilling and sampling from a self-elevating platform ship (Burt and others, 1987, table 7). Dissolved-solids concentrations in water pumped from near the top of the Upper Floridan aquifer and from near the bottom 20–30 m below the top were used to define zones of brackish water (concentrations from 1,000 to 10,000 mg/L) and saltwater (concentrations greater than 10,000 mg/L) beneath the sound and the ocean. The water samples showed brackish water and saltwater in the top of the aquifer beneath the eastern part of Port Royal Sound (fig. 10). Brackish-water and saltwater zones were found near the bottom of the aquifer beneath most of Port Royal Sound (fig. 11). Freshwater was encountered, however, beneath the Atlantic Ocean immediately east of Hilton Head Island.

The transition zone of brackish water and saltwater beneath Port Royal Sound forms a wedge extending into the sound from the east and suggests a source of seawater to the east. Patterns of groundwater flow and the Gyben-Herzberg line estimated for the middle of the aquifer for the period before groundwater withdrawals also indicate a source of seawater in the aquifer east of Port Royal Sound (fig. 8). The proximity of the transition zone of 1984 to the Gyben-Herzberg line estimated for steady-state conditions indicates that the ground-water flow system was in a state of equilibrium with respect to solute concentrations, as well as hydraulic head, before withdrawals of ground water began in 1885. The transition zone has moved, but it is still near the prepumping location beneath Port Royal Sound.

Movement of brackish water in the aquifer northward from Port Royal Sound to beneath Parris Island resulted from local ground-water withdrawals at Parris Island in the early part of the 20th century, as described in an unpublished report by M.J. Mundorff of the USGS. A source of saltwater from the adjacent tidal creeks and flats north and east of Parris Island was the saltwater source implied by Mundorff and Duncan (1972, p. 104). Dissolved-solids concentrations approaching those of seawater beneath northern Parris Island in 1984 indicate a source from the tidal rivers to the north and possibly east of Parris Island as well (Smith, 1988, fig. 20).

Saltwater Encroachment

Water levels of the Upper Floridan aquifer respond readily to changes in pumping and reach a new equilibrium relatively quickly; however, the transition zone between freshwater and saltwater in the aquifer beneath Port Royal Sound has moved relatively slowly toward Hilton Head Island in response to the net lowering in water levels. Hydraulic gradients in the aquifer have directed ground-water flow from the island toward the sound throughout much of history.

The transition zone beneath Port Royal Sound was moving slowly with the direction of ground-water flow toward Hilton Head Island in 1984 and had been moving slowly from an earlier position not far to the east. The velocity of saltwater encroachment toward the northern tip of Hilton Head Island was calculated with data collected from the test wells in the aquifer beneath Port Royal Sound in 1984. Assuming that solutes travel with the average velocity of ground water, it was estimated that the transition zone between Parris and Hilton Head Islands was moving from 15 to 24 m/yr in the late summer and early autumn of 1984 (Smith, 1988, p. 42). The calculated velocity does not account for mechanical dispersion of solutes that occurs because of heterogeneities in the aquifer. The calculated velocity for this site may also be quite different from that at another site, because hydraulic gradients, local heterogeneities, and density gradients at other sites in the aquifer could be different. Hydraulic

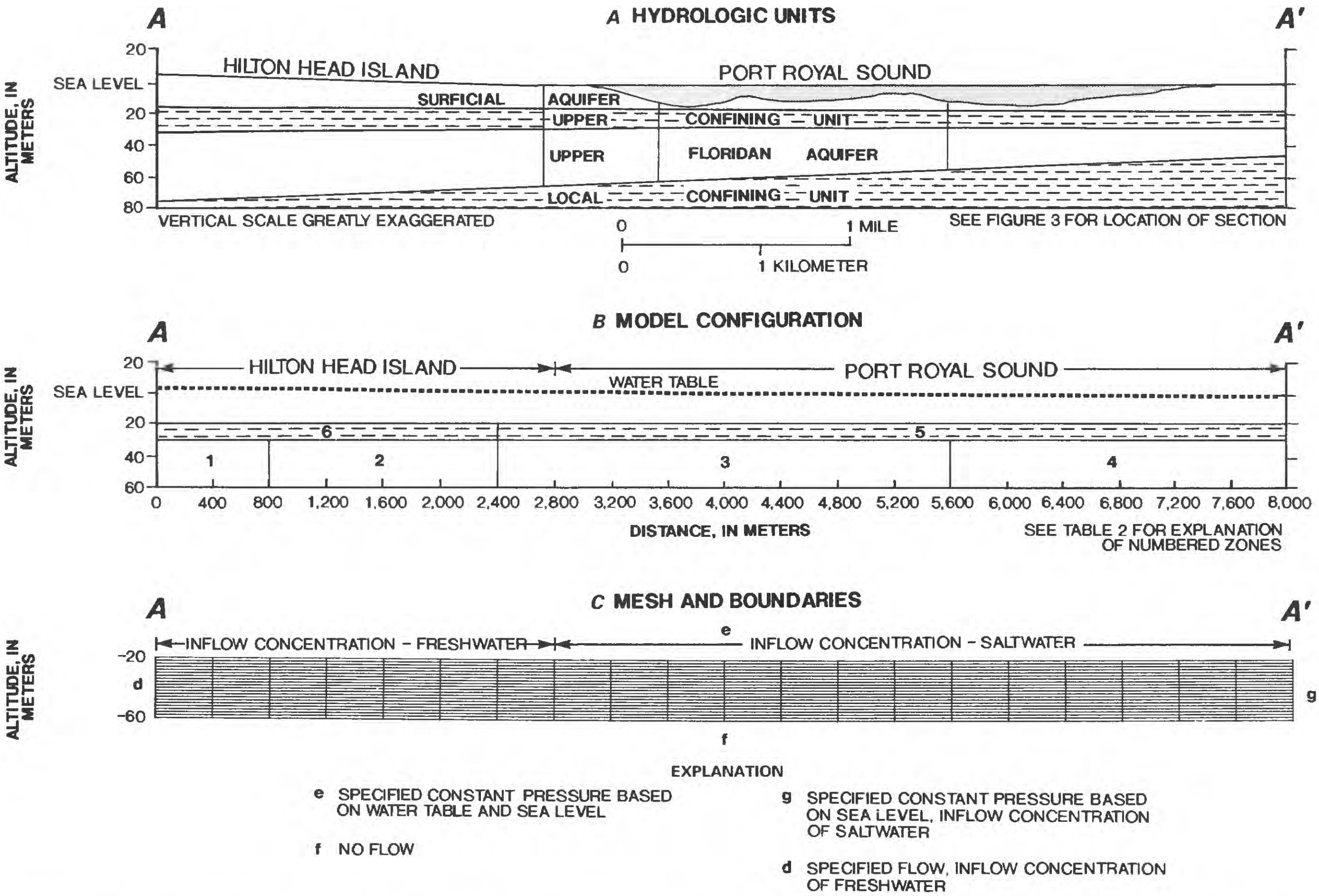

Figure 12. (*A*) Hydrogeologic units, (*B*) model configuration, and (*C*) mesh and boundaries of the vertical section beneath Hilton Head Island and Port Royal Sound.

gradients at other times of the year also change because of changes in water levels and in pumping.

Using a density-dependent flow and solute-transport model of a vertical section beneath Port Royal Sound and northeastern Hilton Head Island, Bush (1988, p. 13–14) simulated an average velocity of 21 m/yr in the upper permeable zone of the Upper Floridan aquifer for 1983. The average velocity, simulated by Bush, for the Upper Floridan aquifer deposits below the upper permeable zone was 4.3 m/yr.

SIMULATION OF SALTWATER MOVEMENT

The SUTRA model of the USGS was used to simulate movement of brackish water and saltwater in response to historical changes in pumping and to simulate potential movements of brackish water and saltwater in response to hypothetical changes in pumping and freshwater injection.

Model Design

Saltwater and brackish-water movement was simulated along an 8-km by 60-m by 1-m vertical section of the Upper Floridan aquifer and upper confining unit beneath Port Royal Sound and northeastern Hilton Head Island (fig. 12*A* and *B*). This section approximates the principal directions of ground-water flow before withdrawals began in 1885 and during pumping in 1984, and, therefore, its use minimizes errors associated with the two-dimensional approach. See figure 3 for the location of the section.

The northeastern end of the section is beyond the Gyben-Herzberg line for the middle of the aquifer beneath eastern Port Royal Sound. The southeastern edge of the section is near municipal wells that were withdrawing water from the aquifer on Hilton Head Island in 1984. The section also passes through two sample sites beneath Port Royal Sound and another beneath Hilton Head Island.

Table 2. Hydraulic conductivities and equivalent permeabilities of the Upper Floridan aquifer and upper confining unit for solute-transport simulation beneath Hilton Head Island and Port Royal Sound

[m/d, meter per day; m^2, square meters]

Unit	Block[1]	Horizontal hydraulic conductivity m/d	Vertical hydraulic conductivity m/d	Horizontal permeability (m^2)	Vertical permeability (m^2)
Upper Floridan aquifer	1	150	15	1.8×10^{-10}	1.8×10^{-11}
	2	120	12	1.4×10^{-10}	1.4×10^{-11}
	3	90	9	1.1×10^{-10}	1.1×10^{-11}
	4	60	6	7.1×10^{-11}	7.1×10^{-12}
Upper confining unit	5	2.0×10^{-3}	2.0×10^{-3}	2.4×10^{-15}	2.4×10^{-15}
	6	1.0×10^{-3}	1.0×10^{-3}	1.2×10^{-15}	1.2×10^{-15}

[1]Blocks are shown in figure 12*B*.

A simple, rectangular finite-element mesh was designed with 400 elements (each 400 m long, 1 m wide, and 2 m deep) to represent the Upper Floridan aquifer and upper confining unit (fig. 12*C*). The bottom of the section was designated a no-flow boundary because vertical leakages through the confining deposits below the aquifer were considered negligible. Along the vertical landward boundary beneath Hilton Head Island, flow was specified for the aquifer and held constant for selected periods of time with concentrations of inflow of freshwater.

Vertical leakage through the upper confining unit from the surficial unit was calculated by the model based on pressures estimated for the water table (specified constant in time beneath Hilton Head Island) and on pressures derived from sea level (specified constant in time beneath Port Royal Sound). Inflows from the surficial unit were specified as freshwater beneath Hilton Head Island and as seawater beneath Port Royal Sound. Pressures and inflow of seawater were also specified along the vertical boundary beneath Port Royal Sound, representing a seaward source of saltwater.

The actual dissolved-solids concentrations along the vertical boundary on the seaward side were not known. Static seawater was assumed at the vertical boundary because a presumed source of seawater exists to the east as indicated by the distribution of saltwater beneath Port Royal Sound in 1984. The tidal creeks north and east of Parris Island also had contributed saltwater approaching the concentration of seawater to the aquifer in response to pumping in the past. It was therefore assumed that a source of seawater was near, if not actually at, the seaward vertical boundary.

Permeabilities simulated for the Upper Floridan aquifer were derived from the transmissivities of the section (fig. 5). Horizontal hydraulic conductivity of the aquifer was separated, for simulation, into four blocks (table 2 and fig. 12*B*) to represent the decrease in transmissivity from southwest to northeast. Variations in aquifer transmissivity were the same as those used in the areal model (Smith, 1988, p. 11). An aquifer thickness of 30 m was used to calculate horizontal hydraulic conductivity from transmissivity.

The vertical hydraulic conductivity of the upper confining unit beneath Port Royal Sound was assigned a value of 0.002 m/d, which is between the primary mode (0.0017 m/d) and the median (0.0026 m/d) of the distribution from permeameter tests of cores. The upper confining unit thickens to the west and southwest, and two blocks were used to represent vertical hydraulic conductivity (table 2). Beneath Hilton Head Island, the depth to the top of the aquifer is about twice that beneath Port Royal Sound. The vertical hydraulic conductivity of the confining unit in this area was reduced by one-half to 0.001 m/d to compensate for the increased thickness of the upper confining unit without changing the geometry of the finite-element mesh.

Permeabilities of the aquifer and upper confining unit used to simulate solute transport were derived from the hydraulic conductivities, using estimated fluid viscosity and density (table 3). Water was assumed to be incompressible. Vertical hydraulic conductivity of the aquifer was assumed to be one-tenth that of the horizontal because of the layered nature of the deposits that constitute the permeable zones of the aquifer. Bush (1988, fig. 5) used the same ratio for the Upper Floridan aquifer in his simulation of solute transport. Horizontal hydraulic conductivity of the upper confining unit in the present model was assumed to be equal to the vertical. Reductions in

Table 3. Physical properties for simulation of solute transport in the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound

Temperature	20 degrees Celsius.
Viscosity	0.001 kilograms per meter-second.
Acceleration due to gravity[1]	9.80 meters per square second.
Density of freshwater	1000 kilograms per cubic meter.
Density of seawater	1025 kilograms per cubic meter.
Coefficient of density change with concentration[2].	700 kilograms seawater squared per kilograms dissolved solids meters cubed.
Molecular diffusivity[3]	1.0×10^{-9} square meters per second.
Base concentration as mass fraction[3].	0.0000 (kilogram dissolved solids) per kilogram (seawater).
Maximum concentration of seawater as mass fraction[3].	0.0357 (kilogram dissolved solids) per kilogram (seawater).

[1]After Davis and DeWiest (1966, p. 447).
[2]Voss (1984, p. 198).
[3]Freeze and Cherry (1979, p. 103).

permeability in the silt and clay fractions of the upper confining unit that might result from physical and chemical reactions of mixing freshwater and saltwater were not simulated.

Storage in the aquifer and upper confining unit was considered negligible. Bush (1988, p. 12) tested storage in a simulation of saltwater movement in the Floridan aquifer system beneath Hilton Head Island and Port Royal Sound and found no difference in the distributions of hydraulic heads or solute concentrations with or without storage considerations. The tests by Bush, thus, supported the findings of Randolph and Krause (1984, p. 15) that a very small fraction of the water withdrawn from the Upper Floridan aquifer by pumping comes from storage.

An aquifer porosity of 33 percent was used in the model. This value is based on the median of the laboratory tests of limestones from Counts and Donsky (1963, p. 43). Porosity of the upper confining unit was simulated as 44 percent, based on the mode and median of the gravimetric tests of sediment cores (fig. 7).

Dispersion is the mechanical and molecular mixing of solutes caused by heterogeneities of various scales within the medium. Variations in porosity and permeability in the aquifer and upper confining unit at various scales, that, as yet, cannot be observed, may provide unknown avenues for the movement of brackish water and saltwater. No measurements are available for dispersivity of the aquifer or confining unit in the study area. Dispersion in porous media measured elsewhere by single-well or double-well tracer tests have ranged from 0.1 to 100.0 m (Javandel and others, 1984, fig. 29, p. 90). Dispersion in porous media is scale dependent, however, and short-term, field-scale measurements of dispersion may not be suitable for long-term, large-scale simulations. In large-scale simulations of solute transport, apparent dispersivities in the direction of flow (longitudinal) for porous media have been reported from 12 to 200 m (Wolff, 1982, table 4.5.2), and those transverse to flow were calculated to be from 0.2 to 20 m on the basis of the ratios reported by Anderson.

A longitudinal dispersivity of 143 m and a transverse dispersivity of 1.14 m were simulated for the Upper and Lower Floridan aquifers and intervening units by Bush (1988, fig. 5). In the present investigation of the Upper Floridan aquifer and the upper confining unit, a longitudinal dispersivity of 100 m and a transverse of 0.1 m were simulated. Differences in the simulated dispersivities would result, in part, because of the differences in finite-element scales used for the simulations. The dispersion of solutes in the present model is in the range of values measured in and simulated for porous media elsewhere and is similar to values simulated previously.

Initial Conditions

Water levels in the Upper Floridan aquifer were probably in a state of dynamic equilibrium before withdrawals from the aquifer began in 1885. Periodic variations in water levels would have occurred because of prolonged droughts, seasonal evapotranspiration and recharge events, and, in coastal areas, ocean tides; however, those variations would have fluctuated about a mean water-level surface.

Before withdrawals began, the transition from freshwater to seawater must have occurred as diffuse zones of brackish water and saltwater because of the seasonal and tidal fluctuations in aquifer water levels. Solutes move slowly in response to changes in aquifer water levels, particularly if compared to the quick response of aquifer water levels to changes in pumping from the aquifer. If water levels were in dynamic equilibrium for a sufficient period of time before withdrawals began, the zones of brackish water and saltwater also would have reached a state of dynamic equilibrium.

The proximity of the transition zone, measured beneath Port Royal Sound in 1984, to the Gyben-Herzberg interface of seawater and freshwater,

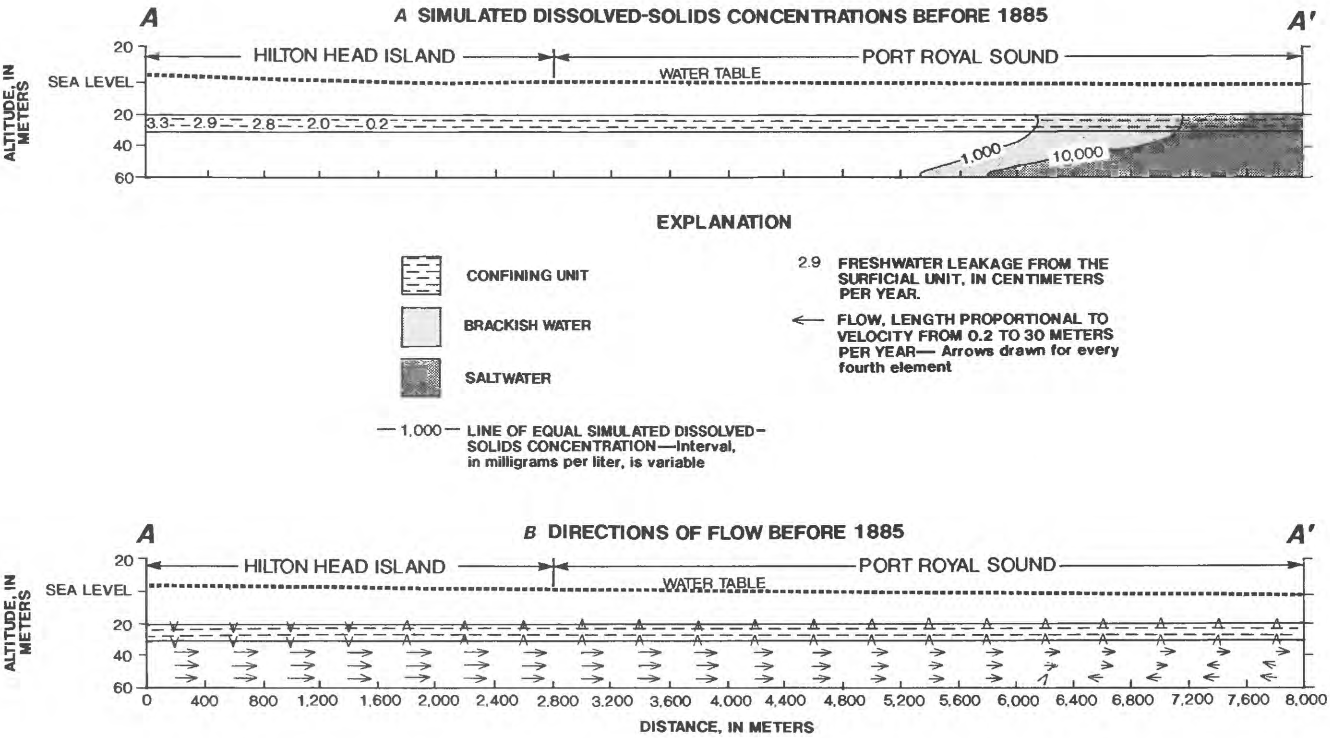

Figure 13. (*A*) Simulated dissolved-solids concentrations and (*B*) directions of flow for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound before 1885.

estimated by areal simulation for the period before pumping, indicates that the transition zone was in or near equilibrium before withdrawals began. It is less likely that an equilibrium with respect to solute concentrations would have been established in the lower parts of the aquifer where permeabilities and flow velocities are low. Under these conditions, a much longer period of time would be required to reach equilibrium with respect to solutes.

Changes in sea level because of global variations in climate (eustatic changes) occur very slowly. Sea level has risen about 90 m over the past 10,000 yr (Meisler and others, 1984, p. 6–7 and fig. 4) because of melting ice from the last glacial episode. Seawater would have advanced slowly into freshwater within the Upper Floridan aquifer as the sea level rose. But, how long might it take for an equilibrium with respect to solute concentrations to be established in the aquifer?

To answer this question, the displacement of freshwater in the Upper Floridan aquifer and upper confining unit with brackish water and saltwater from a seaward source for the period before withdrawals began was simulated. Initial pressures for the simulation were calculated by the solute-transport model on the basis of the boundaries and properties of the aquifer and confining unit described above and on freshwater flow specified in the aquifer from the landward direction beneath Hilton Head Island. Flow of freshwater from the landward direction in the 1-m-wide model section was specified as 0.009 kg/s based on an areal simulation of flow before withdrawals began (Smith, 1988).

Solute movement from the seawater boundary was simulated until a dynamic equilibrium was reached and the landward movement of brackish water and saltwater ceased (fig. 13*A*). Time steps of 0.25 yr were used in the simulation, and subsequent sensitivity analysis showed that time steps one-half of 0.25, or 0.125 yr, gave the same results. Time steps of 0.50 yr gave similar results but showed some numerical oscillation with respect to the distribution of solutes.

In the simulation, equilibrium with respect to solutes in the Upper Floridan aquifer occurred in about 800 yr, a relatively short time compared to the duration of the last major eustatic change in sea level. Brackish water moved 2,200 m in 800 yr, displacing freshwater at a rate of about 3.0 m/yr until equilibrium was established according to the simulation.

Arrows in figure 13*B* show the directions and relative velocities of flow for every fourth element simulated for the Upper Floridan aquifer and upper confining unit for the equilibrium established before withdrawals began. Maximum velocity of flow in the aquifer was 30 m/yr.

Arrows pointing downward beneath Hilton Head Island represent freshwater leakage through the confining unit, indicating natural recharge from the higher land-surface areas of the overlying surficial unit. In the simulation, freshwater recharge through the upper confining unit beneath the island varied from 3.3 cm/yr at the landward boundary to 0.2 cm/yr closer to shore.

Arrows in the aquifer beneath Hilton Head Island pointing in the direction of Port Royal Sound show freshwater flowing from beneath the island toward the sound where the freshwater mixes with and rides over saltwater, which is shown by arrows pointing in the opposite direction. Saltwater moves to the bottom of the aquifer and freshwater moves to the top of the aquifer because of the difference in density between the two types of water. Mixing of freshwater and saltwater forms the zone of brackish water in between.

Arrows pointing upward in the confining unit beneath Port Royal Sound show the upward leakage of freshwater and some brackish water and saltwater into the sound. Arrows pointing upward and seaward at the top of the aquifer near the seaward boundary represent the return flow of saltwater toward the sea, which was described by Cooper (1964, p. C–1) as the result of the dynamic balance between the flow of freshwater and saltwater in coastal aquifers.

Saltwater Movement From 1885 To 1984

Movement of the transition zone from the position simulated for the steady-state period before withdrawals began in 1885 to the position measured in 1984 was approximated by adjusting specified flows at the landward vertical boundary to reflect changes in the seaward flow of freshwater. Changes in the flow of freshwater occurred because of withdrawals from the aquifer, initially near Savannah and later on Hilton Head Island. No other variables in the model were changed for the simulations.

Three pumping periods ending in 1934, 1976, and 1984, respectively, were simulated by specifying different freshwater flows to the aquifer at the landward boundary. Flow of freshwater to the aquifer was adjusted by trial and error for the first two periods until hydraulic heads simulated for the aquifer approximated those measured for the section. Freshwater flow for the last period was taken from the areal simulation of ground-water flow for 1984 (Smith, 1988, p. 28).

The solute-transport model was calibrated to concentrations of dissolved solids measured in 1984 and to hydraulic heads measured in wells open to the aquifer on Hilton Head Island in 1976 (Hayes, 1979, fig. 25) and in 1984 (figs. 10–11). Hydraulic heads along the section were interpolated from the measurements and compared to corresponding hydraulic heads simulated for the Upper Floridan aquifer (fig. 14).

The first pumping period, from 1885 through 1934, was a 50-yr period of slow, steady increases in withdrawals from the aquifer near Savannah. During this period pumping increased to almost 1.0 m^3/s (Counts and Donsky, 1963, p. 46, fig. 3). Inflow of freshwater to the Port Royal Sound area from the landward direction was reduced because of the pumping. Freshwater flow into the 1-m-wide section was simulated as 0.006 kg/s, or 67 percent of the inflow before withdrawals began.

Hydraulic heads and solute movement in the aquifer in the Port Royal Sound area changed minimally during this period (fig. 15*A*). Hydraulic heads of the Upper Floridan aquifer decreased slightly because of the reduction in freshwater flow, according to the simulation (fig. 14), and the general directions of flow changed very little (fig 15*B*). Maximum velocity of flow simulated for the aquifer was 25 m/yr in the freshwater part of the aquifer.

Leakage to the aquifer through the upper confining unit on Hilton Head Island increased slightly because a larger vertical gradient was created between the heads in the aquifer and the constant heads of the surficial unit above the upper confining unit. Simulated freshwater leakages from the higher land-surface areas of Hilton Head Island ranged from 4.7 cm/yr at the landward boundary to 1.3 cm/yr closer to shore.

The second pumping period, from 1935 through 1976, was marked by large and generally steady increases in withdrawals from the upper Floridan aquifer near Savannah and by substantial withdrawals from the aquifer on Hilton Head Island that began in the 1960's. Added together, the withdrawals from both areas are estimated to have approached 3.5 m^3/s by 1976. Flow of freshwater into the Upper Floridan aquifer at the location of the landward boundary simulated for northern Hilton Head Island was reversed during this period; however, water-level and

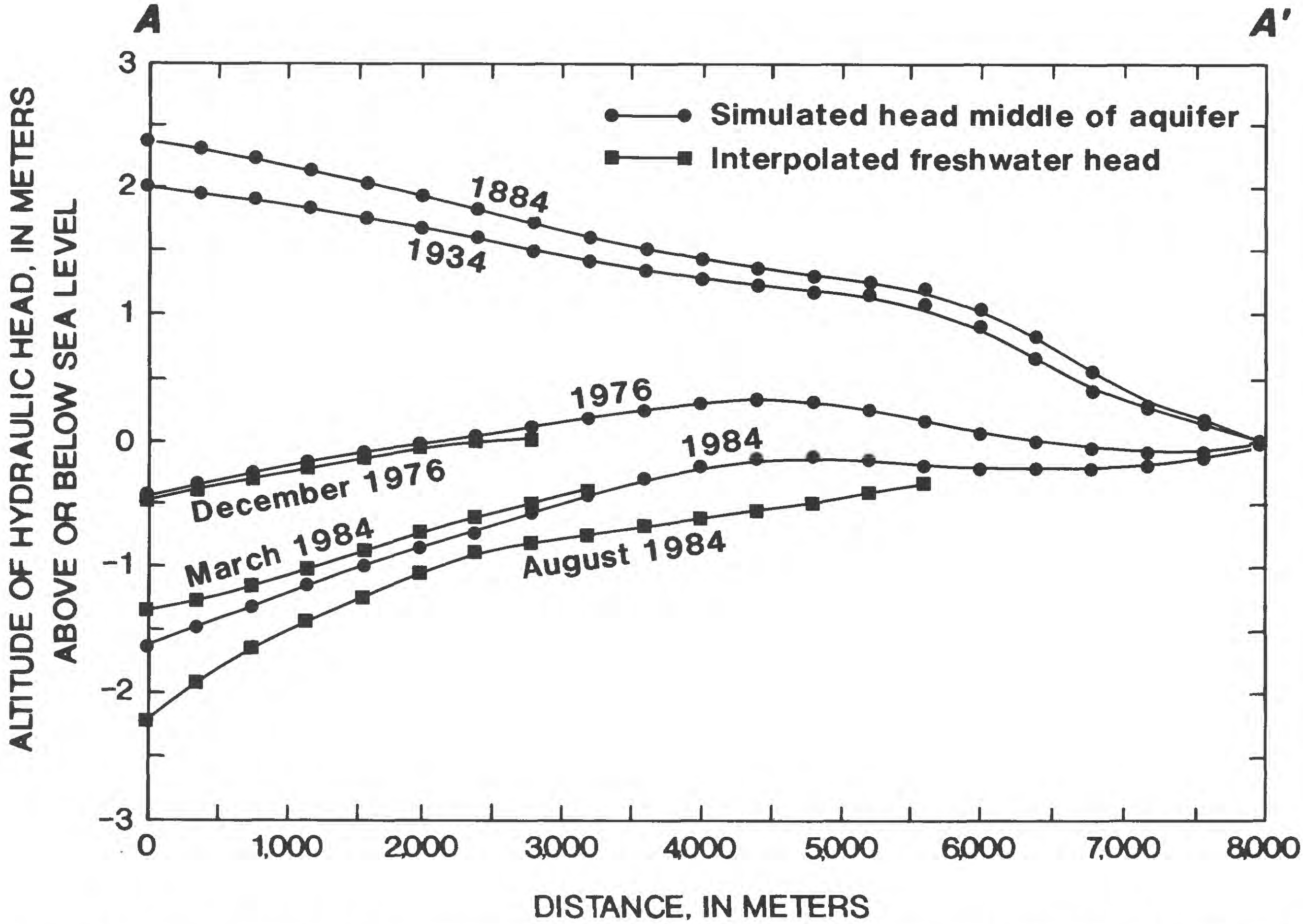

Figure 14. Hydraulic heads of the section in the Upper Floridan aquifer beneath Hilton Head Island and Port Royal Sound.

withdrawal data before 1976 that would indicate when the reversal occurred on Hilton Head Island are not available.

Flow simulated for the second period at the landward boundary was adjusted by trial and error until the hydraulic-head gradients measured in 1976 were approximated (fig. 14); this resulted in a flow rate of –0.014 kg/s. The negative sign indicates flow toward land in the opposite direction from the previous simulation.

During the second pumping period, hydraulic heads declined significantly in the aquifer and, subsequently, movement of solutes took place (fig. 16*A*). Arrows drawn in the aquifer beneath Hilton Head Island show the reversal in flow from the previous period and indicate that freshwater was being displaced by brackish water and saltwater moving landward in the aquifer in response to the decline in hydraulic head (fig. 16*B*). Brackish water moved about 1,200 m in the bottom of the aquifer over the 42 yr of the simulation, indicating a rate of displacement of about 30 m/yr. Maximum velocity of flow in the aquifer was beneath Hilton Head Island where freshwater was moving inland about 40 m/yr, according to the simulation.

Arrows pointing downward in the upper confining unit beneath Hilton Head Island on figure 16*B* show that freshwater from the surficial unit leaked downward during the second period. Downward leakage increased from the previous period because the vertical hydraulic gradient between the surficial unit and the Upper Floridan aquifer increased. Leakages from 14 cm/yr at the landward boundary to 3.5 cm/yr near shore were simulated by the model.

Arrows in the upper confining unit beneath Port Royal Sound for the second pumping period are pointing downward, indicating a reversal in the flow from the previous period. Brackish water and saltwater from the sound were leaking slowly downward toward the aquifer at the shoreline and just offshore where

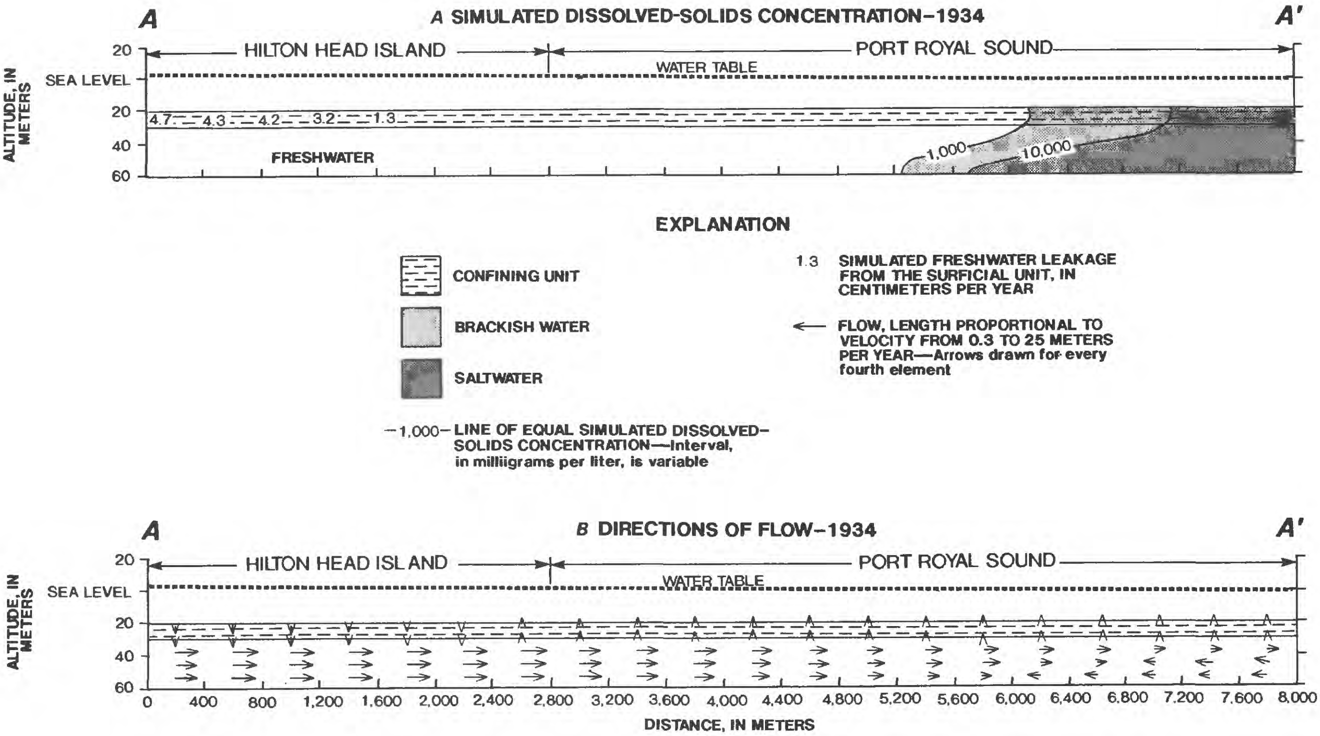

Figure 15. (*A*) Simulated dissolved-solids concentrations and (*B*) directions of flow for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for 1934.

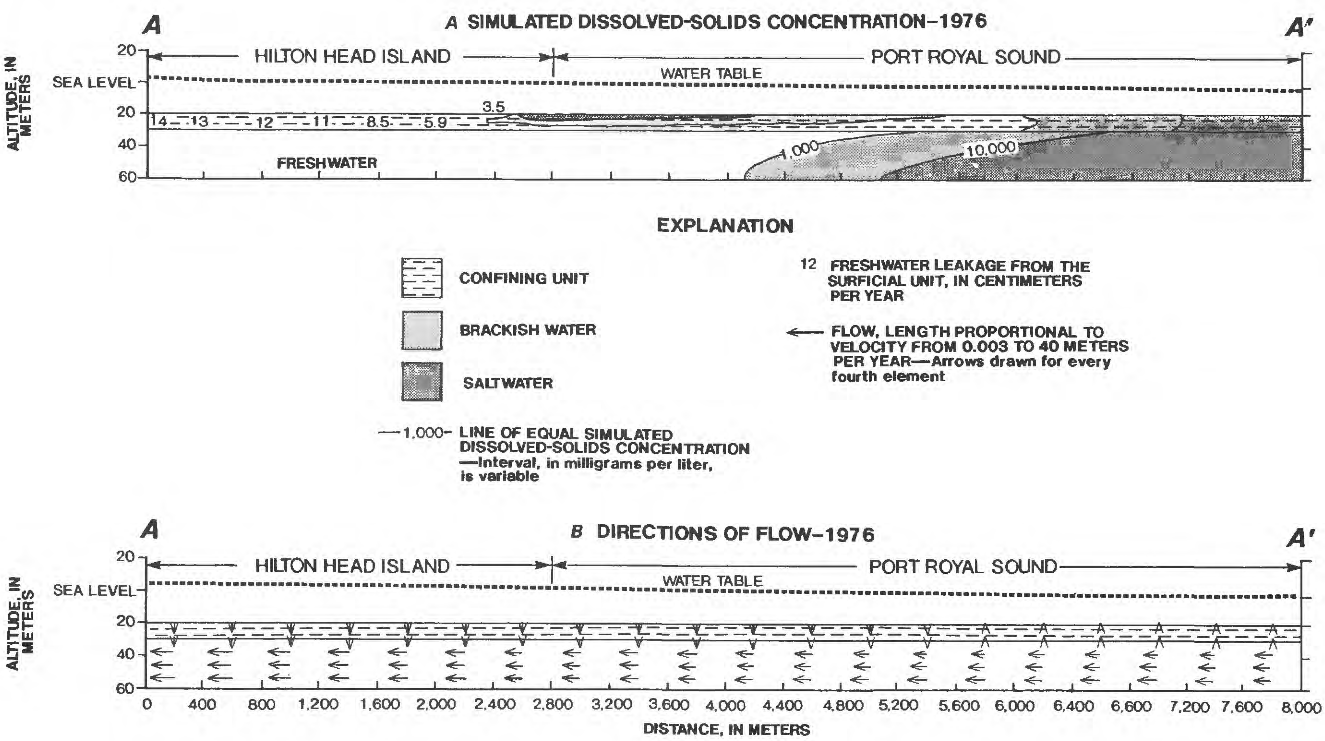

Figure 16. (*A*) Simulated dissolved-solids concentrations and (*B*) directions of flow for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for 1976.

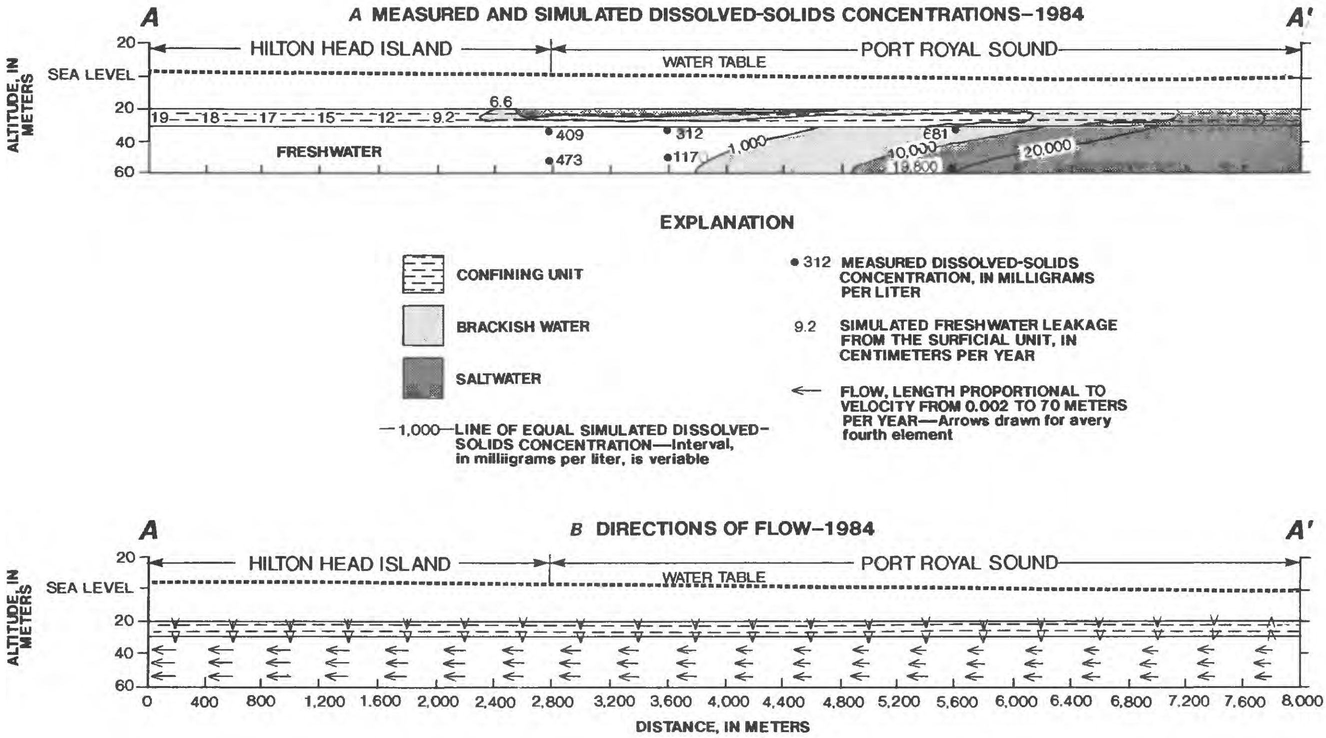

Figure 17. (*A*) Measured and simulated dissolved-solids concentrations and (*B*) directions of flow for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for 1984.

hydraulic heads had declined the most beneath Port Royal Sound. Freshwater remained in the upper confining unit farther seaward beneath Port Royal Sound where hydraulic heads had not declined as much. A null point, where flow was stagnant, occurred in the freshwater zone beneath Port Royal Sound, according to the simulation.

The third pumping period was from 1977 to 1984. Withdrawals continued to increase from 1976 to 1981, and then were slightly reduced. Hydraulic heads declined steadily because of the increase in withdrawals up to 1981, and then hydraulic heads recovered slightly but remained essentially level from 1981 to 1984. Flow of freshwater simulated for the landward boundary was specified as –0.024 kg/s for the third period, which was taken from flow and withdrawals simulated for 1984 with the areal uniform-density model of ground-water flow.

Hydraulic head gradients measured in the aquifer during seasonally high and low times of the year were used as references to calibrate the model with respect to heads in 1984 (fig. 14). Dissolved-solids concentrations in the Upper Floridan aquifer, determined from four samples withdrawn from the aquifer beneath Port Royal Sound in 1984 and from two samples withdrawn from the aquifer beneath Hilton Head Island in 1985, were used to calibrate the model with respect to solutes (fig. 17*A*). Calibration of the model was accomplished by adjusting freshwater inflow in proportion to withdrawal rates for the previous two periods until measured hydraulic heads were approximated for 1976 and 1984, and until the differences between simulated and sampled concentrations of 1984 were minimized.

Dissolved-solids concentrations simulated for the aquifer by the model are reasonably close to those determined from pumped samples (fig. 17*A*). Simulated concentrations of dissolved solids, as displayed by the leading edges of brackish water and saltwater are, however, closer to land at the top of the aquifer and farther from land at the bottom of the aquifer than those concentrations determined by sampling.

Brackish water and saltwater continued to move landward, displacing freshwater in the aquifer during the third period. Velocity of ground water in the brackish-water zone at the bottom of the aquifer was 35 m/yr in 1984, according to the solute-transport simulation.

The rate of flow calculated for the brackish-water zone of the aquifer in 1984 by the solute-transport model, 35 m/yr, is higher than that calculated from hydraulic heads measured in the aquifer between Parris Island and northern Hilton Head Island, which was estimated to be 15–24 m/yr in 1984. The brackish-water zone of the section simulated is closer to wells in the southeastern part of Hilton Head Island and, therefore, is affected by steeper hydraulic gradients caused by local pumping, whereas the area between Parris and Hilton Head Islands is not affected by so steep a gradient. The maximum velocity of flow calculated by the solute-transport model for the aquifer in 1984, about 70 m/yr, was beneath Hilton Head Island where the hydraulic conductivity and the gradient were greater than elsewhere (fig. 17*B*).

Leakage of freshwater through the upper confining unit beneath Hilton Head Island increased from the preceding period because aquifer heads declined and the vertical gradient between the surficial aquifer and the Upper Floridan aquifer increased. Leakages from 6.6 cm/yr near shore to 19 cm/yr near the landward vertical boundary were simulated by the solute-transport model. These results generally coincide with those calculated by the areal flow model for 1984 (8–20 cm/yr) depending on location (Smith, 1988, p. 35).

Brackish water and saltwater continued to leak slowly downward through the upper confining unit at the shoreline and offshore in 1984, and freshwater remained in the upper confining unit farther seaward beneath Port Royal Sound, according to the solute-transport simulation. However, no determinations of solutes within the upper confining deposits beneath Port Royal Sound are available to confirm the presence or movement of freshwater, brackish water, or saltwater above the aquifer.

Sensitivity

The solute-transport model presented here incorporates existing data, follows theoretical concepts of the mixing of freshwater and seawater, and approximates hydraulic gradients and solute concentrations measured or expected from theory with reasonable accuracy. Uncertainties exist, however, in many aspects of the solute-transport simulations. Few data are available to describe the early history of hydraulic heads in the Upper Floridan aquifer and no data are available to indicate the distribution of solute concentrations or the location of the freshwater-saltwater transition zone beneath Port Royal Sound before 1984. Also, data that describe properties of the aquifer and upper confining unit show variations that are generally averaged in the solute-transport model and, thus, contribute uncertainty to the simulations.

To determine which properties had the greatest effect on the results, sensitivity of the model to changes in selected parameters was tested. One parameter at a time was changed, generally by plus or minus 25 percent with all other parameters unchanged from those of the calibrated model. The entire sequence of simulations from the initial conditions (freshwater throughout the section) to 1984 was repeated for each test. The locations of the brackish-water and saltwater zones for 1984 simulated with a 25-percent increase in the selected parameter were then compared to those simulated with a 25-percent decrease. Sensitivity to aquifer permeability, aquifer porosity, confining-unit permeability, hydraulic head, and dispersivity were tested.

The solute-transport model was less sensitive to changes in aquifer permeability than to changes in the permeability of the upper confining unit. Changes of plus and minus 25 percent of aquifer permeability (fig. 18*A* and *B*) shifted the brackish-water front simulated for 1984 landward and seaward a total of about 200 m at the bottom of the aquifer. Increasing aquifer permeability by 25 percent shifted the brackish-water front about 100 m landward at the bottom of the aquifer. Decreasing aquifer permeability by 25 percent shifted the front about 100 m seaward. Changes of plus and minus 25 percent of the permeability of the upper confining unit (fig. 19*A* and *B*) shifted the front a total of about 800 m at the bottom of the aquifer. Increasing the permeability of the confining unit shifted the brackish-water front 400 m landward at the bottom of the aquifer and decreasing the permeability shifted the front 400 m seaward.

The controlling influence of the upper confining unit on ground-water flow and the distribution of solutes in a confined coastal aquifer was shown by simulation of a hypothetical, but similar, confined-aquifer system by Frind (1982, p. 89–97). The upper confining unit controls the flow of ground water in a confined coastal aquifer where freshwater is flowing seaward according to Frind, because the confining unit impedes the leakage of freshwater from the aquifer to the sea above, and, thus, freshwater in the aquifer is diverted seaward.

Permeability of the upper confining unit is even more critical in a confined coastal aquifer where

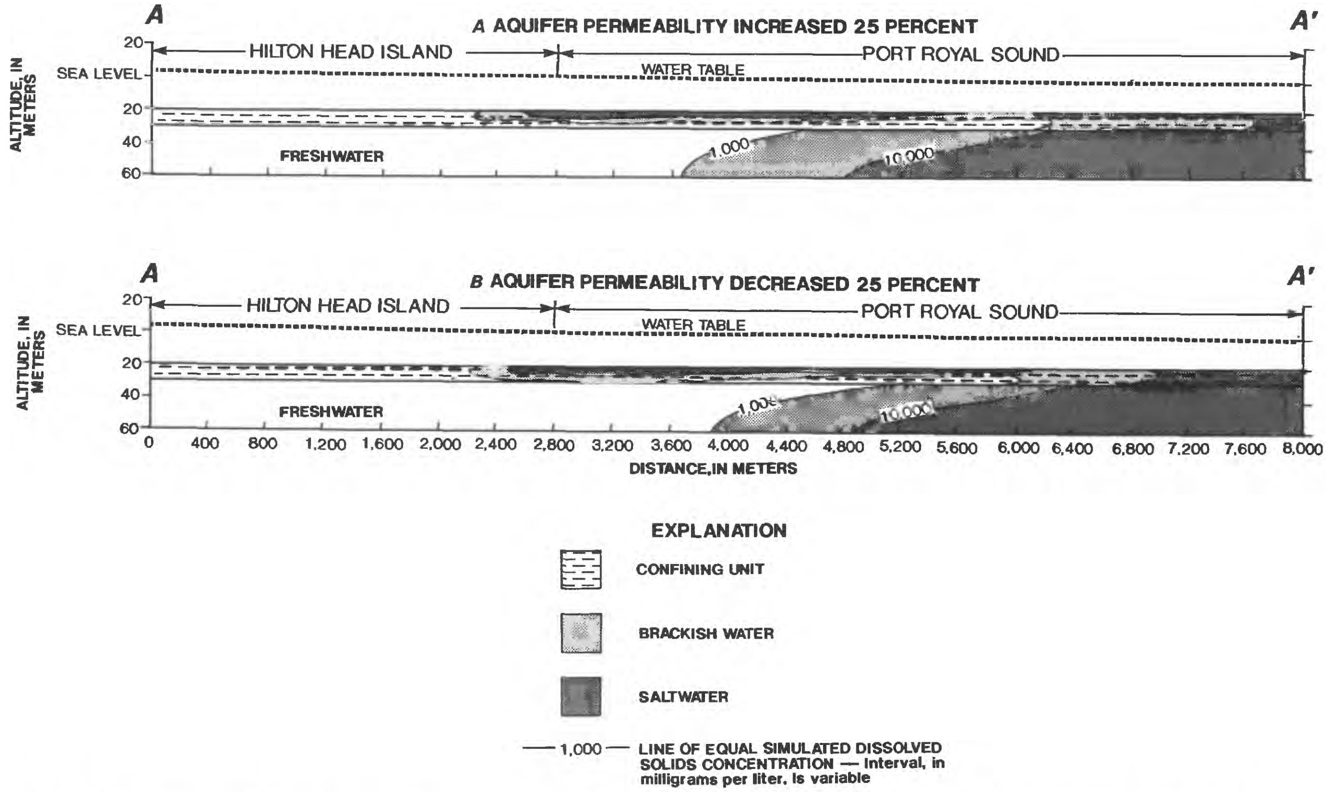

Figure 18. Simulated dissolved-solids concentrations for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for 1984, with (*A*) aquifer permeability increased 25 percent and (*B*) decreased 25 percent.

hydraulic heads in the aquifer have been lowered substantially. The upper confining unit was impeding the downward leakage of freshwater into the Upper Floridan aquifer beneath Hilton Head Island but was also impeding the downward leakage of saltwater toward the aquifer from Port Royal Sound in 1984.

In future studies of saltwater encroachment, collection of data on the permeability of the confining unit probably would be as useful as, if not more useful than, similar data about the aquifer. The effect of permeability changes in the silt and clay fractions of the confining deposits caused by physical and chemical responses to the replacement of freshwater with saltwater, which was not considered in the present study, could also be valuable to future studies of saltwater encroachment.

The model was not sensitive to changes in the porosity of the upper confining unit; however, it was sensitive to changes in the porosity of the aquifer (fig. 20*A* and *B*). An increase of 25 percent in aquifer porosity caused a shift in the simulated brackish-water front about 300 m seaward in the bottom of the aquifer; a decrease of 25 percent in aquifer porosity caused a shift about 500 m landward in the bottom of the aquifer for a net difference of 800 m. All else being the same, a decrease in aquifer porosity would result in higher flow velocities that would move the transition zone closer to land for 1984, whereas an increase in aquifer porosity would result in lower velocities and a front farther seaward.

Data collected on porosity and permeability of the upper confining unit and data reported for the porosity and permeability of the Upper Floridan aquifer indicate some spatial variations. Properties of the aquifer and upper confining unit are averaged in the solute-transport model, and, thus, the simulations provide general indications of solute movement. Variations in porosity and permeability at various scales that have not been simulated or observed can, however, provide unique avenues and dispersions for solute movement.

The solute-transport model was not sensitive to changes in longitudinal dispersivity from 75 to 125 m, and the simulations indicated that the model would not be sensitive to greater changes. Longitudinal dispersivities that were smaller than 75 m, however, tended to produce numerical oscillations in the distribution of

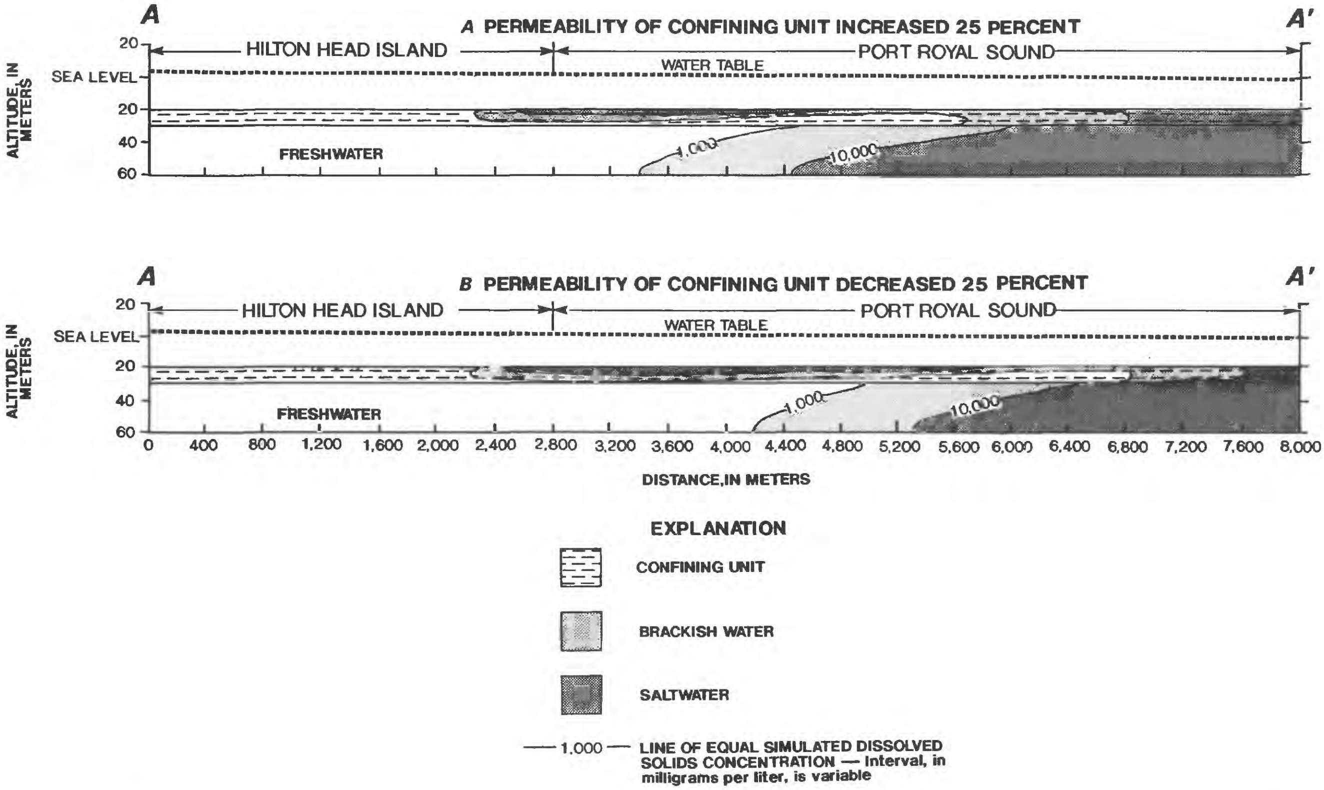

Figure 19. Simulated dissolved-solids concentrations for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for 1984, with (*A*) permeability of the upper confining unit increased 25 percent and (*B*) decreased 25 percent.

simulated concentrations of solute that were unacceptable for the objectives of this report.

The value for transverse dispersivity used in the model was 0.1 m. The model was not particularly sensitive to changes of plus or minus 25 percent of this value; however, changes of 25 percent of such a small number are also very small. Changes in the transverse dispersivity of plus or minus 50 percent, however, changed the slope of the simulated distribution of solute concentrations in the aquifer substantially (fig. 21*A* and *B*). Increasing the transverse dispersivity 50 percent to 0.15 m produced simulated concentrations with a higher angle of slope to the horizontal plane, whereas decreasing the dispersivity 50 percent to 0.05 m produced simulated concentrations with a lower, more horizontal slope.

The slopes of the dissolved-solids concentrations displayed by the leading edges of brackish water (1,000 mg/L) and saltwater (10,000 mg/L) simulated for the aquifer for 1984 are more upright than the low-angle horizontal slopes indicated by sampling of dissolved solids in 1984 (fig. 17*A*). A smaller transverse dispersivity would produce a more horizontal slope for the brackish-water and saltwater fronts but would cause higher simulated concentrations at the bottom of the aquifer on the seaward side than those determined from sampling. Smaller dispersivities also tended to produce unacceptable numerical oscillations in the simulated distributions of concentrations. A model grid with smaller elements would allow smaller dispersivities.

The solute-transport model was particularly sensitive to changes in pressure at the seaward vertical boundary, which was specified at the pressures and inflow concentration of hydrostatic seawater. Increasing the pressure at the boundary to a constant, equivalent to an increase in hydraulic head of 0.1 m, resulted in a shift in the brackish-water front about 450 m landward from that simulated for 1984 by the calibrated model (fig. 22*A*). Decreasing the pressure by an equivalent to 0.1 m resulted in a shift about 450 m seaward (fig. 22*B*). Changing the concentrations of inflow at the vertical boundary would also have a considerable effect on the simulations and, thus, any future studies could benefit by extending the known concentration and head gradients toward the seawater source.

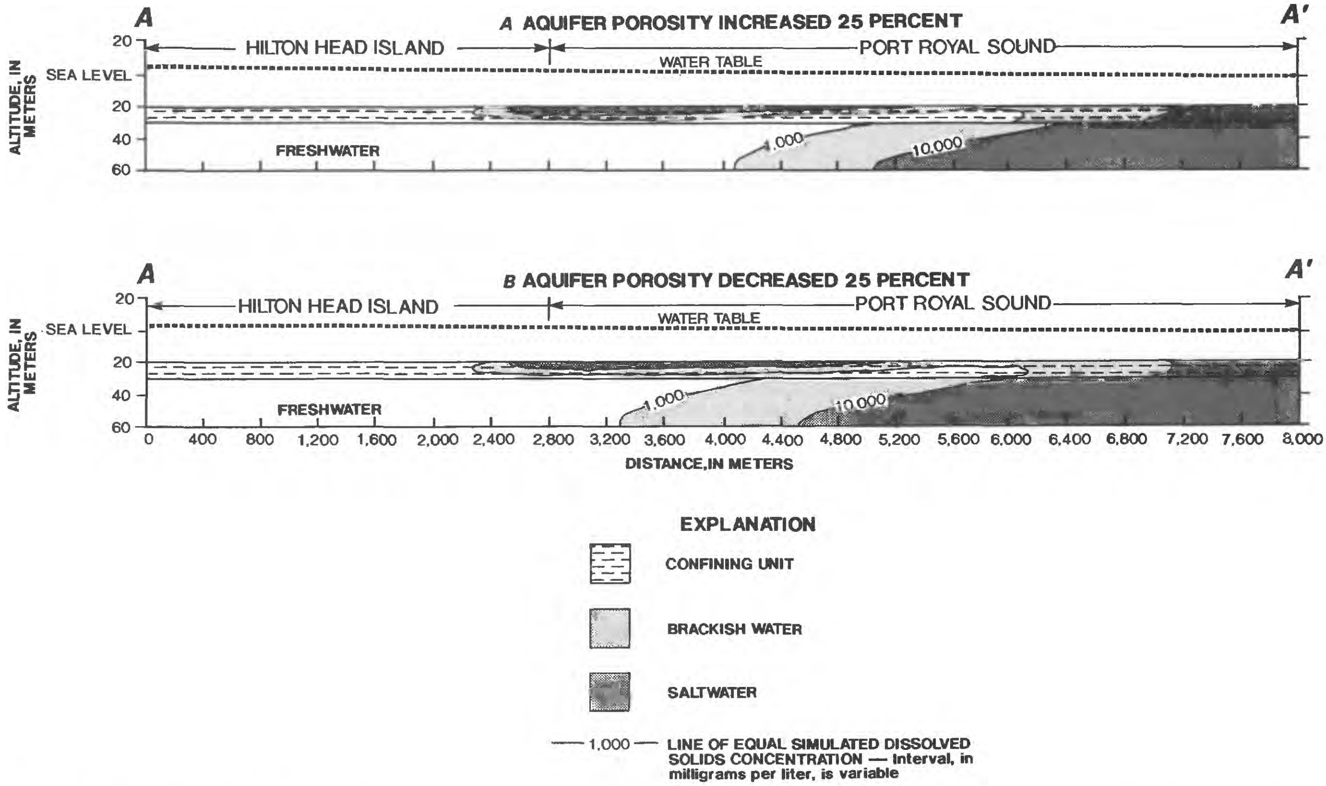

Figure 20. Simulated dissolved-solids concentrations for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for 1984, with (*A*) aquifer porosity increased 25 percent and (*B*) decreased 25 percent.

SALTWATER MOVEMENT FOR HYPOTHETICAL PUMPING SITUATIONS

Saltwater encroachment in coastal aquifers elsewhere has been successfully controlled with the reduction and rearrangement of ground-water withdrawals or the injection of freshwater and maintenance of a freshwater ridge above sea level (Freeze and Cherry, 1979, p. 378). Reductions in withdrawals, rearrangement of withdrawal patterns, additional withdrawals, and freshwater injection wells were simulated previously with the areal uniform-density model of ground-water flow (Smith, 1988). Identical simulations are presented here with hydraulic heads in the freshwater zones from the areal model but with the advantages of density-dependent flow and solute transport in the vertical section.

Movement of the transition zone toward Hilton Head Island was investigated to find the length of time before brackish water would encroach within the aquifer beneath Hilton Head Island and the possibility of inhibiting the movement of the transition zone toward the island by reduction of ground-water withdrawals, rearrangement of patterns of withdrawals, or by injection of freshwater.

Movement of brackish water and saltwater beneath Port Royal Sound toward Hilton Head Island was simulated from 1984 through 2032 for the following situations: (1) no change in ground-water withdrawals from those of 1984; (2) additional ground-water withdrawals of 0.44 m^3/s, approximately double that of 1984, on southern Hilton Head Island beginning in the year 2000; (3) additional ground-water withdrawals of 0.44 m^3/s on the mainland beginning in the year 2000; (4) elimination of ground-water withdrawals on Hilton Head Island beginning in the year 2000; and (5) freshwater injection near the northeastern shore of Hilton Head beginning in the year 2000.

Flow of freshwater at the landward vertical boundary was adjusted for each situation until hydraulic heads simulated by the solute-transport model for the Upper Floridan aquifer beneath Hilton Head Island approximated those of the freshwater zone simulated for the identical hypothetical simulations of ground-water flow with the areal uniform-density model (fig. 23). No other parameters were changed for the

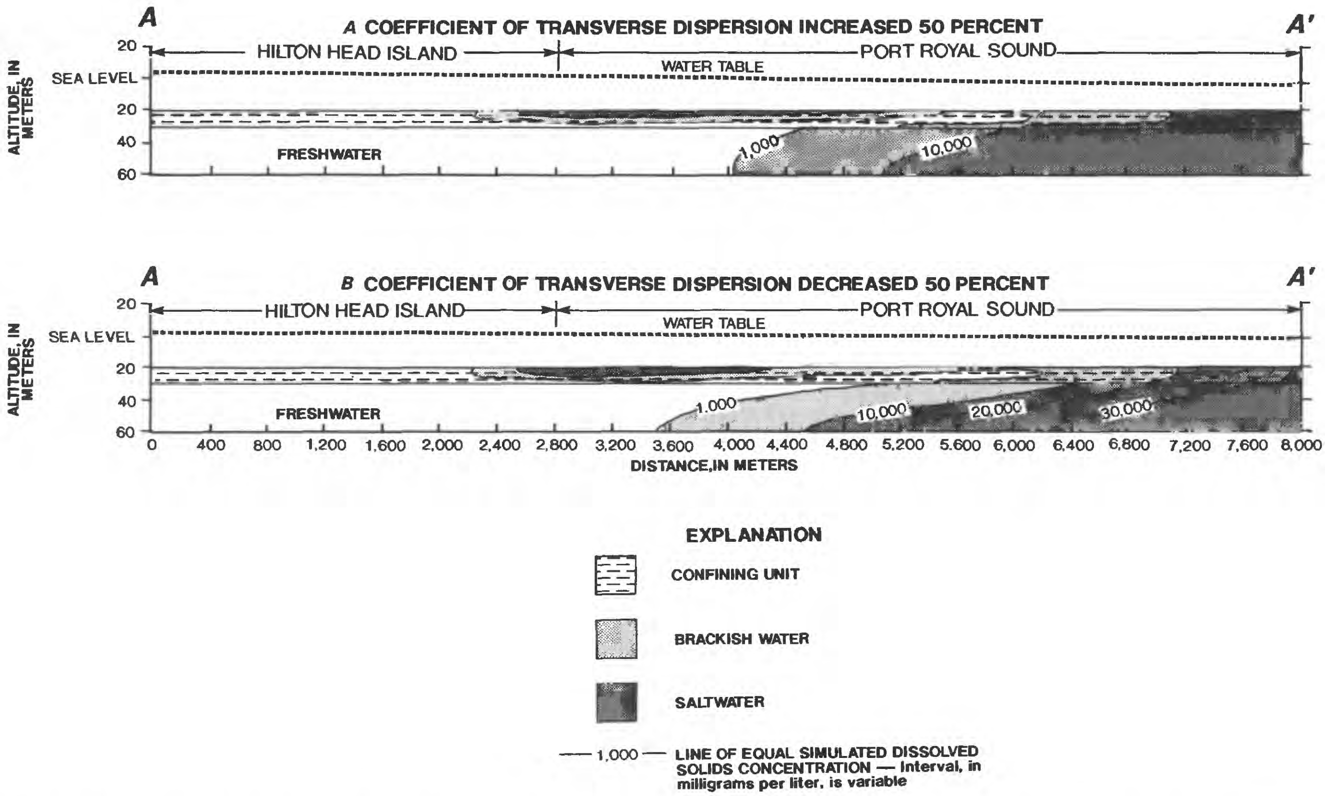

Figure 21. Simulated dissolved-solids concentrations for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for 1984, with (*A*) the coefficient of transverse dispersion increased 50 percent and (*B*) decreased 50 percent.

simulations except that freshwater was injected near shore for the fifth situation. Use of hydraulic heads from the areal model provided a means for determining the hypothetical flow at the landward vertical boundary, which, except for the first situation, would not have been known otherwise and could not have been simulated accurately. Simulations of hypothetical movements of brackish water and saltwater are subject to some uncertainty, but the simulations presented here are useful because the relative effects of reducing, increasing, or rearranging ground-water pumping or of injecting freshwater can be directly compared.

No Change in Ground-Water Withdrawals

Flow rates and hydraulic heads in the aquifer would remain virtually unchanged if there were no significant changes in withdrawals in the region. The model, calibrated to 1984, was continued forward in time to 2032 with no changes for the first scheme to provide a base from which to compare subsequent schemes.

The transition zone would continue to move in the aquifer toward Hilton Head Island if no changes in withdrawals occurred (fig. 24*A*). Brackish water would intrude in the aquifer beneath the shore some time after the year 2000 but before 2016, according the simulation; caution should be exercised in exact prediction from this and subsequent simulations because of the uncertainties described earlier. Also, the model simulates the position of the brackish-water front closer to shore at the top of the aquifer and farther at the bottom than was indicated by chemical analyses of 1984.

The brackish-water front would move about 1,600 m at the bottom of the aquifer from 2000 to 2032, a velocity of displacement of about 50 m/yr, according to the simulation. The velocity of displacement would increase from the 40 m/yr estimated by simulation for 1984 and would continue to accelerate

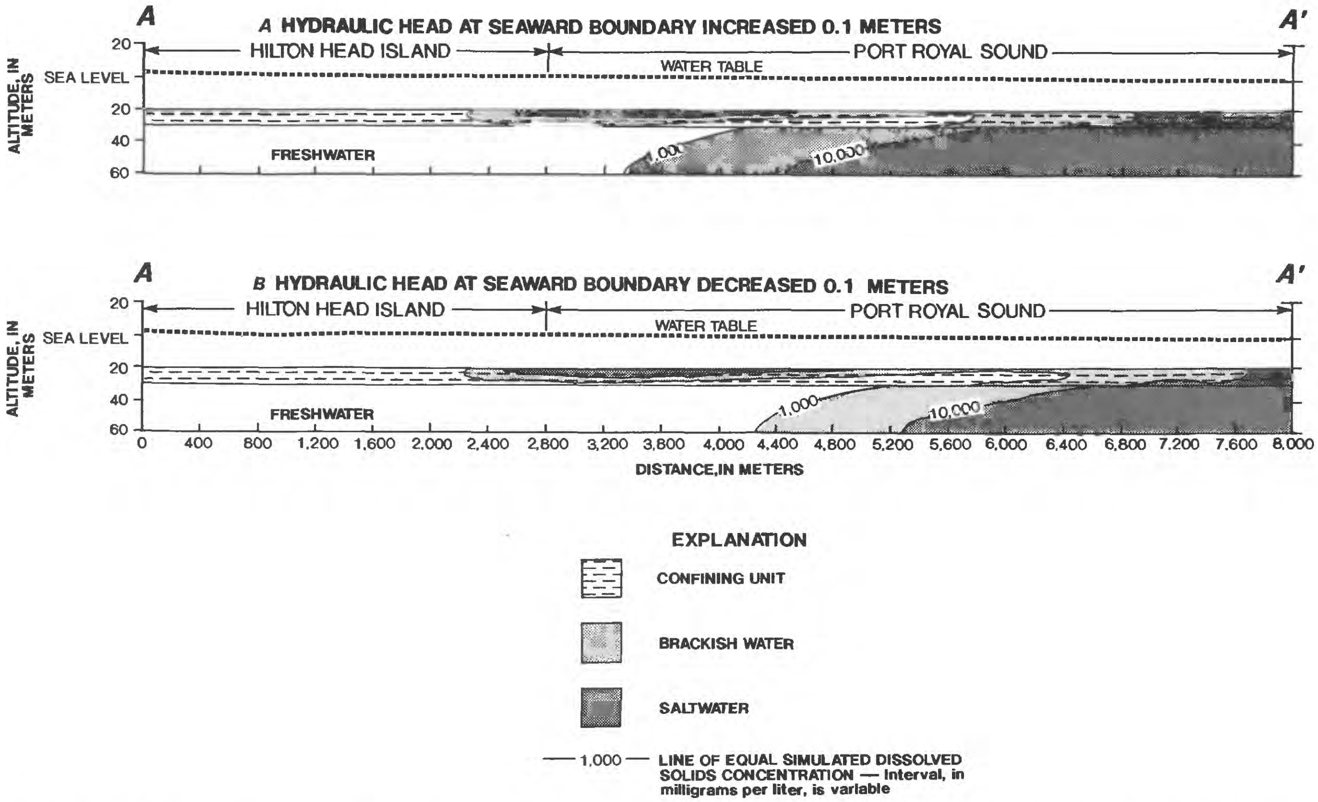

Figure 22. Simulated dissolved-solids concentrations for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for 1984, with pressures at the seaward vertical boundary changed to constants equivalent to (*A*) hydraulic head increased 0.1 m and (*B*) decreased 0.1 m.

in the landward direction because of the increases in hydraulic conductivity and gradient in that direction.

Additional Ground-Water Withdrawals on Hilton Head Island

The second scheme simulates the movement of the transition zone with an additional withdrawal of 0.44 m^3/s from southern Hilton Head Island, beginning in the year 2000. Hydraulic heads would decline locally because of the increase in withdrawal, but the general direction of ground-water flow would not change appreciably as indicated by the simulations using the areal model of ground-water flow.

The transition zone would move toward Hilton Head Island at a faster rate if withdrawals were increased on southern Hilton Head Island. The simulation indicated that brackish water would intrude in the aquifer beneath the shore not long after the year 2000 (fig. 25*A* and *B*) and would approach municipal pumping wells near the landward vertical boundary of the model around the year 2032 (fig. 25*C*). The brackish water front would move about 2,500 m in the bottom of the aquifer from 2000 to 2032, displacing freshwater at a rate of about 80 m/yr.

Additional Ground-Water Withdrawals on the Mainland

The third scheme is identical to the second, but the additional withdrawal of 0.44 m^3/s was simulated beginning in 2000 on the mainland. The simulation indicated that brackish water would still move toward Hilton Head Island (fig. 26), but at a slower velocity than the preceding simulation because the hydraulic gradient toward the island would be less. Regional flow directions would remain relatively unchanged, as with the second scheme. Brackish water would move about 2,000 m in the bottom of the aquifer from 2000 to 2032, displacing freshwater at a rate of approximately 60 m/yr, according to the simulation. The transition zone would continue moving toward the pumped wells beyond the year 2032 as long as the conditions remained similar.

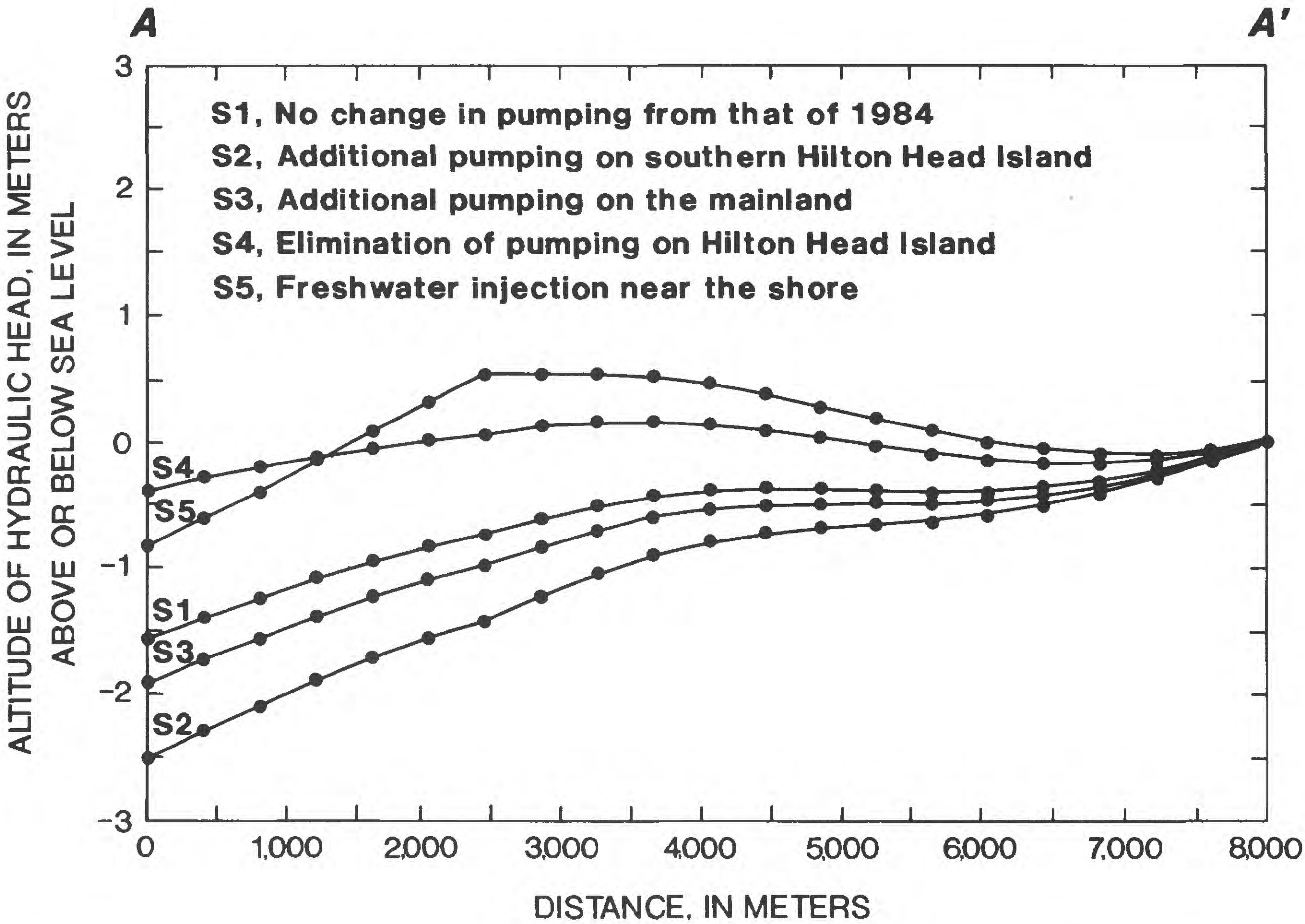

Figure 23. Hydraulic-head gradients simulated for the Upper Floridan aquifer beneath Hilton Head Island and Port Royal Sound for hypothetical schemes.

Elimination of Ground-Water Withdrawals

The fourth scheme simulates no changes in withdrawals until the year 2000, when all major ground-water withdrawals would be eliminated on and near the island. Ground-water withdrawals for municipal supplies on Hilton Head Island could be eliminated if freshwater were transferred to the island from surface or ground-water sources farther inland. An existing canal that transports water from the Savannah River to Port Royal Island could carry more water if upgraded. Pipelines would have to be constructed for transferring the water from the canal to Hilton Head Island.

The transition zone would move toward Hilton Head Island at a much slower rate if all municipal pumping on the island were eliminated. The brackish-water front would not intrude into the aquifer beneath the shore until around the year 2016 according to the simulation (fig. 27). Brackish water would move about 700 m in the bottom of the aquifer from 2000 to 2032, displacing freshwater at a rate of approximately 20 m/yr.

Injection of Freshwater

The fifth scheme simulates no changes in withdrawals from those of 1984, but freshwater is injected into the aquifer near the northeastern shore of Hilton Head, beginning in the year 2000, so that hydraulic heads in the aquifer at the shoreline are above sea level. One possible source of water for injection could be tertiary-treated effluent. The amount of water injected was adjusted by trial and error in conjunction with the outflow of freshwater at the landward vertical boundary until the hydraulic heads simulated by the solute-transport model beneath Hilton Head Island approximated those from an identical hypothetical simulation using the areal model of ground-water flow. A simulated injection rate of 0.022 m^3/s was thus

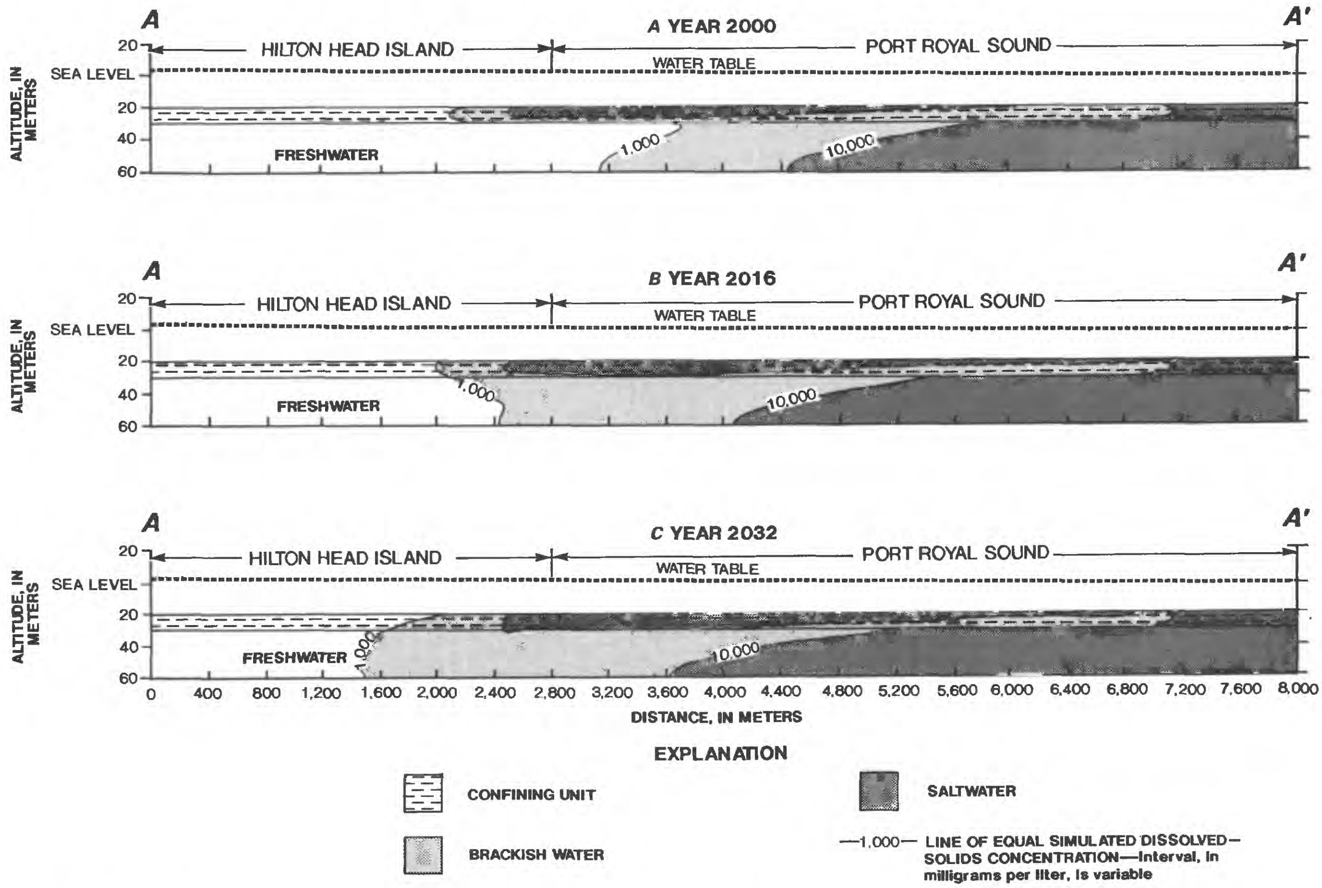

Figure 24. Simulated dissolved-solids concentrations for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for (*A*) 2000, (*B*) 2016, and (*C*) 2032, with no change in ground-water withdrawals from those of 1984.

derived for the well. In the areal model, a line of injection wells [pumping 5 million gallons per day (0.22 m^3/s)] was simulated parallel to the northeastern shore of Hilton Head Island (Smith, 1988, p. 52).

Movement of the transition zone toward Hilton Head Island would be slowed significantly if enough freshwater were injected so that hydraulic heads of the aquifer near the shore were above sea level, according to the simulation (fig. 28). The brackish-water front would move about 300 m in the bottom of the aquifer from the year 2000 to 2032, displacing freshwater at a rate of approximately 9 m/yr. The movement of the transition zone toward the recharge well, however, would decelerate as the recharge mound was approached. The rate of freshwater displacement would slow to about 6 m/yr from 2032 to 2064, according to the simulation. Brackish water would not intrude in the aquifer beneath the shore until some time between the years 2032 and 2064.

SUMMARY AND CONCLUSIONS

Freshwater for Hilton Head Island, S.C., is supplied by wells withdrawing from the Upper Floridan aquifer. Freshwater for the nearby city of Savannah, Ga., and for the industry adjacent to the city has been supplied, in part, by withdrawals from the same aquifer since 1885. The withdrawals of ground water have caused water levels to decline in the Upper Floridan aquifer over a broad area forming a cone of depression in the potentiometric surface centered near Savannah. In 1984, the cone of depression extended beneath Hilton Head Island as far as Port Royal Sound. Flow in the aquifer that had previously been toward Port Royal Sound has been reversed, and, as a result, brackish water and saltwater in the aquifer beneath Port Royal Sound are moving slowly toward Hilton Head Island.

Chemical analyses from wells drilled in 1984 indicated a transition zone between freshwater and

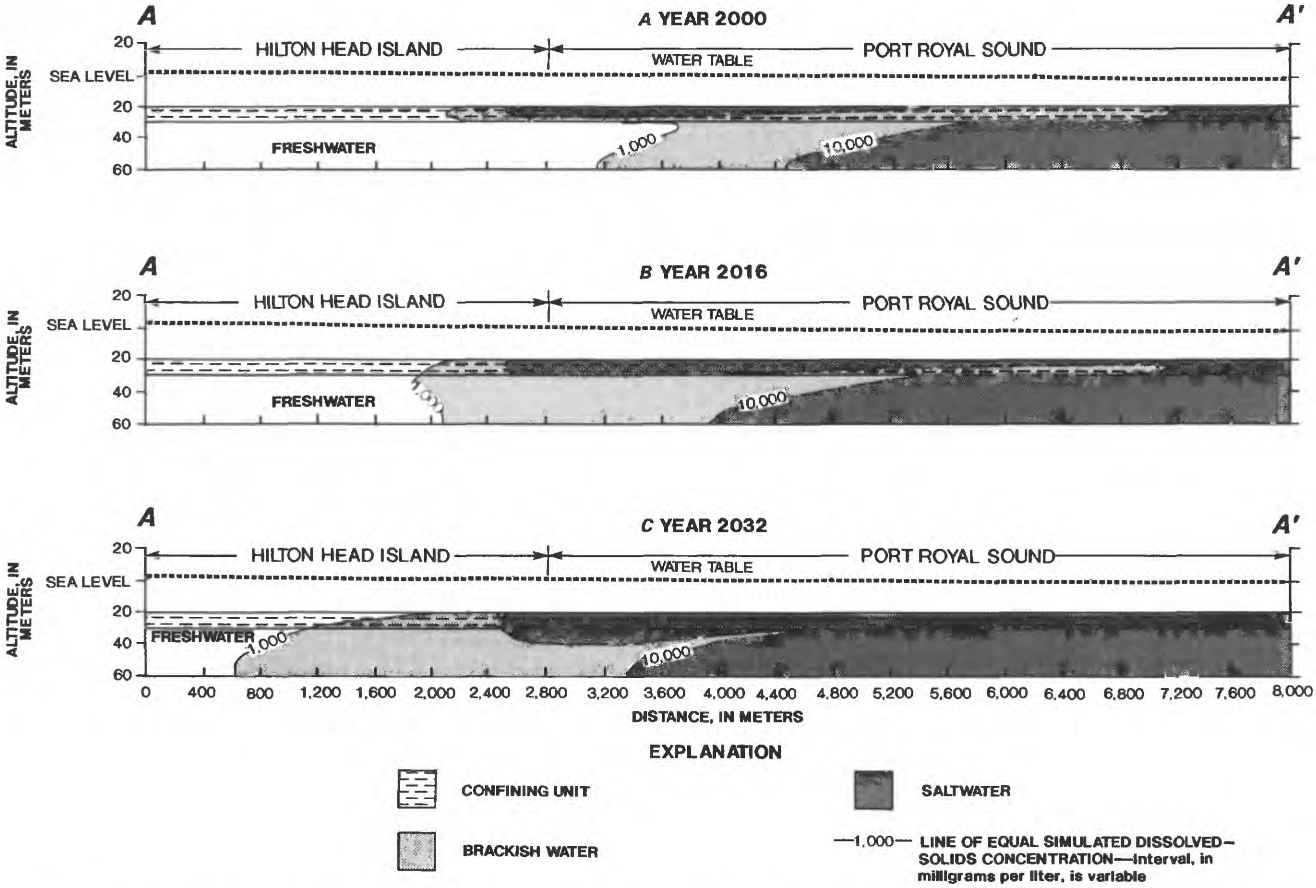

Figure 25. Simulated dissolved-solids concentrations for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for (*A*) 2000, (*B*) 2016, and (*C*) 2032, with additional withdrawal of 0.44 m^3/s from southern Hilton Head Island beginning in 2000.

seawater in the Upper Floridan aquifer beneath Port Royal Sound. A wedge of brackish water and saltwater extended into the Upper Floridan aquifer from the east beneath Port Royal Sound. The transition zone between freshwater and seawater had not moved far from the Gyben-Herzberg interface for freshwater and seawater estimated previously for the period before withdrawals began in 1885. This proximity indicated that the ground-water flow system was in a virtual steady state with respect to solute concentrations, as well as hydraulic heads, before the withdrawals.

The SUTRA model of the USGS was used to simulate density-dependent ground-water flow and solute transport in a vertical section of the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound. The model simulated a dynamic equilibrium between the flow of seawater and freshwater, as expected from theory, near the Gyben-Herzberg position estimated for the period before withdrawal began in 1885; it simulated reasonable movements of brackish water and saltwater from that position to the position determined by chemical analyses of samples withdrawn from the aquifer in 1984, and it approximated hydraulic heads measured in the aquifer in 1976 and 1984.

The solute-transport model was particularly sensitive to the change in pressures at the seaward vertical boundary, but was also sensitive to changes in aquifer and confining-bed permeability, aquifer porosity, and transverse dispersivity. The accuracy of the solute-transport simulations is related, primarily, to the availability and accuracy of data on these characteristics, and particularly to data on pressures and solute concentrations in the aquifer.

Hydraulic heads in the Upper Floridan aquifer on Hilton Head Island have been recorded for a relatively short period of time, and much of the history of hydraulic heads has relied on simulation and hydro-

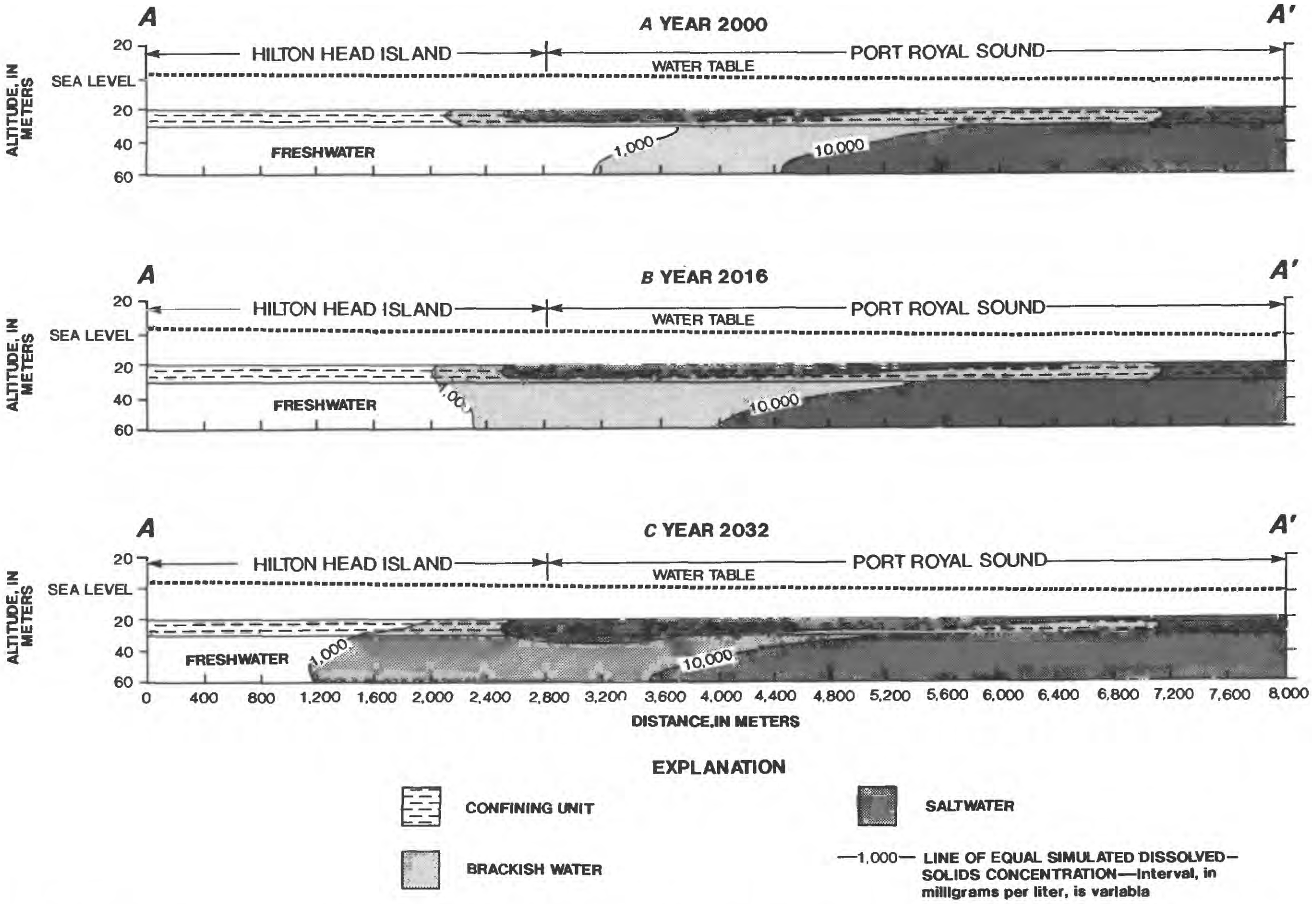

Figure 26. Simulated dissolved-solids concentrations for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for (*A*) 2000, (*B*) 2016, and (*C*) 2032, with additional withdrawal of 0.44 m^3/s from the mainland 16 km inland of the island beginning in 2000.

logic reason. Similarly, the dissolved-solids concentrations in the aquifer beneath Port Royal Sound have been determined for one instant in time, and the history of solute movement also relies on hydrologic reason and simulation. Hydraulic characteristics of the aquifer and confining unit are generally averaged in the model, whereas, in reality, there is some variation at all scales. Because of these factors, the accuracy of solute-transport simulations and an understanding of historic and future movements of the transition zone toward Hilton Head Island are subject to uncertainty.

The solute-transport model does, however, incorporate existing data, follow existing concepts, and approximate the hydraulic gradients and solute concentrations measured or expected from theory with reasonable accuracy. The simulations also provide a basic understanding of the movement of brackish water and saltwater in the Upper Floridan aquifer and upper confining unit from the steady-state period before withdrawals began in 1885 through 1984.

The solute-transport simulations indicate that the transition zone would continue to move toward Hilton Head Island even if withdrawals ceased on the island. Increases in existing withdrawals or additional withdrawal on or near Hilton Head Island would accelerate movement of the transition zone toward the island, but reduction in withdrawals or the injection of freshwater would slow movement toward the island, according to the simulations.

Future movement of the transition zone will depend on hydraulic gradients in the aquifer beneath Hilton Head Island and Port Royal Sound. Hydraulic gradients in the Upper Floridan aquifer are strongly influenced by pumping on the island and near Savannah, Ga. Withdrawals of ground water have increased on Hilton Head Island since 1984.

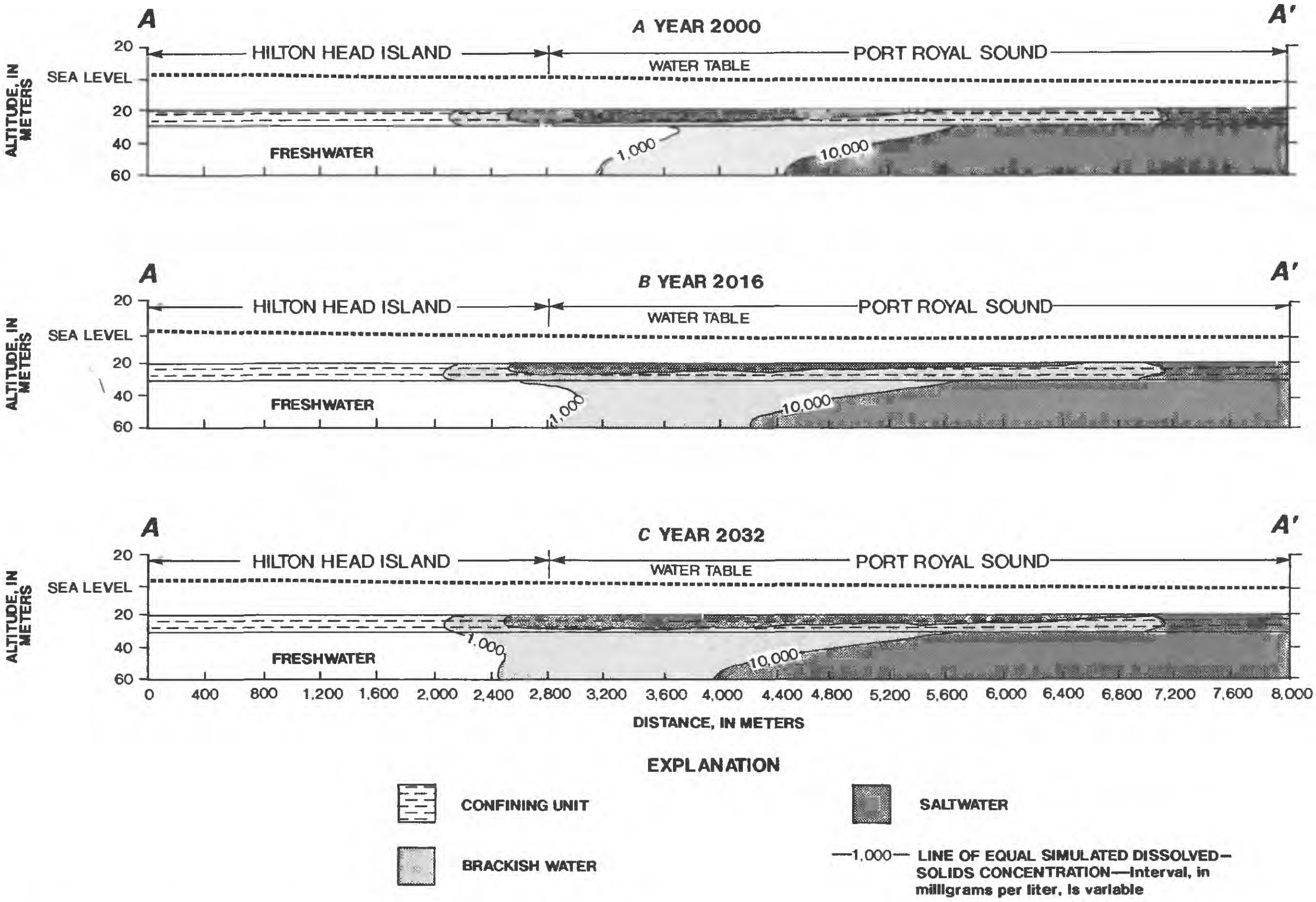

Figure 27. Simulated dissolved-solids concentrations for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for (*A*) 2000, (*B*) 2016, and (*C*) 2032, with no withdrawals from the aquifer on the island beginning in 2000.

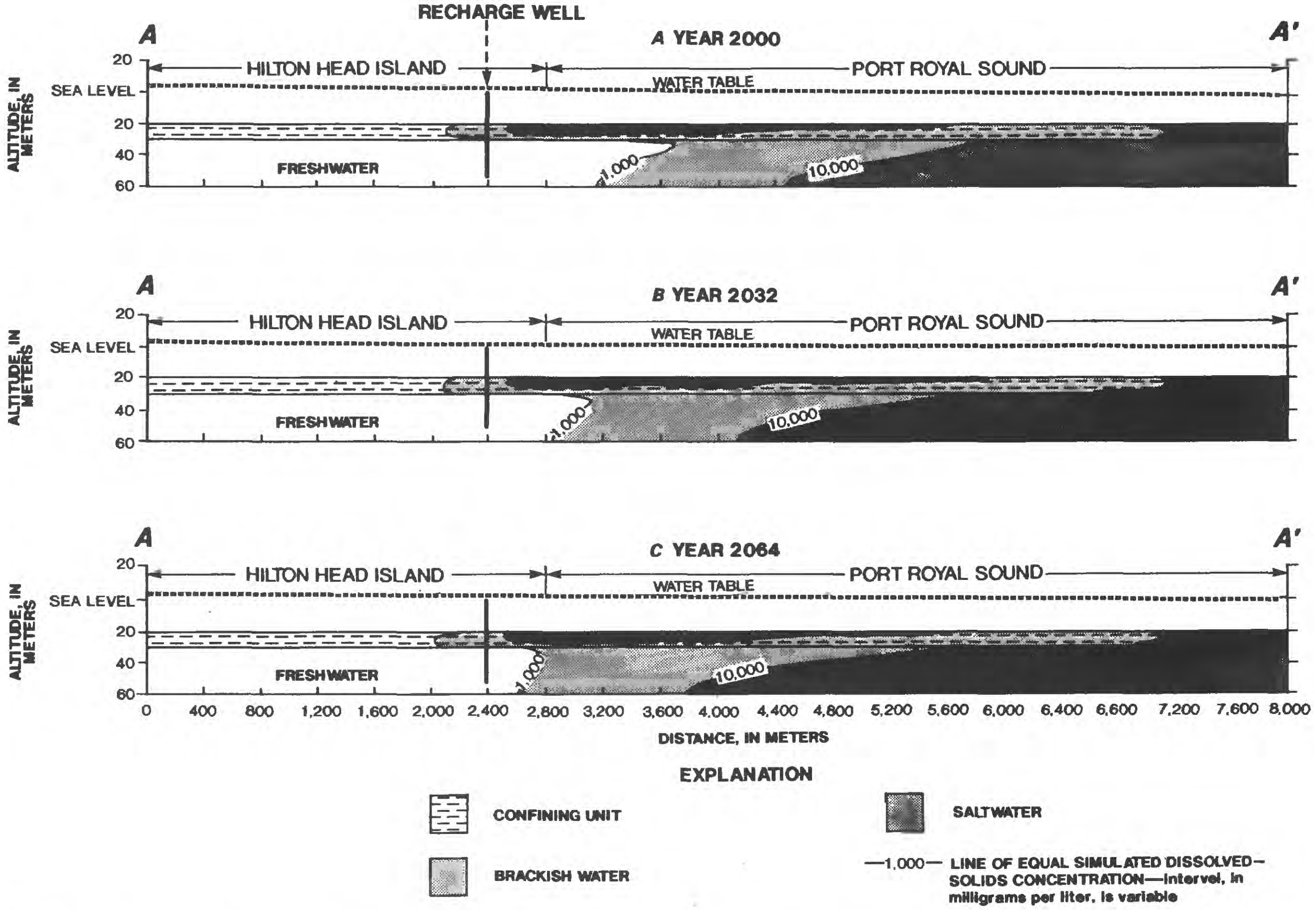

Figure 28. Simulated dissolved-solids concentrations for the Upper Floridan aquifer and upper confining unit beneath Hilton Head Island and Port Royal Sound for (*A*) 2000, (*B*) 2032, and (*C*) 2064, with injection of freshwater near the northeastern shore of the island beginning in 2000.

SELECTED REFERENCES

Back, William, Hanshaw, B.B., and Ruben, Meyer, 1970, Carbon-14 ages related to occurrence of saltwater: American Society of Civil Engineers Proceedings, Journal of the Hydraulics Division, Nov. 1970, p. 2325–2336.

Burnette, T.L., 1952, History of the Parris Island water supply: Department of Public Works, U.S. Navy, Parris Island, S.C., 6 p.

Burt, R.A., Belval, D.L., Crouch, Michael, and Hughes, W.B., 1987, Geohydrologic data from 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.

Clarke, J.S., Longsworth, S.A., McFadden, K.W., and Peck, M.F., 1985, Ground-water data for Georgia, 1984: U.S. Geological Survey Open-File Report 85–331, 163 p.

Cooper, H.H., 1964, A hypothesis concerning the dynamic balance of fresh water and salt water in a coastal aquifer, *in* Sea water in coastal aquifers: U.S. Geological Survey Water-Supply Paper 1613–C, p. C1–C12.

Counts, H.B., and Donsky, Ellis, 1959, Summary of salt-water encroachment, geology, and ground-water resources of Savannah area, Georgia and South Carolina: Georgia Geological Survey Mineral Newsletter, v. 12, no. 3, 16 p.

———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.

Davis, S.N., 1969, Porosity and permeability of natural materials, *in* DiWiest, R.J.M., ed., Flow through porous media: New York, Academic Press, p. 54–89.

Davis, S.N., and DeWiest, R.J.M., 1966, Hydrogeology: New York, John Wiley and Sons, 463 p.

Domenico, P.A., and Schwartz, F.W., 1990, Physical and Chemical Hydrogeology: New York, John Wiley and Sons, 824 p.

Duncan, D.A., 1972, High resolution seismic study, *in* Port Royal Sound Environmental Study: South Carolina Water Resources Commission p. 86–106.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Frind, E.O., 1982, Seawater intrusion in continuous coastal aquifer-aquitard systems: Advances in Water Resources, v. 5, June 1982, CML Publications, p. 89–97.

Hassen, J.A., 1985, Ground-water conditions in the Ladies and St. Helena Islands areas, South Carolina: South Carolina Water Resources Commission Report No. 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 No. 9, 91 p.

Hubbert, M.K., 1940, The theory of ground-water motion: The Journal of Geology, v. 48, no. 8, part 1, p. 785–944.

Hughes, W.B., Crouch, M.S., and Park, A.D., 1989, Hydrogeology and Saltwater contamination of the Floridan Aquifer in Beaufort and Jasper Counties, South Carolina: South Carolina Water Resources Commission Report No. 158, 52 p.

Javandel, Iraj; Doughty, Christine; and Tsang, Chin-Fu, 1984, Groundwater transport, Handbook of mathematical models: American Geophysical Union, Washington, D.C., 228 p.

Kohout, F.A., 1964, The flow of fresh water and salt water in the Biscayne aquifer of the Miami area, Florida, *in* Sea water in coastal aquifers: U.S. Geological Survey Water-Supply Paper 1613–C, p. C12–C35.

Krause, R.E., 1982, Digital model evaluation of the predevelopment flow system of the Tertiary limestone aquifer, southeast Georgia, northeast Florida and southern South Carolina: U.S. Geological Survey Open-File Report 82–173, 27 p.

Krause, R.E., Matthews, S.E., and Gill, H.E., 1984, Evaluation of the ground-water resources of coastal Georgia; Preliminary report on the data available as of July 1983: Georgia Geological Survey Information Circular 62, 55 p.

Lohman, S.W., and others, 1972, Definitions of selected ground-water terms; revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

Matthews, S.E., Hester, W.G., and McFadden, K.W., 1982, Ground-water data for Georgia, 1981: U.S. Geological Survey Open-File Report 82–904, 110 p.

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

Meisler, Harold, Leahy, P.P., and Knobel, L.L., 1984, Effect of eustatic sea-level changes on saltwater-freshwater in the Northern Atlantic Coastal Plain: U.S. Geological Survey Water-Supply Paper 2255, 28 p.

Miller, J.A., 1982, Geology and configuration of the top of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Open-File Report 81–1178, 1 sheet.

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

Randolf, 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.

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.

Spigner, B.C., and Ransom, Camille, 1979, Report on ground-water conditions in the Low Country area, South Carolina: S.C. Water Resources Commission Report No. 132, 144 p.

Stiles, H.R. and Matthews, S.E., 1983, Ground-water data for Georgia, 1982: U.S. Geological Survey Open-File Report 83–678, 147 p.

U.S. Army Corps of Engineers, 1984, Executive summary, metropolitan Savannah area water resources management study: U.S. Army Corps of Engineers, Savannah District, 13 p.

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 Geological Survey Bulletin No. 49, 140 p.

Wolff, R.G., 1982, Physical properties of rocks; porosity, permeability, distribution coefficients, and dispersivity: U.S. Geological Survey Open-File Report 82–166, 118 p.

*U.S. G.P.O.:1994-301-077:7

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations, as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Cost Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases for quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Map Distribution, Box 25286, Bldg. 810, Federal Center, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879–1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962–1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971–1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" are available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.—Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.