HYDROGEOLOGY AND SALTWATER CONTAMINATION OF THE FLORIDAN AQUIFER IN BEAUFORT AND JASPER COUNTIES SOUTH CAROLINA

STATE OF SOUTH CAROLINA

WATER RESOURCES COMMISSION
REPORT NUMBER 158
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Hydrogeology and Saltwater Contamination of the Floridan Aquifer in Beaufort and Jasper Counties, South Carolina

Hughes, Crouch, and Park 1989

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by

W. Brian Hughes, Michael S. Crouch, and A. Drennan Park

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By W. Brian Hughes, Michael S. Crouch, and A. Drennan Park

ABSTRACT

The upper unit of the Floridan aquifer is the primary source of ground water supplies in the Beaufort-Jasper Counties area, S.C., because of its good water quality and high productivity. Ground water can also be obtained from formations of Late Cretaceous through Holocene age in the area.

Prior to 1880, the potentiometric surface of the Floridan aquifer was unaffected by pumping. Water levels were above or just below land surface and ground water flowed in an easterly direction, discharging in Port Royal Sound and the Atlantic Ocean. Owing to heavy pumping at Savannah, Ga., water levels are now below sea level as far north as Port Royal Sound and are 150 feet below sea level in the center of the cone of depression. These changes in water level have reversed the direction of ground water flow in the area between Port Royal Sound and Savannah.

Saltwater contamination occurs in many areas in the Floridan aquifer beneath eastern Beaufort and Jasper Counties, and present ground-water conditions could result in contamination on a regional scale.

Saltwater contamination of the aquifer can occur where brackish water

1. enters through a poorly confining bed or where the confining bed is thin or absent.
2. upcones from the lower part of an aquifer as a result of pumping,
3. enters through improperly constructed wells, or
4. moves laterally through an aquifer in response to a reduction in freshwater head.

All of these mechanisms occur in the study area, but lateral movement is the dominant regional mechanism.

Saltwater is present in the aquifer beneath Port Royal Sound between Hilton Head Island and Parris Island. The saltwater is moving with the regional flow toward Hilton Head Island and the Savannah pumping center. Interstate cooperation in ground-water management could prevent the contamination of the Floridan aquifer beneath Hilton Head Island.

INTRODUCTION

Ground-water withdrawals from the Floridan aquifer near Savannah, Ga., and Hilton Head Island, S.C., have caused a regional decline in the potentiometric surface and, in places, a reversal of the original hydraulic gradient. The decline has induced vertical recharge to the aquifer, and the reversal of the hydraulic gradient has caused brackish water to move southward toward wells on Hilton Head Island. Saltwater contamination of the aquifer in Beaufort County, S.C., has caused local ground-water quality problems, and present ground-water conditions are resulting in contamination on a regional scale. The regional effect of Savannah's pumping has necessitated regulation of ground-water use in the study area in order to slow the intrusion of the saltwater.

Ground-water management requires intensive knowledge of the geologic, hydrologic, and geochemical characteristics of the aquifer system. Therefore, the South Carolina Water Resources Commission (SCWRC), in cooperation with the U. S. Geological Survey (USGS), has undertaken a 4½-year study of the ground water conditions in the area, to assess the extent and nature of saltwater contamination in the Floridan. The study was designed to provide information concerning the aquifer properties, geochemical conditions, and geologic framework of the area. This information is the basis for several reports published by the SCWRC and USGS. The major objectives of the cooperative study are to:

1. Determine how much water can be safely withdrawn from the Floridan aquifer in the Hilton Head Island area.
2. Determine if and when saltwater encroachment will adversely affect the quality of the water supply.
3. Evaluate possible remedial measures that would prolong the use of the Floridan aquifer for water supply.

The specific objectives of this report are as follows:

1. Refine the hydrogeologic framework of the study area.
2. Obtain quantitative data on the hydraulic properties of the Floridan aquifer.
3. Examine the historical changes in water levels and their impacts.
4. Identify the mechanisms of saltwater contamination in the study area.
5. Identify areas of present and potential future saltwater contamination.
6. Examine human activities that may have contributed to saltwater contamination.
7. Present a conceptual model of regional saltwater encroachment.

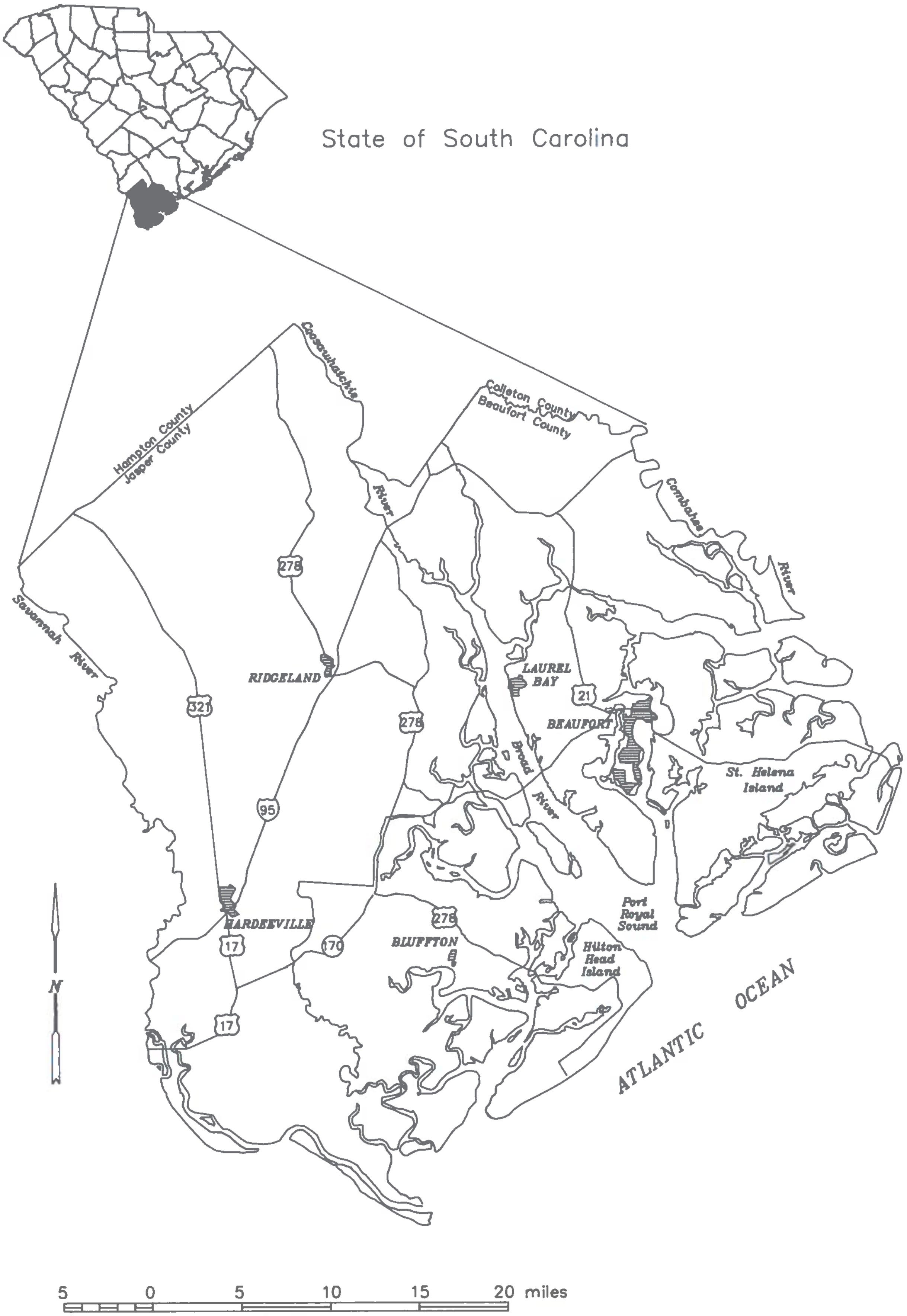

Figure 1. Location and features of Beaufort and Jasper Counties.

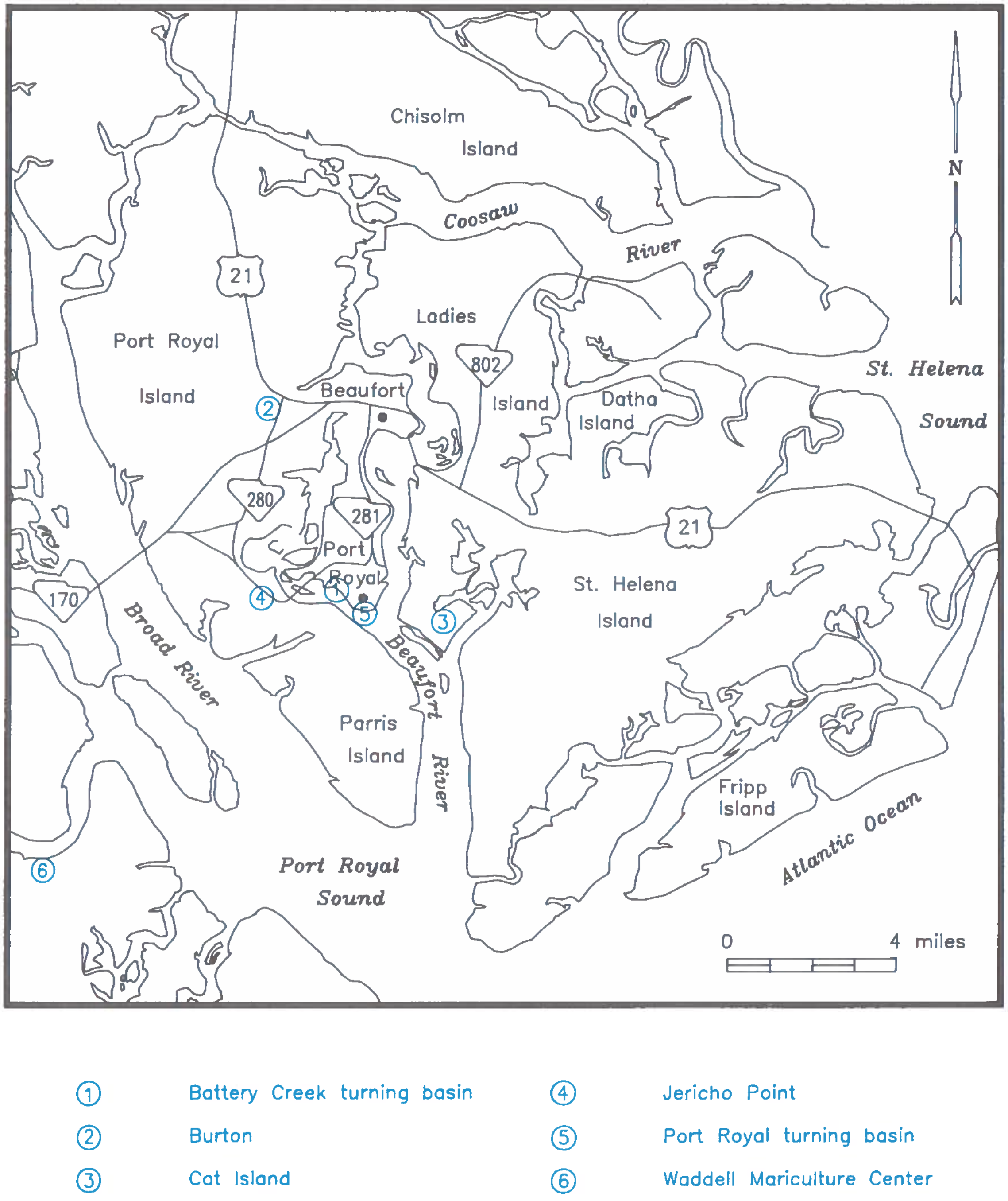

Figure 2. Features in the vicinity of Beaufort, S.C.

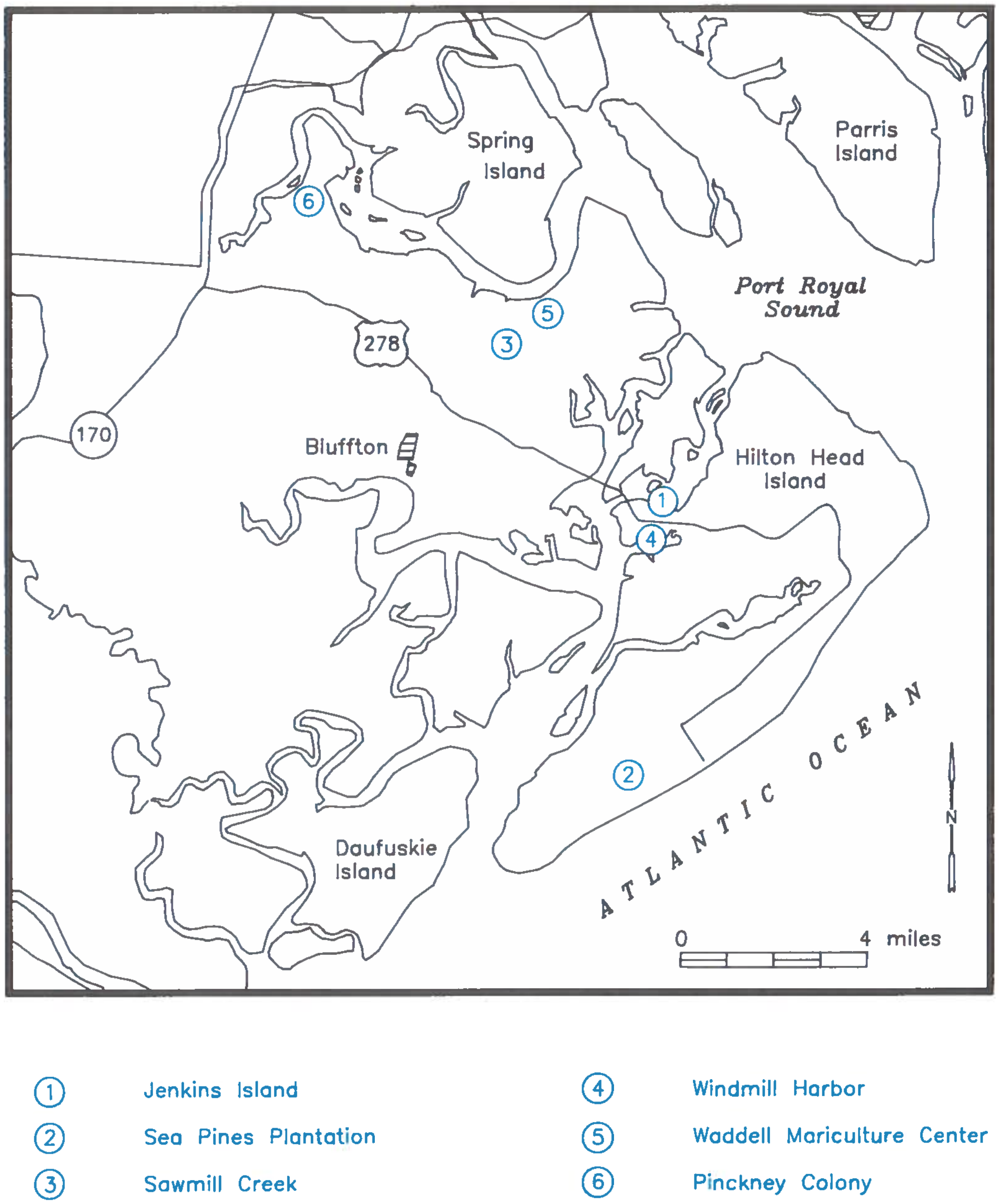

Figure 3. Features in the vicinity of Hilton Head Island, S.C.

LOCATION OF STUDY AREA

The study area is located in the southernmost part of South Carolina in an area known as the Low Country (Figs. 1-3). It comprises Beaufort and Jasper Counties, an area of 1,244 square miles. It is bounded on the north and northeast by Hampton and Colleton Counties, on the east by the Atlantic Ocean and St. Helena Sound, and on the west and south by the Savannah River. The city of Savannah, Ga., is near the mouth of the Savannah River and is across the river from the study area.

CLIMATE

The prevailing climate of the area is temperate to subtropical, marked by hot, humid summers and mild springs, winters, and falls. Average annual temperature is 65 degrees Fahrenheit.

Average annual rainfall is 50 inches, with summer months receiving 20 inches and the remainder equally distributed in the other seasons.

These conditions contribute to a long growing season, averaging 255 days a year. The first freeze normally occurs in late November and the last in early May.

Spring is the season of rapidly changing weather, from windy and cold in March to hot and humid in June. This is also the period when tornado and severe local storm warnings and alerts are most frequently issued.

An increase in hurricane activity is common during late summer, and hurricanes are most frequent in September. Nearby tropical storms yield heavy rains and winds of gale to hurricane force. (South Carolina State Climatological Data).

PHYSIOGRAPHY

The study area is located in the lower Coastal Plain of South Carolina. This area has generally flat-lying topography, with elevations 50 to 100 ft above sea level in most of Jasper County and less than 25 ft in most of Beaufort County. The greatest relief is found in the northern part of the study area where modern streams have cut channels into Pleistocene marine terraces. The southern part of the study area is dominated by low-lying islands, marshes, and beaches.

Numerous streams flow through the area (Fig. 1). The Combahee River forms the northeastern boundary of the study area and the Savannah River forms the western and southwestern boundaries. Between these two are the Coosaw, Beaufort, Broad, Colleton, May, and New Rivers. The Coosaw and Broad Rivers widen at their mouths to form St. Helena Sound and Port Royal Sound, respectively. Many of the rivers are tidally influenced throughout their entire length in the study area. Most of Beaufort County and portions of Jasper County are divided by saltwater marshes and tidal streams into a few large islands and numerous smaller ones. In upland areas of Jasper County, poor drainage results in the formation of large freshwater swamps. The coastline is fringed by barrier islands.

WELL-NUMBERING SYSTEM

The South Carolina Water Resources Commission well numbers are based on a latitude-longitude grid system (Fig. 4). The larger grid encompasses 5 minutes of latitude and 5 minutes of longitude. Each 5-minute grid is further divided into twenty-five 1-minute latitude-longitude grids that are designated by the lower-case letters, "a" through "y." As wells are inventoried, they are assigned a four-part well number that consists of a number, an upper-case letter(s), a lower-case letter, and a number. The first number and the upper-case letter(s) indicate the coordinates of the 5-minute grid; the lower-case letter refers to the 1-minute grid; and the last number(s) refers to a well within the 1-minute grid.

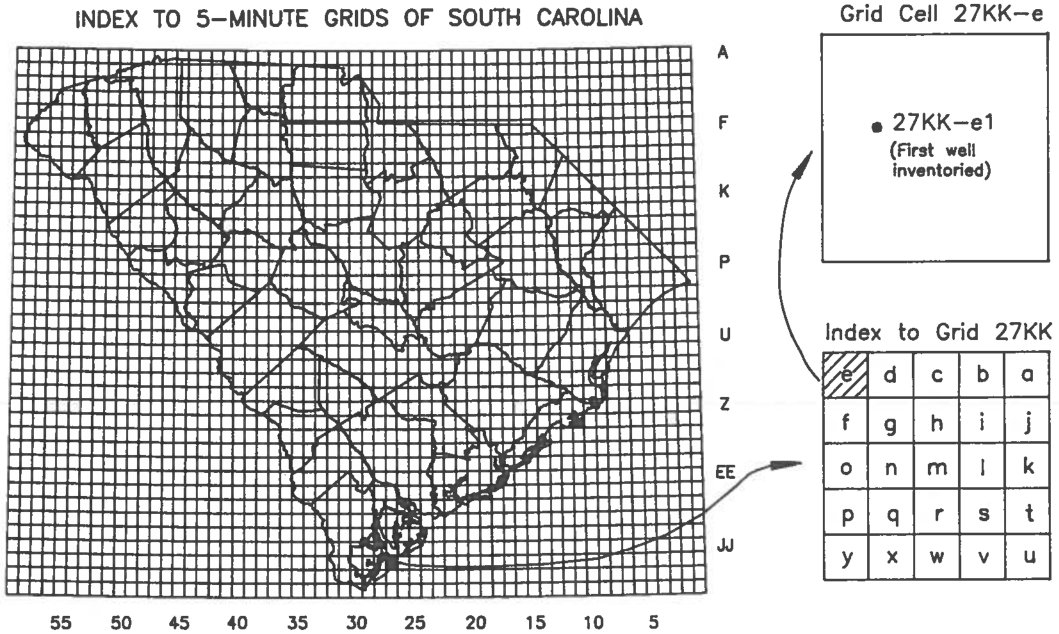

Figure 4. South Carolina Water Resources Commission well-numbering system.

DATA COLLECTION

Data for this report were obtained from previous publications, existing files, and field work conducted between July 1984 and March 1985. The SCWRC maintains records on more than 2,000 wells in Beaufort and Jasper Counties. These records contain geologic, hydrologic, and water quality information of varying usefulness. Approximately 450 of these records contain drillers logs, lithologic logs, and/or geophysical logs that were helpful in delineating hydrogeologic boundaries.

Water levels were obtained for 240 wells that are finished in the upper unit of the Floridan aquifer. The water levels are measured twice yearly, in March when pumping is at a minimum and in late June when it is at a maximum. The elevations of many of the water-level monitoring wells have been determined by survey to provide accuracy of the water level determinations. Another useful source of information was the regular monitoring by SWCRC of chloride concentrations in water from 142 wells in Beaufort County.

Useful data for the project result from the regulations of the Low Country Capacity Use Program. These regulations require all ground water users who withdraw more than 100,000 gallons on any day to obtain ground-water use permits and report monthly usage. Permitted users are also required to provide the SCWRC with well-construction and test data. Since July 1984, in accordance with these regulations, 12 aquifer tests were directed and 20 tests reviewed by SCWRC personnel.

OFFSHORE TEST DRILLING

Nine offshore test wells were drilled into the upper Floridan aquifer beneath Port Royal Sound and the Atlantic Ocean during 1984. The drilling was conducted between July 16 and October 5 from the U. S. Army Corps of Engineers "Sea Horse," a self-propelled drilling ship capable of working in water as deep as 50 ft (feet) while supporting the drilling platform on its three legs.

In order to ensure that saltwater contamination did not occur as a result of the drilling, special consideration was given to well construction. At the beginning of the drilling, 8-inch diameter steel casing was lowered to the sea bed and then washed and driven into the soft sediment until a firm clay or silt layer was encountered. Then the sediments overlying the Floridan aquifer were drilled or cored, using the mud-rotary method. When the top of the aquifer was encountered, the drill stem was removed and 6-inch diameter steel casing was lowered into the well to the top of the aquifer. This casing was then grouted in place by filling the casing with cement, inserting a rubber plug, and then pumping water into the casing to force the cement around the outside of the 6-inch casing. A good seal was confirmed when grout was observed returning between the 6-inch and 8-inch casing. The rubber plug held the grout in place and prevented any mixing of the grout and the water inside the 6-inch casing. The 8-inch casing was removed after placing the grout.

After the grout was allowed to harden overnight, drilling was resumed, this time using the air-rotary method. Water samples were collected at 10-ft intervals during this part of the drilling. The drilling was terminated when the base of the upper permeable section of the Floridan aquifer was reached or when equipment or time would not allow any greater depth of penetration.

The three types of geologic samples collected during the offshore drilling included core samples, split-spoon samples, and drill cuttings. A total of 420 ft of core samples were collected. Falling-head permeability tests, sieve analyses, and gravimetric porosity determinations were conducted on 23 core samples. Borehole geophysical surveys included gamma-ray, resistance, spontaneous-potential, fluid-resistivity, caliper, and temperature logs.

Water level measurements usually began within 12 hours of completion of the wells. An automatic water-level recorder was installed on each well head and on a tide-gaging station attached to the side of the Sea Horse. The record of the tide level and the corresponding water level in the well permitted calculation of the effect of tides on aquifer water levels. Elevations of the water-level measuring points (usually the well head) were surveyed to within ±0.1 ft of accuracy.

Water samples were collected for organic, inorganic, and isotopic analyses. The wells were pumped for several hours until pH, temperature, dissolved oxygen, and conductivity were stabilized. Filtered and unfiltered samples, acid-treated and untreated samples, and samples preserved with sodium hydroxide (for sulfide determination) were collected. Samples as large as 50 gallons were collected for later precipitation of organic carbon.

After the completion of all tests, the wells were filled with sand to about 10 ft below the top of the aquifer. Approximately 40 ft of cement grout was pumped to the top of the sand, and then the casing was cut off below the sea floor. Much of the information obtained during the drilling project was presented in a report by Burt and others (1987).

PREVIOUS INVESTIGATIONS

Few reports have been written solely on the geology of the Beaufort-Jasper Counties area. An early report by Cooke (1936) described the geology and briefly discussed ground-water conditions of the Coastal Plain of South Carolina. Cooke's report included water levels and chemical analyses from nine wells in Beaufort County. Cooke and MacNeil (1952) later reported on the Tertiary stratigraphy of South Carolina. These authors refined correlations between updip continental and downdip marine sediments and established, with minor differences, the Tertiary time stratigraphy presently used. A paleontologic analysis of samples from two deep wells on Parris Island was conducted by McLean (1960). The phosphate deposits of the Hawthorn Formation in northern Jasper County were examined by Johnson and Geyer (1965). Heron and Johnson (1966) studied the clay mineralogy, stratigraphy and structural setting of the Hawthorn Formation. Regional geologic reports by Maher (1971), Gohn and others (1978, 1980), and Colquhoun and others (1983) have incorporated data from deep wells in Beaufort County.

Many reports have been written about ground water conditions in the Beaufort area. Warren (1944) examined artesian conditions in southeastern Georgia and adjacent parts of South Carolina and included much information on ground-water levels and pumpage in the Savannah area. Mundorff (1944) described the history of ground-water use and presented a potentiometric map of the Ocala Formation in the Beaufort area. Siple (1946, 1956) laid the first geologic and hydrologic framework in Beaufort and Jasper Counties. McCollum and Counts (1964) delineated several distinct water-bearing zones in the aquifer beneath Savannah, and traced these zones to the north end of Hilton Head Island. With a series of atlases, Miller (1982a,b,c,d) described the geologic and hydrologic characteristics and extent of the Floridan aquifer in South Carolina, Georgia, Florida, and Alabama and presented structure contour maps and isopachous maps of the Floridan aquifer and the upper Floridan aquifer. Nuzman (1972) studied the ground water supply potential in the Hilton Head area. He conducted two aquifer tests on Hilton Head Island and concluded that the Floridan aquifer was already overstressed and should not be further developed. Hayes (1979) presented a general overview of the water resources in Beaufort, Jasper, Colleton, and Hampton Counties. Hassen (1985) examined the ground water conditions on Ladies and St. Helena Islands in Beaufort County. He identified two recharge zones, one on Ladies Island and the other on St. Helena Island, and included an abundance of water quality information in his report.

The investigations concerned primarily with saltwater contamination are few. Counts and Donsky (1963) presented a general overview of the geology and potential for saltwater encroachment in Savannah. They concluded that lateral migration of saltwater is the most serious threat to the aquifer. Back and others (1970) made Carbon-14 analyses of water samples from Beaufort County. They concluded that saline water in deeper formations is older than water in the upper permeable zone.

Hayes' (1979) study of the water resources of the Low Country was initiated because of saltwater contamination in Beaufort and Colleton Counties. He concluded that heavy pumping on Hilton Head Island and at Savannah induced sea water to enter the aquifer through breaks in the confining bed beneath Port Royal Sound and Battery Creek, causing saltwater encroachment at Hilton Head Island.

GEOLOGIC UNITS

The Coastal Plain of South Carolina is underlain by a sequence of terrestrial, marginal marine, and marine sedimentary rocks (Table 1). This wedge of sediments is thickest in southern Jasper County, where it is approximately 4,000 feet thick, and thins inland. Dominantly clastic sediments of Upper Cretaceous age overlie the igneous and metamorphic basement rocks, which are believed to be an extension of the Piedmont Province. Carbonates make up the majority of the Tertiary sediments, except for the top and bottom of the sequence, which are clastic. All of the post-Tertiary sediments are clastic.

PRE-CRETACEOUS ROCKS

The deepest wells in the study area penetrated upper Cretaceous sandstone at a depth of approximately -3,500 ft msl (mean sea level). North of the study area, near Charleston, a deep corehole encountered an 840-ft thick basalt flow of early Jurassic age (Gohn and others, 1983). The basalt is underlain by at least 397 ft of late Triassic or early Jurassic red beds composed of mudstone, siltstone, argillaceous sandstone, and conglomeratic sandstone. These sediments were deposited in an alluvial fan or fluvial environment within a closed rift basin (Gohn and others, 1983). To the south of the study area, in Liberty County, Ga., one well encountered rhyolite at -4,300 ft msl (Gohn and others, 1980).

Using linear magnetic anomalies as a guide, Daniels and others (1983) located five lower Mesozoic diabase dikes beneath Port Royal Sound and Port Royal Island. Gravity and magnetic anomalies were used to identify a possible gabbroic pluton that cross-cuts sediments in the St. Helena Sound area (Daniels and others, 1983).

The quality and quantity of water in the pre-Cretaceous rocks is unknown; however, water in the overlying Cretaceous formation is known to have a high temperature and a high mineral content. Because temperature and mineral content of ground water tend to increase with depth, it is likely that the pre-Cretaceous rocks contain highly mineralized and high-temperature water.

CRETACEOUS SYSTEM

Upper Cretaceous Series

Four geologic units, all Upper Cretaceous in age, make up the Cretaceous section. Three of the formations, the Middendorf, the Black Creek, and the Peedee crop out towards the Fall Line (Cooke, 1936). The oldest Upper Cretaceous unit, the Cape Fear Formation, does not crop out in South Carolina.

The Upper Cretaceous encompasses mostly continental and marginal marine sediments deposited during a large-scale marine transgression. Smaller scale transgression-regression cycles representing minor environmental shifts are superimposed on the large-scale transgression (Gohn and others, 1977).

In the study area only four wells penetrate to the Cretaceous formations. Because of a relative lack of deep-well information in this area, the geology of these wells has been studied intensively. The micropaleontology of samples from the Fripp Island well (24JJ-c2) were examined by Texaco (SCWRC file data), McNeely. and Vanstrum (1976), Gohn and others (1978), Valentine (1982), and Boylan (1982) and the palynology by Tesch (1975). There is little agreement as to the boundaries of the

Table 1. Summary of hydrogeologic units

Age	Formation		Lithology	Aquifer Character
Pliocene-Holocene	Pamlico and Waccamaw	Shallow aquifer	Sand and clay, much lateral and horizontal variation	Unconfined; subject to localized contamination
Miocene	Hawthorn and Duplin		Sandy clay and clayey sand; some sandy limestone	Usually a confining layer; supplies some small users
Late Eocene	Ocala Limestone	Upper Floridan aquifer	Upper unit - bioclastic limestone	Most productive aquifer in study area
			Lower unit - sandy, clayey limestone	Some permeable zones, mostly low permeability
Middle Eocene	Santee Limestone	Lower Floridan aquifer	Massive, calcarenitic limestone	Very low permeability
Early Eocene and Paleocene	Black Mingo	Tertiary sand aquifer	Sandy, sandy clay, and clay	Possibly yields some freshwater
Late Cretaceous	Peedee	Cretaceous aquifer system	Calcareous sand and mud	Highly mineralized water
	Black Creek		Sand and clay with some limestone	Highly mineralized water
	Middendorf		Sand and clay	Highly mineralized water
	Cape Fear		Sand and clay	Highly mineralized water
Pre-Cretaceous			Igneous rocks and possibly sandstone or conglomerate	Unknown

biostratigraphic units described by these authors. For this report the Cretaceous stratigraphy of Gohn and others (1978) will be used. Their data are most useful because the biostratigraphic units in Beaufort County are correlated with the formational units described in the Clubhouse Crossroads corehole in Dorchester County. The other reports only describe the biostratigraphy.

Cape Fear Formation

The Cape Fear is composed of unconsolidated, interbedded sand and clay. The formation can be divided into an upper and a lower unit. The upper unit is composed of gray to greenish-gray, glauconitic and micaceous, calcareous sandstone and sandy limestone containing minor clay and macrofossils. The lower unit is a noncalcareous sequence of reddish-brown and mottled-blue, green and gray, micaceous silty clay alternating with fine to coarse, feldspathic quartz sand (McLean, 1960). These sediments are mostly continental clastics with some of the fossiliferous sand being marginal marine (Gohn and others, 1977).

Two wells penetrate the Cape Fear Formation in the study area, one on Fripp Island (24JJ-c2) and one on Parris Island (27JJ-c1). The formation was encountered at a depth of -3,050 ft msl at Fripp Island and at -3,150 ft msl at Parris Island. Neither of the wells penetrates the entire thickness of this unit.

Only the Parris Island well (27JJ-c1) is screened in the Cape Fear Formation. Siple (1960) described the water from this unit as having a high temperature (104°-105°F), a high fluoride content [4.5-7.0 mg/L (milligrams per liter)], and a high concentration of dissolved solids (1,200 mg/L).

Middendorf Formation

The Middendorf is composed of sand, clayey silt, and sandy to silty clay. Beds of argillaceous and micaceous, fine to coarse, quartz sand alternate with multicolored, purplish-gray, dark-red, and yellowish-green clay (McLean, 1960). These beds occur in 10- to 20-ft thick sequences. The Middendorf was deposited in a dominantly continental environment, although some of the finer sediments may be marginal marine (Gohn and others, 1977).

Depth to the Middendorf Formation in the study area ranges from -2,600 to -2,700 ft msl. In the two wells that penetrate to the Cape Fear Formation, the thickness of the Middendorf is approximately 500 ft. The dip on the top of the formation, from its outcrop area to Beaufort, is about 30 ft per mile.

Four wells in the study area are open to the Middendorf. Artesian flows of about 75 gpm (gallons per minute) and shut-off pressures that indicate a static water level of + 120 to + 150 ft msl were measured for these wells.

On Fripp Island, well 24JJ-c2 is open to both the Middendorf and the overlying Black Creek Formation. The concentrations of chloride (580 mg/L), fluoride (8.5 mg/L), and dissolved solids (1,700 mg/L) fail to meet the U.S. Public Health Service standards. Water from this well is also high in boron (6.4 mg/L). Well 27II-s2 on Parris Island is also open to the lower Black Creek and Middendorf Formations. Water samples from this well were reported as having a high temperature, high dissolved solids, and high fluoride concentrations. On Hilton Head Island well 27KK-d1 is open only to the Middendorf. Water from this formation exceeded drinking water standards for dissolved solids, chloride, fluoride, and iron. Because of its poor quality, water from the Middendorf Formation is not used except on Fripp Island, where water from the deep well is mixed with better quality water and used for irrigation.

Black Creek Formation

The Black Creek sediments are composed of gray, blue-gray or olive-gray, calcareous and micaceous, silty clay or clay. In some zones the clay contains carbonaceous material and bivalves. Where carbonates are abundant, a calcareous sandstone or silty to sandy limestone is present (McLean, 1960). Siple (1960) described the Black Creek as an upper unit of blue-gray to black shale and marl with some limestone and a lower unit of gray to white, glauconitic, phosphatic, micaceous quartz sand with dark gray to black thinly laminated clay. The Black Creek deposits represent an alternation between marine and marginal marine environments (Gohn and others, 1977).

The top of the Black Creek Formation in the study area is at approximately -2,000 ft msl. The thickness of the formation averages 600 ft and it dips to the southeast. The Fripp Island deep well (24JJ-c2) and one of the Parris Island wells (27II-s2) are screened in both the Black Creek and Middendorf. Water quality for these wells is described above. Well 27JJ-c1 on Parris Island is not open to the Black Creek; however, a water sample taken during drilling had a chloride concentration of 440 mg/L (Siple, 1956). A sample taken in a similar manner at Fripp Island (24JJ-c2) showed 1,100 mg/L chloride (Hayes, 1979).

Peedee Formation

The youngest Cretaceous unit in the study area is the Peedee Formation. This formation consists of interbedded blue-gray calcareous sandy clay, sandy limestone, and calcareous sand. Glauconite and limonite nodules are found throughout the unit (McLean, 1960). This sequence represents an alternation of coarse and fine marine sediments (Gohn and others, 1977).

In the study area, the top of the Peedee is found at -1,500 msl and it averages approximately 500 ft thick. The formation dips to the south-southeast. No wells in the study area use water from the Peedee Formation; however, during the drilling of well 27JJ-c1 on Parris Island, analyses of water samples indicated chloride concentration of 920 mg/L (Siple, 1956).

TERTIARY AND QUATERNARY SYSTEMS

Near the coast of South Carolina the Tertiary System is composed of seven geologic units—the Black Mingo Formation, Santee Limestone, Ocala Limestone, Cooper Formation, Hawthorn Formation, Duplin Marl, and Waccamaw Formation. The types of sediments deposited during the Tertiary period represent a large-scale marine transgression. The bottom of the sequence, Black Mingo, and the top, Hawthorn, Duplin, and Waccamaw, are marine and marginal marine. The central portion, represented by the Santee and Ocala Limestones and the Cooper Formation, formed in an open-shelf marine environment (Gohn and others, 1977).

Paleocene-Eocene Series

Black Mingo Formation

The Black Mingo has been assigned various ages by different authors (Siple, 1960). It has been dated as Paleocene, Lower Eocene, or considered time transgressive and representing both Paleocene and Lower Eocene ages. In this report, since no new data on the Black Mingo are offered, the example of Cooke (1936) will be followed, in that the Black Mingo is considered to encompass all Tertiary sediments older than the Santee Limestone.

The Black Mingo can be divided into upper and lower units (Siple, 1960). The lower unit is composed of gray to black carbonaceous clay and shale. The upper unit is made up of red and brown sandy clay, and white and yellow sand with shell (Siple, 1960). These sediments formed in a marine and marginal marine environment.

The depth to the Black Mingo in three wells in the study area ranges from -840 to -950 ft msl. The thickness of the unit is approximately 500 ft. Siple (1960) indicated that the Black Mingo had no significance as an aquifer, but that clay beds might retard the movement of saltwater into overlying aquifers. Hayes (1979) stated that the formation was unlikely to yield any significant quantities of freshwater in Beaufort County. Two wells in Beaufort County (25GG-p1 and 27GG-t1) appear to tap the upper part of the Black Mingo Formation. Both are flowing wells, and the chloride concentration measured in well 27GG-t1 was 87 mg/L.

Santee Limestone

The Santee Limestone was penetrated by four of the five deep onshore test wells constructed during this study. In three of these wells only the upper 50 to 100 ft was drilled; in the remaining well approximately 400 ft of Santee Limestone was penetrated. This formation is composed of yellowish-gray, glauconitic and fossiliferous calcarenite or calcilutite. The rather sparse biota consist of bivalves, foraminifera, and bryozoa. The depth to the top of the formation ranges from -400 to -600 ft msl in the study area. Limited data indicate that the Santee is 300 to 500 ft thick and dips to the south and southeast.

Cooke (1936) originally assigned a Late Eocene age to the Santee Limestone. Later work by Cooke and MacNeil (1952) and Pooser (1965) established its age as Middle Eocene. Calcareous nanofossils from well 27JJ-q2 on Hilton Head Island were examined by USGS paleontologists to determine the age of the limestone. Samples from the interval between -609 and -804 ft msl suggested an age of either latest Middle Eocene or earliest Late Eocene (Virginia Gonzales, USGS, personal communication). On the basis of lithologic and geophysical data, the top of the Santee in this well was picked at -500 ft msl.

The hydraulic properties of the Santee Limestone vary considerably in South Carolina. In its outcrop area near Orangeburg, Banks (1977) described the Santee as a highly permeable, bryozoan-rich biomicrudite or biosparrudite. In the study area and throughout much of the Low Country, the Santee has a low permeability because of the fine grain size of the calcilutite lithology and the abundance of fine-grained interstitial calcite in the calcarenite lithology.

Ocala Limestone

The Ocala Limestone can be divided into two units. The lower unit is composed of silty, clayey, glauconitic limestone. A clean, extremely permeable, bioclastic limestone composed primarily of friable bryozoan and bivalve fragments makes up the upper unit. The upper 6 inches to 1 ft of Ocala commonly consists of a hard, phosphatic limestone that local drillers call a "cap rock." Because of the lithologic similarity between the Ocala and the Santee in its updip areas, the Ocala has often been identified as the Santee in other Commission reports (Hayes, 1979, Hassen, 1985). If the top of the Eocene limestone in Beaufort County is correlated with the Santee Limestone in Charleston, then approximately 400 ft of uplift would have occurred across St. Helena Sound. This is contraindicated by a lack of a major offset in any of the older sediments across the Sound.

Samples obtained from cores taken during the offshore drilling yielded a Late Eocene (Jackson) age for the upper unit of the Ocala Limestone (Lucy McCartan, USGS, personal communication; Paul Huddleston, Georgia Geologic Survey, personal communication). This information indicates that the Ocala Limestone is time-equivalent to the Parkers Ferry and Harleyville members of the Cooper Formation, which are also Late Eocene in age. The name Ocala Limestone is used in this report for the following reasons:

1. The Upper Eocene limestone is both a lithologic and time equivalent of the Ocala Limestone as described in Georgia.
2. Although the Santee (in its outcrop area) and Ocala are similar lithologically, they are not time equivalent.
3. The Cooper Formation is considered time transgressive, ranging from Oligocene to Late Eocene in age, whereas there are no Oligocene deposits in the study area.
4. The Upper Eocene limestone in the study area is very different lithologically from the "typical" Cooper Formation lithology.

Both units of the Ocala Limestone are of marine origin. The lower unit, containing calcite sand, a small biota, and abundant calcareous mud, was deposited in a lower energy, deeper water environment than the upper unit. The upper unit was deposited in shallow water, where biologic activity was much greater.

The lower unit of the Ocala Limestone is penetrated by few wells in the study area. The top of the unit ranges from -30 to -350 ft msl. The thickness of the lower unit is fairly uniform and is approximately 350 ft. Only one well, located at Bear Creek Golf Course on Hilton Head Island (27KK-g1), is known to produce water from this unit. The water is moderately salty with approximately 600 mg/L chloride, but when mixed with surface water can be used for irrigation.

The upper unit of the Ocala Limestone is the most productive aquifer in Beaufort and Jasper Counties. Nearly all the wells in both counties use this aquifer. The upper unit is found between -20 and -200 ft msl (Fig. 5) and thickens from less than 10 ft in northern Beaufort County to approximately 180 ft near the Savannah River (Fig. 6).

The upper unit contains abundant freshwater in most of Beaufort and Jasper Counties, although brackish water is common in the St. Helena Sound-Beaufort River-Port Royal Sound area. Much information on the water quality of the upper unit of the Ocala Limestone is available. Detailed studies of the water quality in the upper unit include Hayes (1979) and Hassen (1985).

Oligocene Series

North of the study area the Oligocene is represented by the Ashley member of the Cooper Formation (Ward and others, 1979). This unit consists of calcareous, clayey, very fine quartz sand containing abundant glauconite and phosphate. The calcium carbonate content ranges from 60 to 75 percent, quartz sand 5 to 25 percent, clay 10 to 30 percent, and phosphate 1 to 5 percent (Gohn and others, 1977). The calcium carbonate is composed mainly of foraminifera tests. These sediments were deposited in a deep-water marine environment (Gohn and others, 1977).

South of the study area an unnamed Oligocene limy unit composed of sandy marl, calcareous sand, or clean limestone has been recognized (Siple, 1960; Furlow, 1969).

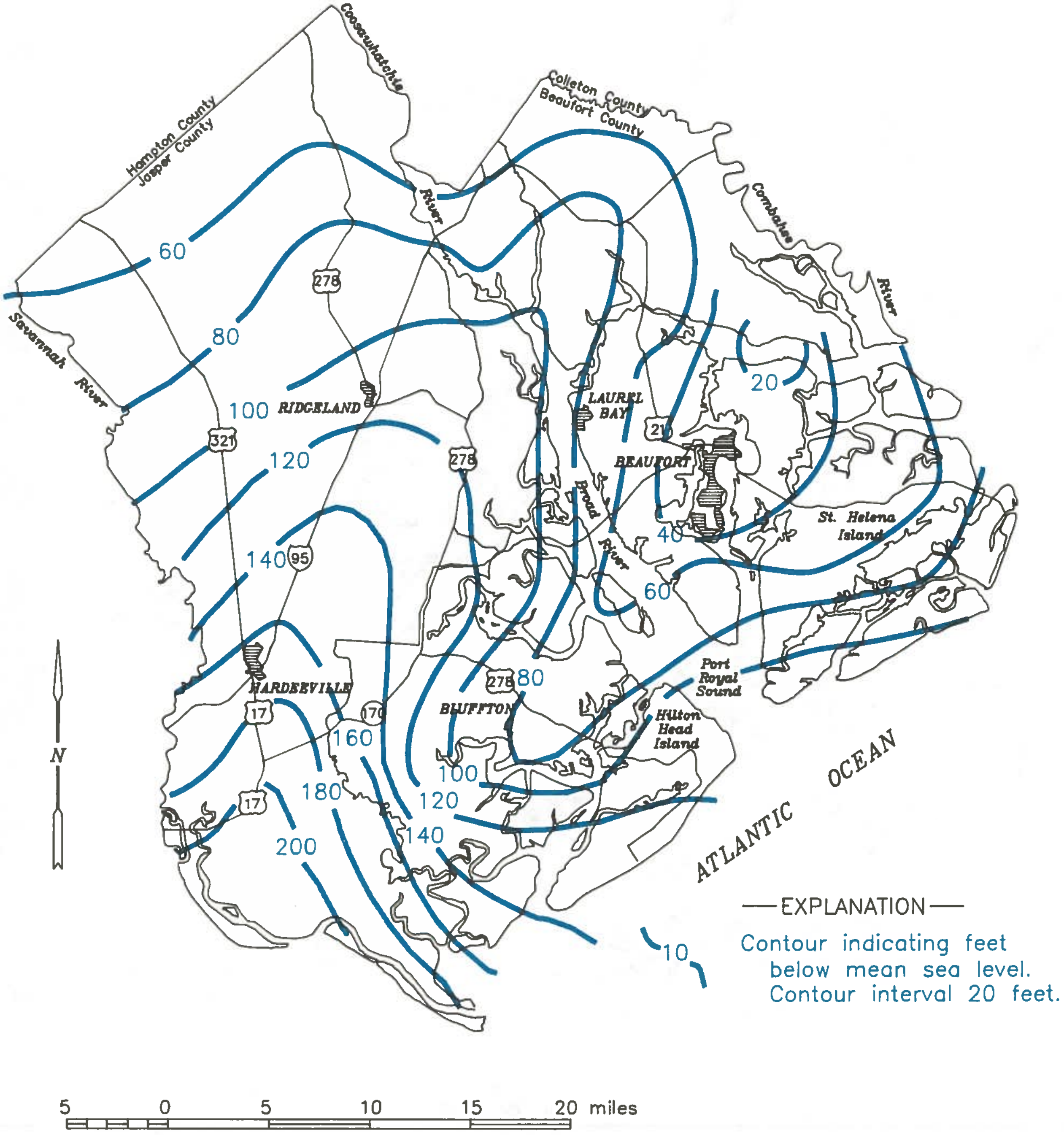

Figure 5. Contours on top of the Ocala Limestone (see also Hayes, 1979, Fig. 10).

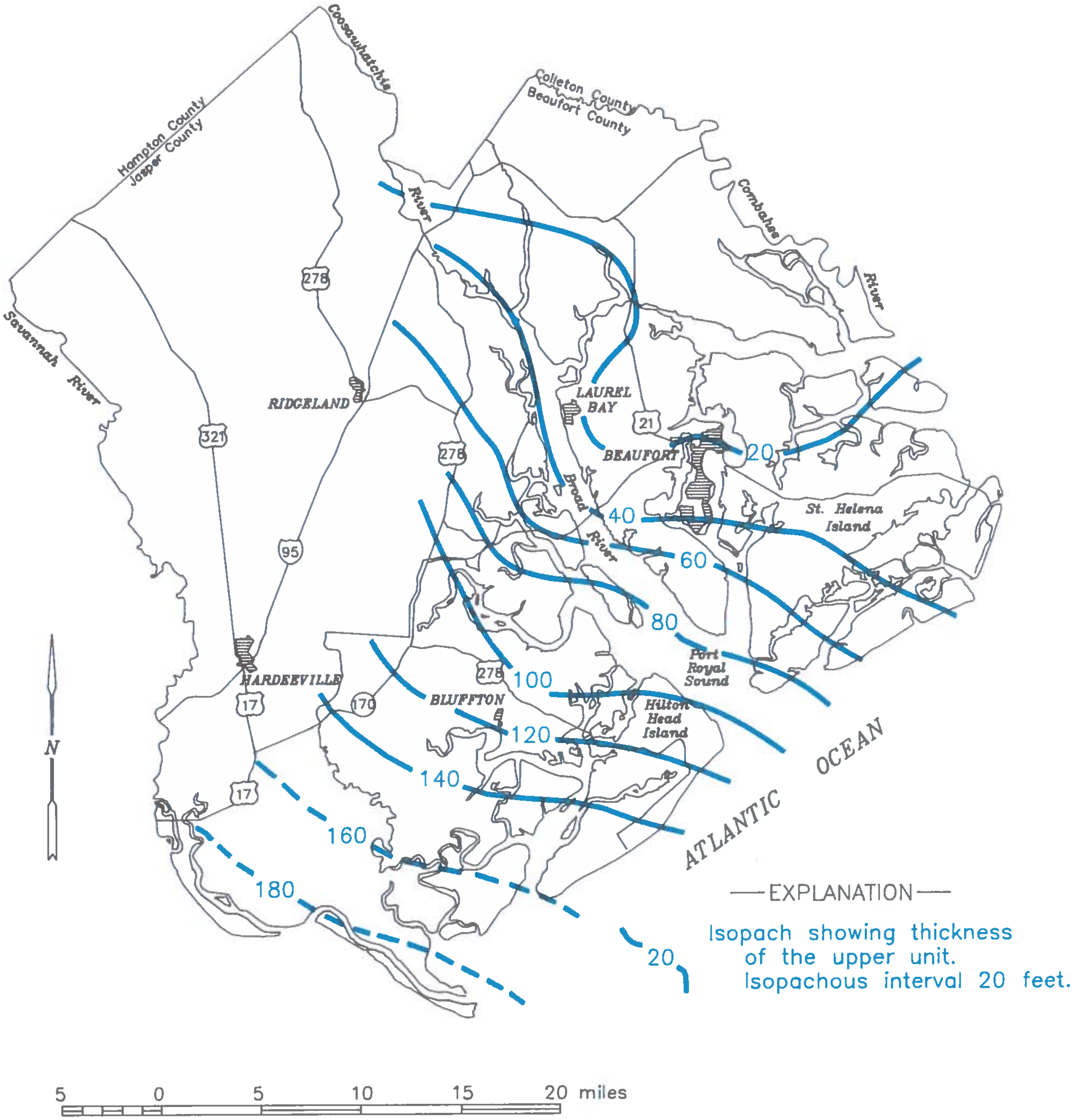

Figure 6. Thickness of the upper unit of the Ocala Limestone.

Neither the Oligocene Cooper Formation nor the unnamed Oligocene unit are known to be present in the study area, but if present they are very thin. The top of the Eocene deposits in the study area is near the surface and dips to greater depths to the north and south, indicating that the Oligocene sediments were either eroded or not deposited.

Miocene Series

Hawthorn Formation

The Hawthorn Formation is represented by an olive gray, phosphatic, clayey sand throughout the study area. Heron and Johnson (1966) divided the Hawthorn into four lithologic units. The lowermost unit is composed, from the bottom up, of phosphatic sand, clayey sand, sandy clay, and phosphatic sand. Observations of the cores from Port Royal Sound and lithologic samples on Hilton Head Island indicate that the lower sand commonly is dolomitic.

Analyses of the cores taken during the offshore drilling (Paul Huddleston, Georgia Geologic Survey, personal communication) indicate that early and middle Miocene faunal assemblages are present. The ostracods and benthic foraminifera indicate a highly restricted, marginal marine environment.

The top of the Hawthorn Formation can be found between -10 ft msl in the northeastern portion of the study area and -130 ft msl in the southwest (Fig. 7). The formation thins to less than 10 ft over the Burton High and thickens to more than 70 ft at the Savannah River (Fig. 8).

The greatest importance of the Hawthorn Formation in the study area is as a confining bed for the underlying limestone aquifer. In some areas, the middle sand unit of the Hawthorn is tapped by wells. About 25 wells in Beaufort County and 15 in Jasper County have been identified as being open to the Hawthorn alone or to both the Hawthorn and Ocala. On Hilton Head Island, several wells produce water from the lower dolomitic sand only. Yields from these wells have been relatively low, between 2 and 20 gpm, but sufficient for their purpose as part of heat-pump systems

There is little information on the quality of water from the Hawthorn. Two wells near Spring Island (29JJ-e1 and 29JJ-e4) and a well on Jenkins Island (28KK-15), adjacent to Hilton Head Island, are open to the Hawthorn Formation. Chlorides in these wells ranged from 3,000 to 12,000 mg/L. In other areas where wells are open to the Hawthorn, the water is fresh.

Duplin Marl

The youngest Miocene formation in the study area is the Duplin Marl. Lithologically this unit is composed of phosphatic, sandy clay. Although the Duplin has a lower phosphate content than the Hawthorn, it is difficult to distinguish between the two formations (Furlow, 1969). The Duplin is recognized in the study area, but no attempt was made to map the unit because of the difficulty of identifying it on geophysical logs. Generally speaking, the Duplin is thin or absent in the St. Helena-Port Royal Island area and thickens to over 50 ft near Savannah. Because its lithology makes this formation an unlikely aquifer, few wells, if any, tap it, and no water quality data are available.

Pliocene - Holocene Series

The Pliocene through Holocene deposits were not differentiated here because of poor drill-sample quality and a lack of characteristic geophysical log signatures. Table 2 lists the units that were assigned to the post-Miocene sediments by Siple (1960).

The primary use of this shallow system is for domestic wells. The water quality of these units probably varies considerably, depending on local conditions; however, no study of the shallow system has been made. Where wells completed in the shallow sediments are located near a saltwater body, saltwater contamination by lateral encroachment can occur (Siple, 1960).

Table 2. Post-Miocene sediments in Beaufort and Jasper Counties (after Siple, 1960)

Age	Formation	Lithology
Holocene	Unnamed	Light-colored fine sand and silt and blue-black marl.
Pleistocene	Talbot	Gray, red, and pink thin-bedded sand and clay; restricted to higher elevations in study area.
	Pamlico	Blue-green to gray plastic clay mixed with shells.
Pliocene	Waccamaw	Blue-gray and yellow sandy marl and green clay.

STRUCTURE

The Atlantic Coast of the southeastern United States is generally considered a passive continental margin with structural elements consisting of gentle upwarpings and depressions. Formations typically dip towards the coast at 1 to 30 ft per mile. Several structural features affect the study area (Fig. 9).

The Cape Fear Arch is a southeastward plunging basement anticline centered near Cape Fear, N.C. Evidence for the uplift can be seen in the Cretaceous and Tertiary outcrop pattern, where Cretaceous rocks are exposed along the crest of the arch and successively younger rocks are exposed to the north and south (Maher, 1971). The age of the uplift was dated as Late Eocene by Cooke (1936) because, he states, "Miocene and younger rocks are undisturbed." Siple (1946) believed that there were two episodes of uplift, one after the deposition of the upper Cretaceous Tuscaloosa (Middendorf) Formation and a second just before Late Eocene time. The primary result of the uplift in the study area was to change the dip direction of the geologic units from southeasterly to more southerly.

The Southeast Georgia embayment is a tectonically passive feature that alters the gentle slope of the basement

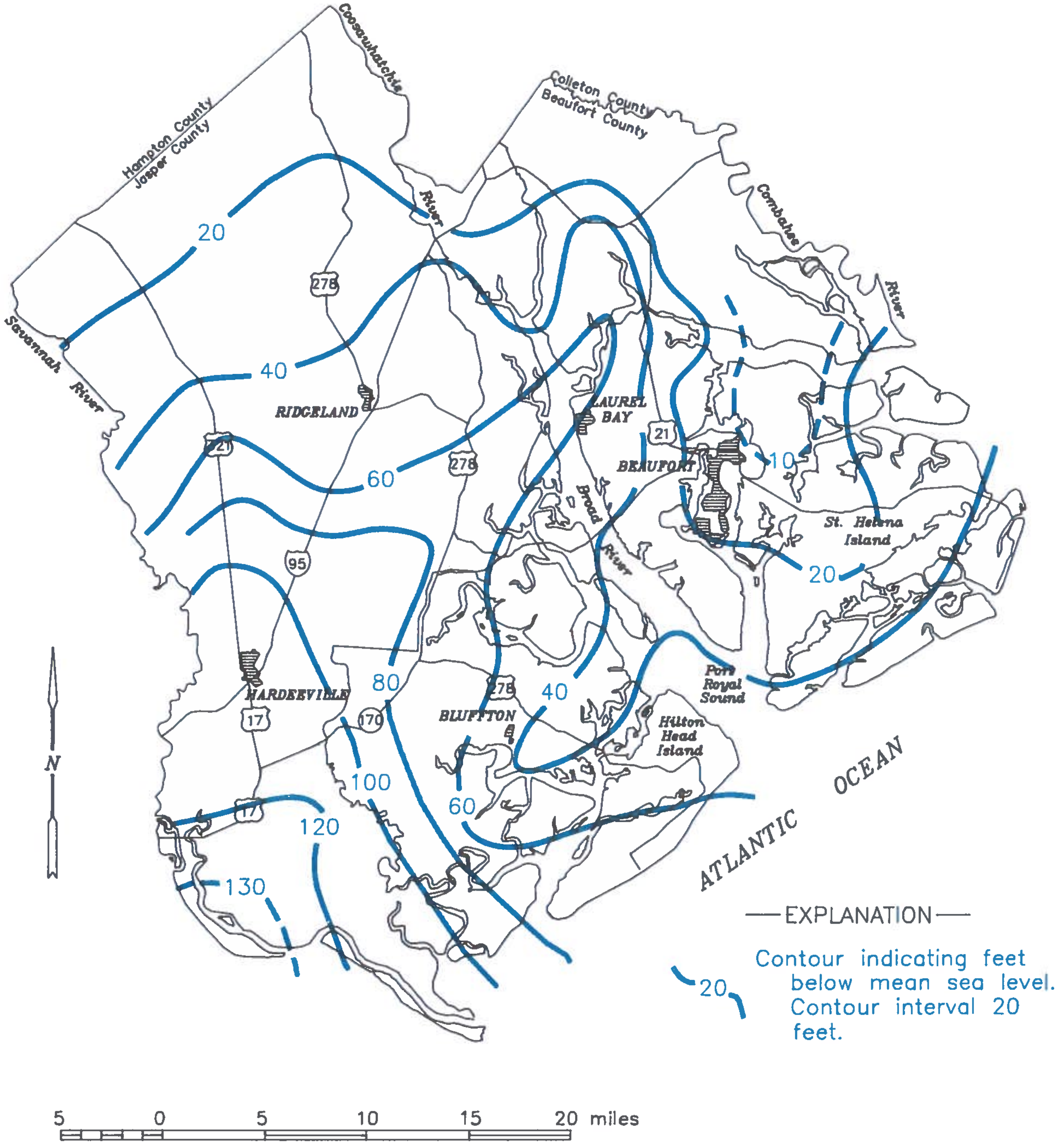

Figure 7. Contours on top of the Hawthorn Formation.

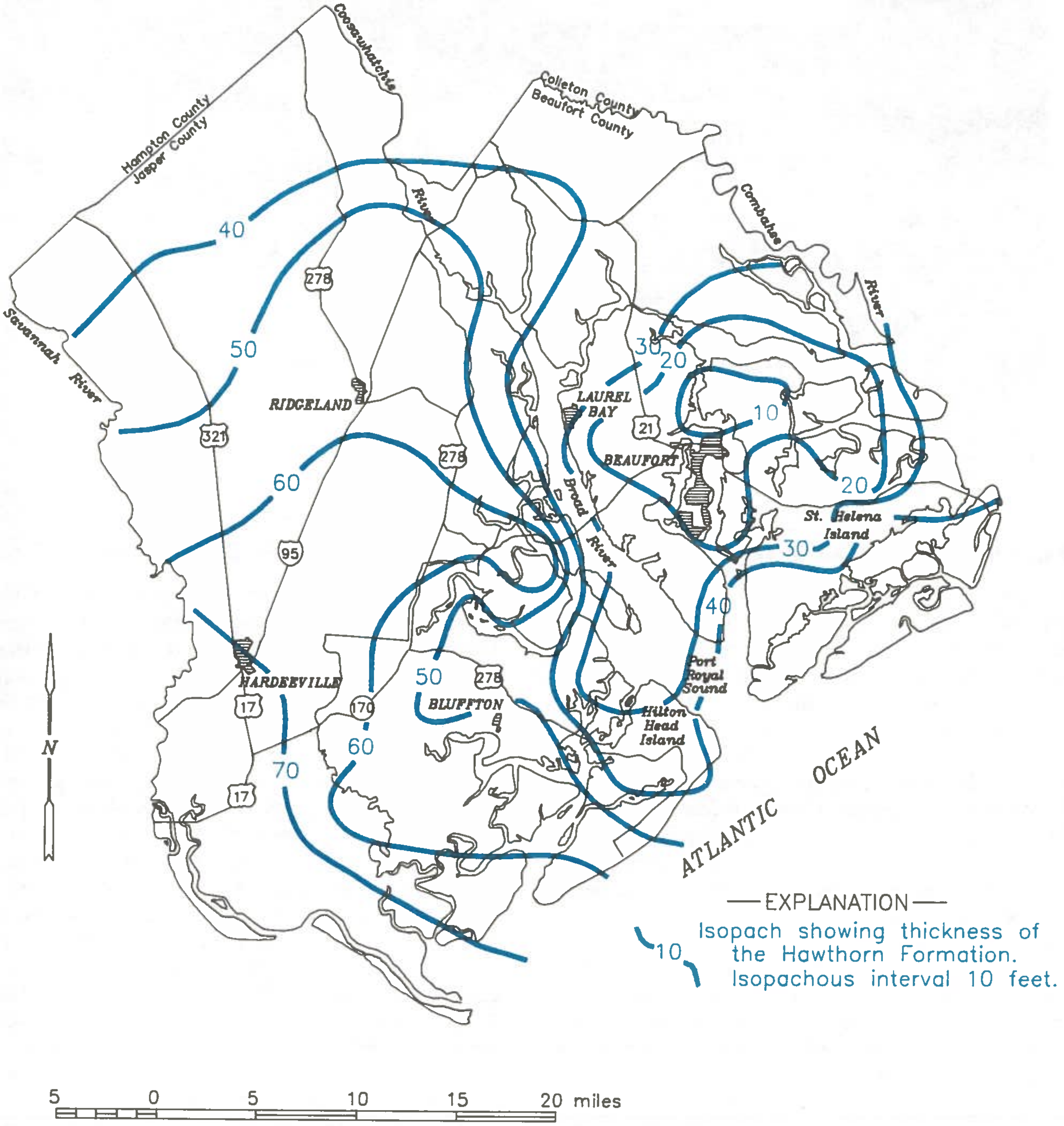

Figure 8. Thickness of the Hawthorn Formation.

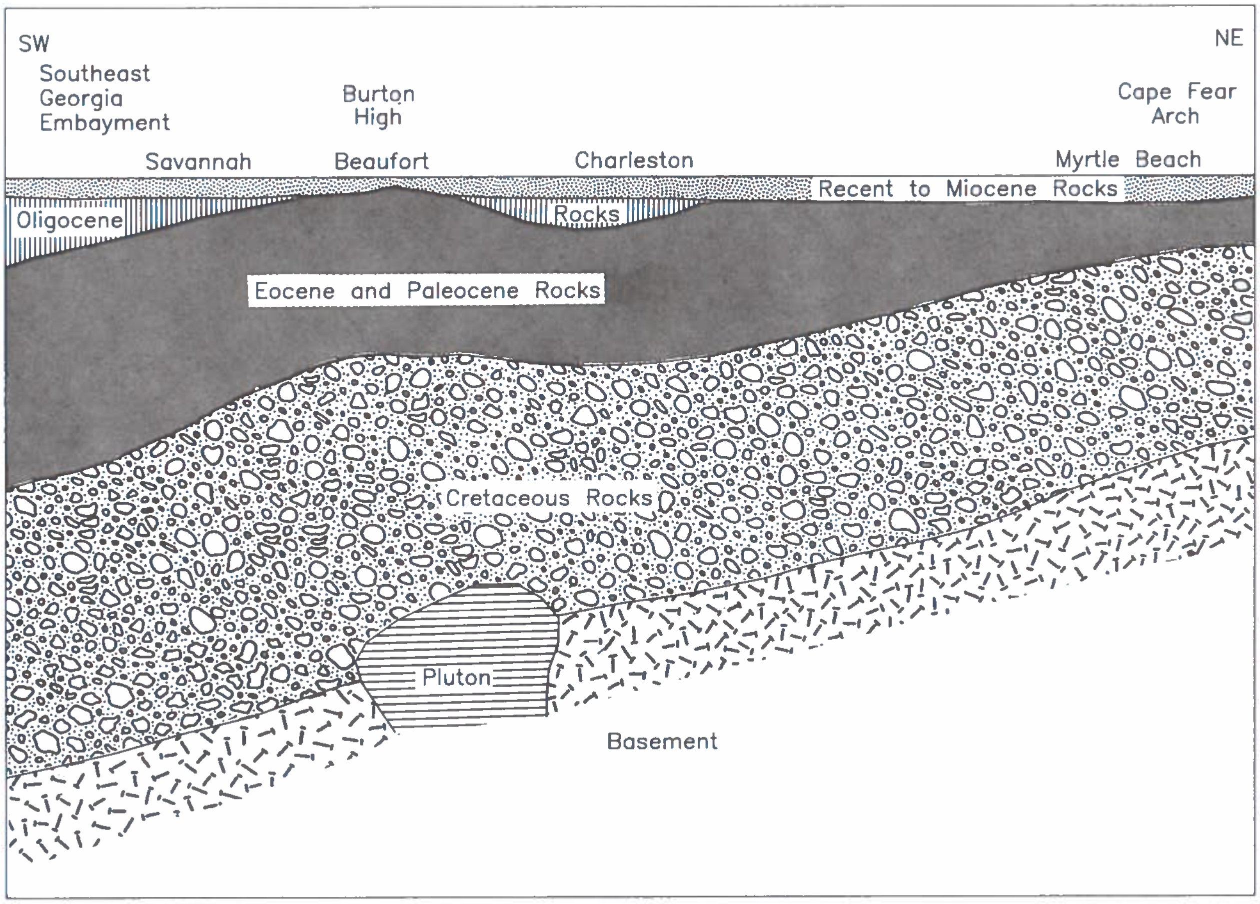

Figure 9. Generalized structural elements along the Atlantic Coast from Savannah, Ga., to Myrtle Beach, S.C.

on the south flank of the Cape Fear Arch to a steeper slope (Maher, 1971). This basement trough is located midway between Jacksonville, Fla., and Savannah, Ga.

The Yamacraw Ridge is a basement ridge that extends into the Southelast Georgia embayment (Maher, 1971). Pooley (1960) described a seismic anomaly between Parris Island, S.C., and Sea Island, Ga., which he believes is a 110-mile long basement ridge (the Yamacraw Ridge) with 1,000 ft of relief. This feature does not affect the overlying sediments (Pooley, 1960). Wells at the south end of the ridge in Georgia do not substantiate its existence. Maher (1971), however, suggested that there may be a basement high in South Carolina.

Siple (1956) was the first to note that the Late Eocene limestone is present within 50 ft of the land surface at Parris Island, indicating a structural high for this area. In a later paper, Siple (1969) designated this structural dome the "Burton High." Siple (1969) described a discrepancy in age between the uppermost limestone at Parris Island, where it is Late Eocene in age, and at Port Royal Island, where it is Middle Eocene in age. He conjectures that this difference in age may be a result of a fault with approximately 400 ft of displacement. It seems unlikely that a fault exists, however, because detailed mapping of the uppermost limestone unit in this report indicates that it is a continuous and lithologically uniform unit throughout the study area. The age discrepancy probably resulted from poor sample quality and subsequent misinterpretation of data.

In the course of this study, structure contour maps of the top of the Ocala Limestone (Fig. 5) and the top of the Hawthorn Formation (Fig. 7) were constructed. Both formations appear to be affected by the uplift that formed the Burton High, indicating that it occurred during or after Miocene time. The Coosawhatchie clay an informally named yellow-green to light-blue montmorillonite that forms the upper part of the Hawthorn Formation in Jasper County (Heron and others, 1965), is observed to overlie successively older units of the Hawthorn Formation (Heron and Johnson, 1966). This overlap indicates that uplift and erosion occurred before the deposition of the Coosawhatchie clay and after the deposition of the Hawthorn, dating the uplift during the Miocene (Heron and Johnson, 1966). A Miocene age for the uplift does not explain the absence of the Oligocene sediments from the Beaufort area. In order to explain this absence, two periods of uplift are necessary. The earlier period of uplift occurred during or after the deposition of the Ocala Limestone and before the deposition of the Hawthorn Formation. During this period, the Oligocene sediments were eroded or not deposited because the land surface at Beaufort was at or above sea level. After the deposition of the Hawthorn, a second period of uplift deformed these younger Miocene sediments (Fig. 7).

It is possible that the uplift in the Beaufort area was caused by an intrusive body beneath St. Helena Sound (Lucy McCartan, USGS, personal communication). Both gravity and magnetic anomalies indicate the presence of

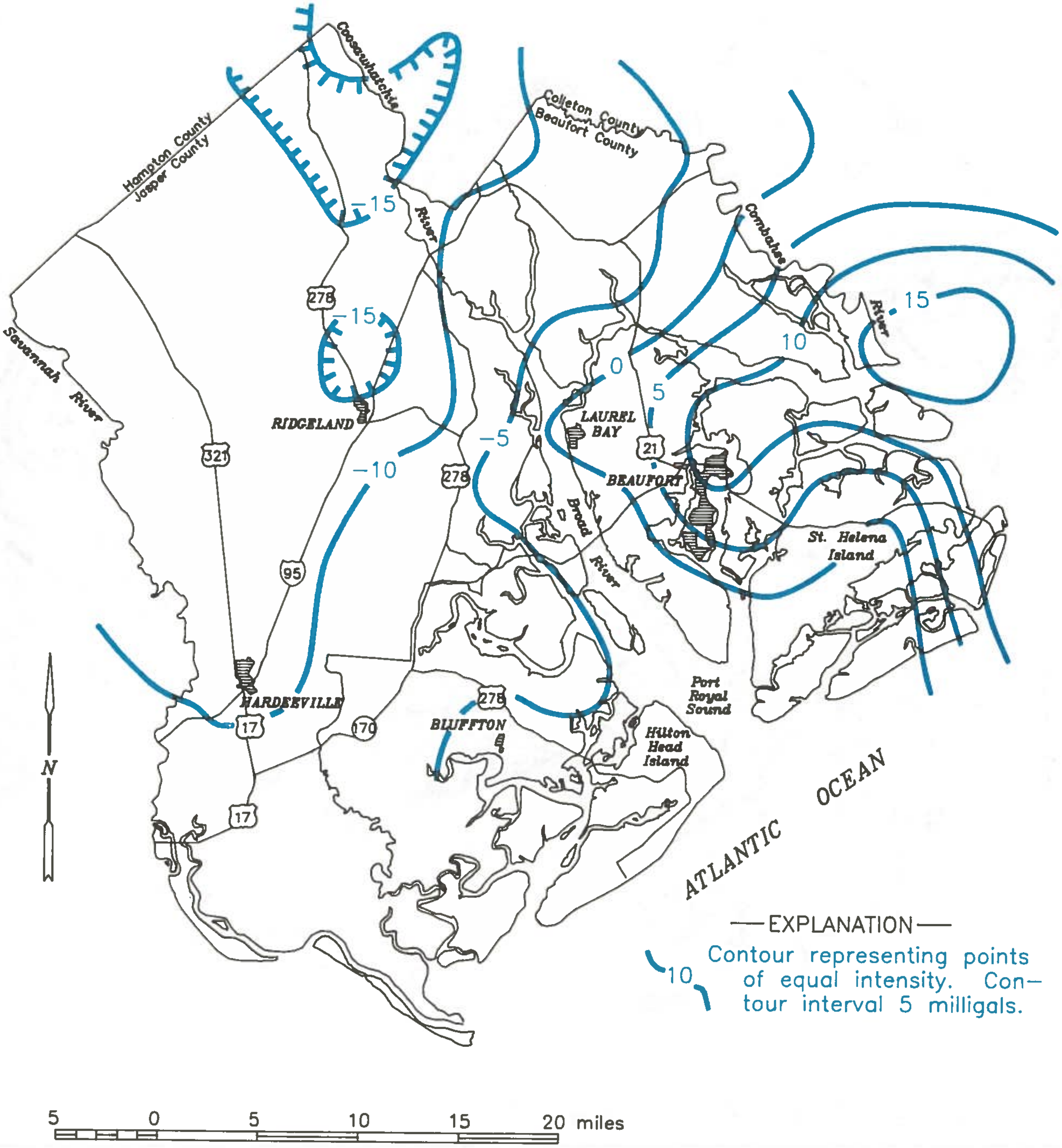

Figure 10. Simple Bouguer gravity anomaly map of study area.

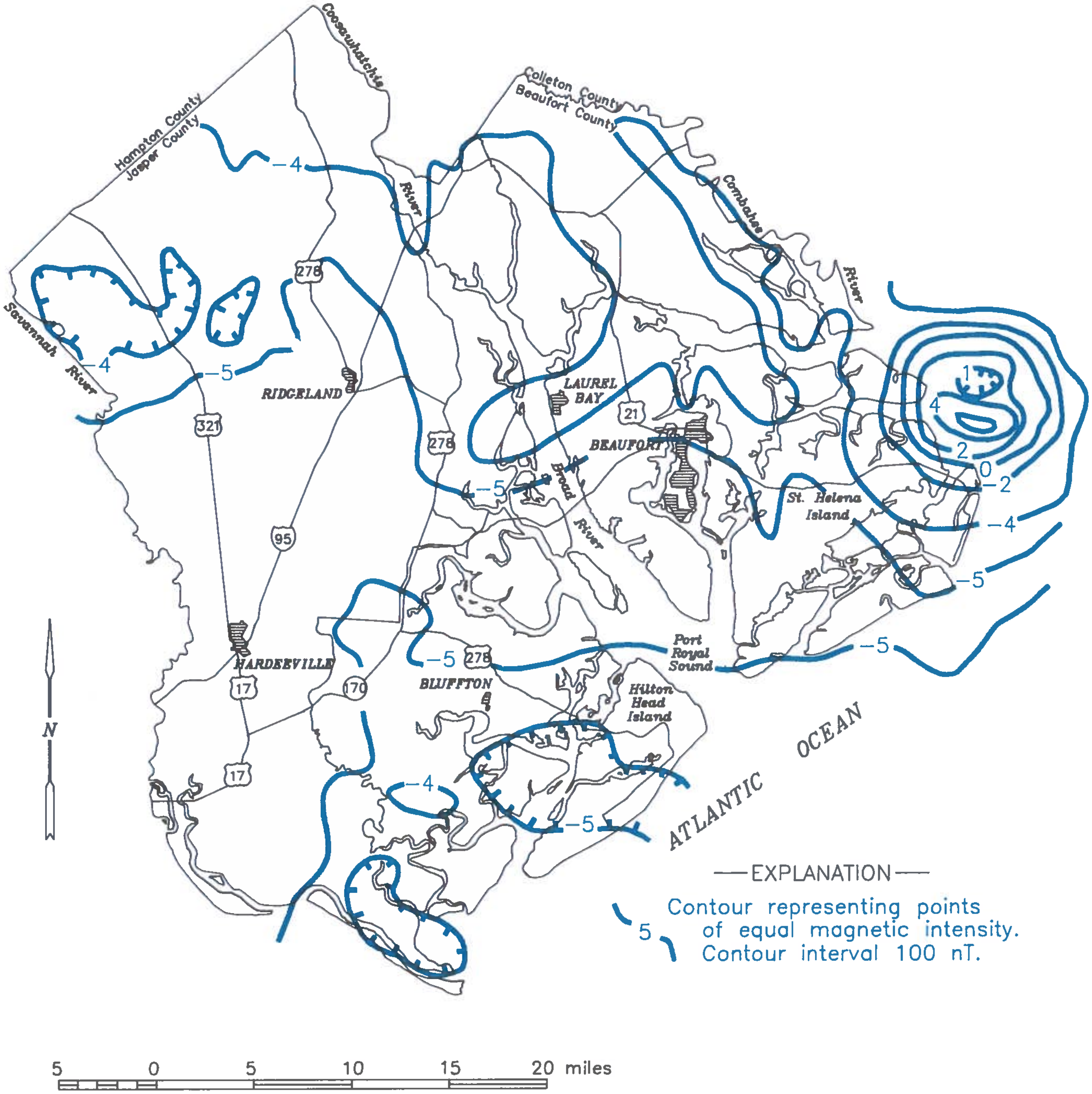

Figure 11. Aeromagnetic contours of the study area.

such a body (Daniels and others, 1983). The Bouguer anomaly map (Fig. 10) shows areas of high and low gravity. A gravity high (closed contours beneath St. Helena Sound) indicates the presence of an intrusive body because the high density and (and consequent greater gravitational attraction) of igneous rocks contrasts sharply with the lower density (and lower gravitational attraction) of the surrounding sedimentary rocks. Other variations in the gravity in the area are caused by changes in bedrock type and possibly by buried bedrock topography. The presence of the intrusive body is illustrated more dramatically on the magnetic map (Fig. 11). The relative abundance of iron-rich minerals in the mafic intrusion produces a strong magnetic field that contrasts with the relatively iron-poor mineral content of the surrounding sedimentary rocks.

The uplift of the Ocala Limestone has affected the hydrology in two ways. In areas where the limestone has been brought into or near contact with saltwater bodies, saltwater intrusion occurs. Where the aquifer is near the land surface and the confining layer is thin or absent, freshwater recharge occurs. The recharge of both freshwater and saltwater are a direct result of the uplift.

A further result of the uplift might be an enhancement of the permeability of the aquifer. The greatest recharge and discharge in a limestone aquifer occurs near the surface in an unconfined area. Over time, upper paths in an aquifer are opened more aggressively because the water near the surface has a shorter residence time and hence is under-saturated in calcium carbonate and contains abundant carbon dioxide. The natural progression is to a higher, shorter flow path. The uplift, bringing the limestone close to the surface, and thinning of the confining bed produced conditions favorable to the development of a highly permeable and transmissive aquifer. This process might account for the relatively high hydraulic conductivities, about 500 ft/day, that occur in the vicinity of the Burton High.

Heron and Johnson (1966) identified an elongate, east-northeast trending basin in central Jasper County, which they called the Ridgeland Basin. According to these authors, the basin is characterized by a greater depth to the Ocala Limestone and a greater thickness of Hawthorn Formation than surrounding areas. Isopachous maps constructed for this study, however, show that the thickness of the Hawthorn Formation does not increase in the basin. The greater thickness of Hawthorn Formation described by Heron and Johnson (1966) is actually an increase in the thickness of the lithologically similar Duplin Marl.

FLORIDAN AQUIFER

The names "principal artesian aquifer" (Counts, 1960; Siple, 1960; Hayes, 1979; and others) and "Tertiary limestone aquifer" (Park, 1979; Spigner and Ransom, 1979; Bush, 1982; Miller, 1982; and others) have been used for the Floridan aquifer in previous reports. South Carolina Water Resources Commission Report 147 (Hassen, 1985) was the first to apply the name "Floridan aquifer" to the Beaufort area. In order to remain consistent with Report 147 and present USGS nomenclature, this report will use the name Floridan aquifer.

The Floridan aquifer is the major coastal-plain aquifer for southern South Carolina, Georgia, Florida, and eastern Alabama (Miller, 1986). The aquifer consists of a more-or-less continuously connected carbonate sequence that ranges in age from Paleocene through early Miocene. In updip areas the aquifer consists of one continuous permeable zone, whereas in downdip areas there are two highly permeable zones separated by a zone of low permeability (Miller, 1986). The upper permeable zone is termed the upper Floridan aquifer and the lower permeable zone is the lower Floridan aquifer.

In the study area, the boundaries of the upper Floridan aquifer coincide with the top and bottom of the Ocala Limestone. This 400- to 500-ft thick carbonate section can be divided into two units. The upper unit corresponds to the highly permeable, bioclastic limestone of the Ocala. This unit is the most productive part of the aquifer. The lower unit is a glauconitic, clayey, fossiliferous limestone with a relatively low permeability. The lower unit is a less desirable source of water because of its lower permeability and generally poorer water quality.

Data on the configuration of the Ocala Limestone were obtained from geophysical logs, drillers logs, and lithologic logs. The natural gamma-ray log is the most useful geophysical log in the study area. On this log, a distinctive deflection occurs at the top of the Hawthorn Formation, resulting from the greater concentration of radioactive minerals in the phosphate zone. Another deflection occurs at the top of the Ocala and corresponds to the phosphate cap rock. The gamma-ray activity is generally at its lowest in the interval corresponding to the upper unit of the Ocala Limestone, and a marked increase in gamma-ray activity occurs at the base of the upper unit where clay becomes abundant. The corresponding sections of an electric log in this area show a high negative spontaneous-potential and high resistance for the upper unit, while the low-permeability section of the lower unit has low resistance and lower negative spontaneous-potential.

Figure 12 shows the location of two sections (A-A′ and B-B′) through Beaufort and Jasper Counties. The sections illustrate the considerable variation in the permeable zones across the study area. In the vicinity of Savannah, five permeable zones are present in the upper Floridan aquifer (Fig. 13). To the northeast, the upper two zones combine to form the upper unit of the Floridan aquifer. Although it is not used by any wells north of Hilton Head Island, the middle of the lower three zones can be traced on geophysical logs to the north side of the Coosaw River. The remaining two zones pinch out south of Hilton Head Island. A deeper permeable zone, possibly in the Black Mingo Formation, is tapped by a well (27GG-t1) on Chisolm Island. This zone can be traced to Parris Island.

A hydrologic section from northern Beaufort County to Fripp Island illustrates the effects of the Burton High (Fig. 14). At the apex of the Burton High, near well 27HH-b3, the limestone is very close to land surface and both the

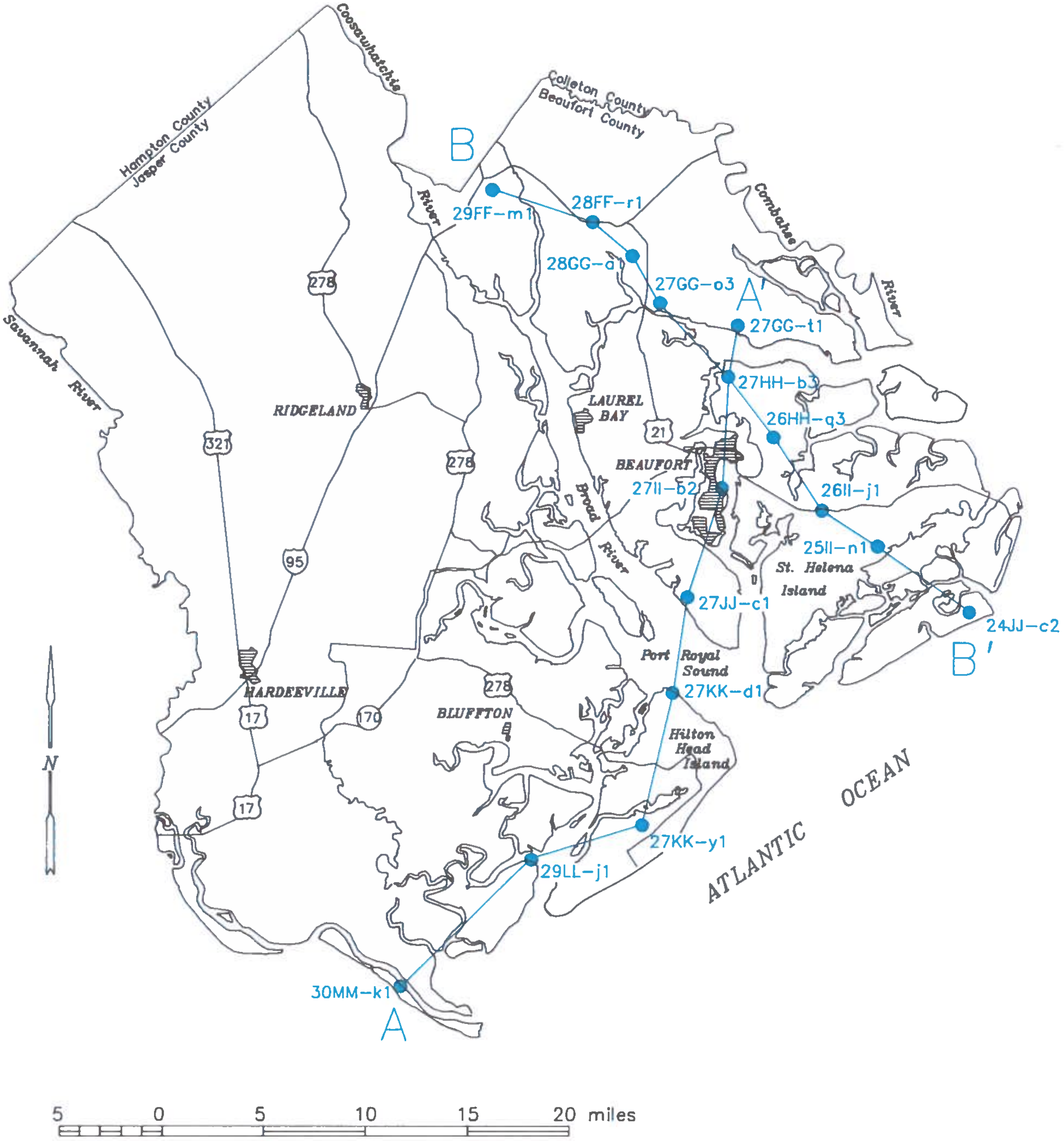

Figure 12. Location of selected wells and hydrologic sections A-A′ and B-B′.

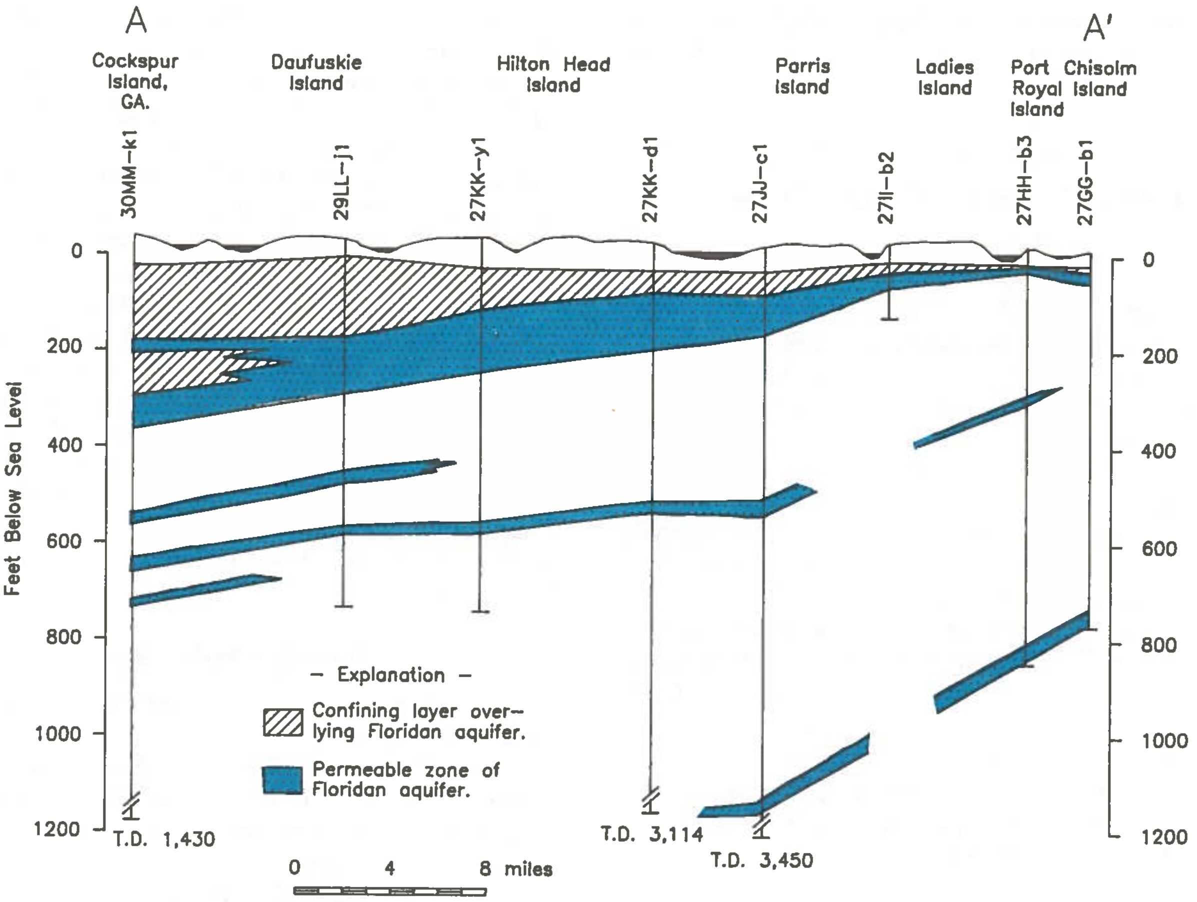

Figure 13. Distribution of permeable zones and confining beds of the Floridan aquifer.

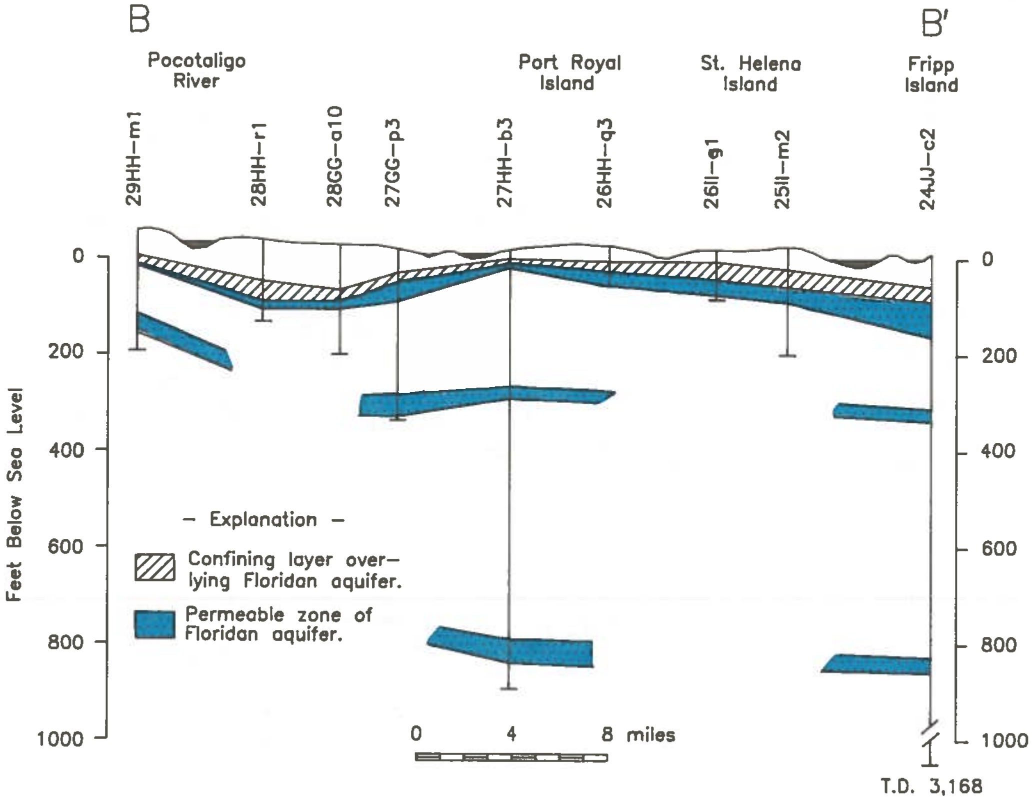

Figure 14. Distribution of permeable zones and confining beds of the Floridan aquifer across the Burton High at Port Royal Island.

aquifer and confining layer are considerably thinned. The thickness of the two deeper permeable zones is unaffected by the uplift.

HYDRAULIC CHARACTERISTICS OF THE UPPER FLORIDAN AQUIFER

General Definitions

Ground-water hydraulics is concerned with the movement of water through the subsurface. The geologic and hydraulic properties of an aquifer system must be understood to predict the reaction of an aquifer to ground-water withdrawal or injection. Hydraulic parameters of importance include hydraulic conductivity (K), transmissivity (T), and storage coefficient (S).

Hydraulic conductivity is a measure of a geologic medium's ability to transmit freshwater. A medium with a hydraulic conductivity of 1 ft/day will transmit 1 ft^3 of water a day through a 1-ft^2 area when the prevailing head decreases 1 ft per foot of flow length (Fig. 15). Although it possesses units of velocity, it is not a velocity but a mathematical reduction of the true flow units of cubic feet per day per square foot of cross-sectional area.

Transmissivity is the rate at which ground water will pass through a unit width of aquifer under a unit hydraulic gradient. In a homogeneous aquifer it is equal to the hydraulic conductivity of an aquifer multiplied by its thickness (Fig. 15). Transmissivity is a measure of an aquifer's ability to transmit ground water through its entire thickness and is dependent on both hydraulic conductivity and thickness.

Another important property of an aquifer is its ability to release water from storage or take water into storage. The storage coefficient of an aquifer is a dimensionless measure of the volume of water an aquifer releases from or receives into storage per unit area of aquifer per unit change in head. For example, assume an aquifer has a storage coefficient of 0.0001. If the head changes 20 ft throughout a 10 ft^2 area, the amount of water released from storage will be $(0.0001) \times (20\ \text{ft}) \times (10\ \text{ft}^2) = 0.020\ \text{ft}^3$ (or 0.15 gallon). Storage coefficients in confined aquifers range from about 0.00001 to 0.003 and are generally about 0.000001 per foot of aquifer thickness. Unconfined aquifers have much higher storage coefficients, ranging from 0.1 to 0.3, owing to the water being derived from gravity drainage of pore space rather than compression of aquifer and expansion of water as in confined systems. Unconfined aquifers can therefore yield more water from storage than confined aquifers for a given drawdown.

Local Aquifer Tests

Hydraulic properties of an aquifer are generally determined by aquifer tests: pumping a well at a constant discharge and measuring the water-level drawdown in the pumping well and, if possible, neighboring wells in the same aquifer. Assumptions of the standard aquifer test analysis are that the aquifer

1. is homogeneous and isotropic, thus the properties do not change with distance or direction;
2. is infinite in areal extent;
3. is of uniform thickness;

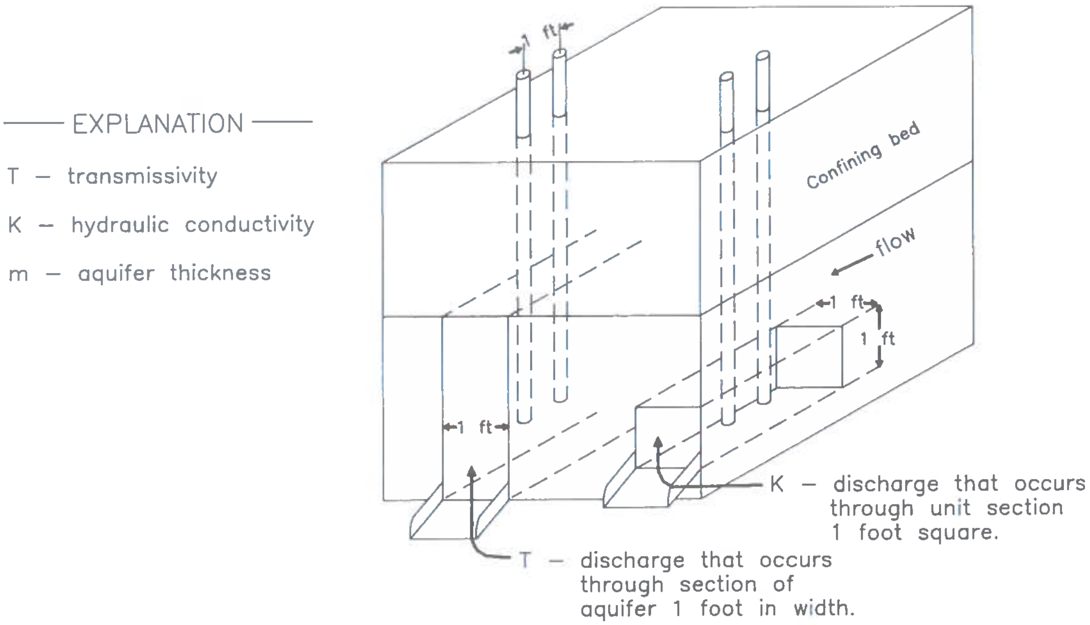

Figure 15. Schematic diagram illustrating transmissivity and hydraulic conductivity.

4. is completely penetrated by the pumping well;
5. releases water from storage instantaneously; and
6. produces radial, laminar flow toward the well.

The upper Floridan aquifer does not meet all of these assumptions, nor does any other aquifer; however, based on the classification of limestone aquifers by White (1969), the upper Floridan is similar to a diffuse-flow aquifer (Stringfield, 1966). Flow is generally similar to a sand-type aquifer and, on a large scale, standard hydraulic flow equations apply, so properly conducted aquifer tests provide reasonable estimates of the hydraulic properties.

Aquifer tests in the study area are difficult to conduct. The Capacity Use Area regulations require water users who withdraw more than 100,000 gallons on any day to have tests performed on their wells. These tests, although valuable for other reasons, are not always suitable for accurate aquifer-characteristics determination. A detailed explanation of the reasons for this inadequacy is beyond the scope of this report, but some of the reasons follow:

1. Tidal effects locally influence water levels in observation wells and are difficult to normalize.
2. Tests are not always conducted with sufficient accuracy.
3. Wells commonly are not drilled through the entire thickness of the aquifer.
4. Observation wells, which are required for storage-coefficient determination, are not available.

Despite these occasional problems, many useful aquifer tests have been conducted in the study area in the past and under the capacity use regulations. Figure 16, a map of the transmissivity distribution in the area, is based on these aquifer tests, local flow net analysis, specific-capacity data, and other methods of transmissivity estimation.

Transmissivities of the upper unit of the Floridan aquifer range from less than 500 ft^2/day on northern Port Royal Island to 70,000 ft^2/day on Hilton Head Island. This range in transmissivity results, in part, from a greater aquifer thickness beneath Hilton Head Island than beneath northern Port Royal Island. A direct relationship between transmissivity and aquifer thickness is indicated by a similar orientation of the contours on the transmissivity distribution map (Fig. 16) and the aquifer thickness map (Fig. 4). An additional cause for the increase in transmissivity to the south results from a regional increase in permeability in that direction. Anomalously high permeabilities in the vicinity of the Burton area probably are associated with local recharge.

The hydraulic conductivity of the upper unit of the Floridan aquifer is 350-500 ft/day except on northern Port Royal Island, where it is 50-150 ft/day. The storage coefficient ranges from 0.000055 on Port Royal Island to 0.0004 in the southwest. Using an average storage coefficient of 0.0001, an average drawdown since development of 35 ft, and a study area of 1,244 square miles, the amount of water removed from storage since pumping began is calculated at 121,000,000 ft^3 (905 million gallons). This amount of water does not seem large when it is considered that 80 mgd is being removed from the aquifer in the Savannah area. The water removed from storage is withdrawn very soon after pumping begins or increases. As water is taken from storage, the cone of depression expands until recharge to the cone of depression by lateral ground water flow approximately equals the withdrawal rate. The relatively small amount of water removed from storage in the study area indicates that the potentiometric surface stabilizes quickly after pumping increases, probably within a matter of weeks.

HISTORICAL GROUND WATER CONDITIONS

Warren (1944) presented a map representing the potentiometric surface of the Floridan aquifer in coastal Georgia prior to development. This map was derived from records of the initial water levels in early limestone wells. The information was taken from McCallie (1898, 1908) and Stephenson and Veatch (1915).

Recent investigators have extrapolated Warren's map into South Carolina. Hayes (1979) referenced the map and presented an isodecline map of water levels in Beaufort, Jasper, Hampton, and Colleton Counties but did not show the predevelopment map. Johnston and others (1980) presented a predevelopment potentiometric map that includes the entire Floridan aquifer in the southeastern United States. Beaufort and Jasper Counties are included on this map and the data are extrapolated from Warren's map. Aucott and Speiran (1985) presented a 25-ft contour predevelopment map of the entire Floridan aquifer within South Carolina. Krause (1982) and Smith (in press) presented predevelopment maps based on digital models. Krause (1982) modeled the Floridan aquifer of southeast Georgia, northern Florida, and southern South Carolina. He used a 4-mile by 4-mile grid and calibrated the model to the map of Johnston and others (1980).

Smith (1987) developed a flow model of the upper Floridan aquifer as part of the study which generated this report. The model is regional, covering the Savannah area. The predevelopment potentiometric map of Beaufort and Jasper Counties (Fig. 17) is modified from those simulated by Smith.

The potentiometric surface prior to 1880 (Fig. 17) was controlled by the natural environment and had not been altered by pumping. Flow in the aquifer was easterly, and ground water was discharged into Port Royal Sound and the Atlantic Ocean. Recharge was from the northwest, regionally, and from Port Royal, Hilton Head, Ladies, and St. Helena Islands locally. Initially, water levels in wells drilled in the eastern section of the study area were above or only a few feet below land surface because of the high potentiometric surface.

Savannah's municipal water supply was taken from the Savannah River until 1887, at which time they began using well water. In 1888 the total pumpage of the city of Savannah was approximately 7 mgd (million gallons per day), and by 1892 the city had 37 wells in operation (Dole, 1915).

A public supply well was drilled near the Beaufort County Courthouse in 1898 and became the major source of water for the city of Beaufort. A year later, three 5-inch wells were drilled on Parris Island (Burnette, 1952). By

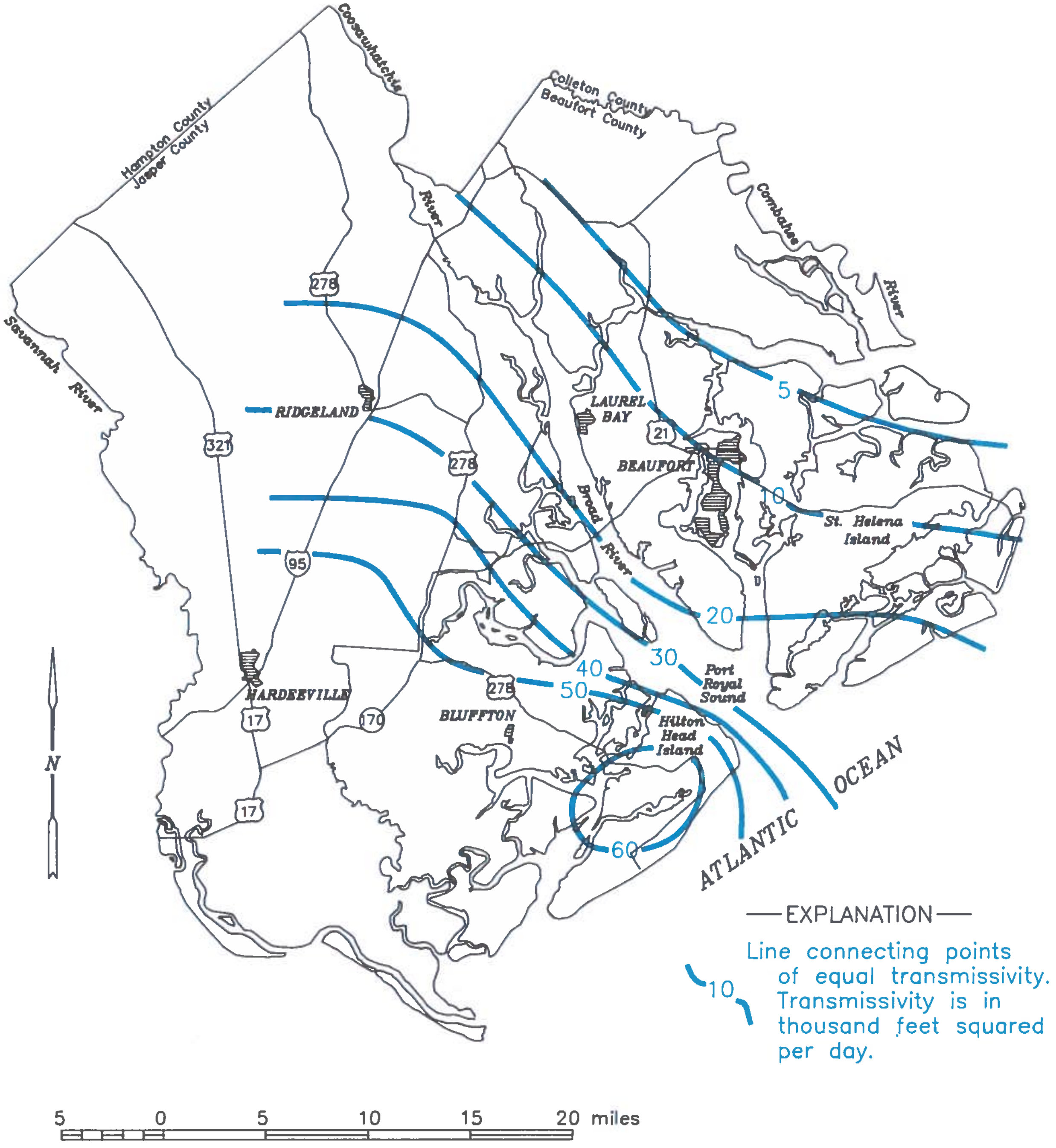

Figure 16. Transmissivity distribution for the Floridan aquifer.

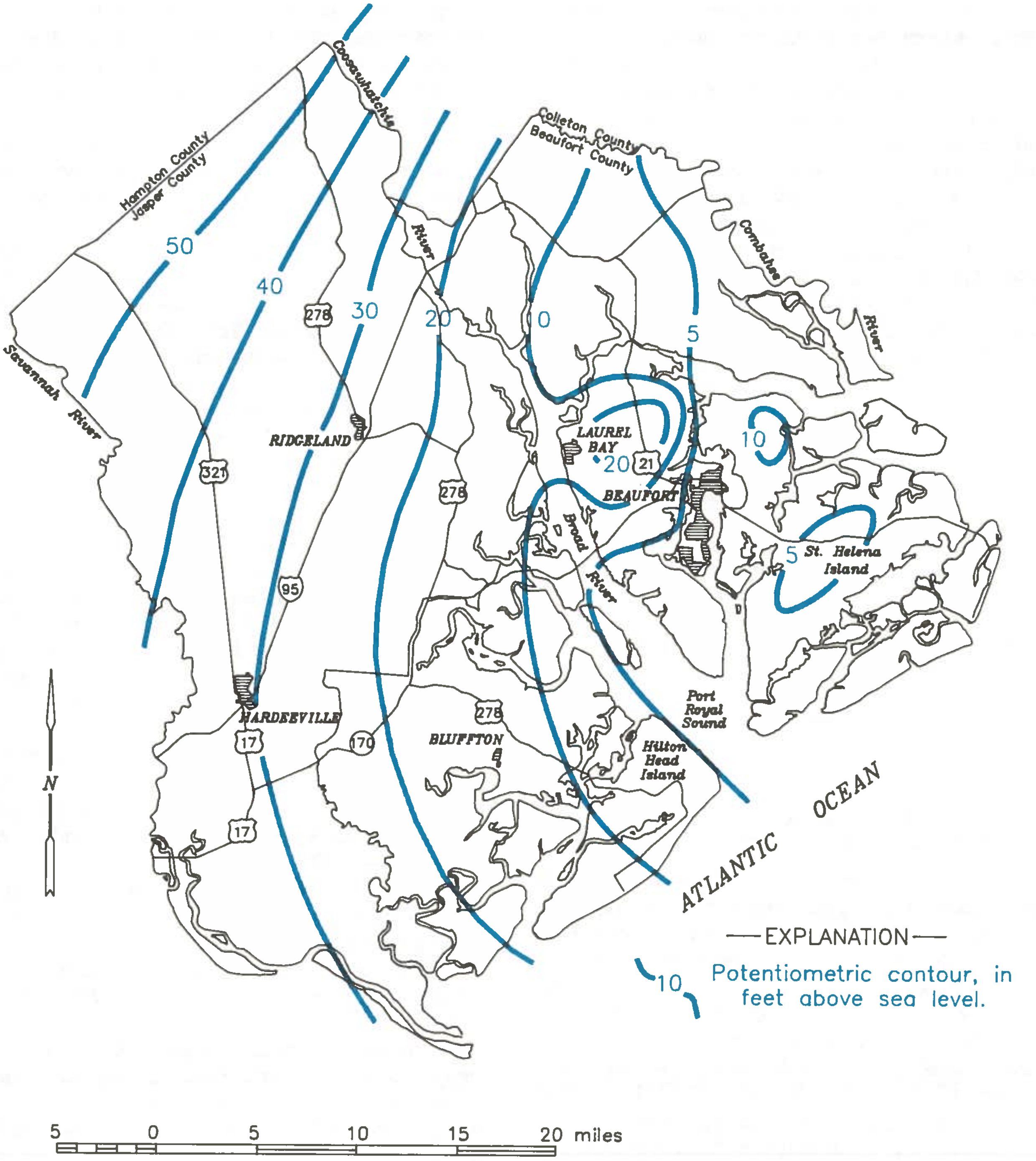

Figure 17. Potentiometric surface of the Floridan aquifer, about 1880.

1903 the Parris Island wells had become salty and were abandoned. Other wells were drilled and used until World War I, at which time water was barged over to the island from wells located in Port Royal. These wells were later abandoned because of bacterial contamination. In 1927, wells were drilled on Jericho Point, just north of Parris Island, and wells were drilled in the Burton area in 1942. Data concerning water use are sparse, but 1.4 mgd and 0.43 mgd were pumped from the Burton and Jericho well fields during March 1944 (Mundorff, 1944).

The well near the Beaufort Courthouse continued to supply the city of Beaufort, and pumpage averaged 0.25 mgd in 1944. This well was abandoned in 1946 owing to high chloride content.

By 1936 the average pumpage in Savannah had risen to 20 mgd (Warren, 1944). At that time, Union Bag and Paper Company went into operation and began pumping 7.3 mgd. By 1943 the company was pumping 18 mgd (Warren, 1944). The Savannah area was pumping approximately 45 mgd by 1944. Figure 18 shows the average daily pumpage from the paper mills, the city of Savannah, and other consumers in the area from 1890 to present.

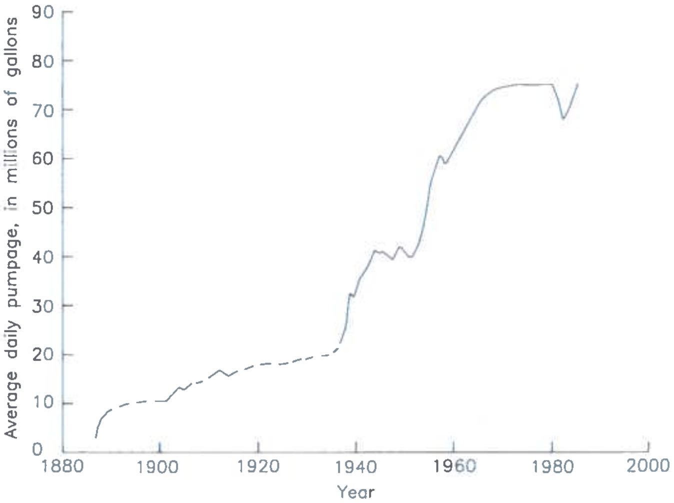

Figure 18. **Average daily withdrawal from the Floridan aquifer in the Savannah, Ga., area (updated from Counts, 1960).**

Water levels during the period 1900-1940 are largely unknown. Water levels from several wells in Beaufort and Jasper Counties in 1917 were presented by Cook (1936), but they were reported in terms of depth below land surface, and elevations are unknown. Warren (1944) and Mundorff (1944) collected water level data between 1941 and 1944. Mundorff (1944) presented a potentiometric map based largely on data collected in April 1944, but some earlier data were also included. This is justified because water levels did not change significantly in that time period. Figure 19 is a potentiometric map of Beaufort and Jasper Counties in 1944 as modified from Mundorff's map. Mundorff drew his map without considering the anomalous high water levels in wells near the U.S. Marine Corps Air Station. He thought these wells tapped aquifers other than the Floridan. Siple (1960) later determined that the high water levels at the air station are indicative of an area where the Floridan is recharged by the overlying shallow (water-table) aquifer.

Between 1880 and 1944, large declines in water level occurred in the region. In 1944 the direction of flow probably was more southeasterly in the study area, and it may have shifted south toward Savannah in southern Beaufort and Jasper Counties. Cones of depression formed around the Burton and Jericho well fields, and water levels were below mean sea level at their centers. Discharge probably was still into Port Royal Sound and the Atlantic Ocean.

Savannah's ground-water pumpage fluctuated around 45 mgd between 1944 and 1951 (Counts, 1959) and then increased steadily to 60 mgd by 1960. Water use for Jasper County for the same time period was insignificant in comparison to Savannah's pumpage.

Ground water for the military installations in the Beaufort area was obtained from the Jericho, Burton, and Naval Air Station well fields between 1944 and 1955. Between 1955 and 1960, the Burton well field was the major source of ground water, providing an average of 1.63 mgd. The Naval Hospital well pumped 0.14 mgd, Naval Air Station wells 0.42 mgd, and 0.55 mgd was pumped from wells near Capehart Housing (Siple, 1960).

The cities of Beaufort and Port Royal were jointly pumping an average of 0.5 mgd by 1959. Pumpage for irrigation in Beaufort County was approximately 1.58 mgd, located mostly in the Lobeco area and on Ladies and St. Helena Islands (Hazen and Sawyer, 1956).

Similar potentiometric maps (Figs. 20 and 21) were drawn by Siple for June 1959 (1960) and by Counts for December 1957 (1960). Both maps show a southwest hydraulic gradient between Hilton Head Island and Savannah, indicating that the natural direction of flow had been reversed by 1958. At the same time, a cone of depression was evident around the Burton well field (Siple's map), with water levels at or below -10 ft msl. Immediately northeast of the cone of depression was a potentiometric high, described by Siple as a recharge mound.

The most significant change occurring between 1944 and 1959 is the great expansion of the Savannah cone of depression. The zero contour moved from between Hilton Head Island and Savannah in 1944 to the middle of Hilton Head Island in 1959.

Development of Hilton Head Island began in the 1960's. By 1976, pumpage on Hilton Head accounted for approximately 65 percent of all pumpage in Beaufort County, with 8.6 mgd withdrawn. The city of Beaufort and all military installations in the area switched to surface water in 1965. The remainder of the pumpage in the county was largely industrial and agricultural and accounted for 4.7 mgd by 1976. Pumpage in Jasper County was estimated at 2 mgd (Hayes, 1979). Ground water withdrawals in Savannah had increased to 75 mgd by 1970 (Counts and Krause, 1970).

Hayes (1979) presented a potentiometric map of the area for December 1976 (Fig. 22) and summarized the changes from Siple's 1959 map as follows:

1. The cone of depression centered at the Burton well field was absent.
2. The potentiometric high at the Marine Corps Air Station changed in shape and increased in size.

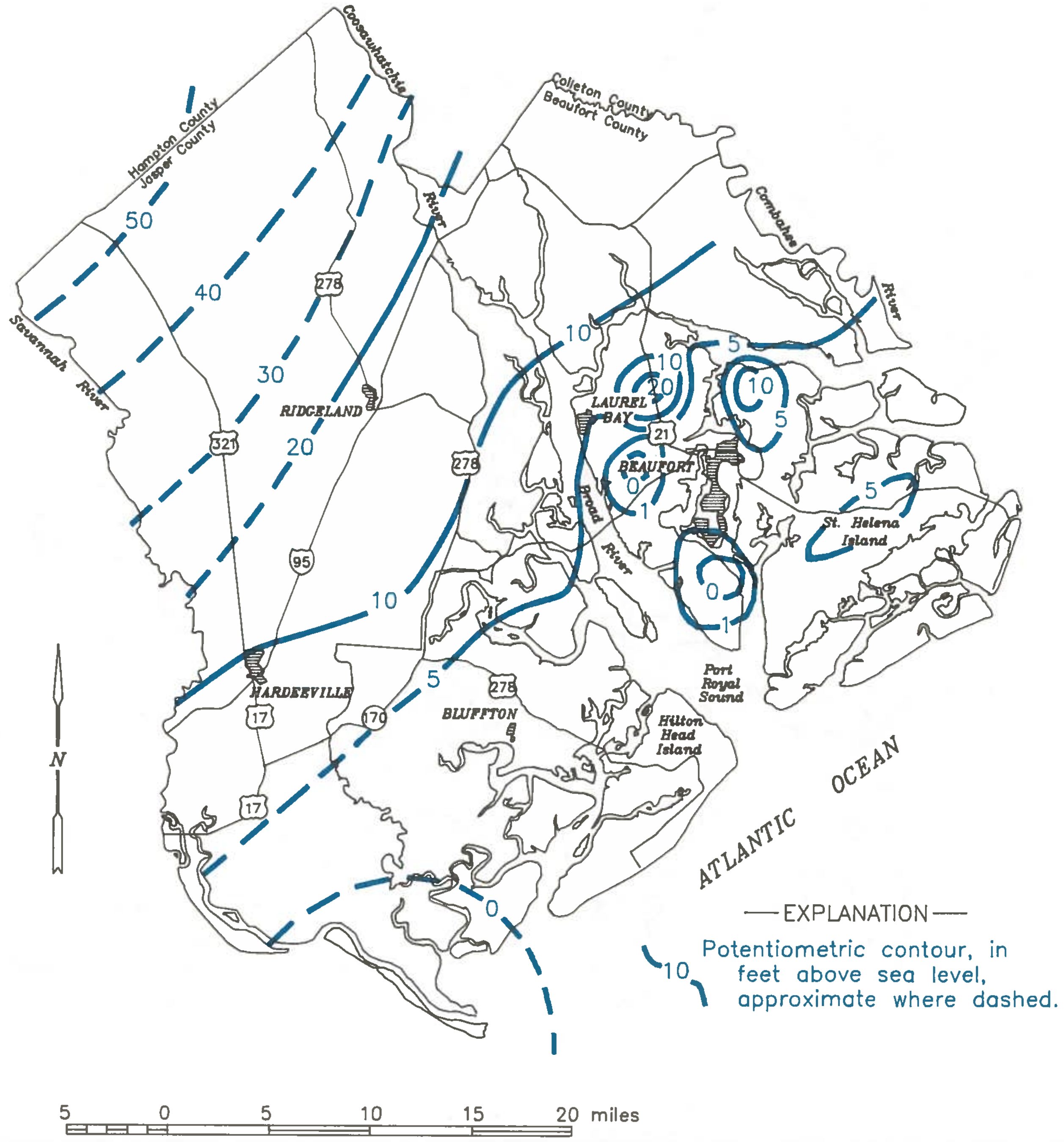

Figure 19. Potentiometric surface for the Floridan aquifer, 1941-1944 (adapted from Mundorff, 1944).

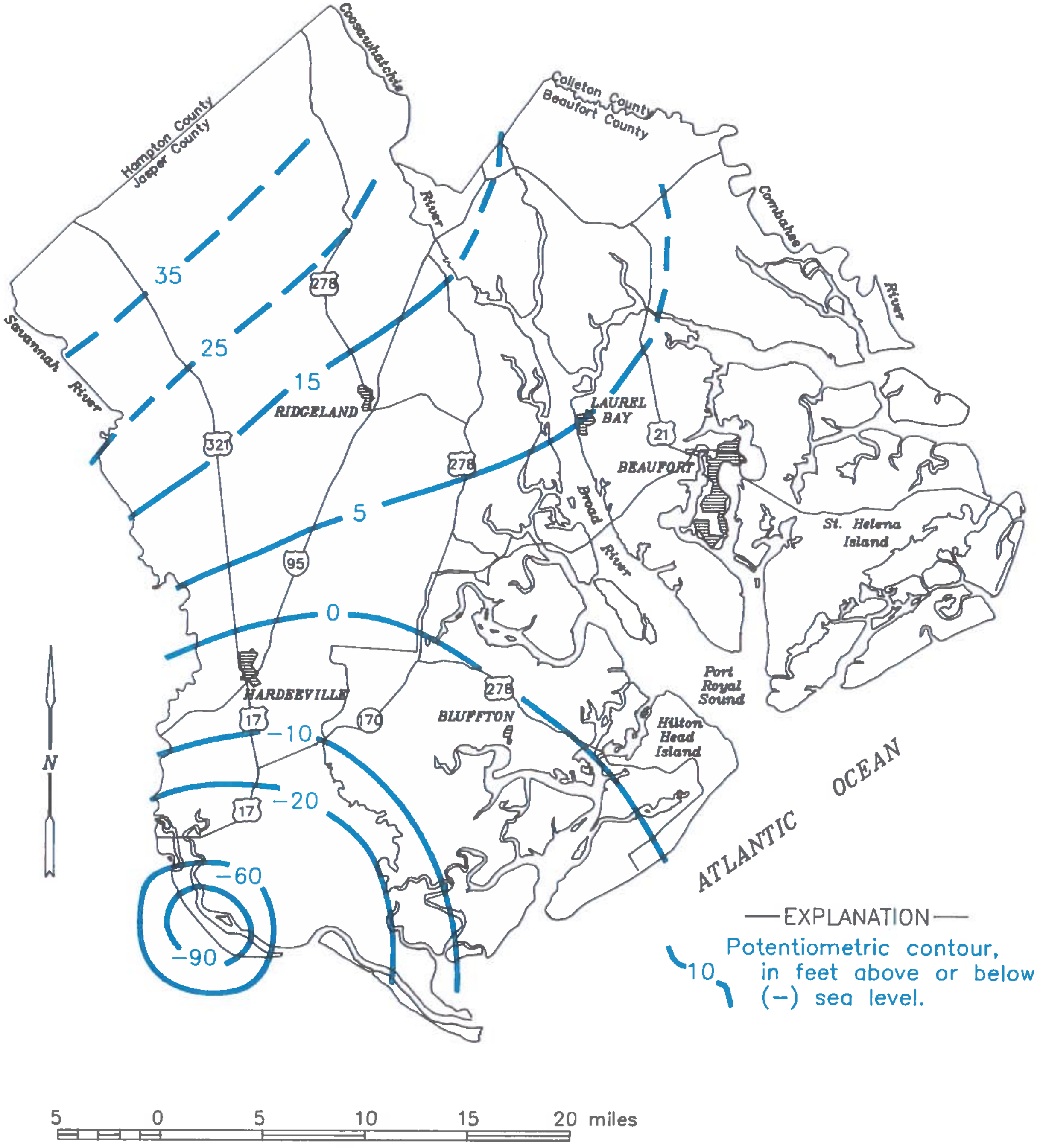

Figure 20. Potentiometric surface for the Floridan aquifer, December 1957 (Counts, 1960).

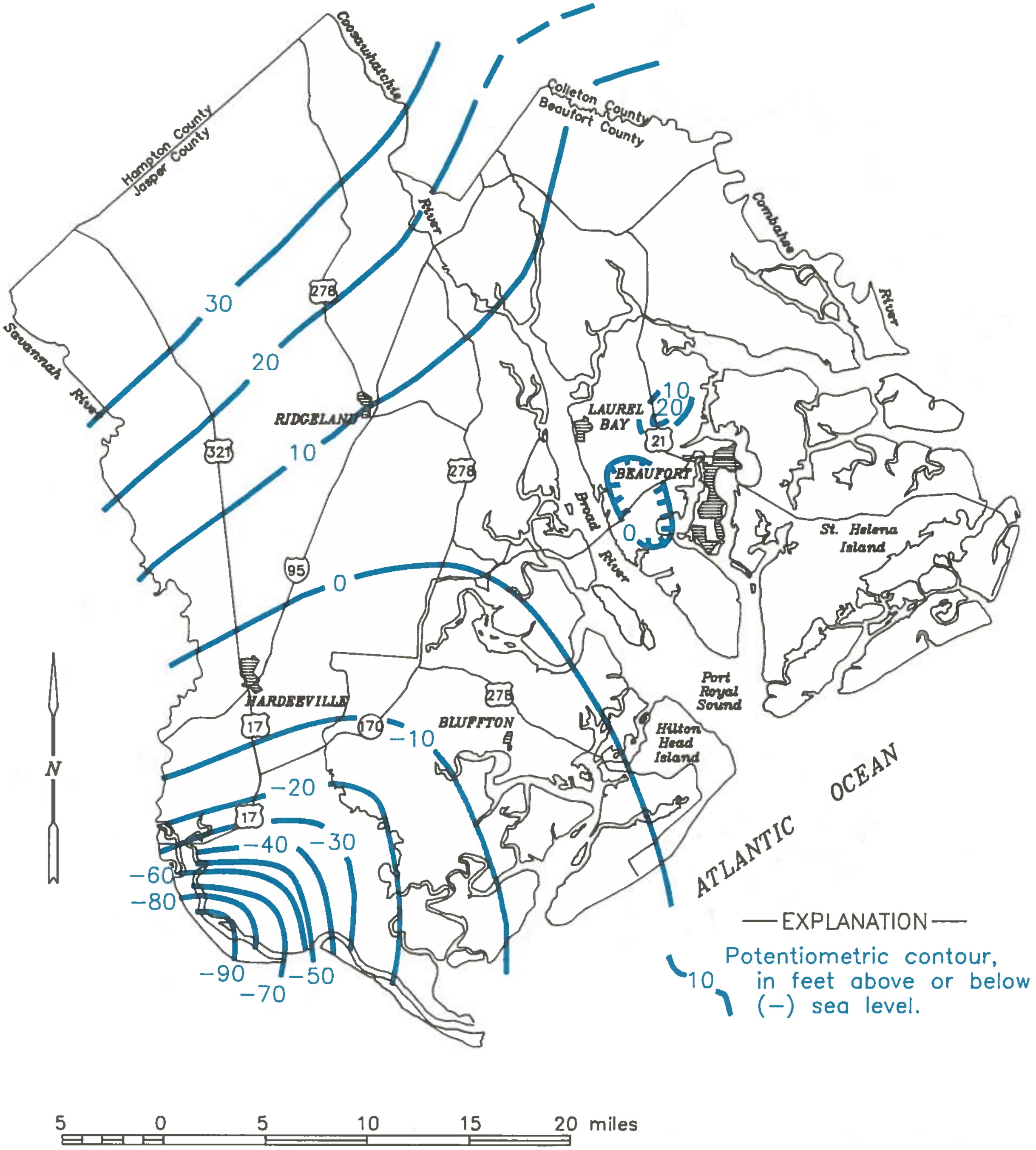

Figure 21. Potentiometric surface for the Floridan aquifer, June 1959 (after Siple, 1960).

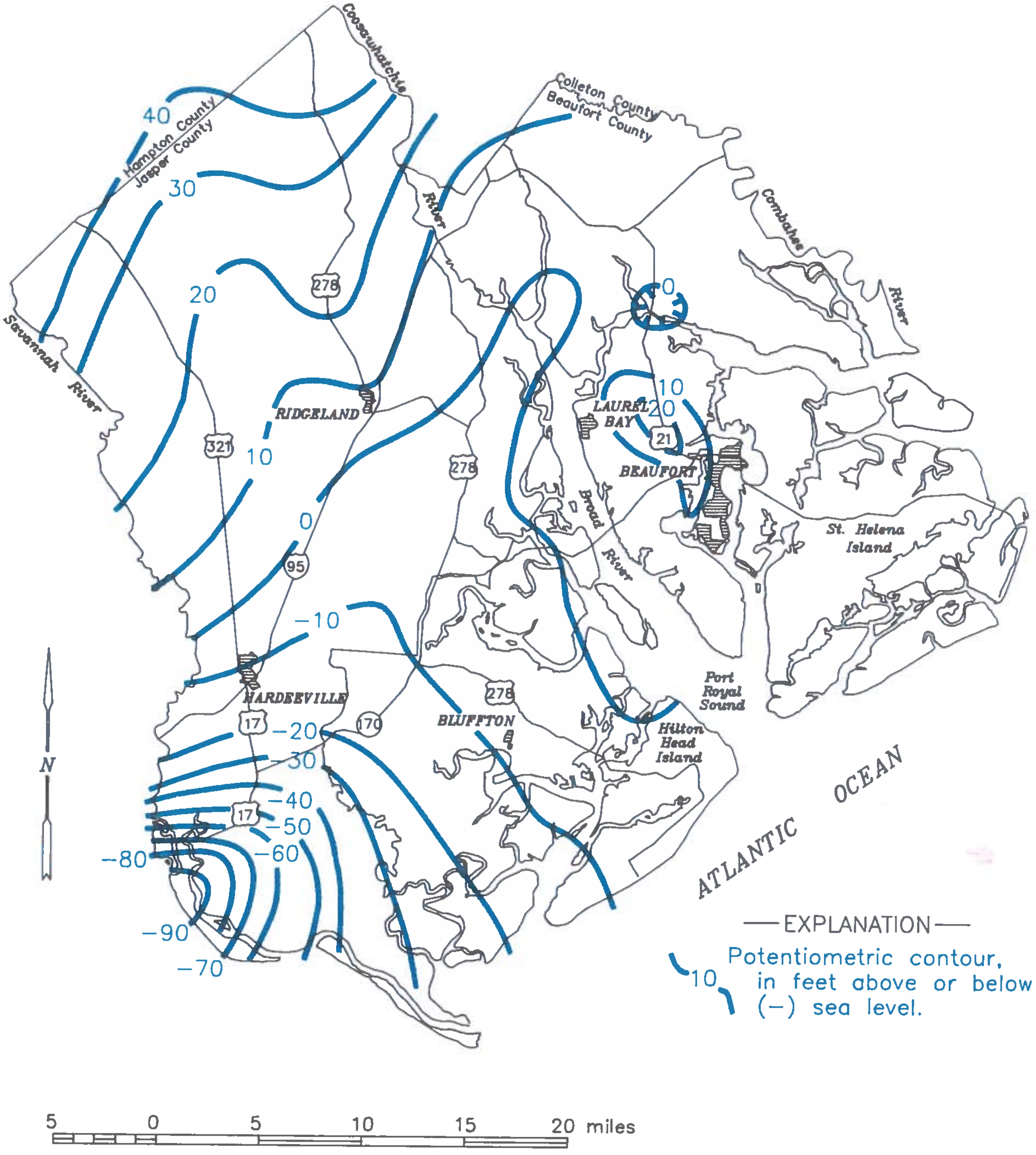

Figure 22. Potentiometric surface for the Floridan aquifer, December 1976 (after Hayes, 1979).

3. The regional zero potentiometric contour moved as much as 15 miles to the northeast.
4. A small cone of depression formed in the Lobeco area.

Pumpage in the Savannah area exceeded 73 mgd in 1986 (Clarke and others, 1987). Industrial withdrawals were reduced between 1981 and 1983 (Clarke and others, 1985), but water-level data published by Clarke and others (1987) indicate that withdrawals have increased since that time.

Ground water use in Beaufort and Jasper Counties is now monitored through the Capacity Use program. Table 3 shows the average Class-A (permitted) pumpage for the first and third quarters of 1985. Pumpage in the area varies from 8 mgd, during non-peak periods, to over 13 mgd during peak use times. The volume of unreported pumpage is not known; however, reporting has improved since 1976, and the current values of reported use are probably more accurate than the estimates made by Hayes (1979).

Table 3. Average reported Class-A pumpage from the Floridan aquifer for the first and third quarters of 1985, in millions of gallons per day

	January - March	April - June
Hilton Head Island	6.30	8.27
Bluffton area	.64	1.37
Ladies Island*	.01	.01
St. Helena Island	.17	2.45
Port Royal Island	.01	.12
Jasper County	.59	.92
Other	.27	.40
Total	7.88	13.45

*Largest user did not report pumpage.

The June 1985 potentiometric map (Fig. 23) was compared to the map for December 1976 constructed by Hayes (1979). The differences are as follows:

1) The contours in the northwestern part of the map are shifted northward on the 1985 map, implying continued water-level decline.
2) Hayes showed the zero contour looping sharply northward across the Broad River, whereas the 1985 map shows a much more gentle bend.
3) The large recharge mound centered near the Marine Corps Air Station is not as extensive as shown on the 1976 map. The 1985 map probably is more accurate, owing to the increase in the number of monitoring wells in the Port Royal Island area since 1976. The 1985 map also shows a small but steep recharge mound at the south end of Parris Island.
4) The zero contour near Hilton Head Island has apparently moved northeastward 2½ to 4½ miles since 1976. The other contours have also moved northeastward, indicating that Savannah's cone of depression is spreading. Local pumping probably is affecting water levels to some extent, as evidenced by the eastward bend in the -10-ft contour.

Figure 24 shows lines of equal decline in the potentiometric surface of the Floridan aquifer from predevelopment time to the present. Water levels have dropped to the extent that flowing wells are no longer common in the study area. The map shows that declines range from less than 5 ft on St. Helena and Ladies Islands to 80 feet or more in southwestern Jasper County, and the gradient of decline increases toward Savannah. This indicates that the main cause of the declining water levels is pumping in the Savannah area.

SALTWATER CONTAMINATION

Concern over saltwater contamination of the Floridan aquifer has grown in recent years because of the area's proximity to large saltwater bodies, declines in the potentiometric surface, and a growing demand for ground water. Ground water in the area is generally of good quality but is not potable in some areas because of high chloride concentrations. Figure 25 is a map of chloride concentrations in water samples pumped from the Floridan aquifer during May 1985 (Davies, 1985). The Environmental Protection Agency's recommended limit of chloride concentration of 250 mg/L is shown to be exceeded at Fripp Island, Cat Island, Datha Island, Lands End, Parris Island, Victoria Bluff, Port Royal, and parts of St. Helena and Ladies Islands. This map cannot be precisely used to show areal or vertical distributions of chloride, because the concentration is not uniform throughout the aquifer's thickness and the samples were not collected from the same depth. Most of the samples were from wells tapping only the upper portion of the aquifer, whereas some samples are from wells penetrating the aquifer's entire thickness. Despite this limitation, the map suggests areas where high chloride concentrations exist at some depth in the aquifer.

Water containing high concentrations of chloride can occur naturally in an aquifer or can be the result of man-induced contamination. Seawater contains approximately 19,000 mg/L of chloride, and small amounts of seawater entering an aquifer can render water in the aquifer nonpotable. Saltwater contamination occurs when brackish water

1. enters from above through a poor confining bed or where the confining bed is absent;
2. rises from the lower part of the aquifer, owing to pumping that reduces the head on overlying freshwater;
3. enters through wells that are constructed in such a manner that freshwater and brackish aquifers are hydraulically connected; or
4. moves laterally through the aquifer in response to reduced freshwater head.

Each of these mechanisms is known to occur in the study area, but lateral movement is the dominant regional mechanism (Counts, 1959).

Saltwater Intrusion in the Port Royal Sound Area

Regional encroachment of saltwater occurs in the Port Royal Sound area, directly northeast of Hilton Head Island and south of Parris Island. Previous investigations

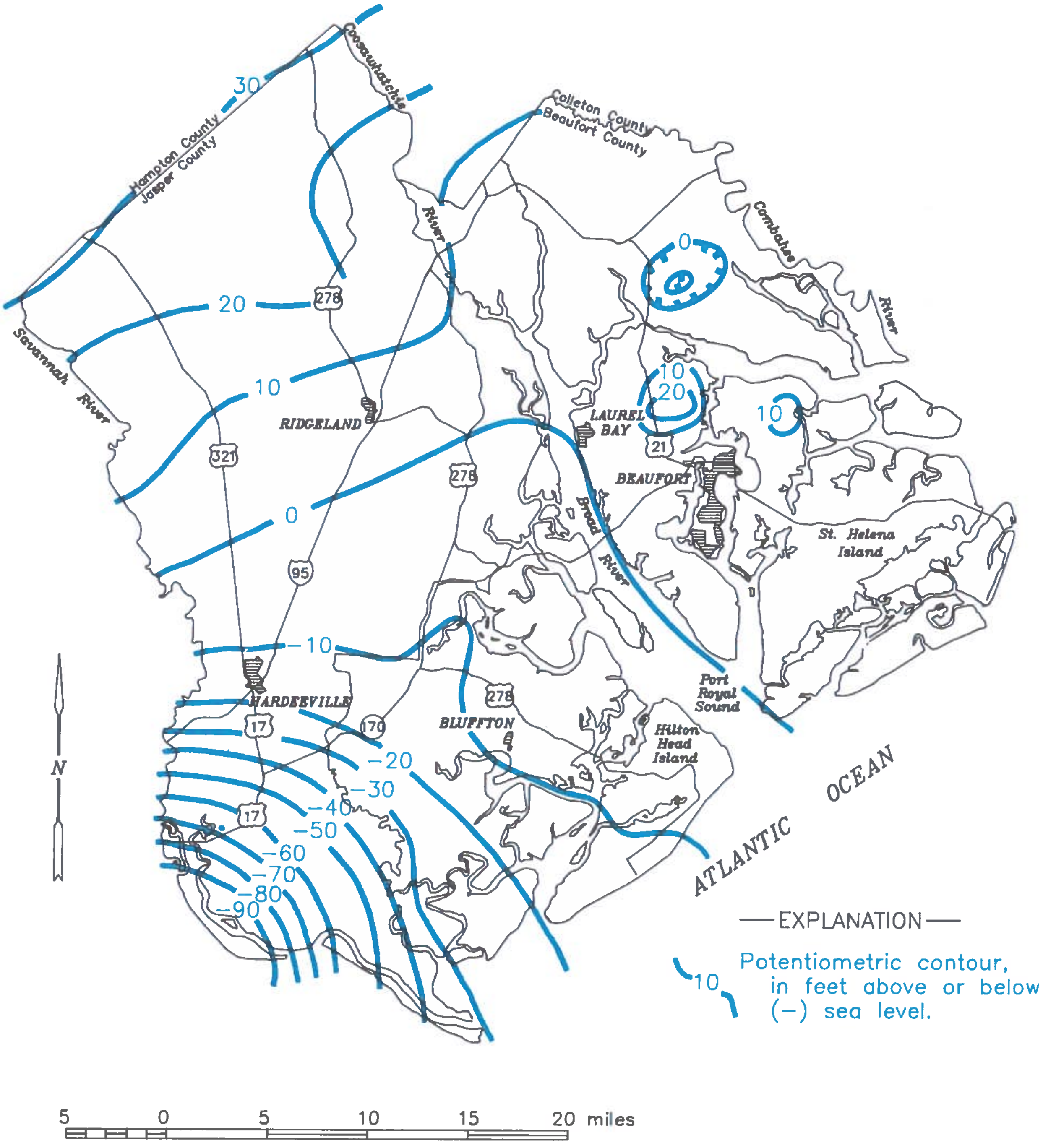

Figure 23. Potentiometric surface for the Floridan aquifer, June 1985.

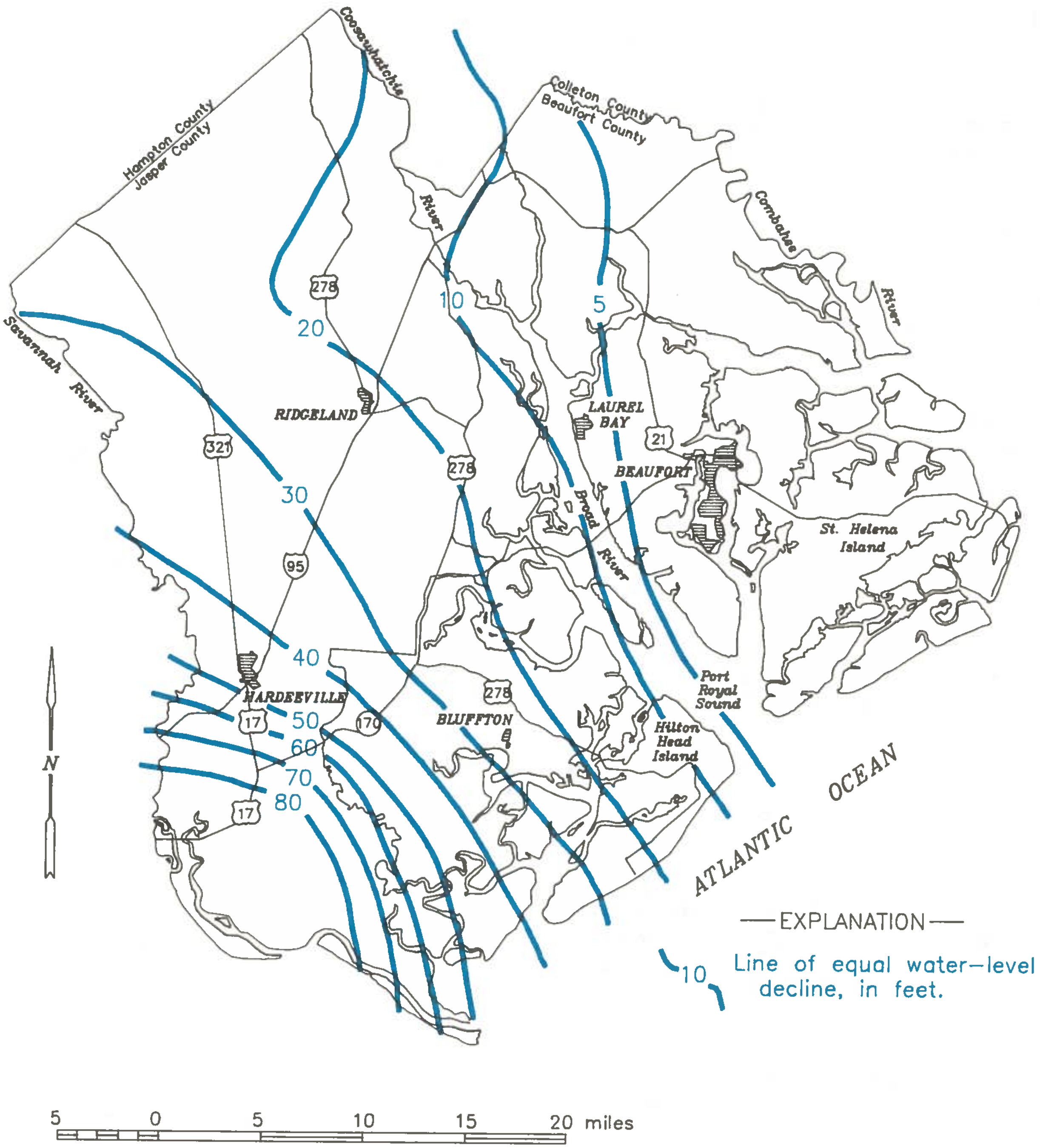

Figure 24. Water level declines in the Floridan aquifer from 1880 to June 1985.

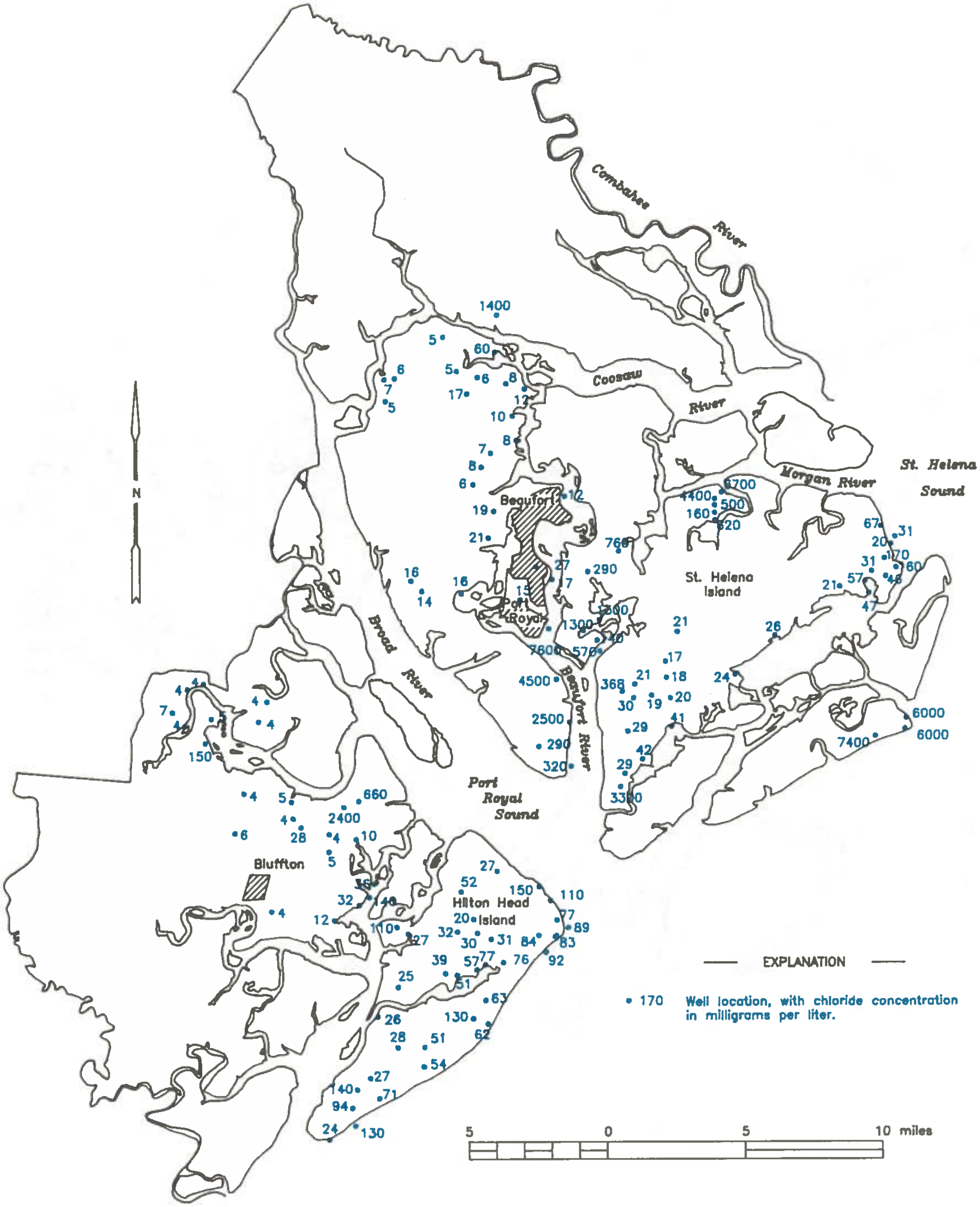

Figure 25. Chloride concentrations in the Floridan aquifer (from Davies, 1986).

(Siple, 1960; Counts and Donsky, 1963) suggested that areas of past discharge in the sound may become areas of recharge and that lateral movement of a saltwater-freshwater interface is possible.

A series of nine offshore test wells were drilled into the Floridan aquifer between June and October 1984 to obtain data that could be of value in understanding saltwater contamination of the Floridan aquifer (Fig. 26). Objectives of the test drilling were as follows:

1. Determine the boundaries of the saltwater-freshwater interface.
2. Determine the extent of the zone of diffusion.
3. Sample water for isotopic analysis.
4. Determine potentiometric heads in the aquifer beneath the sound.
5. Map the upper Floridan aquifer and the overlying confining bed.
6. Determine the hydraulic conductivity of the confining bed.

The objectives were attained by making precise measurements of the water levels in the tidal body and test wells, collecting water samples and geologic samples, and geophysical logging. Considerable post-drilling analysis was necessary to understand these data. Objectives 4 through 6 are discussed in this report, but objectives 1 through 3 are beyond its scope and will be addressed in a future report.

Measurement of water levels

Potentiometric-head measurements are valuable in hydrologic analyses because potentiometric heads dictate direction and influence the magnitude of ground water flow. To permit mapping of potentiometric heads beneath Port Royal Sound, water levels in wells were measured at 6-minute intervals in the offshore drilling project. Analysis of these measurements is complicated by tidal effects and variable-density water in the well bores.

Water levels in wells tapping coastal aquifers fluctuate in response to tidal-stage fluctuations. Ground water levels along the South Carolina coast have been observed to fluctuate as much as 6 ft during a tidal cycle, and therefore no single water-level measurement can be representative of the average water level. The average water levels in the offshore test wells were obtained by the tidal correction method and are listed in Table 4.

Analysis of tidally corrected water levels measured in the SCWRC-USGS offshore test wells was complicated because the wells penetrated zones of differing water quality within the Floridan aquifer's freshwater-saltwater interface. Time consideration prevented allowing the wells to stabilize before water level measurement, so the water quality in the well bore was actually in transition during water level measurement. Water levels in wells containing saltwater are lower than those in identical wells containing freshwater. This is due to the difference in the density of the water, and so it is necessary to adjust all water level measurements with respect to density, thus allowing comparison between water levels in wells containing saltwater and freshwater.

To understand the need for density-difference correction of water levels, it is useful to understand the relationship between water level and pressure head of an aquifer. Water rises in wells penetrating confined aquifers because of the difference in pressure in the aquifer and the well bore. The water rises to a level at which the head (feet of water) balances the pressure exerted by the aquifer. If the fluid in the well is denser than freshwater, the column will not have to rise as far to weigh the same and therefore equal the aquifer pressure.

To compare the conditions of an aquifer areally by water level measurements, there must be compensation for density differences in well-bore water. The problem is solved mathematically, and the calculated freshwater heads are presented in Table 4. These heads, based on measurements made during 1984, are used to approximate the offshore position of water level contours on the June 1985 potentiometric map (Fig. 23).

Table 4. Tidally corrected water levels and freshwater heads adjusted for density variations in offshore test wells (July, August, and September 1984)

Well number	Tidally corrected water level, in feet above or below (-) mean sea level	Freshwater head, in feet
26JJ-y1	-1.14	-1.14
27JJ-m1	-.32	.87
27JJ-r1	-1.43	0.00
27KK-t1	-4.68	-4.58
27KK-a1	Not available	Not available
27JJ-m2	.01	1.33
27JJ-d1	2.15	2.15
26KK-m1	-1.00	-1.09
26JJ-o1	1.06	3.80

Geologic framework

The geologic units beneath Port Royal Sound (Fig. 26) are defined on the basis of lithologic samples and geophysical logs obtained during the offshore drilling. The thickness of and the depth to the upper permeable zone of the upper Floridan aquifer are fairly uniform throughout the sound and adjacent parts of the Atlantic Ocean. A slight increase in depth to the aquifer and an increase in its thickness occurs in the south-southeast direction. The thickness of the confining layer that overlies the aquifer is much less uniform. The general pattern is for the thickness of the confining layer to increase toward the ocean; however, this does not hold true for wells 27JJ-m1 and 27JJ-m2. This lack of a general trend for the thickness suggests that the top of the confining layer is an irregular, erosional surface and that thin spots such as at 27JJ-m2 may occur elsewhere in the sound.

Saltwater occurrence

A saltwater-freshwater interface in the upper Floridan aquifer is expected to exist naturally in the area. A

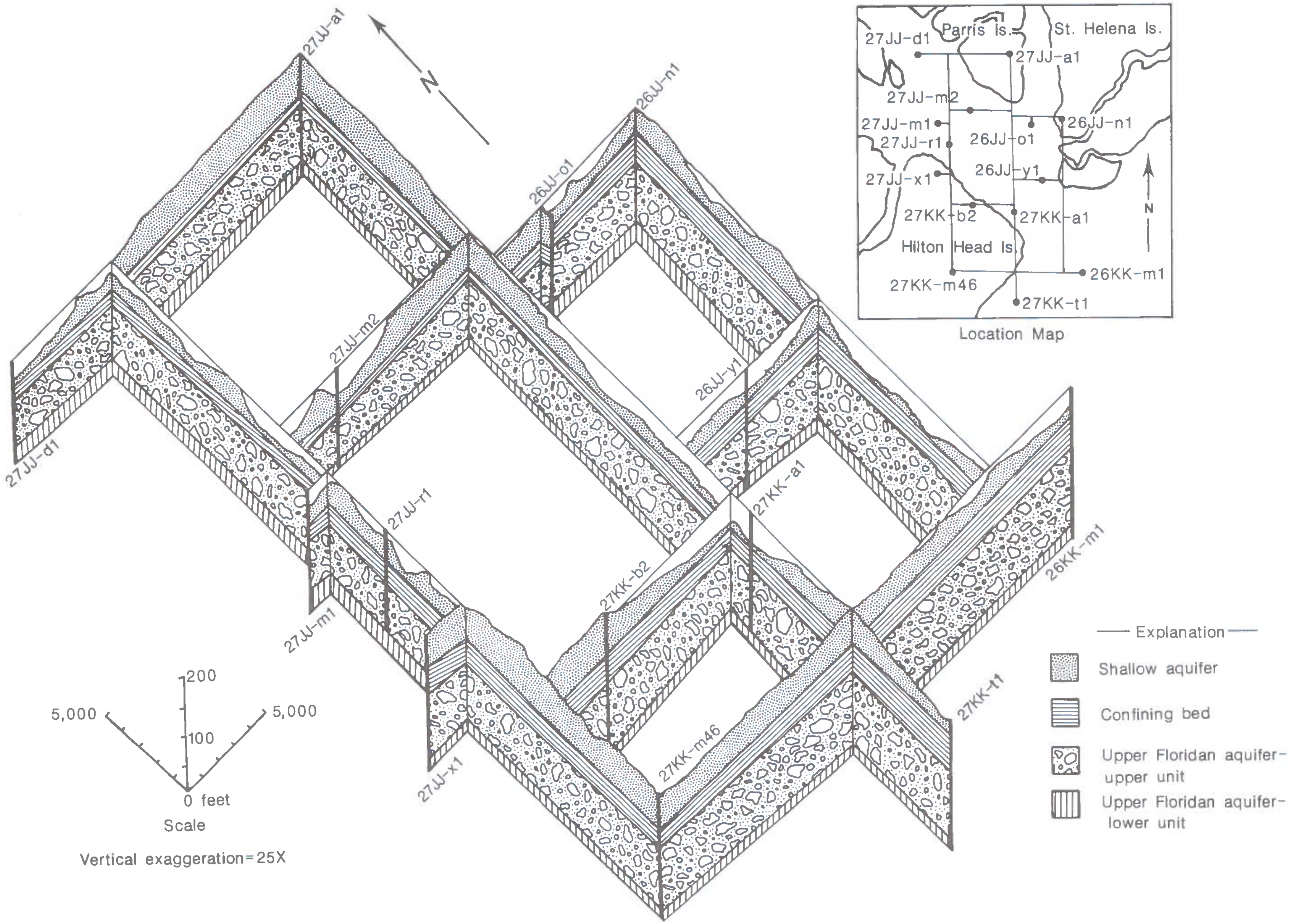

Figure 26. Hydrologic units beneath Port Royal Sound and some adjacent island areas, South Carolina.

saltwater-freshwater balance will occur in coastal aquifers as a result of equilibrium between fluids of differing density. An equation describing this phenomenon is known as the Ghyben-Herzberg relationship. This relationship states that under hydrostatic conditions the depth to a sharp saltwater-freshwater contact will be equal to the height above mean sea level of water in the well times forty. Ground water does not actually occur under hydrostatic conditions, so the relationship is only an approximation. Bear and Dagon (1969) found that the relationship is generally accurate to within 5 percent, but it gives depths that are too shallow near the coast. This principle is only valid for steady-state conditions and should not be applied to a situation in which the system is in transition.

Before 1880 the flow system and position of the saltwater-freshwater interface in the Port Royal Sound area were probably in a steady-state condition. Based on this assumption, the Ghyben-Herzberg relationship was used to approximate the location of the saltwater-freshwater interface. Areas where the upper Floridan aquifer was salty at its base and where the aquifer was salty throughout its entire thickness (Fig. 27) were mapped. These maps were based on the predevelopment potentiometric map of the upper Floridan aquifer (Fig 17), the contour map of the top of the aquifer (Fig. 5), and the thickness map of the aquifer (Fig. 6). These maps show where a theoretical sharp interface would occur. In reality a sharp contact will not exist, rather a zone of transition from seawater (19,000 mg/L chloride) to freshwater exists. The interface boundary represents the approximate midpoint (9,500 mg/L) of this transition zone during equilibrium.

A freshwater lens existed in the aquifer beneath Parris Island before development. This lens was produced by potentiometric heads of several feet above sea level that forced saltwater below the top of the aquifer. Historical evidence supports the existence of this lens. Early wells drilled on Parris Island supplied potable water for several years before becoming salty. Lateral encroachment and upconing of saltwater probably resulted when the high potentiometric heads on Parris Island were lowered. The "fresh" water in Figure 27 refers to water with a chloride concentration of less than 9,500 mg/L, and potable water is water with less than 250 mg/L of chloride. Therefore, areas of "fresh" water on Figure 27 may not be suitable for human consumption, and the quality of water beneath Parris Island probably was never acceptable throughout the entire thickness of the aquifer. The boundary for potable water was upgradient from the boundary shown on the maps.

Figure 27 shows that the saltwater-freshwater interface at the bottom of the aquifer was slightly northeast of Hilton Head Island under natural conditions. Flow conditions and potentiometric heads kept the interface stable, but alteration of these characteristics by pumping may cause the interface to move down gradient. It can be seen that the interface does not have to move very far to occur beneath Hilton Head Island.

The average rate of water movement can be calculated by use of Darcy's Law; however, this velocity is an average velocity and dispersion causes individual water molecules to travel at differing rates. Therefore, travel time for a pollutant cannot be precisely calculated from this velocity. The rate of the "average" water molecule can be determined.

The modified form of Darcy's Law is $V = \frac{Kdh/dl}{n}$

where: V = average Darcy velocity, in feet per day
K = hydraulic conductivity, in feet per day
dh/dl = hydraulic gradient, in feet per mile
n = porosity, in percent as a decimal

The distance between 27JJ-r1 and 27JJ-m2 is 7,300 ft (1.38 miles) and the head difference was 1.34 ft. Therefore, the hydraulic gradient measured during the offshore drilling was 0.97 ft/mile between these wells. The limestone has an estimated porosity of 30 percent (Hayes 1979), average thickness of 90 ft, and transmissivity of 40,000 ft^2/day in the area. Substitution into the modified Darcy equation yields a velocity of 0.27 ft/day or 99 ft/year for water in this area. The interface will move slightly faster than the water because of dispersion, but saltwater behind the interface will move approximately 5 percent slower because of its greater density. The proximity of the interface to Hilton Head Island, coupled with the average velocity of 99 ft/year in the direction of the island, suggests that lateral encroachment will cause saltwater to move beneath the northeastern shore of Hilton Head Island in the future. Wells located on the northeastern shore will show an increase in chloride concentration as the interface encroaches.

Downward Movement of Saltwater through the Confining Unit

The potentiometric levels of the Floridan aquifer are below mean sea level for at least a part of the year beneath Port Royal Sound (Fig. 23). This head differential causes water from the sound to leak downward through the confining unit and eventually into the Floridan aquifer. Water flows from areas of high head toward areas of low head. The rate of movement is controlled by the hydraulic gradient (difference in the head per unit of distance) and the transmissivity of the material the water is passing through. A clay unit, such as the Hawthorn Formation, has low hydraulic conductivity and therefore retards the movement of water. Although it retards flow, flow still occurs and is described by Darcy's Law.

$Q = KAdh/dl$ where:

Q = volume of flow per unit time, in cubic feet per day
K = hydraulic conductivity, in feet per day
A = cross-sectional area of flow, in square feet
dh/dl = hydraulic gradient; the head difference divided by the length of formation in the flow direction, in feet per foot.

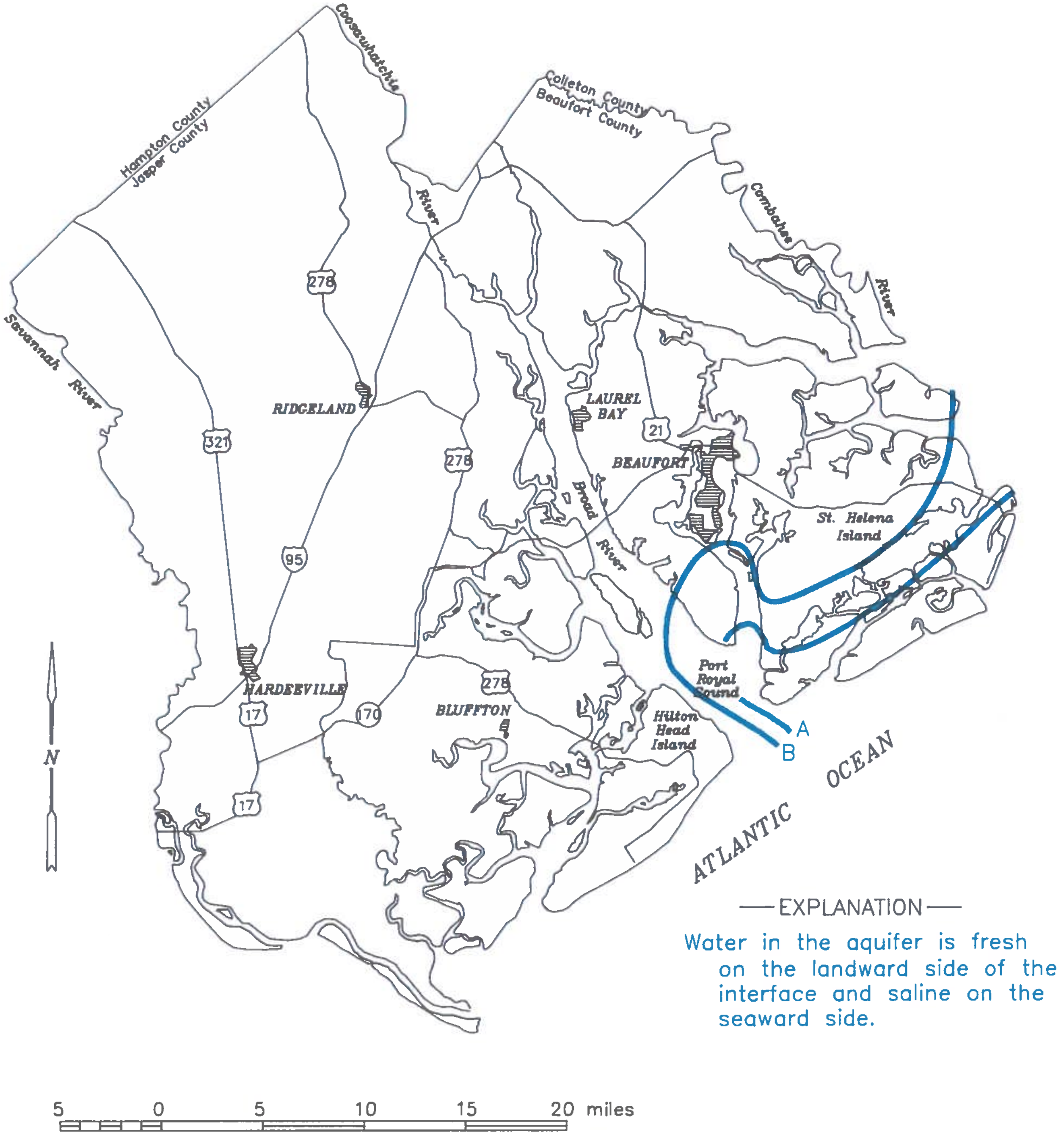

Figure 27. Location of the saltwater-freshwater interface prior to development.

Laboratory permeability tests were conducted on selected core samples taken during the offshore drilling in Port Royal Sound. Results of these tests show a wide range of values (Table 5). These values can be used to determine the net flow of water into the Floridan aquifer through the overlying strata. Using an average thickness for the Hawthorn of 30 ft and an average hydraulic conductivity of 0.006 ft/day, the volume of flow per square foot through the Hawthorn is 0.0002×10^{-4} ft^3/day for every foot of head difference. This means that for every square mile of aquifer beneath Port Royal Sound 39,400 gpd (gallons per day) of seawater is moving into the Hawthorn. Assuming no horizontal flow in the Hawthorn, application of the law of conservation of mass states that an equal amount of water is also moving out of the Hawthorn and into the Floridan aquifer. Thus 39,400 gpd of water per square mile is moving into the Floridan from above. The water currently in the Hawthorn probably contains chloride concentrations of less than 250 mg/L, as the reverse process took place for thousands of years. Until recently, freshwater was discharging into the sound from the Floridan aquifer.

Neglecting dispersion and diffusion, the transit time for seawater moving through the confining unit can be modeled. Assuming an average thickness of 30 ft for the Hawthorn, its bulk volume is $836{,}000{,}000 \times 10^8$ ft^3/mi^2. Using an average porosity of 45 percent (Table 5) and a bulk volume of $836{,}000{,}000 \times 10^8$ ft^3/mi^2, the saturated pore space within the Hawthorn is calculated to be $376{,}000{,}000 \times 10^8$ ft^3/mi^2. This volume of water must be displaced before seawater can move into the Floridan aquifer. If 39,400 gpd/mi^2 (5,270 ft^3/day/mi^2) flow into the Hawthorn and $376{,}000{,}000 \times 10^8$ ft^3/mi^2 of water must be displaced, then almost 200 years would be required to remove all freshwater from the Hawthorn, if the recharge were constant. Hayes' (1979) potentiometric map shows that heads were generally above sea level at Port Royal Sound in 1976, so the head gradient has existed for less than 10 years. Because the head is not constant throughout the year the recharge is not constant, and the flushing would take considerably longer.

Breakthrough is defined as the point in time when water of a given chloride concentration reaches the far side of a confining unit. Neglecting dispersion and diffusion, the freshwater in the confining bed is slowly replaced by seawater and at some point in time the water entering the aquifer from above becomes salty. Because of dispersion and diffusion, the breakthrough time for non-potable water is much shorter than for saltwater. This is illustrated in the hypothetical breakthrough curve in Figure 28, which shows how chloride concentration in water exiting the confining unit will vary through time and depend on diffusivity. The critical concentration of chloride necessary to make the freshwater in the Floridan aquifer non-potable is greater than 250 mg/L, however, because of dilution of the saltwater in the aquifer. The resultant concentration in the aquifer is a function of recharge, total flow, and the mixing ability of the aquifer.

Downward movement of saltwater through the Hawthorn in the Port Royal Sound area is not a cause for immediate concern. Lateral encroachment will degrade water quality in this area long before the concentration of downward-moving water is high enough to cause problems. If present conditions continue, localities where the confining bed is thin or absent could have substantial quantities of saltwater in the aquifer much sooner than predicted.

Table 5. **Hydraulic conductivity (K) and porosity of selected core samples**

Well	Depth (feet)	K(ft/day)	Porosity (percent)
26JJ-y1	96.8- 97.3	0.00567	41
	101.5-102	.00567	39
	104.3-104.8	.01417	85
	109.5-110	.07087	?
27JJ-r1	74.5- 75	.01134	44
	76 - 76.5	.00850	43
	102 -102.5	.22961	38
	112.8-113.3	.00057	64
27KK-t1	58 - 58.5	.00283	72
	96.5- 97	.00567	47
27KK-a1	78 - 78.5	.00283	45
	86.5- 87	3.1181	41
	96.7- 97.1	.03402	48
	104 -104.5	.00567	66
27JJ-d1	72 - 72.5	.00122	?
26KK-m1	74 - 74.5	.00043	60
	87.5- 88	.42520	50
	103.5-104	.06236	44
26JJ-o1	69.5- 70	.00283	?
	82 - 82.5	.08504	45
	94.5- 95	.19843	44
	107 -107.5	.20409	35

Downward movement in the central and southern parts of Hilton Head Island could present an immediate problem. A comparison of seasonal pumping rates and chloride concentrations at Sea Pines Plantation shows an inverse relationship. Chlorides decrease in the summer when pumpage is greatest and increase in winter when pumpage is least. The fluctuation in chloride concentration could be attributable to variation in the rate of recharge to the Floridan. As water levels decline in the summer, the head difference between the Floridan and overlying aquifers increases and, consequently, the rate of freshwater recharge through the confining bed increases, causing chloride concentrations to decrease. Unfortunately, in this area beneath saltwater streams and marshes, saltwater recharge has been active since approximately 1944, or almost 45 years. The recharge has had a head advantage in recent years of as much as 22 ft. Performing calculations similar to those above with an average confining-bed thickness of 60 ft and an average head difference of 10 ft since 1944, the transit time is about 40 years. Obviously these calculations are very general and approximate in nature, but since the

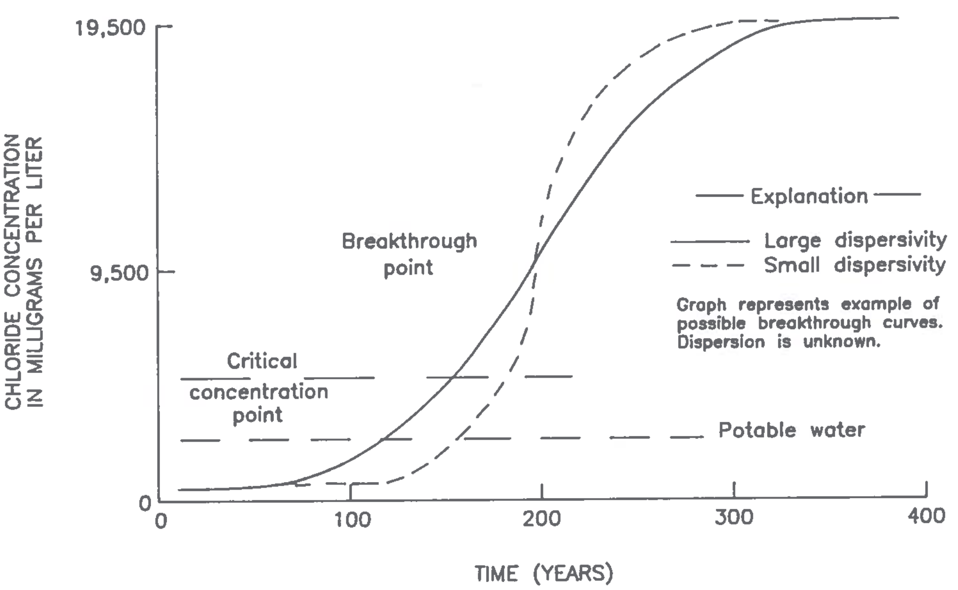

Figure 28. **Predicted input of chloride to the Floridan aquifer from overlying beds, with time.**

transit time calculated shows that high chloride concentrations should be appearing now, the need to closely monitor chloride values is apparent.

Breached Confining Layer

In some parts of the study area, the confining layer that overlies the aquifer is missing. Where such breaches exist beneath a saltwater body, the freshwater in the aquifer and the saltwater will be in hydraulic contact. If the head in the aquifer is lower than the head in the salt-water body, the saltwater will move downward into the aquifer, causing contamination. Where the head in the aquifer is equal to or nearly equal to the head in the saltwater body, diffusion will allow movement of salt-water into the aquifer. However, diffusion proceeds at such a slow rate that it is unlikely to result in much contamination. Five ways that the confining layer is likely to be breached have been identified—tidal scour, stream erosion, sinkhole development, phosphate mining, and harbor dredging.

Tidal scour and stream erosion

In the Port Royal Sound-St. Helena Sound area, tidal ranges in excess of 8 ft are common. The fast currents generated during tidal cycles scour deep channels that may remove a portion or all of the confining bed. The areas most prone to this problem are where narrow channels drain large bodies of tidally influenced inland water.

Siple (1960) noted that lower stands of sea level during the Pleistocene would have caused greater downcutting by the streams of that time. During the Pleistocene ice ages, large amounts of water accumulated on land in the form of glacial ice. The corresponding loss of water from the world's oceans caused an overall drop in sea level. As sea level dropped, streams maintained equilibrium by cutting deeper channels. Flint (1957), using evidence of submerged terraces, coral reef lagoons, and drowned river valleys, calculated that Wisconsinan sea levels were 300 ft lower than present sea level. Based on ocean-bottom topography, a stand of sea level 450 ft lower than the present has been identified for the Illinoian stage (Donn and others, 1962).

Although it is unclear whether Pleistocene or modern erosion is responsible, several locations in the study area have been identified where the confining bed is missing or considerably thinned. Borings in the Beaufort River and Battery Creek revealed areas where the Floridan aquifer is directly exposed to saltwater or covered by only a few feet of sediment (Figs. 29, 30, and 31). During the offshore drilling, several thin spots in the confining bed were observed.

Sinkhole development

Another form of breach in the confining layer is a sinkhole. If sinkholes are presently submerged or were submerged in the past, they could provide a conduit for saltwater contamination. Many sinkholes are presently developed on Port Royal Island and Ladies Island (Fig. 32), where the limestone is nearest to land surface. The highest density of sinkholes occurs between the Beaufort River and Battery Creek. It is also likely that submerged sinkholes are present in the surrounding marshes and tidal creeks, providing a potential avenue for saltwater contamination.

Although there has been no study of sinkholes in this area, Beck (1986) described a similar situation in northern Florida. The Ocala uplift of northern Florida is a broad anticlinal structure where the limestone is at or just below the surface. Sinks develop in this area where chemically aggressive surface-water flow is concentrated. This occurs beneath pre-existing sinks, where streams flow across impermeable sediments and onto the limestone, and at springs. It has been observed that sinks do not develop suddenly, but that as a cavity develops by solution in the Ocala the Hawthorn slowly collapses into the hole.

The age of the sinkholes in Beaufort County has not been established. The sinks are not thought to be modern, because no historical accounts of developing sinkholes are known. It is unlikely that the sinkholes are older than the Wisconsinan stage of the Pleistocene, because higher

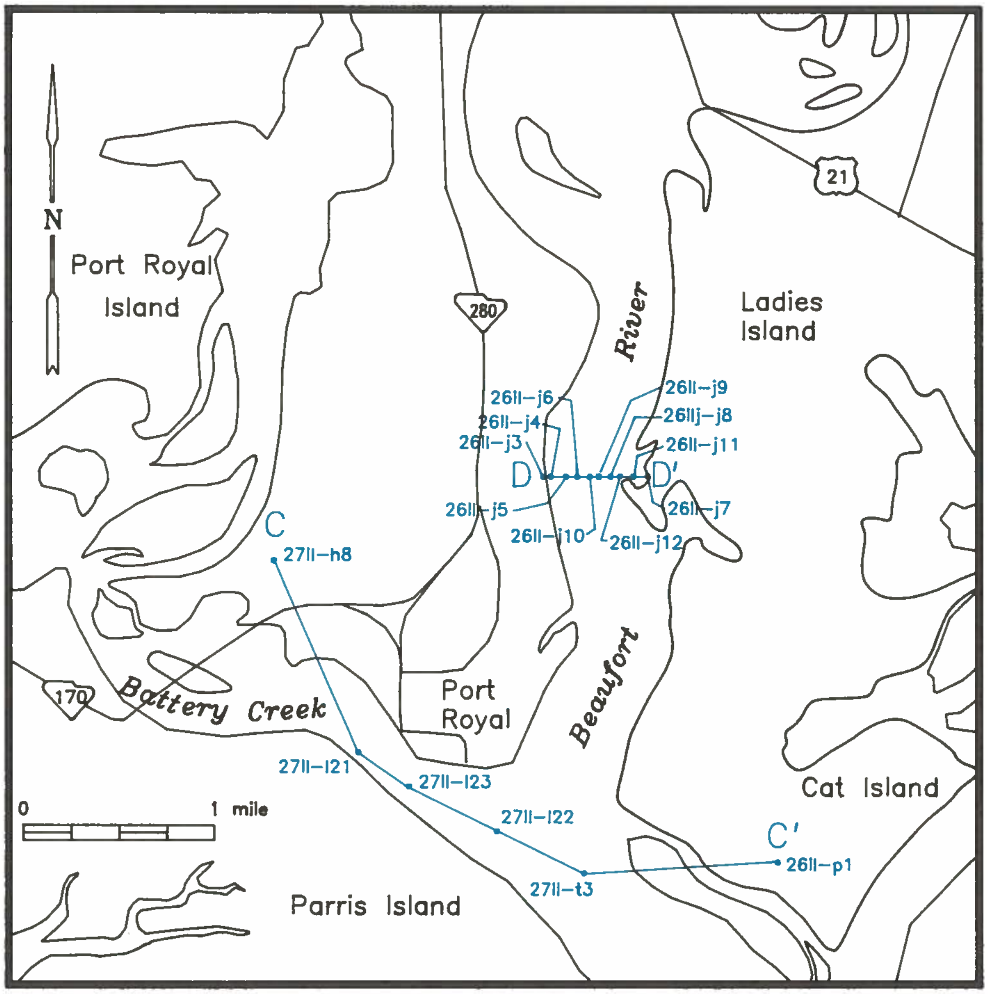

Figure 29. Location of hydrologic sections C-C′ and D-D′.

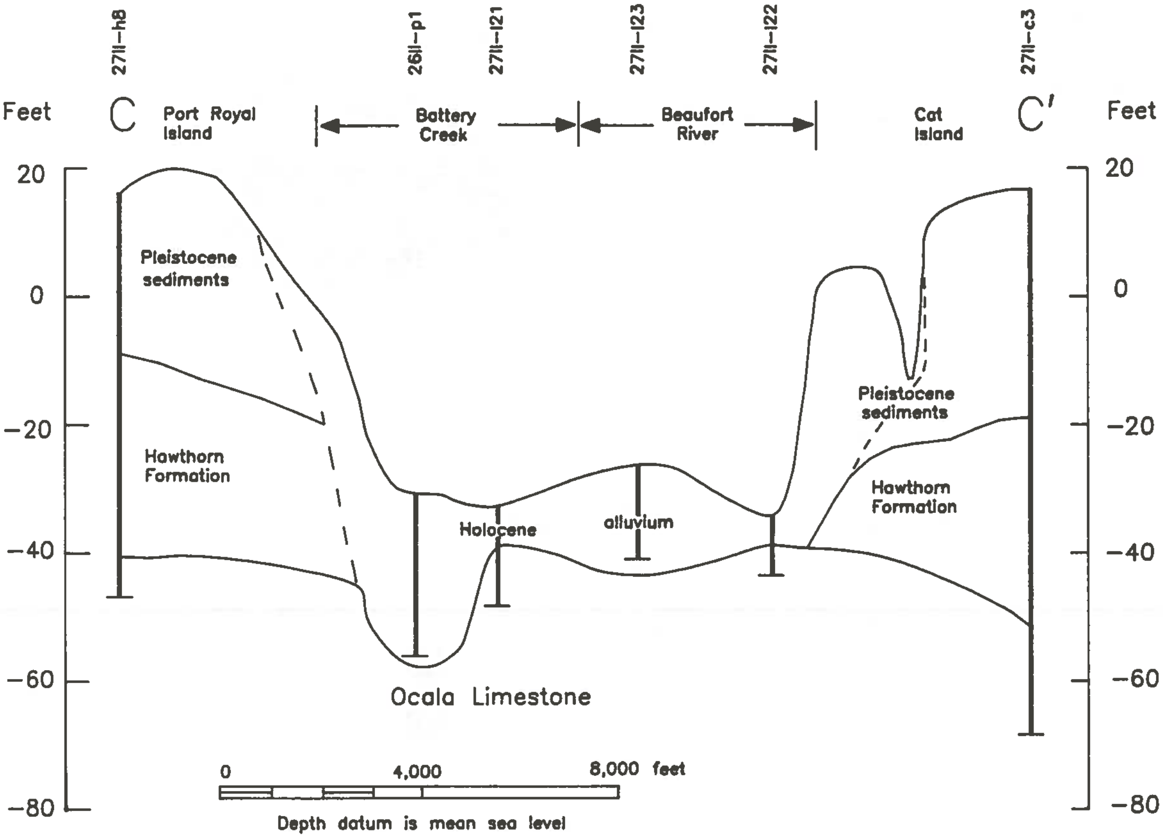

Figure 30. Section across Battery Creek and Beaufort River through the Port Royal turning basin.

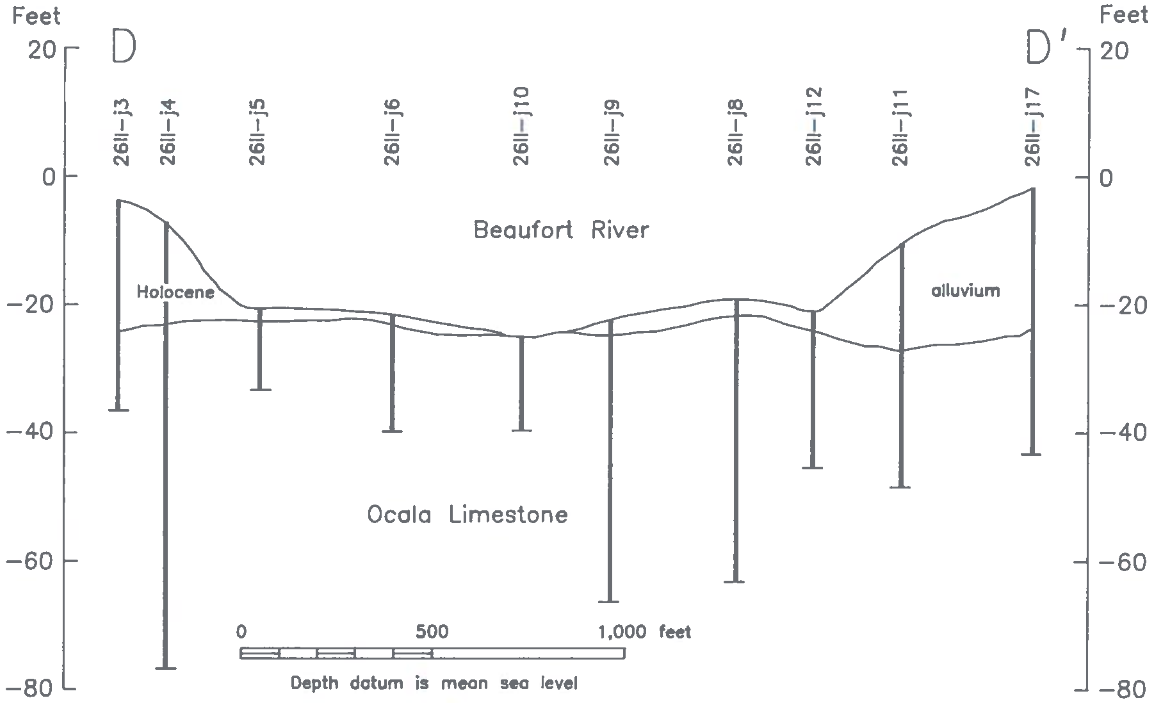

Figure 31. Section across the Beaufort River.

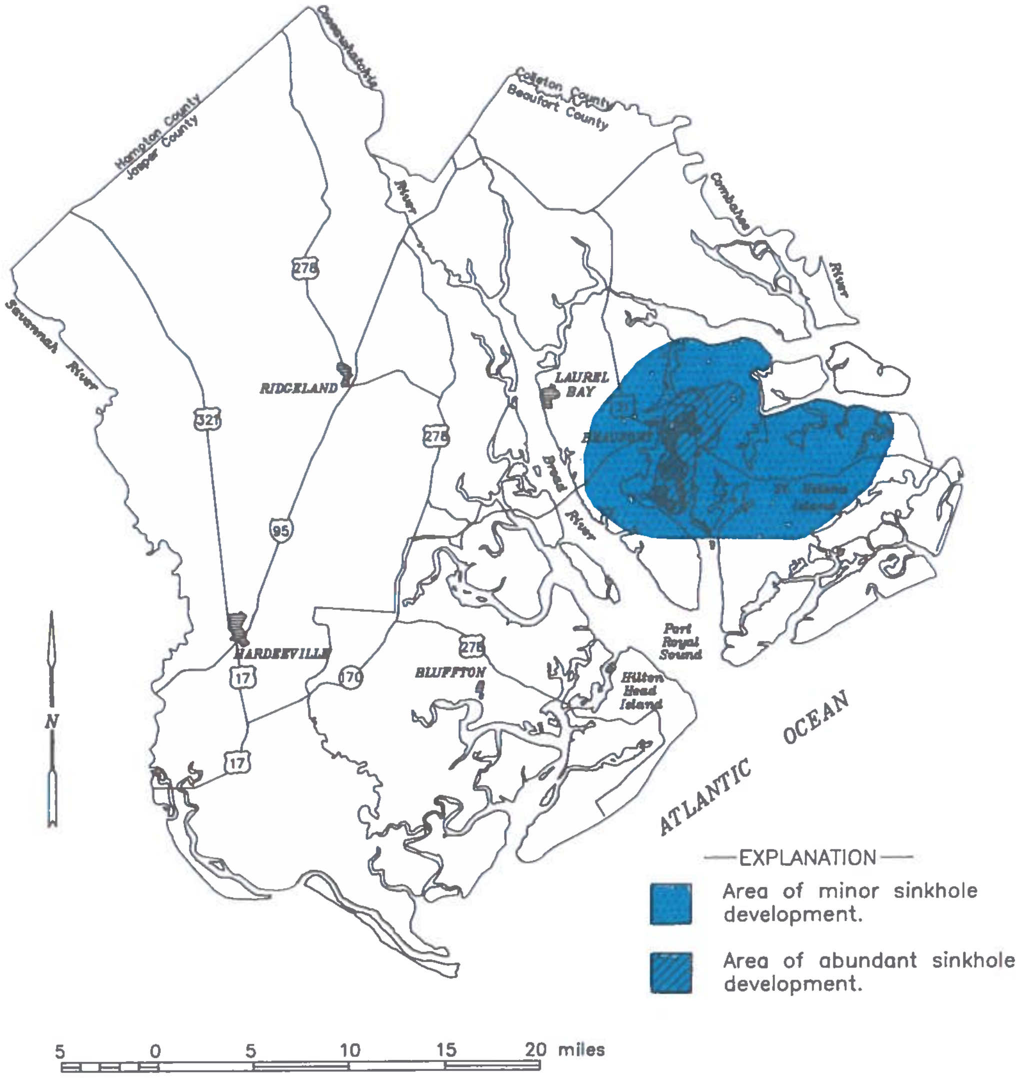

Figure 32. Distribution of sinkholes in study area.

stands of sea level during the Sangamon interglacial stage would have buried the sinks. Although further work is necessary to date the occurrence of the sinkholes, it is possible that their development is related to a lower stand of sea level during the Wisconsinan. The study of the sinkholes in the area is important because, if local water levels drop sufficiently, induced acidic recharge could cause sinkholes to develop in the future.

Phosphate mining and harbor dredging

It is possible that some breaches in the confining layer resulted directly from the activities of man. Phosphate mining took place in South Carolina between 1867 and 1910. During the course of this mining, which was often conducted by the dredging of stream channels, large sections of the confining layer could have been removed.

During a mineral survey of the state in 1842, Mr. Edmund Ruffin examined the phosphate rock but felt that its use as a fertilizer was limited (Holmes, 1870). C.U. Shepard understood the usefulness of the phosphate rock in 1859, but his plans for production were halted by the War Between the States. The first reported chemical analysis of the phosphate was performed by Dr. St. Julien Ravenel in 1867 (Holmes, 1870). Later that year, on November 29, the Charleston, South Carolina, Mining and Manufacturing Company was organized (Mappus, 1935).

In the study area, the mining was concentrated in the Coosaw River, although many of the other rivers and marshes were mined (Fig. 33). The Coosaw River was mined to a maximum depth of 20 ft and the bottom was described as "rock covered" (Mappus, 1935). The Coosaw Mining Company, which was based on Chisolm Island, was given exclusive rights to mine the navigable waters of the State of South Carolina. In 1894, 1,500,000 tons of ore was removed from the Coosaw River, representing half of the total South Carolina production. The Coosaw Mining Company was so prominent that the phosphate rock was called "Coosaw Rock" where it was sold in Europe (Mappus, 1935).

For many years the State government tried to end the exclusive-rights agreement with the Coosaw Mining Company (Mappus, 1935). The primary means to do this was for the State to increase its tax on this lucrative industry. In 1891-92 a Supreme Court injunction stopped all phosphate mining while the case between the Coosaw Company and South Carolina was resolved. While mining was shut down in South Carolina, the Florida mining took over, primarily because the Florida phosphate is of better quality and is cheaper to mine. In 1893 a hurricane destroyed all the mine works in South Carolina and the industry never recovered. By 1910, all river mining had ceased (Mappus, 1935).

Early investigators categorized the phosphate rock as two distinct types, "land rock" and "river rock" (Rogers, 1914). The land rock is a hard, irregular, brown or black, phosphate rock containing many cavities filled with black sandy clay. The river rock is composed of rounded, black pebbles of phosphate and appears to be an erosional remnant of the land rock (Rogers, 1914). The general formula for the mineral found in the phosphate rock is:

$Ca_{10}\,(PO_4, CO_3)_6\,(F, Cl, OH)_2$ (Furlow, 1969).

Malde (1959) showed that the phosphate deposits mined near Charleston were either associated with the top of the Cooper Formation or were eroded remnants of the Hawthorn Formation that had been reworked into Pleistocene sediments. In Savannah the zone with the greatest concentration of phosphate is the Upper Miocene Duplin Marl (Furlow, 1969). In the Coosaw River area, it seems likely that the phosphate deposits resulted from the erosion of either the Duplin or the Hawthorn, or both.

The impact of the phosphate mining on saltwater contamination is minor. In the Coosaw River, where most of the mining took place, the depth of the river exceeds the depth to the top of the aquifer. Therefore, the confining bed was probably missing prior to the mining. In other areas the depth of mining operations was probably not sufficient to remove the confining layer, but it may have been thinned. Since the ore zone is located at the top of the Hawthorn Formation, it is doubtful that much of the confining layer was removed by dredging.

A breached confining layer could also result from harbor dredging. During the improvement of Port Royal harbor, according to Siple (1960) "a considerable amount of limestone" was removed by the dredge. Apparently at that location a direct conduit for saltwater intrusion is present.

Offshore seismic investigation

As a part of this study, a seismic survey was made in Port Royal Sound. The data from the seismic lines and from an earlier seismic survey were correlated with the lithologic logs from the offshore wells to better understand the geologic units in Beaufort County.

The seismic surveys were conducted by Dr. James Henry of the Skidaway Oceanographic Institute. The equipment used in this research includes a ship that pulls a sled equipped with what is essentially a large loud speaker. The speaker gives off an acoustical signal that penetrates the sea floor and reflects from contacts between rocks with different densities or with different degrees of cementation. An example of such a reflector is the contact between the sandy clay of the Hawthorn Formation and the fossiliferous limestone of the Ocala. A transducer pulled in the water behind the boat picks up the returning signal. The time required for the signal to return is translated by a computer into a continuous graphic display showing the depth to each reflective horizon.

Using the offshore seismic data, it was possible to trace the top of the Ocala Limestone in areas where wells do not exist. South and southeast of Cat Island the limestone appears to have a fairly thick cover of sediment (Fig. 34), except at the mouth of the May River in Calibogue Sound where tidal scour has removed much of the overlying sediment (Duncan, 1972). To the north and northwest of Cat Island, the top of the aquifer probably is exposed or nearly exposed at the bottom of the Beaufort River, the Coosaw River, and possibly in other deep tidal streams (Fig. 35). It is difficult to assess exactly what degree of exposure exists

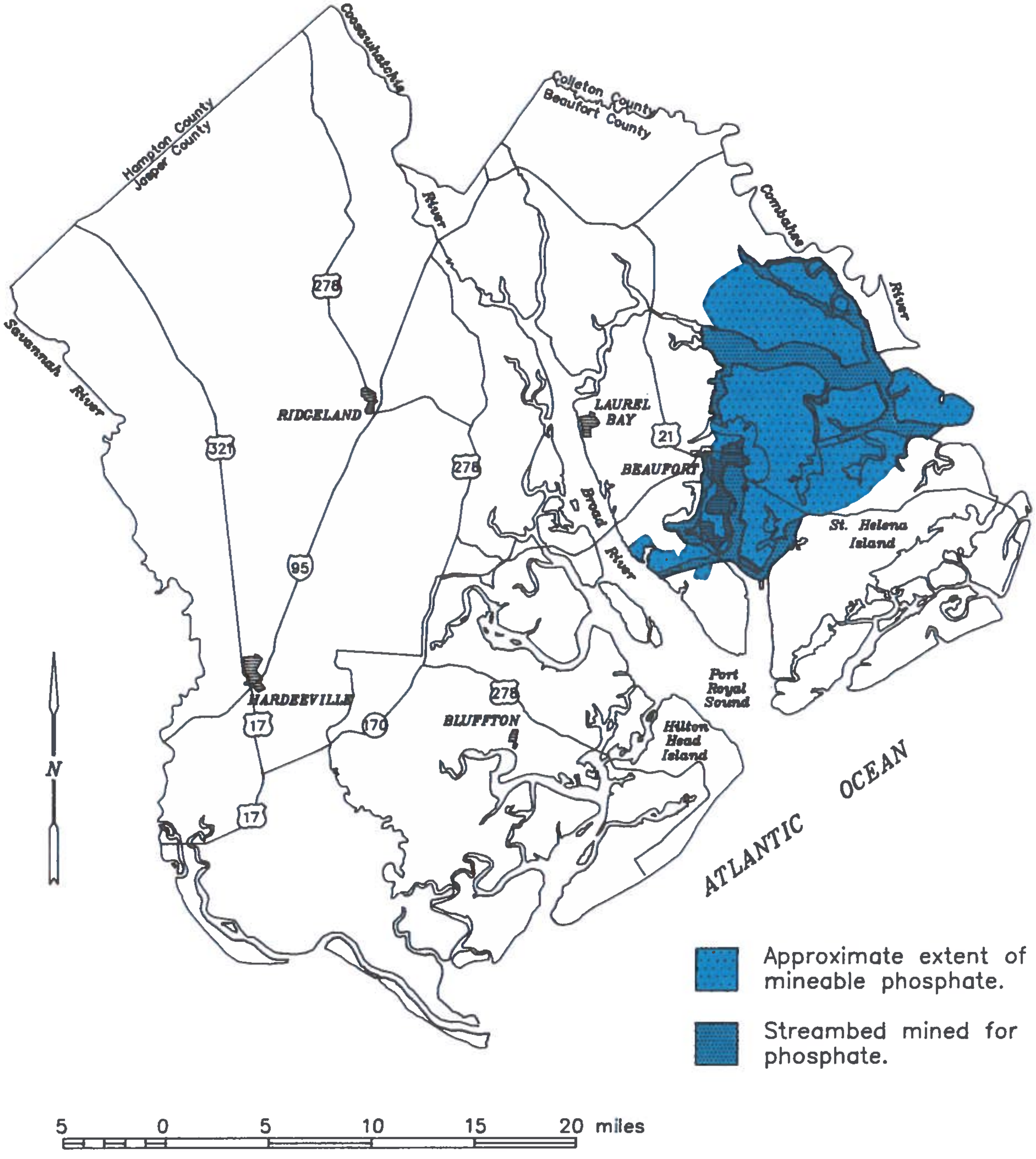

Figure 33. **Location of mineable phosphate deposits and areas mined in the Beaufort vicinity (after Rogers, 1914).**

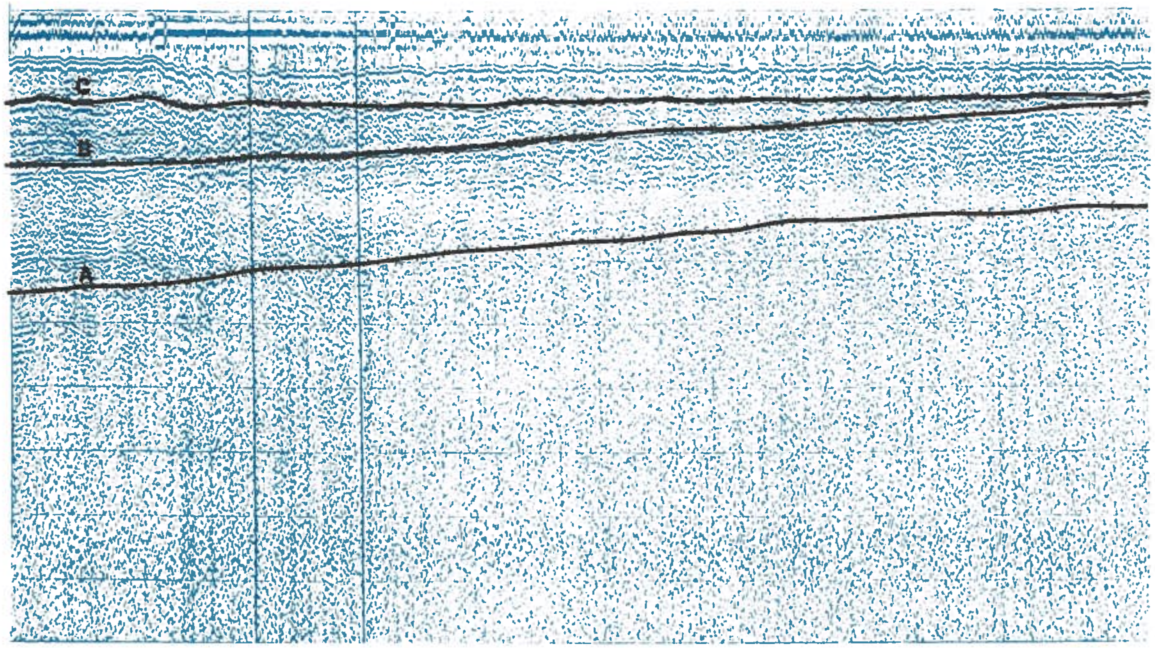

Figure 34. Seismic section of the Beaufort River near Cat Island. A, base of upper unit of Ocala Limestone; B, top of upper unit of Ocala Limestone; C, bottom of river. Note the near exposure of the limestone in the bed of the river.

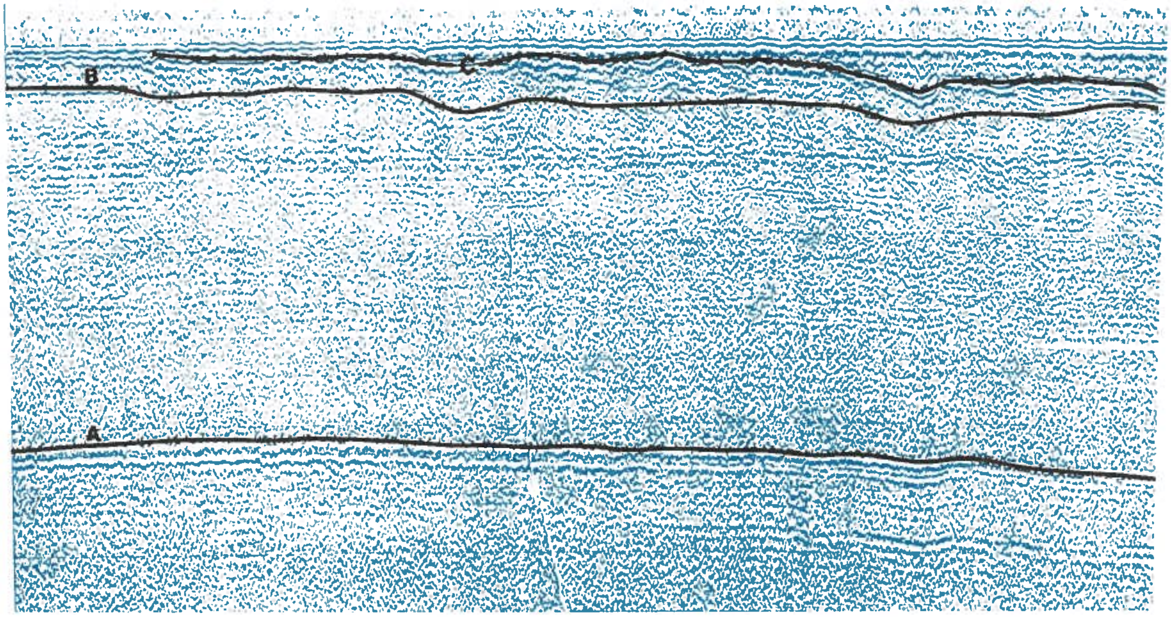

Figure 35. Seismic section of St. Helena Sound near Ladies Island. A, top of Santee Limestone; B, base of upper unit of Ocala Limestone; C, bottom of Sound.

between Cat Island and the city of Beaufort because the reflector signal that represents the top of the limestone and the direct arrival are detected simultaneously. The direct arrival is the signal that travels directly from the speaker to the transducer without being reflected by any surface. Since the only record occurs below the direct arrival, it is impossible to determine if any sediment overlies the limestone in these areas. It is clear, however, that the limestone is close to the bottom of the Beaufort River and is very likely exposed in some areas. The presence of at least one exposure is confirmed by the borings made in the Beaufort River and described earlier. This result agrees with the structure-contour maps in this report and explains the problems with localized saltwater contamination in areas adjacent to the river. The lack of a confining bed in this area will not necessarily cause problems to water users, so long as the head in the aquifer remains above sea level.

Interaquifer Transfer

Interaquifer transfer of ground water occurs where two or more aquifers are connected by wells. Water from the unit with the higher head will tend to flow into the unit of lower head. If the aquifer with the higher head is salty, then contamination of the other aquifer can occur. Interaquifer transfer occurs in the study area primarily as a result of improper well construction. The standard well construction technique recommended for the study area is shown in Figure 36.

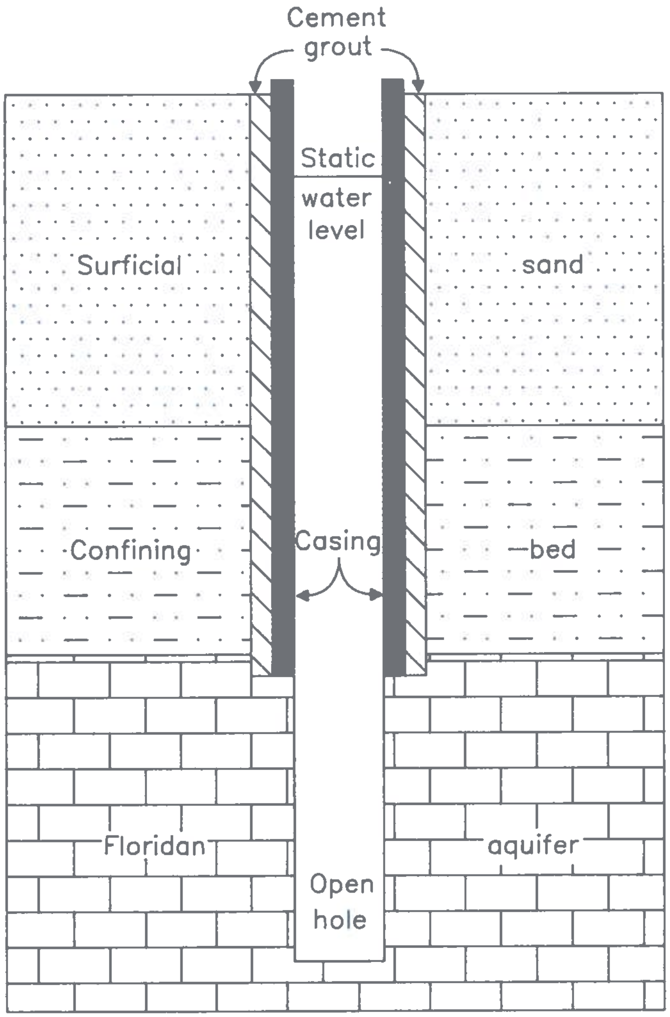

Figure 36. Recommended construction for wells open to the Floridan aquifer in Beaufort and Jasper Counties.

At least 23 wells in Beaufort County and 15 wells in Jasper County are open to a portion of the Hawthorn Formation (Fig. 37A). At two locations saltwater contamination has occurred. At Windmill Harbour on Hilton Head Island, well 28KK-15 is cased in the bottom 8 ft of the Hawthorn. Chloride concentration as high as 12,000 mg/L was measured adjacent to the Hawthorn section. Lower chloride values were measured with depth in this well. Two wells at Pinckney Colony (29JJ-e1 and 29JJ-e4) are open to 20 ft of Hawthorn Formation. Chlorides of approximately 3,000 mg/L were measured in these wells. At both Windmill Harbour and Pinckney Colony the Hawthorn is probably in contact with nearby saltwater bodies and pumping from a nearby well causes saltwater to move laterally toward the well and then downward into the Floridan.

Contamination could also result through interaquifer transfer if a well is open to both the Floridan aquifer and one of the deeper Tertiary or Cretaceous aquifers (Fig. 37B). In this example, because of the higher head in the deeper unit, salty or mineralized water would move vertically up the well bore into the Floridan aquifer. No examples of this type of contamination have been observed in the study area, but similar occurrences have been reported in Charleston where wells interconnect the Floridan aquifer and the underlying Black Mingo Formation (Park, 1985).

Upconing

Upconing occurs where saltwater at the bottom of an aquifer is drawn upward owing to pumping (Fig. 38). In an aquifer containing variable-density water, saltwater will occur beneath freshwater because it is heavier than freshwater. As pumping reduces the freshwater head the saltwater is drawn upward, eventually entering the well. When pumping ceases, the saltwater moves back down to the bottom of the aquifer. A local example occurs at the Waddell Mariculture Center near Victoria Bluff.

Waddell Mariculture Center is located in southwestern Beaufort County. It is bounded by the Colleton River on the north and Sawmill Creek on the east. Ground water in the area is fresh (Nuzman, 1970). The center constructed a well (28JJ-n2) to supply water for the fish ponds and a public-supply well (28JJ-n3) for drinking water. Well 28JJ-n2 was drilled to -172 ft msl and casing was set to -93 ft msl. Chlorides in the well proved to be high, ranging from about 140 mg/L at -100 ft to nearly 1,800 mg/L at the bottom (Fig. 39) on April 29, 1984. A water sample collected on April 30, 1984, while the well was pumping 1,600 gpm, had 2,400 mg/L chloride, higher than any water in the well bore. The pumped water was evidently a mixture that included water from below the bottom of the well.

Further evidence of upconing is provided by the public supply well (28JJ-n3). This well is 300 ft from 28JJ-n2 and

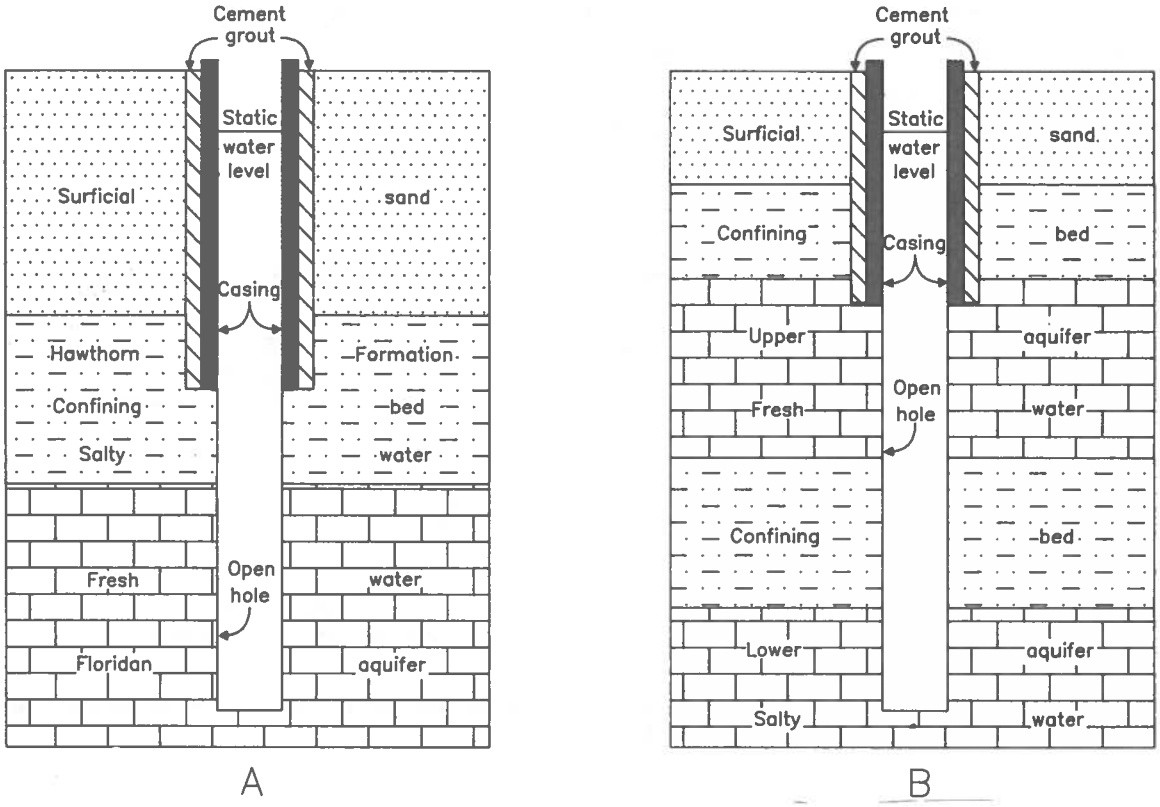

Figure 37. Relationship between well construction and saltwater contamination.

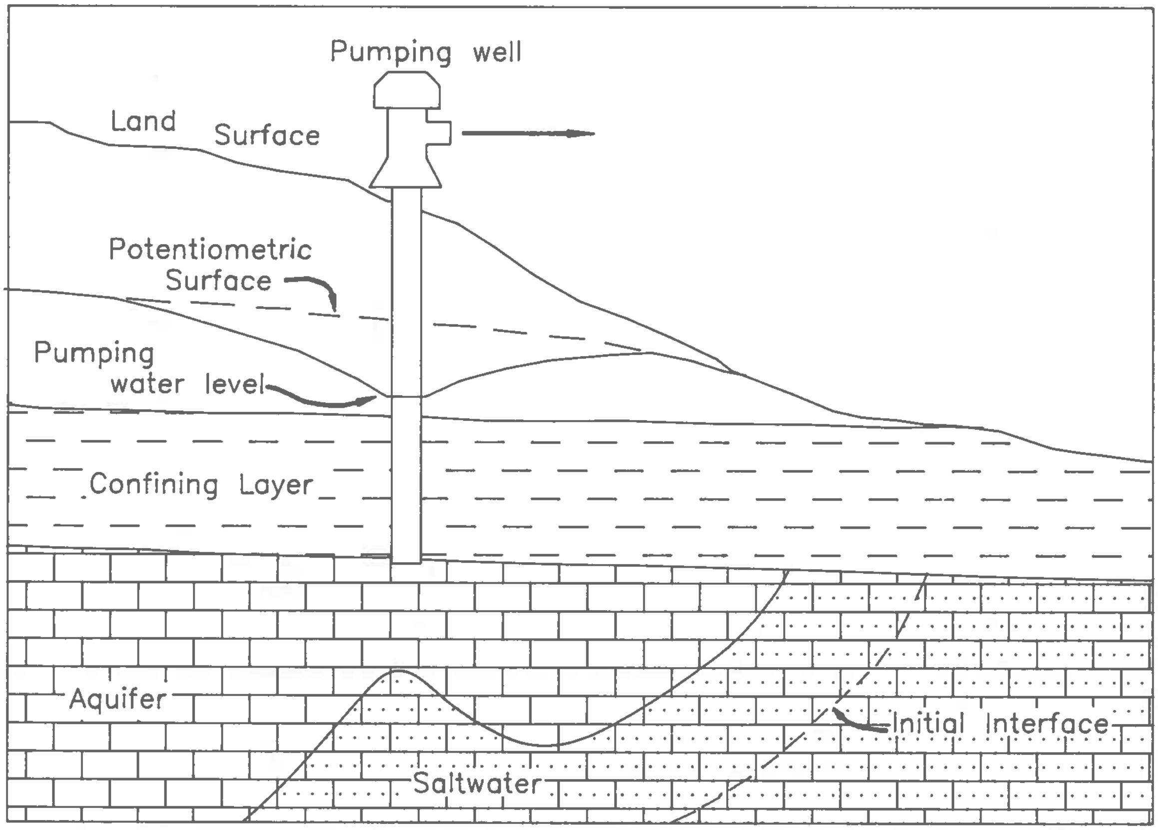

Figure 38. Schematic diagram of lateral intrusion and upconing.

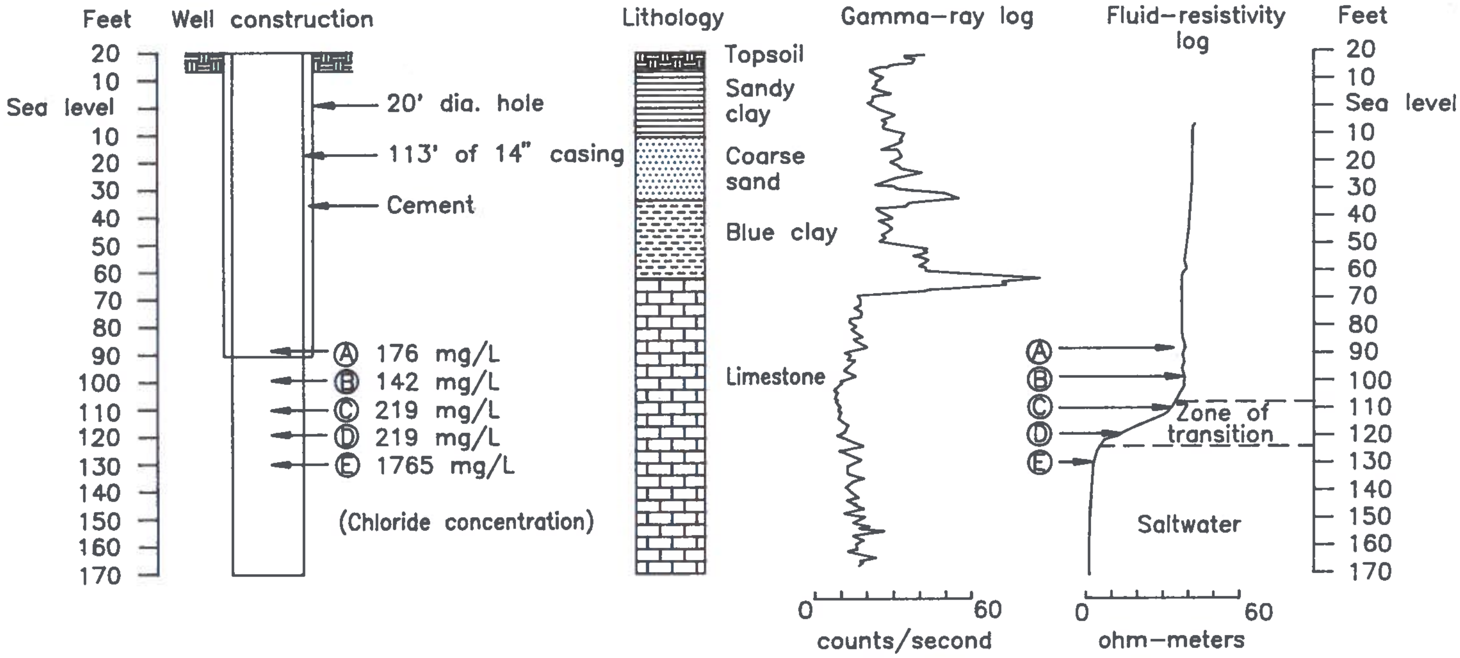

Figure 39. Diagram showing well construction, lithology, and vertical distribution of chloride in well 28JJ-n2 at Victoria Bluff (after Spencer and Parks, 1984).

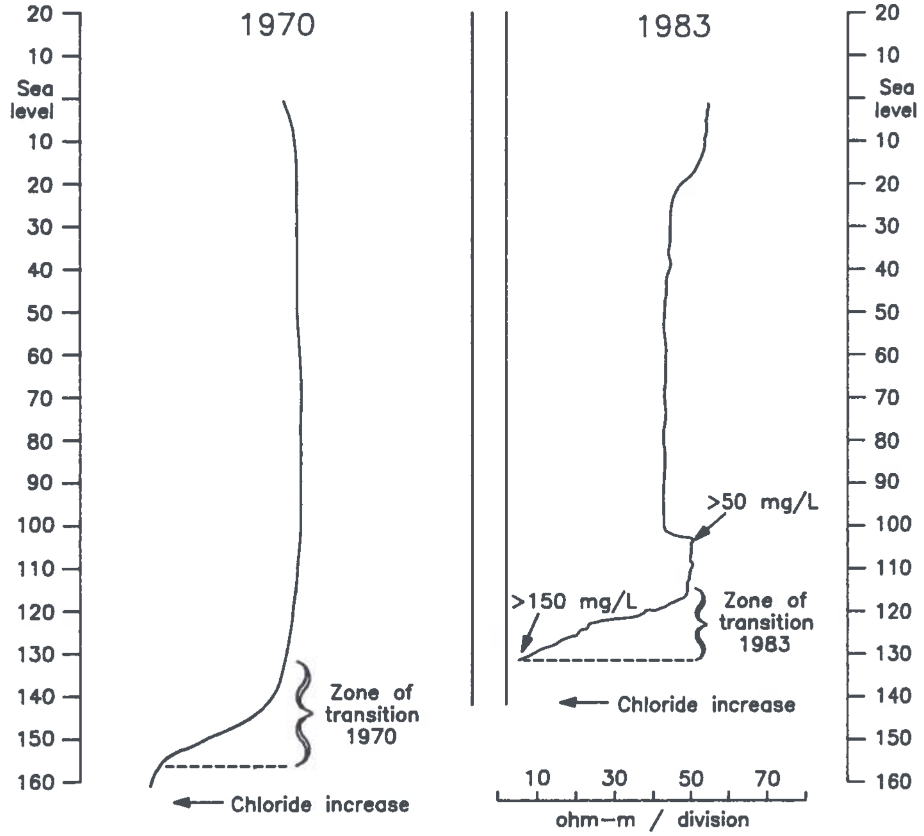

Figure 40. Diagram showing movement of saltwater-freshwater interface, from fluid-resistivity logs of 28JJ-n1 (after Spencer and Park, 1984).

was originally drilled to a depth of -180 ft msl, with casing set to -86 ft msl. Water pumped from the well had a chloride concentration of 1,700 mg/L. A fluid-resistivity log of the well showed a significant decrease in resistivity at -109 ft msl, so the well was backfilled with concrete. Water samples collected after backfilling showed a chloride concentration of 83 mg/L. By January 25, 1985, the chloride concentration had risen to 470 mg/L, owing to increased pumping and water being drawn upward from below the well bottom.

Evidence shows that both upconing and lateral intrusion are occurring in the area. Fluid-resistivity logs from well 28JJ-n1 illustrate the evidence of lateral intrusion. Comparison of fluid-resistivity logs made in 1970 and 1983 show that the freshwater-saltwater interface has risen 15 ft (Spencer and Park, 1984) (Fig. 40). Well 28JJ-n1 is a nonpumping observation well, and the increase in interface elevation is evidence that the toe of the interface is moving down the gradient. As the elevation of the interface increases, upconing effects become more evident. Water that was coming from the lower portion of the aquifer increases in chloride concentration, as does the water pumped from the well. This contamination at Victoria Bluff might be the result of a localized saltwater plume moving downgradient toward Savannah, Ga., and being drawn upward into pumping wells at the mariculture center.

SUMMARY AND CONCLUSIONS

Water quality in the Cretaceous Formations of the study area makes them generally unsuitable for a water supply unless the water is blended or treated by reverse osmosis. The post-Eocene formations, including the Hawthorn, Duplin, Waccamaw, and Pamlico Formations, supply some small domestic wells; however, problems with low yields and local saltwater contamination make these units unsuitable for most industrial or public water systems. The main supply of ground water for the region comes from the Floridan aquifer, primarily the upper unit of the Ocala limestone but also including permeable zones in the lower unit of the Ocala limestone and the top of the Black Mingo Formation. Salty water occurs in the lower zones of the Floridan aquifer in places.

Ground water conditions in the study area are related to geologic structure. The Burton High, where the limestone is near the land surface, provides recharge areas in Beaufort County as well as potential areas for saltwater contamination.

On a regional basis, the upper unit of the Floridan aquifer responds similarly to an unconsolidated sand aquifer. Transmissivities range from 500 ft^2/day in the northern Port Royal Island area to 70,000 ft^2/day in the Hilton Head area. One factor controlling the transmissivity distribution is aquifer thickness. The hydraulic conductivity, transmissivity divided by aquifer thickness, is between 350 and 450 ft/day over the entire study area except the northern part of Port Royal Island, where it ranges from 50 to 150 ft/day. Contour maps of the aquifer's thickness and transmissivity show similar orientation of contours, indicating a direct relationship.

Industrial and public-supply systems in and near Savannah currently withdraw about 75 mgd from the Floridan aquifer. This withdrawal has caused a large cone of depression to form around Savannah, with water levels of -120 ft msl at the center of the cone, 160 ft lower than the original water level of 40 ft msl. Potentiometric declines over much of the study area have caused a reversal of the hydraulic gradient and direction of flow in the aquifer. This change in the flow direction, coupled with the proximity to the coast, has caused concern for the quality of the resource. The reversal of flow in the Port Royal Sound area probably occurred prior to 1958, and saltwater encroachment has been occurring since that time.

Areas of the Floridan aquifer with potentiometric heads at or below sea level and overlain by saltwater bodies could become contaminated by vertical leakage of seawater. A good confining clay unit overlies the limestone in most areas, however, and affords at least short-term protection to the resource. Calculations show that at least 200 years would be required for seawater to move through a 30-ft layer of confining unit if the potentiometric head of the aquifer were 1 ft below sea level. Considerably less time would be required for seawater diluted by diffusion to move through a 30-ft confining unit. If the confining unit is breached, saltwater can move directly into the aquifer. Seismic profiles have shown the confining unit to be absent or thin in portions of the Beaufort River, Battery Creek, St. Helena Sound, and Coosaw River.

Phosphate mining occurred in much of the Beaufort area, but may not have contributed significantly to saltwater contamination because the confining unit was already thin or absent where the mining occurred. Where the confining unit was breached by mining or by natural processes, the head is presently sufficient to prevent saltwater contamination.

Lateral encroachment of saltwater northeast of Hilton Head Island is the major regional problem facing future water-supply development. Naturally occurring saltwater has long been present half a mile to a mile upgradient from Hilton Head Island. Neglecting dispersion, the rate of movement of the saltwater zone downgradient is approximately 100 ft a year. Even though the rate of movement can only be approximated, it may be safely said that the saltwater boundary is moving toward Hilton Head.

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