THE GROUND-WATER RESOURCES OF BEAUFORT, COLLETON, HAMPTON, AND JASPER COUNTIES SOUTH CAROLINA

By
Larry R. Hayes

SOUTH CAROLINA
WATER RESOURCES COMMISSION

REPORT NUMBER 9

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STATE OF SOUTH CAROLINA

Honorable Richard W. Riley, Governor

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The Ground-Water Resources of Beaufort, Colleton, Hampton and Jasper Counties, South Carolina

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Prepared by
U. S. Geological Survey
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Columbia, South Carolina

1979

State of South Carolina
Water Resources Commission

Clair P. Guess, Jr.
Executive Director

May 31, 1979

LETTER OF TRANSMITTAL

Honorable Richard W. Riley, Governor
and Members of the General Assembly of the
State of South Carolina

Gentlemen:

I have the honor to transmit herewith Report No. 9 of the S. C. Water Resources Commission, entitled "The Ground-Water Resources of Beaufort, Colleton, Hampton, and Jasper Counties, South Carolina." This report, authored by Larry R. Hayes, Hydrologist, U. S. Geological Survey (WRD) represents the results of a four-year cooperative study by the S. C. Water Resources Commission and U. S. Geological Survey. The report is the first phase of a ground-water capacity use investigation of the Low Country area conducted pursuant to the S. C. Ground Water Use Act of 1969.

The four counties covered in the study are underlain by a thick sequence of water-bearing formations (aquifers) that supply most of the water for rural domestic and public drinking-water supplies, and agricultural and industrial supplies. The most heavily utilized aquifer, the principal artesian aquifer, yields excellent supplies of ground water for most of the area. However, salt-water encroachment and other problems identified in this report are causing serious water-supply problems for many residents and industrial and agricultural water users.

Report No. 9 contains much of the technical ground-water data needed to address the ground-water problems of the area. Results of this study will aid in the proper development and management of the ground-water resources of this part of South Carolina.

Respectfully,

Clair P. Guess, Jr.

Clair P. Guess, Jr.
Executive Director

CPGJr:dd

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CONVERSION FACTORS

U.S.Customary Units	Multiply By	Metric Units
ft (feet)	3.048×10^{-1}	m (meter)
ft/d (feet per day)	3.048×10^{-1}	m/day (meter per day)
ft/s (feet per second)	3.048×10^{-1}	m/s (meter per second)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meter per second)
ft^2/d (square feet per day)	9.290×10^{-2}	m^2/day (square meter per day)
gal (gallon)	3.785	L (liter)
gal/min (gallon per minute)	6.309×10^{-2}	L/s (liter per second)
(gal/min)/ft (gallon per minute per foot)	2.070×10^{-1}	(L/s)/m (liter per second per meter)
$(gal/min)/in^2$ (gallon per minute per square inch)	$9.778 \times 10^{+1}$	$(L/s)/m^2$ (liter per second per square meter)
in (inch)	2.540	cm (centimeter)
in (inch)	$2.540 \times 10^{+1}$	mm (millimeter)
in^2 (square inch)	6.452×10^{-4}	m^2 (square meter)
mi (mile)	1.609	km (kilometer)
Mgal/d (million gallons per day)	.04381	m^3/s (cubic meter per second)

Temperature conversion

°F (degree Fahrenheit)	5/9(°F-32)	°C (degree Celsius)

The Ground-Water Resources of Beaufort, Colleton, Hampton and Jasper Counties, South Carolina

by

Larry R. Hayes

ABSTRACT

In 1976, Beaufort, Colleton, Hampton, and Jasper Counties used an estimated 7.6 billion gallons of ground water, with about 6.2 billion gallons coming from the principal artesian aquifer. Southwest of the study area the city of Savannah, Georgia and nearby industries pump 75 Mgal/d (million gallons per day) from the principal artesian aquifer. As a result of these withdrawals, water level declines of 20 to about 100 feet have occurred.

With the exception of the Savannah River, the surface water in Beaufort and Jasper Counties is generally too salty for human consumption. In Hampton and Colleton Counties fresh surface water is available but it is not used to any significant extent. The Beaufort-Jasper Water Authority supplies about 5 Mgal/d of treated Savannah River water to the military installations in Beaufort, the residents of the Beaufort-Port Royal area, and some of the residents of Ladies Island.

Sedimentary rocks, ranging in age from Late Cretaceous to Holocene and ranging in thickness from about 2,500 feet in the northern part to about 3,500 feet in the southern part of the study area, store and supply all the ground water used in the area.

Rocks of Tertiary age, consisting of the Black Mingo Formation, Santee Limestone, Cooper Marl, and Hawthorn Formation, are the chief sources of ground-water supplies in the study area. The Black Mingo aquifer is a source of 50 to 250 gal/min (gallons per minute) of good quality water in Colleton and Hampton Counties, but is not used in Beaufort or Jasper Counties.

The Santee Limestone and lower part of the Cooper Marl form the principal artesian aquifer and furnish most of the ground water used in the area.

The principal artesian aquifer is divided into (1) an upper permeable zone, which furnishes about 75 percent of the water pumped from this aquifer in Hampton County and nearly all of the water pumped from this aquifer in Beaufort and Jasper Counties; (2) a middle zone of relatively low permeability, which yields small amounts of water to wells in Hampton and Colleton Counties; and (3) a lower permeable zone, which provides most of the water pumped from this aquifer in Colleton County.

The average transmissivity of the upper permeable zone ranges from about 10,000 ft^2/d (square feet per day) to about 50,000 ft^2/d. The transmissivity of the lower permeable zone ranges from about 500 ft^2/d to about 5,000 ft^2/d. The transmissivity of both zones decreases to the north and east. Yields of wells open to the principal artesian aquifer range from about 50 gal/min to about 2,500 gal/min. Except where saltwater contamination occurs, water from the principal artesian aquifer is usually of good quality. Saltwater contamination of the principal artesian aquifer is usually of good quality occurs from two sources: (1) sea water entering the aquifer through breaks or in areas of relatively high permeability in the overlying confining bed and (2) conate salty water present in underlying formations and in the lower two zones of the aquifer moving upward into the upper permeability zone.

Water containing more than 1,500 mg/L (milligrams per liter) of chloride is present throughout the aquifer at Parris Island, Fripp Island, Edisto Beach, and probably other small sea islands southeast of Beaufort. Salty water is present in the middle and lower permeable zones of the principal artesian aquifer in Beaufort County, in southern Colleton County, and maybe in southern Jasper County.

Water containing about 50 mg/L of chloride is present in the upper permeable zone of the principal artesian aquifer at Hilton Head Island. Salty water is moving laterally toward Hilton Head Island from the northeast and east and vertically upward from the middle and lower permeable zones. Estimates of the rate of salt-water movement towards Hilton Head Island range from 140 to 360 ft/yr (feet per year).

The upper and lower sections of the Hawthorn Formation act as confining beds. The middle section of the Hawthorn is a fairly persistent, sandy, dolomitic limestone (Hawthorn aquifer) and is a source of 50 to 200 gal/min of fairly good quality water in western Beaufort County and in Jasper County.

INTRODUCTION

Ground water is used throughout Beaufort, Colleton, Hampton, and Jasper Counties for domestic, public, agricultural, and industrial purposes. While ground water of sufficient quality and quantity is available almost everywhere in this area, previous investigations have shown that progressive lowering of water levels, impairment of quality, and decrease of quantity in some areas have raised concern that overpumping or improper development might be depleting the aquifers and aggravating the saltwater contamination problem.

The Ground Water Use Act of 1969 [Section 4.(a)] requires that: "The South Carolina Water Resources Commission (SCWRC) upon the request of a county, municipality or other political subdivision of State government, may declare and delineate from time to time, and may modify, capacity use areas of the State where it finds that the use of ground water requires coordination and limited regulation for protection of the interest and rights of residents or property owners of such areas or of the public interest." Prior to declaring a capacity use area, the act requires that an investigation be made to determine if the water problems are significant enough to warrant such an action.

The implementation of such a study was requested by the public officials of Beaufort, Colleton, Hampton, and Jasper Counties. These officials believed that present as well as projected use and development of the ground-water resources had reached a point where assessment and management were necessary. They also believed that a properly designed and implemented ground-water investigation was needed to determine what must be done to insure the availability of water of sufficient quantity and quality for meeting increasing water demands. The SCWRC agreed that a comprehensive ground-water investigation was needed and asked the U.S. Geological Survey to participate in a cooperative study as a part of the Survey's nationwide interest in coastal aquifers.

PURPOSE AND SCOPE OF INVESTIGATION

The fundamental objectives of the study were to collect and interpret data on the geologic, hydraulic, physical, and chemical characteristics of the ground-water system of Beaufort, Colleton, Hampton, and Jasper Counties so that:

(1) An evaluation of the extent, character, and chemical quality of the freshwater-resource system could be made;
(2) The source, rates of movement, directions of flow, and areas of recharge and discharge of the ground water could be determined;
(3) The sources, directions, and rates of movement of saltwater into freshwater aquifers could be evaluated;
(4) The danger to the ground-water resources from saltwater contamination under various conditions as well as the factors governing saltwater intrusion could be determined;
(5) Areas capable of yielding long-term supplies of freshwater could be identified; and
(6) The hydraulic, physical, and chemical properties of the ground-water system could be graphically presented.

This report is intended to serve as a comprehensive reference for persons responsible for developing, managing, and using the water resources. The results of this study may be of use to other coastal and coastal-plain counties where similar geologic and hydrologic conditions exist.

LOCATION OF STUDY AREA

The Lowcountry area, which consists of Beaufort, Colleton, Hampton, and Jasper Counties, is the area under study in this report (fig. 1). The study area, about 2,960 square miles in extent lies between long 80°20' and 81°25' W., and lat 32°00' and 33°10' N. It is bordered on the west and southwest by the Savannah River, on the northeast and east by the Edisto River and by the South Edisto River, and on the southeast by the Atlantic Ocean.

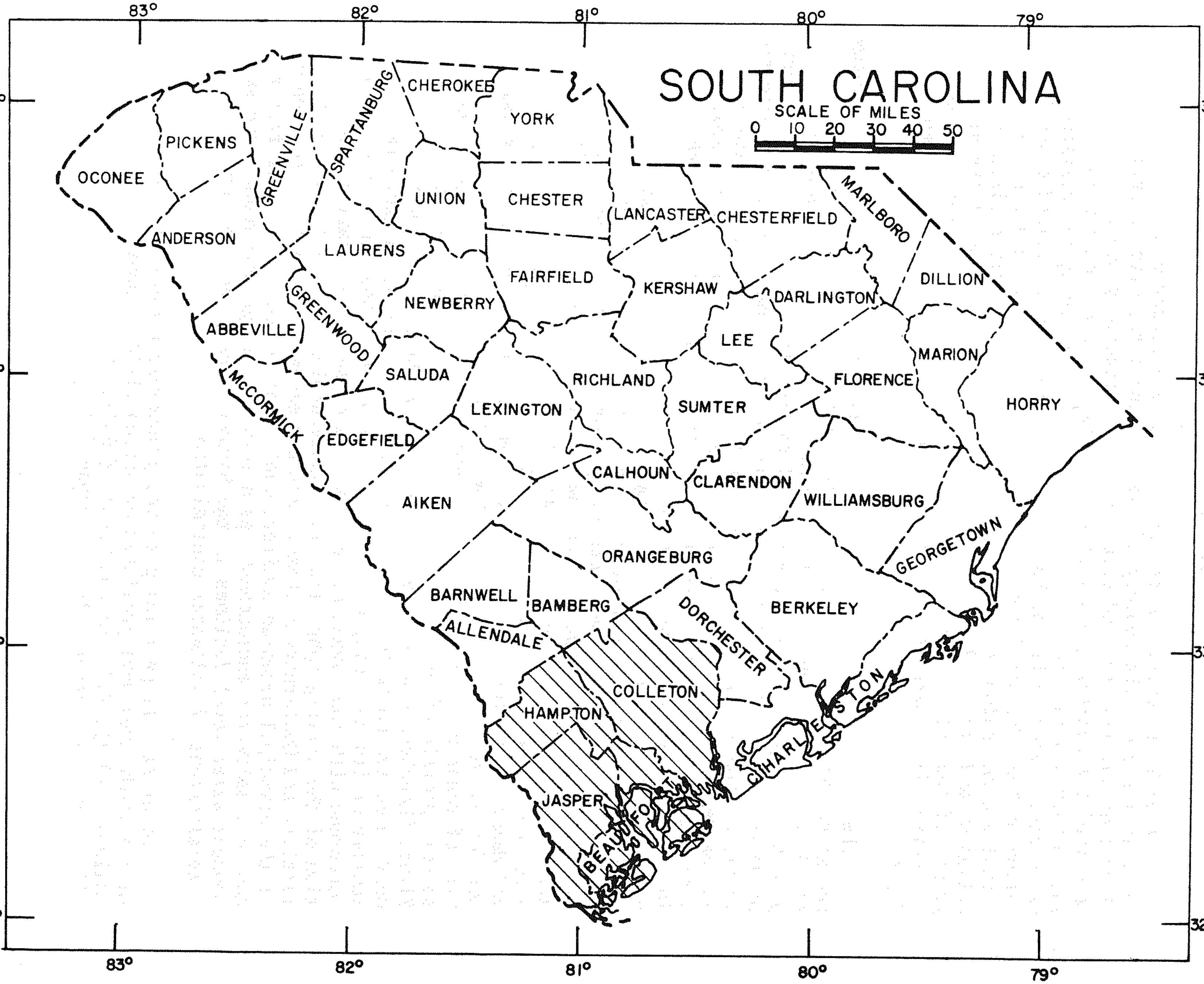


Figure 1. Area of investigation

PREVIOUS INVESTIGATIONS

The earlier reports in the study area were concerned mostly with generalities about the geology of the area and lithologic descriptions of driller samples from individual wells. A report by Cooke (1936) described the general geology of the Coastal Plain of South Carolina and contained a map showing surficial geology underlying the Pleistocene sediments. Later Cooke and MacNeil (1952) presented a revised classification of the Tertiary formations of South Carolina, with a representative lithologic and paleontologic description for each formation discussed. Colquhoun and others (1969) provided a concise description of the stratigraphy of the Paleocene and Eocene strata from their northernmost exposure in Central South Carolina to Burke and Screven Counties in north central Georgia.

The first report to discuss in any detail the relation between geology and ground water in the Lowcountry area (Mundorff, 1944) was prepared for the U.S. Navy Department at Parris Island. This report discussed the general geology of the area, presented the results of several pumping tests on wells owned by the Marine Corps, and included a map showing the potentiometric surface of the principal artesian aquifer. Siple (1956) and Hazen and Sawyer (1956) presented an evaluation of the adequacy of the ground water supply to meet the existing and future military and civilian needs. This report concluded that saltwater encroachment could pose a serious problem in the Beaufort area. A supplement to this study (Hazen and Sawyer, 1957) provided pumping test data from wells in Jasper County and compared the Savannah River water-supply project, the Combahee River water supply project, and a ground-water supply project west of Broad River. Siple (1960) presented a summary of the geology and ground-water resources of Beaufort and Jasper Counties and the lower half of Colleton and Hampton Counties, with particular emphasis on the principal artesian aquifer and on the water needs of the Marine Corps facilities near the City of Beaufort. Duncan (1972) presented the results of a high resolution seismic profile of Port Royal Sound and portions of Beaufort River, Broad River, Cheechessee River, Colleton River, and Skull Creek, with the primary objective being to delineate the top of the principal artesian aquifer or its confining bed. Counts and Donsky (1963) in a study mainly concerned with the Savannah, Georgia area presented a detailed description of the stratigraphy, lithology, paleontology, and hydrology of the Tertiary and Quaternary Systems. Primary emphasis was on the geohydrology of the principal artesian aquifer, quality and quantity of water from this aquifer, saltwater encroachment as a result of large withdrawals and subsequent water-level declines in the Savannah area, and the vertical and lateral extent of saltwater contamination.

Other studies pertaining to the ground-water resources and geology of the study area were published by Warren (1944), Counts (1958), Callahan (1964), McCollum and Counts (1964), Stringfield (1966), Siple (1967), Back and others (1970), Nuzman (1970 and 1972), and Comer (1973).

DATA COLLECTION AND METHODS OF ANALYSIS

GEOLOGIC DATA

Much basic geologic information for this study was obtained through cooperation of, and close liason with, well drillers and their clients. Throughout the period of investigation, caliper, electric, natural gamma, gamma-gamma and neutron logs and drill cuttings (when available) were obtained from selected wells drilled by commercial well drillers. However, existing wells did not provide sufficient information. Therefore a test drilling program was necessary to obtain geophysical logs, drill cuttings, and hydrologic data from areas where no wells existed or where information obtained from existing water wells was inadequate. The Coastal Plains Regional Commission provided funds to SCWRC to drill 25 test wells under commercial contract. An additional six test wells were drilled by the South Carolina State Development Board, Division of Geology (S.C. Dev. Bd. Div. Geol.). The State Ports Authority provided funds to drill three test wells at Port Royal, and the City of Beaufort provided funds to drill one test well at the Beaufort City Marina. In 1971 the South Carolina Department of Highways and Public Transportation drilled test holes across the Beaufort River in the vicinity of the Naval Hospital and test holes across Battery Creek in the Port Royal Turning Basin between Port Royal and Parris Island that provided additional important information.

Natural gamma-radiation, spontaneous-potential, electric resistivity, gamma-gamma, neutron and flow-meter logs were used as an aid in delineating and correlating stratigraphic units and water-yielding zones. Caliper logs were used to evaluate borehole conditions, to provide an indication of fracture and solution characteristics of water-bearing zones in the principal artesian aquifer, and to determine the degree of cementation of materials in rock units. Flow-meter logs were used to delineate relative high water-yielding zones. Geophysical logging for the study was done by the Survey's loggers.

Gamma-ray logs were the primary correlation tool used because confining materials overlying the Tertiary aquifer system in the study area contain phosphate and glauconite. Both phosphate and glauconite emit a much higher gamma-radiation count than do clay, sand, or limestone. Consequently, material containing phosphate or glauconite can be easily traced from well to well by means of the gamma-ray logs.

Columnar sections were prepared from information obtained from the drill cuttings and the columnar sections were compared to the geophysical logs. Formations were distinguished by and correlations were made on the basis of lithology, paleontology, geophysical characteristics, and stratigraphic position.

HYDROLOGIC DATA

The main sources of temperature, precipitation, evaporation and other climatological data are the monthly bulletins entitled "Climatological Data" published by the National Oceanic and Atmospheric Administration (NOAA). NOAA maintains precipitation and temperature gages at Hampton, Walterboro, Yemassee, Ridgeland, Beaufort, and Hilton Head Island.

Data concerning streamflow and stage measurements in and adjacent to the study area are available from various publications of the Survey and SCWRC. Daily records of streamflow are available from the Survey's gaging stations shown in figure 6. Discharge measurements made during periods of high and low flow at sites other than gaging stations are also available.

Water-level fluctuations in the principal artesian aquifer were measured periodically with a steel tape in about 500 wells open only to the principal artesian aquifer. Eight wells were equipped with hourly recording gages. Additional hydraulic data regarding the principal artesian aquifer were obtained from aquifer tests.

QUALITY OF WATER DATA

Samples of water were taken from wells throughout the study area to obtain reliable information about the overall chemical character of the ground water. Field determinations of pH, specific conductance, temperature, iron, chloride, and hardness were made using standard field methods. Detailed chemical analyses were conducted by the Survey's Water Quality Laboratory, Doraville, Georgia, and by the SCWRC laboratory.

In order to determine the extent of saltwater contamination of the ground-water resources for this study, samples from about 180 wells that reflected significant movements of saltwater in the aquifer were collected quarterly and were analyzed for chloride concentration using standard field methods. On a one time basis, the water samples were analyzed by the SCWRC Water Quality Laboratory.

WELL-NUMBERING SYSTEM

The well numbers used in this report were assigned consecutively to the wells in each county as the wells were inventoried. An abbreviation for the county in which the well is located precedes the well number to distinguish it from a well with the same number in another county. For example, well Bft 813 is the 813th well scheduled in Beaufort County; likewise, the prefixes Col, Ham, and Jas stand for wells in Colleton, Hampton, and Jasper Counties.

ACKNOWLEDGMENTS

The author is greatly indebted to representatives of industries, to the well owners, and to water well contractors for their cooperation in supplying information on their ground-water developments and water use. Special thanks is due to Mr. Robert Glover, Hilton Head Plantation, for the lease of a plot of land upon which to drill test wells Bft 786, Bft 787, and Bft 788. Thanks also is due to the officials of Beaufort, Colleton, Hampton, and Jasper Counties as well as the staff of the Lowcountry Council of Governments for their help with this investigation. The assistance provided by South Carolina Development Board, Division of Geology, Shell Oil Co. and Texaco Oil Co. in describing the paleontology and lithology of drill cuttings is greatly appreciated.

A very special note of thanks is due to Louis Nexsen, Larry Drolet, Camille Ransom, Daisy Sammons, and B. C. Spigner, SCWRC, for their valuable assistance with all phases of the study.

GEOGRAPHY

CLIMATE

The climate of the study area is subtropical with hot and humid summers and mild winters. These climatic conditions contribute to a long growing season that, when coupled with the availability of rich land and considerable rain, makes the area agriculturally active. The average length of the freeze-free period is about 280 days.

Maximum temperatures range from 95° to 100°F during July and August; minimum temperatures occasionally range from 20° to 30°F during December, January, and February. The average annual temperature was 65° to 66°F for the period 1972 to 1976 (table 1 and fig. 2). The average annual precipitation for the period of 1972 to 1976 was 50 inches. Precipitation is well distributed; the largest amounts of precipitation occur during June, July and August (fig. 3) primarily as a result of thunderstorm and shower activity.

PHYSIOGRAPHY

The South Carolina Coastal Plain, which lies in the central part of the Atlantic Coastal States, is divided into three regional belts. These belts are roughly parallel to the Atlantic Ocean, extending from the Fall Line to the Atlantic Ocean. The study area lies within the Lower Coastal Plain which is characterized by a series of terraces, ranging from sea level to about 270 feet above sea level. These terraces are highly dissected by numerous streams and contain many shallow depressions. In the study area these depressions may be sinkholes caused either by solution of underlying limestone or by surficial irregularities

Table 1. Average monthly and annual temperature (°F) at Beaufort, Hampton, Hilton Head, Ridgeland, Walterboro, and Yemassee, 1972-76.

Month	Beaufort	Hampton	Hilton Head	Ridgeland	Walterboro	Yemassee
January	54.3	52.8	54.7	52.5	52.1	55.0
February	52.9	52.8	52.2	52.1	50.6	52.3
March	60.1	61.2	60.4	60.5	60.5	60.4
April	64.4	64.7	63.8	62.3	63.7	63.9
May	73.1	71.9	72.0	71.5	71.4	70.5
June	77.3	76.5	76.3	76.2	76.1	76.8
July	81.0	80.2	79.7	79.3	79.7	80.2
August	80.7	79.4	79.2	78.8	79.4	80.0
September	77.2	75.6	76.2	75.2	75.6	75.3
October	66.6	64.1	66.4	65.2	65.0	64.6
November	57.3	56.0	57.3	56.3	55,9	53.5
December	52.1	51.2	51.8	50.4	50.1	50.5
Average Annual	66.4	65.5	65.8	65.0	65.0	65.3

"Modified from" U. S. National Weather Service National Oceanic and Atmospheric Administration, 1977, Climatological Summary for South Carolina.

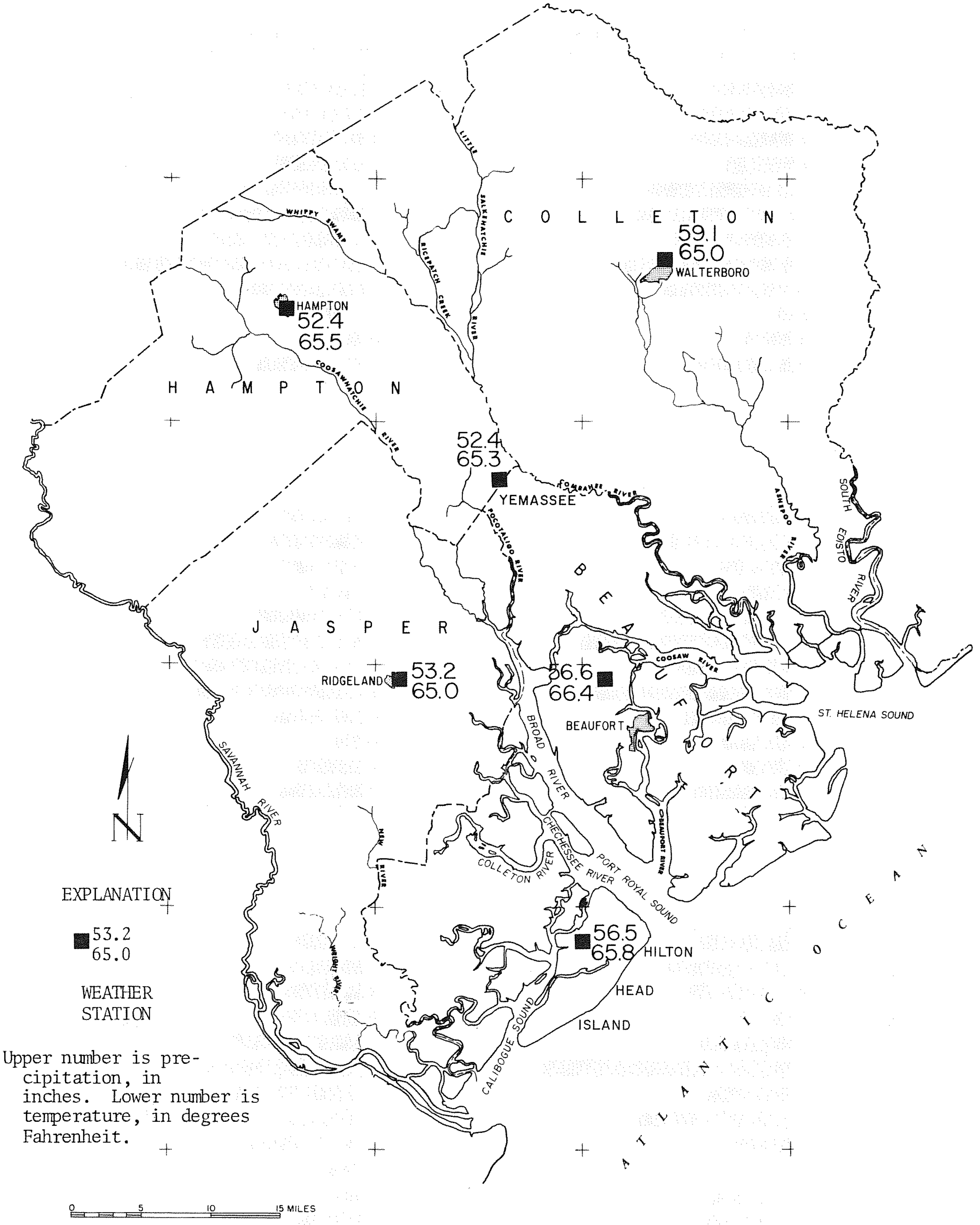


Figure 2. Location of weather stations with average annual precipitation and temperature, 1972-76.

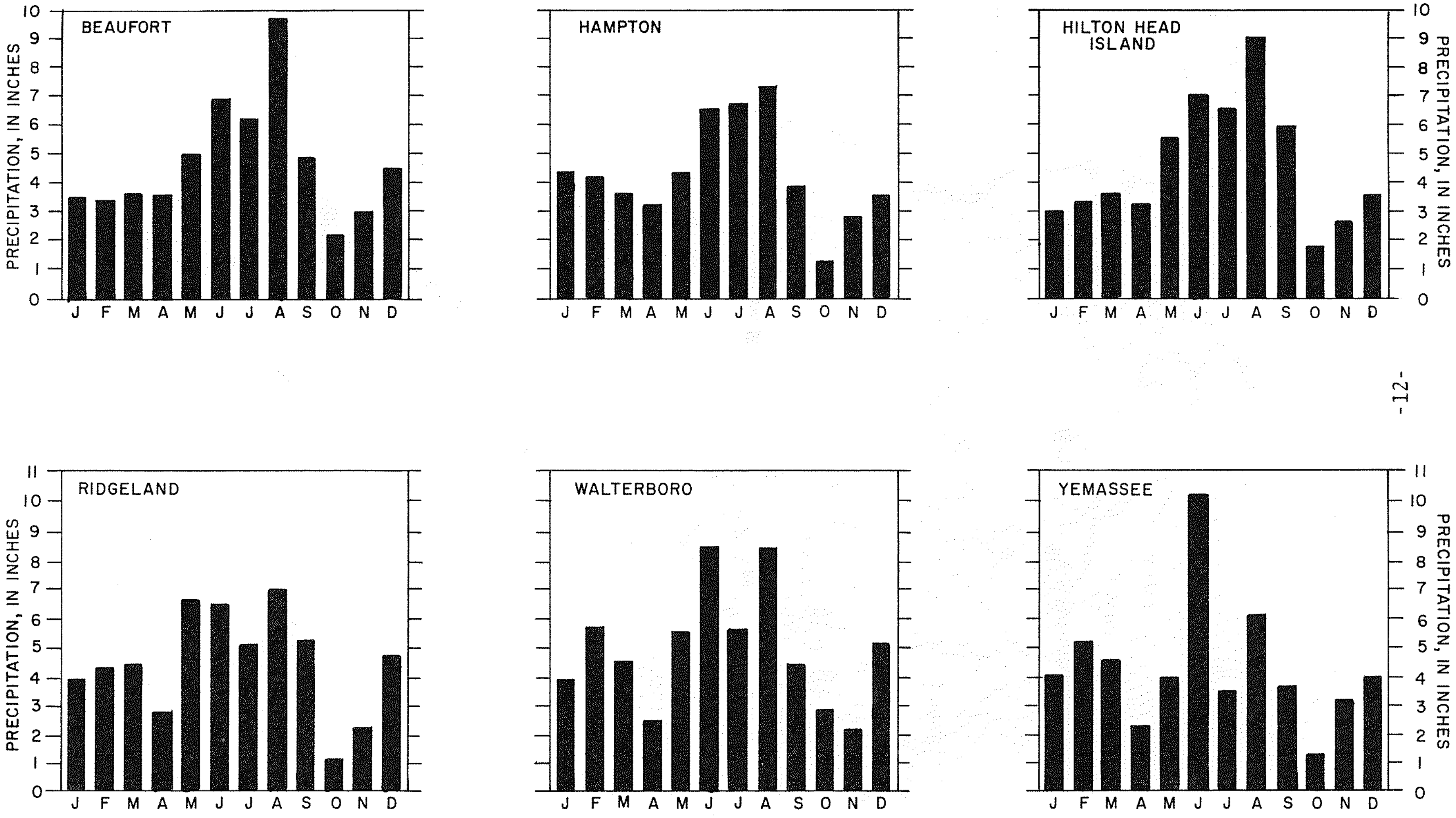


Figure 3. Average monthly precipitation at Beaufort, Hampton, Hilton Head Island, Ridgeland

that were formed on the floor of the ocean or in the shallow water of tidal marshes when the sea stood at a higher level.

Much of the study area is characterized by low flatland inundated with water; by numerous streams, rivers, marshes and lakes; and by moss covered woodland. The area is relatively isolated and is sparsely settled. Transportation within the region is severely restricted by marshes and waterways that impede rapid access from outside of the region. Of the 69 islands in Beaufort County, 20 are inhabited, 18 of which are accessible by bridges or causeways.

POPULATION AND ECONOMY

The Lowcountry area is the least populated region of South Carolina. The 1970 population of 106,521 persons ranked the area lowest in population density with 37.2 persons per square mile. The study area was classified as 32.6 percent urban in 1970. With the exception of Beaufort County, the population of the area has not changed significantly in this century (fig. 4).

Beaufort County is 637 square miles in size and contains four incorporated communities and ten small unincorporated communities. The incorporated area of Beaufort and Port Royal, with a combined population of over 12,000, has the highest population density and the largest industrial and business concentration in the study area. The unincorporated Hilton Head Island resort community, with a 1976 population of about 8,000 persons, is the next largest urban area in Beaufort County.

Colleton County, covering more than 1,000 square miles, is the largest county in the study area. Five incorporated towns and eleven small unincorporated communities are located in the county. With the exception of Walterboro, which has a population of 7,500, the towns are small and rural in nature with less than 500 persons in each.

Hampton County has an area of 562 square miles and contains 15 small towns and communities. The largest town is Hampton, the county seat, with a population of about 3,000 persons.

Jasper County has an area of 662 square miles and contains two small towns, Ridgeland and Hardeeville, and seven community settlements. The town of Ridgeland, the county seat, has only about 1,200 persons. Jasper County is the only county within the study area that is classified as 100 percent rural.

The study area has the lowest average per capita personal income in the state. The largest employment segment in 1970 was federal and local government with 7,130 employees (table 2). From 1965 to 1970, the fastest employment growth in absolute terms was government with 1,600 new positions.

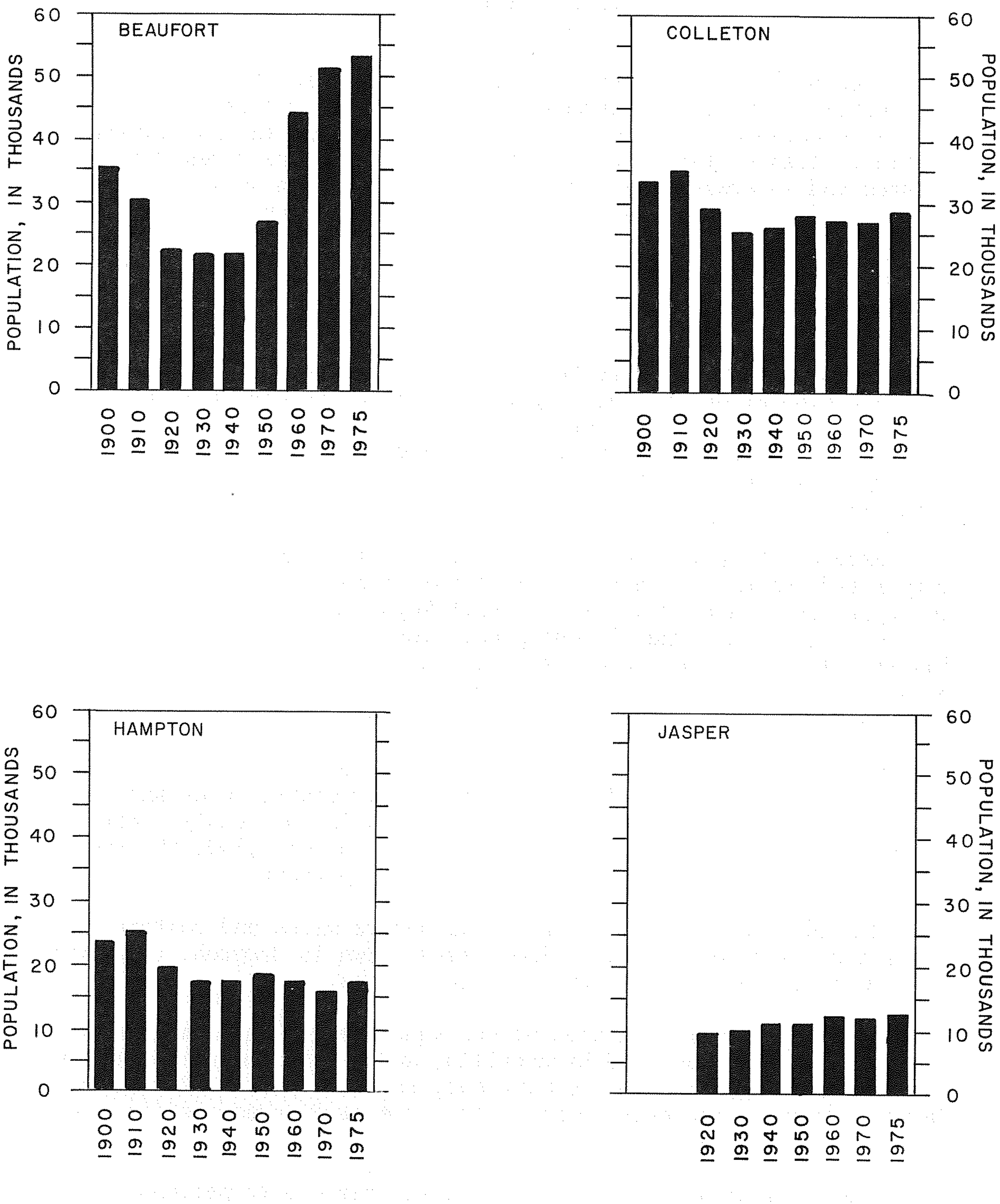


Figure 4. Population trends in Beaufort, Colleton, Hampton , and Jasper Counties, 1900-75.

Table 2. Distribution of civilian employment in the United States, South Carolina, and the study area, 1969 and 1970

DISTRIBUTION OF TOTAL CIVILIAN EMPLOYMENT, 1969 - 1970

Employment Category	Area		
	Study area	South Carolina	United States
Manufacturing	17.3	32.8	25.3
Contract Construction	5.7	4.8	4.3
Trans., Comm., & Utilities	2.1	3.6	5.6
Wholesale and Retail	12.8	13.7	18.4
Finance, Insurance & Real Estate	4.0	2.9	4.5
Services and Miscellaneous	9.2	8.8	14.0
Government	21.2	14.4	15.3
Self-employed, Unpaid Family Workers & Domestics	16.4	12.7	7.3
Agriculture	10.4	6.4	4.5
TOTAL	100.0	100.0	100.0

Source: South Carolina Employment Security Commission, South Carolina's Manpower In Industry, August 1966 and May 1971 and the U. S. Department of Labor, Employment and Earnings.

Agricultural employment in the study area is at its lowest level since before the turn of the century and is expected to decline even more in the future (South Carolina Employment Security Commission, 1971). Nevertheless income derived from farm products is still substantial to the economy of the area since total farm income is increasing as a result of improved farming methods and higher prices for products sold. Income from agriculture was up 51.4 percent in 1970 over 1964 (table 3).

Table 3. Value of all farm products of the study area.

VALUE ADDED BY FARM PRODUCTS ($000)

	Value all farm products sold		Value all crops sold		Value all livestock products sold		Percentage change all farm products sold
	1964	1970	1964	1970	1964	1970	
Beaufort	4,778	7,330	3,776	5,569	924	1,761	53.4
Colleton	4,528	7,408	2,735	3,497	1,783	3,911	63.6
Hampton	6,056	8,073	4,512	4,929	1,540	3,144	33.3
Jasper	1,512	2,740	796	1,390	706	1,350	81.2
TOTAL	16,874	25,551	11,819	15,385	4,953	10,166	51.4

Source: U. S. Department of Commerce, 1964 Census of Agriculture, and Department of Agricultural Economics, S. C. Agricultural Experiment Station, Clemson University in Cooperation with U. S. Department of Agriculture, South Carolina, Cash Receipts From Farm Marketing, 1971.

Income from livestock products was up 105.2 percent during this six-year period and value added by crops sold was up only 30 percent. If past trends hold up, the study area's farm economy will soon be dominated by livestock products as opposed to the current domination of crop products.

Soybeans, the biggest money crop in the area, accounted for 36.2 percent of all crop sales in 1970, followed by the production of vegetables at 22.6 percent. Forest products, peaches, corn, tobacco, and cotton account for 9.8, 5.6, 5.0, 4.0, and 2.9 percent of crop sales, respectively.

SURFACE-WATER RESOURCES

Surface water is abundant throughout most of the study area, but much of this water is salty or brackish; in fact, almost all the surface-water bodies in Beaufort and Jasper Counties contain salty water.

The Beaufort-Port Royal urban area and the military installations (which are the only users of surface water in significant quantities) use about 5 Mgal/d of treated water from the Savannah River.

The locations of major streams in the study area and the location of the Survey's gaging stations are shown in figure 5.

DRAINAGE DESCRIPTION AND FLOW CHARACTERISTICS

Two general types of streams drain the area: (1) through flowing streams (Edisto and Savannah Rivers); and, (2) streams that originate within the area (Ashepoo, Combahee, Salkehatchie, Coosawhatchie, New River, Coosaw, and Broad River). The through flowing streams are characterized by deep, wide, flat-bottom valleys and contain water colored with red or yellow sediments from the Piedmont. Streams that originate within the Coastal Plain may contain water that is colored black or brown from organic matter such as leaves, straw, and humus from the soil.

Average, minimum, and maximum streamflow data for six major fresh-water streams are given in table 4 and the average monthly streamflow of five of these streams is presented in table 5. Maximum flows for these streams usually occur in February or March, and the minimum flows usually occur in October.

Table 4. Average, minimum, and maximum streamflow for six major fresh-water streams in study area, for period of record.

Station Number	Name of River	Drainage area (mi^2)	Maximum flow (ft^3/s)	Minimum flow (ft^3/s)	Average flow (ft^3/s)	Period of record
02174000	Edisto near Branchville	1,720	14,600	323	2,037	1945 to 1976
02175000	Edisto near Givhans	2,730	24,500	290	2,684	1939 to 1976
02175500	Salkehatchie near Miley	341	2,350	17	350	1951 to 1976
02176000	Combahee near Yemassee	1,100	5,325	9	483	1951 to 1976
02176500	Coosawhatchie near Hampton	203	8,160	0	189	1951 to 1957
02198500	Savannah near Clyo, Georgia	9,850	12,068	270,000	1,950	1929 to 1933

Source: U. S. Geological Survey, 1976, Water resources data for South Carolina water year 1976, water data report SC-76-1, 224 p.

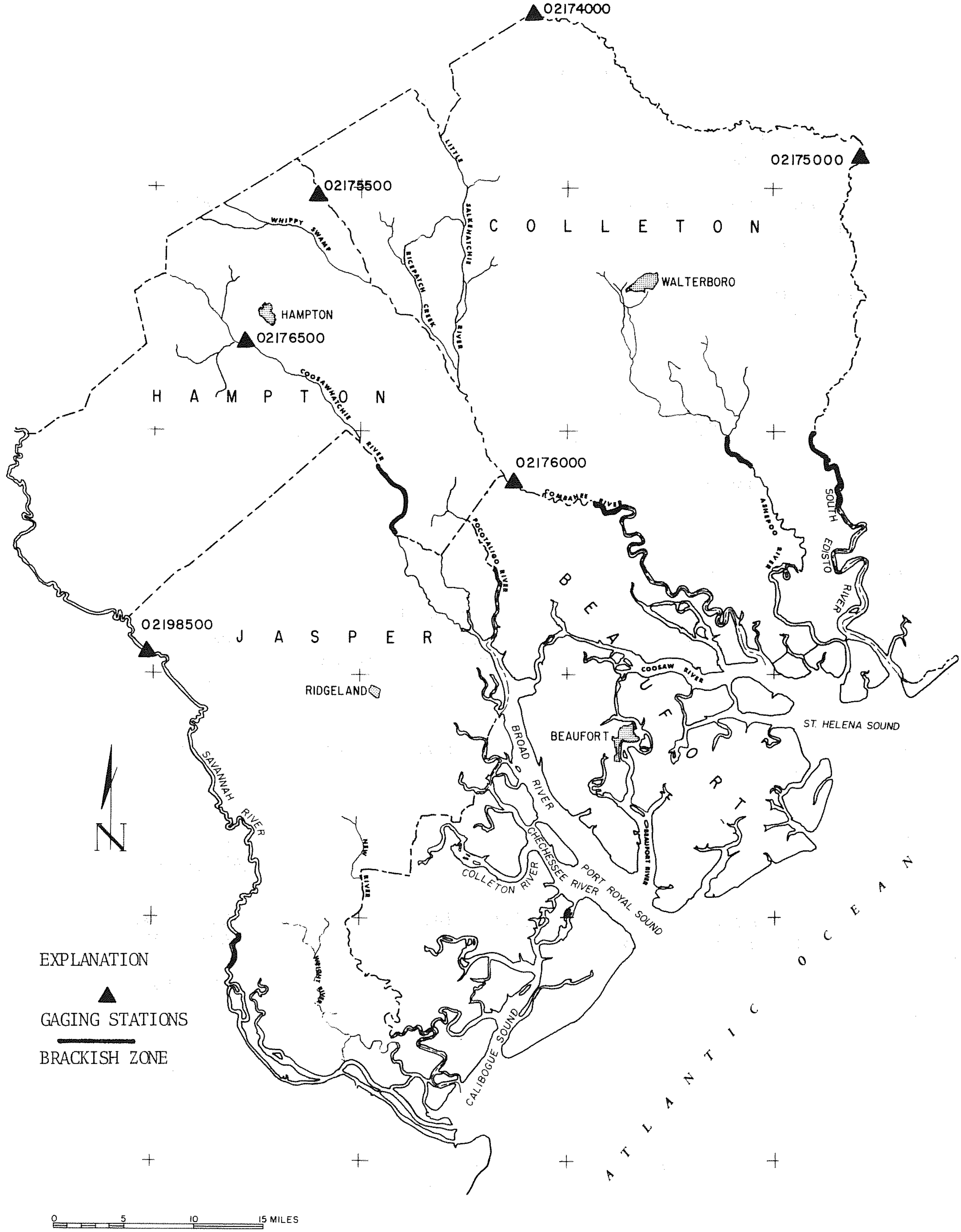


Figure 5. Location of gaging stations and zones of brackish water, (water containing 50 to 1,000 mg/L of chloride).

Table 5. Average monthly streamflow of five streams in study area, 1971-75.

Station	Name of River	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
02174000	Edisto near Branchville	3,162	4,115	9,658	3,154	2,245	2,191	2,081	2,251	1,644	1,374	1,470	2,272
02175000	Edisto near Givhans	3,835	6,983	5,441	4,320	2,646	3,326	2,665	3,192	1,834	1,395	1,416	2,272
02175500	Salkehatchie near Miley	550	824	671	528	382	405	443	471	265	248	278	498
02176500	Coosawhatchie near Hampton	318	549	439	335	127	202	229	273	97	62	70	193
02198500	Savannah near Clyo, Ga.	16,884	22,788	22,136	22,974	12,989	14,252	11,439	10,115	8,923	8,846	9,713	13,014

Source: U.S. Geological Survey, 1976, Water Resources Data for South Carolina
Water Year 1976: Water Data Report SC-76-1, 224 p.

Tables 4 and 5 show that the differences between average, minimum, and maximum streamflow of individual streams vary greatly. These differences are of importance not only because they reflect the relation between streamflow and other facets of the hydrologic cycle, but also because these differences determine to a great extent the suitability of these streams as a long-term dependable source of freshwater. For example, according to a study by Hazen and Sawyer (1956), the Combahee River at a point a few miles below Yemassee and bordering Beaufort and Colleton Counties would be capable of supplying about 15 Mgal/d of freshwater 90 percent of the time. However, during severe droughts or extremely low flow (less than 50 ft^3/s), saltwater intrusion might occur as far north as Yemassee and this source would become contaminated with saltwater.

WATER QUALITY

The Survey collects data on the quality of surface water at stations 02176500 and 02198500 (fig. 5) at a predetermined frequency. Chemical quality, microbiological, water temperature, and fluvial sediment information are presented in the Survey's annual reports entitled "Water Resources Data for South Carolina." Additional data on surface water quality is available from the Bureau of Wastewater and Stream Quality Control, SCDHEC (South Carolina Department of Health and Environmental Control).

Water from the freshwater streams contains less than 100 mg/L of dissolved solids, has pH values of about 7, is soft, contains relatively small amounts of dissolved metals, and usually contains less than 15 mg/L of suspended sediment.

Generally, streams in the study area contain freshwater in the upper reaches and contain salty water near the coast. The contact between freshwater and saltwater is not characterized by a sharp boundary; instead, there is a moving zone of mixing or diffusion where the water is brackish (Total dissolved solids 1,000 to 10,000 mg/L, fig. 5). During periods of low discharge the zone of diffusion moves further inland. Factors that affect the amount of mixing and the location of the zone of diffusion include: (1) stream discharge; (2) width, depth and shape of channel; (3) sinuosity of channel; (4) tidal movements; (5) wind velocity and direction; and (6) disturbances due to navigation. Studies of Cummings (1968) and Johnson (1970, 1977) explain the manner in which saltwater encroachment occurs in estuaries and the mechanics of freshwater-saltwater mixing.

GROUND-WATER RESOURCES

Ground water in quantities adequate for most domestic, public-supply, and farming needs is generally available from one or more artesian aquifers. The three most important artesian aquifers in the study area are, in order of importance, the principal artesian aquifer, the Black Mingo aquifer, and the Middendorf aquifer. Table 6 gives the estimated 1976 water use from these aquifers. About 82 percent of the ground water used came from the principal artesian aquifer, which is composed mainly of the Santee Limestone and the lower part of the Cooper Marl.

Table 6. Estimated surface-water and ground-water use in Beaufort, Colleton, Hampton, and Jasper Counties, in million gallons, for 1976.

County	Surface water	Principal artesian aquifer	Middendorf aquifer	Black Mingo aquifer	Total Water use by county
Beaufort	1,800 1/	4,800	30	0	6,600
Colleton	NS 2/	250	350	160	760
Hampton	NS 2/	500	0	880	1,400
Jasper	NS 2/	650	0	0	650
Total water use by sources	1,800	6,200	380	1,000	9,400

1/ Savannah River
2/ No significant surface-water use

GEOLOGIC FRAMEWORK

Poorly consolidated to unconsolidated sand, clay, marl and limestone, ranging in age from Late Cretaceous to Holocene, underlie the Lowcountry area. The rocks thin to a featheredge at the Fall Line in the central part of the state and thicken to more than 3,500 feet along the coast near Beaufort and the southern part of Jasper County near Savannah. These sedimentary rocks overlie a basement complex composed of granite, gneiss, schist, and diabase rocks of pre-Cretaceous age. Maher (1971, pl. 4) shows the top of the pre-Cretaceous rocks occurring at about 2,000 feet below land surface in the northwestern part of Colleton County and at about 4,000 feet below land surface along the coast in the southern parts of Beaufort and Jasper Counties.

The Cape Fear arch is the most prominent structural feature of the central part of the Atlantic Coastal Plain, as evidenced by Cretaceous outcrop pattern, well data, magnetometer surveys (MacCarthy, 1936, p. 405) and seismic surveys (Bonini, 1955, p. 1533; Meyer, 1957, p. 22). The general shape of the arch is a gentle warp with the axial plunge increasing sharply near the shoreline and gradually decreasing updip toward the Fall Line. The basement rocks dip at an average of 13 feet per mile along the axis of the Cape Fear arch from the Fall Line to the coast (Maher, 1971, pl. 4). Geologists have dated the formation of the Cape Fear arch and of consequent downwarping of the flanks at different times, ranging from Early Cretaceous to Early Miocene. Siple (1946, p. 37) and Eardley (1951, p. 131) have postulated that uplift and erosion occurred during more than one stage.

The Southeast Georgia embayment interrupts the long, uniform slope of the basement away from the south flank of the Cape Fear arch. It extends southwesterly to the Peninsular arch of Florida. According to Maher (1971, p. 25) this embayment is primarily a tectonically passive feature although it may have undergone some downwarping on the continental shelf where the sedimentary rocks exceed 10,000 feet in thickness.

Along the southeastern flank of the Southeast Georgia embayment, there are two local minor structures called the Burton high (Siple, 1956) or Beaufort arch (Colquhoun, and others, 1969, p. 4) and the Ridgeland trough (Heron and Johnson, 1966). Cramer (1974) has suggested that tension forces existing through Cenozoic time as a result of the North American Plates drifting northwestward may be responsible for the uplift and facies changes in Tertiary rocks. Relief associated with these structures apparently is of low magnitude surficially and affects only pre-early Miocene(?) and younger sediments.

As a result of the Beaufort arch, upper Tertiary rocks comprising part of the principal artesian aquifer system have been brought close to the surface (in some places less than 25 feet below land surface). In contrast, in the Ridgeland trough area the confining beds thicken considerably and the top of the principal artesian aquifer system occurs at greater depths (in some places more than 200 feet below land surface).

In describing the stratigraphic sequence of rock units overlying the basement rocks, the simplest interpretation of the geology of the Lower Coastal Plain of South Carolina was followed. Formation names common to South Carolina are used to identify rock units mapped or recorded on cross sections and discussed in the text. With two exceptions, the stratigraphic column used in this report is consistent with the nomenclature used by the U.S. Geological Survey (Higgins and others, 1976), and by the South Carolina Development Board, Division of Geology (Alan-Jon W. Zupan and William H. Abbott, written commun., 1977). The exceptions are that the Beaufort (?) Formation of Paleocene age and the Cape Fear Formation of Late Cretaceous age are not included in the stratigraphic section used in this report. Since these two formations have been reported in only one well (USGS Clubhouse Crossroads core hole), the author believes that evidence is insufficient at this time to include them in the stratigraphic section of South Carolina.

GEOLOGIC FORMATIONS AND THEIR HYDROLOGIC CHARACTERISTICS

GENERAL PRINCIPLES OF GROUNDWATER OCCURRENCE

Water that occurs beneath the surface of the earth in the zone of saturation where it fills all voids is called ground water (Meinzer, 1923). A formation, a group of formations, or a part of a formation that contains sufficient saturated permeable material to yield sufficient quantities of water to wells and springs is called an aquifer (Lohman and others, 1972, p. 2).

Two fundamental hydraulic properties of an aquifer are porosity and hydraulic conductivity. Porosity is the ratio of the total volume of voids in a rock to the volume of the rock. Porosity, usually expressed as a percentage of the bulk volume of the rock material, is a measure of the amount of water that can be stored in the saturated rock material. Although porosity represents the amount of water an aquifer can hold, it does not indicate how much water the aquifer will yield. When water is drained from an aquifer by gravity force, only part of the water in the pores is released; the remaining part is retained in the aquifer against the force of gravity by molecular attraction and capillarity.

Whereas porosity is a measure of the interstices or void space in a rock, hydraulic conductivity is a measure of the ability of a rock to transmit fluid under a hydraulic gradient. Hydraulic conductivity depends not only upon the size and number of voids but also upon the degree of interconnection. Clay and silt generally have high porosity but low hydraulic conductivity because the interstices are so small that water molecules cannot pass easily through the material. Ideally, a productive aquifer has both high porosity and high hydraulic conductivity.

The unsaturated zone is that part of the earth's crust where the water present is generally not under hydrostatic pressure and, for the most part, where the interstices are partly filled with atmospheric gases. However, material in the unsaturated zone may be temporarily saturated with water during or after periods of precipitation or flooding. The thickness of the unsaturated zone varies considerably depending upon the geology, hydrology, and topography of the area. In the study area, the thickness of the unsaturated zone varies from zero to generally less than 10 feet.

Between the unsaturated zone and the saturated zone is the capillary fringe. This capillary fringe contains voids that are filled with water that is under less than atmospheric pressure and is continuous with the water below the water table (Meinzer, 1923, p. 21). The water is held above the water table by capillarity acting against the force of gravity.

Beneath the capillary fringe is the zone of saturation - the source of water for wells, springs, and gaining streams. The upper surface of the zone of saturation is called the water table. Within the zone of saturation, ground water occurs under two general conditions: water table (unconfined) and artesian (confined). The water table is a potentiometric surface at atmospheric pressure, whereas water in an artesian aquifer is confined and under pressure.

CRETACEOUS SYSTEM

The oldest rocks penetrated in the study area were formed during Late Cretaceous time. They represent an interfingering and essentially transgressive relationship between fluvial, marginal marine, and marine deposits (Heron and others, 1965). The Upper Cretaceous deposits discussed in this report are, in ascending order; the Middendorf Formation (equivalent to and locally known as the Tuscaloosa Formation), the Black Creek Formation, and the Peedee Formation. No known wells have penetrated the Upper Cretaceous section in Hampton and Jasper Counties. Consequently the geohydrology of the Cretaceous rocks is unknown in these two counties. It is probable, however, that the geohydrology of the Upper Cretaceous rocks in Hampton County and Jasper County are similar to that of the geohydrology of the Upper Cretaceous rocks in Colleton County and Beaufort County. The depth to the top of the Upper Cretaceous and lower Tertiary formations in selected wells is given in table 7.

Table 7. Depth to the top of Cretaceous and lower Tertiary formations in selected wells.

Depth to top of formation in feet below mean sea level

	Cretaceous formations			Tertiary formations	
Well	Middendorf	Black Creek	Peedee	Black Mingo	Santee Limestone
Bft 10	2,500	1,900	1,510	950	280
Bft 454	2,650	2,030	1,660	856	140
Bft 457	2,580	1,860	1,480	840	--
Col 50	1,550	1,210	830	440	220

Middendorf Formation.--The Middendorf Formation has not been fully penetrated in the study area. The deepest well in the area (Bft 10) was drilled to a depth of 3,455 feet below land surface. The top of the Middendorf Formation occurs at a depth of about 2,500 feet below msl (mean sea level) in this well (table 7) and the lithology consists primarily of green, purple, and maroon clay; greenish-gray, micaceous silt; sandstone; and light-gray, fine to coarse-grain sand (Siple, 1960, p. 21). The thickness of the Middendorf Formation ranges from less than 800 feet in the northeastern part of the study area to more than 1,200 feet in the southwestern part of the study area.

In the northern part of the study area the upper section of the Middendorf Formation, consisting of medium to coarse sand and gravel, is the very productive Middendorf aquifer. The town of Walterboro in Colleton County has two wells open to the Middendorf aquifer (Col 49 and Col 50) that have natural flows of 1,200 gal/min and of 1,400 gal/min of high quality water (table 8). The pressure head in these wells at land surface (about 90 feet above msl) was about 30 lb/in^2 (pounds per square inch). This is equivalent to 160 feet of head above sea level ($30\ lb/in^2 \times 2.31\ (ft\ in^2)/lb + 90\ ft$).

The only other wells in the study area open to the upper part of the Middendorf Formation are in Beaufort County: Bft 10 and 11 at Parris Island, Bft 454 at Hilton Head Island, and Bft 457 at Fripp Island. All these wells have natural flows of about 75 gal/min of highly mineralized water (table 8) that has a temperature of around 38°C. The pressure head in these wells at land surface (about 10 feet above msl) is about 50 lb/in^2, which is equivalent to 125 feet of water at sea level.

The extent of freshwater in the Middendorf Formation south of Walterboro is not known. Fresh water may be present in the Middendorf aquifer as far south as Yemassee.

Black Creek Formation.--In the Beaufort area, the upper part of the Black Creek Formation typically consists of gray to black and greenish-gray, sandy clay; the lower part consists of gray to white, phosphatic, glauconitic, fine sand interbedded with dark-gray and greenish-red clay containing nodules of pyrite and marcasite. Further updip in well Col 50 the Black Creek Formation consists of fine to medium greenish-gray, micaceous sand, silty calcareous clay, and hard layers of calcareous, shelly, fine-grained sand. The top of the Black Creek ranges from about 1,200 feet below msl to more than 2,000 feet below msl (table 7). The thickness of the formation ranges from less than 400 feet in the northwestern part to more than 600 feet in the southern part of the study area.

Although the Black Creek Formation is a productive aquifer in other parts of the state, its potential as an aquifer in the study area is generally unknown. A water sample taken during drilling of well Bft 457 contained 1,100 mg/L of chloride. On the basis of drillers' samples and geophysical logs, it appears unlikely that this formation will yield significant quantities of freshwater in Beaufort County. This formation may be capable of supplying large quantities of fresh water in Colleton and Hampton Counties.

Peedee Formation.--The Peedee Formation is the youngest deposit of Late Cretaceous age in South Carolina. The dominant lithology of the Peedee Formation in the study area is interbedded, dark-gray clay; silty, micaceous, fine to medium sand; and streaks of hard, shelly, argillaceous limestone or calcareous, arenaceous siltstone. The top of this formation ranges from about 800 feet below msl to more than 1,600 feet below msl (table 7). The thickness of this formation ranges from less than 300 feet in the northwestern part of the study area to more than 500 feet in the southern part.

Table 8. Chemical quality of water from the Middendorf, Black Mingo, and Hawthorn aquifers
[Results in milligrams per liter except as indicated. Analyses by U.S. Geol. Survey]

Well	Well Depth (feet)	Date of Collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved Solids	Hardness as $CaCO_3$		Specific Conductance (Micromhos at 25°C)
															Total	Noncarbonate	
Middendorf Aquifer																	
Bft 10	2,915	74-10-21	19	0.1	3.1	0.5	550	5.0	1,250	10	100	6.0	0.02	1,310	10	0	1,970
Bft 11	2,700	54-10-15	19	0.2	1.0	0.5	412	4.4	1,000	1.2	10	4.1	1.6	1,030	4	0	1,630
Bft 454	3,034	74-07-15	21	0.2	1.8	0.4	480	4.5	1,130	2.9	87	4.3	0.07	1,160	6	0	1,800
Col 49	1,748	76-10-12		.05	0.6	0.2	98	1.1		4.0	10				2	0	
Col 50	1,760	76-01-28	19	.02	1.1	0.2	74	0.7	184	1.5	3	0.6	0.0	207	4	0	280
Black Mingo Aquifer																	
Ham 34	822	77-02-23	14	.02	3.2	0.1	58	2.3	150	7.0	2.9	0.5	0.01		8	0	
Ham 49	723	77-02-23	54	.03	4.3	0.1	54	4.3	140	13	2.7	0.5	0.01		11	0	
Ham 85	1,000	77-02-23	70	.04	2.1	0.1	70		170	5.6	2.7	0.7	0.00		6	0	
Col 70	651	76-01-22	20	.00	4.5	0.4	34		91	13	3.9	0.4	0.00		13	0	
Hawthorn Aquifer																	
Bft 788	100	77-01-14	30	.05	100	2.6	25	1.5	315	3.7	34	0.2		352	260	2	625
Bft 789	117	77-02-23	29	.01	3.4	0.1	120	6.0	310	8.6	3.9	1.3	0.00		9	0	
Bft 794	37	77-02-23	460	1.2	170	49	460	20	320	150	840	0.3	0.00		630	370	
Bft 805	130	77-02-23	45	.19	32	6.0	24	3.3	140	12	18	0.7	0.01		100	0	
Bft 823	98	77-02-23	46	.02	50	11	24	2.9	190	0.1	31	0.1	0.00		170	17	

While the Peedee Formation is an important aquifer in parts of the state, it does not appear to be of significant value as an aquifer in the study area. There are no known wells in the study area open exclusively to the Peedee Formation. Well Ham 30 was cased to and open only to this formation, but because of low yield the casing was pulled back to 94 feet below land surface.

TERTIARY SYSTEM

The Tertiary System consists, in ascending order, of the Black Mingo Formation of Paleocene and Early Eocene (Wilcox) age, the Santee Limestone of Middle and early Late Eocene (Claiborne and early Jackson age), the Cooper Marl of latest Eocene (Late Jackson) and Oligocene age, the Hawthorn Formation of Miocene age, and the Duplin Marl of Pliocene age. These Tertiary formations are the chief sources of ground-water supplies in the study area. A generalized geologic section describing the water-bearing characteristics and lithologies of the Tertiary rocks is given in figure 6.

The Oligocene-Miocene and Miocene-Pliocene contacts have been picked primarily on the basis of gamma logs. Near the base of both the Miocene and Pliocene the phosphate content increases markedly (Furlow, 1969; Wait, 1970, p. C202) with resulting high peaks on gamma-ray logs. The top of these peaks are defined in this report as the Oligocene-Miocene and Miocene-Pliocene contacts (fig. 6 points B and A). It is assumed that the high phosphate content in the sediments at the top of both the Oligocene and Miocene follow time lines because these sediments represent an unconformity between the Oligocene and Miocene rocks and between the Miocene and Pliocene rocks (Furlow, 1969, Wait, 1970). This unconformity resulted in a period of interrupted deposition or erosion in late Oligocene or early Miocene time and in late Miocene or early Pliocene time which allowed more time for precipitation and concentration of phosphate.

Black Mingo Formation.--For the purpose of this report, all deposits of early Eocene and Paleocene age are considered to be Black Mingo.

In the Beaufort area, Siple (1960, p. 28) divided the Black Mingo into: (1) an upper part consisting of red to brown, sandy clay; partly indurated, fine, white to yellow sand; and a sugary sandstone containing shell fragments; and (2) a lower part that consists of gray to black, carbonaceous clay and shale showing conchoidal fractures. In Hampton and Colleton Counties, the Black Mingo Formation consists of green-gray clay; phosphatic, glauconitic, fossiliferous limestone; fine to medium, light-gray sand; and shell fragments. The top of the Black Mingo ranges from about 400 feet below msl to more than 1,100 feet below msl (table 7). The formation ranges in thickness from less than 300 feet in the northwestern part of the study area to more than 550 feet in the southern section.

In Hampton and Colleton Counties, about 25 wells that are believed to be open to the Black Mingo have natural flows of 50-250 gal/min of good quality water (table 8). The pressure head of wells open to the Black Mingo Formation generally ranges from 25 to 30 lb/in^2 at land surface, depending upon the depth of the well and the altitude of the land surface. Well depths usually range from 550 to 800 feet below land surface. The Black Mingo aquifer consists of phosphatic, fossiliferous limestone; of sandy limestone; and of calcareous sand.

The potential of the Black Mingo as a source of fresh ground water is unknown in Jasper County because no wells have been drilled this deep. On the basis of geophysical and drillers' logs from deep wells at Parris Island, Hilton Head Island, Fripp Island, and Grays Hill, in Beaufort County the Black Mingo Formation is believed unlikely to yield significant quantities of freshwater.

Santee Limestone.--Pooser (1965) has shown that the middle and upper Eocene rocks of South Carolina (which include the Congaree Formation, Warley Hill Marl, Santee Limestone, McBean Formation, and Barnwell Formation) represent lithofacies laid down in an essentially transgressing sea. For the Middle and Lower Coastal Plain, the fossiliferous, highly calcareous Santee Limestone and the basal Warley Hill Marl Formations make up the entire Middle and most of the Upper Eocene section (Colquhoun and others, 1969, p. 11). Landward, the Santee Limestone grades into clastic sediments such as those of the McBean Formation and of the Barnwell Formation. In the study area, the basal Warley Hill Marl, if present, was not distinguishable from the overlying Santee Limestone; therefore, for the purpose of this report the entire middle (Claiborne age) and the lower upper Eocene (early Jackson age) section is referred to as the Santee Limestone.

The Santee Limestone outcrops in the southeastern Calhoun and Orangeburg Counties along the shores of Lake Marion and along the Santee River in Orangeburg County. The Santee Limestone where exposed is generally described as a creamy-yellow to white, fossiliferous, partly glauconitic limestone containing numerous specimens of bryozoans, mollusks, and microfossils (Siple, 1960, p. 30).

In the study area the Santee Limestone generally can be divided into a lower, middle, and upper unit on the basis of geophysical logs, lithologic logs (Camille Ransom, SCWRC, written commun., 1976) and hydraulic properties. In Beaufort, Colleton and Hampton Counties, the lowermost unit of the Santee Limestone is an indurated, siliceous, glauconitic, light-gray to creamy-yellow limestone and averages about 30 feet in thickness; the Middle unit of the Santee Limestone consists of soft, sandy, clayey limestone and ranges in thickness from less than 200 feet to more than 600 feet; and the upper unit consists of white to light-gray, calcitized, abundantly fossilferous, indurated limestone containing bryozoan and echinoid fragments and ranges in thickness from essentially zero to more than 200 feet. In the north and northeastern part of the study area, the upper unit becomes increasingly clayey, sandy and less indurated. In parts of Beaufort and Hampton Counties and in most of Colleton County the upper unit is indistinguishable from the middle unit on the basis of geohydrologic and geophysical properties.

The upper unit of the Santee Limestone in Jasper County is similar in lithology to that in Beaufort County, but is probably thicker. The lithology and thickness of the middle and lower units are unknown because no wells in Jasper County penetrate below the upper unit.

The top of the Santee Limestone occurs from a few feet below land surface to more than 200 feet below land surface. The total thickness of the Santee Limestone ranges from less than 400 feet in Hampton and Colleton Counties, to more than 900 feet in Beaufort County, and probably more than 1000 feet in Jasper County.

The Santee Limestone is part of the principal artesian aquifer and furnishes much of the ground water used in the area. Except where salt-water contamination has taken place, the Santee Limestone is capable of yielding from 200 to more than 2,000 gal/min per well of good quality water. The waterbearing characteristics of the Santee Limestone will be discussed in detail in the section of the report dealing with the principal artesian aquifer.

Cooper Marl.--For the purpose of this report, the entire Oligocene and uppermost section of the Eocene (late Jackson age) are considered to be Cooper Marl. In most of the study area, the Cooper Marl varies from a very-sandy, calcareous, slightly to moderately phosphatic clay to a silty, sandy, phosphatic, clayey limestone to a light-gray to white limestone. In northeastern Hampton County and in Colleton County, the Cooper Marl becomes more silty and clayey and the white limestone is not present.

The top of the Cooper Marl occurs near land surface in the northern half of the study area, 50 to 75 feet below msl in much of Beaufort and Jasper Counties, and more than 150 feet below msl in the Ridgeland Trough. The Cooper Marl while absent in places is known to be more than 200 feet thick in parts of the area. According to Johnson and Geyer (1965), alternative explanations for the absence of the Cooper Marl are: (1) the Cooper Marl is a facies equivalent of the Santee Limestone, (2) the Cooper Marl was removed by erosion prior to deposition of the Hawthorn Formation; and (3) the Cooper Marl is a facies equivalent of the Hawthorn.

In Colleton County and in parts of northeastern Hampton County, the Cooper Marl is not used extensively as an aquifer. In much of Hampton, Beaufort and Jasper Counties, however, the lower part of the Cooper Marl is considered to be part of the principal artesian aquifer and is considered capable of yielding medium to large amounts of good quality water. The water-bearing characteristics of this formation will be discussed in more detail in the section of the report dealing with the principal artesian aquifer.

Hawthorn Formation.--In the study area, the Hawthorn Formation generally consists of phosphatic, clayey sand to phosphatic, sandy clay; of sandy, dolomitic limestone; and of highly-phosphatic, dolomitic, sandy, clayey limestone. The lateral extent and thickness of the Hawthorn Formation is at present not fully known. Johnson and Geyer (1965) believe that the Hawthorn Formation is present within 50 to 100 feet of the surface over much of the study area, that it dips south-southwestward, that it ranges in thickness from 120 feet in the southern part to a feather edge along the Edisto River, and that it has been completely or partially removed by Pleistocene marine erosion within a few miles of the coast. They put its probable northwest boundary in the vicinity of Allendale or Barnwell, South Carolina. In contrast, William H. Abbott, South Carolina Development Board, Division of Geology, (oral commun. 1977) suggests that the Hawthorn Formation is present only in the vicinity of Ridgeland Trough and possibly in scattered remnants along the Edisto River.

On the basis of lithologic and gamma-ray log correlation, the author believes the Hawthorn Formation is present throughout most of Jasper County, much of the lower part of Hampton County, and parts of the western half of Beaufort County. Scattered remnants may be present in the eastern half of Beaufort County on the flanks of the Beaufort arch and in Colleton County near the Edisto and Combahee Rivers.

The upper and lower sections of the Hawthorn Formation act as confining beds. The middle section of the Hawthorn is a fairly persistent, sandy, dolomitic limestone (Hawthorn aquifer) and is a source of small to medium amounts (50 to 200 gal/min) of fairly good quality water (table 8). Geohydrologic sections A-A' and B-B' (fig. 7) and C-C' (fig. 8) show the thickness and lateral extent of the Hawthorn aquifer.

PLIOCENE TO HOLOCENE SERIES

The post-Miocene sediments in the study area are composed of scattered remnants of Duplin Marl (Pliocene age) and of undifferentiated Pleistocene and Holocene deposits. According to Siple (1960, p. 43), only a few small isolated exposures of Duplin Marl have been recognized in the study area. Where present, the Duplin Marl consists of a buff, sandy, friable, shelly, slightly phosphatic marl.

Pleistocene deposits consist of brown, gray, and green clays interbedded with white to buff, subangular to angular, quartz sand. Shell beds composed primarily of oyster shells embedded in a matrix of dark-green to gray clay are common along the coast. The Pliocene to Holocene deposits range in thickness from less than 25 feet in Beaufort County and more than 100 feet in southwestern Jasper County.

The water-bearing characteristics of these Pliocene and Holocene deposits are not well known. Many shallow domestic wells obtain water from these deposits, particularly in Jasper County where the deposits appear to be thickest. Siple (1960, p. 49) reports that many wells tapping the Pliocene-Holocene deposits yield water of acceptable quality and quantity for domestic or small agricultrual and industrial needs. The yield and quality vary considerably from place to place. Water from these formations may be hard and may contain high concentrations of iron and hydrogen sulfide. Near the coast or saltwater estuaries, water from these deposits may be salty.

HYDROGEOLOGY OF THE PRINCIPAL ARTESIAN AQUIFER

Underlying the study area is an artesian aquifer composed of a series of limestones ranging from Eocene to Oligocene in age. This aquifer extends into southeastern Georgia, Florida, and adjacent parts of Alabama. The aquifer is referred to as the Ocala or principal artesian aquifer in Georgia, as the Floridan aquifer in Florida, and as the principal artesian aquifer in South Carolina.

In the Lowcountry area, the principal artesian aquifer ranges in thickness from less than 400 feet to more than 1,000 feet. The uppermost section of the underlying Black Mingo Formation (which consists of fine, white to yellow sand and red to brown, sandy clay) acts as the lower confining bed. The upper Oligocene (?) section consisting of sandy, calcareous, phosphatic clay and the lower Miocene section consisting of fine, sandy, greenish clay together act as the upper confining bed. The upper confining bed varies in thickness from zero to more than 50 feet. In parts of southern Beaufort County where the upper confining bed is absent, the Hawthorn aquifer is contiguous and hydraulically connected to the principal artesian aquifer.

WATER YIELDING ZONES

The principal artesian aquifer is divided into an upper permeable zone, a middle zone of relatively low yield, and a lower permeable zone. Geohydrologic sections AA' and BB' (fig. 7), CC' (fig. 8), and DD' (fig. 9) show the top of the principal artesian aquifer and the stratigraphic positions of the upper and lower permeable zones. These zones were determined on the basis of lithology, geophysical response, aquifer tests, and current meter tests. The permeable zones as defined herein include all the smaller zones of different yields and no attempt has been made to delineate them. All the smaller wateryielding zones have been combined into one relatively high wateryielding section or "permeable zone."

The upper permeable zone consists of white to light-gray calcitized, indurated, very fossiliferous limestone and varies considerably in thickness and lateral extent. It is more than 200 feet thick in southern Jasper County and western Beaufort County and thins toward the north and northeast, pinching out near the Beaufort-Colleton County line (figs. 7, 8, and 9). The upper permeable zone is very thin in eastern Beaufort County over the Beaufort arch where the top of the principal artesian aquifer is within 25 feet of land surface (figs. 7 and 8). Throughout

Beaufort and Jasper Counties and much of Hampton County, the upper permeable zone of the principal artesian aquifer is the primary source of ground water.

The upper permeable zone is separated from the lower permeable zone by a middle zone of low permeability, consisting of a soft, sandy, clayey limestone ranging in thickness from 200 feet or less in the northwestern part of the study area to more than 700 feet in the southeastern part of the study area (figs. 8 and 9).

The lower permeable zone consists of an indurated, siliceous, slightly-glauconitic, light-gray to creamy-yellow limestone. It ranges in thickness from less than 30 feet in parts of Beaufort County to more than 90 feet in Colleton and Hampton Counties (fig. 8 and 9). This lower permeability zone is the primary source of ground water in Colleton County (except for the city of Walterboro, which obtains water from the Black Creek and Middendorf aquifers) and in northeastern Hampton County, where the upper permeable zone is missing or is very thin.

Eight wells in Beaufort County are known to be open to both the lower and the upper permeable zones. No wells have been found in Jasper County that penetrate below the upper permeable zone; consequently the extent, thickness, and water-bearing characteristics of the lower permeable zone is unknown in Jasper County.

A map showing the top of the principal artesian aquifer in the area was constructed using natural gamma radiation, electric, and lithologic logs (fig. 10). Point C, shown in figure 6, represents the top of the principal artesian aquifer. This point is the top of the water-yielding Oligocene section of the principal artesian aquifer and in most cases the top of the upper permeable zone. The top of the principal artesian aquifer is a highly irregular surface that ranges from less than 20 feet below msl in the Beaufort arch to more than 200 feet below msl in the Ridgeland Trough (fig. 10).

The irregular surface of the top of the principal artesian aquifer may reflect solution occurring as a result of advance and recessions of the Pleistocene Sea. During Pleistocene time when the sea level was much lower than now, the land area extended to the edge of the Continental Shelf and the upper Tertiary sediments were above sea level. At this time, solution cavities and sinkholes were probably formed in the limestone. Numerous circular depressions in the topography of the Beaufort area appear to be the result of settling of sediment filled sinkholes.

HYDRAULIC PROPERTIES

Ground-water hydraulics is concerned with the natural or induced movement of water through permeable formations. Knowledge of the geologic framework and of the hydraulic properties of the formation are necessary in order to understand the operation of the aquifer system. The hydraulic properties of an aquifer are generally determined by field tests of discharging wells. The most common hydraulic properties determined by aquifer test are transmissivity (T) and storage coefficients (S).

An aquifer has a hydraulic conductivity of 1 ft/d if it will transmit in one day 1 ft^3 of ground water (7.48 gallons), at the prevailing viscosity, through a cross section of 1 ft^2 (measured at right angles to the direction of flow) under a hydraulic gradient of 1 ft/ft. Hydraulic conductivity, expressed in feet per day replaces the old term "field coefficient of permeability," expressed in gallons per day per square feet.

The transmissivity of an aquifer is defined (Lohman, 1972, p. 6) as the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. As with hydraulic conductivity, transmissivity is dependent upon the properties of both the aquifer and the contained fluid. Transmissivity is expressed in square feet per day and replaces the old term "coefficient of transmissibility," expressed in gallons per day per foot. Transmissivity is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer.

The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (Lohman, 1972, p. 8). In unconfined aquifers the storage coefficient is approximately equal to the specific yield as most of the water is released by gravity drainage and only a very small part comes from compression of the aquifer and expansion of the water. By contrast, in an artesian aquifer the water released from storage comes from compression of the aquifer skeleton and from expansion of the water in response to a decline in pressure. The storage coefficient is dimensionless and ranges from 0.1 to 0.3 for most unconfined aquifers and from 10^{-5} to 10^{-3} for most confined aquifers. If the artesian aquifer is "leaky," part of the water pumped from the aquifer appears to be water released from storage but may be recharged from overlying or underlying beds. All of the aquifer tests conducted for this study indicated that the principal artesian aquifer is a leaky artesian aquifer.

Although the coefficient of storage in an artesian aquifer is very small, large amounts of water may be released from storage in an extensive aquifer. For example, McCollum and Counts (1964, pl. 4) show that in an approximate 100 square mile area centered at Savannah, Georgia, the potentiometric water level has declined an average of about 100 feet and that possibly about 620 Mgal of water have been removed from compressive storage.

The results of aquifer tests conducted in the study area for the determination of transmissivity and storage coefficients are summarized in table 9. The location of the tests are shown in figure 11.

Table 9. Summary of transmissivity (T) and storage (S) coefficients determined from aquifer tests for the principal artesian aquifer.

Test No.	Location	Date	Coefficients (rounded) T (ft^2/d)	Coefficients (rounded) S	Remarks
1	MCAS, Burton, S.C.	1944	6,600	---	From Mundorff (1944)
2	Burton well field, Burton, S.C.	1944	12,000	---	From Mundorff (1944)
3	MCAS, Burton, S.C.	1956	3,300	3.5×10^{-5}	From Siple (1956)
4	Burton well field, Burton, S.C.	1956	11,000	1.1×10^{-4}	From Siple (1956)
5	0.9 miles west of Loman Island	1956	27,000	3.4×10^{-4}	From Hazen and Sawyer (1956)
6	1.2 miles north of jct. of U.S. 278 and S.C. 170	1957	47,000	3.6×10^{-4}	From Hazen and Sawyer (1957)
7	Daufuskie Island, S.C.	1958	53,000	3.0×10^{-4}	From Counts and Donsky (1963)
8	Savannah area, Ga.	1939 1958	29,000	3.0×10^{-4}	Average of six values from Counts and Donsky (1963)
9	Victoria Bluff, S.C.	1970	57,000	3.0×10^{-4}	From Nuzman (1970)
10	South end of Hilton Head Island, S.C.	1972	52,000	3.0×10^{-3}	From Nuzman (1972)
11	North end of Hilton Head Island, S.C.	1972	71,000	3.0×10^{-4}	From Nuzman (1972)
12	Palmetto Dunes, Hilton Head Island, S. C.	1973	28,000	---	Written communication Layne-Atlantic (1974)
13	1 mile east of Broad River jct. S.C. 281 and S.C. 170	1974	2,700	---	Single-well test
14	Fripp Island, S.C.	1974	4,000	---	Single-well test
15	Burton well field, Burton, S.C.	1975	8,300	2.7×10^{-5}	Leaky aquifer analysis; corrected for tidal effect.
16	Port Royal Clay Co., Port Royal, S.C.	1976	15,000	1.0×10^{-4}	Leaky aquifer analysis; corrected for tidal effect.
17	Wiggins Boat Ramp, Colleton, County, S.C.	1976	7,200	---	Lower permeability zone; single-well test.
18	Jacksonboro Boat Ramp, Colleton County, S.C.	1976	3,100	---	Lower permeability zone; single-well test.
19	1 mile east of Combahee River, Colleton County, S.C.	1976	1,800	---	Lower permeability zone; single-well test.

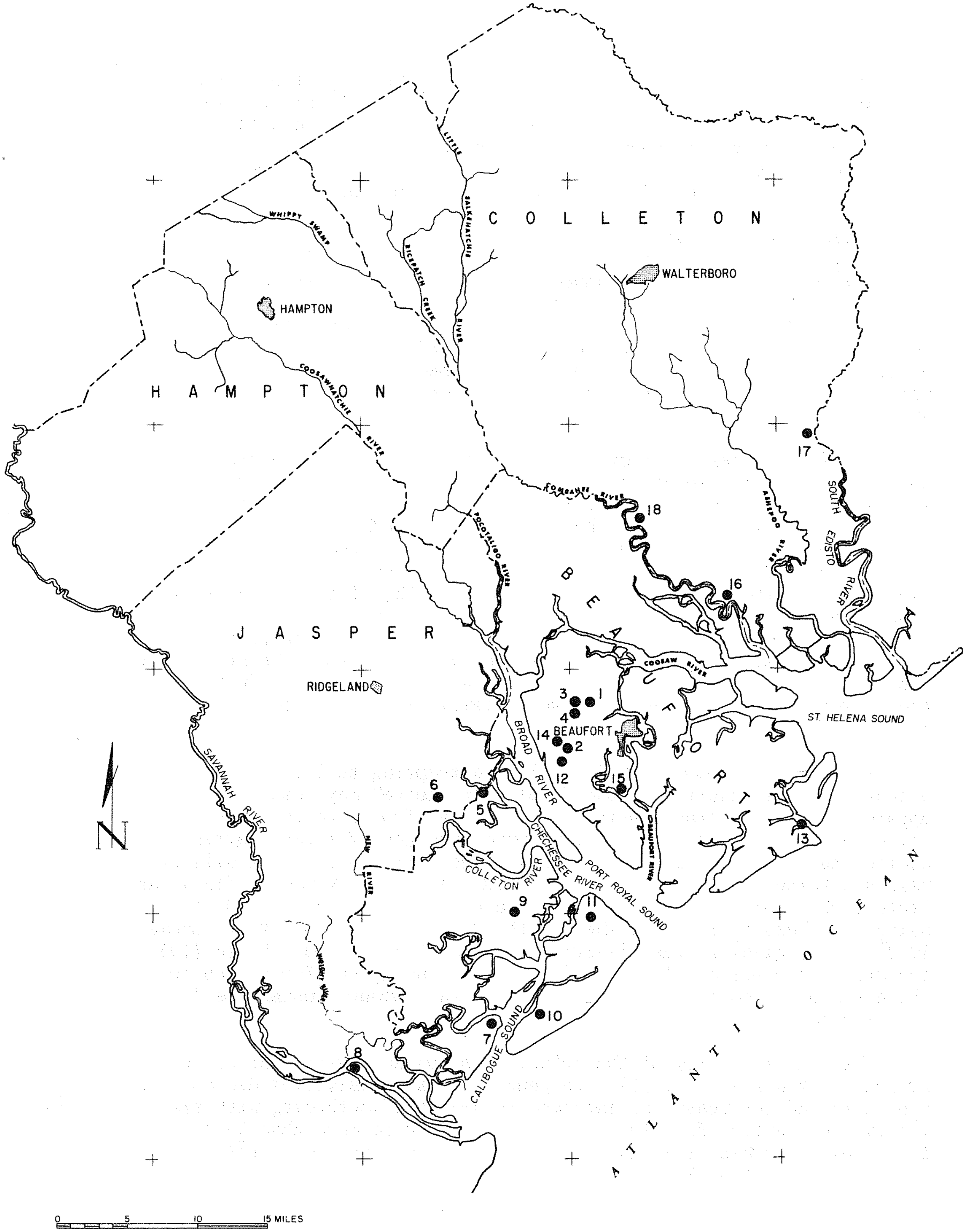


Figure 11. Location of aquifer tests presented in table 9.

The coefficients listed in table 9 were determined from formulas that assume certain conditions necessary for mathematical solutions. These assumptions are that (1) the aquifer is infinite in areal extent; (2) the aquifer is homogeneous and isotropic; (3) the aquifer is bounded at the top and bottom by impermeable materials (in the case where a non-leaky solution is used); (4) the aquifer is of uniform thickness; (5) the discharge and observation wells penetrate the full thickness of the aquifer; (6) the water is released from storage instantaneously; (7) the flow of water toward the well is radial and laminar; and (8) where measurements in a pumped well are used to determine transmissivity (storage cannot be determined without an observation well), the well is 100 percent efficient. While all these conditions are seldom if ever met, results from properly conducted tests that are designed and analyzed with respect to the specific geohydrologic framework of the area being tested can provide coefficients that are reasonably useful.

The aquifer test conducted at the Burton Well Field, Burton, S.C., shows the type of response normally associated with a leaky artesian aquifer in which the storage of water in the semipervious confining beds is considered. In this test, both early and late data do not fit the "Theis type curve" or the ideal confined aquifer response but do fall on the Beta = 1 curve (fig. 12) in the family of type curves for 1/u versus H(u,B), for various values of Beta (Lohman, 1972, plate 4). Appreciable amounts of water being released from storage in the overlying and confining bed from less permeable bed(s) in the aquifer act as recharge to the aquifer and results in a reduction in the amount of water being released from storage in the upper permeable zone and a consequent reduction in the drawdown curve for declining water levels in observation well Bft 116.

According to Lohman (1972, p. 34), attempting to fit test data from a leaky artesian aquifer to the "Theis type curve" may result in apparent values of transmissivity and storage from 5 to 20 times the value that would be computed using curves designed for leaky artesian aquifer tests. This, in part, explains the difference in transmissivity values obtained in the Burton Well Field (table 9). Mundorff (1944) and Siple (1956) computed transmissivity values of 12,000 and 11,000 ft^2/d using the Theis type curve; whereas the Hantush modified method (Lohman, 1972, p. 32) gives a transmissivity value of 3,200 ft^2/d. Siple (1956) computed a storage coefficient of 1.1×10^{-4} using the Theis type curve, while a storage coefficient of 1.3×10^{-5} was computed using the Hantush modified method.

The transmissivity of the principal artesian aquifer varies considerably (table 9, fig. 11). In general, transmissivities decrease to the north and northeast and increase towards the southwest, with transmissivities ranging from less than 30,000 ft^2/d to more than 50,000 ft^2/d west of Broad River and ranging from less than 2,000 ft^2/d to 15,000 ft^2/d east of Broad River.

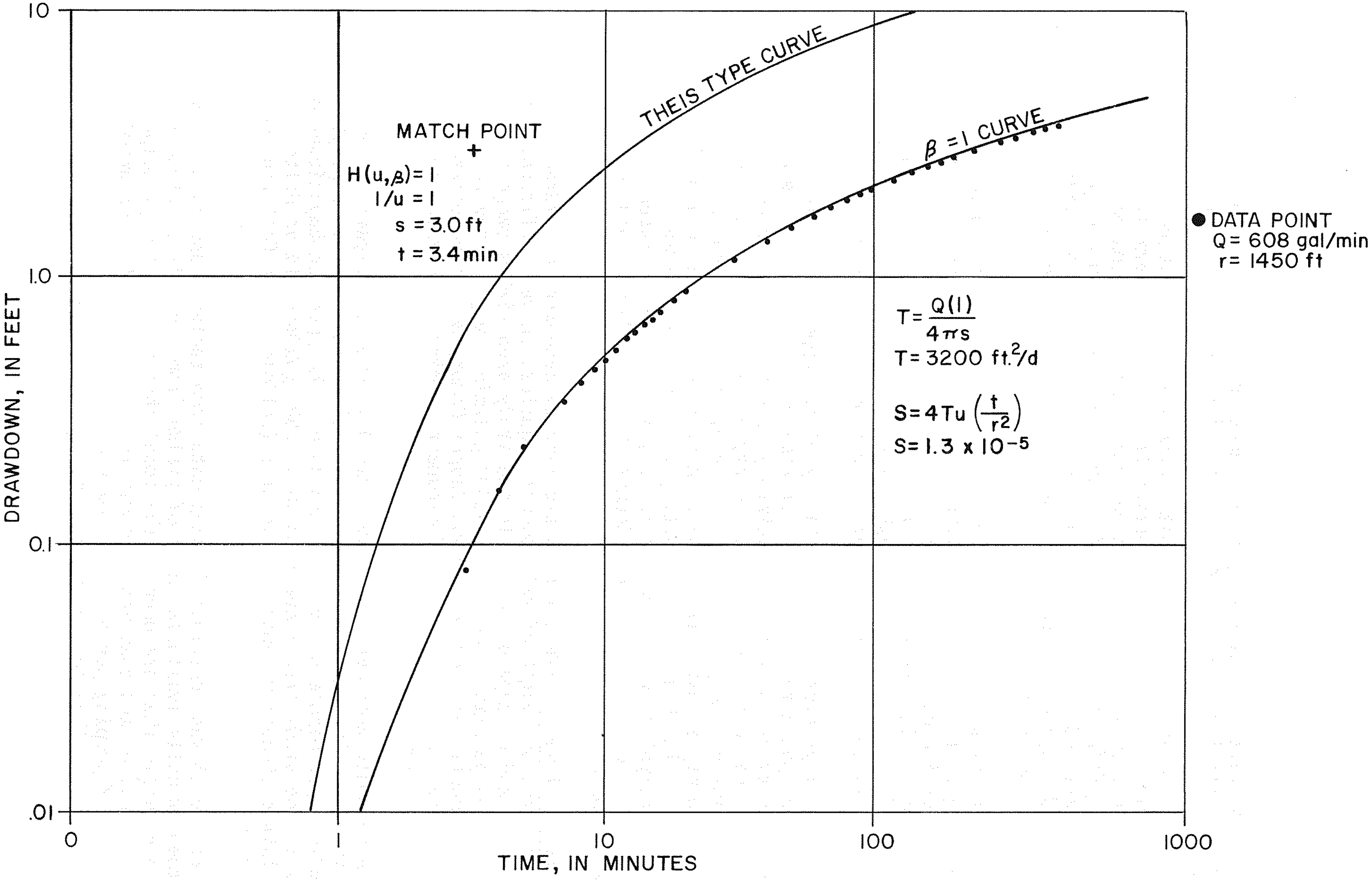


Figure 12. Logarithmic plot of drawdown (s) versus time (t) for observation well Bft 116 at Burton, S. C.

The average transmissivity of the upper permeable zone of the principal artesian aquifer in western Beaufort County (all of Beaufort County west of Broad River) and southern Jasper County is about 50,000 ft^2/d and in eastern Beaufort County notably less than 10,000 ft^2/d. The transmissivity of the upper permeable zone in northern Jasper County and southwestern and southeastern Hampton County is estimated to range from 10,000 ft^2/d to 30,000 ft^2/d, with transmissivity decreasing to the northeast and east. In general, the higher transmissivities in the western and southwestern parts of the area are due to increased thickness of the upper permeable zone.

The transmissivity of the lower permeable zone of the principal artesian aquifer in northern Colleton County and northeastern Hampton County is estimated to range from 5,000 ft^2/d to as low as 500 ft^2/d, with transmissivity decreasing to the north and northeast. The average transmissivity of the lower permeable zone of the principal artesian aquifer in southern Colleton County is estimated to be 4,000 ft^2/d.

The average hydraulic conductivity of the upper permeable zone of the principal artesian aquifer (determined by dividing the average transmissivity by the average thickness) is estimated to be 400 ft/d in western Beaufort County, Jasper County and southeastern and southwestern Hampton County. The upper permeability zone in eastern Beaufort County is estimated to have an average hydraulic conductivity of 175 ft/d. The hydraulic conductivity of the lower permeable zone of the principal artesian aquifer is estimated to vary between 75 and 100 ft/d in the eastern Beaufort County, Colleton County, and northeastern Hampton County.

Yield of wells.--Well yields are largely dependent on hydraulic conductivity, on length of well open to aquifer, on well efficiency, on well size, and on type of pump. In the study area yields range from less than 50 gal/min to more than 2,500 gal/min. Most of the wells in Beaufort County, Hampton County and Jasper County do not penetrate the full thickness of the aquifer. Consequently, many wells yield less than the maximum possible rate.

A commonly used measure of well yield is specific capacity. Specific capacity is defined as the yield per unit of drawdown and is expressed as gallons per minute per foot of drawdown. The specific capacities of wells in the study area range from about 250 (gal/min)/ft at Hilton Head Island (Beaufort County) to about 5 (gal/min)/ft in Colleton County (table 10).

Figure 13 was constructed using data from tables 9 and 10 and gives the theoretically available range of yields from properly constructed and developed wells that are open to the total thickness of the principal artesian aquifer and that would result in less than 25 feet of drawdown in a 24 hour pumping period. The low yields (less than 250 gal/min) available in northeastern Hampton County, Colleton County, and eastern

Table 10. Specific capacities of wells open to the principal artesian aquifer

Well No.	Total Depth	Casing Depth	Yield (gal/min)	Drawdown (ft)	Pumping Duration (hr)	Specific Capacity ((gal/min)/ft)
			Beaufort County			
2	141	66	327	10	4	33
107	100	77	550	12	12	46
121	105	85	126	3.9	2	32
133	109	68	180	68	25	3
146	265	125	500	5	76	100
170	97	39	120	13.5	1	9
173	299	109	400	6.2	5	64
174	292	120	400	5.3	11.5	75
181	115	93	500	5	4	100
302	210	115	100	0.5	4	200
415	90	72	520	17	4	31
440	211	139	1,500	9	24	167
443	213	138	1,500	8	24	187
449	153	96	280	39.8	4	7
453	104	63	8	0.5	1	16
455	102	96	25	5	2	5
456	102	72	25	8.5	2	3
459	106	60	120	5.3	0.25	23
504	92	63	210	36.2	7.5	6
563	210	78	21	1	0.5	20
564	207	84	20	1.2	0.5	17
565	209	89	100	2.1	0.5	48
566	230	84	24	1	0.5	24
652	220	135	1,500	5.9	8	254
706	204	99	340	4.5	8	76
746	203	97	320	4.5	8	71
750	125	100	349	3.5	8	100
771	240	144	500	2.9	8	172
795	94	45	272	3.9	1	69
801	88	64	25	1.3	2	20
825	150	138	16	0.3	1	50

Table 10. Specific capacities of wells open to the principal artesian aquifer--Continued

Well No.	Total Depth	Casing Depth	Yield (gal/min)	Drawdown (ft)	Pumping Duration (hr)	Specific Capacity ((gal/min)/ft)
Colleton County						
29	480	430	400	158	4	2
45	428	51	6	5	4	1
47	440	61	11	15	8	1
62	600	250	15	24	4	1
63	565	540	125	36	2	3
92	600	96	48	20	2	2
94	600	84	62	15	2	4
96	604	95	86	19	2	4
Hampton County						
36	152	105	421	15.2	24	28
48	128	94	421	47	8	9
73	200	60	11	5.7	0.25	2
74	200	110	10	2.1	0.25	5
76	216	94	11	5.8	0.25	2
77	220	80	11	0.66	0.25	17
78	200	120	9	0.27	0.25	33
79	219	120	11	0.67	0.25	16
80	60	26	120	3.3	1	36
81	260	130	11	0.21	0.25	52
82	200	104	11	1.8	0.25	16
83	156	86	11	0.37	0.25	30
Jasper County						
101	450	190	1,012	7.2	3	140
102	210	88	130	23		6
104	310	145	1,594	17.9	600	89
108	340	70	1,865	15	8	124
110	154	65	400	9	2	44
111	420	180	1,040	10.6	24	98
144	189	104	22	11.2	0.5	2
158	167	90	900	20	4	45

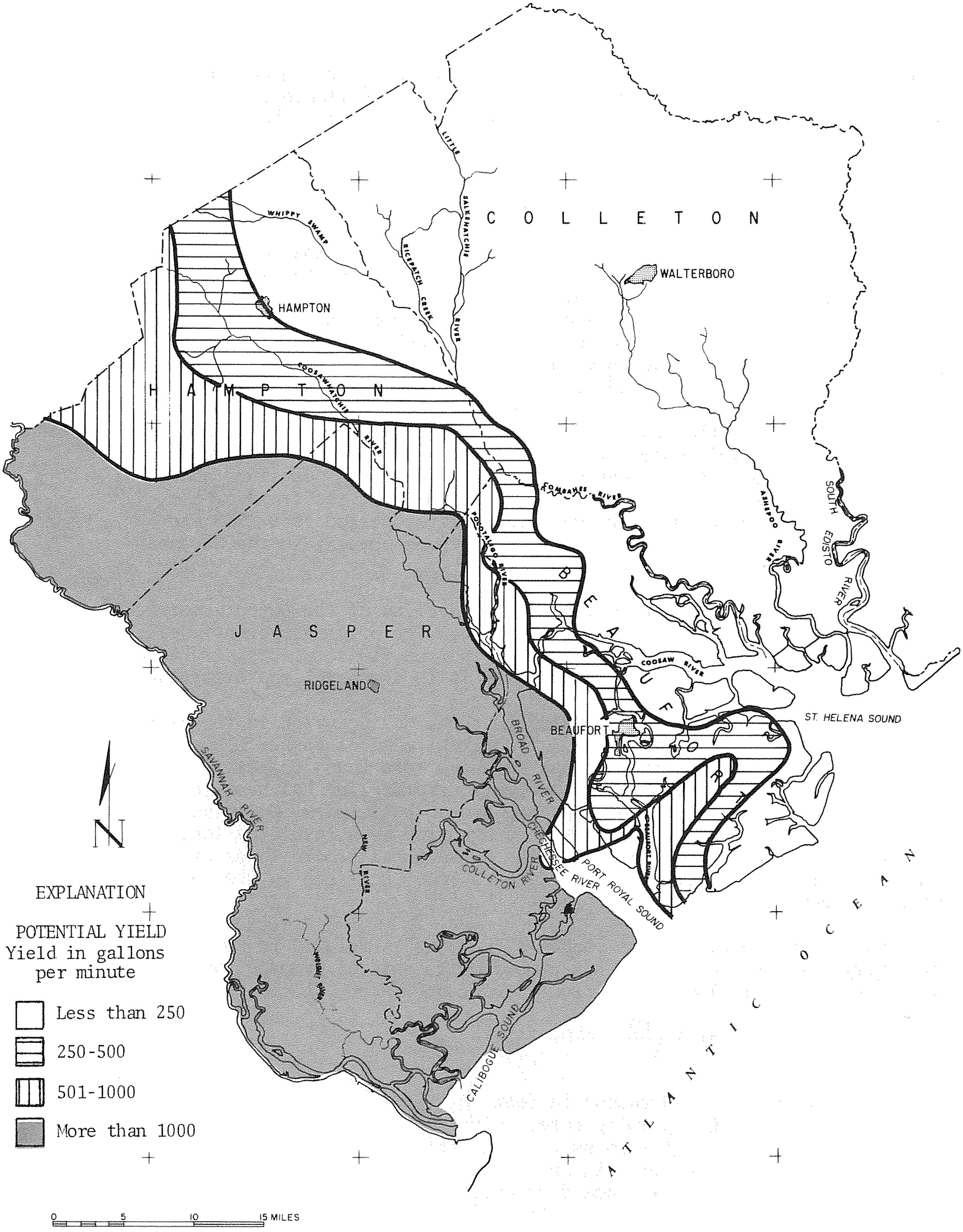


Figure 13. Estimated possible yield from the principal artesian aquifer, with less than 25 feet of drawdown in a 24 hour pumping period.

Beaufort County are due to the thinning or absence of the upper permeable zone. In most of Beaufort County the actual yield available to wells without causing saltwater to enter the wells is less than that indicated by figure 13.

HISTORICAL WATER-LEVEL DECLINES

With the withdrawal of ground water from the principal artesian aquifer by the City of Savannah, Georgia in the 1880's, the water levels in the Savannah-Beaufort area began a steady decline. Since 1880, when the original water level was 35 feet above msl, water levels in the City of Savannah at the center of the cone of depression generated by the Savannah area pumpage have declined 185 feet to a level of about 150 feet below msl (Counts and Krause, 1976, sheet 1). Warren (1944, p. 59) showed that from 1939 to 1943 the water level in well Jas 1 (about 4.25 miles north of the center of Savannah pumping) declined 15 feet and that from 1940 to 1943 water levels in three wells in Beaufort County (9 to 10 miles northeast of center of Savannah pumping) declined about 5 feet. Counts and Donsky (1963, p. 53) showed that the trend of the potentiometric surface has been downward for the period 1938-1958 and that the rate of decline varied with the rate of pumping in the Savannah area.

Figure 14 shows the approximate total decline of the potentiometric surface in the study area from 1880 to 1976. The original potentiometric surface of 1880, which was constructed by Warren (1944, p. 26), is based on limited data, and consequently, figure 14 is a general approximation.

The greatest decline, more than 100 feet, has occurred in the extreme southwestern tip of Jasper County. Throughout most of Jasper County and western Beaufort County, the decline has been more than 20 feet. In Hampton County and eastern Beaufort County, the decline has been generally less than 10 feet. In an area centered around Walterboro, Colleton County, declines of between 10 and 30 feet have occurred as a result of long-term and relatively large withdrawals by the City of Walterboro in an area where the transmissivity of the aquifer is low. Declines in the rest of Colleton County are less than 10 feet.

Water-level decline as a result of pumping is related to transmissivity, storage, distance from pumped well, rate of pumpage, and time according to the following equation (Cooper and Jacob, (1946):

$$s = \frac{2.300}{4T} \quad \frac{\log \quad 2.25Tt}{r^2S}$$

where: s = drawdown in feet
Q = pumping rate, in ft^3/d
T = transmissivity, in ft^2/d
t = time, in days
r = distance from well, in feet
S = storage coefficient

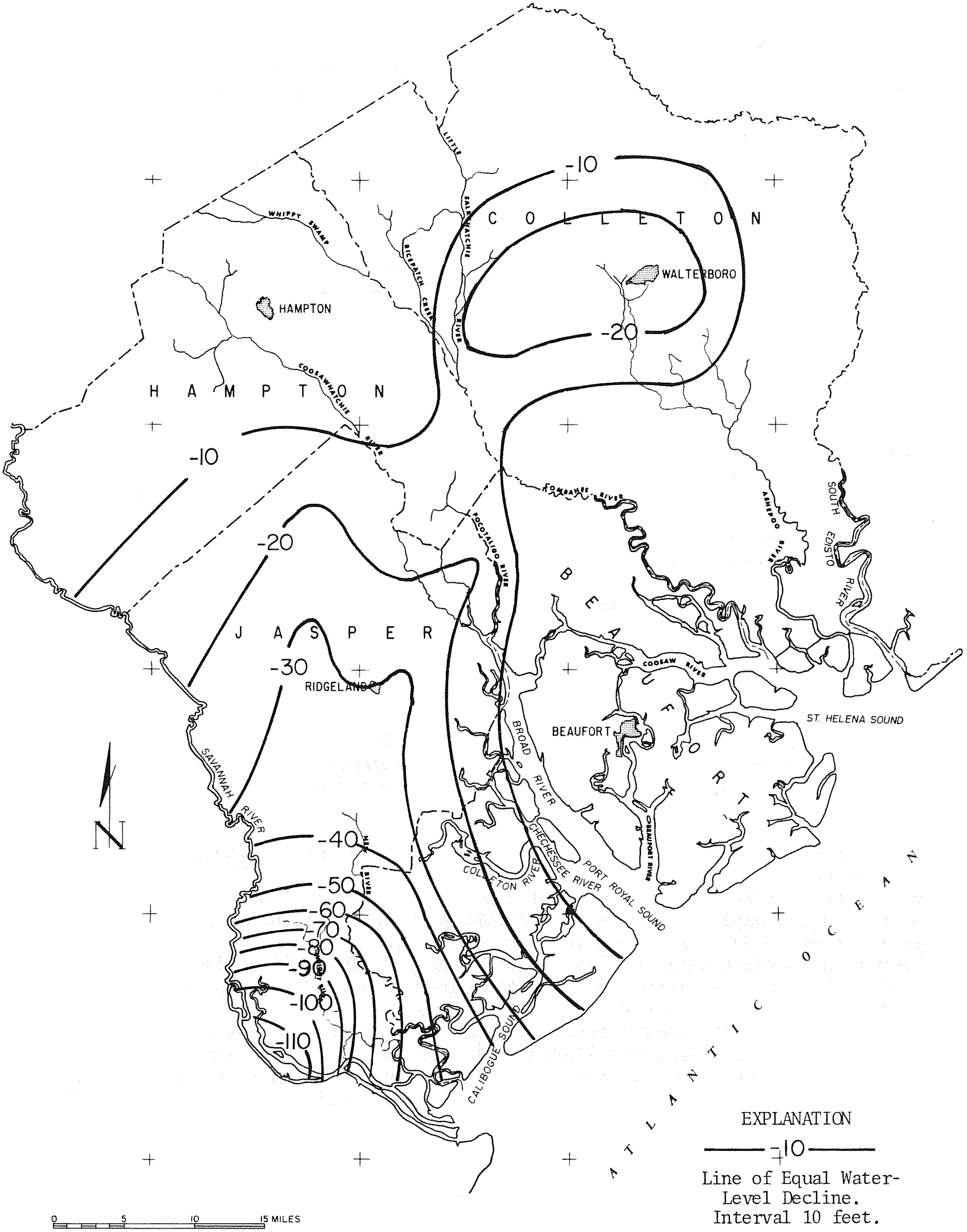


Figure 14. Approximate decline of the potentiometric surface of the principal artesian aquifer, 1880-1976.

Although this equation is based on a set of assumptions that are not fully met in the study area, the equation may be used to roughly approximate the relations between pumping, water level declines, distance from center of pumping, and duration of pumping if applied with due consideration for existing geohydrologic conditions. For example, the theoretical drawdown generated by a constant withdrawal of 1 Mgal/day for 1,000 days, 5,000 feet from the pumping well would be 2.3 feet in an aquifer with a transmissivity of 50,000 ft^2/d and with a storage coefficient of 0.0001 (fig. 15). Where leakage occurs through the confining beds (as in the case of the principal artesian aquifer), the theoretical drawdown predicted by the equation would be greater than the actual drawdown that would occur.

WATER-LEVEL FLUCTUATIONS

Causes of fluctuations.--In many artesian wells, the water levels fluctuate with barometric pressure (fig. 16). When the barometric pressure increases, the additional weight of the air column on the water depresses the water level in the well. Because these fluctuations are often masked by larger fluctuations due to other causes (in this area mainly ocean tides and pumpage) no special study was made of the relation between barometric pressure changes and water level fluctuations in wells. Counts and Donsky (1963 p. 48) determined that well Jas 46 showed a water level change of 0.35 ft for a barometric change of 0.63 feet of water. Water-level fluctuations of as much 1 foot may be expected as a result of atmospheric pressure fluctuations.

Water levels fluctuate as a result of heavy loads being applied above the aquifer. As the load is applied, the weight is transmitted to the aquifer, resulting in a compression of the aquifer and in a rise in water level. When the load is removed, the aquifer expands and the water level declines. Railroad trains, ships, and ocean tides commonly cause this type of loading effect.

The most noticeable cyclic water-level fluctuations in the Lowcountry occur as a result of tidal oscillations (fig. 16). The tidal efficiencies (the ratio of the amplitude of water-level fluctuation in a well to the amplitude of the corresponding tidal oscillation in a nearby tidal body) range from less than 0.05 for wells a mile or more from tidal surface-water bodies to more than 0.75 for wells a few hundred feet or less from tidal surface-water bodies. Tide-response features in wells lag the corresponding features in the effective tidal bodies by 15 to 180 minutes depending upon the distance of the well from the tidal bodies. Tidal oscillations of more than 6 feet in amplitude are common in the Beaufort area; therefore, water-level in wells may fluctuate more than 4.5 feet as a result of tidal oscillations.

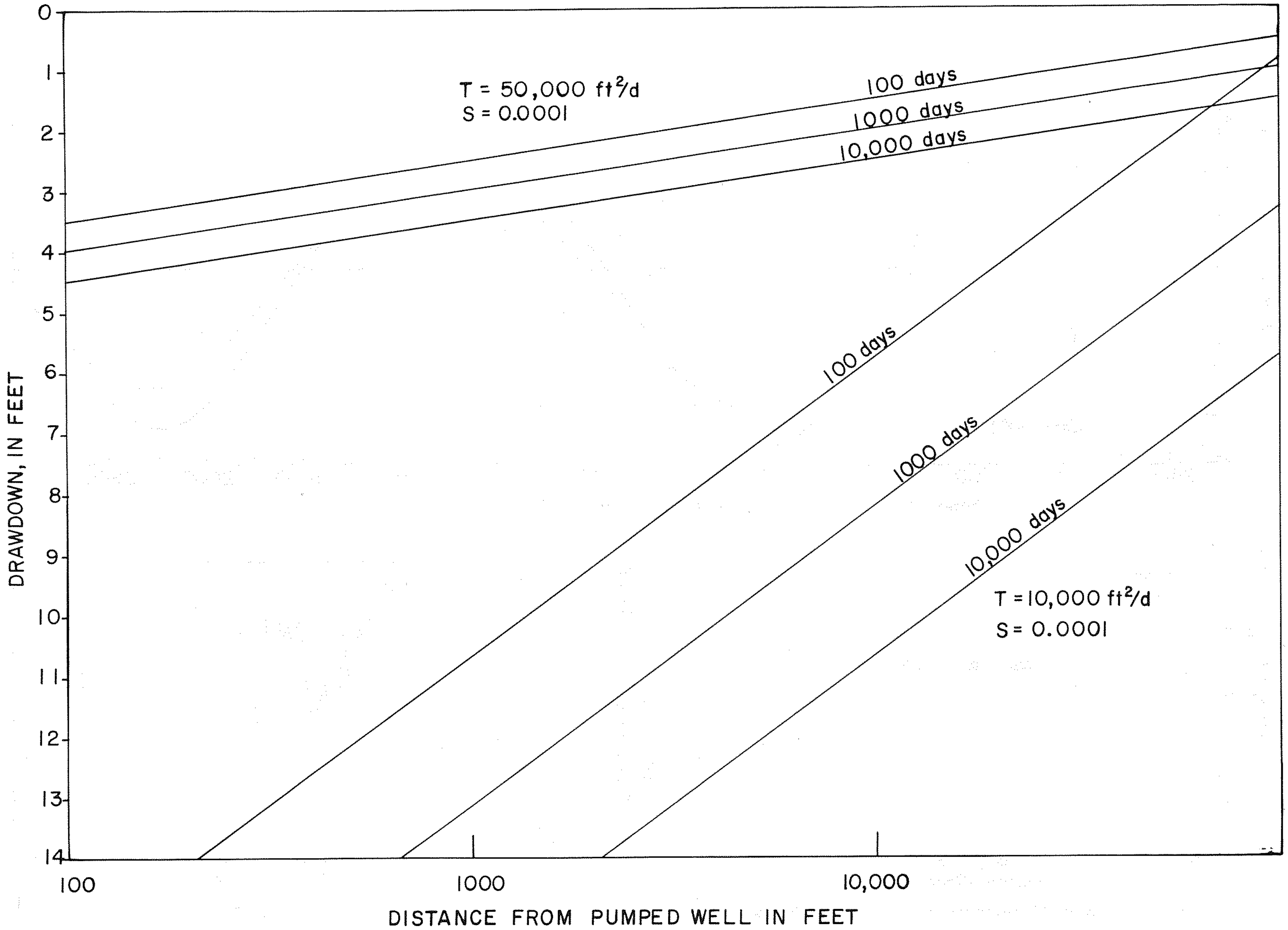
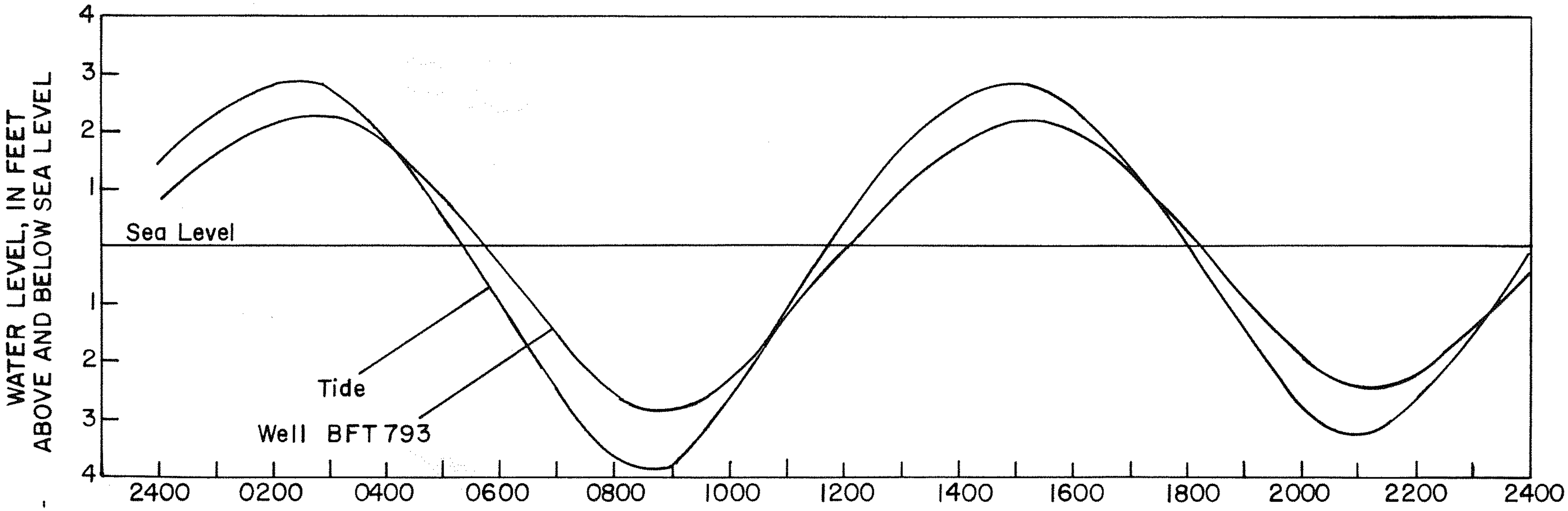
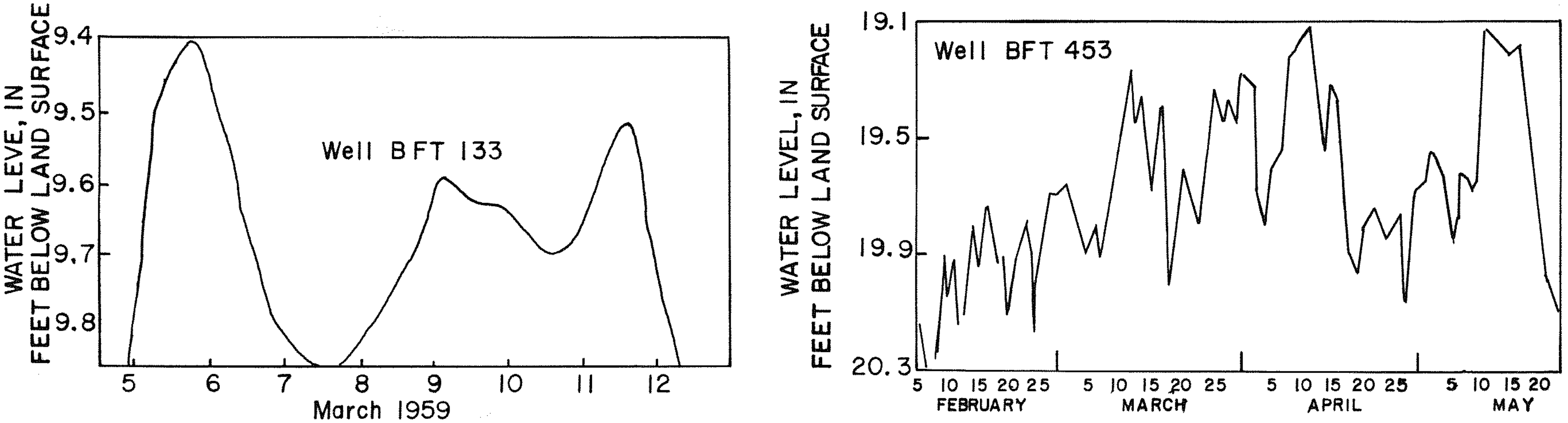


Figure 15. Theoretical decline of water level caused by an increased pumpage of one million gallons per day.



Water-level fluctuations due to tide, 21 May 1976



Fluctuation due to barometric changes (Siple,1960)

Fluatuation due to pumping

Figure 16. Hydrographs of wells showing water-level fluctuations due to tidal oscillations, barometric changes, and pumping.

Jacob (1950, p. 331 and 364) describes two types of tidal stress: (1) that in which a confined aquifer is in direct hydraulic contact with a tide-water body at a submarine outcrop, and (2) that in which the tide acts on a perfectly confining layer through which a mechanical stress is transmitted vertically to the confined aquifer. Both types of tidal response are present in water-level fluctuations of wells open to the principal artesian aquifer. Because the hydraulic connection between the tidal body and the aquifer is generally through material of very low hydraulic conductivity rather than being direct, the amplitude of the hydraulic component is severely attenuated in transmission from the tidal body to the aquifer, with attenuation increasing with travel distance and decreased hydraulic conductivity. The component due to mechanical loading, although also attenuated with both vertical and lateral distance, is probably the predominate cause of water-level fluctuations in wells due to tides in this area.

Because of the high tidal efficiences of some wells, it was necessary to correct for tidal effects when measuring water levels with respect to mean sea level. Average tidal efficiences for selected observation wells were calculated from records of tide gages at the Port Royal Clay Company, Port Royal and at Calibogue Cay, Hilton Head Island and from water-level records of each of the selected wells. Twelve calculations were made for each well with the results averaged to remove the effects of water-level changes not associated with tidal oscillation. The calculated tidal efficiences were then multiplied by the tidal changes in the appropriate tide gage to obtain corrections for the tidal effect. All water-level measurements made in wells that had a calculated tidal efficiency greater than 5 percent were corrected for tidal effects.

Water-level fluctuations in observation wells.--Water levels in eight observation wells were measured hourly on a continuous basis by means of automatic water-level recorders. The hydrographs of water levels in wells located 22 to 73 miles from the center of Savannah pumping are shown in figures 17 and 18. The dashed lines represent missing measurements and the solid lines represent average monthly measurements computed from hourly measurements.

Water levels in wells Bft 444 and 429 dramatically reflect the large pumpage at Hilton Head Island from May through September (fig. 17). The relatively large withdrawals during these months reflect the increased use of water for golf course irrigation and by the heavy tourist influx. Pumpage is generally higher in the months of higher temperatures when evaporation and transpiration rates are higher and more frequent irrigation is necessary (fig. 17). Generally, with the exception of periods of peak rainfall (see July 1975, fig. 17), there does not appear to be a direct relation between precipitation and water levels or between precipitation and pumpage. The lack of a distinct correlation between water levels and precipitation implies that no significant direct recharge to the aquifer from precipitation occurs on Hilton Head Island.

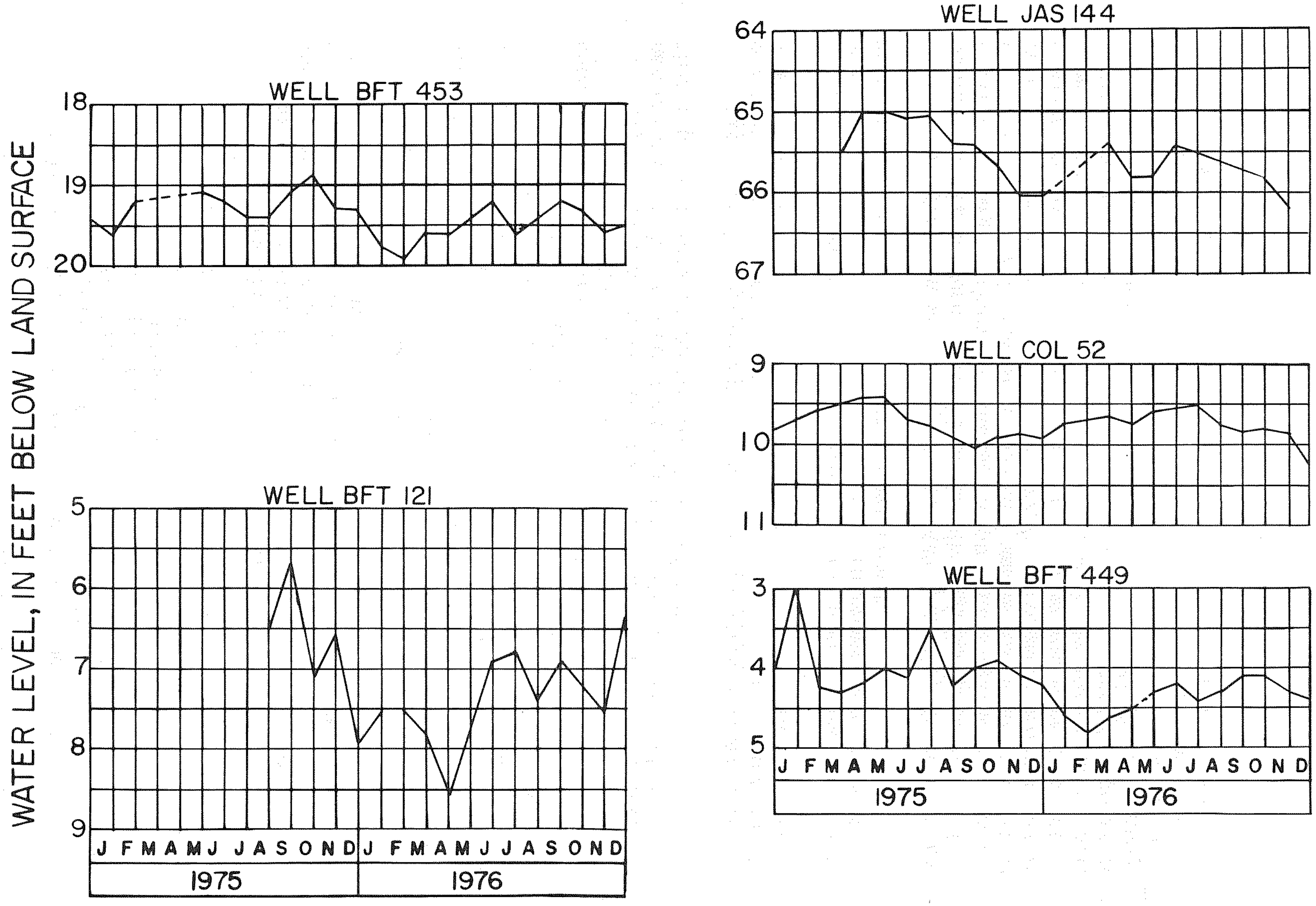


Figure 18. Hydrographs of five observation wells open to the principal artesian aquifer.

For the period 1973-76, Hilton Head area wells Bft 429 and Bft 444, which are respectively 22 and 25 miles northeast of the Savannah pumping, do not show any discernible downward trends (fig. 17). While the hydrographs of wells in Beaufort, Colleton and Jasper Counties (fig. 18) appear to show very small downward trends, the water-level declines are too slight (less than 1 foot), and the period of record is too short (2 years or less) to make any quantitative long-term predictions of water-level trends. Since the Beaufort-Savannah area pumping has not changed appreciably in the past 5 years, it may be reasonable to assume that regional and long-term water-level declines have stopped or are proceeding very slowly. However, the digital model of Counts and Krause (1976) shows that if the 1961-70 pumpage were to increase by 10 Mgal/d in the Savannah area, starting in 1971, the water level would decline about 6 feet in the center of Hilton Head Island by the year 2000 as a result of the increased pumping.

GROUND-WATER RECHARGE

Recharge is the addition of water to the ground-water reservoir and may occur in several ways. A primary source of recharge to the principal artesian aquifer is precipitation falling in the outcrop area in Allendale, Bamberg, and Orangeburg Counties and possibly in northwestern Hampton County. A part of the precipitation runs off on the land surface and enters streams; a part is evaporated or used by plants; a part is held in the unsaturated zone as soil moisture; and a part, generally called recharge, passes through the unsaturated zone into the saturated zone. This water is stored only temporarily because it moves from areas of recharge to areas of discharge as a result of gravity flow. Estimates of ground-water recharge to the principal artesian aquifer from precipitation falling in the outcrop area range from 1 to 11 inches (Callahan, 1964). A recharge of five inches would equal about 0.24 (Mgal/d)/mi^2.

On the basis of a potentiometric map by Counts and Donsky (1963) and a flow net analysis by Nuzman (1972) the estimated average natural recharge flowing into the study area from the outcrop area of the principal artesian aquifer is believed to be about 44.2 Mgal/d. Analyses of data collected for the Lowcountry study indicate that natural recharge flowing from the outcrop area into the study area is probably 40 to 45 Mgal/d.

The exact dimensions of the outcrop recharge area are not known but the area probably exceeds the 170 mi^2 required to supply 40 Mgal/d at an average recharge rate of 0.24 (Mgal/d)/mi^2. Consequently, the amount of water that enters the aquifer in the outcrop area as recharge and moves downgradient to discharge points is limited more by the hydraulic characteristics of the aquifer than by the amount of precipitation falling in the outcrop area.

Recharge also takes place locally by vertical leakage through the overlying confining bed and in places where the confining bed is absent. Recharge to the aquifer through the confining bed is dependent upon the thickness and hydraulic conductivity of the confining bed and upon the hydraulic head differential between the water level in the principal artesian aquifer and the water level in the overlying surficial water table or Hawthorn artesian aquifer where present.

Furlow (1969) determined the average vertical hydraulic conductivity of 52 core samples of the Miocene confining bed in eastern Chatam County, Georgia (which is similar lithologically to the confining bed in the study area) to be about 1.3×10^{-3} ft/d. On the basis of aquifer test analyses using the Hantush-Jacob method, (Lohman, 1972, p. 30) the vertical hydraulic conductivity of the confining bed was calculated to be 1.5×10^{-2} ft/d at the Burton Well field and 5×10^{-3} ft/d at the Port Royal Clay Company. The relatively high value at the Port Royal Clay Company reflects the fact that under Battery Creek in the Port Royal area the upper confining bed is absent in places and where present is usually thin and relatively permeable. As a result, the value may be high since a line source (Battery Creek) would have similar effects on drawdown response to pumping. A vertical hydraulic conductivity of 1×10^{-3} ft/d for the confining bed is believed to be a reasonable average value for most of the southern half of the study area. The hydraulic conductivity of the confining bed in the northern half of the study area is likely one or more orders of magnitude smaller.

Given the following assumptions: (1) the confining bed overlying the principal artesian aquifer has an average hydraulic conductivity of 1×10^{-4} ft/d and an average thickness of 40 ft, and (2) a downward hydraulic head of 1 foot exists between the water level in the principal artesian aquifer and the water level in the overlying Hawthorn aquifer or water table aquifer; then natural recharge to the principal artesian aquifer taking place through vertical leakage in the overlying confining bed would be about 500 (gal/d)/mi^2. For most of the study area, particularly eastern Beaufort County, this figure is probably conservative. Within the boundaries of the study area, recharge to the principal artesian aquifer as a result of vertical leakage is probably in excess of 5 to 10 Mgal/d.

Much of this recharge is taking place in the vicinity of a potentiometric high north of Beaufort (fig. 19). The area of the potentiometric high is also an area of relatively high topography, with land surface altitudes generally ranging from 20 to 40 feet above mean sea level. The water-table surface averages about 5 feet below land surface (Robert White, Lowcountry Council of Governments, oral commun., 1977) and generally is about 10 feet higher than the hydraulic head in the principal artesian aquifer. Consequently, ground water is moving downward from the water-table aquifer through the overlying confining material and into the principal artesian aquifer. The potentiometric high is about 40 mi^2 in extent and the thickness of the overlying confining bed averages about

20 feet. Assuming a vertical hydraulic conductivity of 1×10^{-3} ft/d and a hydraulic gradient of 10 feet, recharge to the principal artesian aquifer from the water-table aquifer is about 4 Mgal/d in the vicinity of the potentiometric high.

GROUND-WATER DISCHARGE

The principal artesian aquifer transmits water from its outcrop area or area of recharge to outlets of natural or artificial discharge. Natural discharge results from upward or downward leakage through adjacent confining beds and from leakage in areas that outcrop or are exposed in streams, estuaries, and the Atlantic Ocean floor. Some areas that once were discharge sites are now recharge sites because the hydraulic head in the principal artesian aquifer has been reduced by pumping.

Withdrawal of water through wells is an artificial stress upon a previously balanced hydrologic system and accounts for most of the ground-water discharge in the area. This stress is generally concentrated in relatively small areas. Figure 20 shows the location, primary types of water use, and relative size of the major pumping centers (those that withdraw more than 1 Mgal/yr) in the area. Water utilization by county and type of use in 1976 is presented in table 11.

Table 11. Estimated water use from the principal artesian aquifer in Beaufort, Colleton, Hampton, and Jasper Counties for 1976.

County	Primary water use, in million gallons					
	Domestic	Public Supply	Industrial	Irrigation	Stock	Total
Beaufort	620	1,400	140	2,600	20	4,800
Colleton	70	80	80	20	--	250
Hampton	130	140	100	20	110	500
Jasper	290	230	--	30	100	650
Total	1,100	1,800	320	2,700	230	6,200

Very little accurate water use data is available in most of the study area. Consequently, the water use figures are often a "best guess" based on number of users and per capita use data. Industrial and agricultural water use figures were generally determined using pump capacity and pumping duration data. The pumpage from water districts and golf courses on Hilton Head Island, while often a best guess estimate, is considered to be more reliable than most of the other pumpage data.

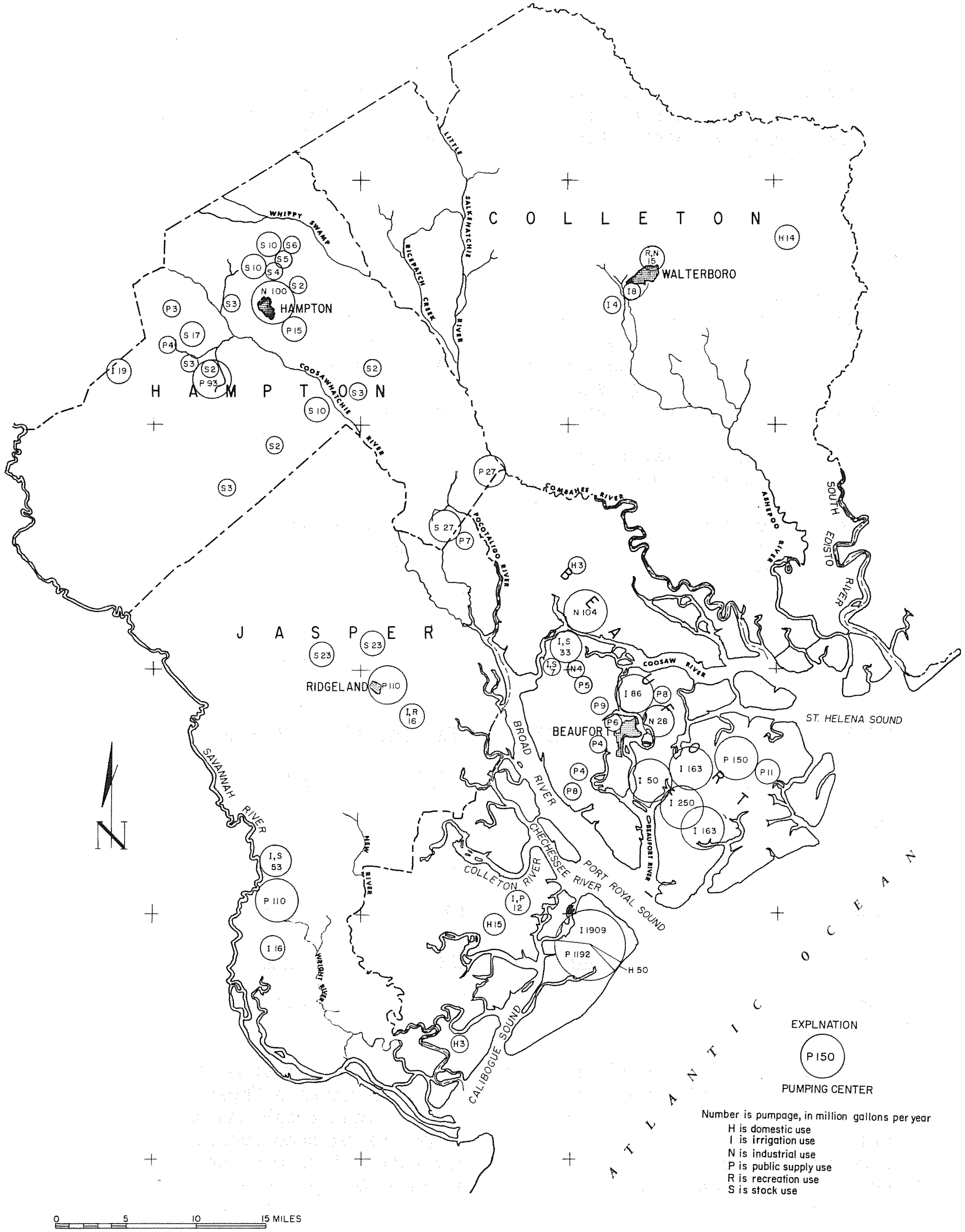


FIGURE 20. DISTRIBUTION OF PUMPAGE FROM THE PRINCIPAL ARTESIAN AQUIFER IN BEAUFORT, COLLETON, HAMPTON, AND JASPER COUNTIES FOR 1976.

Beaufort County accounts for over 75 percent of the total ground-water withdrawal from the principal artesian aquifer in the Lowcountry, with Hilton Head Island accounting for over half of the ground water used in Beaufort County.

Ground-water use in Beaufort County is predominately concentrated in the eastern part of the county and on Hilton Head Island, with golf courses and crop irrigation accounting for over half of the ground water used. Golf course irrigation is heaviest from March through October, and crop irrigation takes place almost exclusively in the months of May, June, September, and October.

The estimated 1976 withdrawal of 650 Mgal in Jasper County was primarily for rural domestic use and for public-supply use in Ridgeland and Hardeeville. Ground-water use in Hampton County is almost equally divided between rural domestic, public supply, and stock use. In Colleton County the largest pumping center is at Walterboro, which pumps about 150 Mgal/yr for public supply and industrial use.

The Savannah area, which includes the City of Savannah and nearby industries, is the largest user of ground water from the principal artesian aquifer in this part of the Coastal Plain area. According to Counts and Krause (1976) the Savannah area pumped an average of 75 Mgal/d in 1970.

POTENTIOMETRIC SURFACE AND GROUND-WATER FLOW

In an artesian aquifer, ground water is always under pressure and moves from points of higher hydraulic pressure to points of lower hydraulic pressure. The rate of movement of water between two points depends upon the hydraulic conductivity and porosity of the aquifer, upon the viscosity of the water, and upon the difference in head pressure between the two points. The slope of the water surface or head change between the two points, generally expressed in feet per mile, is called the hydraulic gradient. By contouring or connecting the heights of measured water levels in feet above or below a common datum in wells tapping an artesian aquifer an imaginary surface is developed which indicates the height to which water will rise in tightly cased wells open only to that particular artesian aquifer.

Before withdrawal of large amounts of water from the principal artesian aquifer, the potentiometric surface was controlled mainly by the hydraulic characteristics of the aquifer and the overlying and underlying confining beds, by the topography and altitude of the outcrop areas, and by natural recharge and discharge. The potentiometric map of 1880 constructed by Warren (1944, p. 26) showed an easterly hydraulic gradient of about 1 ft/mi, with natural discharge occurring in the Port Royal Sound and Parris Island area.

While the potentiometric contour map may be used to determine the general direction of ground-water flow, the actual movement of a single water molecule is very complex and may differ considerably from that which is implied by the two dimensional potentiometric map. The actual flow of ground water is three dimensional and is affected not only by hydraulic gradient but also by changes in aquifer characteristics (such as permeability, porosity, and thickness) and by boundary effects between fluids of different densities (such as a freshwater-saltwater interface). Furthermore, flow characteristics in a limestone aquifer vary widely depending upon the hydrogeologic characteristics of the aquifer.

White (1969) proposed a three part classification of carbonate aquifers based upon recognizable physical features: (1) a diffuse-flow aquifer in which the carbonate rocks have been affected the least by solutional modification; (2) a free-flow aquifer in which ground-water flow paths have been localized by solutional modification into well integrated systems of conduits; and (3) a confined-flow aquifer in which geologic boundaries are the flow-limiting factors rather than hydraulics. Ground-water movement through the diffused-flow system is analagous to flow in a homogeneous aquifer and more nearly follows the "basic" assumptions upon which ground-water flow equations are based. In a free-flow system, flow occurs in distinct conduits or channels while nearby rock may have little porosity or permeability. Flows in these conduits often have high velocities and may be turbulent.

The principal artesian aquifer generally functions as a confined diffuse-flow aquifer. Consequently, flow equations that assume laminar flow in an isotropic and homogeneous medium cannot be rigorously applied to the principal artesian aquifer. Nevertheless, if the limitations of basic flow equations as regards a particular set of geohydrologic conditions are considered, these flow equations and potentiometric maps may be used to indicate the general direction and average velocity of ground-water flow.

Calculations of the average velocity of ground-water movement indicate that water moves very slowly in the principal artesian aquifer. The average velocity of ground-water flow may be computed by the following equation:

$$\bar{v} = \frac{-K\ dh/dl}{\theta} \qquad \text{(Lohman, 1972)}$$

where:

$\bar{v}$ = average velocity, in feet per day
K = hydraulic conductivity, in feet per day
dh/dl = change in head with respect to change in distance, in feet per foot
θ = porosity, as a decimal fraction
- = the minus sign indicates that flow is in direction of decreasing head

It must be stressed that the solution of this equation is the average velocity, which may not be the actual velocity of a discrete unit of water between any two points in the aquifer. Actual ground water velocity may be more or less than this average value, depending upon the flow path followed and upon the geohydrologic conditions.

The average hydraulic conductivity of the upper permeable zone is about 400 ft/d in southern Jasper and western Beaufort Counties and about 175 ft/d in eastern Beaufort County. The average porosity of the upper permeability zone is probably between 20 and 40 percent and is arbitrarily assumed to be 30 percent. The potentiometric map of December 1976 (fig. 18) shows a hydraulic gradient of about 10 ft/mi in the extreme southwestern part of Jasper County and of about 1.5 ft/mi in western Beaufort County; thus, the average rate of movement in these areas is about 920 ft/yr and 140 ft/yr, respectively.

In eastern Beaufort County, with the exception of the recharge mounds in the vicinity of the Marine Corps Air Station and Parris Island, the potentiometric surface is relatively flat. Consequently, the average regional water movement is extremely slow, probably less than a few feet per year.

A potentiometric map of the Beaufort area prepared by Mundorff in 1944 (fig. 21A) shows a zero contour encircling Parris Island and a cone of depression in the Burton Well Field on Port Royal Island. When Mundorff's map was constructed, water was being withdrawn at Parris Island and the Burton well field was in its first stage of development. The regional hydraulic gradient shown in Mundorff's map was generally towards the south and southeast at about one to 2 ft/mi.

Siple (1960) prepared a potentiometric map for June 1959 that showed a pattern similar to that of the Mundorff map in the northwestern and eastern parts of the Beaufort area (fig. 21B). In Siple's map the potentiometric surface in the southwestern part of the Beaufort area, however, is more affected by the pumping at Savannah than in 1944, and the regional zero contour line has moved a few miles to the northeast and crosses through the middle of Hilton Head Island (fig. 21B). In the southwestern part of the area, the cone of depression generated by the Savannah pumping is apparent, with the hydraulic gradient increasing towards the southwest. The zero contour that surrounded Parris Island in 1944 is no longer present, and the cone of depression in the Burton well field (north of Parris Island) is deeper by 10 to 15 feet and larger in areal extent. All of these changes occurred as a result of increased pumpage at Savannah and at Burton Well Field and as a result of decreased pumpage at Parris Island.

Siple's map shows a potentiometric high in the vicinity of the Marine Corps Air Station. He suggests that this high is due to local recharge taking place through a break in the confining bed or a large increase in its hydraulic conductivity.

The potentiometric map of December 1976 (fig. 19) is similar to Siple's map of June 1959 with the exceptions: (1) the cone of depression centered at the Burton Well Field is absent; (2) the potentiometric high at the Marine Corps Air Station has changed in shape and increased in size; (3) the regional zero potentiometric contour has moved about three miles to the northeast; and, (4) a small but relatively deep cone of depression is present southeast of Lobeco.

The cone of depression that was present in the vicinity of the Burton Well Field in 1959 is no longer present because the pumpage in this area ceased almost entirely when the U.S. Marine Corps facilities at Parris Island, the Marine Corps Air Station, and Capehart Housing changed from ground-water to surface-water use in January 1965. The regional zero contour has moved to the northeast as a result of increased pumpage at Hilton Head and Savannah, and has been accompanied by a gradual steepening of the slope of the potentiometric surface toward Savannah and of a gradual increase in the size of the cone of depression. The small but relatively deep cone of depression near Lobeco occurs as a result of large withdrawals (about 500,000 gal/d) from two closely spaced wells where the principal artesian aquifer has a relatively low transmissivity (less than 5,000 ft^2/d).

Since 1880, the potentiometric surface in the area east and southeast of Burton (which includes Beaufort, Ladies Island, St. Helena Island, and numerous small sea islands) has shown little change, with water levels generally ranging between zero and 5 feet above msl. This suggests that recharge has been balanced by discharge for some time. It also suggests that, since very little pumping was taking place in this vicinity before the 1960's, natural discharge from the aquifer must have taken place through breaks in the confining bed or in regions where the hydraulic conductivity of the confining bed is relatively high. Evidence of this is shown by test drilling at Brickyard Point on the northern end of Ladies Island. Also, numerous wells in the vicinity of Brickyard Point and near the estuaries separating the sea islands contain salty water (fig. 22). This salty water is probably entering the aquifer where the confining bed is either thin or missing, and pumping has locally reduced the potentiometric surface below msl.

WATER QUALITY

The quality of ground water is largely controlled by the soluble minerals of the aquifer. Materials lying above or below the aquifer may also contribute dissolved substances. The concentrations of dissolved substances generally increase with greater depths and greater distances from recharge areas.

Ground water is generally more highly mineralized than surface water because of the relatively slow movement of ground water and because of its more intimate contact with soluble minerals. Surface water always contains some suspended inorganic sediment and varying amounts of organic matter such as algae, bacteria, and other micro-organisms. Ground water is relatively free of these substances as a result of the filtering action that takes place as the water passes through the interstices of the aquifer. Another basic difference between ground water and surface water is that ground water generally has a relatively constant temperature as opposed to wide seasonal variations in surface water. The temperature of water from the principal artesian aquifer is usually between 18° and 20°C, which approximates the local mean annual air temperature.

The term "quality of water" includes all factors (whether biological, physical, or chemical) that affect the fitness of water for use. However, in this report only the chemical characteristics of the ground water will be discussed because water from the principal artesian aquifer is generally free from physical or biological contaminants.

Chemical analyses furnish the basic data from which quality of water interpretations are made and indicate the suitability of the water for domestic, public supply, industrial, stock, and irrigation use. In addition, chemical data have been used in this study in determining the source and movement of ground water and in determining the source and extent of saltwater contamination in the principal artesian aquifer.

The chemical composition of water from the principal artesian aquifer in Beaufort, Colleton, Hampton, and Jasper Counties is indicated by 18 selected analyses (table 12). Water from wells Bft 459, 556, 562, 565, 569, 786, and Col 63 show high dissolved solids concentrations as a result of saltwater contamination. Water from the other wells is more representative of the chemical quality of uncontaminated water from the principal artesian aquifer.

Dissolved substances in water account for certain properties that have direct bearing upon the fitness of the supply for various uses. Some dissolved substances in water impart undesirable tastes and odors while others may cause staining, corrosion, scale formation, and precipitation in water systems or in water-using appliances. Almost any dissolved substance may prove objectionable if present in high enough concentrations. Some substances when present in high enough concentrations may render the supply unfit for human consumption because of harmful physiological effects. Table 13 gives the range of concentrations, source, and significance of the major chemical constituents of water from the principal artesian aquifer.

Water from the principal artesian aquifer is generally of suitable quality for most uses. Water temperature is nearly constant in any individual well but may vary slightly from well to well. Hardness as calcium carbonate is usually below 140 mg/L and often below 120 mg/L. Dissolved solids are generally below 200 mg/L, the pH usually ranges between 7.5 and 8, and the chloride concentration is normally less than 15 mg/L. In much of Beaufort County however, the chloride concentration usually ranges between 25 and 75 mg/L, except in more seriously contaminated areas where chloride concentrations range from 500 to more than 5,000 mg/L.

Table 12. Chemical quality of water from selected wells open to the principal artesian aquifer
[Results in milligrams per liter except as indicated. Analyses by U. S. Geol. Survey]

Well	Well Depth (feet)	Date of Collection	Silica (SiO2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCo$_3$)	Sulfate (SO$_4$)	Chloride (Cl)	Fluoride (F)	Nitrate (NO$_3$)	Dissolved Solids	Hardness as CaCO$_3$		Specific Conductance (Micromhos per centimeter) at 25°C
															Total	Noncarbonate	
Bft 121	105	77-01-14	12	.04	45	1.4	5	0.7	135	1.3	7.2	0.1		139	120	7	240
Bft 458	71	74-10-21	43	.00	23	7.8	26	6.2	178	2.4	5.1	0.6	.01	202	90	0	272
Bft 459	106	76-11-15	18	.23	480	790	6,000	300	396	1,400	11,000		.02	20,000	4,500	4,100	24,000
Bft 556	35	77-02-23	30	.02	9	8.9	480	22	410	40	560	2.3	.00	1,562	60	0	2,200
Bft 562	120	75-11-24	52	3.2	340	540	2,000	120	92	69	6,600	0.7	.04	10,700	3,100	3,000	20,000
Bft 563	100	75-11-25	21	6.6	50	5.6	18	2.4	172	4.0	25	1.0	.01	219	150	7	350
Bft 565	170	75-11-25	31	.02	250	66	690	6.0	197	110	1,400	0.4	.04	2,650	900	730	8,000
Bft 569	70	75-11-25	17	.06	840	210	1,700	18	171	430	4,500	0.2	.01	7,800	3,000	2,800	7,500
Bft 786	524	77-01-14	22	.08	19	14	280	27	192	59	350	1.2		867	110	0	1,700
Bft 787	239	77-01-14	28	.01	83	8	32	2.0	237	4.2	67	0.3		341	240	46	600
Bft 825	150	77-02-23	38	.02	30	9.7	10	3.0	150	7.3	5.7	0.3	.01	254	110	0	220
Col 63	567	76-01-22	30	.02	7.7	13	670	21	580	73	750	2.9	.00	1,850	73	0	2,600
Col 92	600	77-02-23	40	.02	79	7.6	42	3.2	240	4.6	79	0.2	.00	495	230	30	750
Col 94	600	77-02-23	25	.01	46	2.5	6	2.3	150	2.4	4.6	0.1	.01	239	130	0	500
Ham 73	200	77-02-23	24	.61	48	2.7	5	2.4	160	4.4	3.7	0.1	.03	250	130	3	260
Ham 77	153	77-02-23	49	.83	56	8.1	10	4.0	140	2.0	46	0.2	.01	316	170	55	
Ham 80	60	77-01-14	3	.02	29	1.9	12	2.0	106	7.2	5.4	0.2		167	80	0	
Jas 101	450	56-10-11	33		43	7.7	10	2.2	188	3.6	4.0	0.1		200	141		305

Note: Col 63, 92, and 94 are from the lower permeable zone; Bft 786 is from the relatively impermeable zone just below the upper permeable zone; and all other samples are from the upper permeable zone.

Table 13. Sources, significance, concentration range, and specific limits for drinking water of common chemical constituents in water from the principal artesian aquifer, Beaufort, Colleton, Hampton, and Jasper Counties

	Concentration Range, in mg/L					
Constituent	Mean[1]	Minimum	Maximum	Permissible Criteria, in mg/L	Principal Sources	Significance with respect to use
Silica (SiO_2)	25	.02	52	NL[2]	Siliceous minerals present in consolidated and unconsolidated deposits.	May form scale in pipes and boilers used in zeolite-type water softners and may be precipitated with other scale-forming minerals in steam boilers.
Iron (Fe)	.95	0	6.6	0.3[3]	Common iron-bearing minerals present in the rocks of the study area and iron pipes and casings.	May impart reddish-brown stain to laundry and utensils; very large quantities may color and impart objectionable taste to water and interfere with efficient operation of zeolite-type water softners. May be removed by simple aeration and filtration.
Calcium (Ca)	39	9.2	840	NL[2]	Limestone, dolomite, and gypsum are the most common sources.	Principal cause of hardness and commonly a major constituent in scale deposits.
Magnesium (Mg)	7.1	1.4	790	NL[2]	Dissolved from almost all rocks present in the area but primarily the ferro-magnesiam minerals and magnesium carbonate, is an abundant constituent of sea water.	Second of the major causes of hardness
Sodium (Na)	14	4.7	6,000	NL[2]	Dissolved from almost all rocks present in the area and an abundant constituent of sea water.	Large amounts in combination with chloride may give water a salty taste. Excessive amounts may reduce soil permeability and limit use of water for irrigation. Concentrations larger than 50 mg/L may cause foaming in boiler water.
Potassium (K)	2.9	0.7	300	NL[2]	Same as sodium	Small amounts essential for proper plant nutrition.
Bicarbonate (HCO_3)	156	66	413	NL[2]	Action of carbon dioxide in water or carbonate minerals. Chief anion in all but the most highly mineralized water in the study area.	Causes carbonate hardness in combination with calcium or magnesium. Bicarbonate of calcium and magnesium decompose in stream boilers and hot-water facilities to form scale and release corrosive carbon dioxide gas.

[1] Mean of only relatively uncontaminated samples.
[2] No specific limit.

[3] U. S. Environmental Protection Agency, 1975, National interim primary drinking water regulations, Federal Register 40(248): Part IV, December 24.

[4] Maximum limit for study area based upon EPA guide lines

Table 13. Sources, significance, concentration range, and specific limits for drinking water of common chemical constituents in water from the principal artesian aquifer, Beaufort, Colleton, Hampton, and Jasper Counties--Continued

Constituent	Concentration Range, in mg/L			Permissible Criteria in mg/L	Principal Sources	Significance with respect to use
	Mean[1]	Minimum	Maximum			
Sulfate (SO_4)	5	1.3	1,400	250[3]	Gypsum, iron sulfides, and other sulfur compounds. Commonly present in many industrial wastes.	Sulfates of calcium and magnesium from hard scale and are cathartic and unpleasant to taste. Sulfide-bearing ground water may contain hydrogen sulfide, which imparts a rotten egg odor to the water and may make water corrosive.
Chloride (Cl)	15	3.7	11,000	250[3]	Chloride salts, mainly NaCl, in consolidated rocks of marine origin. Abundant constituent of sea water.	In high concentrations imparts salty taste to water and makes water highly corrosive and makes water unsuitable for irrigation. May be removed by distillation, reverse osmosis or electrodialysis.
Fluoride (F)	0.3	0	1.2	1.6[4]	Occurs in trace amounts in most of the soils and rocks.	Optimum concentrations tend to reduce tooth decay of children's teeth; larger amounts may cause mottling of the enamel of teeth. Concentrations of more than 4 mg/L may affect bone structure.
Nitrate (NO_3)	.14	0	0.9	NL[2]	Decayed organic matter, sewage, and nitrates in soil.	Values higher than the local average may suggest pollution. An excess of 45 mg/L in drinking water may cause lyanosis, the so called "blue baby" disease in infants.
Dissolved Solids	188	113	20,200	500[3]	An approximation of the total quantity of dissolved mineral matter in a water sample.	The U.S. Geological Survey has classified water according to total dissolved solids in the following manner: fresh - less than 1,000 mg/L; slightly saline - 1,000 to 3,000 mg/L; moderately saline - 3,000 to 10,000 mg/L; very saline - 10,000 to 35,000 mg/L; briny - more than 35,000 mg/L.
Hardness (as $CaCO_3$)	127	60	4,500	NL[2]	Hardness is attributable to the presence of all alkaline earth minerals but is primarily due to calcium and magnesium.	Hardness in water may be recognized by the lack of suds, produced by soap. The U.S. Geological Survey has classified water according to hardness in the following manner: soft 0-60 mg/L; moderately hard 61-120 mg/L; hard 121-180 mg/L; very hard, more than 180 mg/L. Moderately hard water is generally suitable for most purposes, but does increase soap consumption; hard water may be troublesome for some industrial and domestic uses. Hardness may be removed by passing the water through a zeolite-type water softener.

[1] Mean of only relatively uncontaminated samples.

[2] No specific limit.

[3] U. S. Environmental Protection Agency, 1975, National interim primary drinking water regulations, Federal Register 40(248): Part IV, December 24.

[4] Maximum limit for study area based upon EPA guide lines.

SALTWATER CONTAMINATION

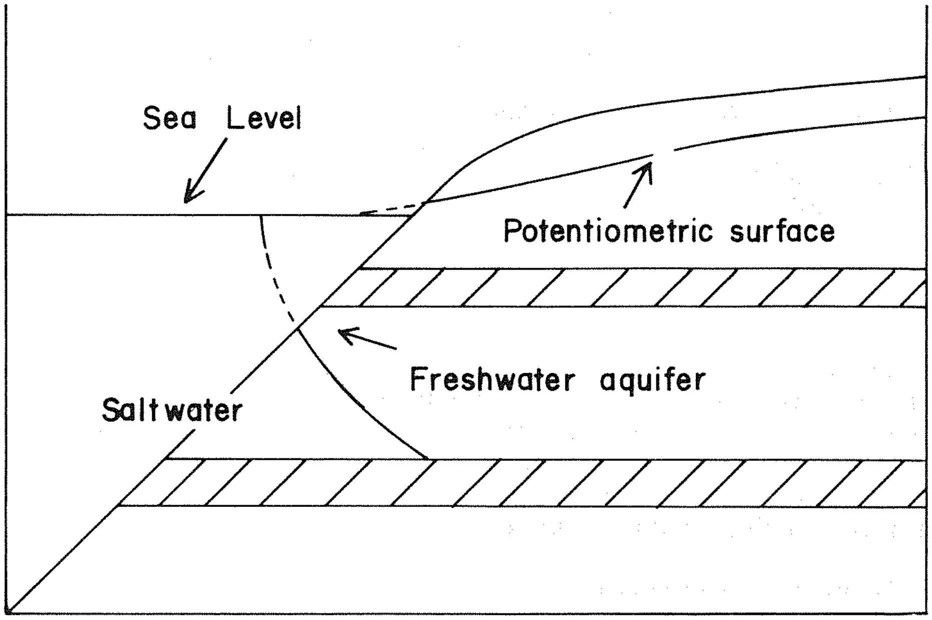
Because water users in the study area are so highly dependent upon water from the principal artesian aquifer, quality of water from the aquifer is of vital concern to them. One of the major concerns of water users in Beaufort County and in southern Colleton County is saltwater contamination of the principal artesian aquifer. Saltwater contamination of the aquifer is widespread and in some areas a very serious problem (fig. 22).

Sea water contains between 19,000 and 20,000 mg/L of chloride. Water containing 500 mg/L or more of chloride has a salty taste to most persons, and water having a chloride concentration of more than 1,500 mg/L is usually considered unacceptable for human consumption. At Edisto Beach, Colleton County and in many parts of Beaufort County, water in the principal artesian aquifer contains more than 500 mg/L of chloride (fig. 22).

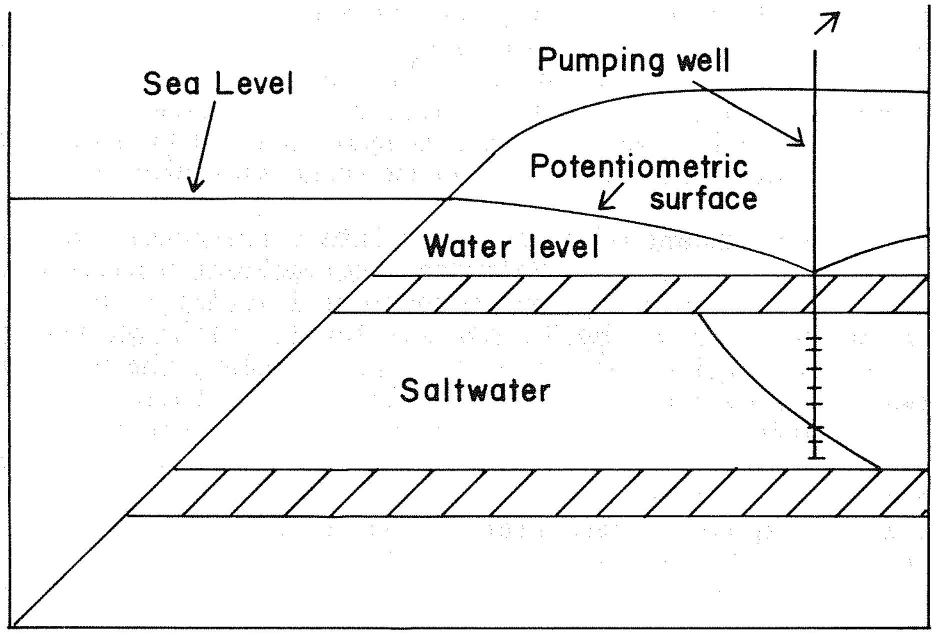
Saltwater contamination occurs primarily from: (1) seawater entering the aquifer where the overlying confining material is thin or missing, (2) unflushed salty water in the underlying formations moving vertically upward into the aquifer, (3) salty water in the lower part of the aquifer moving upward into the upper permeable zone, and (4) salty water in the aquifer moving laterally. In all four cases, stress from pumpage will have caused a reversal of hydraulic gradient.

For the purpose of this report, "saltwater contamination" is a general term referring to the condition wherein the chloride concentration of water in the aquifer is higher than that normally found in the aquifer. The term "saltwater encroachment" as used in this report is defined as the phenomenon occurring when a body of salty water, due to greater density or hydraulic gradient, invades a body of freshwater, either permenently or for a period of time measured in years. The encroachment can take place by lateral or vertical migration of the salty water into the freshwater body. Saltwater encroachment excludes small-scale and temporary intrusions of saltwater tongues induced by local pumping from wells constructed close to an existing saltwater body.

The encroachment of salty water into a freshwater aquifer is common throughout coastal areas. Saltwater encroachment usually occurs as a result of stress (pumping) and consequent lowering of the freshwater potentiometric surface below mean sea level. Although geologic and hydrologic conditions may be exceedingly complex, the mechanics of saltwater encroachment may be visualized in the following manner. Assume that an aquifer crops out in the ocean along the continental shelf or crops out in a saltwater stream and is consequently hydraulically connected to a saltwater body. In the natural state, due to higher head in the aquifer, freshwater discharges from the aquifer into the ocean or into the saltwater stream along the outcrop (fig. 23). As freshwater is pumped from the aquifer, the potentiometric surface in the aquifer will be lowered allowing some encroachment or interface movement



A. NATURAL CONDITIONS



B. SALTWATER INTRUSION

Figure 23. Sketch of an artesian aquifer, showing the theoretical freshwater-saltwater interface.

to a new equilibrium position. Further pumping may reverse the hydraulic gradient. With a reversal of hydraulic gradient, sea water continues to migrate landward and eventually may contaminate the pumping well (fig. 23B).

Records obtained from the City of Beaufort, the Parris Island Public Works Department, well drillers, the Survey, and previous ground water studies indicate that saltwater contamination as a result of wells being drilled close to salty streams is common in Beaufort County. In 1889, well Bft 28 (fig. 22) was drilled as a public supply well for the town of Beaufort. This well was drilled to a depth of 120 feet and was located about 400 feet from Beaufort River. In 1946 the well was taken out of service because water from it had a salty taste. After being unused for 9 years, the well was pumped at a rate of 250 gal/min for more than 2 days. At the end of the pumping period, water from the well contained only 44 mg/L of chloride (Hazan and Sawyer, 1956).

Evidently, continuous pumping of well Bft 28 (from 1889 to 1946) resulted in the development of a hydraulic gradient from Beaufort River to the well. Saltwater from the Beaufort River was then able to infiltrate into the aquifer and move down the hydraulic gradient into the well because, as shown by test drilling, the confining bed is absent or thin and relatively permeable in places underlying Beaufort River. After the well was taken out of service in 1946, water levels in the vicinity of well Bft 28 recovered and a hydraulic gradient from the well to Beaufort River was established. Water moving towards Beaufort River from the vicinity of well Bft 28 moved the salty water away from the well.

Wells Bft 19, 20, and 21 (all drilled as supply wells for Parris Island, fig. 22) show a response similar to that of well Bft 28 (table 14).

Wells Bft 446, 505, 532, 539, and 555 (table 14) show relatively large chloride concentration increases over a short time period. The close proximity of these wells to saltwater bodies (fig. 22) and the lack of a thick confining bed over the principal artesian aquifer resulted in the wells being contaminated when pumping reduced the freshwater potentiometric surface below mean sea level.

Saltwater contamination has also occurred as a result of the movement of saltwater into defective or improperly cased wells located near saltwater bodies. Wells Bft 494 (Hilton Head Island) and 811 (Okatie River) are two examples of this type of contamination. Well Bft 494 (located about 200 yards from the Atlantic Ocean, fig. 25) was drilled to a total depth of 146 feet, cased to a depth of 70 feet, and yielded water having a chloride concentration greater than 5,000 mg/L. Nearby wells had a chloride concentration of less than 75 mg/L. Geophysical logs run on well Bft 494 showed that the well casing ended above the confining bed. Consequently, saltwater was able to move laterally from the ocean through a beach sand overlying the upper confining bed of the principal artesian aquifer, into the open hole section of the well above the aquifer, and then was able to move vertically down into the aquifer.

Table 14. Chloride concentration in water from the principal artesian aquifer, Beaufort County

Well	Sample Depth (feet)	Data of Collection	Chloride (mg/L)	Location
Bft 19[1]	70-125	00-00-44	23	Port Royal Island
do	do	00-00-48	150	do
do	do	00-00-56	54	do
Bft 20[1]	70-90	00-00-45	24	Port Royal Island
do	do	00-00-48	132	do
do	do	00-00-56	44	do
Bft 21[1]	125-185	00-00-44	24	Port Royal Island
do	do	00-00-48	36	do
do	do	00-00-56	18	do
Bft 181	93-115	10-03-58	1,830	Parris Island
do	do	07-05-62	2,400	do
do	do	01-08-76	3,600	do
Bft 287	90-194	03-24-54	34	Hilton Head Island
do	do	02-12-58	35	do
do	do	04-19-77	46	do
Bft 324	120-220	05-24-63	67	Hilton Head Island
do	do	03-30-76	91	do
Bft 337	140-220	07-03-63	25	Hilton Head Island
do	do	05-24-76	38	do
Bft 407	140-214	06-23-64	120	Hilton Head Island
do	do	04-22-76	114	do
do	do	04-21-77	122	do
Bft 435	136-201	11-26-75	38	Hilton Head Island
	do	04-22-77	68	do
Bft 446	60-77	04-17-75	45	Horse Island
	do	04-27-76	90	do
	do	12-16-76	152	do

[1] These wells removed from active service in 1948

Table 14. Chloride concentration in water from the principal artesian aquifer, Beaufort County--Continued

Well	Sample depth (feet)	Data of Collection	Chloride (mg/L)	Location
Bft 455	63-102	03-03-75	7,900	Fripp Island
	do	04-08-76	9,100	do
Bft 505	64-120	09-18-75	162	St. Helena Island
	do	12-14-76	220	do
Bft 532	90-120	09-22-75	126	Lands End
	do	04-22-76	300	do
	do	12-16-76	930	do
Bft 539	60-85	09-22-75	126	Lands End
do	do	04-22-76	180	do
do	do	09-16-76	210	do
Bft 555	60-89	09-17-75	216	Chisolm Island
do	do	02-27-76	420	do
do	do	09-13-76	510	do
Bft 603	100-160	08-08-75	23	Hilton Head Island
do	do	01-09-76	61	do
do	do	04-21-77	76	do
Bft 637	130-220	12-02-75	38	Hilton Head Island
do	do	04-21-76	46	do
do	do	04-20-77	53	do
Bft 647	98-160	08-08-75	160	Hilton Head Island
do	do	03-30-76	390	do
do	do	06-29-76	480	do
do	do	04-20-77	390	do
Bft 721	140-220	11-26-75	68	Hilton Head Island
do	do	04-26-76	84	do
do	do	04-21-77	99	do
Bft 787	126-239	01-14-77	67	Hilton Head Island
do	do	02-11-77	91	do

Well Bft 494 was filled in with cement and a new well (Bft 647), properly cased to the limestone, was drilled about 10 feet from well Bft 494. Water from well Bft 647 has a chloride concentration that has varied from 160 to 480 mg/L (table 14), which probably indicates residual saltwater contamination from well Bft 494. Salty water entering the aquifer through well Bft 494 has contaminated the aquifer to the extent that it may be years before the chloride concentration in water from well Bft 647 will decrease to the level of nearby wells.

Well Bft 811 (located about 300 yards from a saltwater stream, fig. 22) was drilled to a total depth of 171 feet, cased to a depth of 122 feet, and yielded water having a chloride concentration of 2,800 mg/L. Water from nearby wells generally contain less than 25 mg/L of chloride. As with well Bft 494, well Bft 811 was not properly cased and salty water was able to enter the aquifer by moving laterally through overlying sediments into the open bore hole and thence downward into the aquifer. Well Bft 811 was filled in with cement, and a new well (Bft 825), properly cased to the aquifer, was drilled about 200 feet from well Bft 811. Water from well Bft 825 has a chloride concentration of 12 mg/L.

Improperly cased or defective wells can pose a serious threat to the aquifer. When such wells are located they should be plugged by cementing from the bottom up before being abandoned to avoid all possibilities of future saltwater contamination. The casings on all new wells should extend below the top of the principal artesian aquifer, and the space between the casing and the bore hole should be filled with cement grout for the same reason. The structure map on the top of the principal artesian aquifer (fig. 10) can be used as a guide to estimate depths to which wells should be cased. Actual depth to the aquifer as determined during drilling may be less or greater. Proper casing of a well will give protection from contamination from surface water and overlying aquifers and will prevent caving of the unconsolidated material above the limestone.

In addition to local saltwater contamination of individual wells, large parts of the aquifer have become contaminated as a result of saltwater encroachment. Records from the Public Works Department, Marine Corps Recruit Depot, Parris Island, S.C. show that three 5-inch wells, constructed in 1898 on Parris Island, were abandoned in 1903 because of high chloride concentrations. From 1903 until World War I, numerous wells were drilled on Parris Island. These wells were abandoned shortly after being put into use because of rapidly increasing chloride concentrations. The 1880 potentiometric map of Warren (1944) showed natural ground-water discharge taking place in the vicinity of Parris Island. Evidently, with pumping and consequent lowering of the potentiometric surface, this natural discharge area became a recharge area, allowing salty water to enter the aquifer. The extensive saltwater contamination at Parris Island is considered to be saltwater encroachment because since at least 1903, water from the principal artesian aquifer has become salty (greater than 1,000 mg/L of chloride) as a result of pumping and will remain salty in the foreseeable future.

Another condition favorable for encroachment is breaching of the confining bed under saltwater bodies. Evidence for breaching in Battery Creek and Beaufort River is substantial. Siple (1956) reported limestone resembling that of the principal artesian aquifer being dredged from the Beaufort River below Port Royal. Counts and Donsky (1963, p. 56) mention submarine springs in the Beaufort River near Port Royal being reported by old time residents of the area. A seismic survey conducted by the South Carolina Water Resources Commission (Duncan, 1972, p. 104) indicated (1) that the principal artesian aquifer subcrops on the bottom of Beaufort River at the mouth of Battery Creek near Port Royal; (2) that at the confluence of Cat Island Creek with Beaufort River the confining material is very thin and may be absent in places; and (3) that the aquifer subcrops on the bottom of Battery Creek in the vicinity of the Port Royal Dock and Turning Basin. Four of six test holes drilled by the South Carolina Highway Department beginning at the upper end of the Port Royal Turning Basin in Battery Creek and extending to the confluence of Battery Creek and Beaufort River showed the confining material overlying the aquifer to be less than 5 feet in thickness and generally to consist of fine to coarse, slightly-clayey sand. Six core holes drilled by the South Carolina Highway Department across Beaufort River east of the Naval Hospital showed that the top of the aquifer is separated from the bottom of Beaufort River by less than 1 foot to no more than 4 feet of silty sand. Finally, a pumping test conducted at Port Royal Clay Company, Port Royal indicated a hydraulic connection between Battery Creek and the principal artesian aquifer.

Saltwater encroachment occurring as a direct result of large ground-water withdrawal from a relatively small area is presently occurring on Hilton Head Island (fig. 20). Prior to its development as a resort and retirement community, Hilton Head Island was sparsely populated and used relatively little ground water -- probably less than 10 Mgal/yr. As a consequence of the tremendous growth that has taken place since the 1960's, total water used at Hilton Head has increased considerably. Pumpage for 1976 was in excess of 3 billion gallons (fig. 20).

As a result of these large withdrawals and the consequent lowering of the potentiometric surface (large withdrawals at Savannah also contribute to reduced water levels; see fig. 19), chloride concentrations in water from the upper permeable zone of the principal artesian aquifer have increased (table 12).

Saltwater encroachment in the upper permeable zone and the underlying less permeable material is illustrated by the graphs of figure 24 which show slight increases in chloride concentration for the period of record. Additionally, figure 24 shows that, for a particular well, chloride concentration increases with depth. The higher chloride concentration in the 450 to 510 ft interval in well Bft 315 as compared to the 500 to 599 ft interval in well Bft 101 is believed to occur because well Bft 315 is nearer the saltwater recharge area than is well Bft 101 (fig. 25).

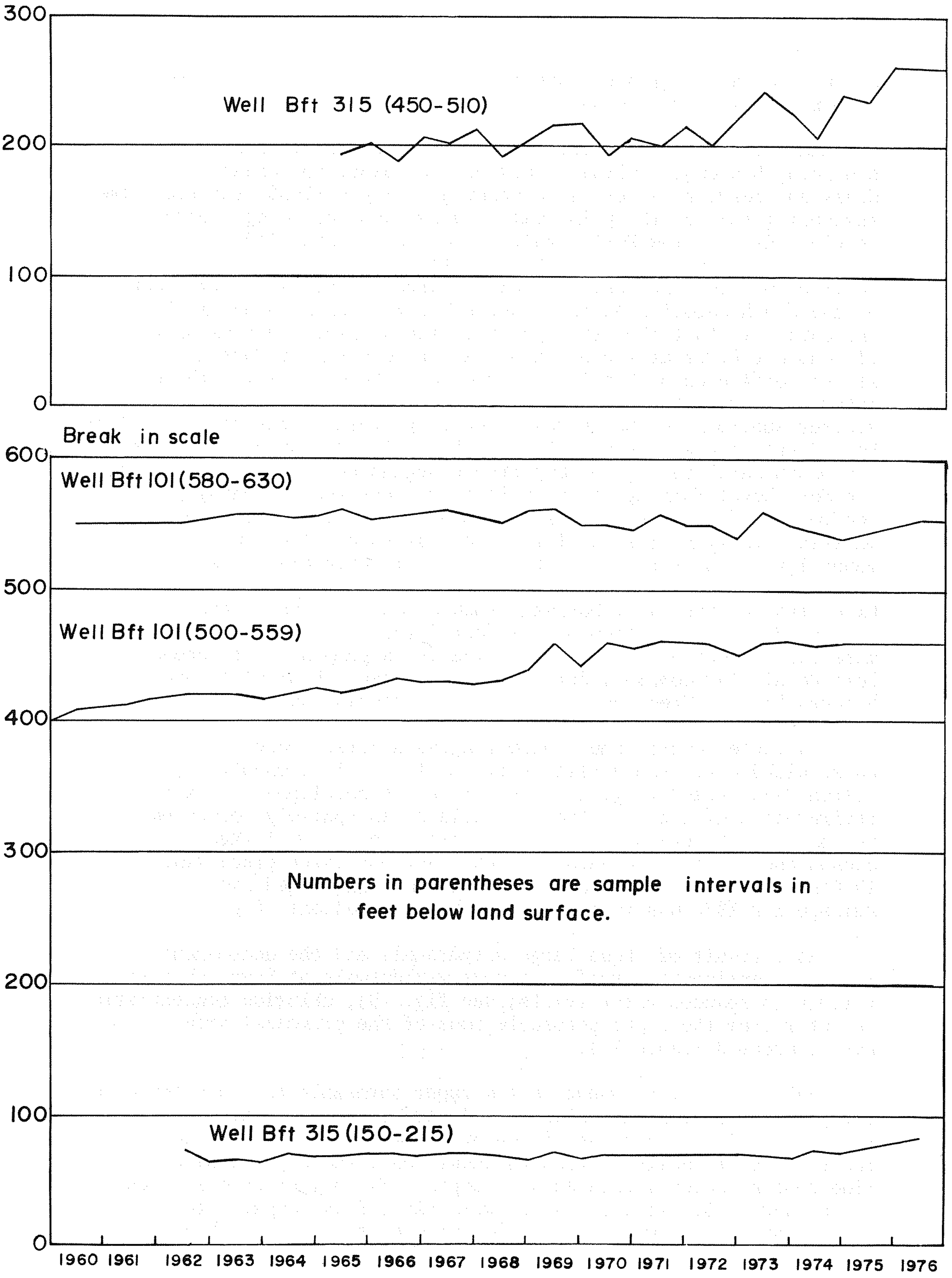


Figure 24. Chloride concentration change with time and depth in the principal artesian aquifer at Hilton Head Island.

Figure 25 shows the potentiometric surface and the areal distribution of chloride concentration of water in the upper permeable zone of the principal artesian aquifer at Hilton Head Island for December 1976. Water containing relatively high chloride concentrations (more than 50 mg/L) occurs along the northeastern end and along the ocean side of the island, extending landward to about the middle of the island. The boundary of this relatively high chloride water is arbitrarily placed at the 50 mg/L line of equal chloride concentration.

Sea water entering the aquifer primarily east of Parris Island in the vicinity of Battery Creek and Beaufort River and moving down the hydraulic gradient towards the northern end of Hilton Head Island is believed to be the most likely source of the high chlorides. Figure 26 shows the zone of diffusion occurring in the aquifer between Port Royal and Hilton Head Island. Also, it is possible that an offshore hydraulic connection exists between the aquifer and the sea bottom to the southeast of the island. On the basis of a comparative study of radiocarbon concentrations in ground water in the vicinity of Hilton Head Island, Back and others (1970) reported that the source of salty water at the northern end of the island is modern ocean water and that the source of salty water near the center of the island is saline formation water.

On the basis of available data, the following is believed to best explain the saltwater encroachment occurring at Hilton Head Island: (1) salty water already present in the aquifer at Parris Island and Fripp Island is moving laterally towards Hilton Head Island as a result of the extensive pumping and consequent water-level declines at Hilton Head Island and Savannah; (2) the salty water appears first at the north end of the island and then moves to the southwest down the hydraulic gradient towards Savannah; and (3) vertical upward movement of underlying salty connate water is contributing to the saltwater encroachment problem.

At present, saltwater encroachment at Hilton Head Island is limited in areal extent and contaminated water generally contains less than 100 mg/L of chloride. The movement of the salty water to the northwest appears to be attenuated by a slight ground-water divide running in a northeasterly direction (fig. 25). But the saltwater encroachment boundary is not static and will continue to move downgradient.

Data collected in April 1977 indicate that the top of the boundary has moved slightly to the southwest and that the landward side of the boundary may have moved slightly further inland. The April positon of the saltwater encroachment boundary probably reflects abnormally heavy pumping since February 1977. Under normal pumping conditions, movement of the saltwater boundary over a period of four months would probably be undetectable.

Any calculation of the rate of saltwater encroachment at Hilton Head Island based on available data is subject to considerable error and doubt. Nevertheless, because of the importance of having some indication of the rate of encroachment, estimates of the rate of saltwater

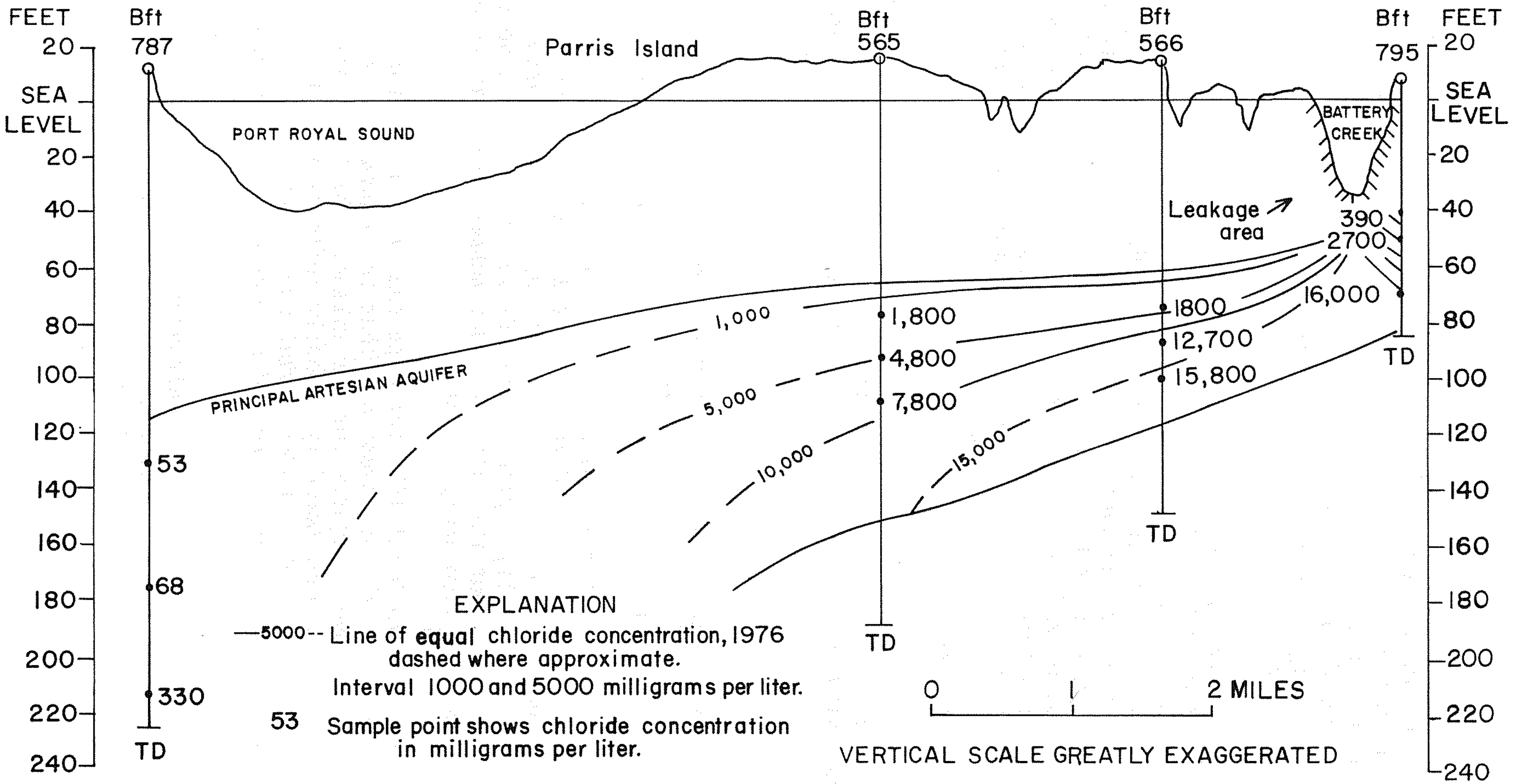


Figure 26. Generalized geohydrologic section from Hilton Head Island to Port Royal Clay Company, showing the zone of diffusion in the upper permeable zone of the principal artesian aquifer.

movement in the upper permeable zone based on regional and local hydraulic gradients are given.

The regional hydraulic gradient is estimated to be roughly 1.5 feet per mile (fig. 25) and the maximum hydraulic gradient in the saltwater toe under moderate and extreme rates of pumping may be in the range of 2 to 4 feet per mile. Based on these ranges in hydraulic gradient, on the assumption of an average porosity of 30 percent, and on an average hydraulic conductivity of 400 ft/d for the upper permeability zone, the calculated rates of movement for gradients of 1.5, 2, and 4 feet per mile are about 140, 180, and 370 feet per year. On the assumption that all movement represents encroachment, the low rates are believed to approximate the rates of regional encroachment. The higher rates may occur in the saltwater toe near centers of heavy pumping for a few months each year, but during the remainder of the year the rates are probably lower. If future conditions are such that withdrawals are greater and the hydraulic gradients are increased, the rate of movement will increase.

In the late 1950's and early 1960's prior to development of Fripp Island as a resort and retirement community, test wells were drilled on the island to ascertain the quantity and quality of ground water. These test wells showed that, while yields of more than 250 gal/min were available, water from the principal artesian aquifer underlying Fripp Island contained more than 5,000 mg/L of chloride (fig. 22).

Fripp Island is a barrier island of generally low relief cut by numerous saltwater channels. The confining bed probably has been removed in places or at least cut into by fluvial erosion allowing saltwater to enter the aquifer. Also, the salty water present in the aquifer may in part be unflushed older seawater. Whatever the source of salty water, water from the principal aquifer underlying Fripp Island is unusable and will remain so in the foreseeable future.

Harbour Island, Hunting Island, Prichards Island, Capers Island, St. Phillips Island, and Bay Point Island (fig. 22) are all topographically and geohydrologically similar to Fripp Island. The small amount of data available on Harbour Island and Hunting Island indicate that water in the principal artesian aquifer underlying these islands contains 5,000 mg/L or more of chloride (fig. 22). No chemical quality of water data is available on the other islands, but it is likely that the aquifer underlying these islands also contains salty water.

Widespread saltwater contamination of the principal artesian aquifer at Edisto Beach, Colleton County (fig. 22) probably occurs as a result of natural processes and as a result of lowering of the potentiometric surface by pumping. Salty water in the aquifer is probably a mixture of salty connate water and modern ocean water. Saltwater contamination of the principal artesian aquifer at Edisto Beach is unique in that water from the upper section of the aquifer usually contains more chloride than does water from the lower section of the aquifer. This may indicate that connate salty water has been flushed from the lower permeability zone to a greater extent than the salty water has been flushed from the upper section of the aquifer. Also, the lower permeable zone may be protected to a greater degree from the intrusion of modern ocean water than is the upper section of the aquifer, due to the zone of lower hydraulic conductivity between them.

Depths to freshwater-saltwater contact.--In this study, as in most coastal studies, the computed depths to the freshwater-saltwater contact based on the Ghyben-Hertzberz principle are generally less than the observed depths to the freshwater-saltwater contact. This discrepancy between the theoretical and actual position of the saltwater encroachment front and the reasons for it are discussed in detail by Cooper and others (1964).

Kohout (1960) showed that cyclic flow of saltwater in the aquifer acts as a deterrent to the encroachment of sea water because of return to the sea of a part of the inland flow. The greater the seaward flow the greater the discrepancy between the actual and the theoretical position of the saltwater encroachment front.

In addition to assuming static conditions, the Ghyben-Hertzberg principle also assumes that the saltwater head is at mean sea level. Calculations of depths to a freshwater-saltwater contact based on an assumed head in saltwater at mean sea level gives erroneous results if the saltwater head is not at mean sea level (Perlmutter and others, 1959). The actual heads and densities of the saltwater must be considered.

The Ghyben-Hertzberg principle is expressed by the following equation:

$$z = \frac{\rho f}{\rho s - \rho f} \cdot h \qquad (1)$$

where:
z = altitude, in feet, reference mean sea level, of a sharp interface between fresh and salt water
ρf = density of fresh water
ρs = density of salty water
h = altitude of fresh water surface directly over the point on the interface

Hubbert (1940) gives a modified version of the Ghyben-Hertzberg formula that takes into consideration the head and density of the saltwater as well as the head and density of the freshwater. The modified formula is as follows:

$$z = \frac{\rho s}{\rho s - \rho f} \cdot h_s \quad \cdot \frac{\rho f}{\rho s - \rho f} \cdot h_f \qquad (2)$$

The notation is the same as equation 1 with the addition that h_s is the head in the saltwater and h_f is the head in the freshwater.

An application of equation 2 to data obtained April 26, 1977 for two wells at Hilton Head Island follows. The open hole section of the wells are about 175 feet apart vertically and 10 feet apart horizontally. Geophysical and hydrological data indicate that vertical flow components in both wells are negligible. A head of 1.38 feet below msl in the salty-water body (density 1.001) was measured in well Bft 786, and a head of 0.94 feet below msl in the overlying fresh-water body (density 1.000) was measured in well Bft 787. According to the Ghyben-Hertzberg theory, there should not be any freshwater in Bft 787. Insertion of the data into equation 2 however, gives the following calculation:

$$z = \frac{1.001}{1.001-1.000} \cdot (1.38) \quad \frac{1.000}{1.001-1.000} \cdot (-0.94 \text{ ft})$$

$$= -1381 \text{ ft} - (-940 \text{ ft})$$

$$= -441 \text{ ft}$$

Assuming a sharp boundary and static conditions, the calculation gives a depth of 441 feet below msl of a contact between freshwater of density 1.000 and salty water of density 1.001.

Obviously not all of the assumptions of equation 2 are fully met by the data in the calculated example. Nevertheless the depth computed by equation 2 does fall within the boundaries of the zone of diffusion, which spans the interval from about 200 feet to more than 500 feet (fig. 25). The main conclusions to be made from the above example are that: (1) the depth to a freshwater-saltwater water boundary depends on the heads and densities of both the freshwater and salty water; (2) large errors can result from calculations based on freshwater data alone; (3) depth to a freshwater-saltwater boundary calculated from equation 2 is only an approximation, mainly because conditions at the boundary fail to fully satisfy all of the assumptions of the equation; and (4) the only way to accurately determine the relation between chloride concentration and depth is through a series of samples taken at different depths at the same test site.

GEOCHEMICAL TESTS FOR SALTWATER CONTAMINATION

In the study area the normal chloride concentration in fresh ground water from the principal artesian aquifer generally ranges from less than 5 to as much as 25 mg/L. Where chloride concentrations are within or slightly above the normal background range, it is not possible from a single chloride analysis to determine if the ground water is contaminated by saltwater. With geochemical studies, however, it is sometimes possible to reveal saltwater contamination when the chloride concentration has been increased by only a few milligrams per liter.

For convenience in diagramatically showing the relationships between the major cations and anions, concentrations in milligrams per liter were converted to milliequivalents per liter (meg/L) by dividing mg/L by the equivalent weight of the ion under consideration. The equivalent weight is equal to the atomic weight divided by the valence.

A diagram of the percentage of milliequivalents per liter (fig. 27), calculated from data in table 12, is a useful illustration of saltwater contamination and of subsequent changes in the chemical character of the ground water. In figure 27 distribution of the percentage milliequivalents per liter of diagrams 1 through 5 indicates no saltwater contamination, while diagrams 6 through 14 represent water containing dissolved constituents introduced by saltwater contamination. Ground water contaminated by saltwater shows a relative increase in the percentage of the milliequivalents per liter of sodium (to which, for convenience in plotting, the milliequivalents per liter of potassium has been added) and chloride. For example, diagrams 6 through 14 show a progressive increase in the percentage of milliequivalents per liter of sodium and of chloride as compared to diagrams 1 through 5, indicating that the chemical character of the water has been changed by saltwater contamination. This change is evident even when the chloride concentration is only 25 mg/L or less.

This method of presentation permits an early indication of saltwater contamination. It also is a means of comparing analyses of water from different zones within the same aquifer, of showing progressive changes in chemical quality of water as it moves away from recharge areas, and of showing analyses of water from different aquifers. A change in chemical quality with depth within the principal artesian aquifer is shown by diagrams 9, 15, 16, 17, and 18 (fig. 27).

Milliequivalents per liter data plotted on a trilinear diagram (fig. 28) described by Piper (1945) show that typical uncontaminated water from the principal artesian aquifer is a calcium bicarbonate type water (numbers 1 through 4). Number 5, which represents water having a chloride concentration of 67 mg/L, is showing a movement away from the typical calcium bicarbonate type water and a movement towards the sodium chloride type water represented by number 6 and numbers 8 through 13. The change from calcium bicarbonate type water to a sodium chloride type water is a result of the calcium bicarbonate water being contaminated by saltwater.

Theoretically, all analyses of different mixtures of ocean water and aquifer water should fall in a straight line between the point representing ocean water and points representing uncontaminated aquifer water when all analyses are plotted on a trilinear diagram. In actuality, however, this does not usually happen because the ground-water system is too complex and sampling is too uncertain to justify an exacting interpretation. The relationships shown on the trilinear diagram can best be used to support conclusions regarding water sources that also have other basis of support.

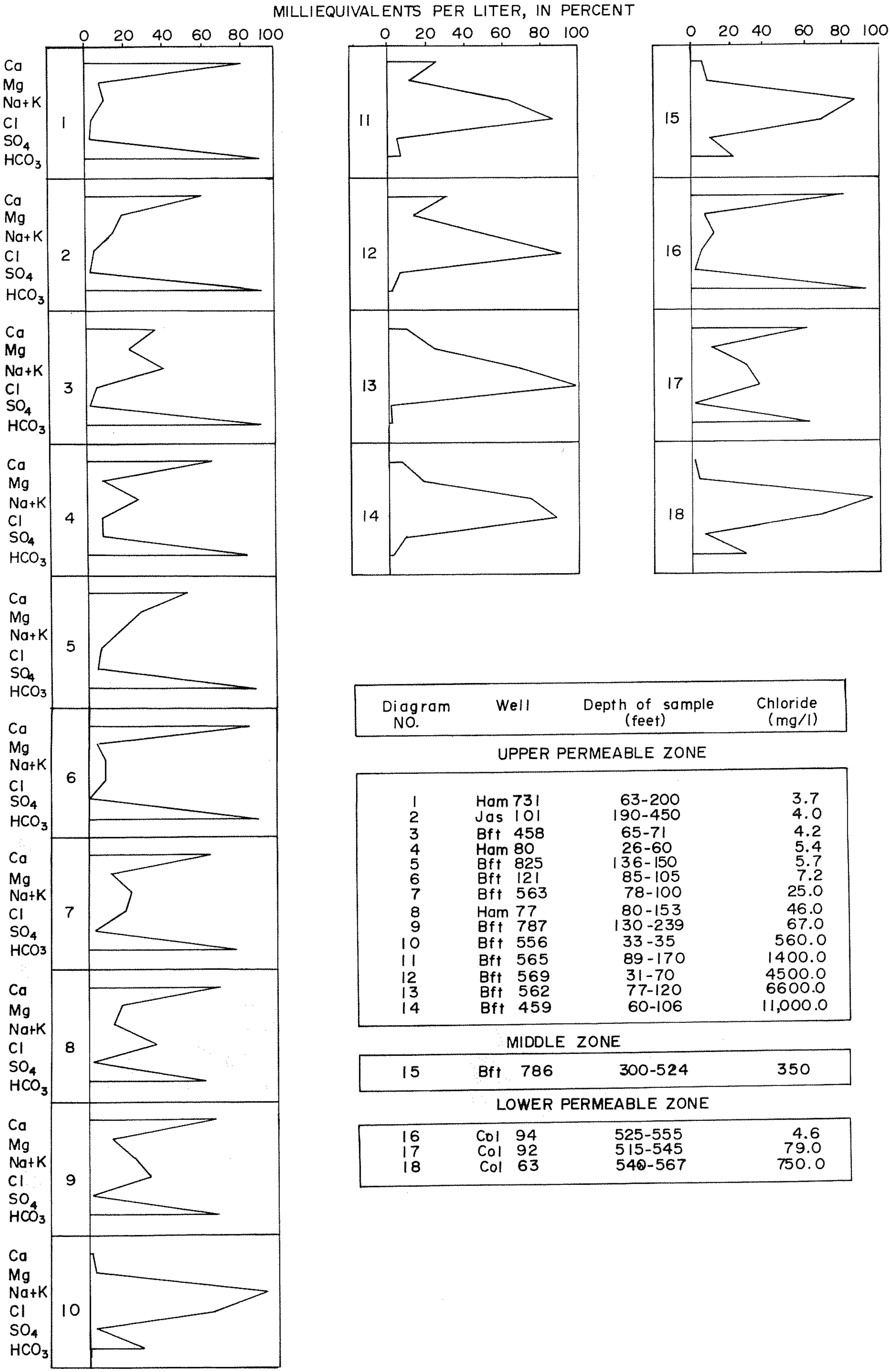
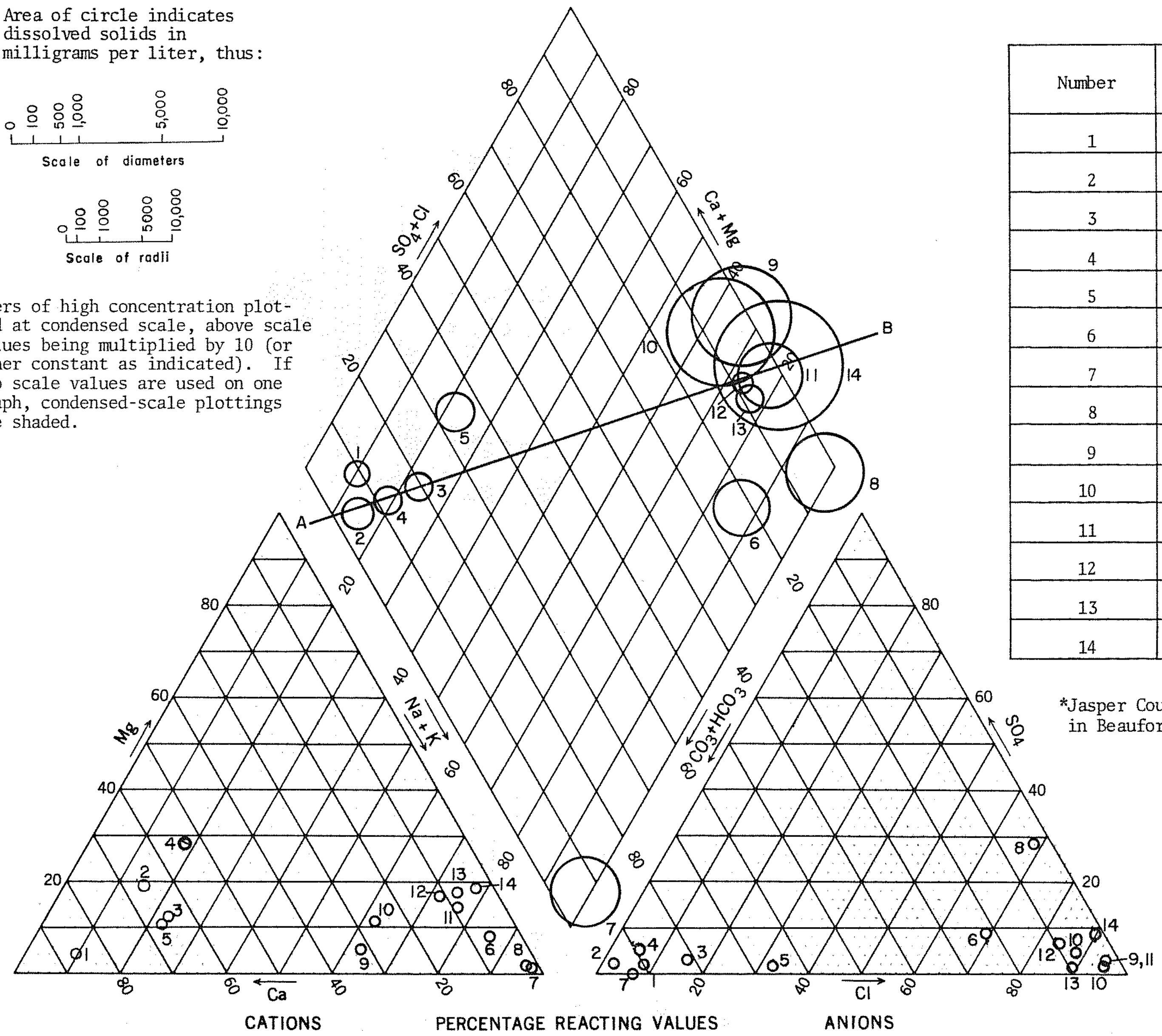


Diagram NO.	Well	Depth of sample (feet)	Chloride (mg/l)
UPPER PERMEABLE ZONE			
1	Ham 731	63-200	3.7
2	Jas 101	190-450	4.0
3	Bft 458	65-71	4.2
4	Ham 80	26-60	5.4
5	Bft 825	136-150	5.7
6	Bft 121	85-105	7.2
7	Bft 563	78-100	25.0
8	Ham 77	80-153	46.0
9	Bft 787	130-239	67.0
10	Bft 556	33-35	560.0
11	Bft 565	89-170	1400.0
12	Bft 569	31-70	4500.0
13	Bft 562	77-120	6600.0
14	Bft 459	60-106	11,000.0
MIDDLE ZONE			
15	Bft 786	300-524	350
LOWER PERMEABLE ZONE			
16	Col 94	525-555	4.6
17	Col 92	515-545	79.0
18	Col 63	540-567	750.0

Figure 27. Percent milliequivilents per liter of chemical constituents in ground water from the principal artesian aquifer, Beaufort, Colleton, Hampton, and Jasper Counties,

WATER-ANALYSIS DIAGRAM



Area of circle indicates dissolved solids in milligrams per liter, thus:

Waters of high concentration plotted at condensed scale, above scale values being multiplied by 10 (or other constant as indicated). If two scale values are used on one graph, condensed-scale plottings are shaded.

Number	Well No.	Dissolved solids (mg/L)	Source
1	121	139	Principal artesian
2	*101	200	Do.
3	563	319	Do.
4	825	254	Do.
5	787	341	Do.
6	786	867	Do.
7	10	1,200	Middendorf
8	556	1,562	Principal artesian
9	795	2,240	Do.
10	565	2,650	Do.
11	449	9,830	Do.
12	793	12,700	Do.
13	459	20,200	Do.
14	Seawater	35,000	Seawater

*Jasper County well; all other wells are in Beaufort County.

Figure 28. Trilinear diagram showing percentage milliequilents per liter of chemical constituents of water from the principal artesian aquifer, from the Middendorf aquifer, and from Port Royal Sound.

A main conclusion of this study concerning the saltwater encroachment in the upper permeable zone of the principal artesian aquifer is that the contamination at Hilton Head and Parris Island results primarily from ocean water entering the aquifer. If this conclusion is correct, analyses of aquifer water showing different degrees of contamination plotted on the trilinear diagram should generally not deviate too far from the predicted theoretical positon, or if they do deviate, these deviations should be explainable.

Points 2, 3, 4, 11, 12, and 13 fall reasonably close to a straight line plot (line A-B, fig. 28) and indicate a simple mixture of water from the upper permeable zone and water from Port Royal Sound. Points 1, 5, 9, and 10 fall somewhat above line A-B and points 6, 7, and 8 fall below line A-B.

Point 1 represents an analysis of water from a well in an area receiving local recharge from the overlying water table aquifer. Point 5 represents a water analysis from a well showing contamination, in part, from the vertical movement of salty water from below. Points 9 and 10 represent analyses of water from wells that are near the saltwater recharge areas underlying Battery Creek. Point 6 represents an analysis of water from a well that is open to the middle zone of the aquifer immediately underlying the upper permeable zone, and point 8 represents an analysis of water from a well that is receiving recharge from Coosaw River and from the overlying water table. Point 7 represents the typical sodium-bicarbonate type water from the Middendorf aquifer at Parris Island. None of these points represents a simple mixture of water from the upper permeable zone and water from Port Royal Sound. Consequently the points deviate from line A-B.

Analyses of water quality data plotted on the trilinear diagram does in part support the conclusion that saltwater contamination in the upper permeable zone of the principal artesian aquifer primarily results from a mixing of ocean water with aquifer water. However, the plotted data also indicate that in some cases the source of the salty water is not simply modern ocean water or else that there has been alteration of the chemical quality of the mixture of modern ocean water and aquifer water by ion exchange.

SUMMARY AND CONCLUSIONS

The Lowcountry area is characterized by low flat land, much of which is inundated with water; by numerous streams, rivers, marshes and lakes; and by moss covered woodland. It is relatively isolated and sparsely settled. Average per capita personal income is the lowest in the State.

Water in quantities adequate for most domestic, public-supply, and agricultural needs is generally available from one or more aquifers. In 1976 Beaufort, Colleton, Hampton, and Jasper Counties used an estimated

7,600 Mgal of ground water. About 6,200 Mgal or 82 percent of the ground water used by these four counties came from the principal artesian aquifer. Of this water, about 77 percent or 4,800 Mgal were used in Beaufort County, with Hilton Head Island accounting for about 64 percent of the water use in Beaufort County. Golf course and crop irrigation accounted for over half of the water usage from the principal artesian aquifer. To the southwest of the study area, the City of Savannah, Georgia and industries in the Savannah area pump more than 25,000 Mgal/yr from the principal artesian aquifer.

As a result of the large ground water use in Savannah, water-level declines of more than 100 feet have occurred in the extreme southwestern tip of Jasper County. Throughout most of Jasper County and western Beaufort County, the decline has been more than 20 feet. In Hampton County and eastern Beaufort County, the decline generally has been less than 10 feet; around Walterboro, Colleton County, declines of 10 to 30 feet have occurred; declines in the rest of Colleton County are less than 10 feet.

Surface water is abundant throughout the area, but in Beaufort and Jasper Counties (with the exception of the Savannah River) this surface water is generally too salty for human consumption. In Hampton and Colleton Counties fresh surface water is available but is not used to any significant extent. The Beaufort-Jasper Water Authority supplies the military installations in Beaufort, the Beaufort-Port Royal area, and some residents of Ladies Island with treated surface water from the Savannah River.

Underlying the study area are a series of unconsolidated and semi-consolidated sedimentary rocks ranging in age from Late Cretaceous to Holocene. These rocks, which range in thickness from less than 2,500 feet in the northern part to more than 3,500 feet in the southern part of the study area, store and transmit all the ground water used in the area.

The oldest penetrated rocks in the study area were formed during Late Cretaceous time. These Upper Cretaceous deposits are, in ascending order, the Middendorf Formation (equivalent to and locally known as the Tuscaloosa Formation), the Black Creek Formation, and the Peedee Formation. No wells have penetrated the Upper Cretaceous section in Hampton and Jasper Counties. Consequently, the geohydrology of the Cretaceous rocks is unknown in these two counties.

Walterboro, Colleton County has two wells open to the upper part of the Middendorf Formation that have natural flows at the land surface of 1,200 gal/min and 1,400 gal/min of high quality water. Wells open to the Middendorf Formation at Parris Island, Hilton Head Island, and Fripp Island have natural flows at land surface of about 75 gal/min of highly mineralized water that has a temperature of around 38°C.

Although the Black Creek Formation is a productive aquifer in other parts of the state, its potential as an aquifer in the study area is unknown. A water sample taken during drilling of well Bft 457 contained 1,100 mg/L of chloride. While it appears unlikely that this formation will yield significant quantities of freshwater in Beaufort County and possibly Jasper County, the Black Creek Formation may be capable of yielding large quantities of good quality water in Colleton and Hampton Counties.

The Peedee Formation is an important aquifer in Georgetown and Horry Counties, but does not appear to be of significant value as an aquifer in the study area.

The Tertiary System consists, in ascending order, of the Black Mingo Formation of Paleocene and Early Eocene (Wilcox) age, the Santee Limestone of Middle and Late Eocene (Claiborne and Jackson) age, the Cooper Marl of late Eocene and Oligocene age, the Hawthorn Formation of Miocene age, and the Duplin Marl of Pliocene age. The Tertiary formations are the chief sources of ground-water supplies in the study area.

The Black Mingo aquifer is a source of moderate quantities of good quality water in Colleton and Hampton Counties. Wells open to this aquifer in these counties have natural flows of 50-250 gal/min at land surface. The water-bearing characteristics of this formation are unknown in Jasper County. In Beaufort County the Black Mingo Formation is unlikely to yield large quantities of fresh water.

The Santee Limestone is part of the principal artesian aquifer and furnishes much of the ground water used in the area. Except where saltwater contamination has taken place, the Santee Limestone is capable of yielding from 200 to more than 2,000 gal/min of good quality water.

In Colleton County and in parts of northeastern Hampton County, the Cooper Marl is not used extensively as an quifer. In much of Hampton, Beaufort and Jasper Counties, however, the lower part of the Cooper Marl is considered to be part of the principal artesian aquifer and capable of yielding more than 200 gal/min of good quality water.

The upper and lower sections of the Hawthorn Formation act as confining beds. The middle section of the Hawthorn is a fairly persistent, sandy, dolomitic limestone (Hawthorn aquifer) and is a source of 50 to 200 gal/min of good quality water in western Beaufort County and in Jasper County.

The water-bearing characteristics of the Pliocene to Holocene deposits are not known. Wells tapping the Pliocene-Holocene deposits are reported to yield water of acceptable quality and quantity for domestic or small agricultural and industrial need. The yield and quality vary considerably from place to place. Water from these formations may be hard and contain high concentrations of iron and hydrogen sulfide. Near the coast or saltwater estuaries, water from these deposits may be salty.

About 82 percent of the ground water used comes from the principal artesian aquifer, which is composed mainly of rocks of the Santee Limestone and lower part of the Cooper Marl. The principal artesian aquifer is divided into three zones: (1) the upper permeable zone, which furnishes most of the water pumped from the aquifer in Hampton County and almost all of the water pumped from the aquifer in Beaufort and Jasper Counties; (2) a middle zone of relatively low hydraulic conductivity, which yields small amounts of water to wells; and (3) the lower permeable zone, which provides about all of the water pumped from the aquifer in Colleton County.

Aquifer tests show that, in general, transmissivities of the principal artesian aquifer decrease to the north and northeast and increase toward the southwest. Transmissivities range from about 30,000 ft^2/d to 50,000 ft^2/d west of Broad River and range from about 2,000 ft^2/d to 15,000 ft^2/d east of Broad River.

The average transmissivity of the upper permeable zone of the principal artesian aquifer in western Beaufort County and southern Jasper County is about 50,000 ft^2/d; in eastern Beaufort County the average transmissivity is probably less than 10,000 ft^2/d.

The transmissivity of the upper permeable zone in northern Jasper County and southwestern and southeastern Hampton County ranges from 10,000 ft^2/d to 30,000 ft^2/d, with transmissivity decreasing to the northeast and east.

The transmissivity of the lower permeable zone of the principal artesian aquifer in northern Colleton County and northeastern Hampton County ranges from 5,000 ft^2/d to as low as 500 ft^2/d, with transmissivity generally decreasing to the north. The average transmissivity of the lower permeable zone of the principal artesian aquifer in southern Colleton County is estimated to be 5,000 ft^2/d.

The coefficient of storage of the principal artesian aquifer ranges from 3×10^{-5} to 3×10^{-3}. The higher values generally occur where the overlying confining material is thin or relatively permeable, allowing leakage into the principal artesian aquifer from the overlying Hawthorn aquifer. Consequently the higher storage values are apparent values and should be considered as upper limit figures only, and subject to considerable error.

Yields of wells open to the principal artesian aquifer vary from less than 50 gal/min to more than 2,500 gal/min. The specific capacities of wells in the study area range from more than 250 (gal/min)/ft) at Hilton Head Island to less than 5 (gal/min)/ft) in Colleton County.

It is estimated that about 40 Mgal/day of recharge enters the principal artesian aquifer in the outcrop area 30 to 40 miles to the west and northwest of the study area. Approximately 5 to 10 Mgal/day of recharge is believed to be entering the principal artesian aquifer within the boundaries of the study area by leakage through overlying or underlying confining beds.

Water from the principal artesian aquifer is generally of suitable quality for most uses. In Beaufort County, however, the chloride concentration usually ranges between 25 to 75 mg/L and in more seriously contaminated areas may range from 500 to more than 5,000 mg/L.

Saltwater contamination is believed to be occurring from two sources: (1) sea water entering the aquifer through breaks in, or in areas of relatively high hydraulic conductivity of, the overlying confining material and (2) unflushed salty water in the lower part of the aquifer moving upward into the upper permeable zone. Saltwater contamination has also occurred as a result of the movement of saltwater into defective or improperly cased wells located near saltwater bodies.

Analyses of water quality data suggest that saltwater contamination in the upper permeable zone of the principal artesian aquifer primarily results from a mixing of modern ocean water with aquifer water. However, the data also indicate that in some cases contamination results from a source of salty water other than modern ocean water or else that there has been alteration of the chemical quality of the aquifer water by ion exchange.

Water containing more than 1,500 mg/L of chloride is present throughout the aquifer at Parris Island, Fripp Island, Edisto Beach, and probably other small sea islands southeast of Beaufort. Salty water is present in the lower part of the principal artesian aquifer in Beaufort County, in southern Colleton County, and probably in southern Jasper County.

Slightly salty water (chloride concentration generally between 50 and 100 mg/L) is present in the upper part of the principal artesian aquifer at Hilton Head Island. Salty water is moving laterally towards Hilton Head Island from the northeast and possibly from the Atlantic Ocean, where saltwater may be entering the aquifer along the sea bottom. Also, salty water present in the sediments underlying the upper permeable zone is moving upward into the upper permeable zone of the aquifer in response to heavy pumping at Hilton Head Island. The salty water entering the upper permeable zone is diluted by freshwater recharge. With the present rate of pumping and existing hydraulic gradients, it probably will be many years before the freshwater resources of Hilton Head Island will be grossly contaminated by saltwater. However, increased pumping at Hilton Head Island and to the north and west of the Island would increase the rate of encroachment and lessen the time before the ground-water resources became seriously contaminated.

Estimates of the rate of saltwater movement at hilton Head Island based on regional and local hydraulic gradients range from 140 to 370 feet per year. The lower rate is believed to approximate the rate of regional encroachment, on the assumption that all calculated movement represents encroachment. The higher rate may occur near centers of heavy pumping for a few months each year, but during the remainder of the year the rate is probably lower.

In general the actual depth to a freshwater-saltwater contact is greater than that predicted by the Ghyben-Hertzberg principle. Hubbert's modified version of the Ghyben-Hertzberg equation may under certain conditions give a reasonable approximation of the depth to a freshwater-saltwater contact. However, the only accurate way to define the interface between freshwater and saltwater is through a set of test wells all located at the same site but open to the aquifer at different depths.

The effects of additional development of the ground-water resources on water levels and on saltwater contamination require careful consideration. The following suggests some of the management considerations that would aid in the long-range protection of the ground-water resources of the study area.

The ground-water problems in the study area warrant consideration of comprehensive and positive water management. The success of any planning and management programs, however, will depend upon continued availability of reliable data. The continued collection of pumpage data throughout the area and periodic water-level measurements in the existing network of observation wells will aid in monitoring changes in water levels due to pumping. The periodic collection and analysis of representative water samples from varying depths in the principal artesian aquifer would provide data about the zone of diffusion and the movement of salty water in the aquifer.

Numerous methods have been used to control saltwater encroachment. These include (1) reduction of pumping, (2) redistribution of major pumping centers, (3) water conservation and economical use, (4) artificial recharge, and (5) conjunctive use of water from different sources. The simplest solution would be to reduce pumping, but this may not be possible to any large extent because of existing water demands. However, the use of treated sewage effluent for irrigation use (if acceptable from a health standpoint) might be one way of reducing pumpage. This, combined with water conservation, may be the most economical and practical way of reducing saltwater encroachment in the study area.

Recharge to an aquifer with water pumped from surface-water sources has been used widely in California and to a lesser extent in other parts of the United States. Methods range from collecting storm runoff in pits to construction of channels and pipelines from distant streams to the recharge basins or injection wells. Because recharge would have to be accomplished through injection wells and because there are no nearby freshwater recharge sources in Beaufort County, artificial recharge would be an expensive undertaking.

It might be feasible in a limited area, such as Hilton Head Island, to use water from the Middendorf aquifer for recharge into the upper permeable zone of the principal artesian aquifer to form a hydraulic barrier between the Hilton Head Island wells and the source of salty water. The hydraulic barrier thus generated may prevent salty water from entering the aquifer. The relatively high hydraulic head in the Middendorf aquifer would eliminate the need for any pumping mechanism. A properly constructed and developed well in the Middendorf aquifer might supply a natural recharge flow of about 1 Mgal/d. On the negative side, however, the water from the Middendorf aquifer is high in some mineral constituents and has a high temperature; consequently, the quality of water from the principal artesian aquifer would be adversely affected.

Predicting the changes in water quality and water levels in response to changes in recharge and discharge is one of the most important aspects of ground-water management. This may be accomplished by the use of analytical or computer modeling techniques. Models are designed to establish a reasonable correspondence between their properties and those of the prototype aquifers; they can simulate ground-water flow, storage, recharge, pumping, natural discharge, impervious boundaries, and transport of solutes in ground water. Electric analog and digital computer models have been used for ground-water management studies. In recent years, the electric analog model has been supplanted by the digital computer, which uses essentially the same logic as the analog model. The principal difference is that a digital computer calculates values, whereas an electric analog measures the same values. The computer technique has generally been found more desirable than the electric analog method, mainly because it is more flexible, more convenient, and less expensive.

The usefulness of the digital model as a management tool is well documented in many ground-water reports, and the use and development of such a model should be considered for the study area. The digital model developed by Counts for the Savannah area, which includes part of the present study area, could probably be adapted for use in the entire Lowcountry study area.

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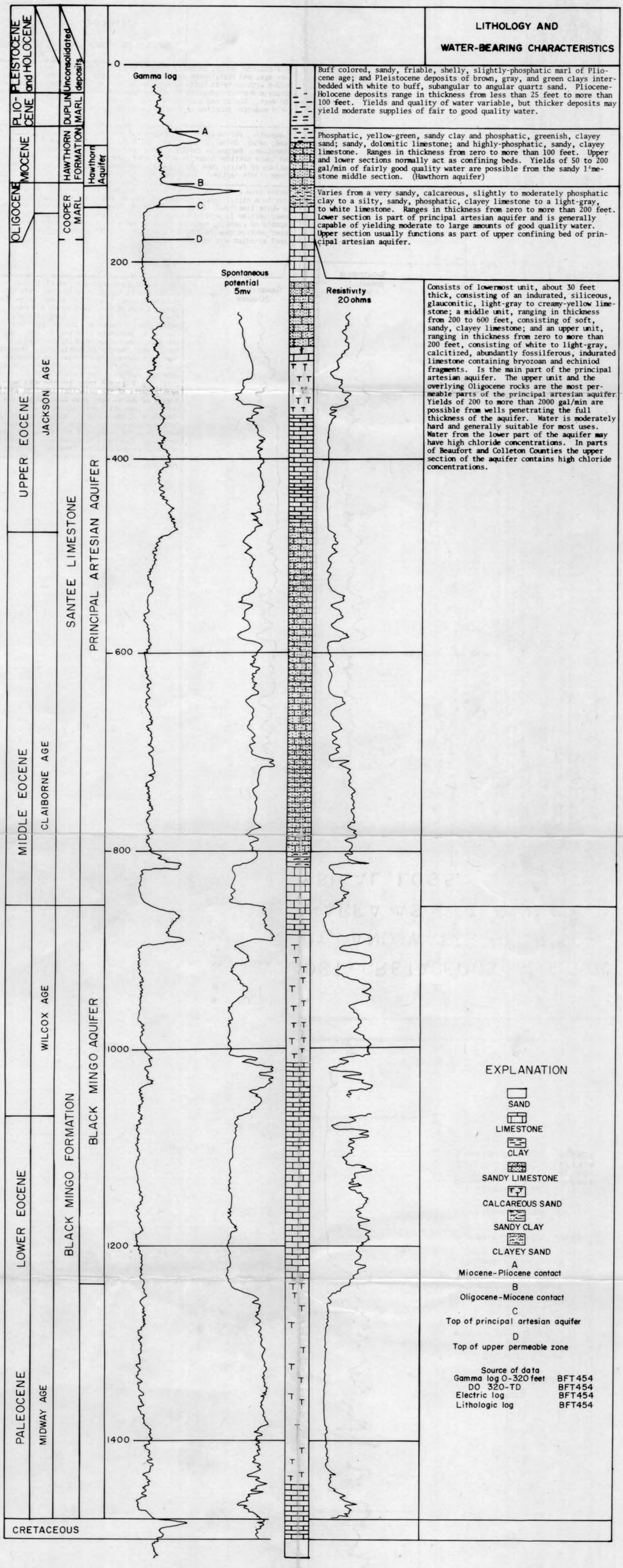


LITHOLOGY AND WATER-BEARING CHARACTERISTICS

Buff colored, sandy, friable, shelly, slightly-phosphatic marl of Pliocene age; and Pleistocene deposits of brown, gray, and green clays interbedded with white to buff, subangular to angular quartz sand. Pliocene-Holocene deposits range in thickness from less than 25 feet to more than 100 feet. Yields and quality of water variable, but thicker deposits may yield moderate supplies of fair to good quality water.

Phosphatic, yellow-green, sandy clay and phosphatic, greenish, clayey sand; sandy, dolomitic limestone; and highly-phosphatic, sandy, clayey limestone. Ranges in thickness from zero to more than 100 feet. Upper and lower sections normally act as confining beds. Yields of 50 to 200 gal/min of fairly good quality water are possible from the sandy limestone middle section. (Hawthorn aquifer)

Varies from a very sandy, calcareous, slightly to moderately phosphatic clay to a silty, sandy, phosphatic, clayey limestone to a light-gray, to white limestone. Ranges in thickness from zero to more than 200 feet. Lower section is part of principal artesian aquifer and is generally capable of yielding moderate to large amounts of good quality water. Upper section usually functions as part of upper confining bed of principal artesian aquifer.

Consists of lowermost unit, about 30 feet thick, consisting of an indurated, siliceous, glauconitic, light-gray to creamy-yellow limestone; a middle unit, ranging in thickness from 200 to 600 feet, consisting of soft, sandy, clayey limestone; and an upper unit, ranging in thickness from zero to more than 200 feet, consisting of white to light-gray, calcitized, abundantly fossilferous, indurated limestone containing bryozoan and echiniod fragments. Is the main part of the principal artesian aquifer. The upper unit and the overlying Oligocene rocks are the most permeable parts of the principal artesian aquifer. Yields of 200 to more than 2000 gal/min are possible from wells penetrating the full thickness of the aquifer. Water is moderately hard and generally suitable for most uses. Water from the lower part of the aquifer may have high chloride concentrations. In parts of Beaufort and Colleton Counties the upper section of the aquifer contains high chloride concentrations.

FIGURE 6. GENERALIZED POST-CRETACEOUS GEOLOGIC SECTION SHOWING LITHOLOGY, AND WATER-BEARING CHARACTERISTICS OF STUDY-AREA AS DETERMINED FROM WELLS AND GEOPHYSICAL LOGS.

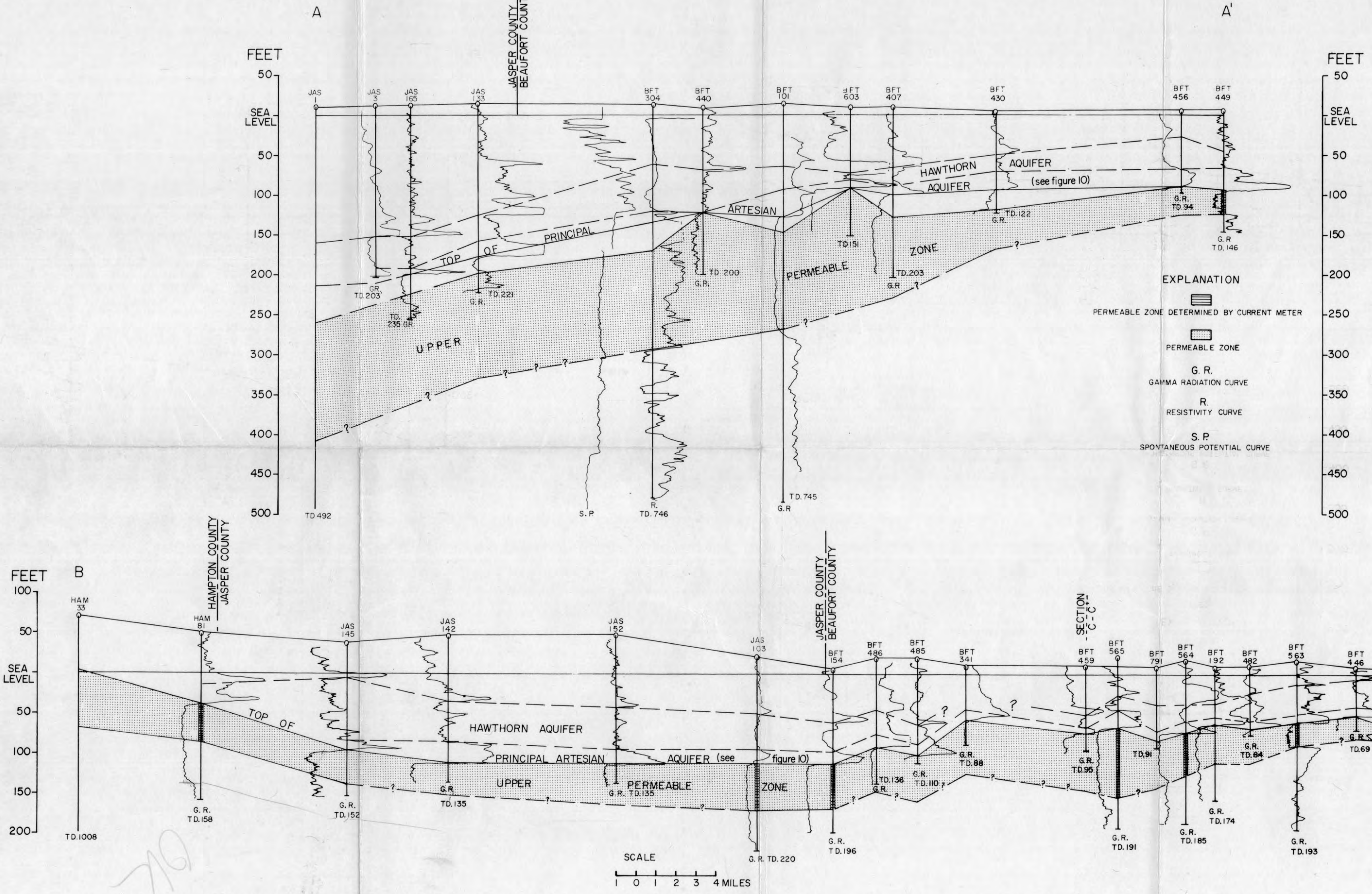


FIGURE 7. GEOHYDROLOGIC CROSS-SECTIONS A-A' AND B-B' SHOWING HAWTHORN AQUIFER AND UPPER PERMEABLE ZONE OF THE PRINCIPAL ARTESIAN AQUIFER

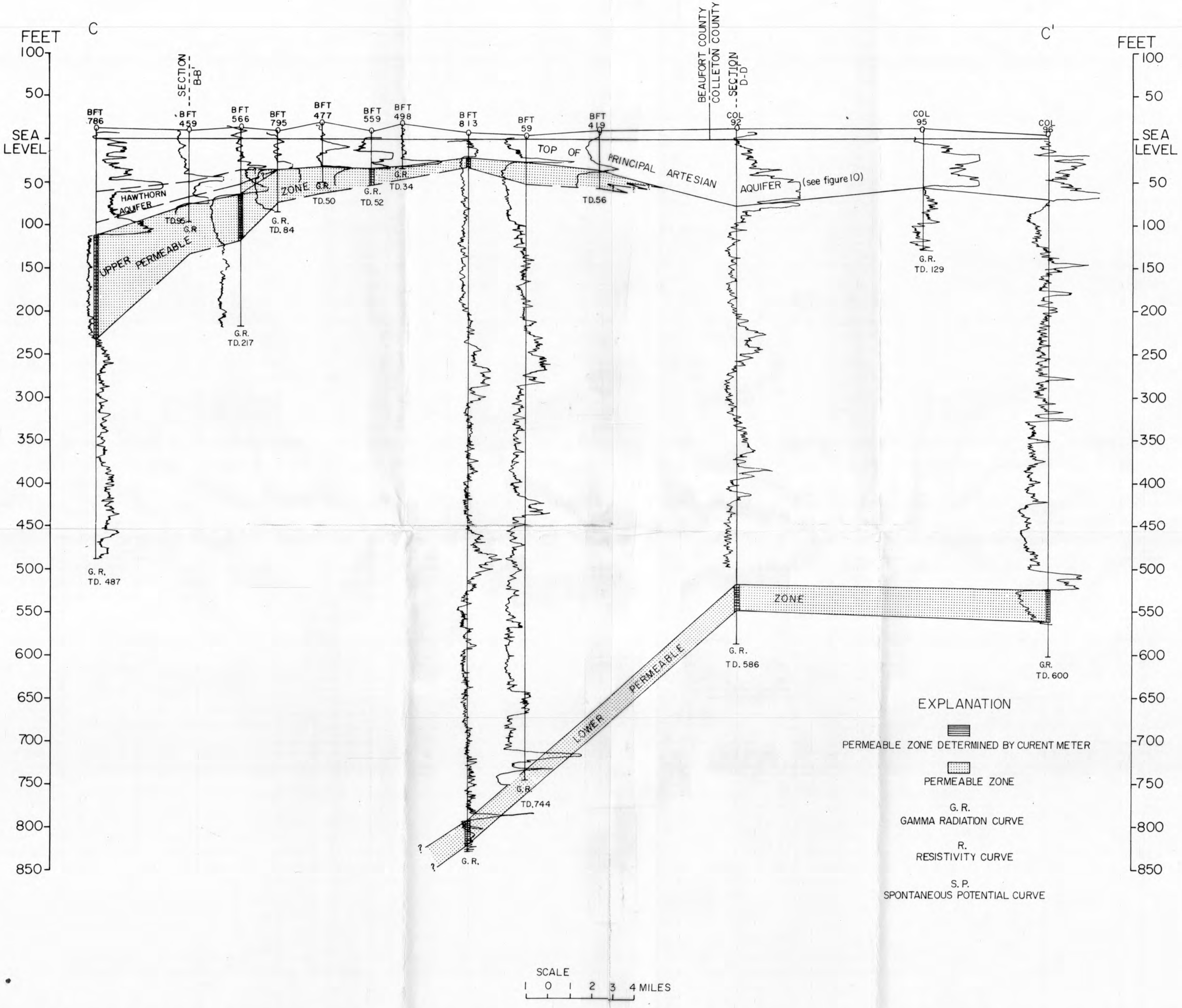


FIGURE 8 GEOHYDROLOGIC SECTION C-C' SHOWING HAWTHORN AQUIFER AND UPPER AND LOWER PERMEABLE ZONES OF THE PRINCIPAL ARTESIAN AQUIFER

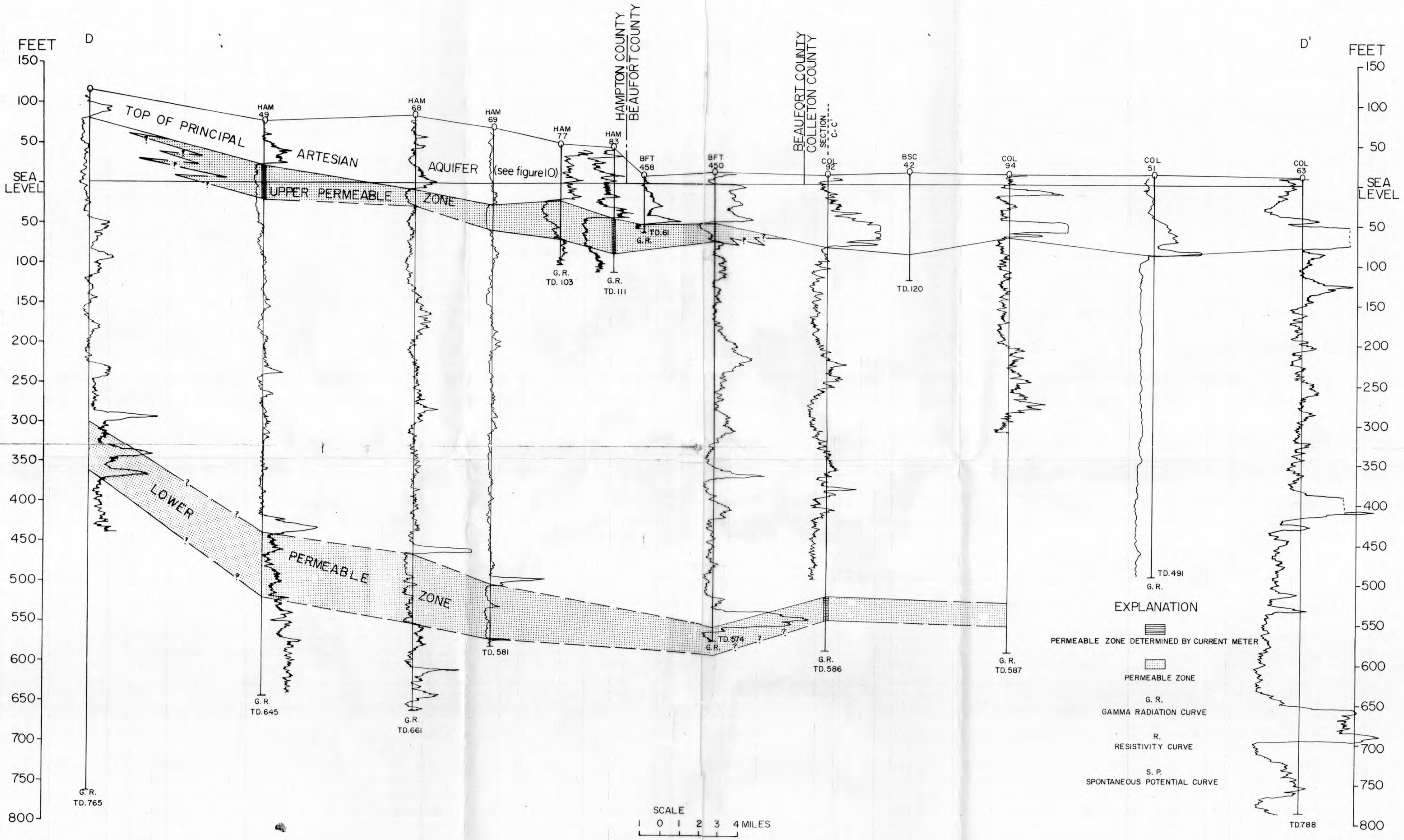
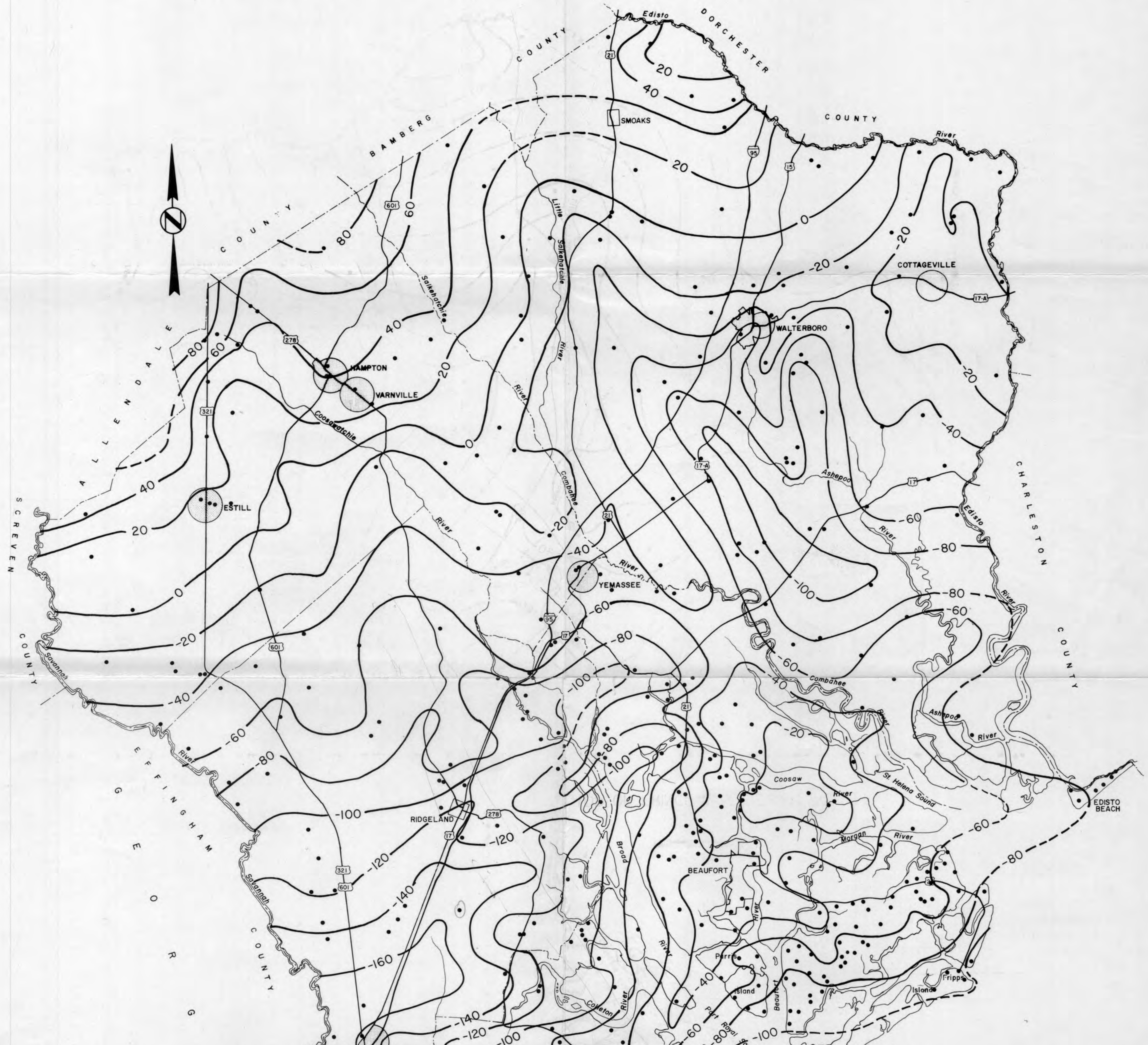


FIGURE 9. GEOHYDROLOGIC SECTION D-D' SHOWING UPPER AND LOWER PERMEABLE ZONES OF THE PRINCIPAL ARTESIAN AQUIFER



Contours show altitude of top of principal artesian aquifer. Dashed where approximate. Contour interval 20 and 40 feet. Datum is mean sea level.

FIGURE 10. SURFACE CONFIGURATION OF TOP OF PRINCIPAL ARTESIAN AQUIFER.

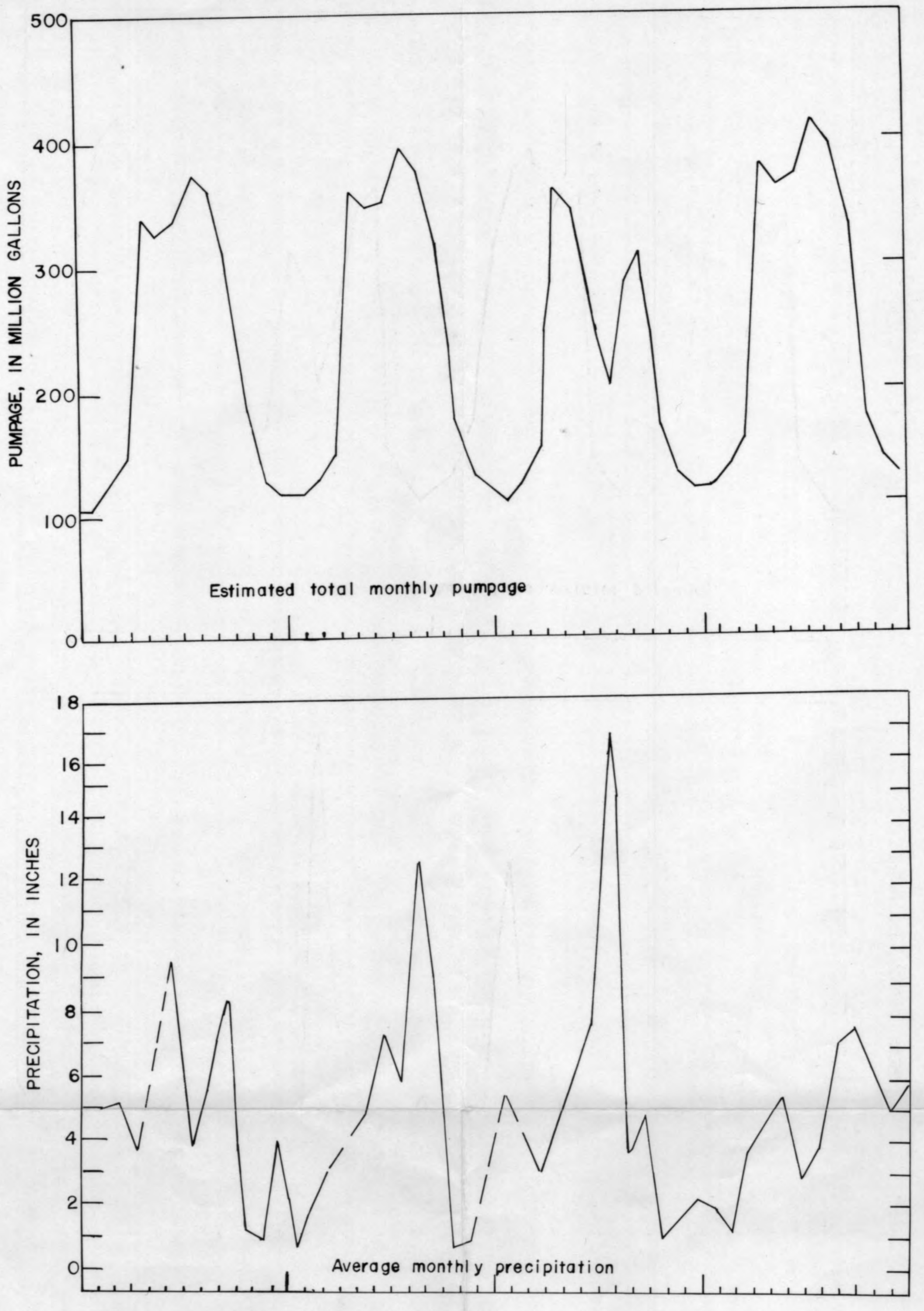
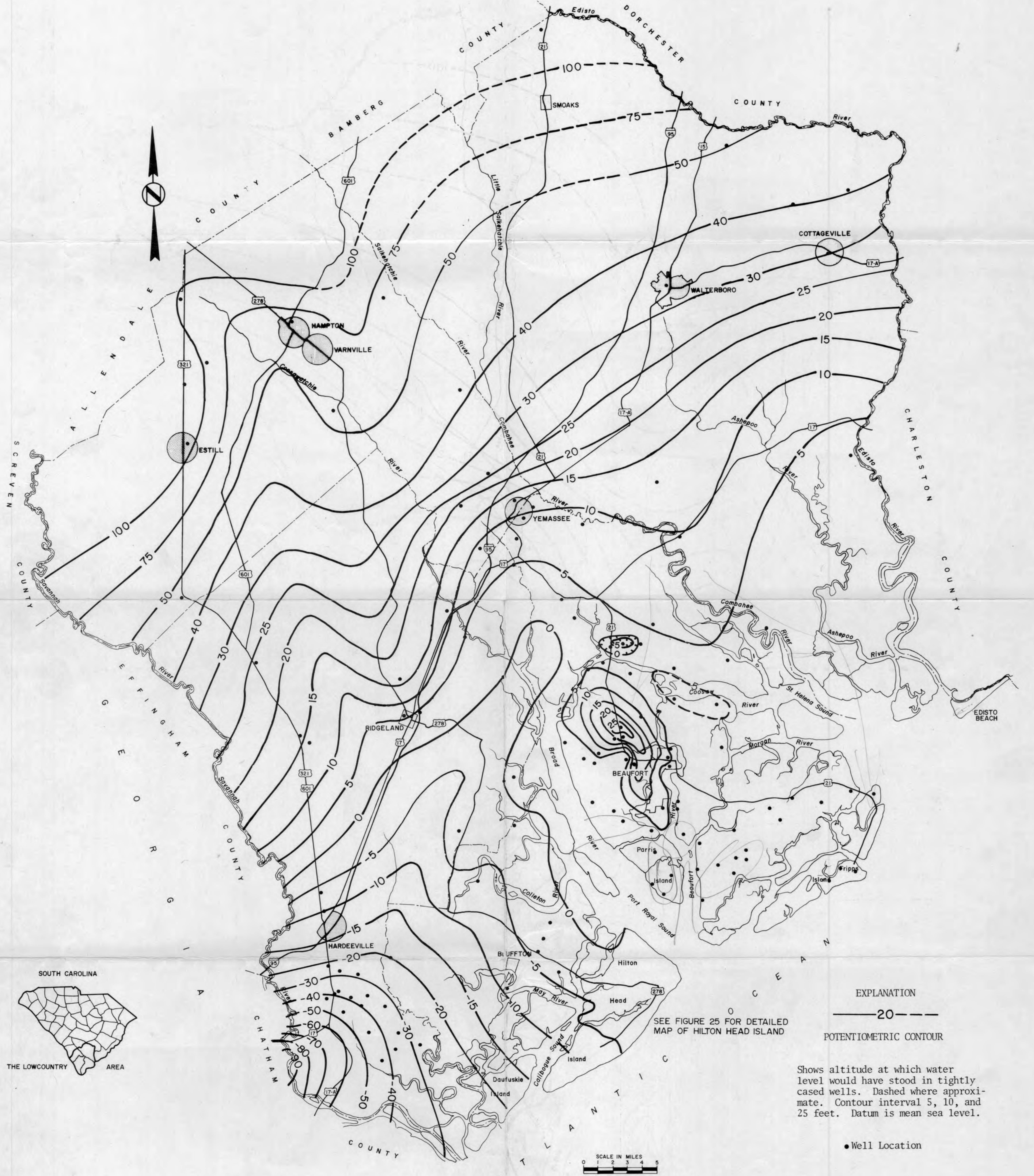
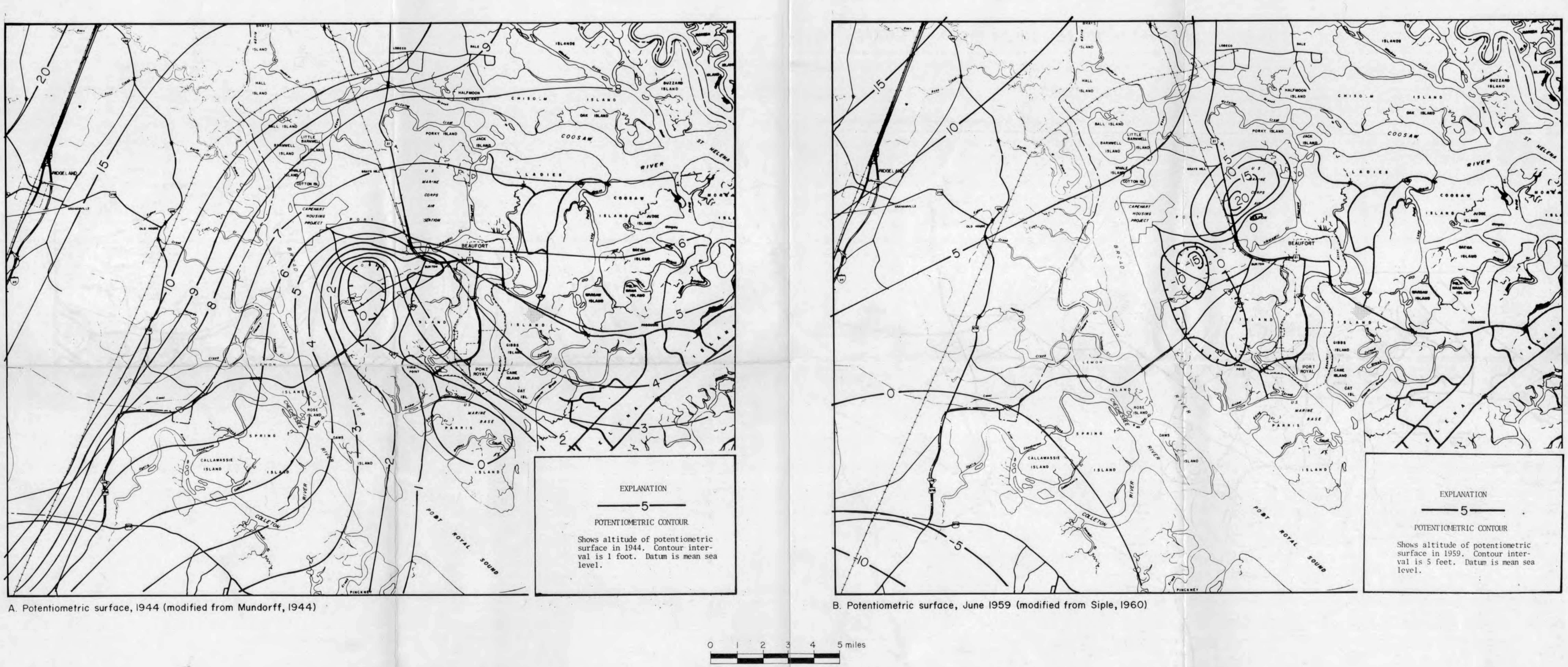


FIGURE 17. Hydrographs of water levels and graphs of average monthly temperature, precipitation, and estimated total monthly pumpage from the upper permeable zone of the principal artesian aquifer at Hilton Head Island.



Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximate. Contour interval 5, 10, and 25 feet. Datum is mean sea level.

FIGURE 19. POTENTIOMETRIC SURFACE OF PRINCIPAL ARTESIAN AQUIFER, DECEMBER, 1976.

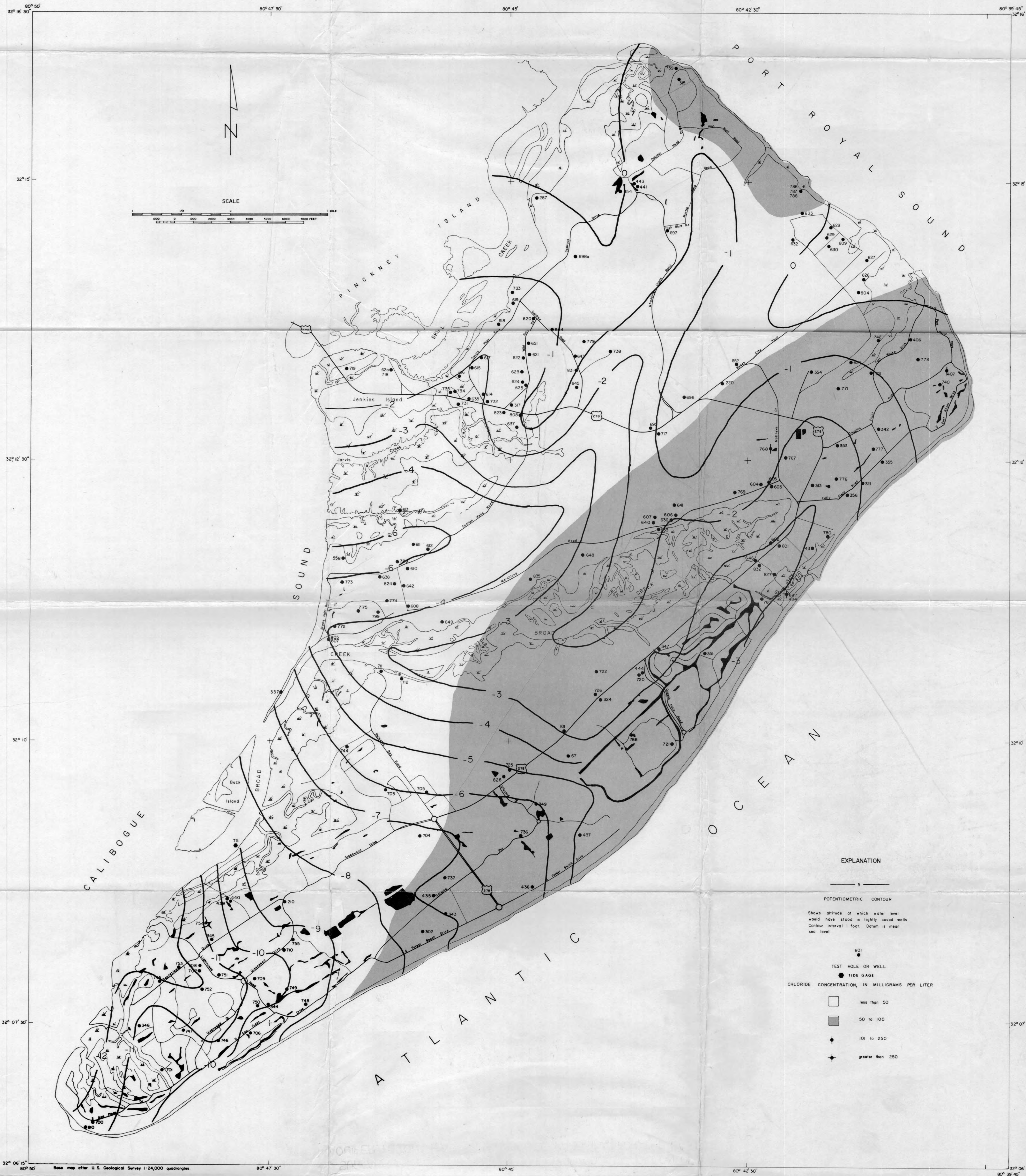


A. Potentiometric surface, 1944 (modified from Mundorff, 1944)

B. Potentiometric surface, June 1959 (modified from Siple, 1960)

FIGURE 21. POTENTIOMETRIC SURFACE OF THE PRINCIPAL ARTESIAN AQUIFER IN THE BEAUFORT AREA 1944 AND JUNE 1959.

FIGURE 22. AREAL DISTRIBUTION OF CHLORIDE CONCENTRATION IN WATER FROM THE UPPER PERMEABLE ZONE OF THE PRINCIPAL ARTESIAN AQUIFER, BEAUFORT COUNTY AND FROM THE LOWER PERMEABLE ZONE OF THE PRINCIPAL ARTESIAN AQUIFER, EDISTO BEACH, COLLETON COUNTY.



Base map after U.S. Geological Survey 1:24,000 quadrangles.

FIGURE 25. ALTITUDE OF POTENTIOMETRIC SURFACE AND DISTRIBUTION OF CHLORIDE CONCENTRATION OF WATER IN THE UPPER PERMEABLE ZONE OF THE PRINCIPAL ARTESIAN AQUIFER, HILTON HEAD ISLAND, SOUTH CAROLINA, FOR THE LAST WEEK OF DECEMBER, 1976.