# Simulation of Saltwater Movement in the Floridan Aquifer System, Hilton Head Island, South Carolina

United States Geological Survey Water-Supply Paper 2331

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By PETER W. BUSH

A study conducted as
part of the Floridan Regional
Aquifer-System Analysis

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2331

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1988

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

**Library of Congress Cataloging-in-Publication Data**

Bush, Peter W.
Simulation of saltwater movement in the Floridan aquifer system, Hilton Head Island, South Carolina.

(U.S. Geological Survey water-supply paper ; 2331)
Bibliography: p.
Supt. of Docs. no.: I 19.13:2331
1. Saltwater encroachment—South Carolina—Hilton Head Island. 2. Floridan Aquifer. I. Title.
II. Series.
GB1197.83.S6B87 1988 628.1'14 87-600475

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## Abbreviations and Conversion Factors

Inch-pound units of measurement used in this report may be converted to metric (Système International) units by using the following factors:

| *Multiply inch-pound unit* | *By* | *To obtain metric unit* |
|---|---|---|
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| square foot ($ft^2$) | 0.0929 | square meter ($m^2$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |
| foot per year (ft/yr) | 0.3048 | meter per year (m/yr) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3/s$) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| square foot per day ($ft^2/d$) | 0.0929 | square meter per day ($m^2/d$) |
| slug per cubic foot ($slug/ft^3$) | 515.4 | kilogram per cubic meter ($kg/m^3$) |
| pound-second per square foot ($lb \cdot s/ft^2$) | 47.88 | pascal second ($Pa \cdot s$) |
| square foot per second ($ft^2/s$) | 9.290 | square meter per second ($m^2/s$) |
| slug | 14.59 | kilogram (kg) |
| degree Fahrenheit (°F) | (°F −32)/1.8 | degree Celsius (°C) |
| --- | --- | milligram per liter (mg/L) |

*Sea level:* In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD 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 "Mean Sea Level of 1929."

# Simulation of Saltwater Movement in the Floridan Aquifer System, Hilton Head Island, South Carolina

*By* Peter W. Bush


**Abstract**

Freshwater to supply Hilton Head Island, S.C., is obtained from the upper permeable zone of the Upper Floridan aquifer. Long-term pumping at Savannah, Ga., and the steadily increasing pumping on Hilton Head Island, have lowered Upper Floridan heads near the center of the island from about 10 feet above sea level to about 6 to 7 feet below sea level. The seaward hydraulic gradient that existed before pumping began has been reversed, thus increasing the potential for saltwater intrusion. Simulations of predevelopment, recent, and future ground-water flow in the Floridan aquifer system beneath the north end of Hilton Head Island and Port Royal Sound are presented. A finite-element model for fluid-density-dependent ground-water flow and solute transport was used in cross section.

The general configuration of the simulated predevelopment flowfield is typical of a coastal aquifer having a seaward gradient in the freshwater. The freshwater flows toward Port Royal Sound over an intruding wedge of saltwater. The simulated flowfield at the end of 1983 shows that ground water in the Floridan aquifer system beneath most of Hilton Head Island has reversed its predevelopment direction and is moving toward Savannah. The distribution of chloride concentrations, based on simulation at the end of 1983, is about the same as the predevelopment distribution of chloride concentrations obtained from simulation.

Results of two 50-year simulations from 1983 to 2034 suggest that there will be no significant threat of saltwater intrusion into the upper permeable zone of the Upper Floridan aquifer if heads on Hilton Head Island remain at current levels for the next 45 to 50 years. However, if head decline continues at the historical rate, any flow that presently occurs from the north end of the island toward Port Royal Sound will cease, allowing lateral intrusion of saltwater to proceed. Even under these conditions, chloride concentrations in the upper permeable zone of the Upper Floridan aquifer beneath Hilton Head Island should remain below 250 milligrams per liter for the next 45 to 50 years.

Aquifer properties and selected boundary conditions were tested with several 1,000-year simulations which show that lateral permeability, transverse dispersivity, and landward boundary flow have the most influence on saltwater movement in the Upper Floridan aquifer.


## INTRODUCTION

Hilton Head Island is a growing resort area on South Carolina's southern coast (fig. 1). Freshwater to supply the island is obtained from wells that tap the upper part of the Upper Floridan aquifer. Currently (1986), water in the upper part of the Upper Floridan under the island is of good quality. However, chloride concentrations in the lower part of the Upper Floridan are greater than 250 mg/L, and water throughout the Floridan aquifer system in most areas immediately northeast of the island varies from brackish to saline.

Large withdrawals from the Upper Floridan aquifer at Savannah, Ga., have created a deep regional cone of depression that has spread beneath Hilton Head Island. Long-term pumping at Savannah, together with steadily increasing pumping on the island, have lowered heads in the Floridan aquifer system under the island to below sea level. The seaward hydraulic gradient that existed before pumping began has been reversed; thus the potential for saltwater contamination of freshwater at Hilton Head Island probably exists. Although heads on the island have declined continually since ground-water development began, chloride concentrations monitored over the past 25 to 30 years have remained relatively stable.

### Purpose and Scope

The purpose of this study, conducted as a part of the Floridan Regional Aquifer-System Analysis, is to provide a better understanding of the potential for saltwater movement in the Floridan aquifer system at Hilton Head Island. Specifically, the objectives are (1) to test the hypothesis, suggested by the data, that saltwater has not moved appreciably from its predevelopment position, even though heads have been lowered substantially, (2) to evaluate the effect of future pumping in the Upper Floridan aquifer on saltwater movement, and (3) to determine the hydrogeologic controls on saltwater movement. The scope of the study is limited to a preliminary analysis because few data exist about aquifer properties and conditions below the upper part of the Upper Floridan aquifer. This report presents the results of the study.

### Approach

Ground-water flow in a selected cross section of the Floridan aquifer system was digitally simulated by using a finite-element model for fluid-density-dependent ground-

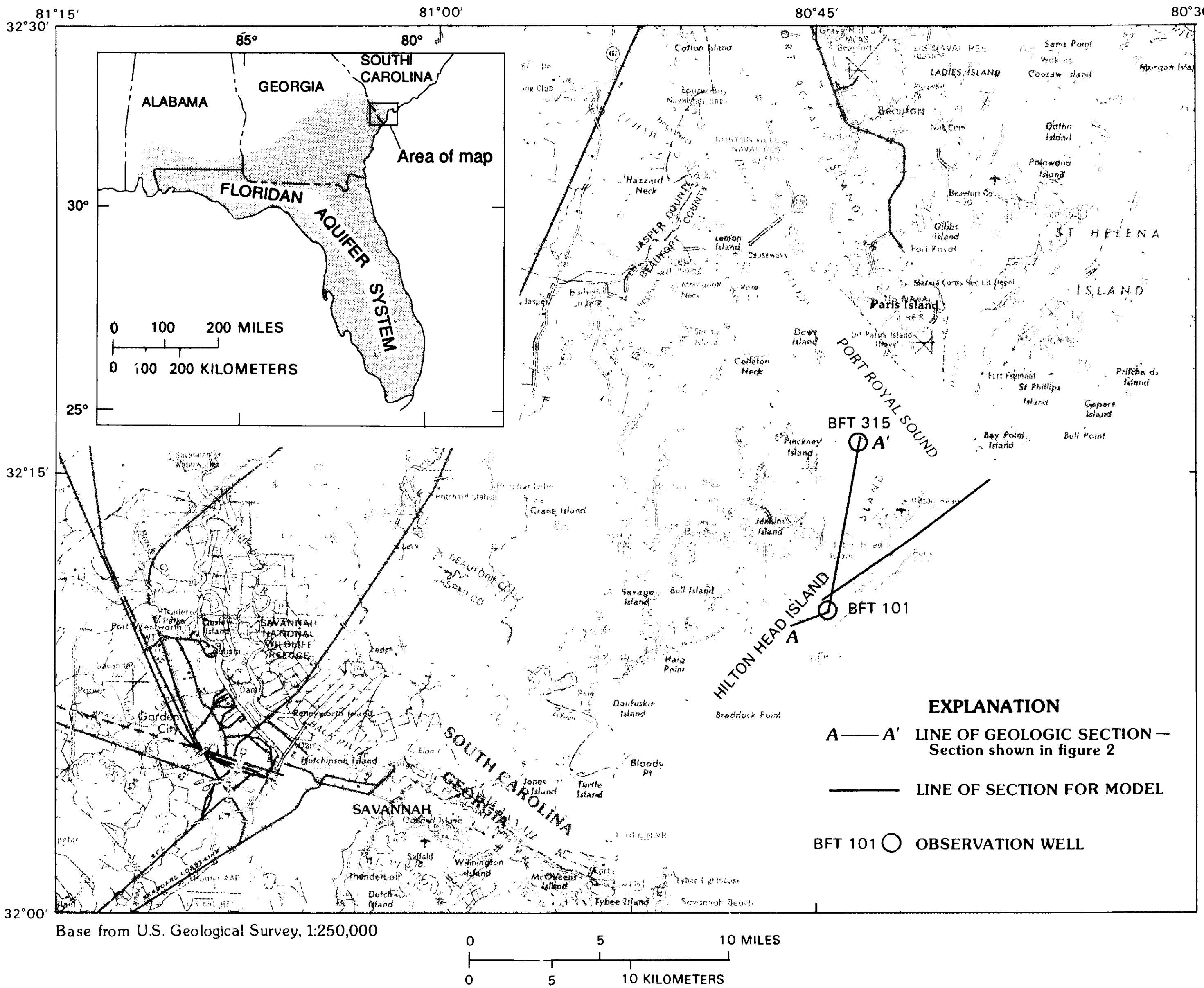



**Figure 1.** Location of Hilton Head Island area, South Carolina and Georgia.

water flow and either energy or solute transport. The Saturated-Unsaturated Transport (SUTRA) model, developed by Voss (1984), was applied to an 8-mi by 810-ft section that extends southwest from Port Royal Sound across the northeast corner of Hilton Head Island to the approximate center of the island (fig. 1). The section is aligned approximately along a flowline and traverses the area where data indicate a transition from salty or brackish water to freshwater. The model was used to simulate estimated predevelopment conditions, assuming that predevelopment chloride concentrations were about the same as those that currently exist. The effects of ground-water development on the predevelopment flow system were simulated, in stepwise fashion, over a series of time periods equivalent to the time of pumping at Savannah. Aquifer properties and boundary conditions were varied individually in a series of predevelopment simulations to determine the resulting changes in the saltwater-freshwater transition zone.

## Previous Work

The possibility of saltwater intrusion into the Upper Floridan aquifer east and northeast of Savannah as a result of pumping at Savannah was documented more than 40 years ago by Stringfield and others (1941) and by Warren (1944). The first two test wells designed to detect saltwater movement in the area were drilled in 1954 (Herrick and Wait, 1955); one of them (BFT 101) is located on Hilton Head Island and provided data for this report. Siple (1960) recognized the potential for contamination of the aquifer in the Hilton Head area by saltwater entering laterally or vertically from above or below. He considered lateral intrusion the most likely and concluded that saltwater was moving down the hydraulic gradient toward Savannah, but at a very slow rate. The most recent comprehensive work on the potential for saltwater intrusion into the Upper Floridan in the Savannah–Hilton Head area has been presented in reports by Counts and Donsky (1963), McCollum and Counts (1964), and McCollum (1964). Each of the reports reiterates Siple's conclusion that lowered heads due to pumping at Savannah were causing slow lateral migration of saltwater from the vicinity of Port Royal Sound toward Savannah. McCollum and Counts (1964) calculated that it would take more than 400 years for the salty water to reach Savannah. However, McCollum (1964) pointed out that ground-water users in the path of saltwater movement (those on Hilton Head Island, among others) will be directly affected before saltwater reaches Savannah. Back and others (1970) used a geochemical approach—carbon-14 dating of waters—to confirm the concept of the regional flow system shown in the previous studies. More recent hydrologic studies that include the Hilton Head area, notably Hayes (1979), have drawn conclusions similar to those of earlier workers regarding saltwater intrusion.

# HYDROGEOLOGY

## Geologic Setting and Hydraulic Properties

The Floridan aquifer system is a thick sequence of hydraulically connected carbonate rocks (primarily limestone with some dolomite), ranging in age from late Paleocene to early Miocene, that underlies all of Florida, southeastern Georgia, and small adjacent parts of Alabama and South Carolina (inset, fig. 1). In general, the system consists of two aquifers, the Upper Floridan aquifer and the Lower Floridan aquifer, separated by a confining unit of highly variable properties. Miller (1986, pls. 26, 27, 33) shows the aquifer system at Hilton Head Island to be about 800 ft thick, occurring from about 100 to 900 ft below sea level.

A geologic section from land surface to the base of the aquifer system at Hilton Head Island is shown in figure 2. The Holocene and Pliocene deposits at the top of the section form a sandy surficial aquifer containing water under unconfined conditions. These sandy deposits grade into less permeable Miocene rocks with depth. The Miocene rocks, primarily consisting of clayey sand interbedded with low-permeability limestone and dolomite, form an upper confining unit on the Floridan aquifer system. No field data on the vertical permeability of the upper confining unit on the island is available. However, Siple (1957, p. 6) states that the confining unit is "quite thin" and "may not be present at all in some parts of the [Parris Island, S.C.] area," across Port Royal Sound from Hilton Head. Counts and Donsky (1963, pl. 3) show the upper confining unit thickening in a section from Hilton Head Island southeast through Savannah.

The Upper Floridan aquifer at Hilton Head Island as defined by Miller (1986) is essentially coincident with the "principal artesian aquifer" as defined by Counts and Donsky (1963) and McCollum and Counts (1964), although there are some minor differences among the three reports in interpretation of the formations composing the aquifer. The Miocene-Oligocene contact about 100 to 150 ft below sea level is generally regarded as the top of the Upper Floridan at Hilton Head Island. The base of the Upper Floridan occurs in middle Eocene rocks about 650 to 700 ft below sea level. The top and base of the aquifer are defined on the basis of permeability, although the base is partly determined by the chemical quality of the water.

Most zones of higher permeability in the Upper Floridan aquifer occur in the upper 150 to 300 ft (fig. 2). Counts and Donsky (1963) described the upper Eocene limestone that composes the upper part of the aquifer as somewhat calcitized, crystalline, and abundantly fossiliferous, with thin zones of very dense limestone that contain numerous solution channels. The results of five aquifer tests, three from wells on the island and two from wells in areas immediately adjacent to the island, bracket a probable range of transmissivity values for the top part of the Upper Floridan aquifer, which contains the upper two permeable zones

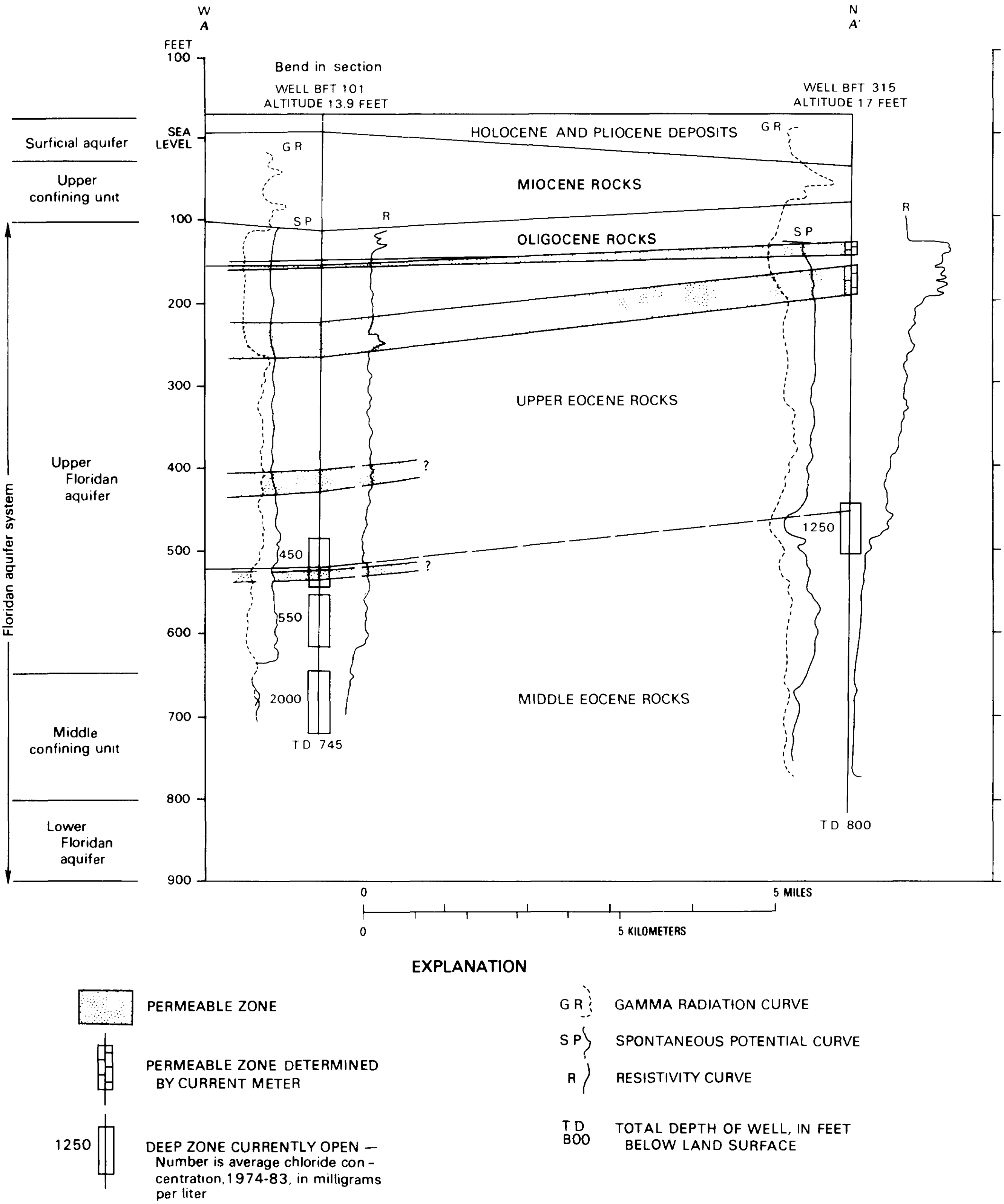



**Figure 2.** Geologic section and associated hydrogeologic units, Hilton Head Island. Well locations shown in figure 1. Geologic section modified from McCollum and Counts (1964, pl. 2). Hydrogeologic units from Miller (1986, pls. 25, 26, 29, 31, 33).

shown in figure 2 (hereafter referred to as the upper permeable zone) (Counts and Donsky, 1963; Nuzman, 1970, 1972; Hayes, 1979). Three of the wells are known to have been open exclusively to the upper permeable zone for the tests. The open intervals of the remaining two wells are unknown but presumed to have been in the upper permeable zone also. Transmissivity values from the aquifer tests range from 28,000 to 71,000 $ft^2/d$ and average 52,000 $ft^2/d$. Almost all the supply wells on Hilton Head Island are finished in the upper permeable zone. Thus, it is the zone of principal interest.

The lower 350 to 400 ft of the Upper Floridan at Hilton Head is less permeable than the zone above it. Counts and Donsky (1963) characterized the upper Eocene rocks of this zone as a predominantly granular, calcitized limestone. It is fossiliferous throughout and has thin layers of dense limestone and sandy, silty, clayey limestone or marl. It is glauconitic in the lower part. The middle Eocene rocks of the basal part of the Upper Floridan are similar in character, described by Counts and Donsky (1963) as dense, sandy, fossiliferous limestone and coarsely glauconitic marl. No transmissivity data are available for the Upper Floridan below its upper permeable zone. However, in the Savannah–Hilton Head area, McCollum and Counts (1964) ran current-meter tests in four test wells open to selected zones throughout the Upper Floridan. One well was BFT 101 on Hilton Head Island and another was on the north end of Dafuskie Island just southeast of Hilton Head Island. They reported that generally more than 70 percent of the water pumped during the tests came from the upper permeable zone.

The thin layers of dense limestone occurring throughout the Upper Floridan, together with the nearly horizontal permeable zones shown in figure 2, suggest that the aquifer has greater lateral permeability than vertical. McCollum and Counts (1964, p. D13) concluded that there is little "interconnection" between the permeable zones because the material between them is "relatively impermeable" and because analyses of water from the permeable zones indicate differences in chemical quality. However, the numerous solution channels reported in the dense layers of the upper permeable zone may lessen anisotropy in that zone.

Very little is known about the middle Eocene rocks below the Upper Floridan at Hilton Head Island, except that they are less permeable than those of the Upper Floridan. Counts and Donsky (1963) found more silt, clay, and marl in these rocks than in those above and thus consider these rocks to be a lower confining unit on the aquifer. On the basis of very limited well control, Miller (1986, pl. 31) estimates the top of the Lower Floridan aquifer to occur about 800 ft below sea level; but the contrast in permeability between rocks of the Lower Floridan and those of a middle confining unit above it is unknown. Miller (1986, pl. 33) picks the base of the Floridan aquifer system at about 900 ft below sea level. In most of southwestern South Carolina, the base of the aquifer system consists of interbedded gray to black clay, red to brown sandy clay, and fine-grained, white, calcareous sand and clayey sand (Miller, 1986, p. B74).

## Hydrologic Conditions Before Ground-Water Development

The estimated potentiometric surface of the Upper Floridan aquifer in the Savannah-Hilton Head area before pumping began at Savannah is shown in figure 3*A*. The contours suggest that ground water flowed northeast under Hilton Head Island toward natural discharge areas in the vicinity of Port Royal Sound and Parris Island, where the upper confining unit is thin or missing. Original heads along the line of section in figure 3*A* ranged from about 10 ft above sea level near the center of Hilton Head Island to slightly above sea level in Port Royal Sound.

Before ground-water development, the vertical hydraulic gradient at Hilton Head Island was upward from the Upper Floridan to the surficial aquifer, except in topographically high dune areas where the water table was probably higher than the potentiometric surface. Areal digital models of the predevelopment Floridan flow system, made as part of the Floridan Regional Aquifer-System Analysis (Bush and Johnston, in press; Krause and Randolph, in press), suggest about 1 in/yr of upward leakage on the northern part of Hilton Head Island and adjacent areas.

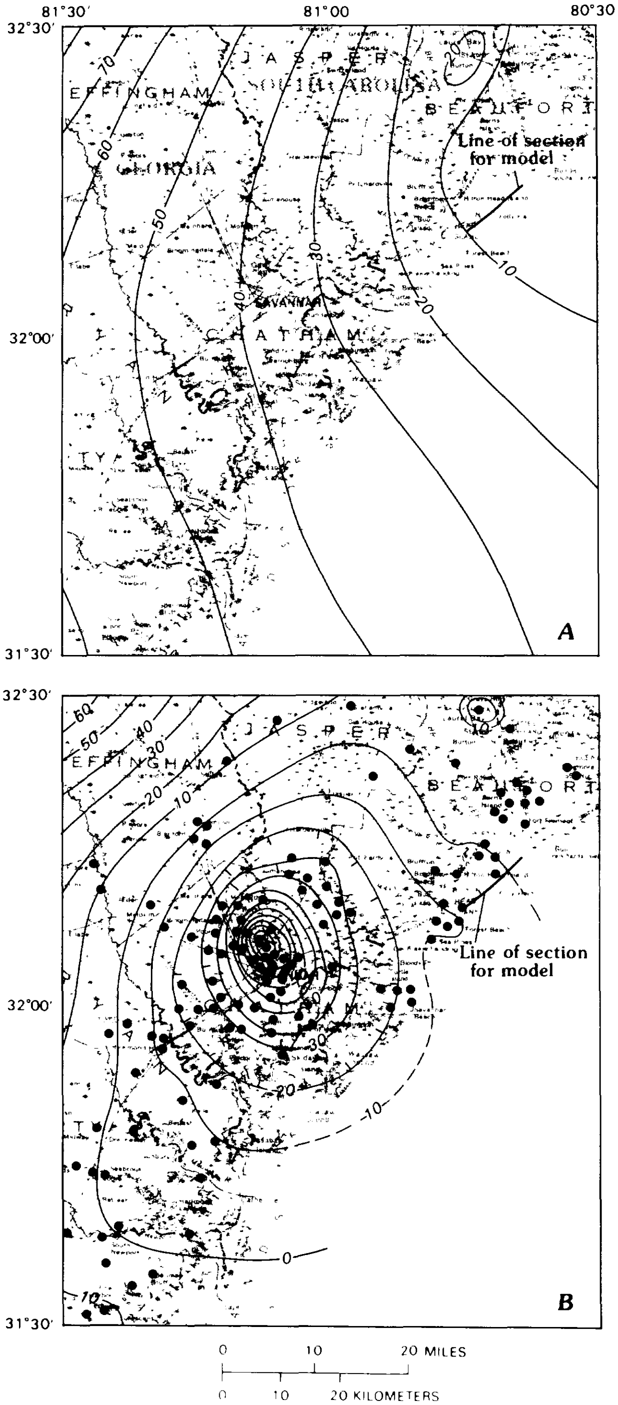
Chloride concentrations of water in the Floridan aquifer system before pumping at Savannah are assumed to have been about the same as they are today; they are discussed in the next section.

## Hydrologic Conditions and Chloride Concentrations After Ground-Water Development

The potentiometric surface of the Upper Floridan aquifer in the Savannah-Hilton Head area in May 1980 is shown in figure 3*B*. Pumping that began about 1885 from the Upper Floridan at Savannah has lowered heads at Savannah more than 150 ft, reversing the original seaward hydraulic gradient in the aquifer. Heads near the center of Hilton Head Island have dropped about 16 to 17 ft since pumping at Savannah began.

Pumpage at Savannah in 1939 was about 31 Mgal/d (Counts and Donsky, 1963, p. 54). Average pumpage from 1943 to 1953 was about 41 Mgal/d. The rate was about 51 Mgal/d by 1954 and 62 Mgal/d in 1957. In 1980, pumpage at Savannah was about 70 Mgal/d (Krause and others, 1984, table 4). Pumpage from the upper permeable zone of the aquifer on Hilton Head Island, which was negligible in the late 1950's, was about 10 Mgal/d in 1980 (Randolph and Krause, 1984, p. 19).

Pumpage in the Savannah–Hilton Head area is supplied primarily by the diversion of natural discharge and induced




EXPLANATION

—20 — — POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells completed in the Upper Floridan aquifer. Dashed where approximately located. Hachures indicate depression. Contour interval 10 feet. Datum is sea level.

• CONTROL POINT—Well in which water level or artesian pressure measurement was made in May 1980. One point may represent several wells.

**Figure 3.** Potentiometric surface of Upper Floridan aquifer in Savannah–Hilton Head Island area. *A*, Predevelopment (Johnston and others, 1980), *B*, May 1980 (Johnston and others, 1981).

recharge rather than by aquifer storage. Randolph and Krause (1984, p. 15) estimate that aquifer storage from a 5,000-$mi^2$ area around Savannah contributed less than 1 percent of the total water withdrawn from the system in 1980.

Upper Floridan heads near the center of Hilton Head Island (the southeast end of the section in fig. 3*B*) had declined about 8 ft to about 2 ft above sea level by 1944 (Mundorff, 1944, pocket plate; Warren, 1944, fig. 33). By 1958, heads near the center of Hilton Head were about at sea level (Counts and Donsky, 1963, pl. 5). In 1980, heads near the island's center were 6 to 7 ft below sea level.

The vertical head gradient at Hilton Head Island has also generally reversed from its original upward direction so that recharge to the Upper Floridan, rather than discharge, now occurs. The 1980 rate of recharge to the Upper Floridan on the northern part of the island and vicinity was in the range of 0.2 to 0.5 in/yr, on the basis of the model simulations made by Randolph and Krause (1984). More recently, an areal digital model of the Hilton Head–Beaufort, S.C., area has indicated higher recharge rates of 3 to 6 in/yr on the northern part of Hilton Head (B.S. Smith, U.S. Geological Survey, written commun., 1986).

Chloride concentrations in selected zones of the Floridan aquifer system in the Savannah–Hilton Head area have been monitored continuously since the late 1950's. The head declines have caused no significant increase in chloride concentrations in monitored wells during the past 20 years (Krause and others, 1984, p. 10). Chloride concentrations generally increase with depth. Below the upper permeable zone on Hilton Head Island, chloride concentrations also increase in the direction of Port Royal Sound.

Chloride concentrations in the upper permeable zone of the northern part of Hilton Head Island are generally less than 100 mg/L. Nine test holes were drilled into the upper permeable zone beneath Port Royal Sound north of Hilton Head during July to October 1984. Chloride concentrations from 17 water samples collected at depths ranging from 80 to 190 ft below sea level ranged from a low of 60 mg/L to a high of 12,340 mg/L (R.A. Burt, U.S. Geological Survey, written commun., 1985).

Chloride concentration data from the aquifer system below the upper permeable zone are very limited. Long-term records of chloride concentrations are available from three deep zones of well BFT 101 and one deep zone of well BFT 315 (figs. 1, 2). The open zones of each well are isolated by separate casings placed within larger diameter open holes. The casings to each zone are finished with screens that are gravel packed. The gravel packs, and thus the open zones, are sealed from above with at least 20 ft of cement. The upper open zone of well BFT 101 is in approximately the same part of the aquifer as the open zone of well BFT 315. Chloride concentration in the lower part of the Upper Floridan increases from about 450 mg/L in well BFT 101 to 1,250 mg/L in well BFT 315. A sharp increase in average chloride concentration from about 550 to 2,000 mg/L occurs between the middle and lower zones of well BFT 101.

This increase is assumed to mark the base of the Upper Floridan.

The source of the relatively high chloride water that currently exists in the deeper parts of the aquifer system of the northern part of Hilton Head has not been firmly established. The brackish or salty water may be partially unflushed water from a previous geologic time, or a mixture of native ground water and ocean water, or a combination of both. On the basis of results of a trilinear diagram from analyses of samples in the area, Counts and Donsky (1963, p. 83) state that "None of the contaminated water in the lower part of the aquifer appears to be a direct mixture of ocean water and native ground water." Also on the basis of a trilinear diagram from analyses of samples in the Hilton Head Island and Parris Island area, Back and others (1970, p. 2331) conclude that "* * * little chemical reaction is occurring other than (1) rainfall dissolving calcareous material and (2) resultant ground-water mixing with normal ocean water." The trilinear diagrams of both previous studies included analyses of samples from the three zones of well BFT 101. Siple (1960) also made a trilinear diagram that included analyses of samples from the three zones of well BFT 101. On the basis of the plotted position of points representing the upper and middle zones of well BFT 101, Siple (1960, p. 63) reports having "* * * some doubt of the inference that the chloride contamination represents ocean water rather than connate or intruded water."

Whatever the source of the relatively high chloride water, if the saltwater-freshwater transition zone responds very slowly to long-term changes in flow conditions, then the chloride concentrations in the four well-zone locations shown in figure 2 would be about the same as they were before pumping began at Savannah.

## SALTWATER MOVEMENT

### Computer Simulation

The SUTRA model (Saturated-Unsaturated Transport) (Voss, 1984) is a modular computer program in Fortran-77 that simulates fluid movement and the transport of either dissolved substances or energy in the subsurface. The model can be applied areally or in cross section. It uses a two-dimensional, combined finite-element and integrated-finite-difference method to approximate the equations that describe the two interdependent processes being simulated. When used to simulate saltwater movement in aquifers in cross section, the two interdependent processes are the density-dependent saturated ground-water flow and the transport of dissolved solids in the ground water. Either local- or regional-scale sections having dispersed or relatively sharp transition zones between saltwater and freshwater may be simulated. The results of a SUTRA simulation of saltwater movement show distributions of fluid pressures and dissolved-solids concentrations as they vary with time and also show the magnitude and direction of fluid velocities as they vary with time. Almost all aquifer properties that are entered into the model may vary in value throughout the simulated section. Sources and boundary conditions of fluid and solute may vary with time. The finite-element method using quadrilateral elements allows the simulation of irregular areas with irregular mesh spacing.

To apply the SUTRA model at Hilton Head Island, the geologic section of figure 2 is simplified, or idealized, into the rectangular section in figure 4. For simulation, the section is divided into 1,296 rectangular elements, each having dimensions of 1,760 by 15 ft, resulting in 1,375 nodes. A nominal section width of 3.28 ft is used. The aquifer system is simulated in the model by five hydrogeologic units representing the upper confining unit, the upper permeable zone of the Upper Floridan aquifer, the lower part of the Upper Floridan aquifer, the middle confining unit, and the Lower Floridan aquifer. The lateral and the vertical permeabilities are assumed to be constant within each of the five units except the middle confining unit.

At the seaward vertical boundary in Port Royal Sound, specified hydrostatic pressures at each node are based on a column of water having dissolved-solids concentrations specified as a function of depth. Hydrostatic pressures are assumed to be appropriate because the rates of flow at the seaward boundary are extremely slow, and no hydrologic basis exists for deriving more accurate pressures. Water that enters the section at a given node as a result of a pressure gradient at the boundary is of the specified concentration; water that exits at such a node is of ambient aquifer concentration. At the landward vertical boundary, rates of lateral flow are specified. The direction of the specified flow depends on the extent of ground-water withdrawals. Hydrostatic pressures equivalent to estimated heads in the surficial aquifer are specified at nodes along the top boundary of the upper confining unit. Thus inflow to, or outflow from, the upper permeable zone of the Upper Floridan occurs, depending on the direction of the gradient across the upper confining unit. The bottom boundary of the Lower Floridan is assumed to be of extremely low permeability and therefore is specified as a no-flow boundary for the model.

### Simulation of Conditions Before Ground-Water Development

It is assumed that before pumping at Savannah began, the saltwater-freshwater transition zone in the Floridan aquifer system at Hilton Head was in an equilibrium position based on current sea level. This assumption may not be exactly correct. Mörner (1969, fig. 145, p. 414; also in Andrews, 1975, fig. 6–4) shows a glacio-eustatic sea-level rise of about 200 ft over the past 13,000 years and a minimal sea-level change for only the past 3,000 to 4,000 years. A test of the assumption would be whether or not a steady-state simulation of estimated predevelopment heads (or pressures), chloride (or dissolved-solids) concentrations, and flow rates can be made using realistic boundary conditions and aquifer properties.

A series of transient SUTRA model runs to steady state were done in which boundary-condition values and aquifer-property values were adjusted by trial and error to simulate predevelopment conditions. Initially, hydrostatic starting pressures, based on the boundary conditions and starting concentrations of zero everywhere, were set throughout the aquifer system. The starting pressures were obtained through a preliminary initial simulation that calculated steady pressures under those conditions (Voss, 1984, p. 276). Subsequent runs often used results from the previous run as initial conditions. Experimentation with space and time discretization allowed appropriate sizes to be chosen to give realistic lateral and vertical distribution of solute concentrations. Appropriate sizes also avoid numerical spatial oscillations that may occur near the concentration front; that is, concentrations ahead of the front that may be unrealistically low, and concentrations behind the front that may be unrealistically high. The mesh spacing shown in figure 4 and time steps of 1 year proved satisfactory.

Aquifer properties and boundary-condition values that produced the best predevelopment simulation results are shown in figure 5, and the fluid properties assumed for the simulation are listed in table 1. The values in figure 5 are derived from an attempt to (1) match chloride concentrations (calculated from simulated dissolved-solids concentrations) with existing measured values where these values exist, (2) match simulated heads (calculated from pressures) in the upper permeable zone to estimated predevelopment heads, (3) keep upward leakage from the Upper Floridan aquifer consistent with rates estimated in the studies of Randolph and Krause (1984) or B.S. Smith (U.S. Geological Survey, written commun., 1986), and (4) keep the values of all properties consistent with known data and hydrogeologic conditions in the area.

The transmissivity value of the upper permeable zone was obtained from the aquifer tests previously discussed. The values of transmissivity for the lower part of the Upper Floridan aquifer and for the Lower Floridan aquifer are estimated from simulation.

The lateral intrinsic permeability values of the water-yielding units are calculated from the transmissivity values, the thicknesses of the water-yielding units, the viscosity, and the density at base concentration. The vertical intrinsic permeability values of all hydrogeologic units are estimated from simulation. Relatively high ratios of lateral to vertical permeability (for the Floridan) are used to simulate predevelopment conditions. Counts and Donsky (1963) and

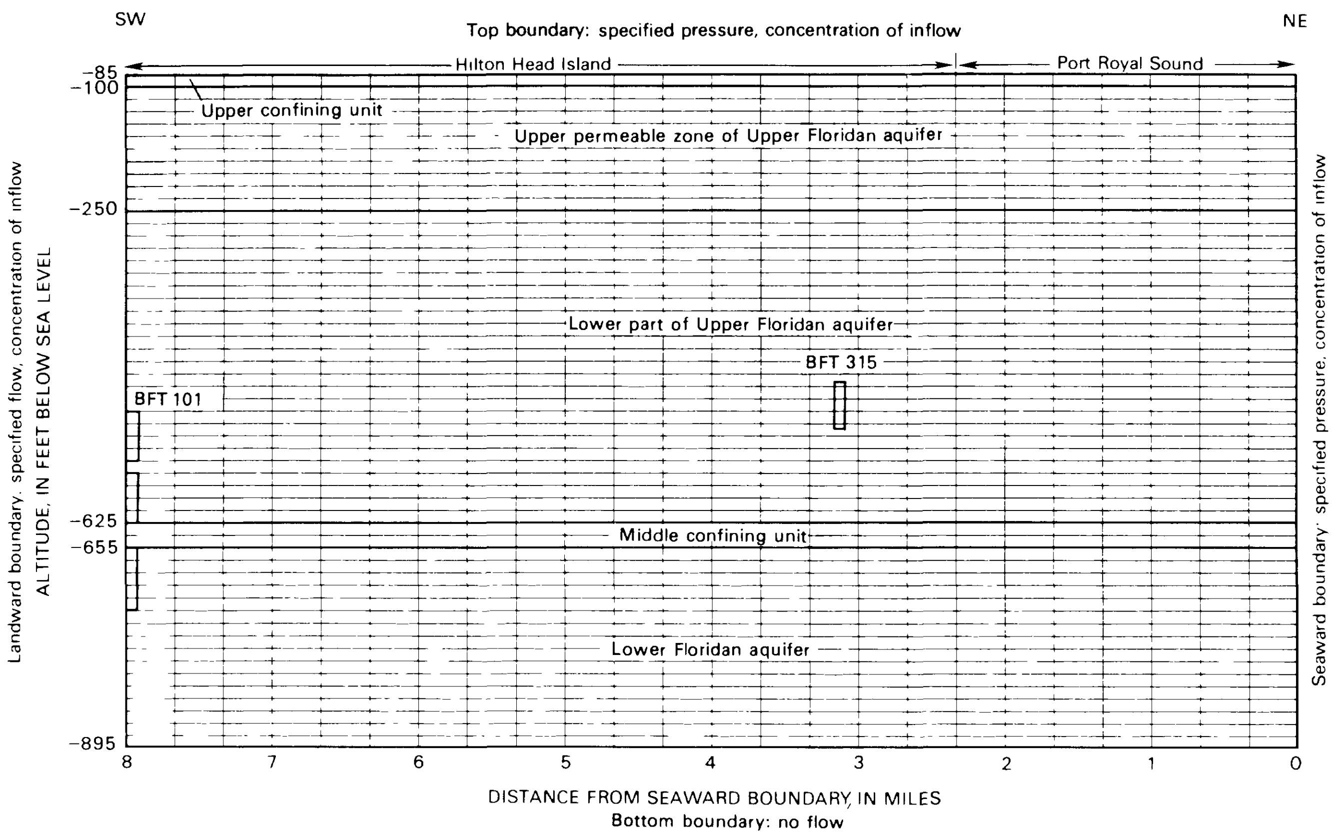
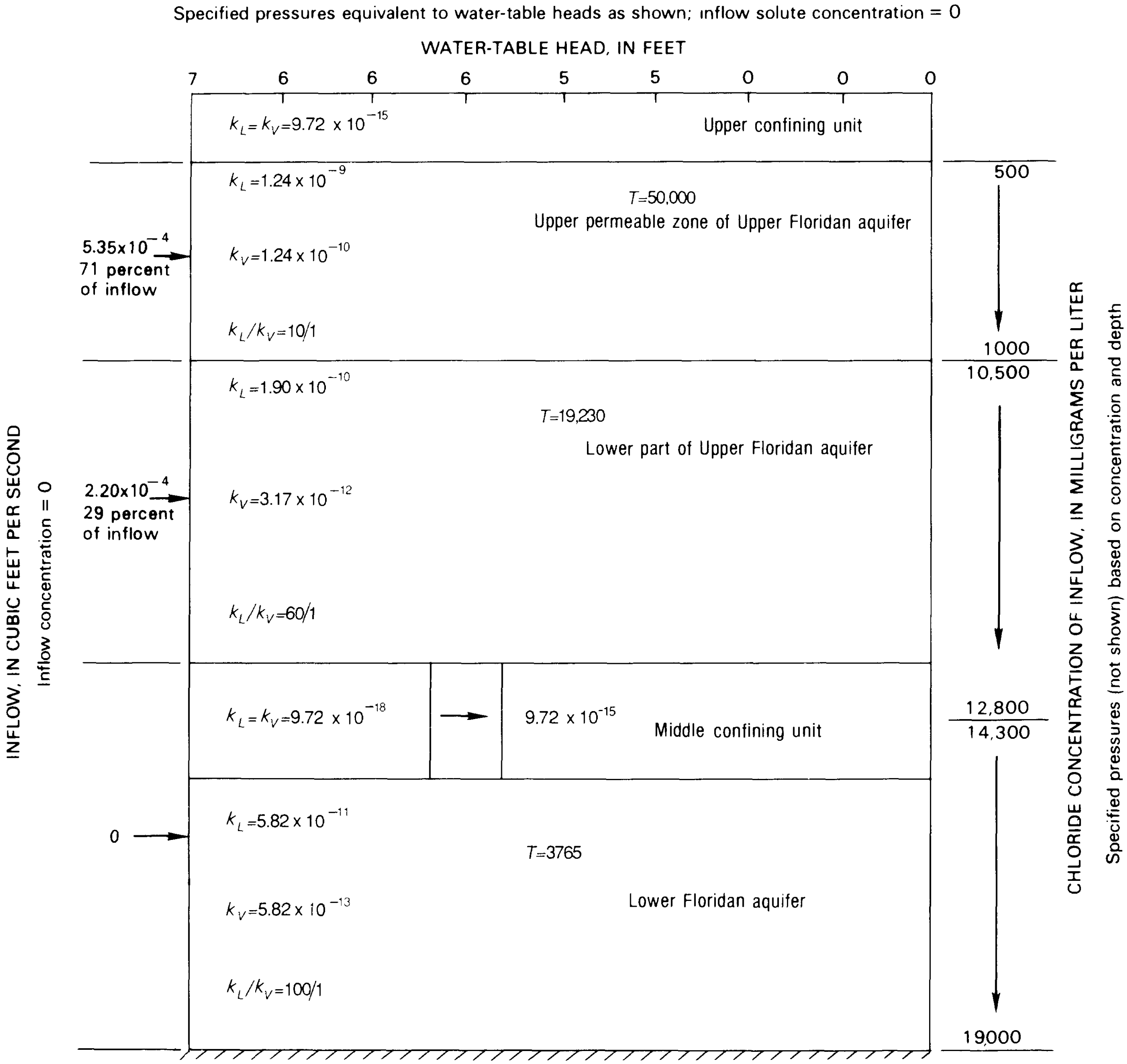



**Figure 4.** Simulated section showing hydrogeologic units, types of boundary conditions, and mesh spacing, Hilton Head Island area. Open intervals of wells (vertical rectangles) projected to section; well locations shown in figure 1.

McCollum and Counts (1964), in their discussions of the geology of the Upper Floridan and its water-yielding zones, described a layered system of fossiliferous permeable limestone zones and dense, less permeable limestone zones. Because the specific configuration of permeable and less permeable zones (assumed to be a series of heterogeneous, isotropic layers) is unknown at Hilton Head Island, the actual system, except for the upper and middle confining units, is simulated collectively as equivalent anisotropic aquifer units.

Dispersion is the solute movement that results from mechanical mixing and molecular diffusion. It is the component of transport that cannot be attributed to the mean flow of the ground water (advection). Values of dispersivity have been shown to be scale dependent (Wolff, 1982, p. 98). No




**EXPLANATION**

$T$ = transmissivity, in square feet per day

$k_L$ = lateral intrinsic permeability, in square feet

$k_V$ = vertical intrinsic permeability, in square feet

**Figure 5.** Predevelopment values of boundary conditions and predevelopment and present-day aquifer properties, Hilton Head Island area. Longitudinal dispersivity ($\alpha_L$) = 44 ft; transverse dispersivity ($\alpha_T$) = 3.75 ft; porosity ($\Theta$) = 0.30.

**Table 1.** *Fluid properties assumed for simulation*

| Fluid property | Assumed value |
|---|---|
| Temperature---------- | 71.6 °F |
| Fluid compressibility and aquifer-matrix compressibility. | 0 $in^2/lb$ |
| Diffusivity------------ | 0 $ft^2/s$ |
| Base concentration as mass fraction. | $0 \frac{\text{slug dissolved solids}}{\text{slug water}}$ |
| Maximum (seawater) concentration as mass fraction. | $0.0342 \frac{\text{slug dissolved solids}}{\text{slug water}}$ |
| Density at base concentration. | 1.935 slug water/$ft^3$ |
| Density at maximum concentration.[1] | 1.986 slug water/$ft^3$ |
| Coefficient of density change with concentration. | $1.491 \frac{(\text{slug water})^2}{(\text{slug dissolved solids})\cdot ft^3}$ |
| Viscosity[2]------------- | $2.00\times10^{-5}$ lb·s/$ft^2$ |

[1]From Chow (1964, fig. 2-2).
[2]From Weast and Astle (1979, p. F-51).

local data to indicate the degree of dispersion exist. However, values of lateral and transverse dispersivity obtained from 16 regional model studies have been summarized by Anderson (1979) and in Wolff (1982, table 4.5.2). Lateral dispersivity values from the studies range from 10 to 656 ft; transverse dispersivity values range from 2 to 450 ft. The values of longitudinal and transverse dispersivity used in the Hilton Head model (440 ft and 3.75 ft, respectively) give a reasonable transition zone in the simulation. The finite-element mesh was designed so that elements have a lateral dimension equal to four times the longitudinal dispersivity to guarantee spatial stability of SUTRA's numerical approximation to the transport equation (Voss, 1984, p. 232).

The value of porosity used in the model, 0.30, is an estimate based on laboratory analyses of six aquifer-material samples from a well on the north end of Dafuskie Island, southeast of Hilton Head Island (Counts and Donsky, 1963, table 4).

No data exist to guide in the selection of boundary-condition values for units below the upper permeable zone. The dissolved-solids concentration (and thus the chloride concentration calculated from it) of inflow at the boundary in Port Royal Sound below the upper permeable zone was estimated from simulation.

The simulated predevelopment flowfield is portrayed in figure 6. The general configuration of the flowfield is typical of a coastal aquifer having a seaward gradient in the freshwater. The freshwater flows toward Port Royal Sound over an intruding wedge of saltwater that meets the freshwater in a zone of mixing. The saltwater mixes with the freshwater, reverses direction, and is cycled back toward Port Royal Sound. The process is slow. The average simulated predevelopment velocity is 1.3 ft/yr in the Lower Floridan, 12 ft/yr in the Upper Floridan below the upper permeable zone, and 96 ft/yr in the upper permeable zone. Upward leakage occurs along the top of the simulated section except near the shore of Hilton Head. Some recharge to the Upper Floridan actually may have occurred through the topographically high sandy sediments. Land-surface altitudes on the north end of Hilton Head Island are greater than 10 ft almost to the shoreline. Simulated heads in the upper permeable zone range from 10 ft near the landward boundary to 0.4 ft near the Port Royal Sound boundary. The simulated net rate of upward leakage along the top boundary is 0.85 in/yr.

The distribution of predevelopment chloride concentrations associated with the flowfield of figure 6 is shown in figure 7. The simulated flowfield and distribution of chloride concentrations are essentially at steady state. They result from a 12,000-year simulation using constant boundary-condition and aquifer-property values. The chloride concentrations were calculated from simulated dissolved-solids concentrations by using two linear relations. For chloride concentrations less than 2,500 mg/L, a linear relation between chloride and dissolved solids derived from data in the Hilton Head Island area (Counts and Donsky, 1963, table 5) was used. For chloride concentrations between 2,500 and 19,000 mg/L (seawater concentration), the linear relation used was based on the assumption that the dissolved-solids concentration of seawater in the area is 35,000 mg/L.

The simulation of the transition zone is plausible, and the simulated concentration values at the projections on the section of well BFT 315 and the lower zone of well BFT 101 match average measured values very well. However, simulated solute concentrations are about zero near the landward boundary of the Upper Floridan, where average chloride concentrations measured in well BFT 101 are 450 to 550 mg/L. The low solute concentrations near the landward boundary probably result from assumptions about the flow system that influence how the system is simulated. The geochemical evidence from the zones of the system tapped by well BFT 101 does not clearly establish the source of the salty water in the vicinity of that well. The source could be the zones of relatively high-chloride water that occur in the system in the Port Royal Sound-Parris Island area. Another possible source is a connection to the aquifer system beneath the Atlantic Ocean normal to the simulated section. For purposes of simulation, the vertical boundary in Port Royal Sound is assumed to be the only source of solute to the model;

thus, specified boundary flows at the landward boundary are of zero concentration.

To simulate measured chloride concentrations of about 2,000 mg/L near the lower zone of well BFT 101 with the Port Royal Sound boundary as the only source of solute requires two additional assumptions: (1) a thinner middle confining unit than Miller (1986, pls. 29, 31) indicates, and (2) no inflow to the Lower Floridan at the landward boundary. The impossibility of accurately simulating solute concentrations in the Upper Floridan near the landward boundary, assuming the Port Royal Sound boundary to be the only source of solute, may imply that an additional predevelopment source of solute to the system existed. If the existence of salty water at well BFT 101 is due to the flow of high-chloride water normal to the simulated section, then the cross-sectional simulation near the landward boundary is inadequate. Nevertheless, because so little is known about the properties of the rocks beneath the upper permeable zone, and because the primary interest is in learning more about the potential for movement of saltwater from the Port Royal Sound-Parris Island area, simulation using one source of solute is probably defensible.

## Simulation of Conditions During Ground-Water Development, 1885 to 1984

To test the hypothesis that the saltwater-freshwater transition zone in the aquifer system has not moved appreciably from its predevelopment position, the effects of ground-water development on the predevelopment flow system were simulated in a series of four time periods from 1885 to 1984. The effects of pumping were simulated in the model by changing the values of specified flow at the landward boundary. All other boundary-condition and aquifer-property values remained the same as in the simulation of predevelopment conditions. The first time period, 1885 to 1934, was chosen because heads at Savannah apparently began to decline at a greater rate in the early 1930's (Counts and Donsky, 1963, fig. 6). The following two time periods, 1934 to 1944 and 1944 to 1959, were selected because approximate heads at the landward boundary of the simulated section in 1943 and 1958 are known. The last time period, 1959 to 1984, covers the years for which water-level measurements are available from four zones of well BFT 101 and two zones of well BFT 315. The initial conditions for each simulated time period

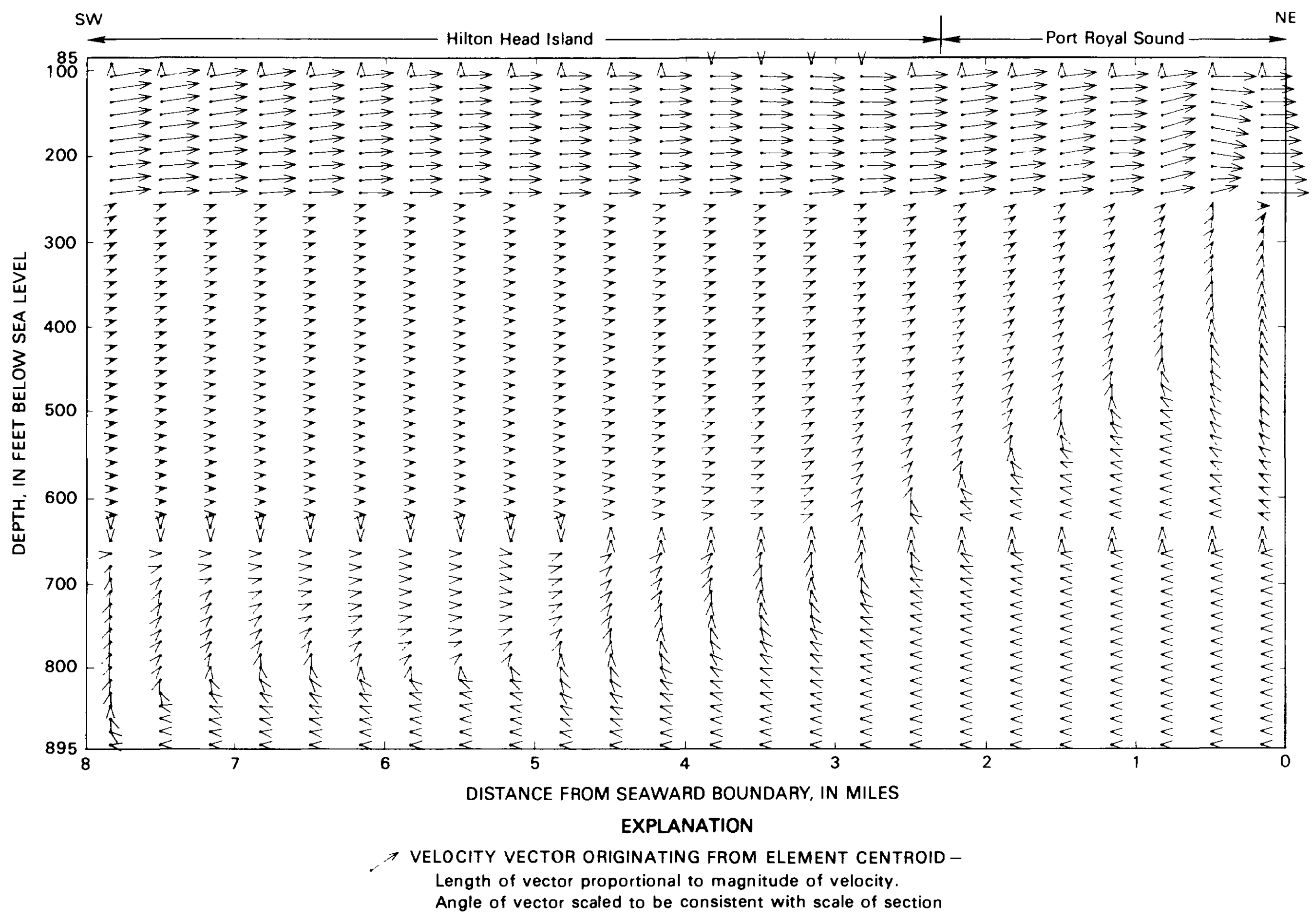



**Figure 6.** Simulated flow-velocity vectors in Floridan aquifer system under predevelopment conditions, Hilton Head Island area.

are the results from the previous time period. Landward boundary flows, specified as constant during each time period, were adjusted in trial-and-error SUTRA runs until point-water heads at the landward boundary, calculated from simulated pressures and concentrations, closely matched estimated or measured heads at the end of each time period. A point-water head in ground water of varying density is the water level (referred to a given datum, sea level in this report) obtained if the water in the well above the point has the same density as the water at the point (Lusczynski, 1961, p. 4247). The measured heads in wells BFT 101 and BFT 315 are assumed to be point-water heads.

Values of storage coefficient, which are computed by SUTRA from fluid and aquifer-matrix compressibility values, are zero for the transient simulations because fluid and aquifer-matrix compressibility values (table 1) are assumed to be zero. To test the validity of this assumption, the simulation of the period 1959 to 1984 was repeated, using reasonable finite values for fluid and aquifer-matrix compressibility. The absence of differences in the simulated distributions of point-water heads or concentrations from previous results, using compressibilities of zero, supports the finding of Randolph and Krause (1984, p. 15) that a very small fraction of the pumpage is supplied by aquifer storage.

The simulated flowfield at the end of 1983, the values of landward boundary flow simulated during the period 1959 to 1984, and measured and simulated point-water heads in the open intervals of wells BFT 101 and BFT 315 are shown in figure 8. Measured heads for 1980 rather than for 1983 were used for comparison to simulated heads because the head differences among the zones of well BFT 101 during 1981 to 1984 do not closely match the average head differences among the zones over the 26-year period of record, 1958 to 1984; 1980 head differences among the zones, however, are very similar to the average head differences among the zones. The vector plot indicates that, by the end

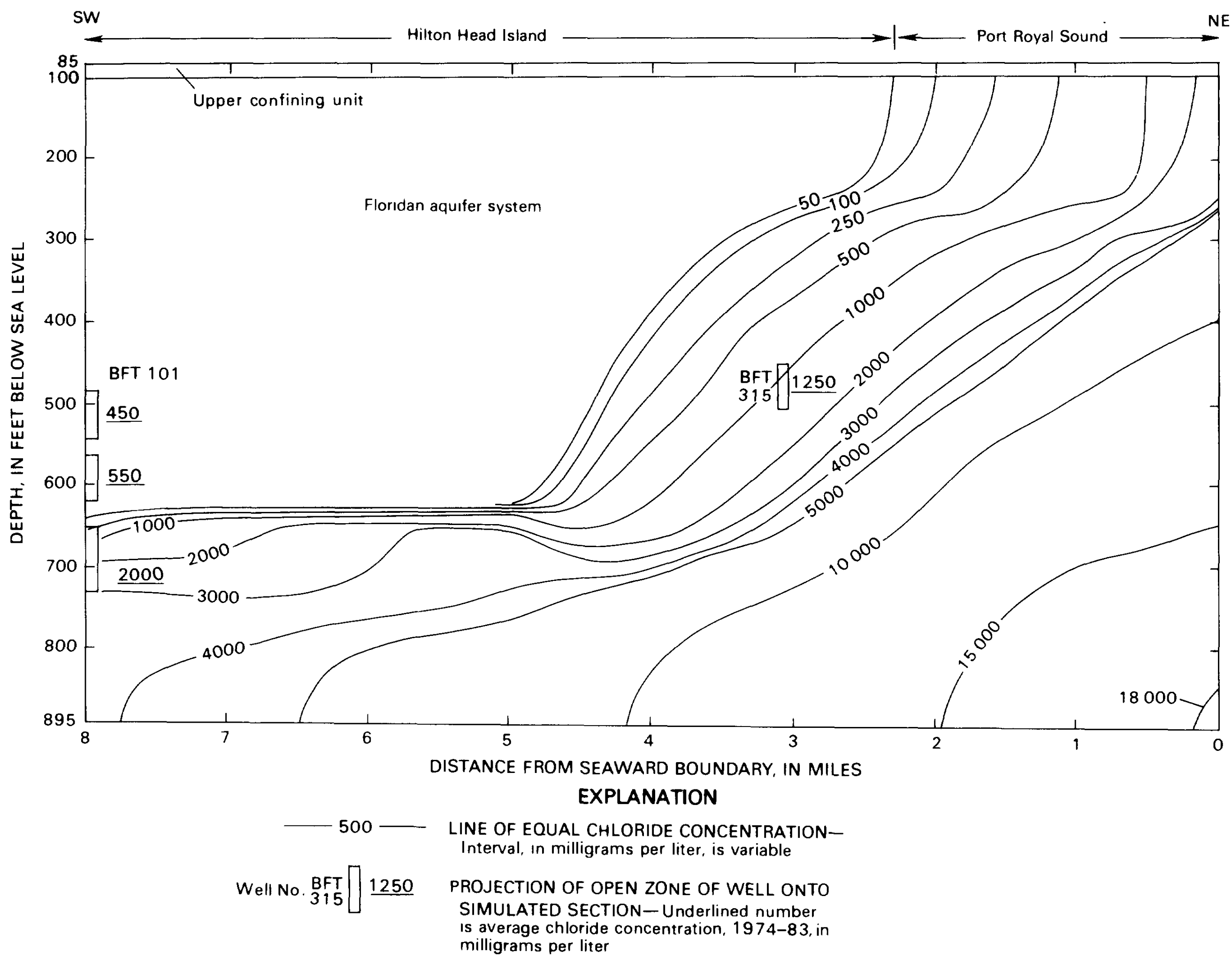



**Figure 7.** Simulated chloride concentrations in Floridan aquifer system under predevelpment conditions, Hilton Head Island area.

of 1983, ground-water flow in the Floridan aquifer system beneath most of Hilton Head Island was toward Savannah. But the simulation also suggests a ground-water divide in the upper permeable zone just onshore of the island. Furthermore, the simulation suggests that flow in the upper permeable zone in the northernmost parts of Hilton Head Island is still toward Port Royal Sound and is sustained by recharge from the surficial aquifer in the topographically high sandy areas near the island's north shore. However, during most of 1984, measured heads everywhere in the upper permeable zone on Hilton Head Island were below sea level, and no measurable evidence of a ground-water divide existed (B.S. Smith, U.S. Geological Survey, written commun., 1986). The simulated distribution of point-water heads in the upper permeable zone at the end of 1983 shows a lateral gradient of 0.2 ft/mi from the divide toward Port Royal Sound. Were a divide to exist as simulated, its proximity to the shoreline, the minimal gradient toward the sound, and the fluctuation of heads due to tides would make its detection difficult. The fact that the average measured head in the upper permeable zone at well BFT 315 was more than 2 ft above sea level until 1977, and more than 1 ft above sea level until 1983, implies that a lateral gradient toward the sound may have existed in the recent past, if not currently.

In the Upper Floridan aquifer beneath the upper permeable zone on Hilton Head Island, the vectors have a downward component, apparently the result of recharge from the surficial aquifer. The simulated net rate of recharge along the top boundary is 3.8 in/yr. Thus, with the flow pattern as shown, no vertical saltwater intrusion into the upper permeable zone beneath Hilton Head Island can occur. The vector plot implies that the upper permeable zone beneath Hilton Head Island has been protected since pumping began by a favorable pattern of ground-water flow.

The average simulated flow velocities in the Upper Floridan at the end of 1983 are similar to those under predevelopment conditions, although mostly in the opposite direction, landward, rather than toward Port Royal Sound. The average simulated velocity is 68 ft/yr in the upper permeable zone and 14 ft/yr in the Upper Floridan below

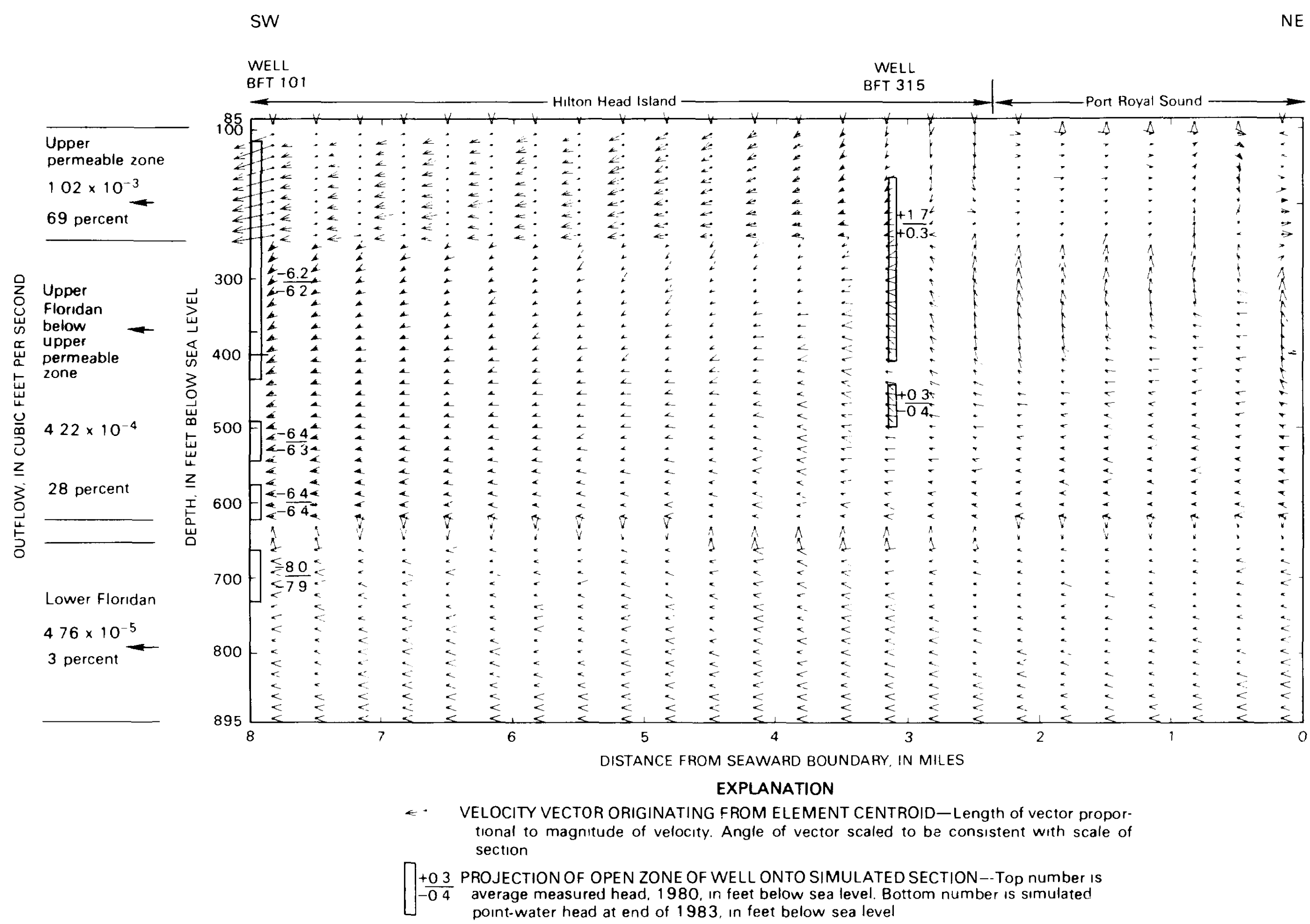



**Figure 8.** Simulated flow-velocity vectors, landward boundary flows, and selected point-water heads in Floridan aquifer system, Hilton Head Island area, at end of 1983.

the upper permeable zone. In the Lower Floridan, the average simulated velocity under current conditions is 6.6 ft/yr, which is several times higher than the simulated velocity under predevelopment conditions (1.3 ft/yr).

The distribution of chloride concentrations over the simulated section at the end of 1983 is shown in figure 9. Concentrations are about the same as those simulated under predevelopment conditions. The slight simulated encroachment of the 250- and 1,000-mg/L isochlors toward Hilton Head Island since before ground-water development is highlighted in figure 9. The simulation results support the hypothesis that the saltwater-freshwater transition zone has not moved appreciably from its predevelopment position.

## Simulation of Selected Future Conditions

To learn more about the effect of future pumping on the saltwater-freshwater transition zone, the model was run for 50 years beyond 1983, to 2034, under two different assumed pumping scenarios. In the first scenario, it was assumed that the pumping rate would not increase and that heads would be stable at late-1983 levels for the 50-year period. In simulating the first scenario, landward boundary flows are the same as those for the period 1959 to 1984. In the second scenario, it was assumed that the pumping rate would increase and that heads at the landward boundary would decline at an average rate of 0.25 ft/yr between 1983

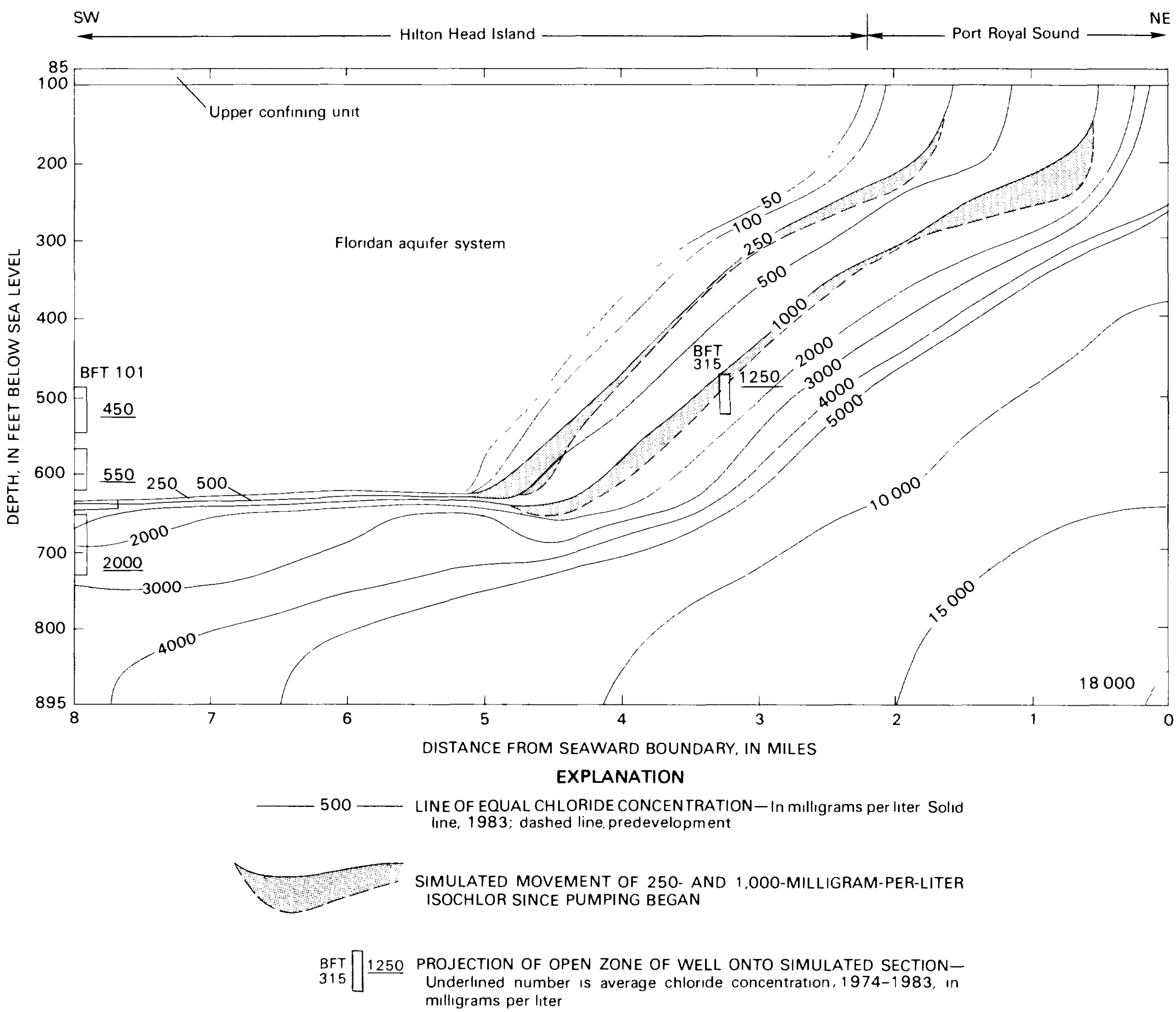



**Figure 9.** Simulated chloride concentrations at end of 1983 and movement of 250- and 1,000-mg/L isochlors in Floridan aquifer system since pumping began, Hilton Head Island area.

and 2034, which is the average observed annual decline for the 26-year period of record of well BFT 101. Heads at 6.2 ft below sea level in the upper zone of well BFT 101 in 1983 (fig. 8) would have dropped 12.5 ft to 18.7 ft below sea level by 2034. Landward boundary flows were adjusted in trial-and-error simulations until initial Upper Floridan heads of −6.2 ft became −18.9 ft by the year 2034. Simulated Lower Floridan heads (lower zone of well BFT 101) would become −19.6 ft by 2034.

The increase in pumpage that would cause the head at the center of Hilton Head Island to continue to decline at the historical rate of 0.25 ft/yr, and thus be 12 to 13 ft lower by 2034, is difficult to estimate because future head decline also depends on the distribution of future pumpage throughout the area of Savannah and Hilton Head Island. Randolph and Krause (1984, fig. 6), using their model of the Savannah–Hilton Head area, show that doubling the simulated pumpage at Hilton Head Island (to 20 Mgal/d) causes the head at the center of the island to decline about 8 ft. Their results from another simulation (1984, fig. 5) indicate that an overall 25-percent increase in pumpage throughout their modeled area (to 100 Mgal/d) reduces the head at the center of the island about 4 ft. If the results of both of the above simulations are superimposed, implying a change in pumpage at Hilton Head from 10 to 22.5 Mgal/d and a change in pumpage in the Savannah area from 70 to 87.5 Mgal/d, the head decline at the center of the island is about 12 ft. This is one scenario of future pumpage/pumpage distribution, based on simulation, that would result in a head decline until 2034 that continues at approximately the historical rate. However, other pumpage/pumpage-distribution scenarios could produce the same result.

Movement of the 250- and the 1,000-mg/L isochlors in the Upper Floridan was simulated for the next 50 years under the two assumed scenarios (fig. 10): (1) no increase in pumpage, and (2) an increase in pumpage such that the future rate of head decline equals the historical rate. In the first scenario, little additional saltwater intrusion is evident. The simulated flowfield in 2033 is the same as the flowfield in 1983 (fig. 8). In the second scenario, considerably more landward movement of salty water occurs in the upper permeable zone during the simulated 50 years. The 250- and 1,000-mg/L isochlors move landward about 0.8 mi in the upper permeable zone. The simulated flowfield in 2033 suggests no ground-water divide. All of the vectors in the Upper Floridan indicate predominantly landward flow. The simulation results suggest that if heads on Hilton Head Island remain at current levels for the next 45 to 50 years, there will be no significant threat of saltwater intrusion into the upper permeable zone. However, if head decline continues at the historical rate, lateral intrusion will proceed. Even under these conditions, however, the simulation results show that chloride concentrations in the upper permeable zone beneath the island should remain approximately 250 mg/L or less for the next 45 to 50 years.

## Hydrogeologic Controls on Saltwater Movement

When the results of a simulation study are based largely upon estimated rather than measured data, as in this case, determining which of the aquifer properties and boundary conditions have major control on the flow system is of particular interest. Such information can indicate which field data are the most important to acquire in order to refine and substantiate the simulation results. To learn which properties and conditions have the most influence on simulated saltwater movement, several 1,000-year runs were made that started with simulated predevelopment results as initial conditions. For each run, the value of one aquifer property or boundary condition was changed by an amount that it might reasonably be expected to vary from the value used in the predevelopment simulation. The results of those runs at two points on the model section line, the Upper Floridan aquifer at the projection of well BFT 315 and the upper permeable zone at the Hilton Head Island–Port Royal Sound shoreline, are summarized in table 2.

Among the varied aquifer properties, lateral permeability appears to have the most influence on saltwater movement throughout the Upper Floridan. Vertical permeability also has an appreciable effect on saltwater movement when it is changed by an order of magnitude rather than by 50 percent. The vertical anisotropy of the simulated aquifer units (fig. 5) is probably at the high end (and therefore the vertical permeability is at the low end) of a range of potential values that is much wider than the ranges of potential values of the other properties.

Transverse dispersivity also has a major effect on the relatively low solute concentrations of the upper permeable zone (predevelopment chloride concentration of 74 mg/L at the Hilton Head Island–Port Royal Sound shoreline). Solute concentrations are probably more sensitive to this property in the upper permeable zone than in the zone beneath it because the velocities are higher in the upper permeable zone (C.I. Voss, U.S. Geological Survey, written commun., 1986). Although transverse dispersivity may be an influential factor relative to saltwater movement in the upper permeable zone, field tests to estimate this property are probably impractical. However, estimation based on simulation experiments with a well-defined model (one based on good field data where practical) may be the best approach.

Simulations indicate that flow at the landward boundary has more control on the location of the saltwater-freshwater transition zone in the Upper Floridan than do solute concentrations (and associated pressures) at the Port Royal Sound seaward boundary. However, landward boundary flow was considered a dependent variable in the simulation; that is, the rates of landward boundary flow that resulted in the best head match depended primarily on the permeabilities of the units.

Simulation supports a conclusion of previous workers, that lateral saltwater migration is the principal threat to the freshwater supply of the upper permeable zone. If the ground-water divide shown by the simulation in the upper permeable zone on the northeast end of Hilton Head Island exists (fig. 8), or has existed until recently, then it has acted as a deterrent to lateral saltwater migration into the upper permeable zone. The location and configuration of such a divide also are linked to the permeabilities of the units.

The results of this study suggest that the precision of digital saltwater modeling in the Hilton Head area could be improved the most by better definition of lateral and vertical permeabilities in the Upper Floridan aquifer, particularly in the upper permeable zone, and by more and better measurements of the distribution of dissolved-solids concentrations of the ground water.

## SUMMARY AND CONCLUSIONS

At Hilton Head Island, the Floridan aquifer system consists of two limestone aquifers, the Upper Floridan aquifer and the Lower Floridan aquifer, separated by a middle confining unit of highly variable properties. The aquifer system is separated from a sandy surficial aquifer above by a clayey upper confining unit. The most permeable part of the Upper Floridan beneath the island is its uppermost 150 to 300 ft, which is designated as the upper permeable zone in this report. Average transmissivity of the upper permeable zone from aquifer tests is 52,000 $ft^2/d$.

Freshwater to supply Hilton Head Island is obtained from wells on the island that are open to the upper permeable zone. Chloride concentrations of water in the upper permeable zone at Hilton Head Island are currently (1986) less than

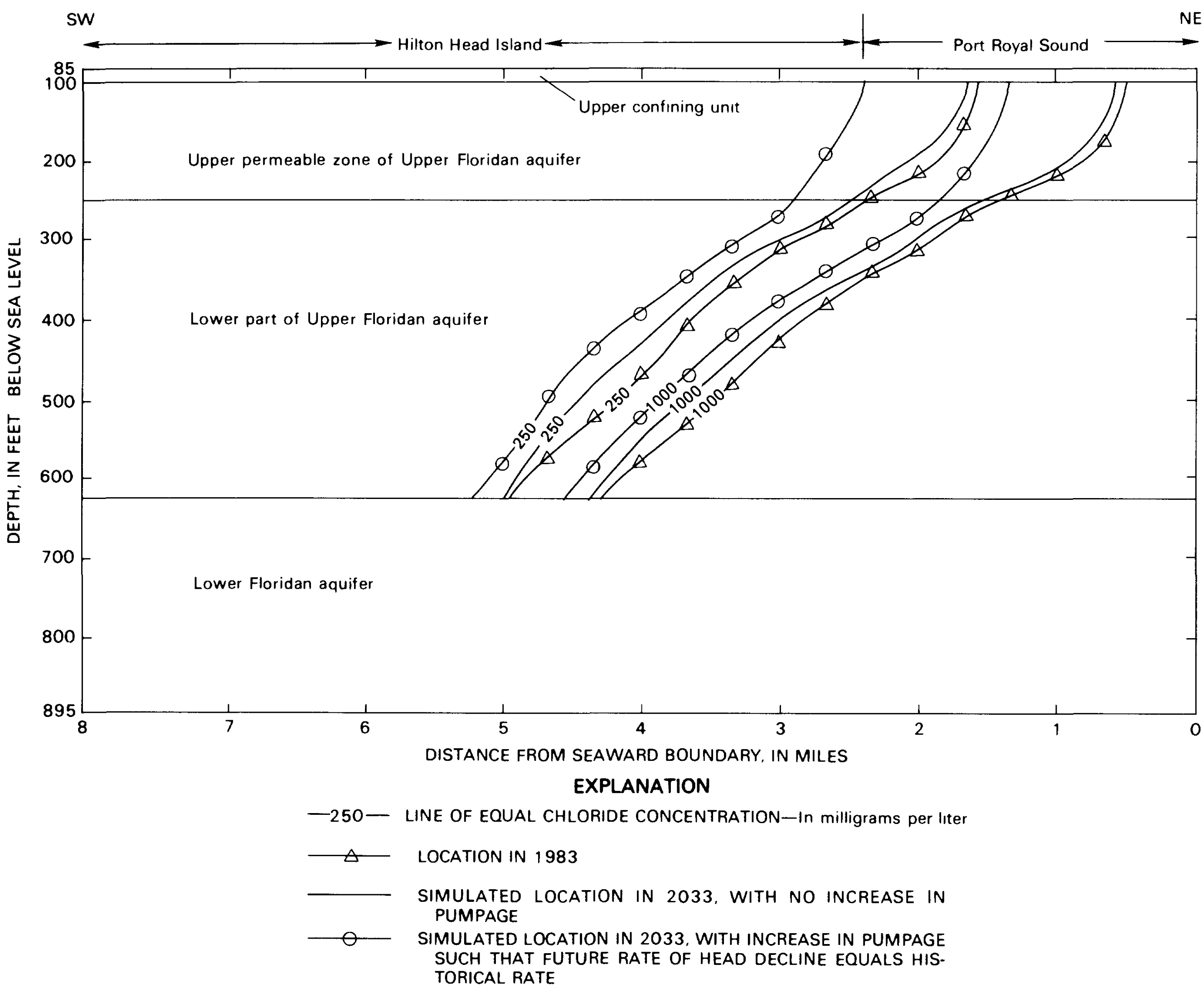



**Figure 10.** Simulated future movement of 250- and 1,000-mg/L isochlors in Upper Floridan aquifer under selected conditions, Hilton Head Island area.

**Table 2.** *Sensitivity of solute concentration to simulated changes in Floridan aquifer system properties and boundary conditions, Hilton Head Island area*

[Results of 1,000-yr simulations, starting with simulated predevelopment results as initial conditions, at two points on model section line (fig. 1)]

| Change in aquifer properties and conditions in 1,000 years | Change in solute concentration (in percentage) | |
|---|---|---|
| | Projection of Well BFT 315, lower part of Upper Floridan aquifer | Shoreline at Hilton Head Island, upper permeable zone |
| Porosity (pct) | | |
| +50 | <1.0 | <1.0 |
| -50 | <1.0 | <1.0 |
| Lateral permeability (pct) | | |
| +50 | +32 | +24 |
| -50 | -8.3 | +1.5 |
| Vertical permeability (pct) | | |
| Aquifers only, ×10 | -16 | -18 |
| Aquifers and confining units, ×10 | -8.4 | -15 |
| Lateral dispersivity (pct) | | |
| +50 | +8.0 | +12 |
| -50 | -11 | -6.5 |
| Transverse dispersivity (pct) | | |
| +50 | -1.0 | +48 |
| -50 | -3.4 | -55 |
| Solute concentrate at seaward boundary (pct) | | |
| [1]+50 | +2.2 | +3.0 |
| -50 | -10 | -13 |
| Landward boundary flow (pct) | | |
| +50 | -36 | -29 |
| -50 | +57 | +36 |

[1]Maximum concentration less than or equal to seawater concentration.

100 mg/L in most places. Concentrations of dissolved solids in the Floridan aquifer system increase with depth and to the northeast. Water beneath the upper permeable zone and throughout the aquifer system in the Port Royal Sound-Parris Island area generally varies from brackish to saline. Thus, a transition zone from saltwater to freshwater occurs beneath the Hilton Head Island area.

Large withdrawals from the Upper Floridan aquifer at Savannah have created a deep regional cone of depression that has spread beneath Hilton Head Island. Long-term pumping at Savannah, together with steadily increasing pumping on the island, have lowered Upper Floridan heads near the center of the island from about 10 ft above sea level to about 6 to 7 ft below sea level. The seaward hydraulic gradient that existed before pumping began has been reversed. However, chloride concentrations monitored over the past 25 to 30 years have remained relatively stable in the aquifer system at Hilton Head Island.

Ground-water flow in the Floridan aquifer system beneath the northeast end of Hilton Head Island and Port Royal Sound was simulated in cross section by using the SUTRA model, a finite-element model for fluid-density-dependent ground-water flow and solute transport (Voss, 1984). Predevelopment conditions were simulated, assuming that predevelopment chloride concentrations were about the same as those that currently exist and that a vertical boundary in Port Royal Sound is the only source of saltwater in the aquifer system. The effects of ground-water development on the system were simulated in four successive time periods spanning the approximately 100 years of pumping at Savannah; they were also simulated for 50 years into the future under two different assumed pumping scenarios. Boundary-condition and aquifer-property values were varied individually in a series of predevelopment simulations to determine the major hydrogeologic controls on the location of the saltwater-freshwater transition zone.

The general configuration of the simulated predevelopment flowfield is typical of a coastal aquifer having a seaward gradient in the freshwater. The freshwater flows toward Port Royal Sound over an intruding wedge of saltwater that meets the freshwater in a zone of mixing. The saltwater mixes with the freshwater, reverses direction, and is cycled back toward Port Royal Sound. Except for solute concentrations that are too low near the landward boundary in the Upper Floridan aquifer, the simulation of the predevelopment transition zone seems reasonable. Simulated solute concentrations closely match observed concentrations where data are available, except near the landward boundary of the Upper Floridan near the middle of the island. The concentration mismatch in that area may imply a predevelopment source of solute in addition to the source at Port Royal Sound.

The simulated flowfield at the end of 1983 shows that ground-water flow in the Floridan aquifer system beneath most of Hilton Head Island has reversed its predevelopment direction and is moving toward Savannah. The simulated flowfield at the end of 1983 also shows a ground-water divide in the upper permeable zone just onshore of the island from Port Royal Sound. No measurable evidence of a ground-water divide existed in 1984, although its detection, if it does exist, would be difficult because of its proximity to the shoreline, a minimal gradient toward the sound, and the fluctuation of heads due to tides. Historical head data imply that a divide may have existed in the recent past, if not currently. In the Upper Floridan beneath the upper permeable zone on the island, the 1983 simulated flow vectors have downward components, apparently the result of recharge from the surficial aquifer.

The assumption that the current distribution of chloride concentrations is about the same as the distribution of predevelopment chloride concentrations is substantiated by the simulation results.

A 50-year simulation that assumes no head decline from 1983 to 2034 results in no change in the simulated flowfield from its 1983 configuration and only nominal lateral saltwater movement in the Upper Floridan aquifer. A 50-year simulation that assumes continued head decline at the historical rate at the landward boundary, also from 1983 to 2034, results in the disappearance of the simulated ground-water divide in the upper permeable zone at the northeast end of Hilton Head Island and an 0.8-mi landward movement of the 250- and 1,000-mg/L isochlors in the upper permeable zone. This simulation indicates that the 250-mg/L isochlor in the upper permeable zone would move approximately to the Hilton Head Island–Port Royal Sound shoreline by 2034 if head decline continues at the historical rate.

Among aquifer properties and selected boundary conditions, the lateral permeability, transverse dispersivity, and landward boundary flow have the most influence on saltwater movement in the Upper Floridan aquifer.

The simulation results allow several preliminary conclusions to be drawn regarding saltwater movement in the Upper Floridan aquifer at Hilton Head Island.

1. The hypothesis that the saltwater-freshwater transition zone has not moved appreciably from its predevelopment position is supported.
2. Previous workers were correct in concluding that lateral rather than vertical migration of saltwater into the upper permeable zone poses the greatest threat to the freshwater supply.
3. A ground-water divide may have existed in the recent past in the upper permeable zone at the north shore of Hilton Head Island. This divide would have hindered lateral saltwater intrusion into the upper permeable zone beneath the island from Port Royal Sound.
4. Recharge from the surficial aquifer into the upper permeable zone beneath the island results in a downward component of flow that has prevented upward intrusion of water having higher chloride concentrations into the upper permeable zone.
5. If heads on Hilton Head Island remain at current levels for the next 45 to 50 years, there will be no significant threat of saltwater intrusion into the upper permeable zone. However, if head decline continues at the historical rate, any flow that presently occurs from the north end of the island toward Port Royal Sound will cease, allowing lateral intrusion to proceed. Even under these conditions, however, chloride concentrations in the upper permeable zone beneath the island should remain below 250 mg/L for the next 45 to 50 years.
6. The precision of digital saltwater modeling in the Hilton Head Island area could be improved the most by better definition of lateral and vertical permeabilities in the Upper Floridan aquifer, particularly in the upper permeable zone, and by better definition of the current distribution of dissolved-solids concentrations in the ground water.

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