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Distribution, Sources, and Migration of Relict and Modern Salt Water in the Upper Floridan Aquifer, Southern Beaufort County, South Carolina, and adjacent parts of Georgia

S.C. Department of Health and Environmental Control

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Front cover image: This sinkhole, on the bank of the Colleton River in Colleton River Plantation, is one of many in the study area. Such collapse features are common where the top of the Upper Floridan aquifer lies close to the land surface. These features influence the landscape and breach the confining unit that overlays the Upper Floridan aquifer. Sinkholes may also exist beneath the saltwater marshes and channels where they provide conduits through which sea water can move directly into the aquifer. Photography: Camille Ransom, III, 2011

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Acronyms and Abbreviations

AOC	Area of Concern
ASR	Aquifer Storage and Recovery
bgs	below ground surface
BP	Before Present
cps	counts per second
CSSI	Georgia Coastal Sound Science Initiative
EPA	U.S. Environmental Protection Agency
GaEPD	Georgia Environmental Protection Division
GMA	Groundwater Management & Associates
gpm/ft	gallons per minute per foot of drawdown
LIDAR	light detection and range
mg/L	milligrams per liter
Mgal/d	million gallons per day
Msl	mean sea level (NGVD 29)
NGVD 29	National Geodetic Vertical Datum of 1929
NAVD 88	North American Vertical Datum of 1988
NAD 83	North American Datum of 1983
pptv	parts per trillion by volume
PSD	Public Service District
R/O	reverse osmosis
SCDHEC	South Carolina Department of Health and Environmental Control
SCDNR	South Carolina Department of Natural Resources
SCWRC	South Carolina Water Resources Commission
SHE	Savannah Harbor Expansion
TU	tritium unit
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
µS/cm	microsiemens per centimeter at 25 degrees Celsius

ABSTRACT

The investigations reported herein were undertaken between 1997 and 2015 as part of the South Carolina Department of Environmental Control's contribution to the Georgia Coastal Sound Science Initiative and were conducted in cooperation with the U.S. Geological Survey-South Carolina Water Science Center, the South Carolina Department of Natural Resources, and the Beaufort-Jasper Water and Sewer Authority. Data were obtained, in part, from 49 test wells completed in the Upper Floridan aquifer and included geophysical logs and lithologic samples used to interpret the depth and thickness of hydrogeologic units. The distribution of chloride, principally in the Upper Floridan aquifer, was determined at each well site in the vicinity of Hilton Head Island, South Carolina and adjoining parts of Savannah, Georgia.

Hydrogeologic strata relevant to this investigation are, in descending order, the surficial aquifer, the upper confining unit, the Upper Floridan aquifer, the middle confining unit, the middle Floridan aquifer, and the Lower Floridan aquifer. These units are thickest in the southwestern part of the study area, near Savannah, Georgia, and thin as they near the underlying Beaufort Arch to the northeast in the vicinity of Beaufort, South Carolina. Uplift of strata overlying the Beaufort Arch resulted in erosion and less deposition of the upper confining unit, leaving the underlying Upper Floridan aquifer susceptible to saltwater intrusion.

Salt water is migrating downward from the bottom of the surficial aquifer into the upper confining unit because of downward gradients created by withdrawals from the Upper Floridan aquifer. Five test wells were specifically constructed to determine the regional extent of downward migration. Determination of chloride concentration in the upper confining unit was accomplished by extracting pore water from core sediment at selected depths: chloride was present in the upper confining unit at all locations sampled and generally decreased with depth.

For selected wells completed in the Upper Floridan aquifer, water levels were monitored hourly to determine hydraulic gradients. Specific-conductance profiles were taken in the open well bore to determine the computed chloride concentration and monitor the movement of the freshwater-saltwater interface (chloride plumes). Relict salt water, present before groundwater withdrawals, is distinguished from modern salt water that entered the system after groundwater withdrawals had begun. The age of salt water, or time since entering the groundwater system, at the bottom of the Upper Floridan aquifer within the plume boundaries was dated using atmospheric tracers that included dissolved-oxygen concentration data and anthropogenically-derived chlorofluorocarbon and tritium concentrations.

Eleven chloride plumes have been identified at the bottom of the Upper Floridan aquifer in the South Carolina part of the study area. Two chloride plumes, mapped in earlier investigations, are named herein the Parris Island and Port Royal chloride plumes, and consist of relict brackish to salt water. Seven previously unknown chloride plumes formed by modern saltwater sources were discovered southwest of the Port Royal Sound area as part of this investigation. The plumes are named herein according to nearby geographic locations and are the Hilton Head Island, Pinckney Island, Colleton River, Sawmill Creek, Jenkin's Island, Broad Creek, and Bull Island chloride plumes. The tenth chloride plume, also believed to be formed by relict and modern salt water, was inferred from seismic data that indicated a large area where the upper confining unit may be absent six miles east of Hilton Head Island beneath the Atlantic Ocean. The hypothetical plume is named herein the Hilton Head High chloride plume. The eleventh plume known herein as the 8-mile chloride plume, also located beneath the Atlantic Ocean east of Hilton Head Island, was discovered during offshore drilling by the U.S. Geological Survey and is believed to have formed from modern salt water moving downward where the confining unit is thin or absent.

Southwest of Port Royal Sound, the Hilton Head Island, Pinckney Island, and Colleton River chloride plumes emanate from source areas beneath Port Royal Sound, the Chechessee River, and the Colleton River, respectively. Generally, chloride concentrations were highest near the estimated source areas and ranged between 8,000 and 12,000 milligrams per liter with decreasing concentrations away from the source areas. Analyses of atmospheric tracers showed a similar pattern and indicated that the time-since-recharge age of the Hilton Head Island chloride was at least 52 years prior to 2005. Thus, recharge of modern salt water to the Upper Floridan aquifer began during or about 1953. Independent tritium analyses provided similar recharge dates. These age data are consistent with historic water-level data that indicate potentiometric levels in the Upper Floridan aquifer had declined to near mean sea level during the mid to late 1950's at northern Hilton Head Island, thereby providing conditions for salt water to move down from overlying sources.

Relict salt water comprising the Parris Island and Port Royal Sound chloride plumes probably underlay most of Port Royal Sound by 2007, partly from unflushed relict salt water and later from a southwest movement of the plumes caused by groundwater withdrawals at Savannah, Georgia and Hilton Head Island, South Carolina. Modern salt water comprising the Hilton Head Island, Pinckney Island, and Colleton River plumes had migrated inland as far as 2 miles south of their estimated saltwater source areas near the Port Royal Sound estuary by 2007. The Pinckney Island chloride plume had migrated more than 4 miles inland because of a second source area suspected farther to the southwest near the mid-part of the island. By 2007, the five plumes had merged with a combined area of about 80 square miles and were advancing southwestward as a general front designated herein as the greater Port Royal Sound chloride plume. The average rate of movement of the greater Port Royal Sound chloride plume between 1953 and 2007 is estimated to be greater than 195 feet per year based on the distance (2 miles) between the plume's leading edge and saltwater source areas divided by an estimated recharge time of about 54 years.

Farther to the southwest of Port Royal Sound, the Sawmill Creek, Jenkins Island, Broad Creek, Bull Island, Hilton Head high, and eight-mile chloride plumes are located west and east of Hilton Head Island beneath tidal channels, saltwater estuaries, and the Atlantic Ocean. Here, the plumes are indicated by high computed chloride concentrations and greater downward hydraulic gradients at monitoring well sites. However, model simulations were used because data were not available to map the geographical extent of these southwestern plumes. The eleven chloride plumes were simulated with the South Carolina Department of Health and Environmental Control's three-dimensional variable-density groundwater flow and solute-transport model to further investigate the formation and expansion of the plumes from predevelopment conditions (1885) through the year 2050.

INTRODUCTION

This investigation was designed to evaluate the sources and extent of saltwater intrusion occurring in the Upper Floridan aquifer in southern Beaufort County, South Carolina and part of coastal Chatham County, Georgia (fig. 1), and was conducted as part of the Georgia Environmental Protection Division's (GaEPD) Coastal Sound Science Initiative (CSSI). The South Carolina Department of Health and Environmental Control (SCDHEC) continued with additional investigations in cooperation with the USGS – South Carolina Water Science Center and the Beaufort-Jasper Water and Sewer Authority. Further evaluation included fieldwork to determine the location of areas where seawater enters the Upper Floridan aquifer; time that saltwater intrusion began; the extent of chloride contamination in the aquifer; and the direction and rate of saltwater movement through the aquifer.

The Upper Floridan aquifer is a primary water source for public supply, agriculture, and industry; exceptions occur where surface water supplies are available. The aquifer comprises the top part of the Floridan aquifer system, which underlies nine counties in southwestern South Carolina and extends throughout large areas of the Georgia Coastal Plain and all of Florida. Concern over water-level declines and the potential for saltwater encroachment because of unrestricted and increasing groundwater withdrawals from the aquifer at Savannah, Ga., and at Hilton Head Island, S.C., led the states of Georgia and South Carolina to pass legislation in 1972 and 1982, respectively, creating Capacity Use Areas to manage groundwater withdrawals.

Prior to groundwater withdrawals from the Floridan aquifer system in southeast Georgia, the direction of groundwater flow in the Upper Floridan aquifer was southwest to northeast. Freshwater discharged upward into the upper confining unit and discharged in the vicinity of Port Royal Sound and other areas near the axis of the Beaufort Arch, where the upper confining unit was absent or thin. The seaward hydraulic gradient maintained the freshwater/saltwater interface offshore of Hilton Head Island and the nearby mainland. Development of public and industrial water supplies from the Floridan aquifer system began at Savannah about 1885 and increased to about 88 million gallons per day (Mgal/d) by the end of the 20th Century. Groundwater withdrawals for public supply and irrigation at Hilton Head Island began in the 1960's, and average withdrawals peaked at about 14.8 Mgal/d by 1986. Total groundwater withdrawals in the Savannah-Hilton Head Island area remained about 100 Mgal/d between 1988 and 1998 (Fanning, 2003). During the period between 1885 and 1998, the potentiometric surface in the Upper Floridan aquifer declined as much as 185 feet from predevelopment levels near the center of Savannah; at the northeast end of Hilton Head Island the potentiometric surface declined approximately 9 feet; and the cone of depression centered at Savannah, Ga., encompassed approximately 2,300 square miles (mi^2) where aquifer heads were below mean sea level.

By 1952, groundwater withdrawals in Savannah had probably begun to reverse the northeast trending predevelopment hydraulic gradient in the Upper Floridan aquifer. Groundwater that originally flowed northeast and from the Savannah area and discharged into Port Royal Sound now flowed from the area of Port Royal Sound toward the cone of depression centered at Savannah, Ga. A reversal of hydraulic gradients in the Upper Floridan aquifer from northeast to southwest diminished fresh groundwater discharge into the Port Royal Sound area, and relict salt water in the aquifer comprising the Parris Island and Port Royal Sound chloride plumes began migrating southwestward. Modern seawater also began migrating downward through the upper confining unit and, where the unit was thin or absent, salt water migrated directly down into the Upper Floridan aquifer.

Groundwater-use permits issued by the SCDHEC as required by the South Carolina Low Country Capacity Use program (Groundwater Use Act of 1969) reduced average daily groundwater withdrawals at Hilton Head Island from 14.8 to 9.7 Mgal/d as alternative sources were developed and water-conservation programs took effect. The Beaufort-Jasper Water and Sewer Authority provided surface water from the Savannah River to most of Beaufort County, S.C., and made available 6 Mgal/d to supplement the reduced groundwater supply at Hilton Head Island. Irrigation permits for golf courses at Hilton Head Island prohibited withdrawals from the Upper Floridan aquifer. Consequently, public utilities and golf-course owners began using treated wastewater, shallow ponds, and the middle Floridan aquifer for irrigation. The Town of Hilton Head Island prohibited the use of Upper Floridan domestic wells and required irrigation installers to be licensed. To investigate an alternative source of potable water, a 3,800 ft Cretaceous aquifer test well (BFT-2055) was funded by the town in 1993 and completed on the northern part of the island (Landmeyer and Bradley, 1998). The data obtained from the test well was promising and, in 1998, South Island Utilities proceeded with construction of a public supply well in the Cretaceous aquifer on the southern part of Hilton Head Island. The well was about 3,800 feet (ft) deep and yielded about 2 Mgal/d: the mineralized water required reverse-osmosis treatment.

Figure 1. Location of study area.

In 1997, the Georgia Environmental Protection Division (GAEPD) responded to concerns that groundwater withdrawals from the Floridan aquifer system in the Savannah area were contributing to saltwater encroachment at Hilton Head Island. The GAEPD organized a joint effort with the Georgia Legislature, U.S. Geological Survey (USGS), South Carolina Department of Health and Environmental Control (SCDHEC), and local stakeholders to develop an interim strategy for the sustainable use of the Floridan aquifer system in the 24 coastal counties of Georgia. The strategy mandated that no new permits would be issued to withdraw water from the Upper Floridan aquifer; imposed a 10

Mgal/d reduction in groundwater pumpage in the Savannah area; and implemented the Georgia Coastal Sound Science Initiative (CSSI) to further investigate the hydrogeology of the Floridan aquifer system.

Purpose and Scope

The objectives of this investigation were to: (1) compile the history of water-level declines in the Upper Floridan aquifer in the study area; (2) document the distribution and sources of saltwater contamination in the Upper Floridan aquifer near Hilton Head Island, S.C.; (3) determine a year or range of years during which seawater entered the Upper Floridan aquifer; and (4) estimate the direction and rate of saltwater migration into and through the Upper Floridan aquifer at Port Royal Sound and Hilton Head Island through the year 2050.

Location of Study Area

The primary study area (fig. 1) lies in the lower Coastal Plain of southern South Carolina and includes parts of Beaufort and Jasper Counties and adjacent areas of Georgia. To the northeast, southwest, and east, the study area is bounded by Parris Island and St. Helena Island, S.C.; Chatham County, Ga.; and the Atlantic Ocean, respectively. Land-surface topography is generally flat, and tidal streams and saltwater marshes extend 15 to 20 miles inland. Sea Islands characterize much of the area, and land-surface elevation ranges from mean sea level to about 25 ft NGVD 29.

Previous Investigations and History of Saltwater Intrusion

The following overview summarizes the history of groundwater investigations spanning more than 100 years and how it shaped present day knowledge of the Upper Floridan aquifer in Chatham County, Ga., and southern Beaufort County, S.C. This section has been expanded, in part, from Spigner and Ransom (1979), with updates where appropriate, but does not include all investigations. The names Upper Floridan aquifer and upper confining unit are used for consistency and replace the various but generally comparable names used in the cited reports.

The quest for a freshwater supply in Beaufort County, S.C., began more than 400 years ago on Parris Island. Here, the first known European settlement was the French settlement of Charlesfort, established in 1562. Charlesfort was replaced in 1566 by the Spanish settlement of Santa Elena (fig. 2) where the first documented use of groundwater came with the discovery and excavation of wooden barrel wells (South, 1985).

Early settlers obtained water by excavating 5- to 9-ft diameter holes and positioning open-ended wooden barrels from several feet below the water table to land surface. (fig. 2, inset). The wells provided potable water but were susceptible to contamination and drought. Evidence suggest that an epic drought persisted in North America during the middle of the 16th Century (University of Arkansas, 2000). The number of well sites on Santa Elena suggests that many wells had been replaced in search of potable water. The discovery of brick-lined excavations on Parris Island indicate that bricks eventually replaced wood barrels, probably around the 19th Century, as they were more durable. Shallow wells were common throughout the Georgia and South Carolina coastal area until mechanical drill rigs began to drill deeper and more dependable wells. The City of Savannah, Ga., relied on about 150 shallow brick wells prior to 1854 (Conant, 1918) and used the Savannah River for potable supply between 1854 and the early 1880's. The city completed their first deep well into the Floridan aquifer in 1882 (Conant, 1918). Surface-water use diminished and was discontinued in 1886 as groundwater pumpage increased. By the end of 1887, fifteen wells had been completed in the Floridan aquifer and were supplying about 3 Mgal/d. Three years later, twenty-three Floridan aquifer wells had failed to meet the increased water demand and the Savannah River water plant was temporarily placed in service to provide additional volume (City of Savannah Mayor's Report, 1890: Appendix A2). As Savannah continued to grow into a major port city, more wells were needed for increasing municipal and industrial water use (Appendix A).

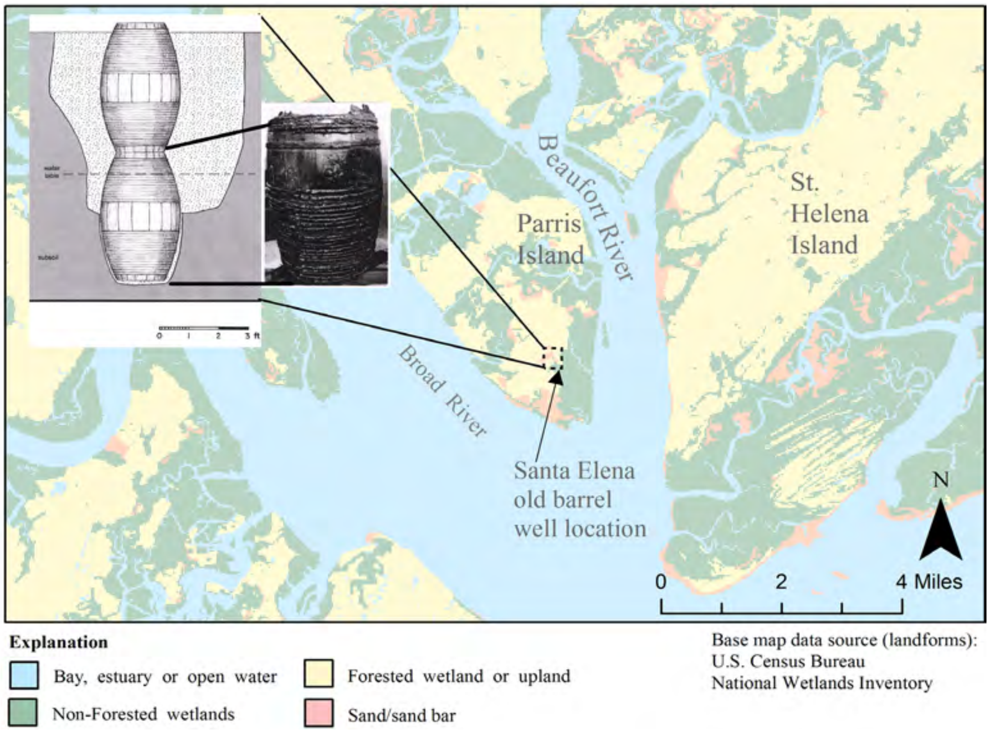

Figure 2. Location of the Spanish settlement Santa Elena (c.1566) and inset showing sketch of typical barrel-well construction with 400-year-old barrel excavated from a site at Santa Elena (South, 1985).

Northeast of Savannah, Ga., the demand for potable water on Parris Island, S.C. increased after the military established a training base during the latter 19th Century; however, efforts to develop a reliable groundwater source for the larger population were unsuccessful. T.L. Burnette, Mechanical Engineer, detailed the water-supply history of the Parris Island Marine Corps Recruit Depot (MCRD) in 1952 while stationed on Parris Island (Appendix A1). His review began with the first three wells drilled into the Upper Floridan aquifer in 1899. After a few years, these wells produced unacceptable chloride concentrations as salt water moved toward the pumping wells. Several other wells drilled in 1907 also became salty and were abandoned. By 1916, the groundwater supply on Parris Island was depleted owing to chloride contamination and further efforts to obtain a potable supply from wells on Parris Island were abandoned. With the onset of World War I, the demand for potable water increased and from 1916 to 1919 and groundwater was transported by barge to Parris Island from wells owned by the railroad and the Town of Port Royal (fig. 3). After 1919, water was piped from eight new 6-inch wells in the Town of Port Royal. The wells were abandoned by 1930 because of hydrogen sulfide in the water and potential chloride contamination. A second well field (the Jericho well field) was drilled on Jericho Point near the south end of Port Royal Island in 1927. Pumping was eventually reduced because wells near Battery Creek were contaminated with chloride. The Jericho well field was placed on standby in 1942, and use was discontinued after World War II. During and following World War II, water was obtained from two wells in the Burton community, west of the Town of Port Royal, S.C.

The first scientific investigation of the Floridan aquifer system in Savannah, Ga., and adjacent areas of South Carolina was begun by the USGS in 1938 to address declining water levels in the aquifer (Warren, 1944a, 1944b). The study area encompassed the twelve coastal-most counties within the Georgia Coastal Plain and part of Beaufort and Jasper Counties, S.C. The report included a structure contour map for the top of the Upper Floridan aquifer in Georgia and provided estimates for Floridan aquifer transmissivity and storage obtained from aquifer tests conducted on five wells in Savannah. Three potentiometric-surface maps for the Floridan aquifer were

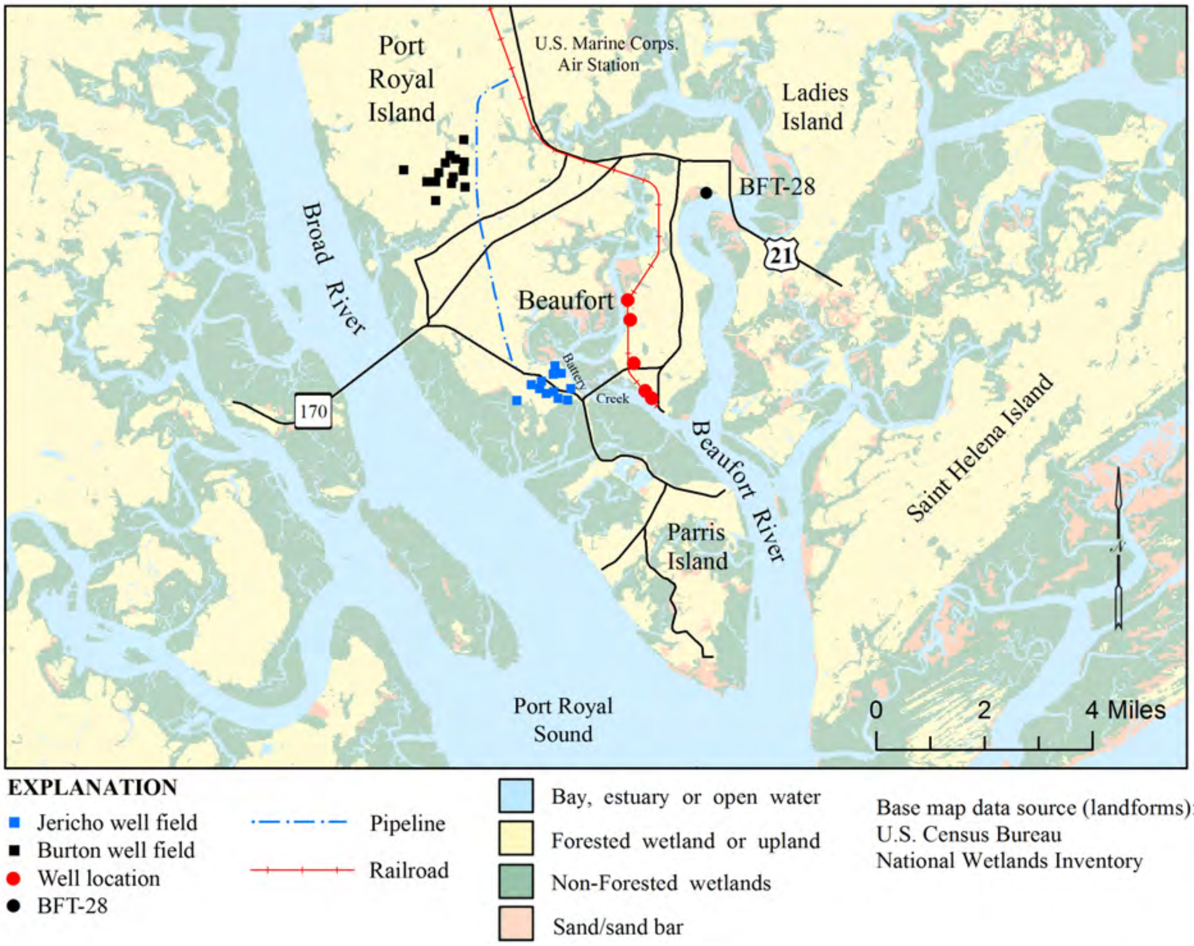

Figure 3. Locations of former well fields in the Beaufort, S.C., area.

constructed by Warren and showed (1) the estimated potentiometric surface prior to 1880, before groundwater development, (2) the measured potentiometric surface in 1943 when groundwater withdrawals were estimated to total about 41 Mgal/d, creating water-level declines of about 78 feet near the center of the cone of depression at Savannah, Ga., and (3) the predicted potentiometric surface if groundwater withdrawals in the Savannah area increased to 60 Mgal/d. The report also discussed water-level declines and their relationship to salt water that might encroach toward Savannah from the east and northeast near Parris Island and Port Royal Sound. Warren estimated that groundwater withdrawals needed to be maintained at less than 25 Mgal/d in Savannah if a divide in the potentiometric surface between Savannah and the natural freshwater discharge from the aquifer near Port Royal Sound was to be maintained. He noted that chloride concentrations in the aquifer increased with depth and suggested that low permeability in the lower parts of the aquifer had prevented the complete flushing of relict salt water.

Beginning in the early 1940's, officials representing the Beaufort County municipalities and nearby military installations believed that a more dependable water supply was needed because of increasing groundwater pumpage locally and at Savannah, Ga. Wells at the Burton field were not contaminated; however, chloride concentrations had increased in a municipal well near the Beaufort River (BFT-28) during World War II. The Bureau of Yards and Docks, Department of the Navy, requested that the USGS investigate groundwater in the area of Parris Island and the Marine Corps Air Station and make recommendations for a future water supply. The USGS investigation (Mundorff, 1944) provided the first potentiometric surface map of the Upper Floridan aquifer for the Beaufort County area. Mundorff's map indicated that the aquifer was probably in hydraulic connection with Port Royal Sound, nearby tidal channels, and marshes, suggesting that the source of salt contamination to the wells at Parris Island was brackish water intruding from Port Royal Sound and the Beaufort River to the south and east, respectively. He noted that the rapid water-quality changes at Parris Island demonstrated the fragility of the freshwater/saltwater balance near the island and speculated that the probable source of chloride contamination at the Jericho well field was Battery Creek (fig. 3). The wells at Beaufort, the Burton well field, and the Marine Corps Air Station also were discussed. Recommendations were made to avoid saltwater contamination by limiting water-level declines in wells to a few feet, drilling new wells as far as possible from saltwater channels, and abandoning wells that showed increasing chloride concentrations. Although the report concluded that the Upper Floridan aquifer groundwater supply near Beaufort was limited, the extent of the supply was not assessed.

The status of the existing Parris Island groundwater supply was further evaluated after Kendall (1948) submitted a report to the Bureau of Yards and Docks, Department of the Navy, Kendall provided estimates for future water-use requirements on the island and alternatives were proposed for attaining the maximum safe yield from freshwater aquifers. He also made recommendations regarding new well construction and water-system modifications to meet future needs and noted that the existing Parris Island groundwater demand would nearly double. The report concluded that saltwater contamination was influenced by water-level declines at Savannah, Ga. and elsewhere and that the declines were impossible to control: a study of the Combahee River water-supply potential was recommended.

The Combahee River, approximately 20 miles north of Beaufort, S.C. (fig. 1), gained additional support for a water supply source after Barber, Keels & Associates, Inc. prepared a water-supply report in 1955 for the Beaufort County Water Authority. This report and a supplemental report (Barber, Keels, & Assoc., 1955) included descriptions of the chemical quality and availability of surface water and groundwater in the Beaufort County area and provided estimates of water-supply needs for major users. B. P. Barber & Associates (1956) agreed that groundwater supplies on Port Royal Island were inadequate for future demands, particularly during war, and recommended the Combahee River as the best alternative for water supplies to Beaufort County municipalities and military installations.

At the request of the Department of the Navy, the USGS prepared a more comprehensive report describing the geology and groundwater of the Parris Island area. The report by Siple (1956) referenced other aquifers in the area but focused primarily on the Upper Floridan aquifer. Siple installed water-level recorders on selected wells to obtain continuous measurements. He reported relatively high-water levels in some Upper Floridan aquifer wells at Parris Island and concluded that the potentiometric highs were caused by freshwater recharge from the overlying surficial aquifer. Water levels and chloride concentrations in selected wells were compared to groundwater withdrawals, but a definitive correlation between withdrawals and chloride concentrations was not apparent. Siple also noted surface depressions (sinkholes) present throughout the area and suggested that they were caused by the collapse of the underlying upper confining unit, possibly creating a connection between the Upper Floridan aquifer and saltwater channels: he concurred with Mundorff (1944) on the source of brackish water intruding from nearby saltwater channels and marshes. Unknown tidal effects and discrepancies regarding measuring point elevations in previous studies prevented a definitive analysis of historical water-level declines, particularly at the Burton well field. Estimates were made regarding the total supply of groundwater available to Parris Island from the Upper Floridan aquifer, and Siple hypothesized that the mineralized water from existing deep wells completed at Parris Island might yield fresh water northwest of Burton. The report concluded that increasing demand for public supply and irrigation would diminish the supply of groundwater available for military installations. Siple recommended that future wells be drilled northwest of Burton, west of the Broad

River, and north of Spring Island, and that routine measurements of water levels and chloride concentrations continue.

Hazen and Sawyer Engineers (1956) disagreed with B.P. Barber & Associates' (1956) recommendation that the Combahee River was the best alternative water supply. Based on their interpretation of USGS stream flow records, the Combahee River was prone to extreme low flows during drought and could only be used 90 percent of the time unless reservoirs were constructed; thereby making the project too costly. As an alternative, Hazen and Sawyer Engineers recommended a well field west of the Broad River. B. P. Barber & Associates (1956) defended their earlier conclusion that the Combahee River was the best alternative water source. Their estimates showed the cost of developing and distributing surface-water supplies from the Combahee River was only slightly greater than the cost of a well field west of the Broad River and disputed Hazen and Sawyer's (1956) conclusion that flows in the Combahee River would be inadequate during a drought. B.P. Barber & Associates (1956) again emphasized that Savannah-area pumping would endanger a well field west of the Broad River because Beaufort-area authorities had no control over groundwater use in Georgia.

Bowen (1956) also prepared a report that recommended future sources of water supply for Parris Island. He favored development of the Combahee River over a well field west of the Broad River, reasoning that the increasing demand for irrigation wells and the resulting competition for groundwater would steadily degrade the Parris Island water supply. He recommended that the Beaufort County Water Authority was the best agency to undertake development of the Combahee River and that no further funds be expended by the Navy for a proposed well field west of the Broad River.

Hazen and Sawyer Engineers (1957) presented additional reasons for constructing a well field west of the Broad River; however, the South Carolina General Assembly passed an Act that prohibited the transfer of more than 5,000 gallons per day of groundwater beyond the boundaries of Jasper County (Section 70-421, 422, 1962 S.C. Code of Laws), thereby ending further consideration of the Broad River well field. Hazen & Sawyer Engineers subsequently recommended that the Savannah River would be a more reliable source.

A more expansive report by Siple (1960) included well records, water-quality analyses, a geologic section, and a 1959 potentiometric surface map of the Upper Floridan aquifer in Beaufort and Jasper Counties, S.C. The 1959 potentiometric surface indicated that increased groundwater withdrawals from the Upper Floridan aquifer at Savannah had lowered water levels in Beaufort and Jasper Counties, S.C., since 1943. However, the declines (Appendix D3-D5) did not extend to northern Hilton Head Island; Siple suggested that the aquifer was receiving local recharge on the northern part of the island. His map showed a cone of depression in the Upper Floridan aquifer around the Burton well field and, like Mundorff's map, also showed areas of anomalously high water levels. The most notable being near the Marine Corps Auxiliary Air Station. He believed that the anomalous water levels were possibly caused by local recharge through breaks in the upper confining unit. Siple concluded that saltwater contamination was less extensive than previously thought, but the problem would worsen if groundwater development continued in certain areas. He recommended that, if new well fields were drilled, including one west of the Broad River, the water needs of the civilian and military population could be met for many years without fear of saltwater contamination. His recommendation agreed with Hazen & Sawyer Engineers (1956 and 1957).

Groundwater withdrawals continued to increase in Savannah, Ga., and by 1957 had reached 60 Mgal/d. The subsequent decline in the potentiometric surface caused concern that saltwater was encroaching from the Beaufort-Parris Island area toward Hilton Head Island and Savannah to the southwest. Additional investigations by the USGS in cooperation with the Georgia Department of Mining and Geology, the City of Savannah, and Chatham County were initiated to acquire a better understanding of the hydrogeology, to determine where salt water was present in the aquifer, and to monitor its movement. Several reports were published including Warren (1955), Herrick and Wait (1955), Counts and Donsky (1963), Counts and McCollum (1964) and McCollum (1964).

The report by Counts and Donsky (1963) included data from test wells in Savannah, Ga. and three test wells in southern Beaufort County: they included borehole geophysical logs, water-quality analyses, water-use inventories, aquifer tests, and a 1957 potentiometric surface map of the Savannah, Ga. – Hilton Head Island, S.C. area that showed water levels had declined 10 ft at the center of Hilton Head Island. They concluded that, since the first wells at Savannah were drilled in the late 19th Century, there had been little change in Upper Floridan aquifer water quality near Savannah. However, salt water was present in the Upper Floridan aquifer to the northeast of Savannah near the Parris Island area, S.C., and in the middle and lower Floridan aquifers throughout the coastal area east of Savannah. The authors noted that salty water encroaching toward Savannah represented less than one-third of the total water withdrawn at the center of pumping and that it would take years before salt water reached Savannah at the current pumping rate of 62 Mgal/d. The potential for salt water to move downward from overlying sources and upward from deeper sources was also discussed. And they recommended future groundwater supplies for the Savannah area be developed from well fields 15 to 20 miles northwest, west, and southwest of Savannah.

McCollum and Counts (1964) focused on delineating specific water-bearing (permeable) zones within the Floridan aquifer system between Hilton Head Island and the Savannah area to determine the rate of saltwater movement associated with each zone. The authors modified a deep well in Savannah and conducted flow meter test on other monitoring wells. Five principle permeable zones were identified in coastal Chatham County of which four extended northeast to Daufuskie Island and three to the northern end of Hilton Head Island. They noted that chemical analyses showed increasing chloride concentration in the lower part of the aquifer, supporting Warren's (1944) and Counts and Donsky's earlier conclusion that lower permeability in the lower sections of the Floridan aquifer system prevented relict seawater from being completely removed. McCollum and Counts concluded that the overall direction of groundwater movement in the Floridan aquifer system in Beaufort and Jasper Counties, S.C. was toward Savannah and that the rate of movement varied in each permeable zone. Although the rate of saltwater movement was uncertain, flow-meter tests suggested that most water moves through the more permeable upper part of the aquifer and that further water-level declines would hasten the lateral movement of saltwater through the upper part toward Hilton Head Island and Savannah. They calculated that it would take about 400 years for salt water near Port Royal Sound to move through the uppermost permeable zones of the aquifer and reach Savannah; but wells at Savannah would probably become contaminated first from salt water present in the lower water-bearing zones because it was closer to Savannah as opposed to salt water near Port Royal Sound. Recommendations included moving future municipal and industrial wells 15 to 20 miles west of the city, consistent with previous investigations.

McCollum (1964) summarized findings of his earlier 1964 investigation and provided additional information on the rate of saltwater movement through the five permeable zones in the Upper Floridan aquifer. His report documented an increase of groundwater withdrawals to 65 Mgal/d in 1962, and a 1963 potentiometric-surface map was constructed for the aquifer. McCollum believed that a slight increase in chloride concentration had occurred in the lower zones of the Floridan aquifer near Savannah compared to previous studies and stated that salt water in the lower zones would reach Savannah in about 75 years. He concluded that the threat of saltwater contamination at Savannah would be minimal because only 20 percent of the groundwater captured by wells at Savannah was flowing from contaminated areas. Recommendations included monitoring the permeable zones for changes in chloride concentration.

In 1962, amid debate over increasing demand for water supplies and concern about saltwater intrusion, federal funding became available, and development of a surface-water supply from the Savannah River was considered the best option. Thus, a surface-water supply from the Savannah River was chosen to replace both the military and the City of Beaufort's reliance on groundwater: The Savannah River Project was completed in 1964. Afterwards, the Burton well field and wells at the Beaufort Naval Air Station that had served the area since 1942 were taken out of service and maintained as standby systems.

In the late 1960's, the mining of phosphate deposits from the upper confining unit in coastal Chatham County, Ga. was considered. Studies were undertaken to evaluate the potential for saltwater intrusion into the Upper Floridan aquifer because dredging operations would reduce the thickness of the upper confining unit. Carver (1968) summarized the results of test drilling in the upper confining unit overlying the aquifer in the proposed mining area. Based on interpretations of borehole and geophysical logs from the test wells, Carver concluded that mining operations were probably feasible if environmental safeguards were followed. A later report by Furlow (1969) discussed the economic potential for mining phosphate from the upper confining unit in eastern Chatham County, Ga. As part of this investigation, he estimated the potential impact that dredging would have on water quality in the underlying Upper Floridan aquifer if the top section (approximately 40 to 50 ft) of the upper confining unit was removed. Fifty-two cores from the upper confining unit were collected and analyzed to obtain hydraulic conductivity and evaluate phosphate deposits. Furlow used Darcy's Law to calculate the downward saltwater migration assuming: (1) an average hydraulic conductivity of 9.6×10^{-3} gpd/ft^2, (2) that 40 ft of upper confining unit sediment would remain after dredging, and (3) a -15 ft average head difference across the upper confining unit caused by pumping the underlying Upper Floridan aquifer 63 Mgal/d. Based on his calculations, salt water would migrate downward at a rate of about 160 gallons per acre per day (gal/acre/day) or 102,400 gpd/mi^2. Furlow concluded that the increased rate of saltwater leakage would not significantly affect wells at Savannah and further stated that even without dredging; salt water was currently migrating downward at a similar rate over the coastal areas near Savannah.

In Beaufort County, S.C., dredging to expand the Port of Port Royal was also considered for parts of Battery Creek and the Beaufort River; the proposed dredging became an issue with respect to the potential for saltwater intrusion into the Upper Floridan aquifer. In 1970, the South Carolina Water Resources Commission (SCWRC) in cooperation with other State and Federal agencies addressed the problem by conducting an environmental impact study of the Port Royal Sound area. The study included a seismic survey of the channels in the Port Royal Sound area and 19 boreholes drilled adjacent to the channels to evaluate the depth and thickness of the upper confining unit overlying the Upper Floridan aquifer. The data showed that the Upper Floridan aquifer lay at shallow depths and could be breached in parts of the river during dredging operations. These interpretations were like those of Mundorff (1944) and Warren (1944), who hypothesized that the aquifer occurred at shallow depths beneath several navigation channels in in the vicinity of Port Royal Sound. The study concluded that "No further dredging should be allowed in the Beaufort River unless reliable investigations can demonstrate that additional dredging to deepen the shipping channel can be conducted without jeopardizing the groundwater resource." A technical committee overseeing the study recommended that a groundwater investigation be conducted under the provisions of the South Carolina Ground Water Use Act of 1969 to answer the dredging question and to provide direction for groundwater management (South Carolina Water Resources Commission, 1972).

Southwest of Port Royal Sound near Hilton Head Island, the presence of salt water in the Upper Floridan aquifer had not been documented. However, increasing demand for groundwater at Hilton Head Island and a proposed industrial development west of the island at nearby Victoria Bluff caused concern for the long-term sustainability of the resource. The Victoria Bluff area also was considered as a possible alternative groundwater supply for Hilton Head Island if island wells became contaminated. Nuzman (1970, 1972) evaluated water-supply potential at Victoria Bluff and Hilton Head Island: his report provided a review of the groundwater conditions, results of aquifer tests, and recommendations to manage the resource. Using Darcy's Law, he estimated that salt water known to be present in the aquifer beneath Parris Island was moving toward Hilton Head Island at a rate of about 62 feet per year (ft/yr). Aquifer tests were conducted on Hilton Head Island and Victoria Bluff to determine the hydraulic properties of the aquifer and to assess the relationship between pumping and drawdown. The aquifer test at Victoria Bluff consisted of pumping well BFT-499 at a rate of 3,000 gpm and measuring drawdown in an observation well 100 ft from BFT-499. After 186 hours of pumping, the measured drawdown in well BFT-499 was 10 ft with only 1 foot measured in the observation well. Water samples taken near the end of the test showed chloride concentration to be 9 mg/L. Based on the high transmissivity calculated from the aquifer tests and the water-quality analysis, Nuzman concluded that, with pumping limits, proper well spacing, and an alternative groundwater supply from the Victoria Bluff area, the island could obtain large volumes of groundwater from the Upper Floridan aquifer without threat of saltwater intrusion for 40 to 70 years.

Completion of the Port Royal Sound Environmental Study (1972) convinced local officials representing Beaufort, Jasper, Hampton, and Colleton Counties, S.C. to request a Capacity Use Investigation under the Ground Water Use Act of 1969. The request was made amid concerns that saltwater intrusion could only be controlled by a greater understanding of the aquifer and requiring permits for large groundwater withdrawals. The Low Country Capacity Use Investigation was conducted by the USGS in cooperation with the SCWRC. The resulting report (Hayes, 1979) produced numerous technical maps including a 1976 potentiometric surface map of the Upper Floridan aquifer for the Low Country area and for Hilton Head Island that incorporated surveyed wellhead elevations and tidal-correction factors; a structure map for the top of the Upper Floridan aquifer based on geologic descriptions and natural gamma-ray logs; and two 1976 chloride-distribution maps that documented the water quality from pumping wells completed in the Upper Floridan aquifer for southern Beaufort County and Hilton Head Island. The report provided estimates for groundwater withdrawals at Hilton Head Island, S.C., and Savannah, Ga., which were 8 and 75 Mgal/d, respectively. Estimates of the rate of saltwater movement in the aquifer beneath Port Royal Sound from Parris Island toward Hilton Head Island were revised to 140 ft/year after updating the average potentiometric gradient beneath the Port Royal Sound to 1.5 feet per mile (ft/mi). Hayes noted that chloride concentration had increased in several monitoring wells on the northeastern part of Hilton Head Island and suggested that the increase was caused by salt water moving from Parris Island as a result of groundwater withdrawals on Hilton Head Island, S.C. and Savannah, Ga. The study concluded that where the confining unit overlying the Upper Floridan aquifer was absent, freshwater head was the primary factor controlling saltwater intrusion. Recommendations were made to better estimate the benefits of increasing the freshwater head by developing digital models of the aquifer to simulate distribution of new well locations and changes in pumpage. Following completion of the study, the SCWRC declared the Lowcountry area of Beaufort, Jasper, and Colleton Counties a Capacity-Use area (Hampton County was included later). In 1982, regulations were implemented by the South Carolina legislature to permit large capacity wells and a regional office was established in Beaufort to oversee the permitting program.

In Georgia, the USGS in cooperation with the City of Savannah, Ga., Chatham County, Ga., and the Georgia Department of Natural Resources, completed the first groundwater flow model (Counts and Krause, 1976) in the Savannah area to simulate the potentiometric surface of the Upper Floridan aquifer. The study as defined by the authors was: (1) to develop and calibrate a groundwater-flow model that would simulate the response of the Upper Floridan aquifer in the Savannah area to various pumping rates, and (2) to demonstrate the usefulness of the model as a management tool for evaluating and predicting water-level changes in the aquifer to 2000. The model simulated hypothetical changes in pumping and redistribution of wells to predict changes in the potentiometric surface of the Upper Florian aquifer. The report included three simulations that showed changes in the potentiometric surface caused by adding to the 1970 pumpage: (1) 10 Mgal/d at hypothetical well sites on Hilton Head Island, S.C., (2) 10 Mgal/d at Hutchinson Island, Ga., about 3 miles east of Savannah, and (3) 6 Mgal/d at Monteith, Ga., about 7 miles northwest of Savannah. Two other simulated potentiometric surfaces for the year 2000 included: (1) transferring 10 Mgal/d of the 1970 pumpage from Savannah, Ga., to Bloomingdale, Ga., 10 miles to the west of Savannah, and (2) reducing 1970 pumpage by 20 Mgal/d at the center of the cone of depression at Savannah. The authors concluded that, even though the model did not exactly duplicate conditions in the Upper Floridan aquifer, the modelling efforts were successful, and their model could be a useful tool for managing the aquifer in the Savannah area.

In October 1979, the U.S. Army Corps of Engineers (USACE) authorized Bernard Johnson Incorporated (BJI) to proceed with a groundwater investigation as part of the Metropolitan Savannah Water-Resources Management Study and investigate water-supply alternatives for the Savannah area. At the request of the SCWRC, the study was expanded to include the adjoining area of Beaufort, Jasper, Hampton, and Colleton Counties, South Carolina. Eventually, a cooperative effort developed that included the U.S. Environmental Protection Agency, the Georgia Environmental Protection Division under the Georgia Department of Natural Resources, the South Carolina Water Resources Commission, the Chatham County-Savannah Metropolitan Planning Commission, the Coastal Area Planning and Development Commission, the Low Country Council of Governments, and citizen advisory and executive committees. The USACE evaluated many options proposed by the participating groups and concluded that there was a water-supply problem in the most sensitive part of the study area near Savannah and Hilton Head Island where water-level declines and potential for saltwater intrusion were greatest. Sensitivity analyses by the USGS groundwater model showed that increased groundwater pumpage outside the sensitive area would have negligible impact on water levels at Hilton Head Island. Final recommendations from the study presented in December 1983 allowed Savannah to increase up to 62 Mgal/d from the Savannah River for industrial use and to increase groundwater pumpage up to 5 Mgal/d for domestic use in areas west of Savannah. For Hilton Head Island, the study recommended that 50 percent of future domestic use come from groundwater pumped west of the island on the mainland near Victoria Bluff and the Town of Bluffton. South Carolina did not agree with the long-term plan and maintained their position that Savannah needed to reduce groundwater withdrawals. The level of cooperation brought about by this study to address interstate issues between South Carolina and Georgia was unprecedented in the study area and set the trend for the two states to continue their cooperative effort to manage and share the resource.

Groundwater withdrawals continued to increase through the early 1980's at Hilton Head Island, S.C., and Savannah, Ga. Beginning in 1974, chloride concentrations increased in an Upper Floridan well (BFT-315) monitored by the USGS near the northwest shoreline of Hilton Head Island. The increases raised the possibility that salt water from Parris Island had moved beneath Port Royal Sound and had reached Hilton Head Island. Amid questions as to where the salt was originating, the USGS in cooperation with SCWRC and the U.S. Army Corps of Engineers constructed nine temporary offshore test wells in the Upper Floridan aquifer beneath Port Royal Sound and the Atlantic Ocean in 1984. As part of the study, Burt and others (1987) published a base-data report for the nine test wells that included well locations, well construction, geophysical logs, lithologic descriptions of geologic cores and drill cuttings, and water quality data.

Following the Port Royal Sound drilling, further groundwater investigations continued by the USGS and the SCWRC. Smith (1988) developed a groundwater-flow model for the Upper Floridan aquifer that included data from the 1984 offshore drilling in Port Royal Sound. The 1984 model simulations were based on groundwater withdrawals of about 70 and 9.5 Mgal/d in Savannah, Ga. and Hilton Head Island, S.C., respectively. The model was used to predict changes in the potentiometric surface in response to (1) redistribution of wells, (2) changes in pumping rates, and (3) simulating freshwater injection wells to raise the potentiometric surface in the aquifer and slow the advancement of salt to brackish water toward Hilton Head Island. Total dissolved solids were mapped at the bottom and top of the aquifer beneath Port Royal Sound, the resulting plume map for the bottom of the aquifer showed salt water and brackish water about 4,000 ft and 2,500 ft from the northeastern shore of Hilton Head Island, respectively. Along the northwestern shoreline, brackish water at the bottom of the aquifer was already beneath the shoreline of the island. Smith used Darcy's Law to estimate the movement of brackish water in the aquifer beneath Port Royal Sound: the average rate of brackish water movement across Port Royal Sound at the bottom of the aquifer was 50 to 80 ft/yr.

Data from the drilling beneath Port Royal Sound was also included as part of the studies conducted by the Beaufort regional office of the SCWRC. Hughes and others (1989) summarized groundwater conditions, mechanisms for saltwater intrusion, and mapped hydrogeologic strata in Beaufort and Jasper

Counties S.C. The report discussed formation of the Beaufort Arch and breaches in the upper confining unit caused by erosion, sinkhole development, and dredging, noting that the Upper Floridan aquifer was directly exposed to seawater in the channels of Beaufort River and Battery Creek. Using Darcy's Law, the authors estimated about 200 years for 100-percent seawater from Port Royal Sound to move downward and break through the upper confining unit assuming hydraulic heads remain unchanged: dispersion was not considered. A similar calculation was made near the Broad Creek area midway on Hilton Head Island where greater head differences between mean sea level and the Upper Floridan aquifer had existed since the 1960's. Here, calculations showed an estimated breakthrough time of about 40 years.

Clarke and others (1990) summarized the geohydrologic framework of the late Eocene to Miocene formations in Georgia's eastern Lower Coastal Plain Province. Their work included the construction and modification of 23 test wells, review of lithologic and geophysical logs from about 500 wells, and laboratory analyses of 178 groundwater samples. The authors constructed potentiometric maps (see Clarke, 1987), presented USGS hydrograph data, and identified three geophysical-log signatures that coincide with the bottoms of the lower, middle, and upper Miocene (markers A,B, and C) near their study area; discussed head differences and groundwater movement between aquifers; presented a regional Upper Floridan aquifer isochlor map; and described the effects of local structural features on geothermal gradients, water levels, and saltwater contamination.

By 1990, groundwater withdrawals from the Upper Floridan aquifer at Savannah and Hilton Head Island had reached about 88 and 14.5 Mgal/d, respectively. Citizens and officials with the Town of Hilton Head Island had followed the groundwater investigations and were concerned about the future of their potable supply after learning that salt water was present in the Upper Floridan aquifer near the northern edge of the island. In response, the Hilton Head Island Water Management Task Force was created in 1990 to review the issue with state and local officials and provide the town with recommendations. After extensive review and public discussion, the task force recommended that the town proceed with a test well designed to penetrate the deeper Cretaceous formations and evaluate their potential as an alternative groundwater source. Atlanta Testing and Engineering (AT&E) was contracted to oversee the Cretaceous test well (BFT-2055), the well was completed through the full thickness of the Coastal Plain sediment to the top of bedrock encountered at a depth of 3833 feet in 1992. The Department of Energy contributed funding for sophisticated geophysical logging on the well to evaluate the geology and hydraulic properties of the sediment. Sidewall core samples were taken and used to determine laboratory permeability of potential water bearing zones and to extract pore water to assess the quality of water at selected depths. Temples and Waddell (1996) reported on data obtained from the geophysical logging and sidewall cores that included identification of permeable zones and water quality: their efforts assisted AT&E's decision to place 18 screened intervals totaling 195 ft in the Cape Fear and Middendorf Formations. Landmeyer and Bradley (1998) reviewed the data and provided a discussion on the well construction, water-quality data, aquifer tests, and a flow-meter test. They reported that 75 percent of the natural flow (253 gpm) came from permeable zones above 3,100 ft and that the total dissolved solids were about 1,400 mg/L. The Cretaceous aquifer system was not considered for a new source of water supply on Hilton Head Island at that time, but the data would prove invaluable for a future water supply.

Following the Port Royal Sound offshore drilling project, Smith (1993 and 1994) completed a solute-transport model to better estimate the rate of saltwater to brackish-water movement along a northeast-southwest trending vertical section across Port Royal Sound for the underlying upper confining unit and Upper Floridan aquifer. The model simulation for the predevelopment position (1885) showed that saltwater stabilized along the northeastern part of the sound prior to 1885. Afterwards, three pumping rates were simulated between 1885 and 1984 to account for changes to the hydraulic gradient and to measure the rate of movement and position of brackish water near the bottom of the aquifer as it advanced toward Hilton Head Island. The combined model simulations, through 1984, indicated that the toe of the brackish-water front had moved 8,400 ft, placing brackish water about a half mile from the northeastern shore of Hilton Head Island: the position of the freshwater-brackish water interface correlated reasonably well with the data from the offshore test wells. Simulating 1984 pumpage to 2032 showed that brackish water near the bottom of the aquifer would move beneath Hilton Head Island between 2000 and 2016 and would advance about one mile beneath the island by 2032: Smith noted that the rate of brackish-water movement would increase if pumpage increased. Even if pumpage on the island ceased, brackish water would continue to move southwest at a rate of about 65ft/yr because of existing gradients created by pumpage in Savannah, Ga. Vertical saltwater leakage through the upper confining unit from the surficial aquifer was also simulated along the vertical section across the sound. The simulation showed that brackish water would enter the top of the aquifer at the north shore of Hilton Head Island at about the same time the toe of the brackish-water wedge would pass beneath the north shore of the island at the bottom of the aquifer.

The offshore test drilling in Port Royal Sound also contributed to an investigation by the USGS (Burt, 1993) to study the geochemical evolution of groundwater and how these reactions affected the diagenesis of the Upper Floridan aquifer. Burt published geologic and water-quality data and mapped the distribution of salt water within the aquifer beneath Port Royal Sound and nearby areas. The study defined two distinct zones of water quality in the study area; a downgradient zone of influence near the coast where seawater mixed with fresh groundwater and a zone of freshwater further inland, upgradient, and outside the influence of seawater mixing. The two zones were modeled along a single flow line along which groundwater flowed from the zone of freshwater toward the zone of freshwater-seawater mixing. The conceptual model incorporated seven chemical processes; with some exceptions to the observed variation in the groundwater chemistry, the model produced plausible results across a segment of the aquifer. Burt noted that the groundwater chemistry changed as it moved down gradient, but the evolutionary pattern was consistent, suggesting that the groundwater chemistry along each flow line is controlled by similar chemical processes, including the net dissolution or precipitation of calcite, the major component of the aquifer. To better explain the distribution of calcite, Burt considered carbon dioxide input as an eighth chemical process. Possible mechanisms contributing to carbon dioxide are atmospheric influx, respiration, fermentation, oxygen reduction, nitrate reduction, and sulfate reduction; however, local recharge was shown to be transporting carbon dioxide to the Upper Floridan aquifer and causing a net dissolution of carbonate minerals. The highest concentrations were associated with seawater recharge. Burt noted that the dissolution of carbonate minerals has probably been a factor in the evolution of hydraulic conductivity where high values are apparent in the Port Royal Sound area as opposed to lower values where calcite precipitation is taking place. The dissolution of carbonate material in the aquifer can be observed also by the significant number of sinkholes in the areas surrounding Port Royal Sound.

The water chemistry of the Upper Floridan aquifer in the vicinity of Port Royal Sound was investigated by Landmeyer and Belval (1996) who provided a historical data base to (1) document trends and changes in water chemistry and chloride concentrations that occurred after groundwater withdrawals began, (2) assess the effect of changes in chloride concentration in response to tides, and (3) compile a review of water chemistry between 1917 and 1993 from selected wells primarily in Beaufort County, S.C. Data from offshore test wells in Port Royal Sound were included in the study, and additional water samples were collected for chemical analysis at discrete depths from selected wells on nearby Sea Islands. The data were plotted on a graph to show the relationship between chloride concentration and specific conductance in the Upper Floridan aquifer for the Port Royal Sound area. The authors noted that specific conductance near the bottom of the Upper Floridan aquifer at well BFT-1810 (near well BFT-315), at the northwest shoreline of Hilton Head Island, had increased from 4,000 to 10,000 microsiemens per centimeter (µS/cm) between 1987 and 1993. Applying the multiple (see **METHODS** section), chloride concentration was computed to be 1,400 mg/L and 3,500 mg/L in 1987 and 1993, respectively.

Groundwater withdrawals remained at peak levels throughout the 1990's, and chloride concentrations continued to increase in wells near the northern part of Hilton Head Island and west of the island. Efforts to mitigate water-level declines in the Upper

Floridan aquifer had been ongoing and SCDHEC (responsible for the Capacity-Use program beginning in 1994) had begun negotiating alternative sources with permitted users to include surface water, deeper aquifers, and reclaimed water for irrigation use. Eventually, only two-year permits were issued for golf-course irrigation; afterwards, an alternative source for long-term use was required. As a result, many irrigation wells began to exploit a deeper stratum of the Floridan aquifer system identified as permeable zone 4 (McCollum and Counts, 1964). Gawne and Park (1992) released an open-file report informally naming permeable zone 4 the middle Floridan aquifer in South Carolina. Both SCDHEC and SCDNR considered the middle Floridan aquifer a possible long-term alternative for golf course irrigation because 300 ft of less permeable sediment (middle confining unit) separated the two aquifers. Using geophysical logs and current-meter tests, the authors mapped the middle Floridan aquifer in the Hilton Head Island area; they reported that the middle Floridan aquifer thinned from about 40 ft near Hilton Head Island to about 7 ft at Parris Island: transmissivities decreased from 27,000 ft^2/day to 2,000 ft^2/day at Hilton Head Island and Parris Island, respectively. Water in the aquifer was fresh beneath the mainland west of Hilton Head Island, brackish at Hilton Head Island, and moderately saline at Parris Island. Measured chloride concentration in the middle Floridan aquifer ranged from 160 milligrams per liter (mg/L) on Daufuskie Island and increased northeastward to 4,250 mg/L at Parris Island. Smith's (1988) flow model for the Upper Floridan aquifer was modified by Gawne and Park (1992), who included the middle confining unit and middle Floridan aquifer to simulate the impact of pumpage from the middle Floridan aquifer to the Upper Floridan aquifer. The model simulated about 0.3 ft of decline in the Upper Floridan aquifer at Hilton Head Island when 1.14 Mgal/d of middle Floridan aquifer pumpage was distributed throughout Hilton Head Island: simulated inflow from beneath Port Royal Sound increased 4 to 5 percent.

By the mid-1990's South Carolina officials and local water users had renewed their discussions on how to best manage the groundwater resource, including possible legal action; eventually, representatives of the GaEPD and the SCDHEC met in 1995. The meeting focused on the rate of saltwater intrusion and the sustainability of the Upper Floridan aquifer to support future generations that depend on the Floridan aquifer the Savannah-Hilton Head Island area. SCDHEC emphasized that South Carolina had expended approximately fifty-million dollars for research, expansion of the surface water supply from the Savannah River to much of southern Beaufort County for public supply, and development of alternative sources such as the middle Floridan aquifer and treated-effluent use for golf course irrigation. The States ultimately agreed that more study was needed to document the rate of saltwater intrusion. The GaEPD proceeded to coordinate with the Georgia Legislature, USGS, SCDHEC, and local stakeholders to develop an interim strategy for the sustainable use of the Floridan aquifer system in the 24 coastal counties of Georgia and adjoining parts of South Carolina. The interim strategy mandated an immediate 10 Mgal/d reduction in groundwater pumpage in the Savannah area and implemented the CSSI at a cost of about five million dollars to further investigate the hydrogeology of the Floridan aquifer system. The CSSI provided the most comprehensive study to date and comprised multiple investigations in the study area including offshore and onshore test drilling, offshore seismic surveys, water-use accountability, groundwater models, and options for alternative sources.

SCDHEC was preparing to restrict water use from the Upper Floridan aquifer to 9.7 Mgal/d for permitted wells on Hilton Head Island. The looming restrictions raised further concern with island utilities that the States of Georgia and South Carolina would not reach an agreement in time to avoid saltwater contamination of public supply wells. South Island Utilities decided to investigate their own options for an alternative water supply and, using data from the earlier 1992 deep-well project initiated by the Town of Hilton Head Island, decided to complete a 3,800 ft well in the Middendorf and Black Creek aquifers (Cretaceous system). The well was permitted by the SCDHEC in 1998 through the Capacity Use and Public Supply permitting programs and included reverse-osmosis (R/O) treatment to filter dissolved solids. The Cretaceous well was successful and became an important supplemental water source for the southern part of the island.

Initially, the CSSI funded the SCDHEC to oversee construction of test wells in the Upper Floridan aquifer near the northern part of Hilton Head Island, and later funded additional wells west of the island. Monitoring included water-level measurements and vertical specific-conductance profiles to compute chloride concentrations. The data were used to construct a 1998 potentiometric surface map of the Upper Floridan aquifer (Ransom and White, 1999) and led to the discovery of three large chloride plumes mapped by SCDHEC as part of this investigation. Geophysical logs and geologic samples showed that the greatest chloride concentrations in the Upper Floridan aquifer were found closest to Port Royal Sound where there was little or no confining sediment above the aquifer. Offshore seismic-reflection surveys between Wassaw Sound, Ga., and Port Royal Sound, S.C., conducted by Foyle and others (2001), identified areas where the upper confining unit was thin or absent in parts of the Port Royal Sound estuary and offshore of Hilton Head Island. The new track lines added 415 miles to the existing 800 miles of archived data. Interpretation of the data led the authors to identify eleven Areas of Concern (AOC) where the upper confining unit was absent. The potentiometric surface of the Upper Floridan aquifer was below mean sea level and subject to seawater intrusion in ten AOC that included two areas where SCDHEC had identified three new chloride plumes. The most prominent offshore area was located about six miles east of Hilton Head Island: here, the Upper Floridan aquifer had been uplifted to a height of about -60 ft mean sea level (Msl) and the thickness of the overlying upper confining unit was between 0 and 10 ft. The area was informally named the Hilton Head High by Foyle and others (1999).

In 1999, the AOCs identified east of Hilton Head (Foyle, 1999 and 2001) Island during the offshore seismic surveys were further investigated with funds from the CSSI. The investigation was a joint effort between the GaEPD, USGS, SCDHEC, and the USACE to determine water quality in the Upper Floridan aquifer at five offshore sites: one site beneath Calibogue Sound and four beneath the Atlantic Ocean seaward of Hilton Head Island, S.C., and northeast of Tybee Island, Ga. Falls and others (2005) reported on seven temporary offshore Upper Floridan aquifer boreholes of which five were completed as temporary test wells. The locations were named the Calibogue Sound, the 7-mile, the 8-mile, the 10-mile, and the 15-mile sites, corresponding to their distance northeast of Tybee Island, Ga. The investigation found that the upper confining unit ranged in thickness from 0.8 to 32 ft at the four offshore sites and compared favorably with interpretations from the seismic surveys. Potentiometric heads ranged from -17.4 ft NAVD 88 for the most southwestern well (7-mile site) to 1ft NAVD 88 for the most northeastern well (15-mile site) and corresponded favorably with extrapolations from the onshore measurements reported by Peak and others (1999) and Ransom and White (1999), who reported elevations for NGVD 29. Pore water extracted from upper confining unit core samples at four sites was analyzed for chloride. Brackish to salt water was found at the top of the unit and decreased downward at all four sites (Calibogue Sound site and three offshore sites), elevated chlorides were found in the top of the Upper Floridan aquifer at two of the four sites where the aquifer was penetrated and were attributed to downward migration of modern seawater (Appendix G). The report concluded that the hydrogeologic conditions offshore of Hilton Head Island were comparable to other near-shore areas where saltwater intrusion had occurred.

As groundwater investigations progressed, both South Carolina and Georgia officials agreed that management of the Upper Floridan aquifer included reducing groundwater withdrawals to slow or stop saltwater intrusion and predicting when public supply wells would be abandoned because of increasing chloride concentration. To address these issues the GaEPD, as part of the CSSI, contracted the USGS to construct a groundwater-flow model (Payne and others, 2005) to simulate water levels in the Lower and Upper Floridan aquifers for a 42,000 square mile area of Georgia and adjacent parts of South Carolina and Florida. Later, a variable-density groundwater-flow and solute-transport model was used (Provost and others, 2006) to simulate saltwater movement. Concern focused on three recently discovered saltwater plumes mapped by SCDHEC as part of the CSSI near the northern shores of Hilton Head Island, Pinckney Island, and the Colleton River. Model simulations projected changes in the position of the 250 mg/L isochlor under varying pumping conditions for the Savannah, Ga., and Hilton Head Island, S.C., area through 2800. Simulations showed that, if pumpage for the year 2000 was uninterrupted, the three saltwater plumes would continue to move and expand across Hilton Head Island and west of the island toward Savannah. The estimated rate of lateral movement for the 250 mg/L isochlor was between 144 and 190 ft/yr and could reach Savannah in 800 years.

SCDHEC and the USGS continued to investigate the downward movement of seawater through the upper confining unit because the aquifer was overlain by about 1,200 square miles (mi^2) of sea water within the 0 ft Msl potentiometric contour of the Savannah – Hilton Head Island area cone of depression. Preliminary work started about 1996 and, beginning in 1999, pore water was extracted from selected core from the upper confining unit at offshore sites as part of the previous study by Falls and others (2005). In 2001, a temporary borehole was completed on the causeway (Ga. Highway 80) near Bull River, Ga. (Ransom and others, 2006). The site was surrounded by a large saltwater estuary between Wilmington Island and Tybee Island, Ga. Pore water was extracted at 5-ft intervals from ground surface to a depth of 200 ft at the top of the Eocene limestone. Laboratory analyses showed that the distribution of chloride concentration across the upper confining unit ranged from about 8,000 mg/L near the top to about 50 mg/L near the bottom, indicating that sea water in tidal marshes, channels, and the Atlantic Ocean was moving downward through the upper confining unit where water levels in the Upper Floridan aquifer were below mean sea level. Concentrations in the top part of the Upper Floridan aquifer (Oligocene limestone) were above background concentrations. The authors used a one-dimensional solute transport model to estimate the breakthrough times of salt water entering the top of the Upper Floridan aquifer. Model simulations estimated that, in a 382 mi^2 area where the confining unit was thin, 7.7 Mgal/d would migrate downward into the top of the Upper Floridan aquifer with a chloride concentration of 500 mg/L for times that ranged from 25 to 113 years from the year 2005. Differences in breakthrough times for this model depended on thickness of the upper confining unit and head difference across the unit for a given model cell. The model did not consider varying chloride concentration at the source area (bottom of the surficial aquifer) which in most intracoastal areas would be less than salt water nor did the model consider changes in hydraulic conductivity of the upper confining unit.

To determine the source concentration of chlorides at the bottom of the surficial aquifer, an investigation of chloride concentrations at the bottom of the surficial aquifer beneath saltwater channels and estuaries was undertaken by SCDHEC in cooperation with the SCDNR (Ransom and Park, 2011). Offshore concentration of chloride in the surficial aquifer is dependent on the degree of mixing between seawater migrating downward from overlying sources and lateral discharge of freshwater from nearby landmasses that include the mainland, Sea Islands, and barrier Islands. The study used an offshore drill platform to complete 27 temporary boreholes between Port Royal Sound, S.C., and Ossabaw Sound, Ga. Fifty-six discrete water samples were obtained while the sealed drill stem was advanced by direct push or hammer method to reach the desired sampling depth. Field analyses for specific conductance of overlying surface water showed a range between 26,700 to 55,800 µS/cm. Chloride concentrations at the bottom of the surficial aquifer unit ranged between 160 and 18,500 mg/L and generally decreased with depth and increased with distance from landmasses. The data indicated that future groundwater models designed to simulate downward migration of seawater across the upper confining unit should consider the distribution of chloride concentrations expected to at the bottom of the surficial aquifer beneath saltwater channels, estuaries, and offshore areas near the coastline.

The deep Cretaceous well had been successful as an alternative source of water supply for southern part of Hilton Head Island, but on the northern part of the Island, Hilton Head Island Public Service District No. 1 (HHIPSD#1) was also confronted with increasing water demand amid a cap on groundwater withdrawals from the Upper Floridan aquifer. To develop a solution, HHIPSD#1 contracted with Groundwater Management & Associates (GMA) to evaluate the middle Floridan aquifer as an alternative source of potable water supply for the northern part of the island: the GMA investigation produced favorable results. In 2013, SCDHEC permitted three middle Floridan wells that included R/O treatment to remove dissolved chloride, the well field was originally designed to supply 3 Mgal/d but later increased to 4 Mgal/d.

The Lower Floridan aquifer was also evaluated in Georgia as an alternative to the Upper Floridan aquifer. A test well was completed at Hunter Army Airfield, Savannah, Ga., in 2009 by the USGS in cooperation with the Department of the Army. The well was drilled to 1,168 ft bgs and open to both the Upper and Lower Floridan aquifers (Lower Floridan includes S.C.'s middle Floridan aquifer). Williams (2010) used a flow meter and packer assembly to isolate individual permeable zones during testing and conducted geophysical surveys, flowmeter surveys to determine yield of individual zones, packer-slug tests, water-quality analyses, and aquifer tests at up to 1 Mgal/d. The report concluded that the Upper Floridan aquifer supplied 83.5 percent of the total yield from five permeable zones and the Lower Floridan aquifer supplied the remaining 16.5 percent from six permeable zones. One Lower Floridan aquifer zone at 768 to 785 ft bgs produced 47 percent of the total yield from the Lower Floridan aquifer and probably corresponds to the middle Floridan aquifer in South Carolina. The test findings were comparable to those of McCollum and Counts (1964), who concluded that 70 percent of the yield was from the Upper Floridan aquifer. Following field testing, the USGS modified their steady-state regional groundwater flow model (Clarke and others, 2010) to simulate changes in drawdown in the Upper Floridan aquifer caused by leakance from pumping the Lower Floridan aquifer at Hunter Army Airfield. A second Lower Floridan aquifer well was drilled at Pooler, Ga., and the model was likewise used to simulate interaction between the two aquifers (Cherry and Clarke, 2013). The model simulations indicated that an overall increase in withdrawals is feasible if a permittee's Upper Floridan aquifer pumpage is partially reduced to offset leakage loss and water-level decline caused by Lower Floridan aquifer pumpage. The net gain in permitted capacity would depend on limitations of the model and whether GaEPD based their permit decisions on maximum drawdown in, or leakage from, the overlying Upper Floridan aquifer.

Over the years, new projects in various areas had increased the Floridan aquifer data base. These data provided a platform for Williams and kuniansky (2015) to revise Miller's (1986) hydrogeologic framework for the southeastern states. They defined the major and minor hydrogeologic and litho-stratigraphic units and zones; described new units and zones; revised parts of the regional and sub-regional hydrostratigraphic nomenclature; estimated the elevations of salt water with well-log data; and discussed the influences of geology and pumpage on groundwater behavior and salinity variation. Section (G-G') provided a regional perspective of the hydrogeologic units along the Atlantic coast from Beaufort County, S.C., to Volusia County, Fla.

The States of Georgia and South Carolina continue to work closely through their respective agencies, GaEPD and SCDHEC, to manage by reducing groundwater withdrawals in the Upper Floridan aquifer by conservation and alternative sources. The City of Savannah in cooperation with GaEPD has decreased permitted withdrawals from the Upper Floridan aquifer to 1950 levels through conservation and increased use of surface water. Farther south, the Town of Tybee Island, Ga. began construction of a deep well in 2015 to evaluate the feasibility of R/O treatment of the Cretaceous aquifer system if their Upper Floridan aquifer wells become contaminated with salt water. SCDHEC continues to hold Hilton Head Island's permitted withdrawals from the aquifer at 9.7 Mgal/d since 1998.

Acknowledgements

The authors wish to acknowledge the GAEPD for funding the construction and instrumentation of 34 monitor wells and the time-domain electro-magnetic surveys in selected areas. The Beaufort-Jasper Water and Sewer Authority; the Melrose Company; the Haig Point Corporation; the South Island Public Service District; the Hilton Head Public Service District Number 1; and the Broad Creek Public Service District are recognized for their support and funding to purchase eleven data-loggers.

Appreciation is extended to those who permitted access to their property for the purposes of drilling monitoring wells and establishing monitoring stations, including the Hilton Head Plantation Home Owners Association; the Pinckney Island National Wildlife Refuge; Moss Creek Plantation; Colleton River Plantation; Hank and Pete Cram; Beaufort County; Palmetto Bluff Corporation; Hilton Head Island Public Service District No. 1; Haig Point Development Corporation; Melrose Corporation; the

Beaufort-Jasper Water & Sewer Authority; Allen Ulmer; Daniel Dreissen; and Hilton Head Plantation Golf Course; and to Paul Vogel who assisted field personnel with monitoring and for securing local funding and site location for an additional monitoring well at Haig Point Plantation, Daufuskie Island, S.C.

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METHODS

Test well construction

As part of this investigation, 51 Upper Floridan aquifer test wells were constructed between 1997 and 2015 in southern Beaufort and Jasper Counties, S.C., and Chatham County, Ga. (Appendix B). Test-well construction was accomplished by mud-rotary drilling techniques to penetrate the surficial sediment and upper confining unit to the top of the Upper Floridan aquifer. Afterwards, the borehole was reamed to 8 inches and 4 or 4 ½-inch (ID) PVC well casing was lowered to the top of the aquifer with centralizers installed at 20-foot intervals. The casing was sealed with a continuous pressure grout installed by lowering a tremie pipe to the bottom of the casing with a pressure seal secured at the top of the well casing. Grout was pumped through the tremie pipe and returned through the well annulus to the surface; the casing was then flushed with water to remove excess grout and pressure sealed for 24 to 48 hours. In some cases, a plug was inserted into the casing

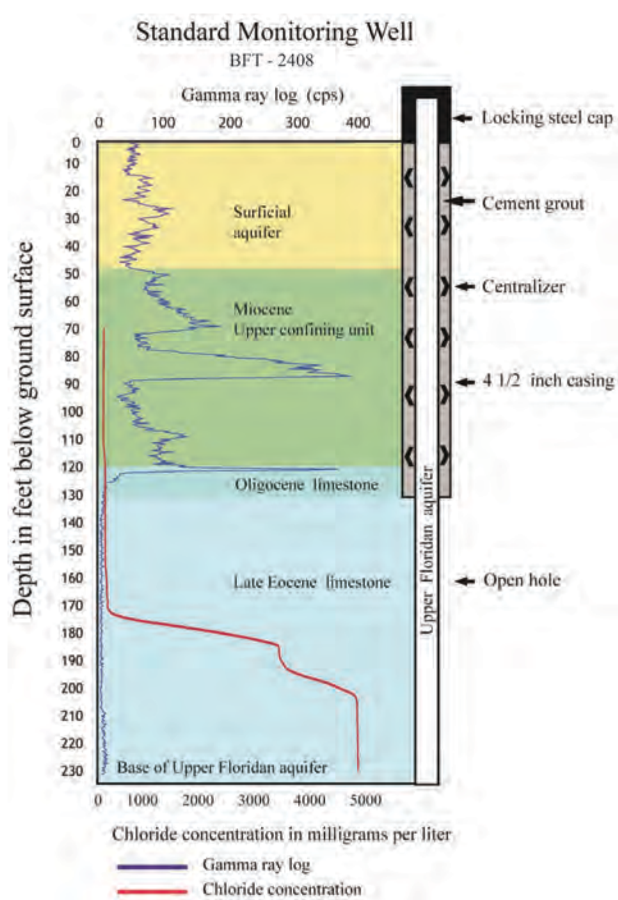


Figure 4. Well BFT-2408 showing standard monitoring-well construction, natural gamma-ray log, and chloride concentration computed from specific-conductance

behind the grout and advanced by water pressure to the bottom of the well casing. Prior to advancing the borehole beneath the casing, measurements were taken inside the casing to determine if the grout had remained outside the casing. A 4.5-inch open borehole advanced to the bottom of the Upper Floridan aquifer completed the well (fig. 4).

Data collection

Data used in this investigation were obtained from new test wells, published reports, and well records on file with SCDHEC, SCDNR, and the USGS. For each test well, electrical-resistivity and natural gamma-ray logs were completed in the borehole to identify the thicknesses of major strata and to verify that the well casing was positioned at the top of the Ocala Limestone (late Eocene). A measuring-point elevation was surveyed at the wellhead of each test well completed for this project (Appendix B), with reference to Msl defined as 0 ft, to an accuracy of 0.01 ft NGVD 29 prior to installing monitoring probes. The probes initially recorded hourly measurements of specific conductance at the bottom of the aquifer and water levels. Hourly specific-conductance measurements were eventually discontinued and replaced with vertical specific-conductance profiles that were conducted through the full thickness of the Upper Floridan aquifer for selected depths. Depth of measurements was accomplished with an optical depth reader installed on a cable reel with an accuracy of 0.1 ft. The accuracy of conductance measurements was generally less than 10 µS/cm. For this study, most chloride concentrations were computed from specific conductance data from Landmeyer and Belval (1996) who graphed the relationship between chloride concentrations and specific conductance for the Upper Floridan aquifer (fig. 5) in the study area. Based on their graph, the former SCWRC used a multiplier of 0.35 to compute estimated chloride concentrations from specific-conductance measurements for values greater than 1,000 µS/cm (Gawne and Crouch, SCWRC file data), the multiplier was used also by Provost and others (2006). Extraction of pore water for chloride analysis was accomplished on 5 test wells. These wells were completed without drilling fluid by using the roto-sonic drilling method to advance the borehole with continuous cores sealed in plastic liners to prevent contamination. Pore water was extracted at selected depths from near surface to total depth of the borehole and a laboratory analysis was obtained for chloride concentration. Continuous water-level recorders are maintained for selected wells as part of SCDHEC's program with the USGS and SCDNR who also maintain continuous water-level monitoring for wells in the study area.

Environmental tracers

Groundwater samples were collected in 25 monitor wells to determine the ages of saltwater at the bottom of the Upper Floridan aquifer during 2004–2005 and 2009 sampling events. The specific

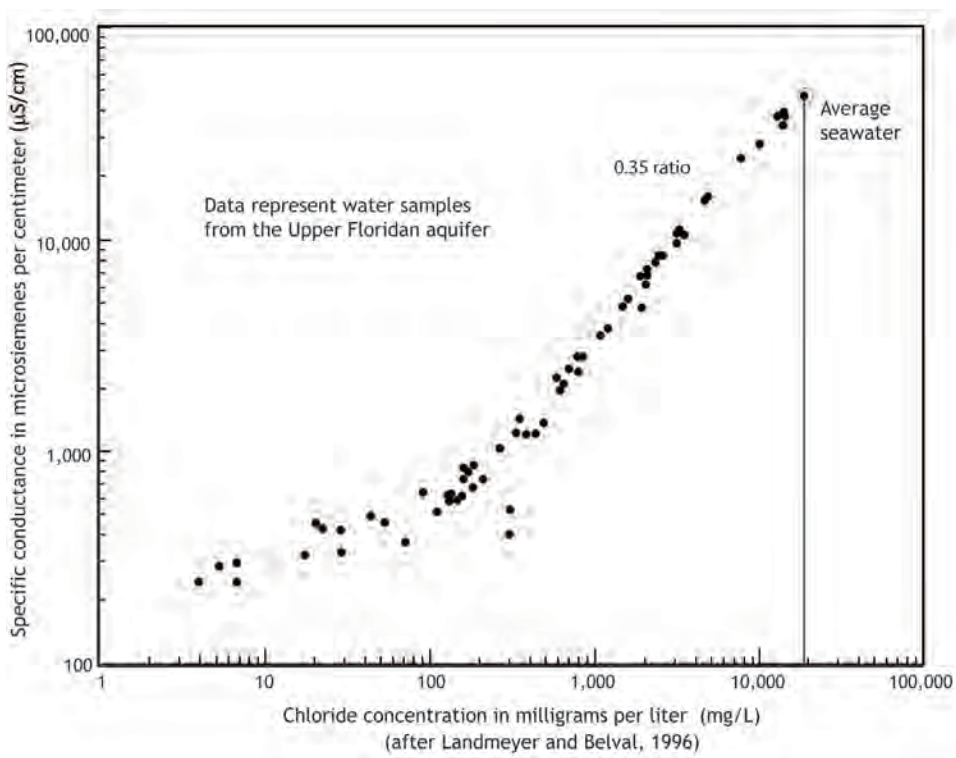


Figure 5. Chloride concentration vs. specific conductance in the Upper Floridan aquifer (Landmeyer and Belval, 1996).

conductance of seawater was measured in four surface-water sample sites in Port Royal Sound and nearby channels and was compared to groundwater samples from the bottom of the aquifer. Samples were analyzed for physical and chemical properties (temperature, specific conductance, dissolved oxygen, etc.), and tested for stable isotopes (as δ^2H and $\delta^{18}O$), tritium (^3H), and chlorofluorocarbon (CFC). Groundwater levels were measured with an electrical tape prior to sample collection. Unfiltered groundwater samples at the bottom of the aquifer were collected with a peristaltic pump and Nylon® tubing where the depth to water was less than 30 ft below land surface and with a Fultz® submersible pump and dedicated Teflon® tubing where the depth to water was greater than 30 ft. USGS sampling protocols (USGS National Field Manual, variously dated) were followed for the low-flow sampling process. The pump discharge was monitored in a flow-through cell for temperature, turbidity, specific conductance, dissolved oxygen (DO), and pH with a YSI@ (Yellow Springs Instruments) 6920 multi-parameter sonde: samples were bottled after water quality stabilized. The multi-parameter sonde was calibrated each day prior to sampling, and pH standards of 4 and 7 were used. The four surface-water samples were collected by attaching a weight to the end of Nylon® tubing and throwing the weight as far as could be achieved from the bank. The tubing was attached to the peristaltic pump and sample collection was conducted as previously described for groundwater. To reduce the possibility of cross-contamination, the pump was decontaminated between samples using a soapy water scrub and rinses with tap water, deionized water, and methanol, after which the equipment was given time to dry. The pump wiring was decontaminated in the same manner, but without the methanol rinse except for wiring nearest the pump. The Teflon® tubing was discarded between wells.

Water samples for δ^2H and $\delta^{18}O$, ^3H, and CFC's analysis were collected only after the physical properties and chemical constituents of temperature, DO, specific conductance, and pH had stabilized in the flow-through cell. Samples were collected in 60 mL glass bottles and sealed with a polyseal cap and shipped at ambient temperatures to the USGS Reston Stable Isotope Laboratory in Reston, Va. Ground- and surface-water samples for ^3H analysis were collected in 250 milliliter (mL) polyethylene bottles and capped with a polyseal cap. The ^3H concentration was analyzed by electrolytic enrichment and gas counting by the University of Miami Tritium Laboratory (Miami, Fla.). The method reporting level (MRL) was 0.30 picocuries per liter (pCi/L). Groundwater and surface-water samples collected for CFC and dissolved gas analysis were required to be collected such that the samples did not contact air during sampling. To accomplish this, 250 mL glass vials were filled beneath a column of groundwater pumped from the well into a deep bucket. The sample tubing, made of Nylon® to eliminate contact of the sample with air, was placed in each vial under water, allowed to overflow; afterwards, each sample vial was capped with a metal screw cap with an aluminum foil liner, also under water. Sample vials were then removed from the bucket, checked for the presence of air bubbles, and sealed with electrical tape. The sample bottles for CFC analysis were stored on ice and shipped directly to the USGS Reston Chlorofluorocarbon Laboratory in Reston, Va. The concentrations of CFCs, in picograms per kilogram (pg/kg) detected in the samples were used to interpret the recharge date of the sample, based on a piston-type flow model (for groundwater samples) according to Plummer and Friedman (1999).

SCDHEC groundwater model

The South Carolina Department of Health and Environmental Control constructed a three-dimensional variable-density groundwater-flow and solute-transport model using Visual MODFLOW. The model was designed to evaluate the potentiometric surface and saltwater intrusion in the Upper Floridan aquifer from 1885 through 2050 for the Savannah, Georgia and Hilton Head Island, South Carolina area (Appendix J). The model was constructed with a grid consisting of ¼ mile cells that extended through thirty layers representing the surficial aquifer, upper confining unit, Upper Floridan aquifer, middle confining unit, and the middle Floridan aquifer. Data input into the model included data collected as part of this study and that of previous investigations. Water-use data were taken from early reports, by permitted groundwater users, estimates for unpermitted water use for the Upper Floridan aquifer in Georgia and South Carolina, and permitted water use for middle Floridan wells in South Carolina.

GEOLOGY

The study area lies in the southern part of the Lower Coastal Plain of South Carolina and adjoining parts of Georgia; here, the sedimentary deposits are superimposed over the Southeast Georgia Embayment (Toulmin, 1955; Stringfield and Legrand, 1964; Colquhoun and Johnson, 1968; Huddlestun, 1988). The sequence of sedimentary deposits is part of a stratigraphic wedge that extends from the fall line where the sediment are only a few feet thick, to the shoreline where the sediment thickness exceeds 4,000 ft in southern South Carolina (Siple, 1959). Well BFT-2255 on the southern part of Hilton Head Island penetrated about 3,800 ft of Coastal Plain sediment (Temples and Waddell, 1996). The sediment in the study area range from late Cretaceous to Holocene; however, for this investigation only sediment from the early Eocene to Holocene are discussed. In ascending order, they are: the early, middle, and late Eocene, the Oligocene, the Miocene, and the Holocene and Plio-Pleistocene series (fig.6). The sediment were deposited in a marine environment influenced by transgressive and regressive shorelines that later were subjected to tectonic uplift and erosion (Clarke and others, 1990; Weems and Edwards, 2001).

The stratigraphic relationship of sediment has been the subject of numerous investigations that utilized geologic core for lithologic descriptions, geophysical logs to determine contacts between geologic strata, and fossil assemblages to assign geologic ages to sediment.

Eocene Series

The Eocene lithologic units in southern South Carolina and adjoining parts of Chatham County, Ga. considered in this investigation include the early Eocene Fishburne Formation equivalent to the Oldsmar Formation in Georgia, the middle Eocene Santee Limestone equivalent to the Avon Park Formation in Georgia (Clarke and others, 1990), and the late Eocene (Jackson age) Ocala Limestone (Herrick, 1961). The Ocala limestone is time-equivalent to the Parkers Ferry and Harleyville members of the Cooper Formation in South Carolina. Generally, the carbonate sediment consists of bioclastic limestone; silty to clayey limestone; calcarenite; calcilutite and dolomite. The Eocene sediment attain a combined thickness of about 1,100 ft in the southwestern part of the study area near Fort Pulaski (fig. 1) (Clarke and others, 1990). The sediment were deposited in warm, shallow, open-marine waters of a carbonate-bank environment (Miller, 1986).

Early (Lower) Eocene Oldsmar Formation

The early Eocene Oldsmar Formation in Georgia was described by Miller (1986) as a glauconitic limestone and dolomite. Three well sites drilled in the Savannah area near the South Carolina border penetrated the early Eocene, and Clarke and others (1990) described the sediment as being consistent with the Oldsmar Formation. They reported thicknesses of 120 ft and 180 ft at the Hutchinson Island and Fort Pulaski sites, respectively. In southern South Carolina, few wells have penetrated the early Eocene. Well BFT-2473, located about midway on Hilton Head Island, was drilled by the USGS as an open borehole to a depth of 1,248 ft bgs to obtain geologic core; here, indurated calcified sediment was encountered from about 700 ft bgs to the bottom of the borehole.

Middle Eocene Santee limestone

The middle Eocene Santee Limestone in South Carolina is time-equivalent to the Avon Park Formation in Georgia. The Santee Limestone was originally assigned to the late Eocene by Cooke (1936) and later to the middle Eocene (Cooke and MacNeil, 1952: Pooser, 1965). The middle Eocene sediment in Georgia consist mostly of glauconitic dolomite and limestone and unconformably overlie the early Eocene Oldsmar Formation (Miller, 1986). Clarke and others (1990) report that the basal sediment of the Avon Park Formation are difficult to distinguish from the underlying early Eocene Oldsmar Formation because the lithology of the two units are similar but can be differentiated on the basis of fossil evidence. In Chatham County, Ga., at the Hutchinson Island and Fort Pulaski test sites, Clarke and others (1990) report that the thickness of the middle Eocene sediment are 700 and 540 ft, respectively. In southern South Carolina, the Santee Limestone was described by Hughes and others (1989) from cuttings and cores collected from four wells in the vicinity of Port Royal Sound as a yellowish-gray, glauconitic and fossiliferous calcarenite (with fine-grained interstitial calcite) or calcilutite with sparse biota that consist of bivalves, foraminifera, and bryozoa. Most samples were poorly consolidated and interbedded with thin layers of hard limestone. The upper part of the Santee Limestone is more permeable: Gawne and Park

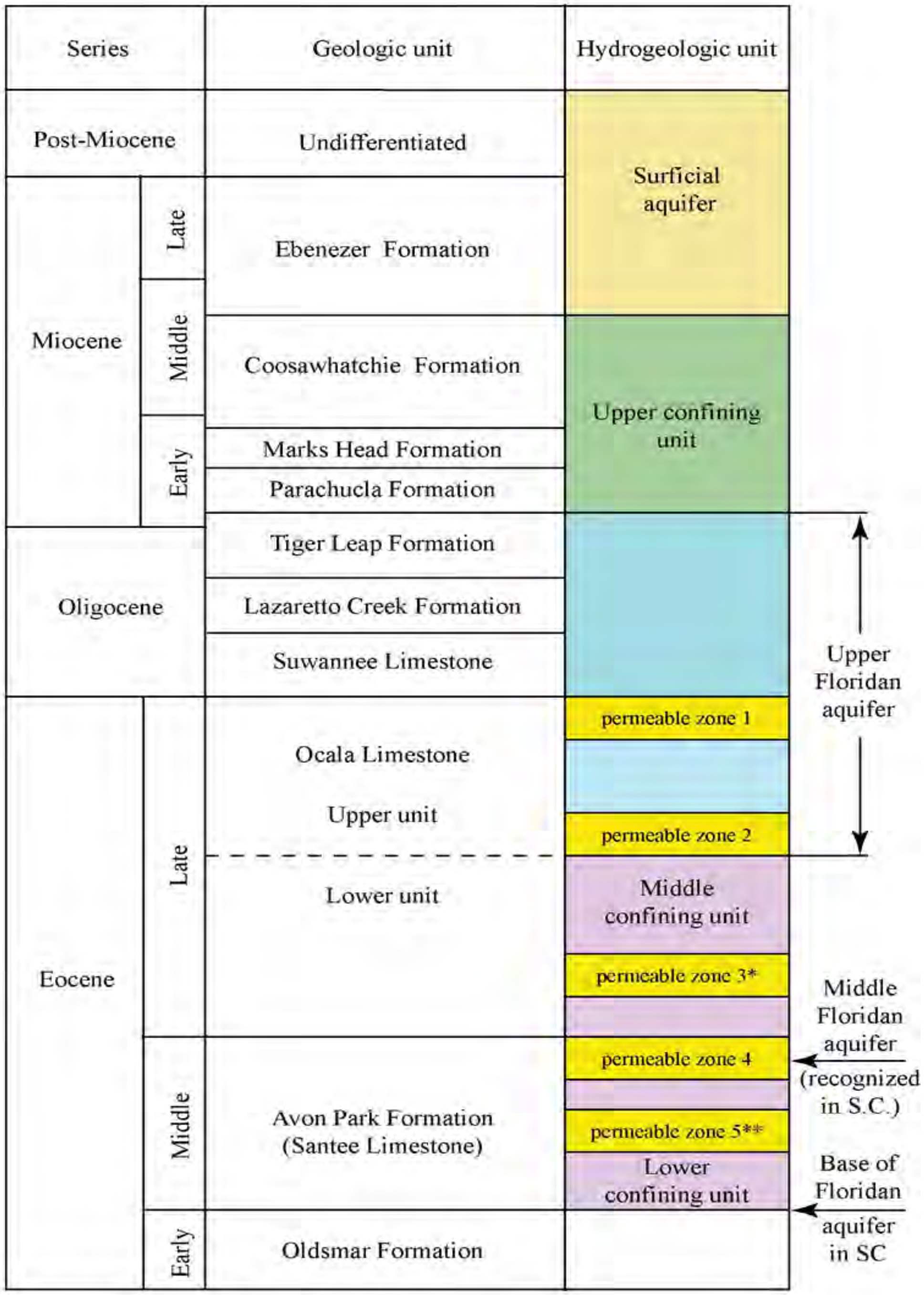


Figure 6. Stratigraphic and hydrogeologic column for the study area (Counts and Donsky (1963); McCollum and Counts (1964); Huddlestun (1988); Weems and Edwards (2001); Williams and Gill (2010); Williams and Kuniansky (2016). *Reported to partially extend into South Carolina only by McCollum and Counts (1964). **Not reported in South Carolina.

(1992) describe the top 30 to 60 ft as originally consisting of whole shell fragments (mainly gastropods, bivalves, and bryozoans) in a matrix of lime-mud. They hypothesized that the original lime mud, consisting mostly of aragonite, was dissolved by freshwater flow thereby leaving a hard, permeable limestone with a high proportion of interconnected cavities. The surface elevation of the Santee Limestone is about -400 ft Msl near Parris Island and dips to the southwest where the elevation is about -600 ft Msl: thickness increases from Parris Island to the south-southeast and ranges from 300 ft to 500 ft (Hughes and others, 1989: Gawne and Park, 1992).

Late (Upper) Eocene Ocala Limestone

The late Eocene Ocala Limestone (Jackson Group) was first described and named by Dall and Harris (1892) from exposures in Ocala, Florida. Puri (1953, 1957) raised the Ocala Limestone to group status, recognizing its component formations based on foraminiferal fauna. The Ocala Limestone has since been reduced to formational status (Scott, 1991) in accordance with the North American Commission on Stratigraphic Nomenclature (1983). The Ocala Limestone can be found in the subsurface throughout most of Florida, southeast Alabama, the Georgia Coastal Plain, and southernmost South Carolina (Furlow, 1969; Miller, 1986, p. b30). The limestone overlies the Avon Park Formation in

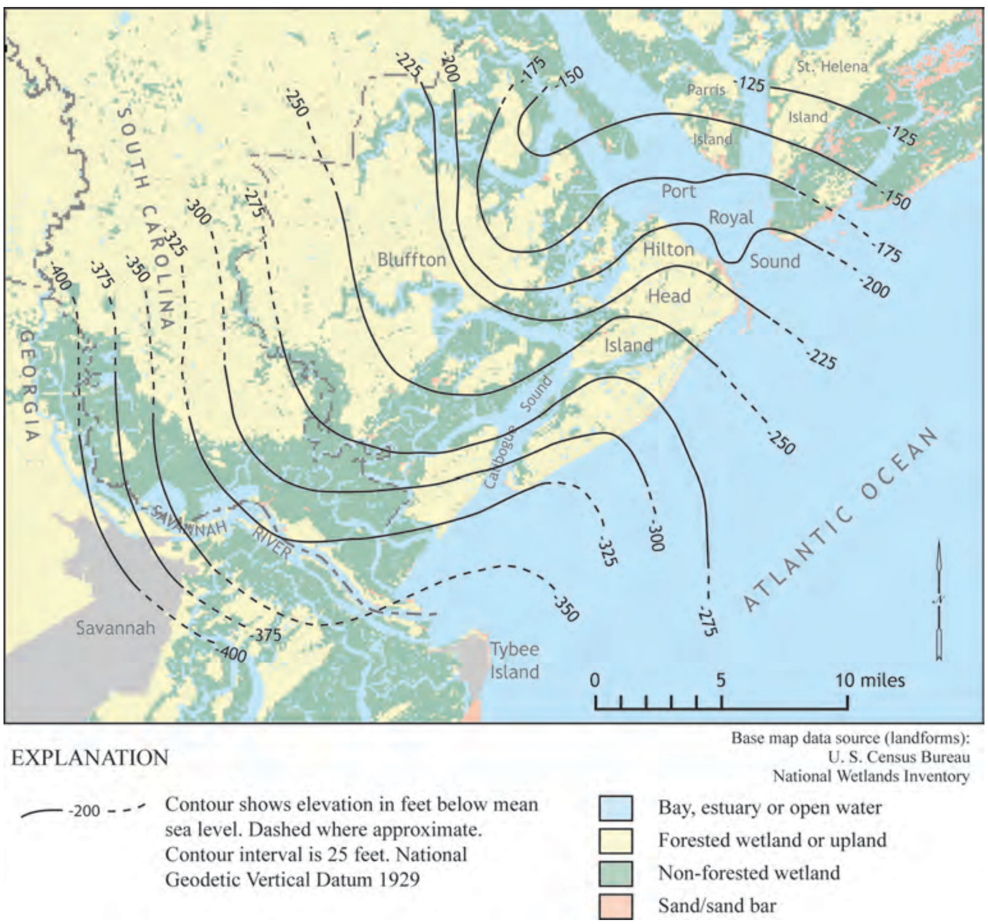


Figure 7. Structure contours showing top of lower unit of the late Eocene Ocala Limestone near Savannah, Ga., and Hilton Head Island, S.C.

Georgia and Santee Limestone in South Carolina. Based on lithology, geophysical logs, and hydrologic properties, Counts and Donsky (1963) divided the Ocala Limestone into an upper and lower unit in the Savannah area. The two units are distinguished in adjoining parts of South Carolina with natural gamma-ray logs (SCDHEC files) and geologic core.

The lower unit of the Ocala Limestone in the Savannah area was first described by Counts and Donsky as primarily a buff granular calcitized limestone, fossiliferous throughout, containing thin layers or stringers of dense pale-blue limestone and sandy, silty, or argillaceous limestone or marl, with glauconite present near the bottom of the unit. Near Hilton Head Island, the unit was described by Gawne and Park (1992) from geologic core and drill cuttings. They described the unit to consist of a matrix of silty, clayey, glauconitic limestone interbedded with fine calcarenite and calcilutite; identifiable macrofossils are uncommon; the sand-size shell fragments and microfossils are worn and altered leaving identification difficult; and most of the calcarenite and calcilutite are poorly consolidated and interbedded with thin layers of hard limestone. About 15 miles north of Hilton Head Island, Rine (2003) studied cores of the lower unit of the Ocala Limestone taken from well BFT-2370 at the Marine Corps Air Station in northern

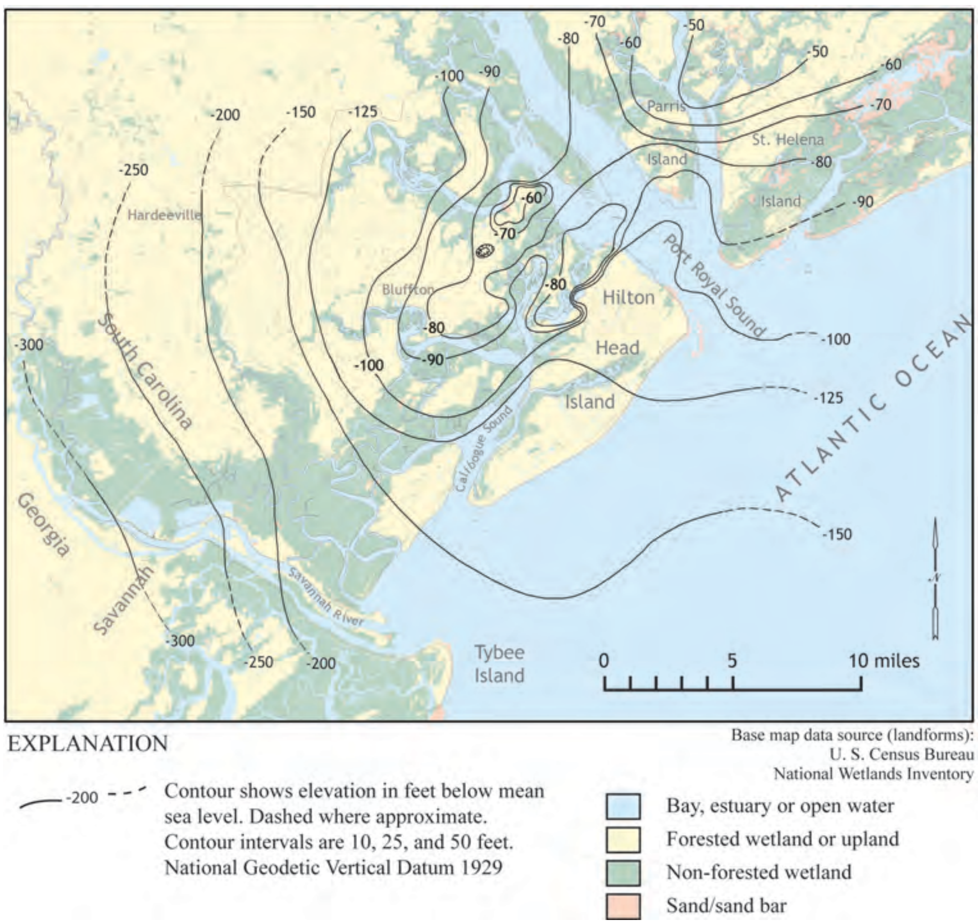


Figure 8. Structure contours showing top of the upper unit of the late Eocene Ocala Limestone near Savannah, Ga., and Hilton Head Island, S.C.

Beaufort County. Based on petrographic examination, he described the sediment as a packstone consisting primarily of foraminiferal tests and shell fragments with micrite infilling of intergranular spaces. The contact between the lower unit and the upper unit is easily distinguished by the natural gamma-ray log signatures that average between 10 and 25 cps and 2 and 10 cps (counts per second), respectively. Clarke and others (1990) reported that the relatively high radiation present in what they identified as the lower part of the Ocala Limestone is caused by the presence of Potassium 40 in the glauconite. Natural gamma-ray logs used to construct a structure map of the lower unit show the unit at an elevation of about -70 ft Msl a few miles northeast of Parris Island and dipping to about -350 to -290 ft Msl in the southwestern part of the study area (fig. 7). The thickness of the lower unit was reported by Gawne and Park (1992) to range from 220 ft northeast of Hilton Head Island to 300 ft toward the southwestern part of the island.The upper unit of the Ocala Limestone in the study area has been described by Counts and Donsky (1963) to consist of white to grey limestone, somewhat calcitized, crystalline, and abundantly fossiliferous. Certain zones consist almost entirely of bryozoan fragments, echinoid spines, sponge spicules, and foraminifers; there are thin zones of very dense limestone consisting of macroshells and fragments that have been compacted, cemented, contain numerous solution channels and, in some cases, cavities. Deposition occurred in a near-shore, shallow-marine environment where higher energy and active biota contributed to increased permeability of the unit. Geophysical logs (SCDNR files) indicate that the highest documented elevation of the upper unit is about -20 ft Msl near the western side of Lady's Island 8 miles north of Parris Island, S.C. (Hayes, 1979, fig. 10); here, the unit has a thickness of about 60 ft. Farther to the northeast, the upper unit thins and is generally absent north of the Coosaw River and St. Helena Sound. To the southwest of the study area between Hilton Head Island and the Savannah River, the upper unit dips downward and thickens to about 100 ft. Near Savannah, Ga., geophysical logs indicate the surface elevation of the unit is about -300 ft Msl and is about -180 ft Msl near Tybee Island, Ga. (fig. 8).

Oligocene Series

The Oligocene limestone unconformably overlies the late Eocene Ocala Limestone (Counts and Donsky, 1963) in the study area. In southeastern Georgia, Oligocene sediment are, from oldest to youngest, the early Oligocene Suwannee Limestone (Cooke and Mansfield, 1936), the early Oligocene Lazaretto Creek Formation (Huddlestun, 1993) and late Oligocene Tiger Leap Formation (Weems and Edwards, 2001). To the northeast of Savannah, Ga., the Oligocene sediment dip upward toward the crest of the Beaufort Arch until the unit pinches out northeast near Port Royal Sound (fig. 9). Huddlestun identified the Lazaretto Creek Formation in northeast Georgia and believed the formation was the age equivalent of the lower Oligocene Suwannee Limestone in Florida. Weems and Edwards (2001) later concluded that the Lazaretto Creek Formation was early Oligocene but slightly younger than the Suwannee Limestone. They also recognized a late Oligocene stratum in Huddlestun's Tiger Leap member within the overlying Miocene Parachucla Formation. Based on faunal assemblages, Weems and Edwards (2001) removed the Tiger Leap Member from the Parachucla Formation and raised it to formation status with four unnamed members within the Hawthorn Group (fig. 6).

Hayes (1979) considered the Oligocene limestone to be the facies equivalent of the Cooper Marl (Malde, 1959) and described it as a “very sandy, calcareous, slightly to moderately phosphatic clay to a silty, sandy, phosphatic, clayey limestone to a light gray to white limestone.” Ward and others (1979) determined that the Ashley member of the Cooper Formation northeast of the study area was equivalent to the Oligocene sediment in the study area. They described the Oligocene limestone in the study area of South Carolina to consist of “calcareous, clayey, very fine quartz sand containing abundant glauconite and phosphate.” The late Oligocene Tiger Leap and Lazaretto Creek Formations and the Suwannee Limestone were traced from the Tybee Island reference site to four offshore tests well sites southeast of Hilton Head Island and a fifth site in Calibogue Sound (Falls and others, 2005).

Figure 9. Structure contours showing top of the Oligocene limestone near Savannah, Ga., and Hilton Head Island, S.C.

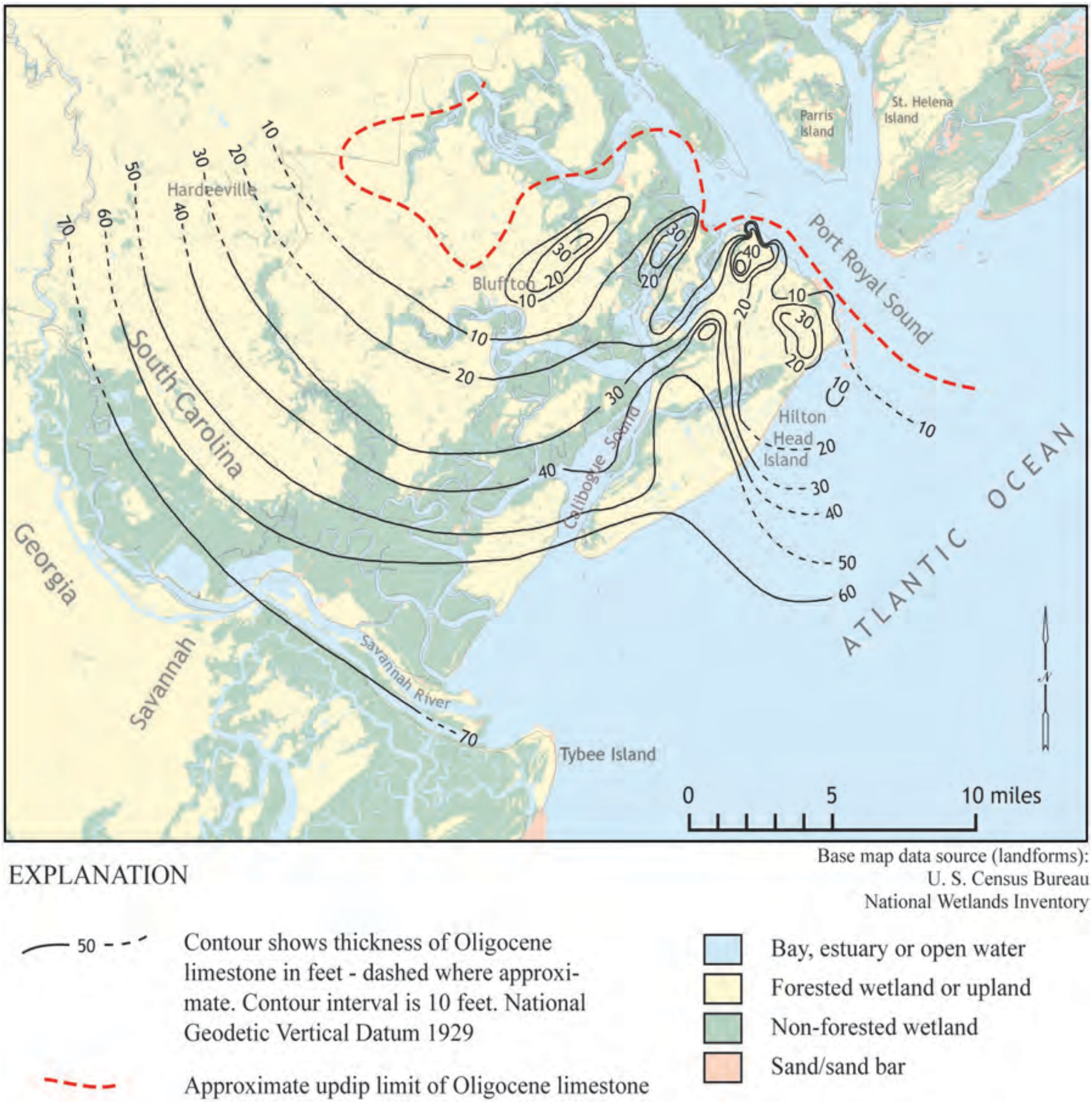


Figure 10. Isopach map showing thickness of the Oligocene limestone near Savannah, Ga., and Hilton Head Island, S.C.

However, the Oligocene limestone throughout much of the project area is undifferentiated.

The Oligocene limestone can be identified from geologic samples or by natural gamma-ray log signatures as reported by Hayes (1979), Clarke and others (1990), Weems and Edwards (2001), Falls and others (2005), and Ransom and others (2006).

Natural gamma-ray logs are used to identify the Oligocene limestone bottom on a signature of 15 to 25 cps (Note: drilling fluid can diminish the Oligocene signature). By contrast, the overlying Miocene sediment have a signature of about 200 cps at the bottom of the overlying upper confining unit (Parachucla Formation in Georgia, or the Marks Head Formation in South Carolina), and the

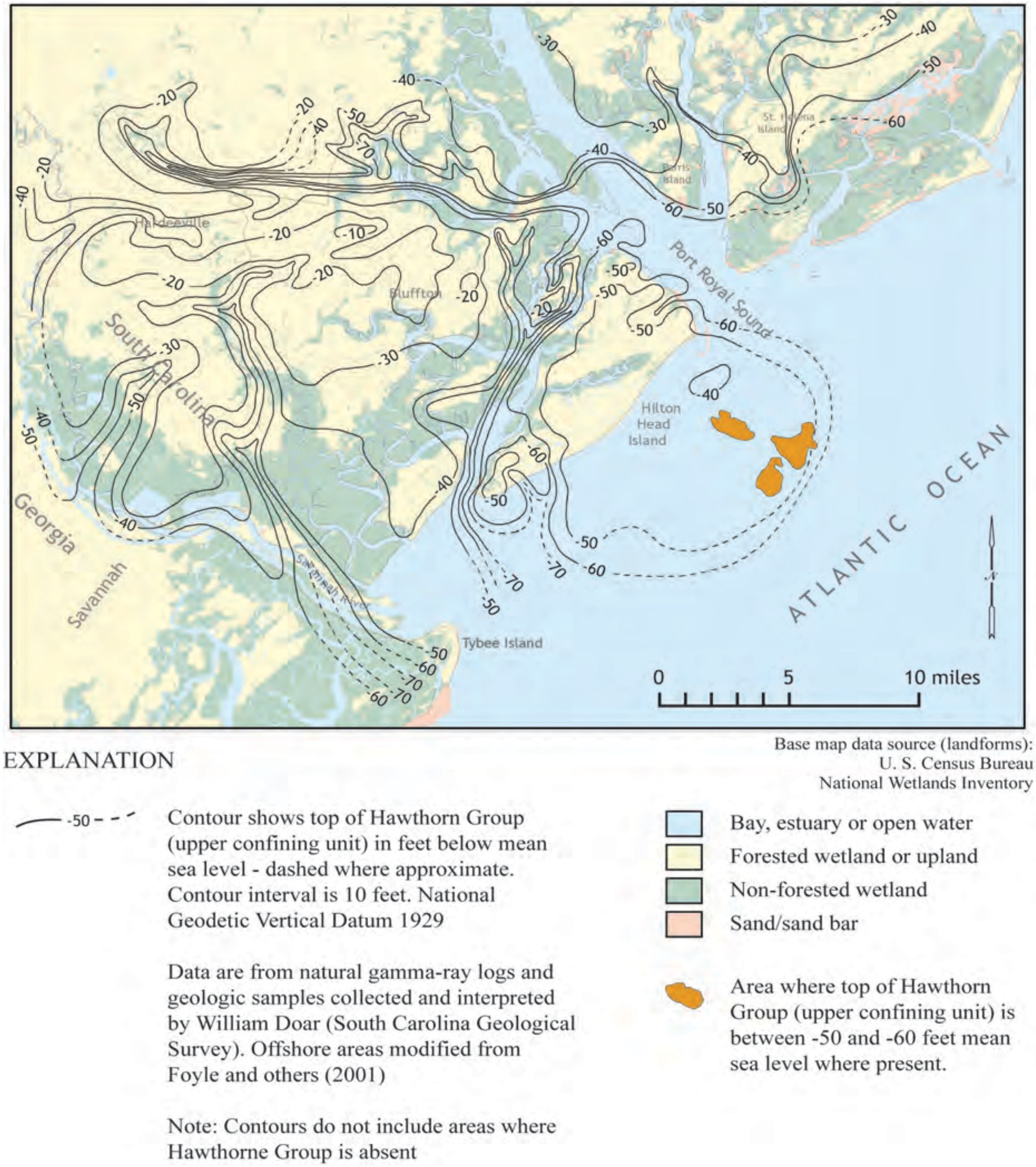


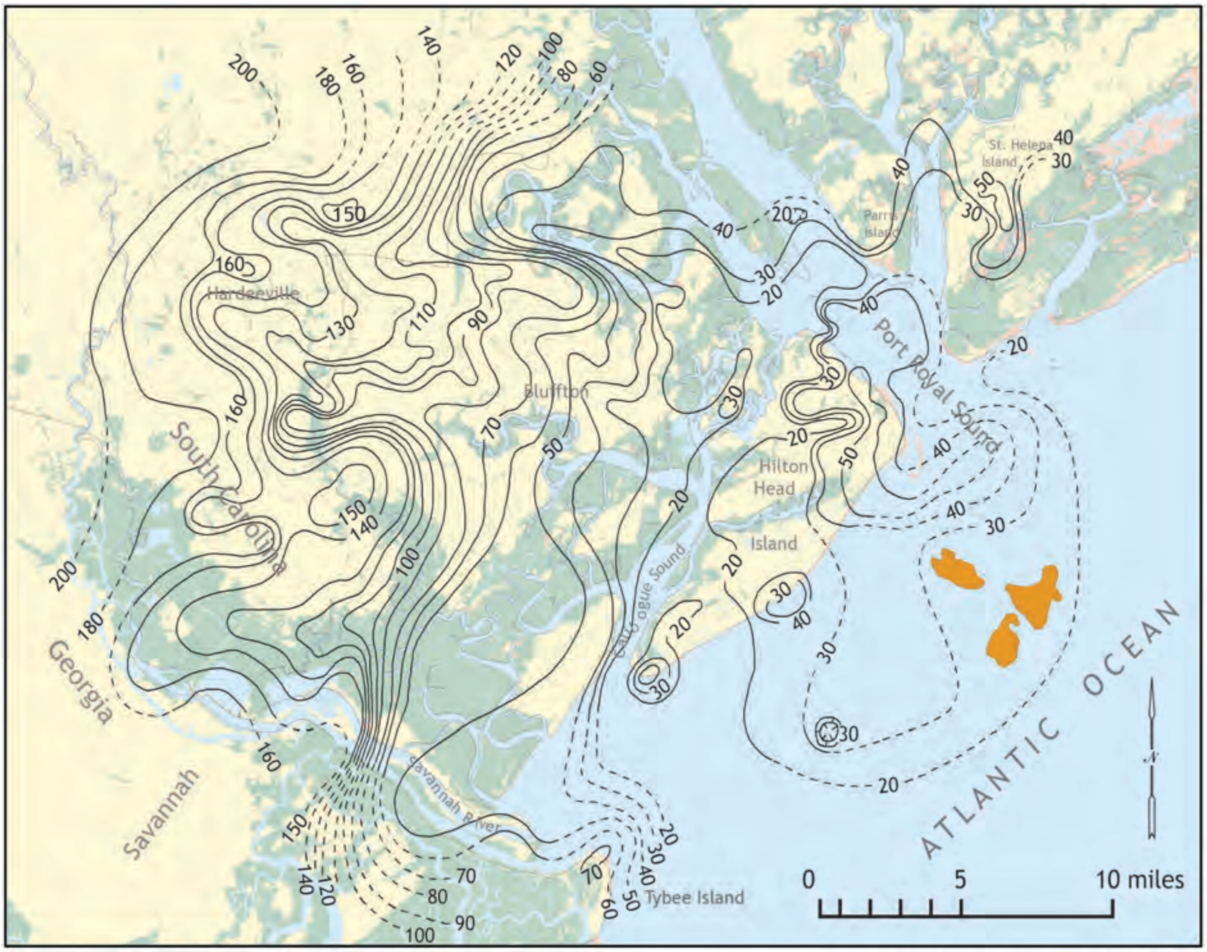
Figure 11. Structure contours showing top of the Hawthorn Group near Savannah, Ga., and Hilton Head Island, S.C.

underlying Eocene limestone generally has a gamma-ray signature of less than 10 cps. The structure map (fig. 9) for the Oligocene limestone was constructed using gamma-ray logs and shows he surface elevation near Savannah at about -200 ft Msl; to the northeast toward Beaufort, S.C., the sediment slope upward and the surface elevation ranges from -60 to -100 ft Msl near the northern part of Hilton Head Island. Near Savannah, Ga., the Oligocene sediment have a maximum thickness of about 80 ft but thin northeastward and pinch out near Port Royal Sound (fig. 10). Lucy McCartan (USGS) inspected cores taken from test wells beneath Port Royal Sound and reported 1 to 2 ft of possible Oligocene section at only one of nine well sites (written communication to B.W. Hughes, 1984).

Miocene Series

The Hawthorne (Hawthorn) Formation was first recognized by Dall (1892) for Miocene exposures near Hawthorne, Fla., that he referred to as Hawthorne beds; and later, Madison and Clapp (1909) raised the rank of Hawthorne beds to Hawthorne Formation. Cook (1936, page 101) extended the name to lower Miocene sediment in southern South Carolina. Later, the Hawthorn Formation was subdivided into three members identified in descending order as the Coosawhatchie clay (Heron and others (1965), Marks Head (Marks Head Marl; Sloan, 1908), and Parachucla (Parachucla marl and shale; Sloan, 1908). Huddlestun (1988) revised the stratigraphic framework of Miocene sediment by raising the Hawthorn Formation to group status in Georgia and raising the members of the Hawthorn Formation to formation status with several members. Hence, the Hawthorn Group in Georgia, beginning with the youngest deposits, was comprised of the middle Miocene Coosawhatchie Formation, to include the Ebenezer Member, the Berryville Clay Member, and the Tybee Phosphorite Member; the early Miocene Marks Head Formation; and the earliest Miocene Parachucla Formation, to include the Porter Landing and the Tiger Leap Members. Weems and Edwards (2001, fig. 2) followed Huddlestun's stratigraphic nomenclature with the following exceptions: (1) the Ebenezer Member of late Miocene was removed from the middle Miocene Coosawhatchie Formation and raised to formation rank within the Hawthorn Group to include five unnamed members, (2) the early Miocene Marks Head Formation was recognized to include three unnamed members and, (3) the Tiger Leap Member of latest Oligocene to earliest Miocene was removed from the overlying Parachucla Formation of earliest Miocene and raised to formation rank within the Hawthorn Group to include four unnamed members, and (4) the Porters Landing Member of the Parachucla Formation was abandoned (fig. 6).

In southern South Carolina and adjoining parts of Georgia it is difficult to distinguish the lithology of the Miocene formations where more than one exists, but the sediment comprising the dominant Marks Head Formation generally can be recognized by light- to dark-olive green clayey to silty sand and sandy to silty clay with varying amounts of mica, sparse fish scales, and phosphatic sand. Sand and phosphatic sand may range from very fine to coarse. Heron and others (1965) described the Coosawhatchie clay (Berryville Clay Member) west of the study area in Jasper County, S.C., as light yellow-grey to light-blue clay with a "cheesy" texture characterized by a zone of diatomaceous earth; Huddlestun (1988) provided a more detailed lithology of the middle Miocene Berryville Clay Member and discussed the thickness and lateral extent from Jasper County, S.C., to the coastal area of southern Beaufort County, S.C., throughout the Georgia Coastal Plain, and along the continental shelf to northeast Florida. Clarke and others (1990) describe the middle Miocene sediment beneath the Coosawhatchie clay in Georgia as generally composed of carbonates, clay, very-fine clayey to silty sand, and sandy to silty clay, with various amounts of fine-to medium-, phosphatic sand grains: minor constituents include very fine mica, dolomite rhombs, and shark teeth. They reported that the sediment were deposited in a nearshore marine environment during three transgressive-regressive episodes and that the beginning of each episode can be identified with natural gamma-ray log signatures that they designated as markers C, B, and A. The Parachucla, Marks Head, and Coosawhatchie Formations, as recognized by Woolsey (1977) and Huddlestun (1988), correlate with Markers C, B, and A, respectively. Each episode formed a geologic unit that progressively grades upward from (C) a basal carbonate layer, to (B) a clay layer, and to (A) a clastic sandy layer. Offshore seismic surveys conducted by Foyle and others (2001) found that, where present, gamma-A and gamma-B marker horizons are typically associated with indurated high-phosphate carbonate beds that generally lie just above the Miocene-A and Miocene-B basal unconformities, respectively (Furlow. 1969; Clarke and others, 1990).



EXPLANATION

Base map data source (landforms):
U. S. Census Bureau
National Wetlands Inventory

50 — Contour shows thickness of Hawthorn Group (upper confining unit) in feet - dashed where approximate. Contour intervals are 10 and 20 feet. National Geodetic Vertical Datum 1929

Data are from natural gamma-ray logs, geologic core, and published reports. Offshore areas modified from Foyle and others (2001)

- Bay, estuary or open water
- Forested wetland or upland
- Non-forested wetland
- Sand/sand bar
- Area where Hawthorn Group (upper confining unit) is between 0 and 10 feet thick.

Figure 12. Isopach map showing thickness of the Hawthorn Group near Savannah, Ga., and Hilton Head Island, S.C.

In the study area, the sediment comprising the Hawthorn Group may be represented by one or more of the following: the late Miocene Ebenezer Formation, the middle Miocene Coosawhatchie Formation, the early Miocene Marks Head Formation, and the earliest Miocene Parachucla Formation. The surface of the Hawthorn Group was altered in the study area by post-depositional erosion and reworking of the sediment during episodes of a regressive and advancing sea. Paleochannels formed during times of lower sea level thinned, and in some areas completely removed the sediment, leaving only the underlying Oligocene or Eocene limestone beneath the Plio-Pleistocene sediment that served as a source of infill. Paleochannels were identified during offshore seismic surveys near Port Royal Sound; southeast and east of Hilton Head Island (Duncan, 1972; Foyle and others, 2001); and near the Savannah River between the river mouth and the City of Savannah, Ga. (U.S. Army Corps of Engineers, 1998). Toward the crest and flanks of the Beaufort Arch northeast of Savannah, lack of deposition also reduced the thickness of the Miocene sediment. Erosion of the Hawthorn Group is apparent in geologic cores recovered from seven offshore test wells reported by Falls and others (2005): one test well was completed in Calibogue Sound (BFT-2297) and six test wells at four sites (BFT-2258 and -2251; -2250 and -2251; -2249, -2295) were completed beneath the Atlantic Ocean east and southeast of Hilton Head Island. Here, the Marks Head Formation was absent at BFT-2297 but was present at the offshore sites with thicknesses that ranged from 1 to 32 ft; the Ebenezer, Coosawhatchie, and Parachucla Formations were absent at all five sites. Offshore seismic surveys (Foyle and others, 2001) did not identify the Parachucla Formation; however, Clarke and others (1990) reported 10 ft and 3 ft of the lower basal carbonate layer at Hutchinson Island and Fort Pulaski, respectively. The possible presence of the Ebenezer and Coosawhatchie Formation in the extreme southern part of South Carolina is based on the Fort Pulaski test site (Clarke and others, 1990) and the Tybee Island reference site (Weems and Edwards, 2001); both sites are near the Savannah River in Chatham County, Ga. The Coosawhatchie Formation was encountered at the Fort Pulaski site and Tybee Island reference site and was 20 ft and 10 ft thick, respectively; the Ebenezer Formation was encountered at the Tybee Island reference site and was 23.5 ft thick. Offshore, along the flank of the Beaufort Arch, Foyle and others (2001) reported that the Coosawhatchie Formation (Marker A) was interpreted in their seismic survey. Other evidence was provided by Paul Huddlestun, who recognized middle and early Miocene faunal assemblages in cores collected during the 1984 offshore drilling beneath Port Royal Sound (Personal Communication; Hughes and others, 1989). Except for scattered remnants of late and middle Miocene (Ebenezer and Coosawhatchie Formations), the early Miocene Marks Head Formation remains the predominate sediment representing the Hawthorne Group in South Carolina.

The structure map for the Hawthorn Group shown in Figure 11 was based on geophysical logs, published reports, and augered boreholes by the SCDNR (Doar, **SELECTED REFERENCES**, S.C. Geological Survey; Appendix C). Here, the contours show a complex erosional pattern across the surface of the Hawthorn Group. The highest elevation shown in the study area is about -10 ft Msl in parts of South Carolina decreasing to about -70 ft Msl near Savannah, Ga. Other structure maps in the study area were completed by Hughes and others (1989); Clarke and others (1990); Foyle and others (2001); and Falls and others (2005). The isopach map (fig. 12) shows that the thickness of the Hawthorn Group ranges from about 20 to 40 ft in the northeastern part of the study area but is thin or absent near the crest of the Beaufort Arch. In the southwestern part of the study area, the Hawthorne Group is about 50 ft in thickness at Tybee Island and is about 165 ft and 150 ft near Savannah, Ga. (USACE Savannah River cores SHE-9 and SHE-19), respectively. The Duplin Marl of the Pliocene has no characteristic geophysical signature and the Miocene structure and isopach maps herein may include Duplin Marl locally.

Holocene and Plio-Pleistocene Series

Undifferentiated clastic sediment of the Pliocene, Pleistocene, and Holocene form surficial deposits having an average thickness of 50 ft in southern Beaufort County, S.C. and adjoining parts of Chatham County, Ga. Miller (1986) interpreted these undifferentiated sediment to be a basal sequence of marginal to shallow marine beds overlain by a series of sand and terrace deposits. Where paleochannels have incised the underlying Miocene sediment, thicknesses near 75 ft are present, as seen in well BFT-2313 (fig.43) on the north end of Pinckney Island S.C.

In general, deposition occurred during episodes of marine transgression and regression that produced varied and discontinuous lithologies over short distances. Marine deposits in the study area are dominated by well-sorted to poorly sorted, fine- to medium-quartz sand but also include clay, sandy clay, clayey-to-silty sand, offshore and estuarine mud, shell beds, and calcareous to shelly quartz sand and mud. Alluvial deposition caused by erosion of sediment at higher elevations is also present as medium- to coarse-grain sand and gravel with less silt and clay than found in delta plains, flood plains, and channels. Where present as surface deposits, the sediment display various geomorphological and topographic features that characterize the study area: beaches, dunes, estuaries, channel bars, sinkholes, and terrace deposits.

The Pliocene Duplin Marl, where present, unconformably overlies the Miocene Hawthorn Group (Furlow, 1969). Hughes and others (1989) reported that sediment comprising the Duplin Marl in South Carolina consists of phosphatic sandy clay that is difficult to distinguish from the underlying Miocene sediment because the lithology is similar and geophysical logs do not exhibit a characteristic signature. Near the Beaufort Arch, in the vicinity of St. Helena and Port Royal Islands, the Duplin Marl is thin or absent: Siple (1960) noted that, in the Beaufort area, the Duplin Marl was limited to only a few small, isolated exposures. The SCGS does not recognize significant deposits of Duplin Marl in the South Carolina part of the study area. There is evidence that the ancient flood plain of the Savannah River covered much of the area and might have migrated 10 to 30 miles to the northeast (Doar, 2014; verbal communication, Oct. 20, 2016) and therefore eroded most of the Duplin Marl (Hudson and others, 2003; Doar, 2008a, 2008b, and 2008c). By comparison, Furlow (1969) reported a thickness of about 50 ft in eastern Chatham County, Ga., and described the Duplin Marl as olive-green sand, sandy clay, and clayey sand. He noted that the Duplin Marl was locally difficult to distinguish from the underlying Hawthorn Group other than by the phosphate concentration (13%) at the base of the Duplin Marl compared to the concentration (3%) in the underlying Hawthorn Group. Foyle and others (2001) interpreted Pliocene sediment in an elongated embayment stretching northward from the Savannah River to areas behind Hilton Head Island and southward behind the Tybee Island shoreface and are consistent with Furlow (1969).

Pleistocene scarps and terraces are surface features found in the South Carolina Coastal Plain, first mapped by Cooke (1936), and represent elevations of past shorelines and plains formed during high stands of sea level. Identification of terrace deposits is difficult owing to younger oceanic high stands eroding and reworking the landward extent of previous deposits and later geomorphic processes that further modify the deposits. Consequently, beginning with the concepts put forth by Shattuck (1901a, 1901b, and 1906), terrace deposits in South Carolina have been revised by more recent investigators (Dubar and others, 1974; Colquhoun, 1974 and 1991; Weems and Edwards, 1987). The SCGS recognizes eight Pleistocene terrace deposits (Doar, 2014; verbal communication, Oct. 20, 2016) in the South Carolina Coastal Plain and the current transgression; four terrace deposits are recognized in the study area and include the Ten Mile Hill, the Pamlico, the Princess Anne, and the Silver Bluff, in addition to the current transgression (Doar and Kendall, 2014).

Structure

The Beaufort Arch (Colquhoun and others, 1969) and the Ridgeland Trough, first identified as the Ridgeland Basin by Heron and others (1966), are prominent tectonically related structural features (fig. 13) caused by uplift of overlying sediment that, in turn, interrupted the generally southeastward regional dip of Coastal Plain sediment in the study area. The presence of the Beaufort Arch is plausible based on geophysical logs, seismic surveys, and geologic samples that show higher elevations of overlying sediment relative to surrounding areas. Additionally, gravity and magnetic anomalies can detect the presence of underlying intrusive rock. The axis of the Beaufort Arch trends northeast to southwest, generally parallel to the present-day coastline. It has been mapped onshore to the northeast as far as Lady's Island, S.C., and is believed to extend 90 miles southwest to Cumberland Island, Ga., based on offshore seismic surveys (Woolsey, 1976). Perpendicular to the axis of the Beaufort Arch across Hilton Head Island, the northwest-southeast extent of the arch is estimated to span about 20 miles (Provost and others, 2006, fig. 1).

A Bouguer anomaly map shows a gravitational high below St. Helena Island, S.C. caused by greater density of an intrusive body (igneous rock) and the magnetic map shows a strong magnetic field caused by high iron content characteristic of a mafic intrusive body (Hughes and others, 1989). Northeast of Beaufort, S.C., gravity and magnetic anomalies in the St. Helena Sound area were interpreted by Daniels and others (1983) to be the result of an intrusive body that McCartan (oral commun. *in* Hughes and others, 1989, p. 16) suggested as a cause of uplift and subsequent formation of the Beaufort Arch. Heron and Johnson (1966) reported that the Coosawhatchie clay of the upper Miocene was absent near crest of the arch, indicating that the uplift took place during the early to middle Miocene. Hughes and others (1989) noted that Oligocene sediment also were absent northeast of Hilton Head Island and they suggested that an earlier uplift took place during or after the late Eocene and prior to deposition of Miocene sediment.

Along the axis and toward the crest of the Beaufort Arch, sediment comprising the late Eocene (Ocala Limestone), unnamed Oligocene limestone, and Miocene Hawthorne Group are found at higher elevations and are thinner or absent compared to similar sediment on the flank of the arch and to the southwest. Thinner sediment near the arch are attributed to limited deposition and to erosion that created complex surface structure on the late Eocene, Oligocene, and Miocene strata during lower sea-level stands. The surface of the Eocene limestone overlying the arch displays several areas of higher elevation. Siple (1956) identified the Burton High, later named by Heron and Johnson (1966) as the Beaufort High. Nearby, Hayes (1979) used geophysical logs to map the top of the Eocene limestone at an elevation of -20 ft on Ladies Island S.C. To the southwest, Furlow used geologic core (1969; fig. 3) to identify an area near Tybee Island, Ga. where the top of the Oligocene limestone is at about -110 ft Msl, which he called the Tybee High. Offshore seismic surveys by Foyle and others (1999) identified a structural high five miles southeast of Hilton Head Island where the top of the Oligocene lay at about -60 ft Msl, which they designated the Hilton Head High. Test drilling near Broad Creek on Hilton Head Island, as part of this report, identified another high where the top of the Eocene limestone lies at -60 ft Msl and is designated herein as the Broad Creek High (figure 13).

Sinkholes can be observed as topographic features near the crest of the Beaufort Arch (fig. 13) and are found where the Eocene limestone lies close to the surface. Here, the limestone is dissolved by recharge water that has been acidified by carbon dioxide (carbonic acid) in the atmosphere and soil prior to moving down through the overlying sediment column. Dissolution of the limestone causes cutters and channels to form, increasing porosity in the upper part of the limestone. Given sufficient time, the voids may become large enough to cause overlying sediment to collapse slowly or rapidly inward, resulting in the formation of a sinkhole. Eventually, overlying sediment are transported into the topographic depression causing infilling. In areas near the crest of the Beaufort Arch and associated highs, seismic surveys have found evidence of sinkholes beneath tidal channels and the Atlantic Ocean (SCWRC, 1972; Foyle and others, 2001).

The Ridgeland Trough (fig. 13) lies northwest of the Beaufort Arch in South Carolina and is an east-northeast-trending basin in central Jasper County, S.C. Clark and others (1990, fig. 2 and plt. 4) extended the Ridgeland Trough southwest of the town of Ridgeland from the Savannah River into northwestern Chatham County, Ga.

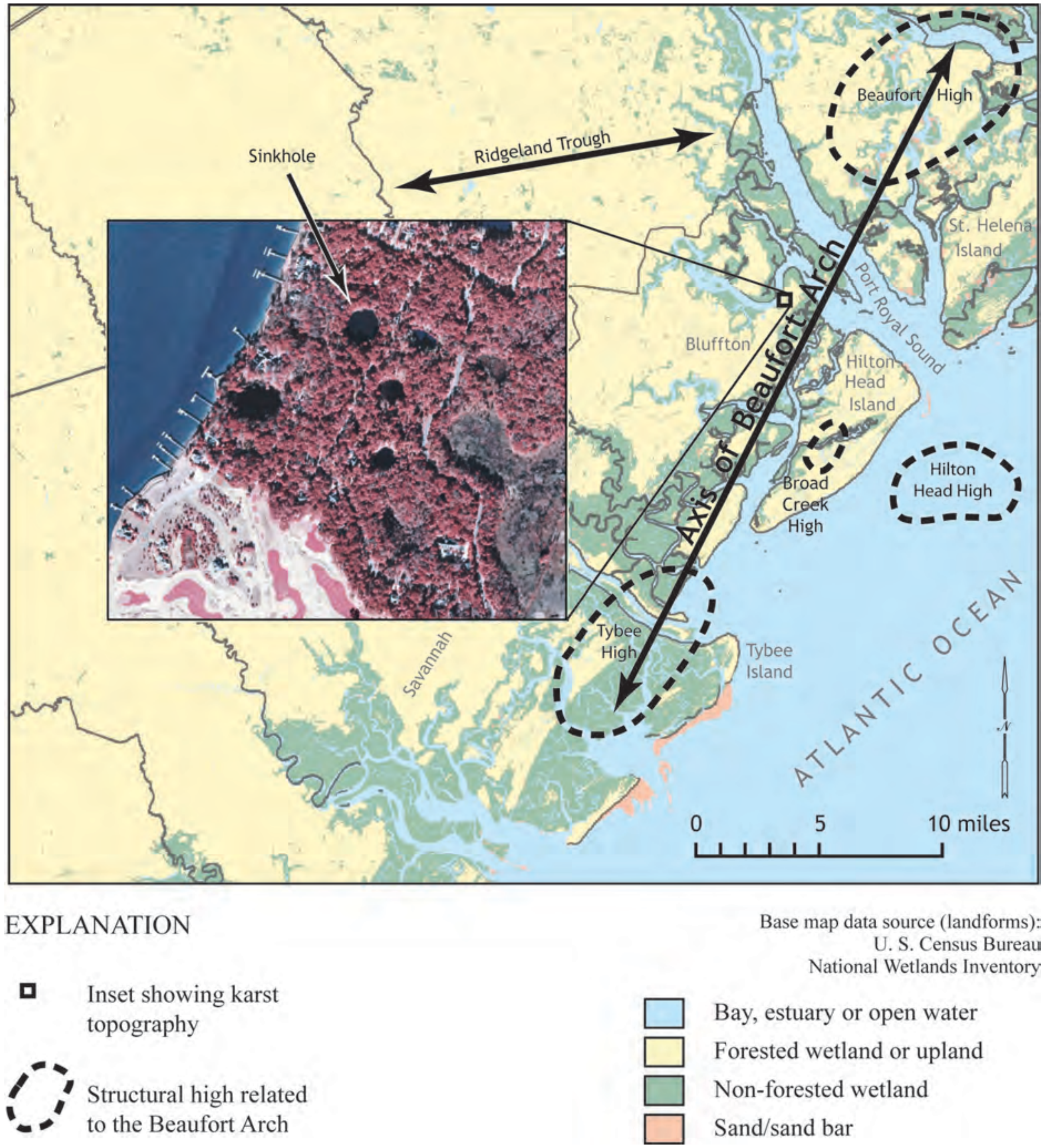


Figure 13. Prominent structural and geomorphic features in the study area. Inset: sinkholes at Colleton River Plantation near Colleton River, S.C.

HYDROGEOLOGY

Hydrogeologic strata are classified as aquifers or confining units depending on the strata's potential to transmit or impede the flow of water. Aquifers and confining units may consist of only part of a geologic formation or include one or more formations that share common hydraulic properties. Groundwater flow through the strata occurs laterally and vertically; the direction of flow depends on hydraulic head, elevation of landmasses, rainfall, and evapotranspiration, pumpage, and confining sediment.

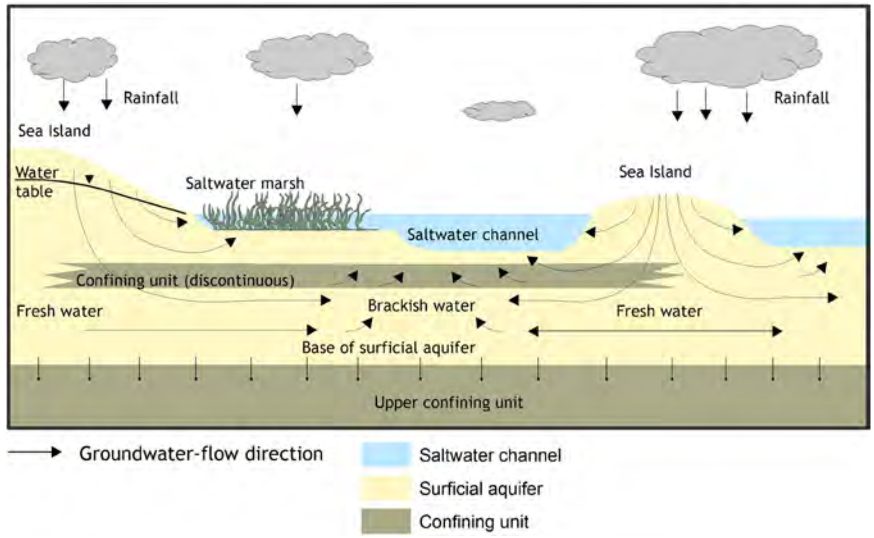


Figure 14. Schematic representation of groundwater flow in the surficial aquifer in response to recharge and discharge.

The hydrogeologic units most important to this investigation follow those of previous investigators (Counts and Donsky, 1963; McCollum and Counts, 1964; Smith, 1988; Clarke and others, 1990; Gawne and Park, 1992; Falls and others, 2005; Williams and Kuniansky, 2010) and include (1) the Pliocene to recent sediment identified herein as the surficial aquifer; (2) the Miocene Hawthorne Group identified herein as the upper confining unit; (3) the Oligocene limestone and the upper unit of the late Eocene Ocala Limestone identified herein as the Upper Floridan aquifer; (4) the lower unit of the late Eocene Ocala Limestone identified herein as the middle confining unit of the Floridan aquifer; and (5) the upper part of the middle Eocene Santee Limestone identified herein as the middle Floridan aquifer in South Carolina. The stratigraphic column (fig. 6) shows the geologic formations and hydrogeologic units in the study area.

Surficial Aquifer

The surficial aquifer commonly includes a water-table aquifer and, in some areas, a discontinuous semi-confined basal aquifer. Dale and Park (1999) reported two sandy permeable units in the surficial aquifer beneath parts of Hilton Head Island: a shallow water-table aquifer in the upper 15 to 25 ft and a confined, basal aquifer overlying the upper confining unit. Clarke and others (1990) and Leeth and others (2003) also reported that the surficial aquifer in parts of Chatham County, Ga., can be divided into a water-table aquifer and a semi-confined aquifer.

Where the surface of the surficial aquifer underlies landmasses, most recharge will occur directly from rainfall. Water levels fluctuate depending on the amount of rainfall but generally will mimic the topography (to a lesser extent) as groundwater flows down gradient from higher elevations toward areas of lower elevation where fresh water discharges into streams. Near the coast, the surficial aquifer underlies and is hydraulically connected to saltwater marshes and tidal channels. Where heads are lower in the Floridan aquifer, brackish to saltwater in the surficial aquifer migrates downward through the upper confining unit (fig. 14).

The surficial aquifer is not widely used for potable supply and data are limited for individual wells. Dale and Park (1999) conducted a five-day aquifer test at Hilton Head Island for a well screened between 16 and 28 ft bgs in the surficial aquifer: they reported a hydraulic conductivity between 5 and 20 ft/day, a transmissivity of 210 ft^2/day, and a specific yield of 0.2. Wells open to the surficial aquifer in the Port Royal Sound area typically yield 10 gpm or less but may be greater if the aquifer is fully developed, and specific capacities are about 1 gpm/ft of drawdown. Local confining units are composed of organic-rich, poorly to well-sorted clay and silt deposited in offshore and back-barrier environments (Dale and Park, 1999).

Siple (1960), noted that the potentiometric surface of the Upper Floridan aquifer remained unchanged on the north end of Hilton Head Island in contrast to the southern part of the island where the potentiometric surface declined in response to increased pumpage at Savannah, Ga. He hypothesized that a hydraulic connection exists between the surficial aquifer and the Upper Floridan aquifer, and that local recharge on the northern part of the island prevented further declines. Carbon-14 and tritium analyses also indicate that recharge from the surficial aquifer to the Upper Floridan aquifer occurs in the vicinity of northern Hilton Head Island (Back and others, 1970; Landmeyer and Stone, 1995). Dale and Park (1999) measured water levels in the surficial aquifer at northern Hilton Head Island and compared those measurements to water-level fluctuations in wells open to the Upper Floridan aquifer. Their data showed that the water table (surficial aquifer) responds to changes in groundwater withdrawals from the Upper Floridan aquifer, their conclusion further supports a hydraulic connection between the two aquifers.

Upper Confining Unit

The upper confining unit of the Floridan Aquifer system in the study area includes one or more formations of the Hawthorne Group (undifferentiated), and in some areas the upper confining unit may also include the overlying Duplin Marl (Colqhoun and others, 1969; Furlow, 1969; Hughes and others, 1989; Foyle and others, 2001). Where the upper confining unit overlies the Upper Floridan aquifer, the lower permeability of the unit provides a barrier that inhibits flow between the surficial aquifer and the underlying Upper Floridan aquifer. Prior to groundwater withdrawals, the direction of groundwater flow across the upper confining unit was upward in most of the study area, the result of higher heads discharging water from the underlying Upper Floridan aquifer. However, as groundwater withdrawals increased, heads declined and the direction of groundwater flow across the upper confining unit reversed. The surficial aquifer now recharged the Upper Floridan aquifer and where the surficial aquifer existed beneath the coastal marshes, tidal channels, and the Atlantic Ocean, brackish to salt water would move downward. The hydraulic parameters that control direction and volume of flow across the upper confining unit are: (1) thickness, (2) hydraulic conductivity, (3) porosity, and (4) the hydraulic gradient across the unit.

The thickness of the upper confining unit varies greatly in the study area. It is thinnest, less than 10 ft, where it overlies the crest of the Beaufort Arch. It is thickest to the northwest around the Ridgeland Trough (Hughes and others, 1989), and southwest near Savannah, Ga., where it may exceed 150 ft (fig. 12). Geophysical mapping by Foyle and others (2001) identified eleven areas where the confining unit has been thinned or removed offshore of Hilton Head Island and in nearby tidal channels. Where the confining unit is removed, a vertical pathway is created for water (salt water) of higher head in the overlying surficial aquifer to flow directly downward. As part of this study, vertical specific conductance profiles were conducted in test wells to detect brackish to saltwater: other methods included geophysical logs and geologic cuttings. Seven new source areas were identified where the upper confining unit is believed to be absent. Relict sinkholes also breach the confining unit over the crest of the Beaufort Arch between Pinckney Island and St. Helena Sound, S.C. (fig. 13). Potentiometric surface maps of the Upper Floridan aquifer constructed for 1976 (Hayes, 1979), 1991, 1992, 1993 (Gawne, 1993), and 1998 (Ransom and White, 1999) show a high along the crest of the Beaufort Arch west of Hilton Head Island near Pinckney Island (Appendix D: figs. D21, D8a, D14-20). The higher heads are attributed to relatively greater downward recharge where the upper confining unit is thin or absent.

Vertical hydraulic conductivity of the upper confining unit will vary at individual well sites; however, it generally increases from areas southwest of Savannah to the northeast in the vicinity of Port Royal Sound. In coastal Chatham County, Ga., Furlow (1969, page 23) reported an average value for vertical hydraulic conductivity of 1.3^{e-3} ft/day based on 52 laboratory analyses of core taken from the upper confining unit. Hughes and others (1989) reported values of hydraulic conductivity and porosity for the upper confining unit based on laboratory analyses of 22 core samples taken from seven boreholes in Port Royal Sound to be 6^{e-3} ft/day and .45 percent, respectively. Converting leakance taken from Smith's flow model (1988) to hydraulic conductivity for the area west of Savannah where the upper confining unit is about 150 ft thick, the central area between Savannah and northern Hilton Head Island, and the northeastern area beginning near Port Royal Sound where the thickness of the upper confining unit averaged about 30 ft, revealed values for hydraulic conductivity of 1.5^{e-5}, 3.0^{e-5}, and 3.0^{e-3} ft/day, respectively. Hydraulic conductivities derived from calibrating SCDHEC's model (Appendix J5) were 0.6^{e-6} ft/day for the area west of Savannah, 8.0^{e-5} ft/day for the central area, and 2.5^{-3} to 0.03 ft/day for Port Royal Sound and areas to the northeast: values similar to those used in other investigations. Two methods were considered by Ransom and others (2006) to estimate a value for vertical hydraulic conductivity and porosity for the upper confining unit where the potentiometric surface within the eastern half of the Savannah cone of depression was less than 0 ft Msl. The first method varied the vertical hydraulic conductivity and porosity assigned to a one-dimensional solute-transport equation to match simulated and measured chloride concentrations moving down through the confining unit. The second method used Darcy's Law to compute an average vertical hydraulic conductivity that, when used with estimated gradients across the confining unit in the Savannah – Hilton Head Island area approximated the water budgets for downward flow (leakage) through the upper confining unit published by Smith (1988) and Garza and Krause (1992). The vertical hydraulic conductivity and porosity determined from the first method was 2.0^{e-4} ft/day and 0.35 percent, respectively; and the second method calculated an average hydraulic conductivity of 3.0^{e-4} ft/day.

As part of this study, five monitoring well sites (BFT-2410, BFT-2411, South Tybee Island, Bull River 2, and Shipyard Road) were selected near Savannah, Ga., and southwestern South Carolina (Appendix B). Data included continuous, sealed core throughout the borehole depth for laboratory analyses of pore water and hydraulic parameters. A sixth well was similarly completed by the USACE as part of a separate study (laboratory analyses of cores were included in this study). A total of two-hundred and ninety core samples from selected depths in the six wells (including Bull River 3 completed by the USACE) were analyzed by the USGS laboratory. Eighty samples from the upper confining unit at four sites had hydraulic conductivity values between 1.6^{e-1} and 9^{e-3} ft/day: the average value for vertical hydraulic conductivity and effective porosity was 8.2^{e-2} ft/day and 51.9 percent, respectively (Appendix F). Overall, the laboratory values were higher than those derived from SCDHEC's model calibration (Appendix J).

Floridan Aquifer System

The names Upper Floridan aquifer and upper confining unit are used here for consistency and replace the various but generally comparable names used in the cited reports.

The Floridan aquifer system is one of the most extensive and productive groundwater reservoirs in the United States (Miller, 1990), supplying up to 4,020 Mgal/d during drought conditions that occurred about 2000 (Marella and Berndt, 2005). The aquifer comprises a vast sequence of Tertiary carbonate rock that underlies the entire state of Florida, the Coastal Plain of southeast Georgia, part of southern Alabama and southeastern Mississippi, and extends into southern South Carolina (Stringfield 1936; Warren, 1944; Parker and others, 1955; Miller, 1986). For this study, except for a brief discussion of the lower Floridan aquifer, only part of the Floridan aquifer system was considered: the middle Eocene Santee Limestone, the late Eocene Ocala Limestone, and the mostly undifferentiated Oligocene limestone that probably is equivalent to the Tiger Leap and Lazaretto Creek Formations in Georgia (Weems and Edwards, 2001) and offshore of Hilton Head Island, S.C. (Falls and others, 2005).

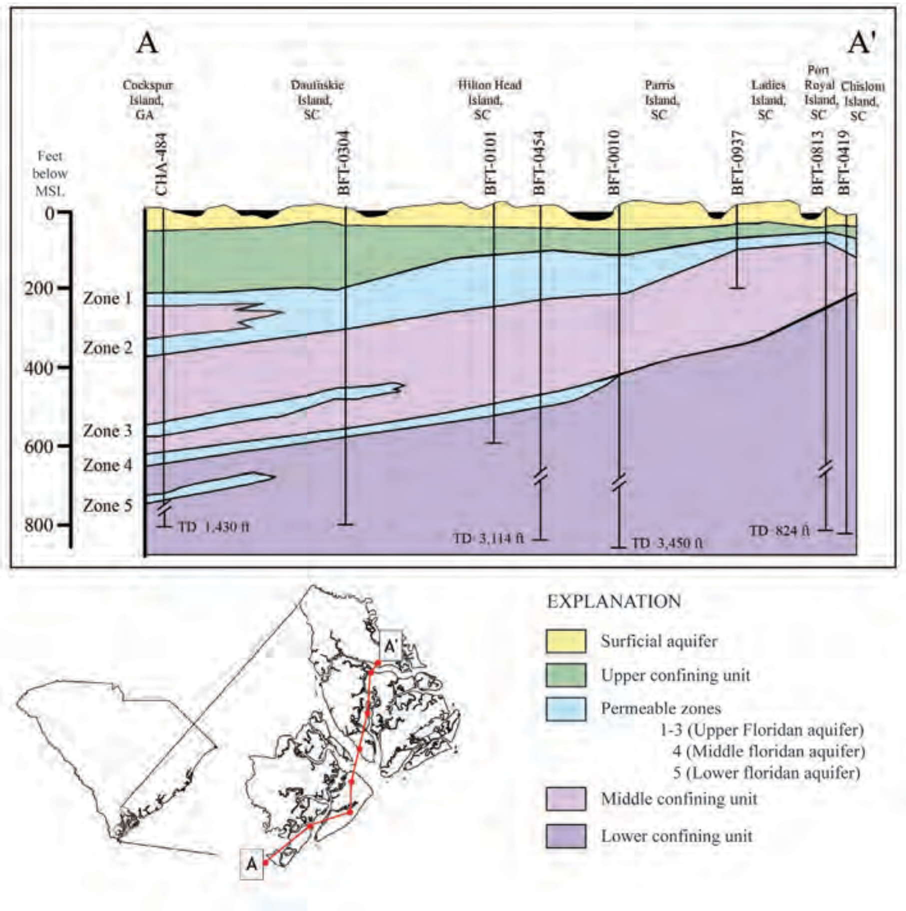


Figure 15. Permeable zones in the Floridan aquifer (after McCollum and Counts, 1964, pl. 4, and Hughes and others, 1989).

The hydrogeologic framework in the South Carolina part of the study area somewhat differs from adjoining parts of Georgia. In southern South Carolina, the late Eocene Ocala Formation is divided into an upper and lower unit (Counts and Donsky, 1963); only the upper unit is considered to represent the Upper Floridan aquifer. The lower unit is considered to represent the middle confining unit (McCollum and Counts, 1964; Miller, 1986). The middle Eocene Santee Limestone lies beneath the middle confining unit; here, the top part of the Santee Limestone represents the middle Floridan aquifer (Gawne and Park,1992). Beneath the middle Floridan aquifer lie undifferentiated indurated early Eocene limestones comprising the lower Floridan aquifer; no productive lower Floridan aquifer wells have been completed in South Carolina. The USGS (Williams and Kuniansky, 2016) revised the hydrogeologic framework of the Floridan aquifer system that is followed in Georgia. It differs from South Carolina in that the top of the middle Eocene Santee Limestone (middle Floridan aquifer in South Carolina) is included in the lower Floridan aquifer. The combined thickness of the Floridan aquifer system is about 700 ft in the northeastern part of Port Royal Sound and increases to about 1,200 ft in adjoining Chatham County, Ga.

In the study area, five permeable zones were identified in the Floridan aquifer system that are separated by semi-confining units comprised of carbonate sediment of lower permeability (McCollum and Counts, 1964; McCollum, 1964). Four of the five permeable zones identified in Chatham County, Ga., were identified in South Carolina. Identification of permeable zones was determined primarily from flow-meter tests but included geophysical logs, and geologic samples from five test wells open to the Floridan aquifer system in Chatham County, Ga., and three test wells in southern South Carolina (fig. 15). Permeable zones 1 and 2 were identified in the upper unit of the Ocala Limestone and mapped to the northern part of Hilton Head Island at well BFT-315: Hughes and others (1989) noted that zones 1 and 2 may merge and rise close to the surface near the Beaufort Arch. Permeable zone 3 was identified in the middle confining unit in well BFT-304 on the northern part of Daufuskie Island. Permeable zone 4 (middle Floridan aquifer in South Carolina) was identified at the top of the middle Eocene Santee Limestone (equivalent to the Avon Park Formation in Georgia) and mapped to the northern part of Hilton Head Island. Gawne and Park (1992) used a flow-meter test at well BFT-1840 to extend permeable zone 4 farther north to Parris Island where they estimated a thickness of 7 ft. Permeable zone 5, identified about 250 ft below zone 4 in Chatham County (Williams, 2010), has only been mapped in Georgia.

The SCDHEC model (Appendix J), designed to predict the development and movement of chloride plumes, was calibrated using isochlor maps constructed from vertical-conductivity profiles (Fig.5: Appendix I). The model simulations suggest that permeable zone 1 might not extend to the northern part of Hilton Head Island and areas west of the island. Initial model simulations included both permeable zones 1 and 2 at the northern part of Hilton Head Island: here, the simulations showed a large chloride plume in each of the two zones. However, numerous vertical specific-conductance profiles and electrical-resistivity logs conducted in test wells in the area have only detected significant lateral movement of brackish to salt water in permeable zone 2 near the bottom of the aquifer (Appendix I). Therefore, it is plausible that permeable zone 1 may pinch out near the northern part of Hilton Head Island before encountering a chloride source area. Removing permeable zone 1 in the northern part of Hilton Head Island and areas to the west allowed the simulated chloride plumes to develop and more closely match the field data.

The depths and thicknesses of permeable zones reported in McCollum and Counts (1964) are used herein. The top of permeable zone 1 lies at an elevation of about -200 ft Msl at well CHA-484 (fig. 76) 6 miles east of Savannah and attains a maximum thickness of about 50 ft. To the northeast, the zone shallows to about -100 ft Msl as it nears the northern end of Hilton Head Island and might have a thickness of about 20 ft as it approaches the Port Royal Sound area (fig. 15). The top of permeable zone 2 lies at an elevation of about -270 ft Msl near Savannah (well CHA-484) and has a thickness of about 50 ft at well CHA-484 and 70 ft at CHA-487 on Tybee Island. At the northern part of Hilton Head Island, zone 2 lies at the bottom of the Upper Floridan aquifer and has a thickness of about 30 ft. Its thickness decreases to less than 20 ft north of Port Royal Sound, and both permeable zones 1 and 2 are absent 18 miles to the northeast, near the Coosaw River and St. Helena Sound.

Permeable zone 3 has an elevation of about -470 ft Msl at well CHA-484 and a thickness of 10 to 30 ft in the Savannah area. McCollum and Counts (1964) mapped permeable zone 3 with geophysical logs from their Savannah-area test wells to wells BFT-304 and BFT-101 at northern Daufuskie Island and mid Hilton Head Island, respectively. Flow-meter traverses in well BFT-315, on the northern part of Hilton Head Island, indicated permeable zone 3 is absent. Flow-meter traverses by Gawne and Park (1992, fig. 2) in wells that penetrated permeable zone 4 (middle Floridan aquifer) at Hilton Head Island and Parris Island failed to detect flow from the expected depths of permeable zone 3. McCollum and Counts (1964) reported that the elevation of permeable zone 4 increases from about -620 to -450 ft Msl between Cockspur Island, Ga., and the northeastern part of Hilton Head Island, the zone has a thickness of about 60 ft at Savannah. Gawne and Park (1992) reported thicknesses between 30 and 60 ft for zone 4 near the center of Hilton Head Island and noted that zone 4 is absent or of negligible thickness north of Port Royal Sound. Permeable zone 5 lies at an elevation of about -700 ft Msl near Cockspur Island, Ga., where the zone is about 40 ft thick but was not extended into South Carolina.

Flow-meter tests in wells open to most of the Floridan aquifer system near Savannah indicated that permeable zones 1 and 2 produced more than 70 percent of the water discharged to wells. Zone 3 yielded between 2 to 8 percent and zones 4 and 5 each yielded 3 to 20 percent (McCollum and Counts, 1964). Gawne and Park (1992) calculated transmissivities between 27,000 ft^2/d and 7,000 ft^2/d for permeable zone 4 at five wells on and near Hilton Head Island, suggesting comparatively greater yield could be achieved southwest of Port Royal Sound than to the northeast, where they calculated the transmissivity to be 2,300 ft^2/d on Parris Island. Since at least the 1930's, some municipal and industrial wells at Savannah were deep enough to obtain water from one or more of the three deepest permeable zones (zones 3, 4, and 5). Five miles south of Savannah, Ga., at Hunter Army Airfield, flow-meter surveys were conducted by Williams (2010) on a Floridan aquifer test well initially open to both the Upper and Lower Floridan aquifers between 333 and 1,168 ft bgs. The flow-meter surveys indicated that 5 permeable zones in the Upper Floridan aquifer and 5 permeable zones in the Lower Floridan aquifer supplied 83.5 and 16.5 percent of the total yield, respectively. One zone between 768 and 785 ft produced about half of the total yield originating from the Lower Floridan aquifer and probably correlates to permeable zone 4 (middle Floridan aquifer) as used in this report.

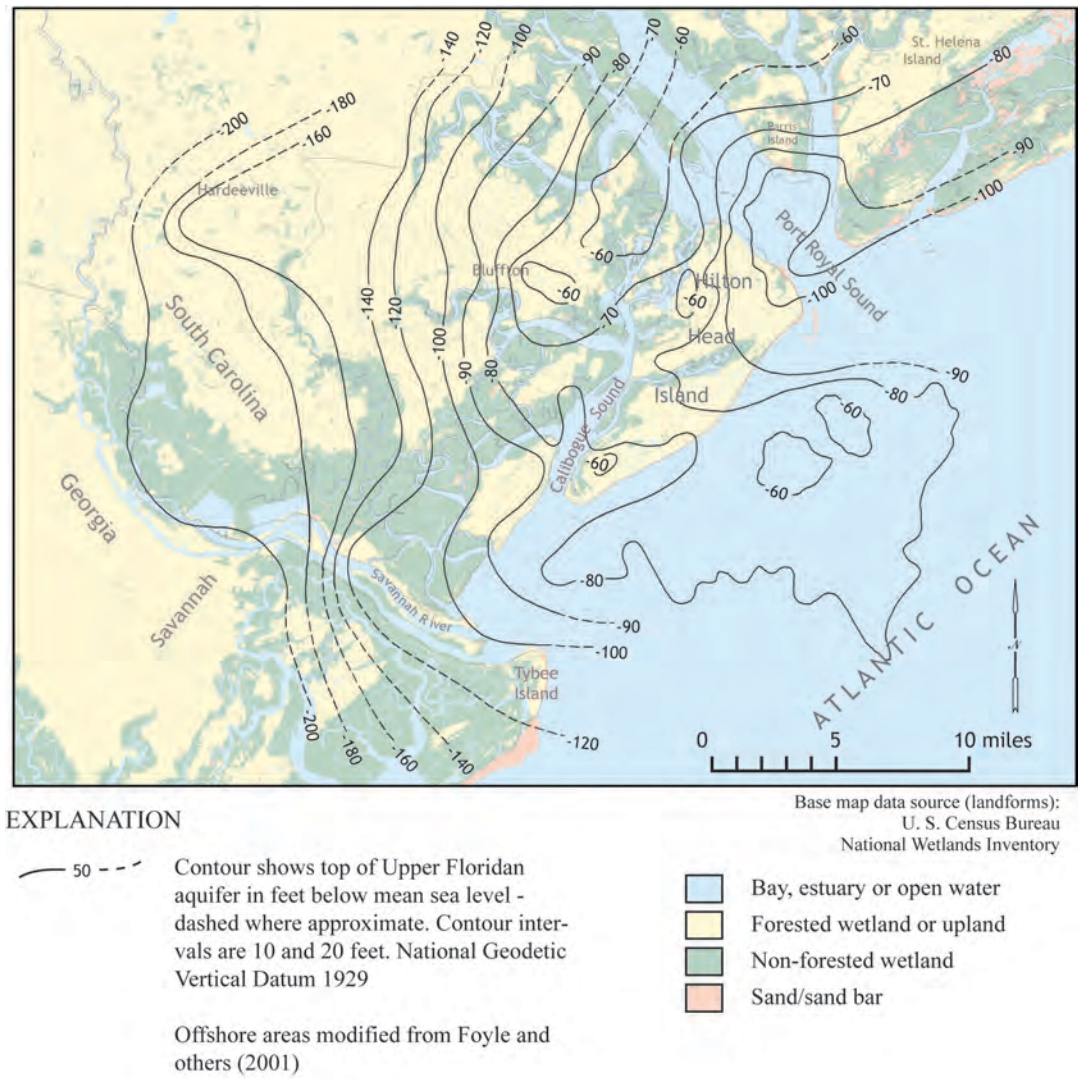


Figure 16. Structure contours for top of the Upper Floridan aquifer near Savannah, Ga., and Hilton Head Island, S.C.

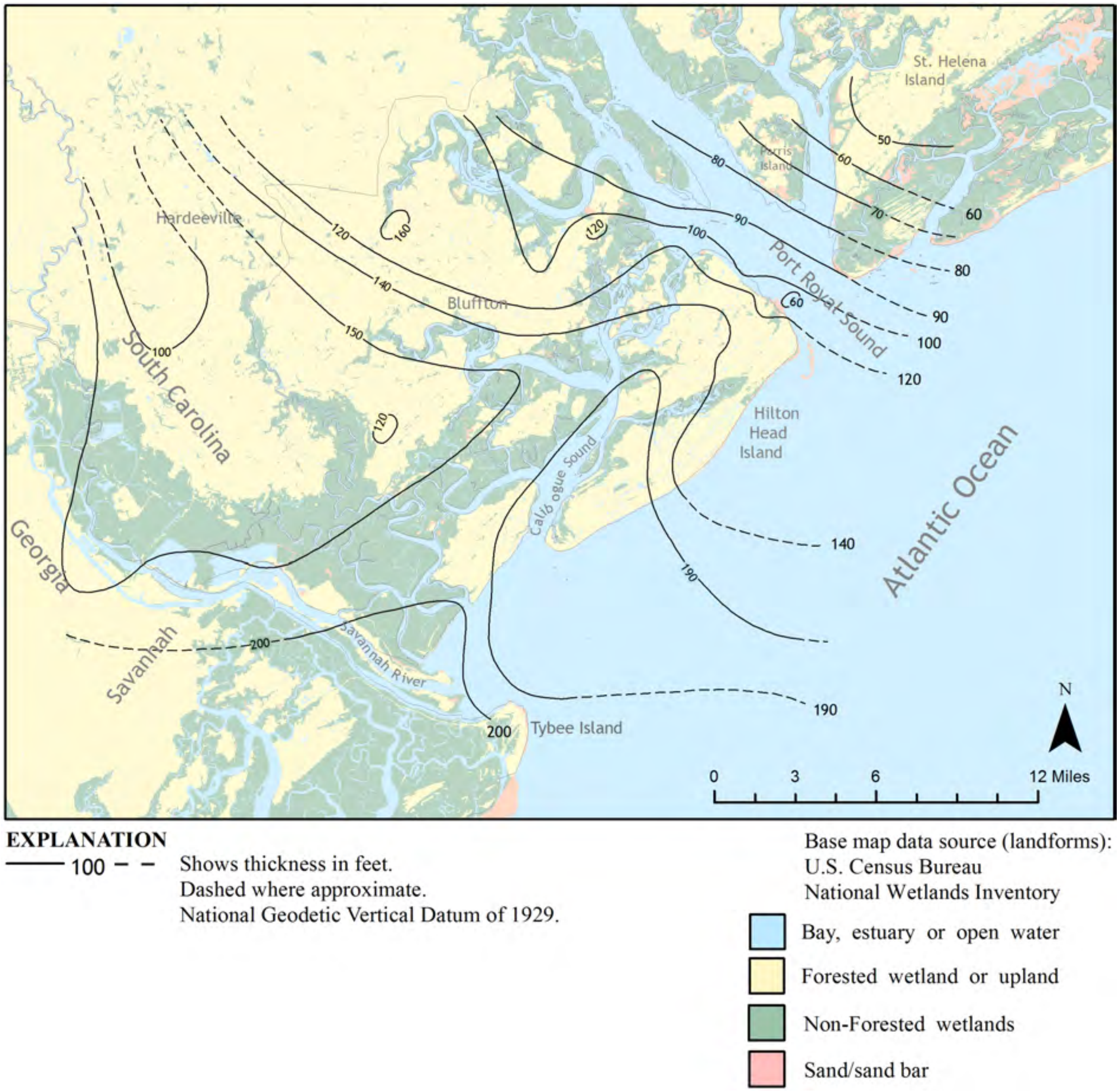


Figure 17. Isopach map showing thickness of the Upper Floridan aquifer near Savannah, Ga., and Hilton Head Island, S.C.

Upper Floridan Aquifer

The Upper Floridan aquifer[1], as the term is used in this report, comprises only the Oligocene limestone and the upper unit of the Ocala Limestone (Counts and Donsky, 1963). The upper unit includes permeable zones 1 and 2 (McCollum and Counts (1964) and a denser, lower permeability limestone between the two permeable zones: this denser limestone may also yield water from fractures and conduits (Counts and Donsky, 1963). Names used in previous investigations, which may also include a greater thickness of limestone, are "*principle*

[11] Miller's (1986) terminology, related to the Oligocene and late Eocene limestone, is more widely used by USGS and other investigators.

artesian aquifer" Counts and McCollum (1964), "*upper permeable zone of the Principle Artesian Aquifer*" of Hayes (1979), *Tertiary limestone aquifer* (Miller, 1982) and, later, the "*Upper Floridan aquifer*" of Hassen (1985), Smith (1988), Hughes (1989), Ransom and White (1999), and Ransom and others (2006).

The surface of the Upper Floridan aquifer is irregular owing to uplift by the Beaufort Arch and erosion as shown on the surface-contours of the Upper Floridan aquifer by Hayes (1979, fig. 10), who used natural gamma-ray logs to pick the top of the late to middle Eocene limestone in Beaufort, Jasper, Hampton and Colleton Counties, S.C. Hayes' map shows the highest elevation to be about -20 ft Msl beneath northern-most Lady's Island, S.C., and the Coosaw River; lower elevations occur in the Ridgeland Trough (fig. 13) and to the southwest near Savannah, where Hayes reported elevations of about -160 ft Msl. With the exception of Hughes and others (1989), later investigators (Foyle and others, 2001; Falls and others, 2005), including this report, consider the top of the Oligocene limestone to represent the surface of the Upper Floridan aquifer and consequently have assigned higher elevations (by as much as 70 to 80 ft for areas near Chatham County, Ga.) for the Upper Floridan aquifer in areas southwest of Port Royal Sound where the Oligocene limestone thickens (fig 16). The thickness of carbonate strata comprising the Upper Floridan aquifer in the study area is shown in Figure 17. Generally, the aquifer thickens from about 50 ft in the northeast to as much as 200 ft in the southwest. Hydraulic parameters of the Upper Floridan aquifer most important to well yield include transmissivity, porosity, and storage coefficient; these are known to vary greatly across the study area. The degree of variation depends on the depositional environment and post-depositional changes to include biological activity (burrowing) of marine organisms, dissolution from acidic water resulting in minute conduits and cavities, calcite precipitation, and faulting/fracturing of the sediment. Aquifer tests conducted in the field and laboratory analyses of geologic cores are the most common technique for determining hydraulic properties of the aquifer, but these are compromised by formulas that assume ideal conditions such as the isotropic distribution of sedimentary properties; however, sediment comprising the aquifer varies both vertically and laterally over short distances. Clarke and others (2004) noted that core recovery may affect samples that have secondary permeability features such as fractured, solution-riddled, and friable rocks, resulting in bias toward samples of lower permeability that were more easily recovered for analysis. While ambiguities may exist within localized data, the preponderance of tests conducted over a large area can provide average values for the hydraulic properties of the aquifer.

Transmissivity values for the Upper Floridan aquifer have been estimated in the study area by Warren (1944a), Hazen and Sawyer, (1957), Counts and Donsky, (1963), Nuzman (1972), Hayes, (1979), Smith (1988), and Newcome (1993, 2005). The data were summarized by Hughes and others (1989), who constructed a transmissivity map of the Upper Floridan aquifer in southern South Carolina. The average transmissivity north and northeast of Parris Island was between 5,000 and 10,000 ft^2/d and progressively increased to the southwest where the highest value was 60,000 ft^2/d on at Hilton Head Island. Newcome (1993, 2001) reported transmissivity values at individual well sites to range from 50,000 to 100,000 ft^2/d on Hilton Head Island and between 10,000 and 50,000 ft^2/d west of the island. Additional data on the hydraulic properties of the aquifer were prepared by Clarke and others (2004) for southern South Carolina, Georgia, and Florida. For adjoining parts of Chatham County, Ga., they reported values for transmissivity between 20,000 and 46,000 ft^2/d; Counts and Donsky (1963) reported an average transmissivity of 33,000 ft^2/day from six tests conducted by Warren (1944a) in Chatham County, Ga. The locations where transmissivity test values are reported for the Upper Floridan aquifer in southern Beaufort and Jasper Counties, S.C., are shown on Figure 18.

As part of this study, laboratory measurements of effective porosity in the Oligocene limestone were performed on 27 core samples taken at two test wells (BFT-2410 and BFT-2411) in South Carolina and two test wells (Bull River III and south Tybee Island) in Chatham County, Ga. Measurements also were taken in five core samples from the underlying Ocala Limestone at well BFT-2410, Hilton Head Island, S.C. (Appendix F), and three effective-porosity measurements were reported by Counts and Donsky (1963, Table 4) for the Ocala Limestone at well BFT-304, Daufuskie Island, S.C. Effective porosity in the Oligocene limestone cores ranged from about 0.15 to 0.36 with an average of 0.26. The average effective porosity values at wells BFT-2411, BFT-2410, Bull River III, and south Tybee Island, were 0.15 (one sample), 0.3, 0.31, and 0.36, respectively. Presuming that the one sample at well BFT-2411 could not adequately represent the site, the average effective porosity for the remaining three sites was 0.32. Effective porosity in the eight Ocala Limestone core samples from well BFT-2410 ranged from 0.26 to 0.42 with an average of 0.34. The three core samples from well BFT-304 had an average effective porosity of 0.25.

The storage coefficient for the Upper Floridan aquifer was calculated from 16 tests in Beaufort County, S.C., (Newcome, 1993; 2005) where values ranged from 0.0016 to 0.00004 and averaged 0.00025. In adjoining Chatham County, Ga., Clarke and others (2004) reported storage coefficients from nine wells where values ranged from .001 to .00009 and averaged 0.00095. Yield from storage was estimated by Hughes and others (1989) for the

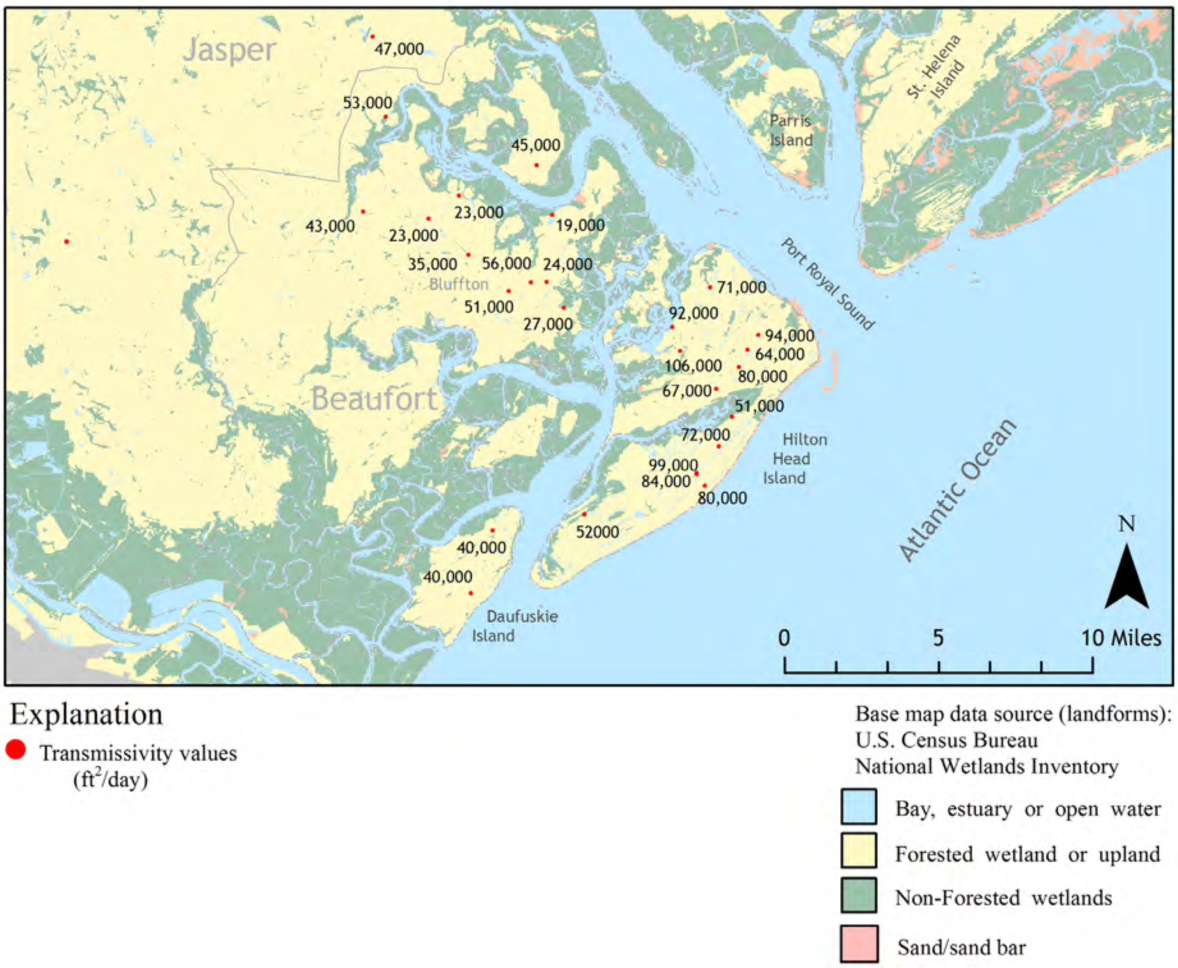


Figure 18. Transmissivity distribution in the Upper Floridan aquifer, southern Beaufort County, S.C. (from Newcome 1993).

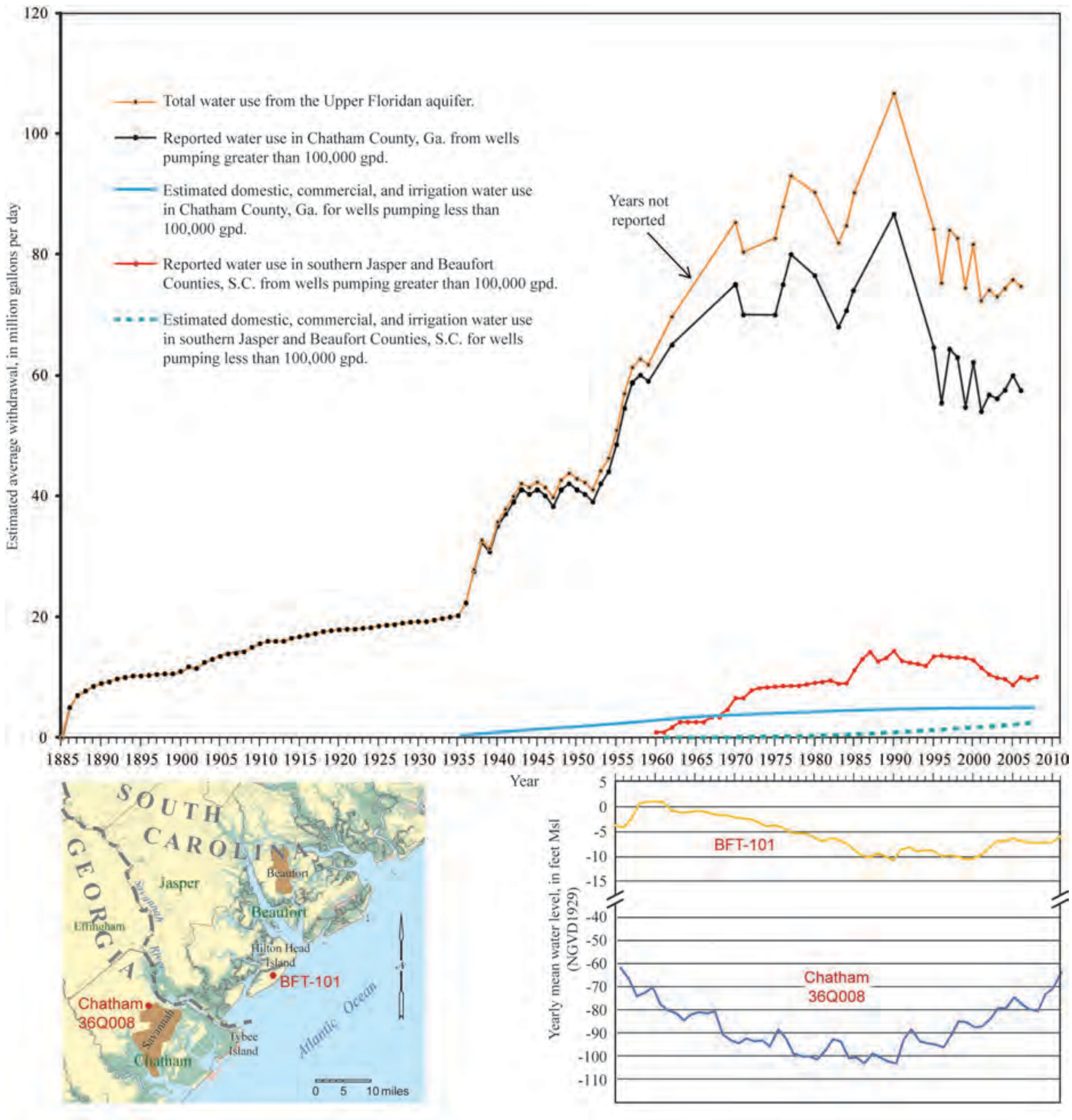


Figure 19. Upper Floridan aquifer water use in Chatham County, Ga., and southern Beaufort County, S.C., 1886–2006, and water levels in well BFT-101, Hilton Head Island, S.C., 1955-2007.

Savannah area cone of depression by using an average storage coefficient of 0.0001 and an average drawdown of 35 ft over an area of 1,244 mi^2: they estimated that about 903 million gallons had been removed from storage since pumping began.

Water Use

The Upper Floridan aquifer can yield more than 2,000 gpm (gallons per minute) of potable water from a single well in some areas and is the primary source of water for the Savannah – Hilton Head

Island area. Water-use estimates presented herein were taken from published reports and reported use for permitted wells; unpermitted wells were estimated based on unincorporated areas requiring potable water or irrigation use, and historical population growth rates.

Counts and Donsky (1963) reported that the first artesian well for the City of Savannah was drilled in 1885, and, in 1886, the city completed a well field thereby initiating the large-scale public use of the aquifer. By 1888 the artesian wells were producing about 5.8 Mgal/d (fig. 19). Annual production of groundwater at Savannah increased to 10 Mgal/d by 1895, to 19.0 Mgal/d from 1900 to 1935, to 31 Mgal/d by 1938, and 42 Mgal/day by 1943 (Warren, 1944, p. 114), and, by 1958, water use had increased to 68 Mgal/d to meet the demand for public supply and industrial growth (Counts and Donsky, 1963). Dale (2001) reported pumpage for municipal and industrial use in the Chatham County area of about 70, 73, and 80 Mgal/d in 1971, 1977, and 1985, respectively. Withdrawals peaked in 1990 at about 90 Mgal/d (Payne and others, 2005; Provost and others, 2006). In 1997, annual groundwater use had decreased to about 76 Mgal/d (Fanning, 1999), to about 70 Mgal/d by the year 2000 (Fanning, 2000), and to about 57 Mgal/d in 2006 (GaEPD, permitted pumpage - written communication). The withdrawals mainly reflect Upper Floridan pumpage from permeable zones 1 and 2 but also include wells open to permeable zones 3, 4 (middle Floridan aquifer in South Carolina), and 5 (Lower Floridan aquifer; not identified in South Carolina).

Groundwater withdrawals from the Upper Floridan aquifer at Hilton Head Island began in the 1960's and increased as the island experienced rapid growth as a resort and retirement area. Average daily pumpage increased to about 8.6 Mgal/d by 1976 (Hayes, 1979), to about 10.1 Mgal/d by 1984 (SCDNR file data), to about 13.3 Mgal/d by 1987 (McCready, 1989), and peaked at about 14.5 Mgal/d in 1990 (SCDHEC water use reporting and file records). Seasonal pumpage varied on the island and peak summer months possibly exceeded 17 Mgal/d.

The combined groundwater withdrawals from the Upper Floridan aquifer in Chatham County, Ga., and Hilton Head Island, S.C. peaked in 1990 at an average of 104.5 Mgal/d; 90 Mgal/d and 14.5 Mgal/d, respectively. Between 1990 and 1998 withdrawals decreased in Savannah (Provost and others, 2006) but increased at Hilton Head Island, thereby remaining close to 100 Mgal/d through 1998. Permitted groundwater withdrawals on Hilton Head Island were reduced to 9.7 Mgal/d after alternative sources were placed in service, and pumpage in the combined areas decreased to about 67 Mgal/d (unpermitted pumpage estimated) by 2006 (fig. 19). Permitted groundwater withdrawals do not include users who pump less than 100,000 gallons per day (gal/d) or withdrawals from wells open to the middle Floridan aquifer in South Carolina. The decrease was in response to efforts by state and local officials to place withdrawal limits on the Upper Floridan aquifer because of saltwater intrusion issues; alternative sources and water conservation measures were implemented to compensate for reductions. Average daily groundwater withdrawals, mostly from the Upper Floridan aquifer on Hilton Head Island and in Chatham County, Ga. (where some wells include the Lower Floridan aquifer) for the years 1886 to 2006 are shown on Figure 19). The hydrographs illustrate the relationships between water levels in the Upper Floridan aquifer at well CHA-36Q008 (Savannah, Ga.) and well BFT-101 (mid Hilton Head Island, S.C.) and regional water use from 1955 through about 2008, water use was interpolated if data were incomplete. Water levels began to partly recover in about 1990 at Savannah and in about 2000 on Hilton Head Island. The recovery was in response to discontinued permits and the adoption of alternative sources for golf course irrigation (treated effluent, lagoons, and the middle Floridan aquifer) and public supply systems (conversion to middle Floridan aquifer wells and reverse osmosis treatment).

Potentiometric-Surface Maps and Groundwater Movement

Prior to groundwater pumping in the study area, recharge to the Upper Floridan aquifer southwest of Savannah was balanced by the volume of water discharging from the aquifer to the northeast near Hilton Head Island, Parris Island, and Port Royal Sound. Where the hydraulic heads remain greater in the Upper Floridan aquifer than those in overlying sediment, discharge from the aquifer will be upward into the upper confining unit or, if the upper confining unit is absent, discharge will occur directly into the surficial aquifer. Where the upper confining unit is absent, a larger volume of water will discharge leading to lower hydraulic heads in the aquifer. Potentiometric-surface maps constructed for 1885 (predevelopment surface) to 1999 by various investigators documented changes in response to groundwater withdrawals (Appendix D).

The estimated predevelopment potentiometric surface of the Upper Floridan aquifer in Georgia, mapped first by Warren (1944), showed the potentiometric surface at Savannah to be about 35 to 40 ft Msl (fig. 20). Counts and Donsky (1963)

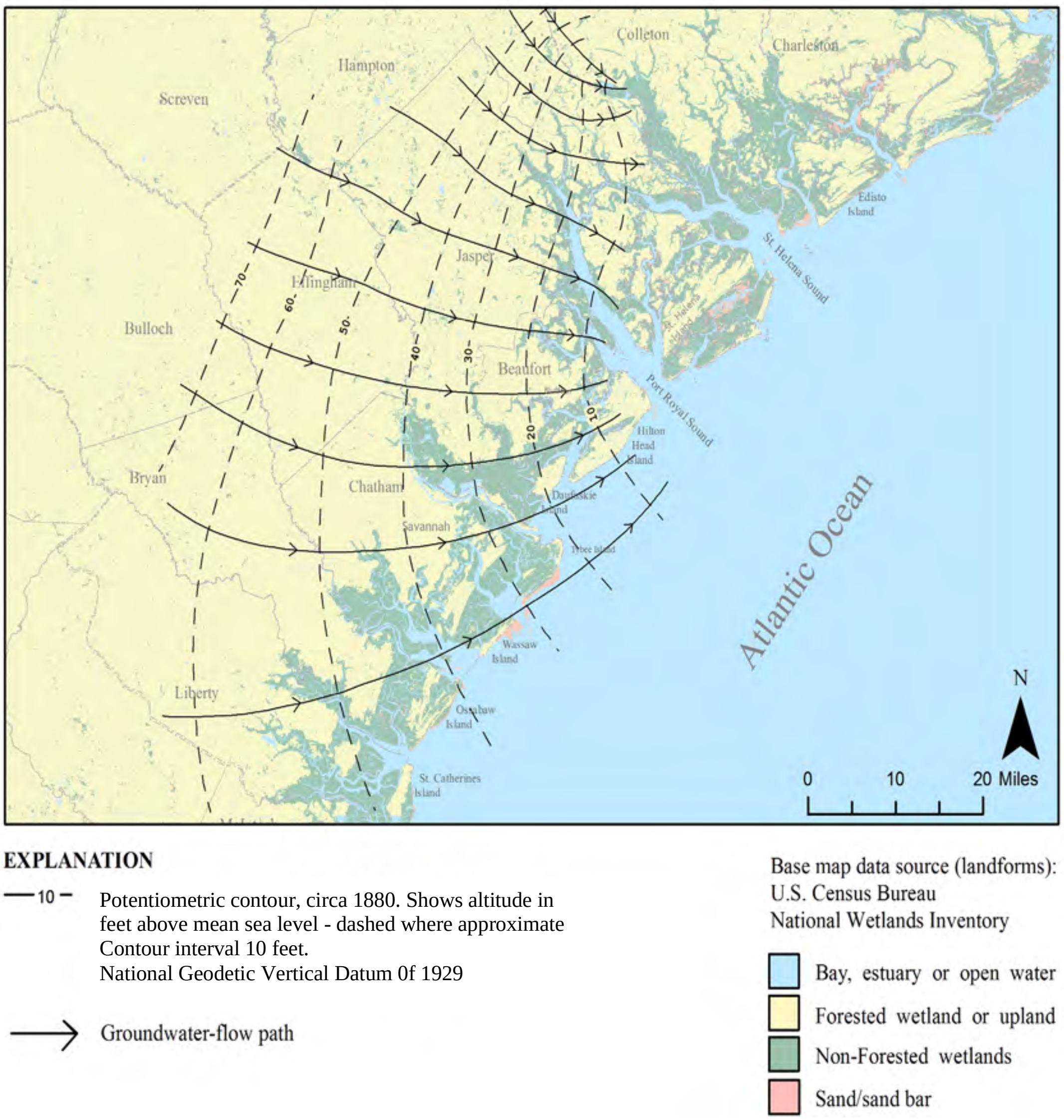


Figure 20. The estimated pre-1880 potentiometric surface of the Floridan aquifer in the Savannah, Ga., area and adjoining parts of South Carolina (after Warren, 1944; Counts and Donsky, 1963, pl. 5B).

extended Warren's map to the middle of Hilton Head Island (fig. 21), where they estimated the potentiometric surface to be about 10 ft Msl. Smith's groundwater-flow model (1988) extended the simulated predevelopment surface to the northern shoreline of the island near Port Royal Sound, where the estimated surface was about 5 ft Msl (fig. 22). Other predevelopment simulations, beginning with Counts and Krause (1974) and followed by Johnson and Krause (1980), Bush (1988), Smith (1988), Garza and Krause (1992), and the SCDHEC model included in Appendix J, closely match Warren's, and Counts and Donsky's estimated predevelopment surfaces; these models also simulated reasonable matches with later pumping conditions which add credibility to the

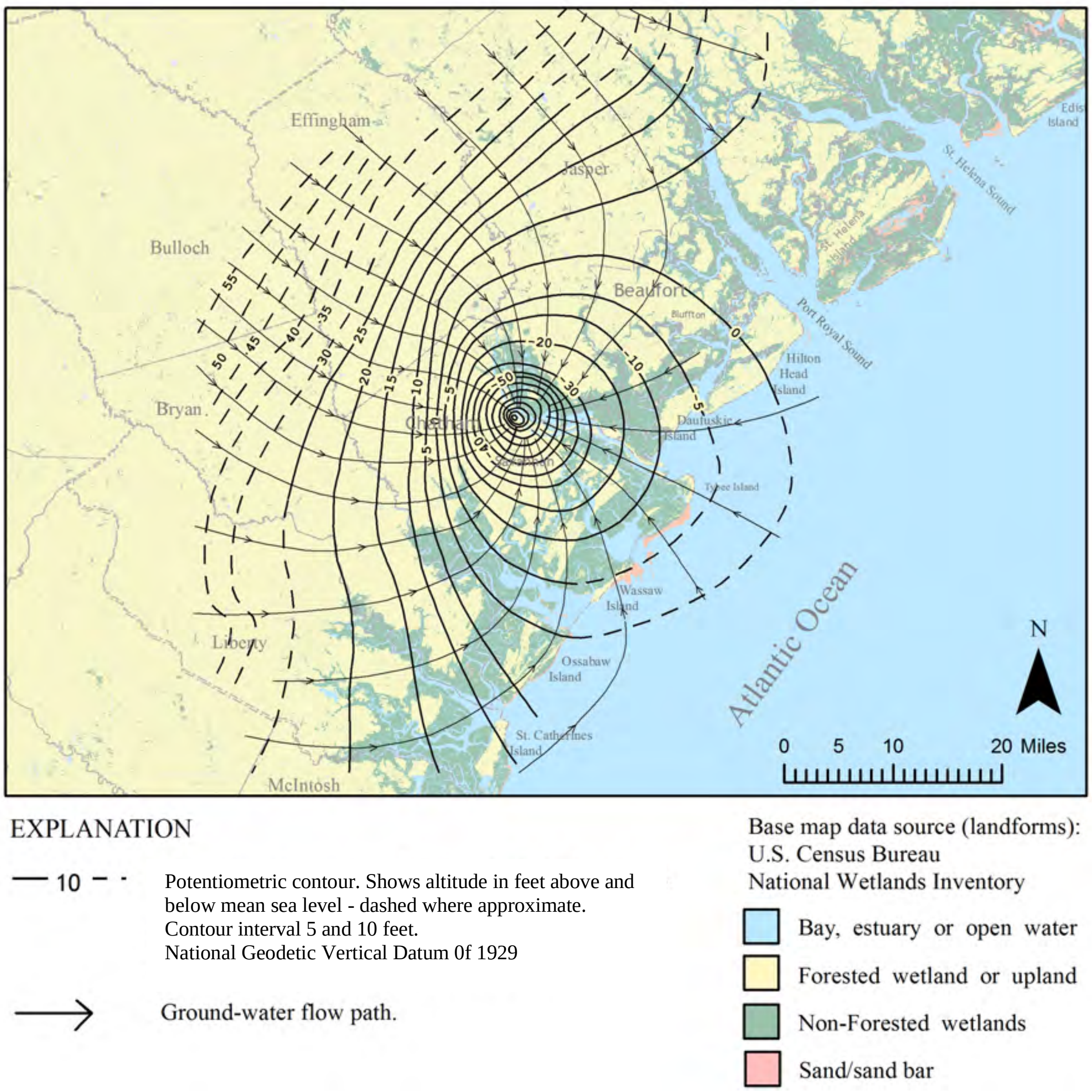


Figure 21. The 1957 potentiometric surface and direction of groundwater flow for the Floridan aquifer, Savannah, Ga., area and adjoining parts of South Carolina (Counts and Donsky, 1963).

estimated predevelopment potentiometric-surface maps.

In 1957, groundwater pumpage, mostly from the Upper Floridan aquifer at Savannah, was approximately 60 Mgal/d. A corresponding potentiometric-surface map constructed by Counts and Donsky (1963) shows that the potentiometric surface at the center of the cone of depression in Savannah was at about -120 ft Msl, and total water-level decline from predevelopment conditions was about 155 ft. Twenty miles to the northeast, near the middle of Hilton Head Island, S.C., the potentiometric surface had declined from about 10 ft Msl to 0 ft Msl (fig. 21).

Potentiometric-surface maps of the Upper Floridan aquifer, particularly those for the period between 1943 and 1961, show that the cone of depression around Savannah expanded more toward the northeast than toward the west and southwest (Counts and Donsky, 1963). The predevelopment hydraulic gradient between Savannah and Port Royal Sound began to reverse in the early 1900's. Former discharge areas (fig. 22) in the Port Royal Sound estuary and Atlantic Ocean became areas of saltwater recharge. Simultaneously, freshwater recharge from landmasses increased as Floridan aquifer water levels declined, most noticeably at northern Hilton Head Island.

The isodecline map for the Upper Floridan aquifer (Counts and Donsky, 1963) shows less change near the northern part of Hilton Head Island than areas of similar distance south of Savannah. Siple (1960) noted that the position of the 0-ft potentiometric contour had moved little from its position near the middle of Hilton Head Island and attributed the fact to greater recharge rates near the northern Hilton Head Island area. Siple's observation was quantified by Smith (1988), who simulated changes in recharge and discharge areas between the potentiometric surface of the Upper Floridan aquifer prior to groundwater development and during 1984 pumping conditions (not shown) for southern Beaufort and Jasper Counties S.C. During predevelopment conditions, the simulated northern Hilton Head Island recharge was 0- to 3-inches per year, with 3- to 6-inches per year rate in a small area where land-surface elevations were highest (fig.22). The higher surface elevations created greater surficial-aquifer heads that, in turn, induced greater rates of freshwater recharge. For 1984 pumping conditions, recharge increased from 3- to 6-inches per year for the same area (Smith, 1988). The greater recharge from the surficial aquifer resulted from a greater head difference, caused by lower pumping heads in the Upper Floridan aquifer.

Recharge of modern water to the Upper Floridan aquifer near the northern part of Hilton Head Island has also been shown by Landmeyer and Stone (1995). They determined the approximate groundwater age using radiocarbon concentrations (as Percent Modern Carbon) and stable carbon isotope ratios (as $\delta^{13}C$ in dissolved inorganic carbon) at the southern part of the island and compared their data with those of Back and others (1970) and Burt (1993) for the northern part of the island. The authors concluded that the age of water in the Upper Floridan aquifer in the southern part of the island was at least 16,000 years before present (BP) compared to groundwater that was no older than 4,000 years BP on the northern part of the island. The groundwater age in the northern part of the island probably represents modern groundwater from the surficial aquifer recharging the Upper Floridan aquifer and mixing with relict groundwater where the confining unit is thin or absent. Using a different approach, Back and others (1970), Landmeyer (1992), and Landmeyer and Stone (1995) collected water samples from the Upper Floridan aquifer on the northern part of Hilton Head Island and based on tritium analyses and carbon-14 dates, also concluded that modern water was recharging the aquifer.

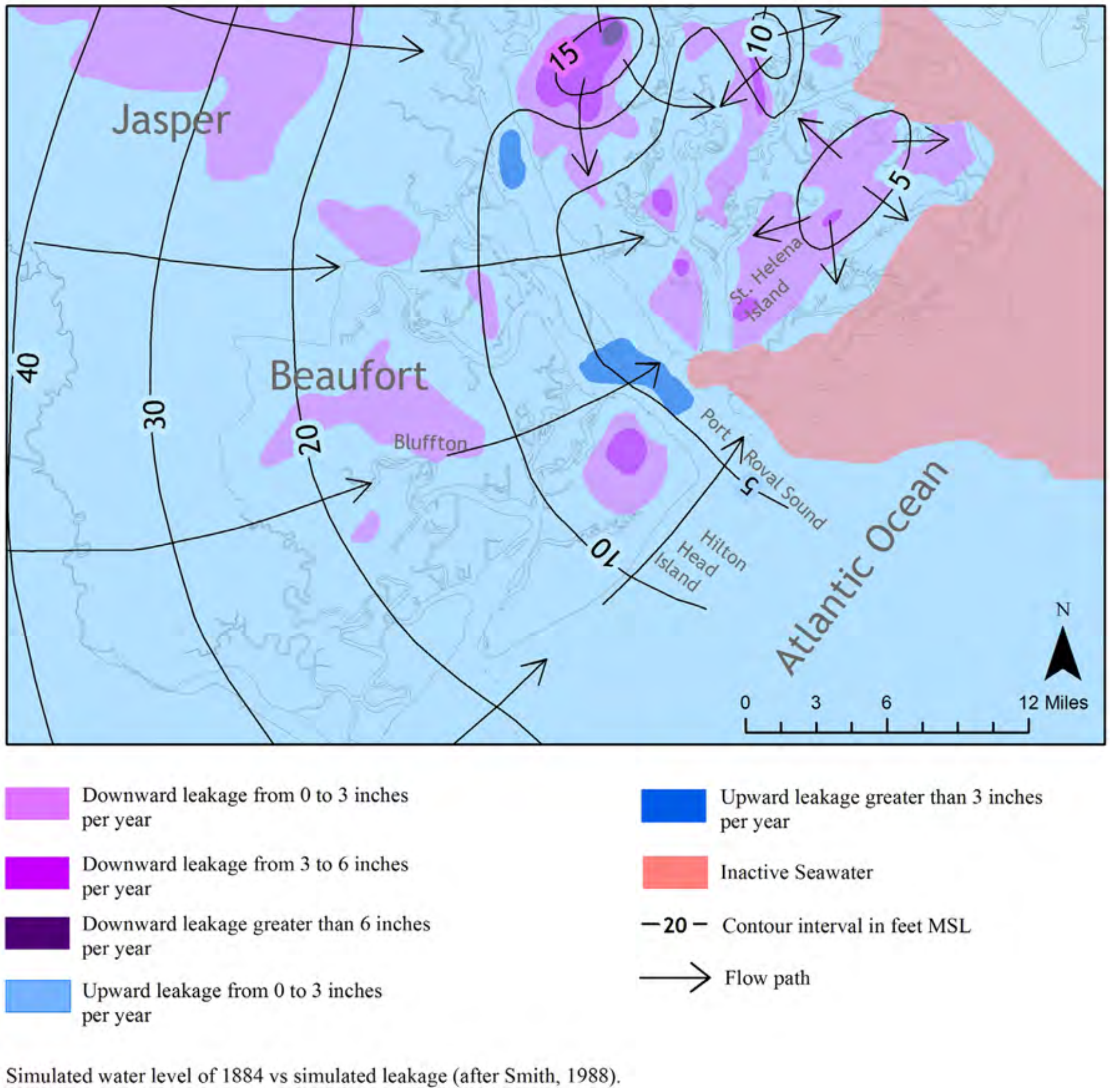


Figure 22. Simulated 1888 potentiometric surface, recharge areas, discharge areas, and flow paths for the Upper Floridan aquifer near Hilton Head, S.C. (after Smith, 1988, fig. 10)

Maximum water-level declines in the Upper Floridan aquifer occurred in 1990 for the Savannah area and continued to 1998 for Hilton Head Island (fig. 19). During that period, the potentiometric surface averaged about -10 ft Msl near the middle of Hilton Head Island and -3- to -4 ft Msl at the northern shore of the island (Gawne, 1994; Ransom and White, 1999). At Savannah, the 1998 potentiometric-surface map (fig. 23) constructed by Peck and others (1999), show water levels near the center of the cone of depression to be about -90 ft Msl but closer to the center of pumpage in 1970, Counts and Kraus (1974) reported water levels of about -150 Msl at a pumping rate of 75 Mgal/d. The SCDHEC model (Appendix J) simulated 1998 pumpage with declines of -129 ft Msl near the center of the cone of depression, which had expanded to encompass 2,300 mi^2 inside the 0 ft Msl contour (Ransom, III and others, 2006).

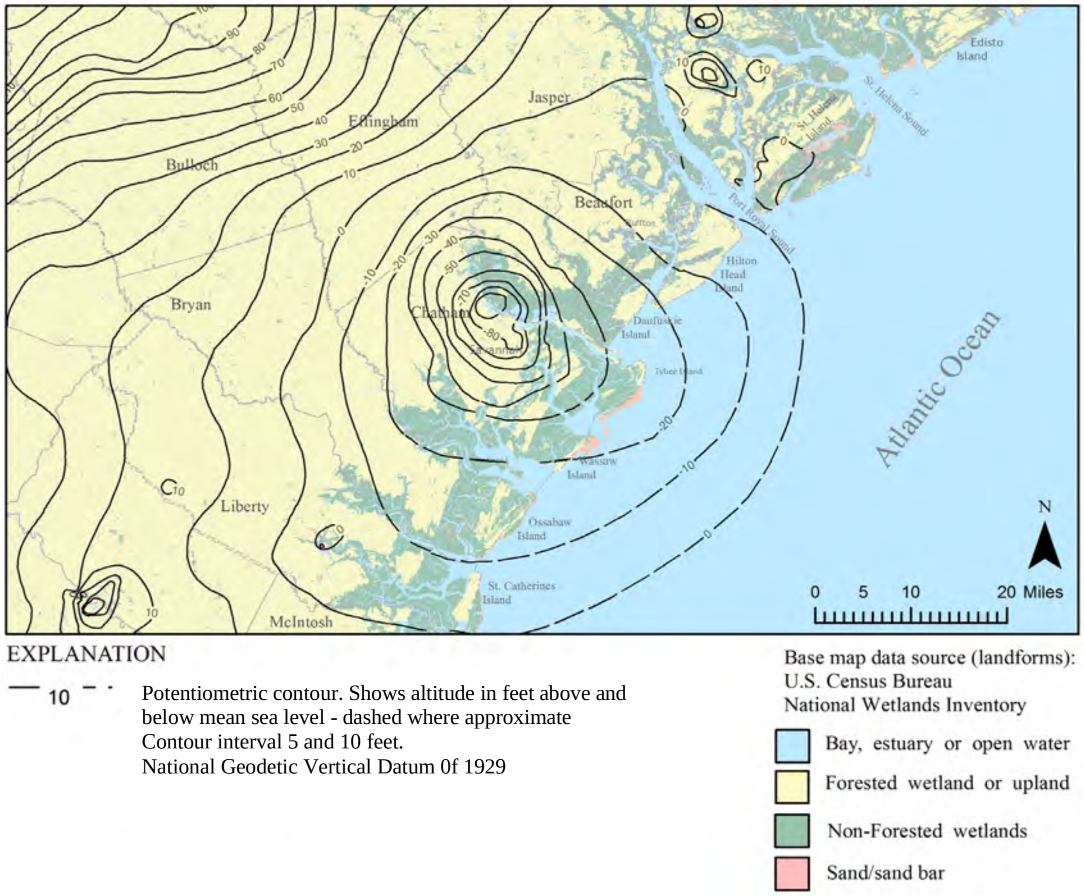


Figure 23. The 1998 potentiometric surface of the Upper Floridan aquifer in the Savannah, Ga., area and adjoining parts of South Carolina (Peck and others, 1999).

Mundorff 's 1944 and Siple's 1959 potentiometric-surface maps (Appendix D4) identified potentiometric highs on Port Royal and Parris Islands; later Hayes (1979) measured the greatest head on Port Royal Island at about 25 ft Msl. Siple interpreted these highs to represent areas of local recharge to the aquifer. Here, the upper confining unit is thin or absent beneath relatively high topographic and water-table elevations, thereby creating a steep vertical gradient between the surficial aquifer and Upper Floridan aquifer. Potentiometric highs in the Upper Floridan aquifer are documented also on Lady's and St. Helena Islands, S.C., and are shown on potentiometric-surface maps (Appendix D) constructed by Mundorff (1944), Smith (1988), Hassen (1985), Gawne (1993), and Ransom and White (1999). On northern Lady's Island and St. Helena Island, the highest heads were measured between November and March at 18 ft and 6 to 7 ft Msl (Hassen, 1985), respectively; the lowest heads were measured between May and September in 1998 and were 10 to 15 ft Msl and 1 to 3 ft Msl, respectively (Ransom and White, 1999). Here, changes in the potentiometric surface are the result of fluctuations in rainfall, increases in agricultural and domestic water use, and seasonal demand. Regional potentiometric-surface maps published by Hayes (1979), Smith (1988), Gawne (1994), and Ransom and White (1999) show a southwestward trending

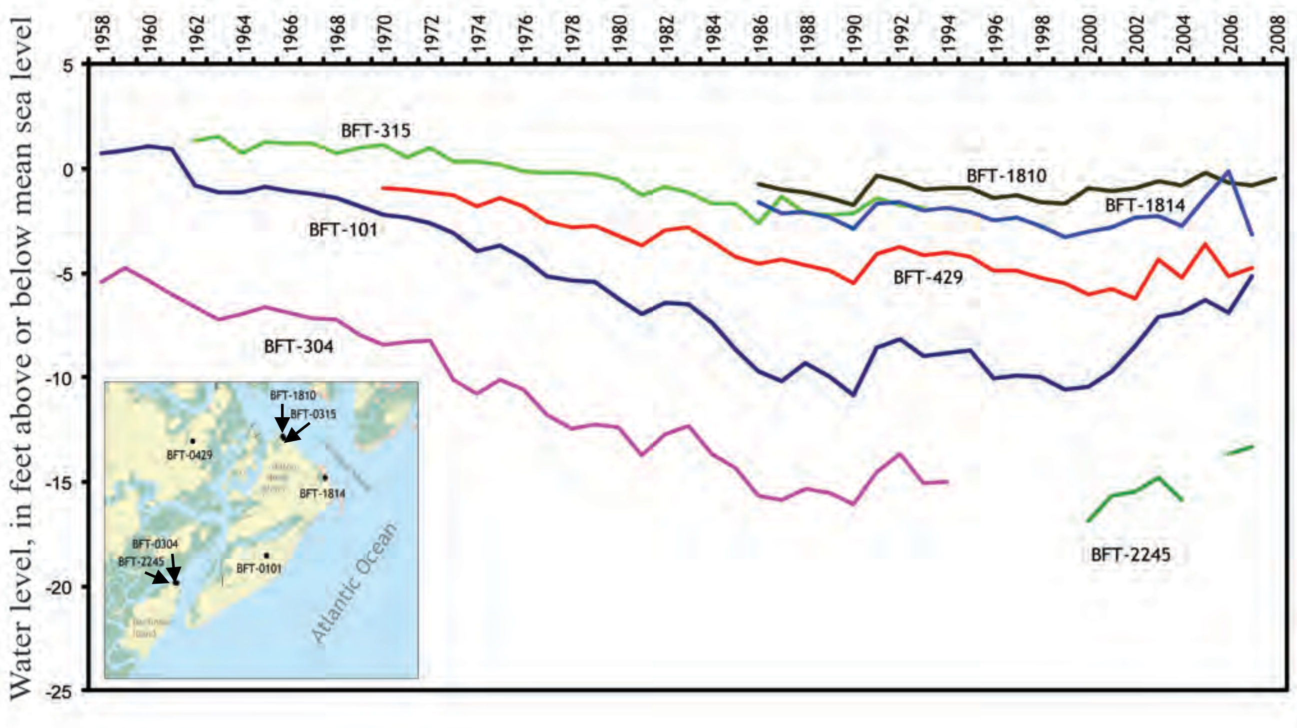


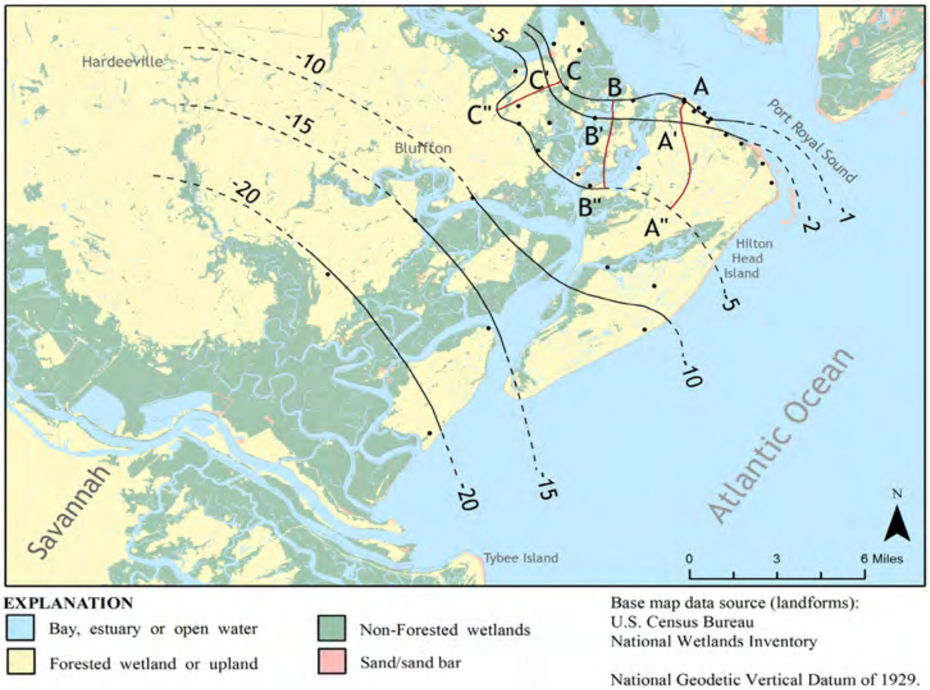
Figure 24. Daily-average water levels in southern Beaufort County observation wells, 1958–2007.

dip in the potentiometric surface west of Hilton Head Island, in the Pinckney Island – Colleton River area. Ransom and White (1999) interpreted the southwestward trending contours to represent an area of nearby recharge to the aquifer.

Historical trends in water-level fluctuations can be seen also in six hydrographs constructed with data from selected monitoring wells open to the Upper Floridan aquifer in southern Beaufort County, S.C. (fig. 24). Two hydrographs show the earliest data from Daufuskie Island (BFT-304) and Hilton Head Island (BFT-101), beginning in 1958 before significant groundwater development on Hilton Head Island. The head at well BFT-315, at the northwestern end of Hilton Head Island bordering Port Royal Sound, averaged about 1.4 ft Msl in 1962. The head, exerted by sea water in the sound, was approximately the same (1.1- to 1.6-ft Msl) after density correction for a 20- to 40-ft seawater column (0.5 – 1.0 ft); Mean Tide Level (0.4 ft); and estimated sea-level rise since 1929 (0.2 ft). Therefore, the average head in the aquifer at well BFT-315 and the average seawater level in the sound were approximately equal. Under the conditions that probably existed during the 1950's, former discharge areas beneath Port Royal Sound became areas of saltwater recharge. After about 1960, measurements show the combined influence of groundwater withdrawals on the potentiometric surface at Savannah and at southern Hilton Head Island. Potentiometric-surface elevations were lowest between 1990 and 1998, when total permitted pumpage at Savannah and Hilton Head Island peaked at about 102.5 Mgal/d. Exceptions to the downward trend occurred between 1981 and 1982 and in 1990 and 1992 when the potentiometric surface recovered slightly, perhaps because of the economic recession that occurred about that time.

The regional flow pattern in the study area principally has been controlled by pumping at Savannah, Ga., since the early 1900's; however, local pumping centers have deflected the regional flow pattern in some areas. Smith (1994, fig. 10) shows the direction of groundwater flow during 1984 in the upper part of the Upper Floridan aquifer in the area including Hilton Head Island and the

Colleton River, S.C. The flow lines indicate that pumpage near the northern part of the island introduced an easterly component to the generally south-southwestward regional flow direction. West of Hilton Head Island, near Pinckney Island and the Colleton River, the direction of groundwater flow is



Area	Transect	k (ft/d)	Δh (ft)	L (ft)	p	V_{pore} (ft/y)	p	V_{pore} (ft/y)
Hilton Head Island	A - A'	500	1	3,991	0.25	183	0.35	131
Hilton Head Island	A' - A"	500	3	17,369	0.25	126	0.35	90
Pinckney Island	B - B'	500	1	3,707	0.25	197	0.35	141
Pinckney Island	B' - B"	500	3	13,957	0.25	157	0.35	112
Colleton River	C - C'	500	1	2,808	0.25	260	0.35	186
Colleton River	C' - C"	500	3	10,389	0.25	211	0.35	151

K, horizontal hydraulic conductivity in feet/day.

Δh, head difference through transect, in feet.

L, length of transect, in feet.

p, effective porosity, dimensionless.

V_{darcy}, K (Δh, in ft / length of transect, in ft).

V_{pore}, V_{darcy} / porosity, in ft/year.

Figure 25. The average potentiometric surface of the Upper Floridan aquifer near Hilton Head Island, S.C, June 2003–June 2004, and locations of hydraulic-gradient transects used to calculate groundwater-flow velocities.

consistent with the overall regional direction and is mostly southwestward toward Savannah (fig. 25).

The average rate of groundwater flow in the Upper Floridan aquifer can be estimated with Darcy's Law if the hydraulic parameters for transmissivity (T), hydraulic conductivity (n), hydraulic gradient ($\Delta h/L$), and porosity are known. Darcy's Law does not consider dispersion and diffusion of a solute such as chloride; however, these effects are small relative to the advective flow in the aquifer. Dispersion and diffusion are considered in solute transport models (Appendix J).

Early estimates of groundwater-flow velocity in the Upper Floridan aquifer were determined along transects that generally conformed to estimated flow lines beneath Port Royal Sound, S.C. Counts and Donsky (1963), Nuzman (1972), and Hayes (1979) computed respective rates of 18, 74, and 140 ft/yr in the vicinity of Port Royal Sound. The variation in rate depended on the hydraulic parameters and gradients assigned to the transect location. Model simulations by Smith (1988, 1994), using data obtained from offshore tests in Port Royal Sound in 1984, estimated rates of 50 to 80 ft/yr between St. Helena Island and Hilton Head Island and greater than 200 ft/yr on Hilton Head Island.

Groundwater-flow velocities in the Upper Floridan aquifer were estimated along six transects (fig. 25) through the Dolphin Head, Pinckney Island, and Colleton River chloride plumes. Hydraulic gradients differed across each transect because of local pumping distribution, recharge-source areas, and the hydraulic properties of the aquifer. Darcy's equation was used to calculate travel times using hydraulic gradients from an average potentiometric-surface map estimated with 2004 average-daily water levels recorded by local data loggers (fig. 25); an average horizontal hydraulic conductivity of 500 ft/d; and porosities of 0.25 and 0.35. Horizontal hydraulic conductivity for the aquifer was computed using an average transmissivity of 50,000 ft^2/d and an average aquifer thickness of 100 ft. Saltwater-density corrections were not applied to water-level measurements because of the relatively small volumes and low concentrations of salt water compared to seawater. The estimated flow velocities derived from Darcy's Law were 90 to 183 ft/yr at the northeast shoreline of Hilton Head Island; 141 to 197 ft/yr beneath Pinckney Island; and 151 to 260 ft/yr near the Colleton River.

Middle Confining Unit

The middle confining unit underlies the Upper Floridan aquifer and corresponds to the lower unit of the Ocala Limestone (Herrick and Wait, 1955; Counts and Donsky, 1963; Hughes and others, 1989; Gawne and Park, 1992). The unit is less permeable than major water-yielding zones above and below the unit, thus it impedes vertical flow between the Upper and middle Floridan aquifers.

Flow-meter tests completed at six well sites in Chatham County, Ga., and Hilton Head Island, S.C., reported by McCollum and Counts (1964), indicated negligible yield from their permeable zone 3 near the center of the middle confining unit (identified in one well on Daufuskie Island). Similarly, Gawne and Park (1992) observed no inflow from open-hole flow-meter tests completed through the middle confining unit at four wells in the vicinity of Hilton Head Island. Gawne and Park (1992) also reported the results of drawdown and recovery tests at five sites using middle Floridan aquifer wells (BFT-1845, BFT-1840, BFT-1809, BFT-1820, BFT-1813) paired with Upper Floridan aquifer observation wells: a sixth middle Floridan aquifer well (BFT-315) was used as an observation well for BFT-1809 (fig. 26). After pumping the middle Floridan aquifer 150 to 200 gpm for 24 hours, no meaningful drawdown was measured in the adjacent Upper Floridan well; the low pumping rate probably contributed to lack of measurable drawdown. In another approach, Gawne and Park (1992) modified Smith's (1988) flow model to include the middle confining unit and the middle Floridan aquifer: the authors adjusted the vertical hydraulic conductivity of the middle confining unit to match simulated and observed Upper and middle Floridan aquifer water levels at Hilton Head Island. The best simulation was produced with a vertical hydraulic conductivity of 0.009 ft/day for the middle confining-unit.

The most comprehensive multi-well middle Floridan aquifer test was conducted at Jenkins Island to the west of Hilton Head Island (fig. 26) by Groundwater Management and Associates (GMA, 2006). Here, the pumping well BFT-2479 and the monitoring well BFT-2478 were cased and grouted near the top of the middle Floridan aquifer at about 512 ft bgs and completed as an open-borehole to a depth of 600 ft bgs; a second well (BFT-2480) completed in the Upper Floridan aquifer was monitored also. The test induced about 0.5 ft of drawdown in the nearby Upper Floridan aquifer after pumping 1,000 gpm for 96 hours from the middle Floridan aquifer well; the data indicated also that a recharge boundary occurred after about 7 minutes. Data from the test was evaluated using the Neuman-Witherspoon Method (1969) to calculate a vertical hydraulic conductivity of 2.4 ft/d for the middle confining unit. GMA concluded that leakage from the middle confining unit probably accounted for the source of recharge, and their finding was consistent with Krause and Randolph (1989) and Gawne and Park (1992) who concluded that the Lower Floridan and middle Floridan aquifer, respectively, were hydrologically connected to the Upper Floridan aquifer and that the middle confining unit, while less permeable, was sufficiently permeable to transmit changes in head between the two aquifers given enough time. The SCDHEC model (Appendix J) for the Savannah – Hilton Head Island area was also used to evaluate the connection between the Upper and middle Floridan aquifers. The base model used a more conservative value of 0.05 ft/d for conductivity and a thickness of about 300 ft for the middle confining unit. To test the degree of connection, model parameters configured in the base model remained unchanged, except that pumpage from the Upper Floridan aquifer was removed by lowering the casing to the top of the middle Floridan aquifer. The resulting simulated potentiometric-surface map (unpublished) for the Upper Floridan aquifer with only middle Floridan aquifer pumpage was similar to the 1998 map (Ransom and White, 1999), supporting the conclusion that the middle Floridan aquifer is hydraulically connected to the Upper Floridan aquifer.

Middle Floridan Aquifer

The middle Floridan aquifer was informally named by Gawne and Park (1992) in southern South Carolina, but other reports have included the aquifer as part of the Upper or Lower Floridan aquifer. The aquifer is equivalent to the upper part of the middle Eocene Santee Limestone and corresponds with permeable zone 4 identified by McCollum and Counts (1964) in the Savannah area (included in the Lower Floridan aquifer in Georgia). The aquifer extends as far south as Rincon, Ga. (Gill and Williams, 2010), and it is widely used for golf course irrigation west of Hilton Head Island. Here, twenty-five production wells open to the middle Floridan aquifer were drilled between 1993 and 2007 (fig. 26) and pumped an average of 3 Mgal/d during 2007 (fig. 27). Most pumping occurred within the April-to-September irrigation season. Middle Floridan aquifer withdrawals for public-supply on Hilton Head Island began on Jenkins Island in 2009 and currently pump an additional 4 Mgal/d: reverse-osmosis treatment (R/O) was required to remove dissolved chloride. Other uses included aquifer storage and recovery for treated surface water and reclaimed water.

The middle Floridan aquifer lies beneath the middle confining unit near the top of the Santee limestone and is underlain by limestone of low permeability that acts as the lower confining unit of the Floridan aquifer system. In the study area, the aquifer can sometimes be identified by an electrical-resistivity log and by a natural gamma-ray log signature having relatively less radiation compared to the carbonate sediment above and below; however, identification is best made by flow-meter tests to determine the actual depth and thickness of the middle Floridan aquifer. Depth from ground surface to the top of the aquifer is between 450 and 600 ft Msl in the study area. Flow-meter traverses conducted in four wells indicate that the middle Floridan aquifer ranges from 30 to 60 ft in thickness on Hilton Head Island and northwest of the island but thins northward and is generally absent north of Port Royal Sound and the Broad River (Gawne and Park, 1992).

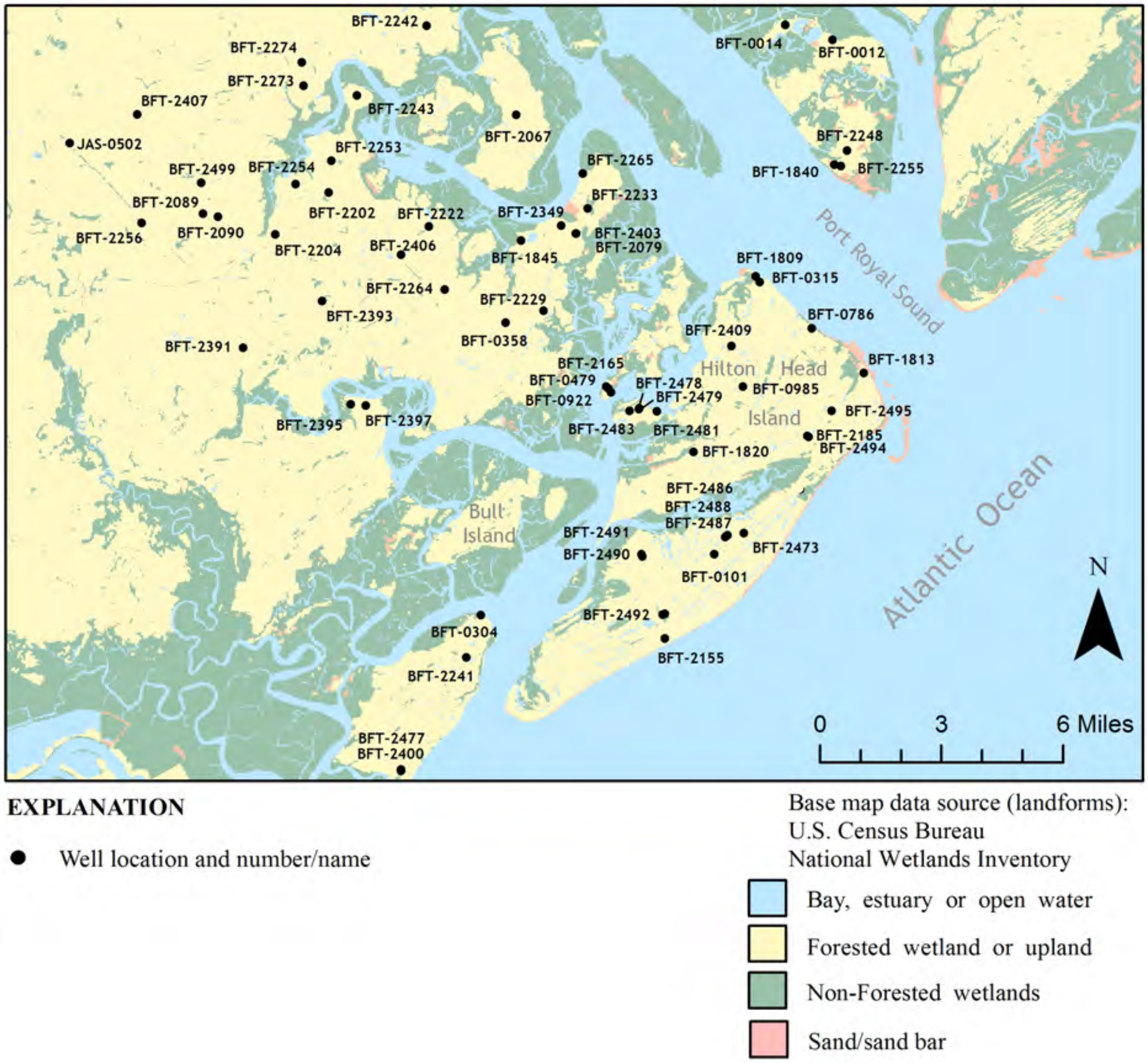


Figure 26. Middle Floridan aquifer observation and production wells in the study area.

Hydraulic parameters for the middle Floridan aquifer are problematic in southern South Carolina because most data are based on single well pumping tests that cannot identify recharge boundaries. Gawne and Park (1992) analyzed six middle Floridan aquifer well sites in the Hilton Head Island area of which five were single well tests; pumping rates did not exceed 200 gpm except for well BFT-985 where the pumping rate was 600 gpm. A sixth site was tested by pumping well BFT-1809, originally completed as an open-borehole between 300 and 900 ft Msl. Drawdown was measured also in a nearby middle Floridan aquifer monitoring well (BFT-315) with 30 ft of open borehole located about 1,500 ft from well BFT-1809. The highest transmissivity, 26,000 ft^2/d, was calculated at well BFT-985; the remaining five sites averaged 7,240 ft^2/d. Newcome (1993, 2002, and 2005) calculated transmissivities from 25 middle Floridan aquifer wells in southern Beaufort County southwest of Port Royal using single well pumping tests; another nine sites were located north of Port Royal Sound. For the southwestern well sites near Hilton Head Island and west of the island, with an average reported pumping rate of 513 gpm, the average value for transmissivity was 8,630 ft^2/d; specific capacity averaged 21 gpm/ft and ranged between 5.8 and 52 gpm/ft. For the northern sites, with an average pumping rate of 265 gpm, the average value for transmissivity was 554 ft^2/d; specific capacity ranged from 0.5 and 4.7 gpm/ft and averaged 1.6 gpm/ft. These data support earlier conclusions that the middle Floridan aquifer pinches out to the northeast and limited well yield is caused by low permeability of the sediment compared to similar wells to the southwest of Port Royal Sound. Two middle Floridan wells (BFT-2248 and BFT-2255) located on Parris Island were cased and grouted to the top of the middle Floridan aquifer thereby eliminating yield in the open-borehole from the low permeability middle confining unit; here, the specific capacity of both wells was 1.1 gpm/ft.

The comprehensive multi-well aquifer test (discussed earlier under middle confining unit) conducted by GMA (2006) for the middle Floridan well field on Jenkins Island (west and adjoining Hilton Head Island) was analyzed to determine transmissivity of the middle Floridan aquifer. Because pump-test data indicated a recharge boundary 7 minutes after pumping started, GMA used the Neuman-Witherspoon Method (1969) designed for a leaky confining unit. GMA calculated the transmissivity and storage coefficient for the middle Floridan aquifer to be 2,250 ft^2/d and 0.00027, respectively. Specific capacity at well BFT-2279 was 14.2 gpm/ft, and two additional production wells, BFT-2483 and BFT-2481, had specific capacities of 14.3 and 11.1 gpm/ft, respectively. Greater specific capacities computed by Newcome (2005) may be attributed to greater open borehole (average casing depth of about 350 ft bgs as opposed to 512 ft bgs at the Jenkins Island well field) thereby allowing thin zones of higher permeability within the lower permeability middle confining unit to contribute additional discharge.

Water levels were measured in February 1991 at five sites near Hilton Head and Parris Island; each included a monitoring well in the Upper Floridan aquifer and one in the middle Floridan aquifer (Gawne and Park, 1992, fig. 4). The measurements taken for each aquifer showed water levels were nearly equal and that the middle Floridan aquifer responded to changes in the Upper Floridan aquifer, including seasonal pumping patterns. Heads in the middle Floridan aquifer were higher except at the well pairs closest to Port Royal Sound, where vertical head gradients ranged from 0.7 to -2.27 for the Upper Floridan and middle Floridan aquifers, respectively. Thus, hydraulic gradients in the middle Floridan aquifer were generally upward;

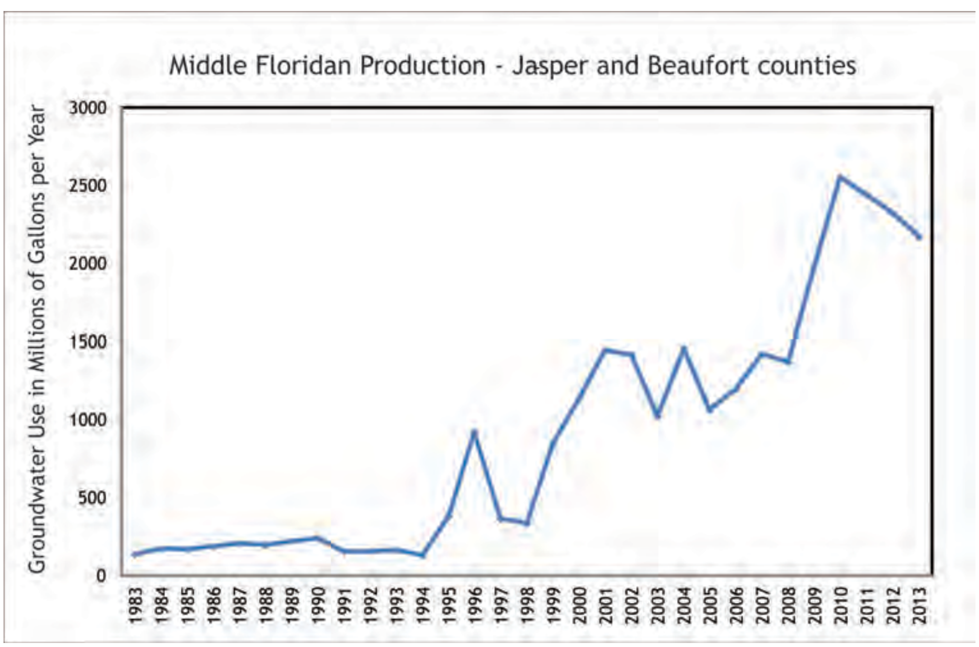


Figure 27. Groundwater use from the middle Floridan aquifer, southern Beaufort County, S.C., 1983–2013.

however, post-1992 (fig. 27) pumpage from the middle Floridan aquifer increased west of Hilton Head Island and likely reversed the upward hydraulic gradient in the Colleton River and Bluffton areas.

Lower Confining Unit – Lower Floridan Aquifer

In the Savannah, Ga., area, the lower Floridan aquifer is comprised of sediment equivalent to the middle Eocene Avon Park Formation (equivalent to Santee limestone in South Carolina) and includes permeable zones 4 (informally the middle Floridan aquifer in South Carolina) and 5 (fig. 6). In southern South Carolina, the Lower Floridan aquifer is comprised of sediment that is time-equivalent to the middle Eocene Santee Limestone and, if present, would include permeable zones 3 and 5. Permeable zone 3 has only been identified in one well on Daufuskie Island and zone 5 appears to be absent. These two zones were estimated to supply 20 to 30 percent of the combined yield of the Upper and Lower Floridan aquifer in Chatham County, Ga. (McCollum and Counts, 1964). Five miles south of Savannah, at Hunter Army Airfield, Williams (2010) constructed a test well that penetrated most of the Floridan aquifer. He conducted flow meter test on discrete zones and identified five to six permeable zones in the Lower Floridan aquifer and measured their combined yield at 16.5 percent of the total Floridan aquifer yield. Two investigations by the USGS and GMA in 2011 and 2012, respectively, examined the sediment and water-bearing properties of the lower Floridan aquifer in South Carolina. The USGS geologic borehole (BFT-2473) completed at Hilton Head Island (fig. 28) was advanced by continuous core to a depth of 1,250 ft bgs. Recovered cores showed that the lower sediment is comprised mostly of hard calcified carbonate rock. A second investigation to determine the potential of the Lower Floridan aquifer as an alternative source at Hilton Head Island was conducted by GMA for South Island Utilities. The investigation included a test well (BFT-2485) cased and grouted to 1,002 ft bgs and completed to 1,140 ft bgs (fig. 28). The well was pumped at a rate of 35 gpm for six hours and produced a total drawdown of 438 ft, resulting in a specific capacity of 0.08 gpm/ft. Evidence to date suggests that in South Carolina the top of middle Eocene sediment lies from about 500 ft bgs at Parris Island to about 700 ft bgs at Hilton Head Island, and the sediment primarily function as the lower confining unit of the Floridan aquifer system.

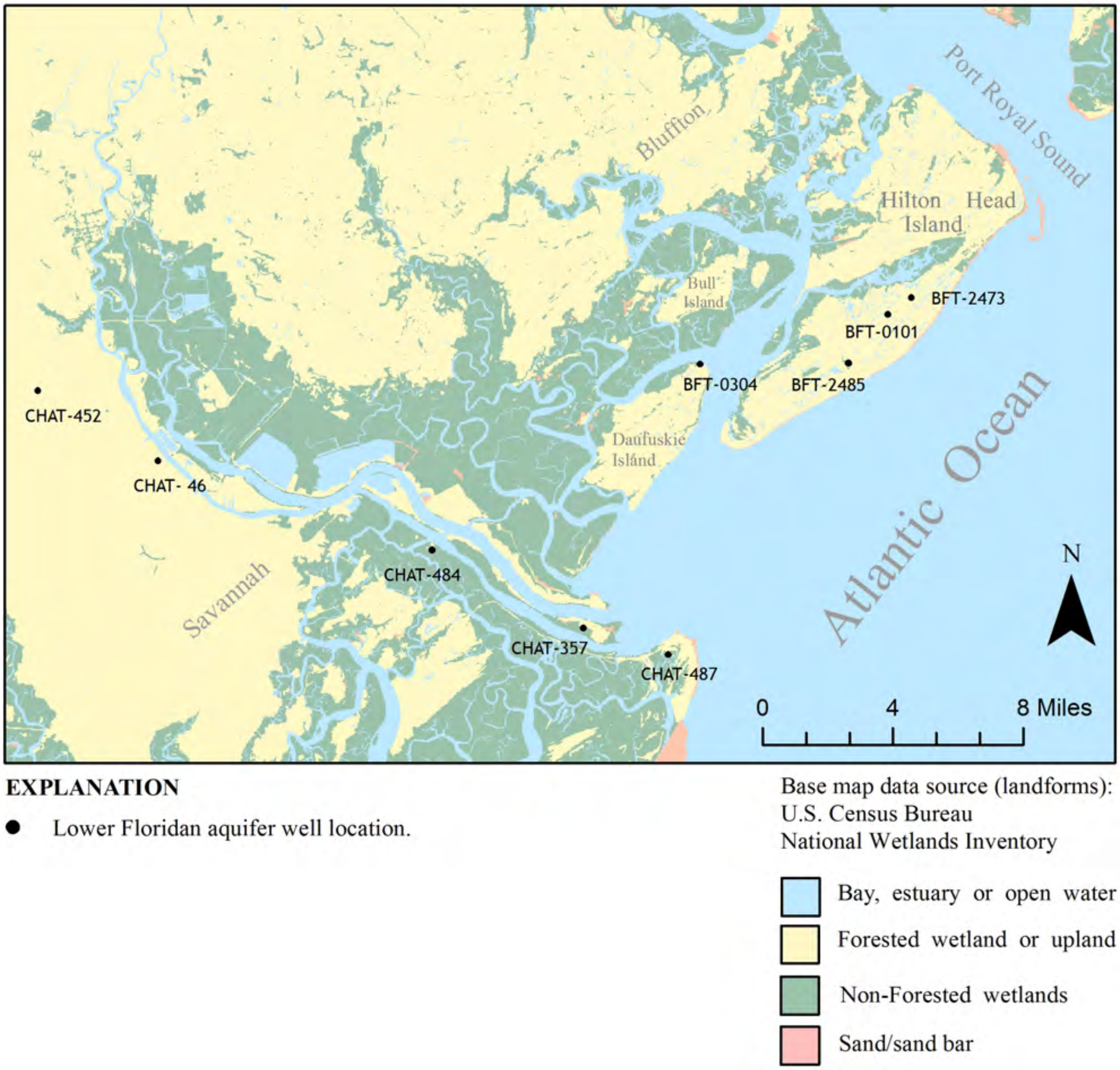


Figure 28. Location of test wells penetrating the Lower Floridan aquifer.

SALTWATER CONTAMINATION

Saltwater contamination as discussed in this report refers to chloride contamination by relict and modern seawater. Referring to the U.S. Environmental Protection Agency (EPA) definitions, fresh water contains less than 250 mg/L chloride; brackish water contains between 250 to 9,500 mg/L chloride (to 50-percent seawater); and salt water contains between 9,500 to 19,000 mg/L chloride (100-percent seawater). The American Society for Testing and Material (ASTM) defines fresh water, brackish water and salt water as water having total dissolved-solids concentrations less than 500 mg/L, 500 to 30,000 mg/L, and 30,000 to 50,000 mg/L, respectively (ASTM D3875 08). The maximum chloride concentration recommended by the EPA and enforced by SCDHEC for public water supply is 250 mg/L; most people will taste dissolved chloride at concentrations of 400 mg/L and greater (Note: computed chloride used in this section is discussed in the Methodology section of this report).

The Last Glacial Maximum began about 122,000 years ago when sea level was declining and ended approximately 26,500 years ago. As sea level declined, the shoreline retreated toward the east leaving higher landmasses to the west. Higher landmasses allowed for increasingly higher freshwater heads in the Upper Floridan aquifer that, in turn, created greater lateral and upward discharge across the hydrogeologic units, eventually purging relict saltwater from the sediment. After a pause, the glacial maximum ended, sea level began to rise about 19,000 years ago from about 400 ft lower than present (from Wikipedia). A gradual loss of freshwater head occurred in the hydrogeologic units as the shoreline advanced westward over landmasses to about 10 ft above its current position between 10,000 and 5,000 BP (early- to mid-Holocene). Afterwards, sea level declined to its current position.

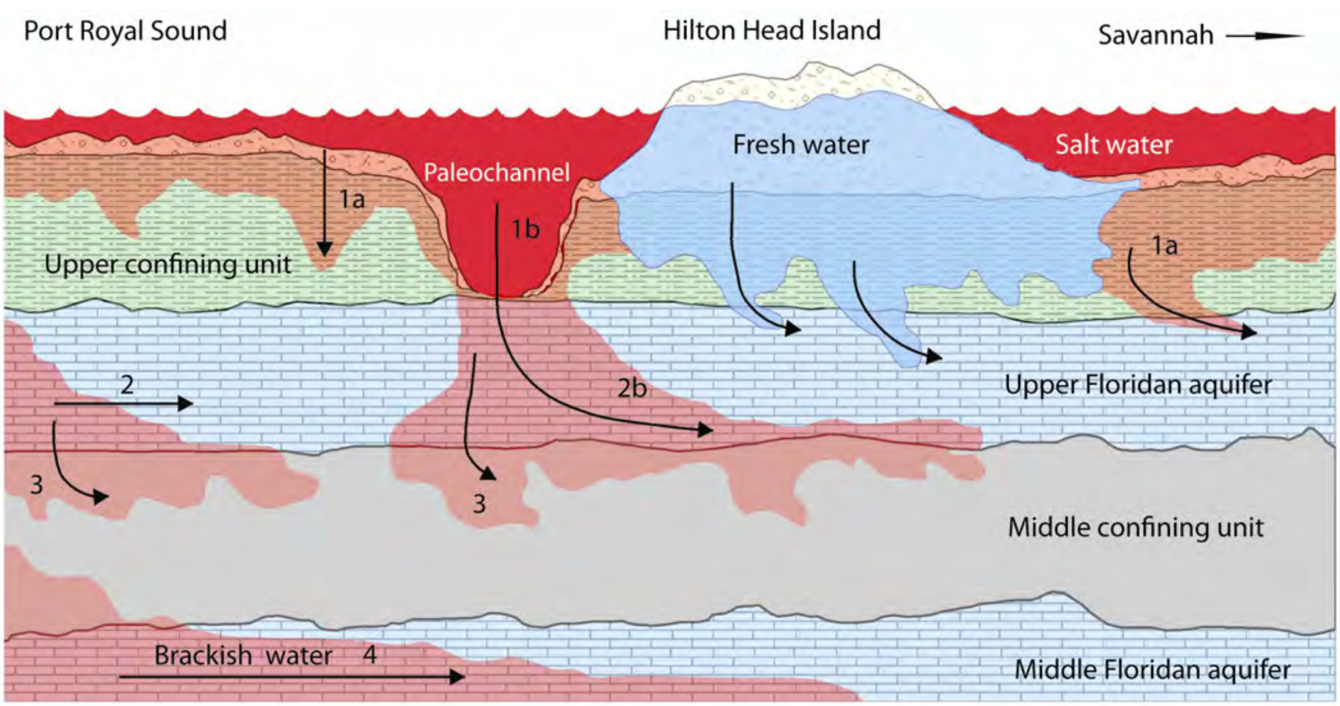


Figure 29. Generalized diagram showing saltwater movement in the Upper Floridan aquifer and adjacent confining units after groundwater withdrawals lowered the potentiometric head.

Freshwater heads to the southwest of Port Royal Sound remained sufficient to prevent lateral saltwater encroachment into the Upper Floridan aquifer beneath the Savannah - Hilton Head Island area. Exceptions occur near the Port Royal Sound and Parris Island areas and northeast of the sound where areas of freshwater discharge lowered the potentiometric heads to within a few feet of mean sea level beneath saltwater tidelands and the Atlantic Ocean. Here, the relict brackish-to-saltwater interface remained in equilibrium for the middle Floridan aquifer, the middle confining unit, the upper confining unit, and part of the surficial and Upper Floridan aquifers. Beginning in about 1950, large groundwater withdrawals in the southwest reversed lateral and upward hydraulic gradient and initiated lateral movement of relict brackish to saltwater toward pumping wells and downward migration of modern salt water. Rising sea level continues to contribute to saltwater intrusion.

The paths by which salt water moves through

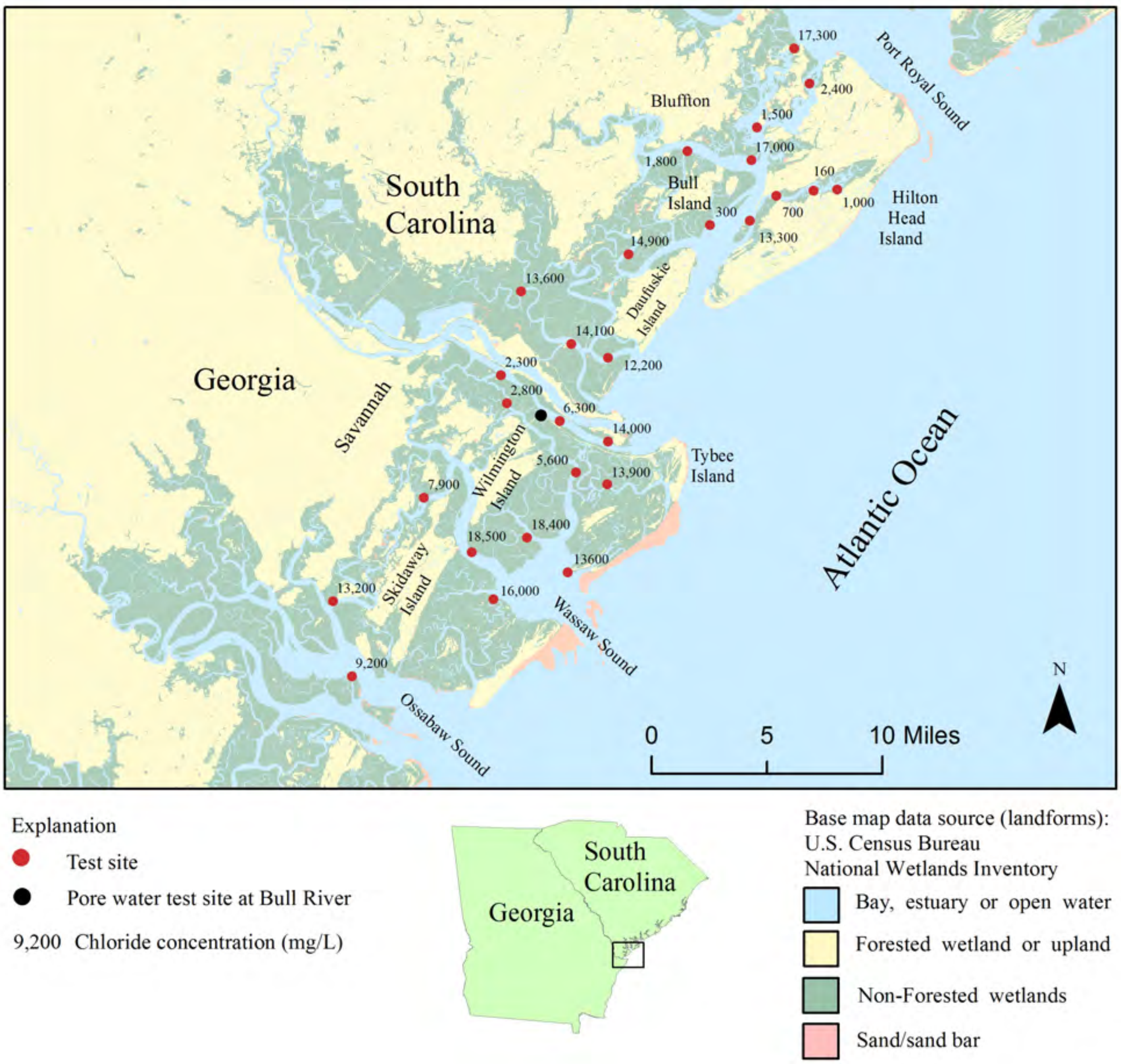


Figure 30. Test-boring locations and chloride concentrations near the bottom of the surficial aquifer between Port Royal Sound, S.C., and Ossabaw Sound, Ga. (Ransom and Park, 2011).

confining units and aquifers in the study area include: (1) modern seawater migrating from saltwater estuaries and the Atlantic to the Upper Floridan aquifer by (a) relatively slow movement through the upper confining unit and by (b) more rapid movement where the upper confining unit is thin or absent; (2) lateral movement of relict brackish water and modern seawater in the Upper Floridan aquifer; (3) salt water moving from the bottom of the Upper Floridan aquifer into the middle confining unit toward the middle Florida aquifer; and (4) lateral movement of relict brackish water in the middle Floridan aquifer (fig. 29).

Surficial Aquifer

The surficial aquifer provides recharge to the underlying upper confining unit and, where the upper confining unit is absent, recharge takes place directly to the Upper Floridan aquifer. Beneath the mainland and Sea Islands, chloride concentration in the surficial aquifer is consistently low owing to rainfall; there, chloride concentrations are about 5 to 25 mg/L (Siple, 1960; Hayes, 1979; Hassen, 1985; Dale and Park, 1999). Salt water to brackish water is present in the surficial aquifer beneath the Atlantic Ocean, tidal streams, and saltwater marshes.

Fresh water discharge from landmasses plays an important role near intracoastal areas by diluting seawater as it migrates downward from overlying sources. Here, fresh water in the surficial aquifer moves laterally from landmasses where heads are higher (owing to higher elevation) toward offshore areas where heads are near 0 ft Msl. Ransom and Park (2011) collected water samples at 27 offshore sites beneath intracoastal Beaufort County, S.C., and Chatham County, Ga. (fig. 30). The observed chloride concentrations at the bottom of the aquifer ranged from 167 to 18,000 mg/L. The principle factors affecting chloride concentrations were (1) the proximity, size, and elevation of the nearby landmasses that capture rainfall and discharge fresh water laterally through the subsurface toward their boundaries; (2) seawater dilution by discharge from the Savannah River; and (3) proximity to the Atlantic Ocean and Port Royal Sound where seawater dilution is minor. At most of the test sites chloride concentration decreased with depth and increased with distance from land, indicating that, locally, the lower part of the surficial aquifer is partly confined and influenced by lateral freshwater recharge from nearby land. Lower than expected chloride concentrations were found between Bull Island and Hilton Head Island (300 mg/L), east of Wilmington Island (5,600 mg/L), and at the northwest end of Ossabaw Sound (9,200 mg/L): the unexpected low chloride concentrations at those sites might indicate that the confinement of the lower part of the surficial aquifer was uncommonly effective. Chloride concentrations were greater than expected near the confluence of Skull Creek and Broad Creek (13,300 mg/L), north of Pinckney Island (17,000 mg/L), and south of Jenkins Island (17,000 mg/L). The upper confining unit is known to be thin at locales near the three sample sites, and the high concentrations could result from greater interconnection between the surficial aquifer and the Upper Floridan aquifer.

Upper Confining Unit

Downward saltwater migration takes place beneath about 1,200 mi^2 where the Upper Floridan aquifer is overlain by seawater and the aquifer's potentiometric surface is at or below mean sea level. In the Savannah - Hilton Head Island study area the upper confining unit generally protects the underlying Upper Floridan aquifer by slowing the downward movement of chloride (salt water to brackish water) from the overlying surficial aquifer. Sources of chloride in the surficial aquifer include the Atlantic Ocean, the Port Royal Sound estuary, and saltwater channels and wetlands between the sound and northeastern Georgia. Chloride analyses of pore water extracted from upper confining unit cores have documented the downward migration and dispersion of seawater at 17 boreholes (Fig. 31) taken from sixteen sites as part of this study and from earlier studies in South Carolina and Georgia (Falls and others, 2005; Ransom and others, 2006; U.S. Army Corps of Engineers, 2007).

The rate of downward movement and the chloride concentration at a given depth in the upper confining unit depend on (1) the chloride-concentration source at the bottom of the surficial aquifer, (2) the thickness of the unit, (3) the vertical hydraulic conductivity in the unit and, (4) the hydraulic gradient across the unit that varies principally in response to (a) recharge from rainfall and (b) groundwater withdrawals, (5) sea-level rise, and (6) the time since chloride began to migrate through the confining unit, thereby progressively increasing the chloride concentration and fluid density. Because the above referenced controlling factors differ with location and depth, chloride concentrations in the upper confining unit will vary greatly and range from about 5 mg/L in uncontaminated water to concentrations near that in sea water.

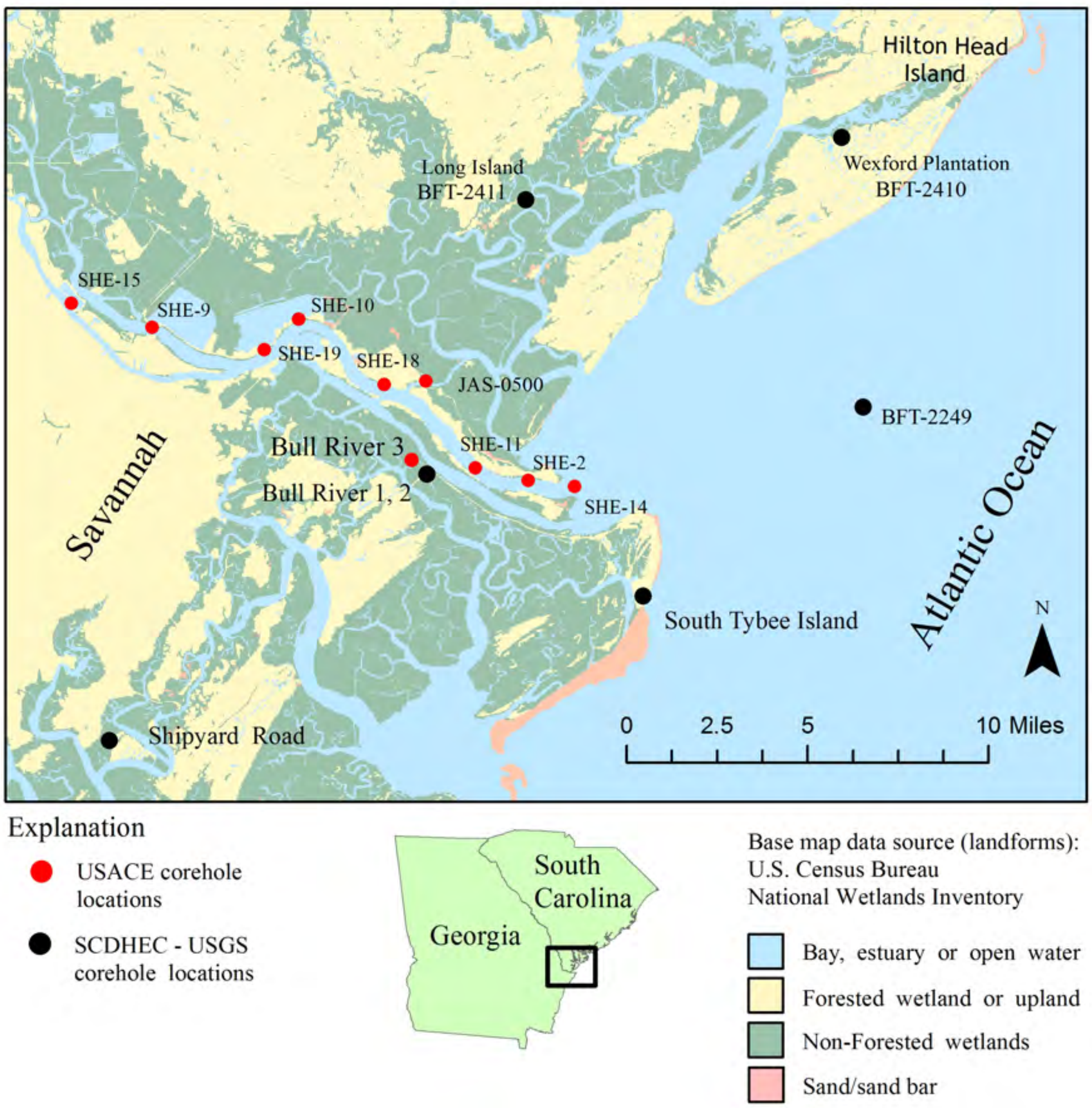


Figure 31. Locations of pore-water samples and chloride-concentration profiles in the upper confining unit

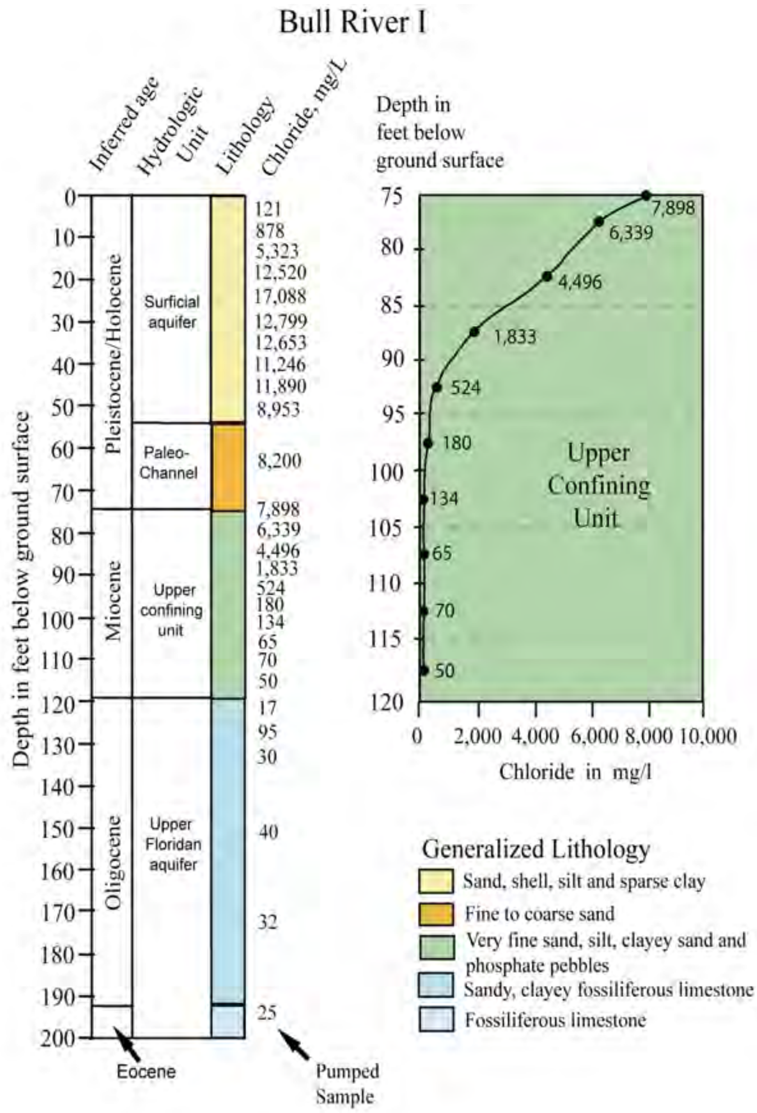


Figure 32. Chloride concentrations in pore-water samples from the surficial aquifer, upper confining unit, and Upper Floridan aquifer at well-site Bull River 1, 2005 (Ransom and others, 2006).

Pore-water extraction to determine chloride concentrations in the upper confining unit was performed at the Bull River I test site between Savannah and Tybee Island, Ga., in 2001 (Ransom and others, 2006). Twenty-six pore-water samples were extracted from continuous 4-inch cores collected between ground surface and 200 ft bgs (fig. 32). Chloride concentrations in the surficial aquifer progressively increased from 121 mg/L at 5 ft bgs to 17,100 mg/L at 25 ft bgs. Chloride concentration decreased from 17,100 mg/L at 25 ft bgs to about 8,000 mg/L in a sand-filled paleochannel between 54 and 74 ft bgs, possibly owing to lateral freshwater discharge from the Sea Islands and mainland (see fig. 14 in **HYDROGEOLOGY – Surficial aquifer** section). Chloride contamination was present through the full thickness of the upper confining unit, and breakthrough into the Upper Floridan aquifer was indicated by chloride concentrations of 17 mg/L to 95 mg/L in the Oligocene section of the aquifer.

The estimated time for chloride concentrations to reach 250 mg/L in the Upper Floridan aquifer from downward chloride migration through the upper confining unit was simulated by applying a one-dimensional solute-transport model to the most susceptible area located east to northeast of Savannah Ga (Ransom and others, 2006). The model covers an area of about 380 mi^2 where the upper confining unit is relatively thin, has a steep hydraulic gradient, and supplies an estimated 7.7 Mgal/d downward recharge to the aquifer. Using the data from Bull River I to assist with model calibration, breakthrough times (in years from 2005) at the bottom of the upper confining unit were simulated for a 500 mg/L chloride concentration for 110 cells (fig. 33). The model used a chloride-source concentration of 19,000 mg/L at the bottom of the surficial aquifer, a concentration that is too high for the intracoastal areas (fig. 30) as demonstrated by Ransom and Park (2011). Smith (1988) calculated that, on average, about 50 percent of the water withdrawn from the aquifer is supplied by downward recharge and a similar volume of water flows laterally through the aquifer toward pumping wells. This suggests that as recharge water

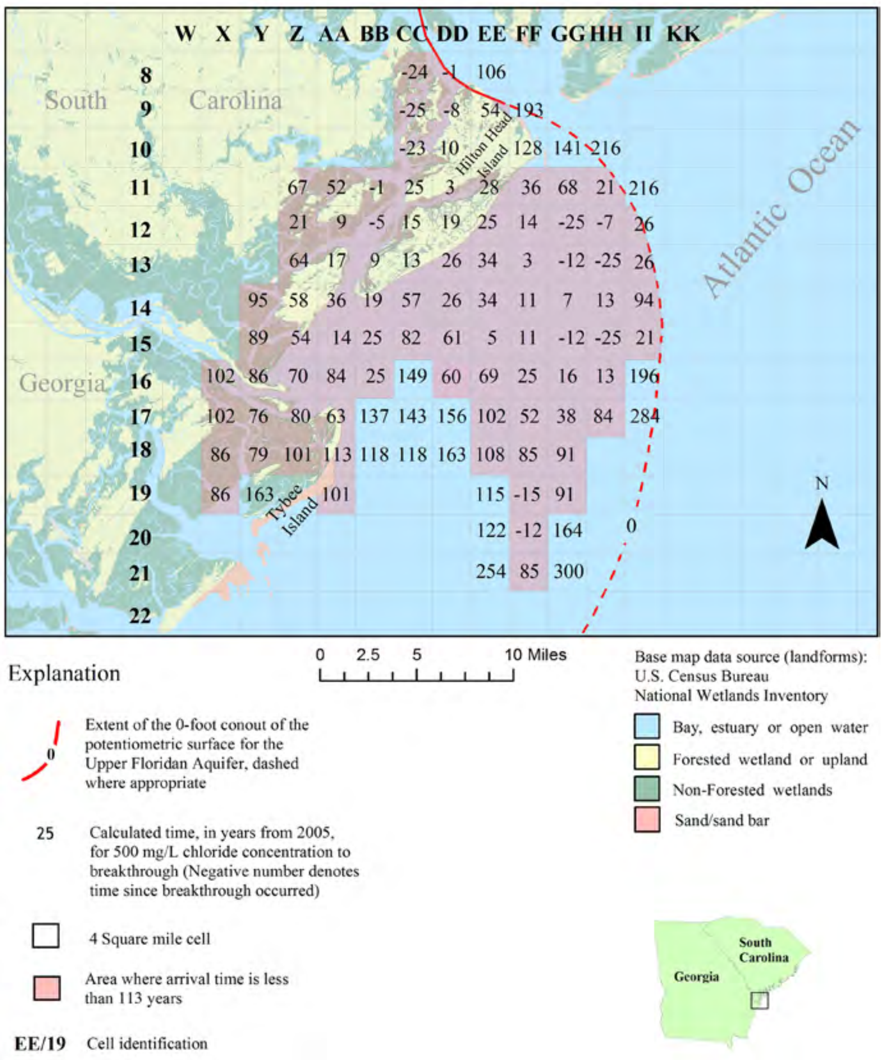


Figure 33. Estimated arrival times of a 500-mg/L chloride concentration at the top of the Upper Floridan aquifer relative to the year 2005, Savannah, Ga. – Hilton Head Island, S.C., area (Ransom and others, 2006).

approaches 500 mg/L at the bottom of the upper confining unit, the average diluted chloride concentration in the aquifer will begin to exceed 250 mg/L.

Upper Floridan Aquifer

Nine chloride plumes have been mapped or partly mapped at the bottom of the Upper Floridan aquifer. The tenth and eleventh plumes are hypothesized to exist beneath the Atlantic Ocean based on the hydrogeology and offshore seismic profiles (Foyle and others, 200l) and temporary offshore test wells (Burt and others, 1987; Falls and others, 2005). The eleven plumes are named according to their source-area localities and are: (1) the Parris Island chloride plume, (2) the Port Royal Sound chloride plume, (3) the Dolphin Head chloride plume, (4) the Pinckney Island chloride plume, (5) the Colleton River chloride plume, (6) the Sawmill Creek chloride plume, (7) the Jenkins Island chloride plume, (8) the Broad Creek chloride plume, (9) the Bull Island chloride plume, (10) the Hilton Head High chloride plume (inferred from seismic data) and, (11) the 8-mile chloride plume. The plumes lie near the axis of the Beaufort Arch and are scattered over an area extending about fifteen miles southwest of Parris Island and Port Royal Sound (fig. 34).

The Parris Island and Port Royal Sound chloride plumes contain mostly relict salt water that was not completely flushed from the aquifer; the nine remaining plumes began to develop during the early 1950's and consist primarily of modern salt water. These plumes originate where aquifer heads are below mean sea level and the confining unit is thin or absent, permitting brackish water at the bottom of the surficial aquifer to migrate into the Upper

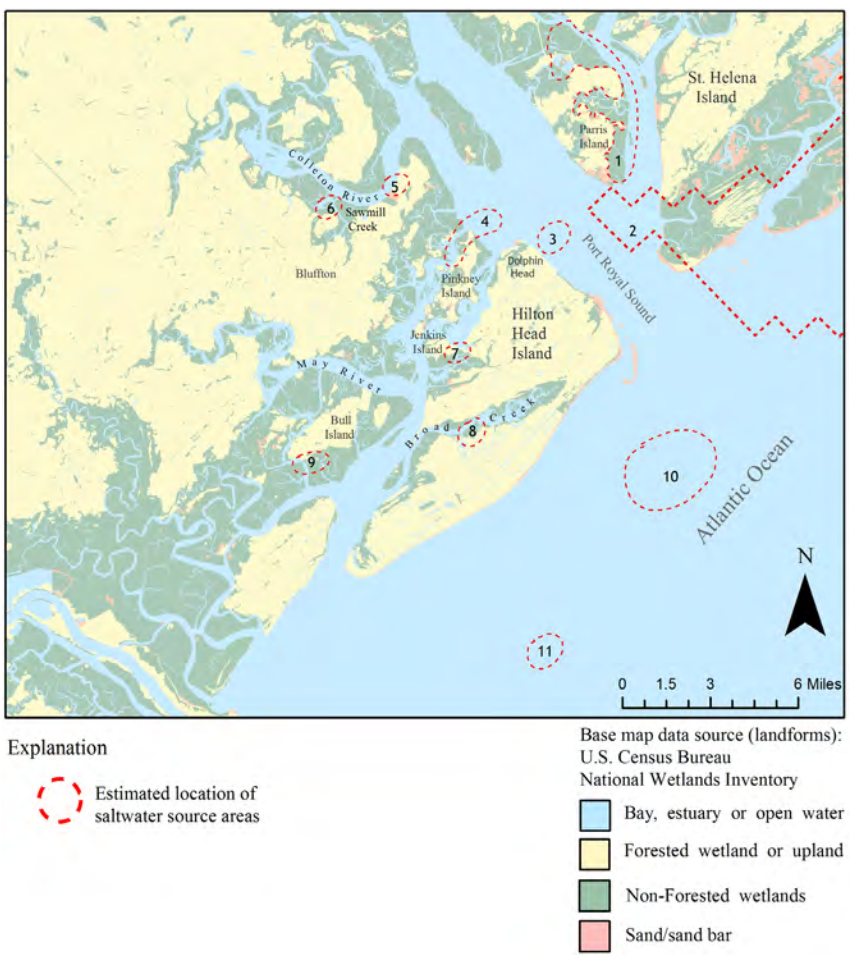


Figure 34. Estimated locations of saltwater source areas for the Upper Floridan aquifer, Port Royal Sound area, S.C.

Floridan aquifer. Brackish to salty water is present in the aquifer from top to bottom near source areas. As distance down gradient from the source areas increases, fresh water is found in the upper part of the aquifer and brackish to salt water is found in the lower 10 to 30 ft of the aquifer (Appendix I); owing to seawater density and to freshwater recharge where plumes migrate beneath landmasses. The SCDHEC model simulates the position and expansion of eleven chloride plumes from 1885 to 2050 (Appendix J).

Parris Island Chloride Plume

The first Upper Floridan aquifer wells on Parris Island were constructed in 1899 to supply water for the Parris Island Marine Corps Recruit Depot; these wells produced small quantities of potable water. But by 1916, the supply was depleted because of saltwater intrusion and further efforts to maintain a potable groundwater supply on the island were abandoned (Burnnett, 1952; Appendix A1). Saltwater contamination at the Parris Island wells was first investigated by Mundorff (1944) and later by Siple (1960): both speculated that the contamination source was brackish water moving toward pumping wells from Port Royal Sound, tidal channels, and marshes to the north and east. They also reported relatively high water levels in some Upper Floridan aquifer wells at Port Royal and Parris Island. Siple concluded that the potentiometric highs were caused by freshwater recharge migrating downward from higher heads in the overlying surficial aquifer. The initial success of some wells on the island can be attributed to the small freshwater lenses at the top of the Upper Floridan aquifer. Here, the greater head in the surficial aquifer beneath the island landmasses moved freshwater into the underlying Upper Floridan aquifer, displacing salty or brackish water laterally toward areas of discharge (channels and estuaries) where heads were lower.

The freshwater/saltwater interface near Parris Island was sensitive to pumping owing partly to tectonic uplift that formed the Beaufort Arch (**GEOLOGY - Structure** section), leaving the top of the Upper Floridan aquifer at shallow depths. Where the upper confining unit was absent, upward discharge from the underlying Upper Floridan aquifer diminished predevelopment freshwater head near Parris Island, Port Royal Sound, and areas to the northeast. Here, freshwater moving in the aquifer from the southwest lacked sufficient flow to completely displace relict brackish to salt water in the aquifer surrounding Parris Island to the north and east. Colquhoun (1972) and Foyle (2001) conducted offshore seismic surveys and reported that the upper confining unit was absent beneath parts of Battery Creek to the north, and Foyle reported the unit to be absent beneath the Beaufort River along the east side of Parris Island. It is likely that the increasing demand for a potable supply on the island had lowered the potentiometric surface in the aquifer and contributed to high chloride concentrations caused by (1) the nearby relic brackish to saltwater interface moving laterally toward pumping wells, (2) modern salt water moving downward toward the top of the aquifer and, (3) brackish water present at the aquifer bottom moving upward toward pumping wells.

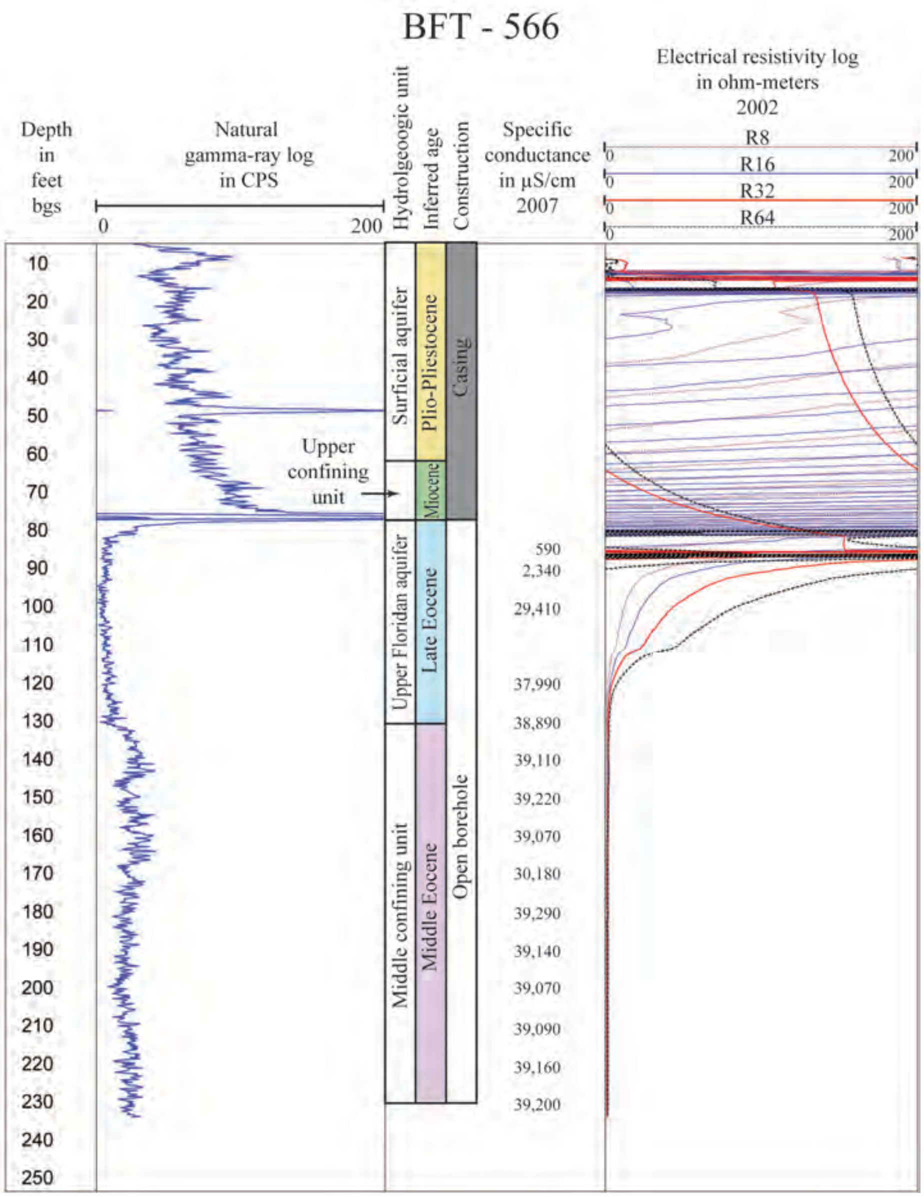


Figure 35. Natural gamma-ray log and vertical specific-conductance profile (2007) for monitor well BFT-566 at Parris Island, S.C.

Availability of potable groundwater was also limited on Parris Island by topography; the low-lying island landmass was composed of four islands and small hammocks intertwined with saltwater channels and estuaries. This limited each landmass to a relatively small geographical area, insufficient to support the volume of freshwater recharge needed to displace salty or brackish water in the underlying Upper Floridan aquifer. Warren (1944) suggested that the salt water beneath the northeastern part of Port Royal Sound and surrounding channels (the Parris Island and Port Royal Sound chloride plumes) consisted primarily of relict seawater. Back others (1970) later calculated a 7,100 year ^{14}C (Carbon-14) age for a Parris Island well sample, and Castro (1997) calculated 5,600- and 14,800-year ^{14}C ages

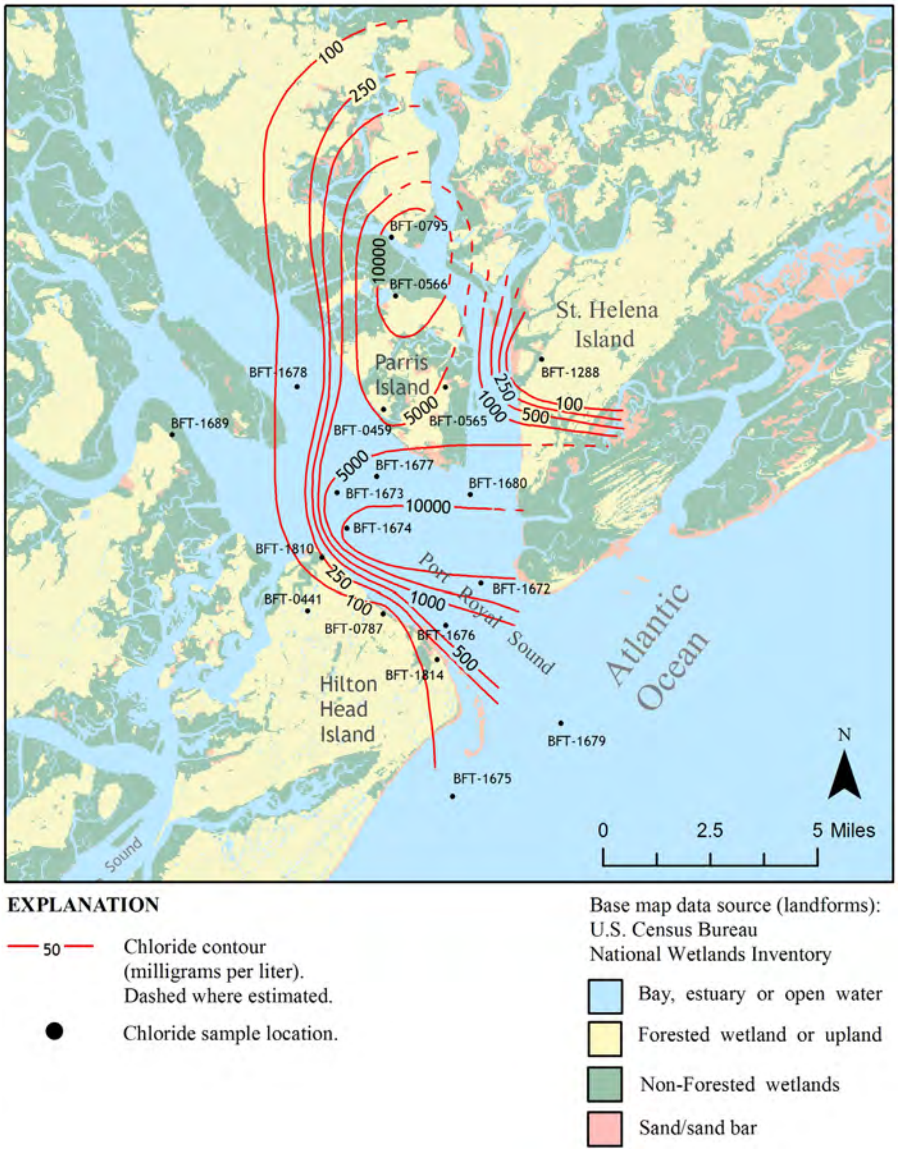


Figure 36. Isochlors near the bottom of the Upper Floridan aquifer showing the approximate extent of the Parris Island and Port Royal Sound plumes, 1984 (Landmeyer and Belval, 1996).

for samples taken from two Upper Floridan aquifer test wells beneath Port Royal Sound. Exceptions occurred north and northeast of Parris Island where similar conditions were offset by the geographically larger island landmasses with relatively high elevations. These islands capture greater rainfall that raise the potentiometric surface of the aquifer by increasing downward recharge of modern fresh water from the overlying surficial aquifer which support greater groundwater withdrawals from the Upper Floridan aquifer (Appendix D11).

Hayes (1979) completed and collected pumped water samples from two test wells (BFT-565 and BFT-566) on the Parris island and from three existing wells; he reported chloride concentrations that ranged from 1,500 and 11,000 mg/L. Landmeyer and Belval (1996) collected samples from the bottom of the aquifer at 18 wells in the area and reported chloride concentrations of 5,000 to 15,000 mg/L in three wells on Parris Island. Geophysical logs at well BFT-566 (fig. 35) showed the Upper Floridan aquifer between about 80 ft and 130 ft bgs. Here, a vertical specific-conductance profile at the well in 2007 indicated a shallow freshwater lens at about 80 ft bgs near the top of the aquifer. At about 90 ft bgs, specific conductance increased to 2,340 µS/cm and the computed chloride concentration was about 800 mg/L. From 90 ft to 130 ft bgs near the aquifer bottom, computed chloride concentrations were consistent throughout the open borehole and were 13,000 mg/L. The underlying middle confining unit was logged from 130 ft to about 230 ft bgs and computed chloride concentrations were consistent at about 13,600 mg/L. The data suggest that a massive source area is present where seawater lies in direct contact with the Upper Floridan aquifer at Parris Island and in areas north and northeast of the island. The brackish to salt water in the Upper Floridan aquifer beneath Parris Island, Battery Creek, and the Beaufort River is designated herein the Parris Island chloride plume (fig. 36).

Port Royal Sound Chloride Plume

Port Royal Sound is bounded to the northeast by Parris and St. Helena Islands and to the southwest by Hilton Head Island: the sound averages about 3 miles in width. As Hilton Head Island developed during the 1960's, concern arose over the potential for saltwater encroachment and its effect on the reliability of the Upper Floridan aquifer as a long-term potable supply. Nuzman (1970) and Hayes (1979) applied the Darcy flow equation to estimate plume velocities beneath the sound and arrival times at Hilton Head Island; however, data were insufficient to reach a well-founded conclusion.

In 1984, the SCWRC and USGS retained the U.S. Army Corps of Engineers to construct seven temporary wells beneath Port Royal Sound and two temporary wells beneath the Atlantic Ocean east of Hilton Head Island (fig. 36). Data were collected to determine the depth, thickness, and hydraulic properties of the upper confining unit; and to measure the hydraulic gradient, chloride distribution, and to map the position of the freshwater/saltwater interface in the Upper Floridan aquifer. These data showed fresh water in the mid to upper sections of the aquifer beneath most of the sound. Chloride concentrations present at the aquifer bottom decreased from about 10,000 mg/L near the northeastern part of Port Royal Sound and decreased to about 100 mg/L to the southwest near the north shore of Hilton Head Island. Exceptions were found at wells BFT-1672, BFT-1677, and BFT-1680 near Parris Island and in the northeastern part of the sound where brackish to salt water was present throughout the full thickness of the aquifer (Burt and others, 1987; Hughes and others, 1989; Smith, 1988, 1993; Landmeyer and Belval, 1996). This area of high chloride concentration is designated herein the Port Royal Sound chloride plume.

The Port Royal Sound chloride plume is comprised mainly of relict brackish water. The age of the plume is indicated by: (1) the dissolved oxygen (DO) concentrations of 0.1 mg/L and less found in the upper section of the aquifer in eight of the nine 1984 offshore test wells (Burt and others, 1987), (2) the low ^{14}C activity at the aquifer bottom beneath Port Royal Sound (Burt, 1993), and (3) the 7,500- and 14,800-year (BP) ^{14}C ages calculated by Castro (1997) for the plume at two tests well sites in Port Royal Sound. The 1984 isochlor map published by Landmeyer and Belval (1996) shows the southwesterly extent of relict brackish water at the bottom of the Upper Floridan aquifer and depicts the Port Royal Sound and Parris Island chloride plumes combined (fig. 36).

Dolphin Head Chloride Plume

The USGS constructed three monitoring wells between 1954 and 1962 on Daufuskie and Hilton Head Islands to monitor salt water in the Upper Floridan aquifer believed to be moving beneath Port Royal Sound toward Hilton Head Island. These wells were monitored monthly to record changes in the potentiometric surface and chloride-concentration (Counts and Donsky, 1963; McCollum, 1984; McCollum and Counts, 1964) until 1982. Well BFT-315 was drilled on the northern-most part of Hilton Head Island in the Dolphin Head residential area, a decision based on the belief that salt water would first arrive near Dolphin Head.

Well BFT-315, completed in 1962, consisted of a 10-inch diameter steel casing grouted to 150 ft bgs; a 10-inch open borehole from 150 to 795 ft bgs; and two 2-inch diameter steel pipes and sampling points consisting of 3-ft well screens (fig 37). The first sample point was set near the bottom of the Upper Floridan aquifer between 187 and 190 ft bgs and hung in the open-borehole section between 150 to 410 ft bgs, which included about 200 ft of the underlying middle confining unit. The second sampling point was set in the middle Floridan aquifer between 480 and 483 ft bgs, and the middle Floridan aquifer screen was isolated by neat cement plugs placed between 450 ft and 510 ft bgs.

Data collection from well BFT-315 consisted of a monthly water-level measurement and chloride analysis; water samples were collected by air lift method at an estimated 50 gpm for one hour prior to sampling (O.B. Odom, verbal commun., 1983; USGS file data). Initial chloride concentrations of about 70 mg/L at the Upper Floridan aquifer sampling point remained consistent from 1962 through 1973. Chloride concentration began to increase at well BFT-315 in 1974, marking the first increases recorded in the Upper Floridan aquifer southwest of Port Royal Sound. By 1983, chloride concentration had increased to 583 mg/L (fig. 38).

The source of the chloride-concentration increase was evaluated based on whether brackish water present between 200 ft to 410 ft bgs in the middle confining unit had moved upward during the sampling procedure or whether brackish water had moved laterally from Port Royal Sound along the bottom of the Upper Floridan aquifer. The middle confining unit could be the source of chloride owing to (1) the presence of high chloride concentrations in the unit, (2) the depth of the Upper Floridan aquifer sampling point, which was positioned in a borehole open to both the Upper Floridan aquifer and the middle confining unit, (3) region-wide declines in Upper Floridan head driving water upward in the well, and (4) sampling procedure, which might have induced up coning.

Point samples were collected by the SCWRC (Kemmerer sampler) in the open borehole between 150 and 410 ft bgs in March 1982 and 1983. In 1982, chloride concentrations in the Upper Floridan aquifer were 50, 50, and 274 mg/L at 150, 162, and 194 ft bgs, respectively: chloride concentrations in the borehole adjacent to the middle confining unit were 1,010 and 992 mg/L at 280 and 375 ft bgs, respectively. Point samples were collected again in June 1983, and Upper Floridan aquifer chloride concentrations appeared to have increased and were 66 and 551 mg/L at 175 and 200 ft bgs, respectively; concentrations in the middle confining unit also appeared to have increased and were 1,489 mg/L at 220 ft bgs and 1,645 mg/L at 384 ft bgs. Immediately after the point samples were collected, the USGS air-lifted water from the Upper Floridan aquifer sampling point at 190 ft bgs. Seven samples were collected by the SCWRC between 10 and 99 minutes and during that time chloride concentration increased from 525 mg/L to 603 mg/L, about one third of the concentrations found near the top of the middle confining unit (SCDNR file data). The test results indicated that the sampling procedure induced some upward flow in the open borehole; however, the concentration change was small compared to the 1,489 mg/L concentration near the top of the middle confining unit, and the potential groundwater contribution from the middle confining unit is small compared to that of the Upper Floridan aquifer where the transmissivity is about 50,000 ft^2/day or more. However, chloride contribution from the middle confining unit is possible because chloride concentrations measured from 1962 through 1973 were stable at about 70 mg/L, greater than the approximately 50 mg/L background concentrations indicated by Hayes' (1979) chloride-distribution map for Hilton Head Island.

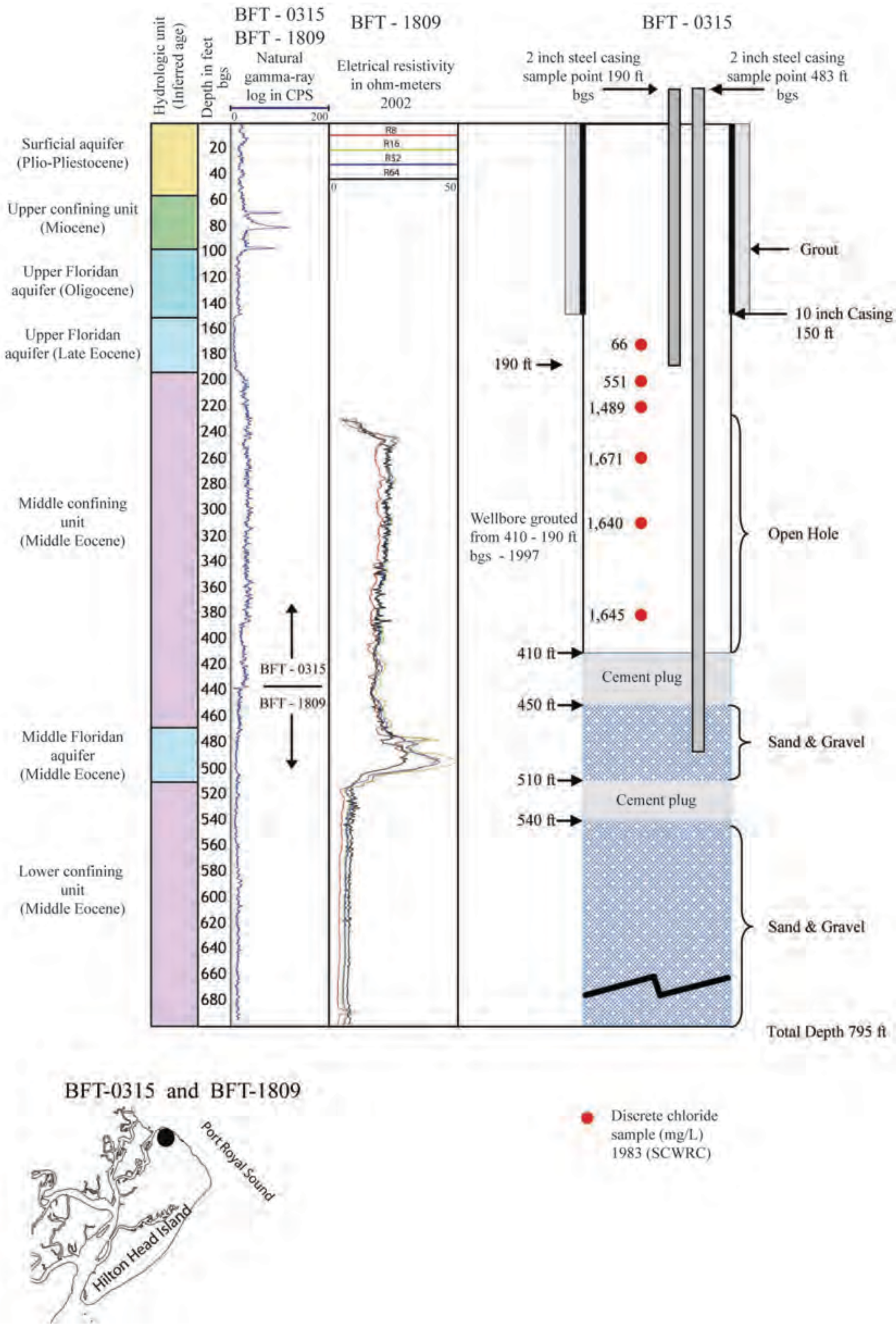


Figure 37. Hydrogeology, well construction, and 1983 chloride distribution at BFT-315, northern Hilton Head Island, S.C.

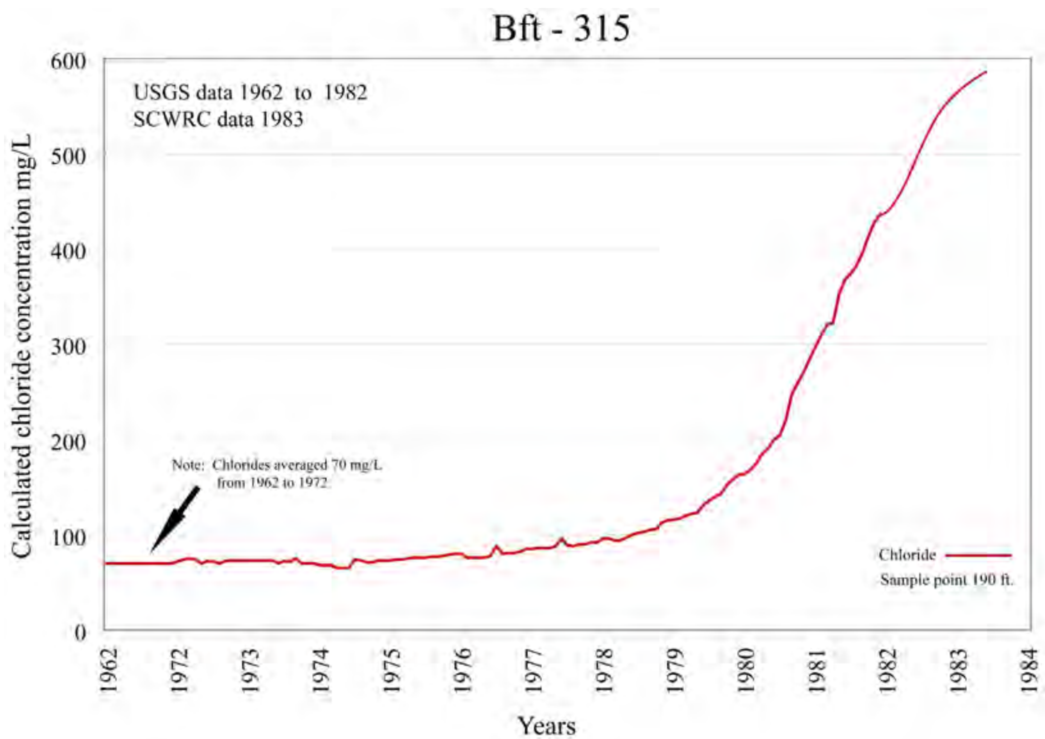


Figure 38. Chloride-concentration increases in the Upper Floridan aquifer at well BFT-315, 1962–1982, northern Hilton Head Island, S.C. (USGS data).

In summary, the sampling procedure at well BFT-315's upper sampling point (190 ft bgs) was consistent from 1962 to 1982, chloride concentration remained stable at 70 mg/L but greater than background (less than 50 mg/L) through 1973. The chlorides likely occurred, in part, from small volumes of relict brackish water in the middle confining unit moving upward in the open borehole and reaching the Upper Floridan sampling point during the sampling procedure. Beginning in 1974, chloride concentration at the upper sampling point progressively increased through 1983. Additional sampling, including the 1982- and 1983-point samples in the open borehole, showed that chloride concentrations were increasing at the bottom of the Upper Floridan aquifer and in 1983 had increased also in the borehole adjacent to the middle confining unit. An explanation for the brackish water at the bottom of the Upper Floridan aquifer is that lower potentiometric heads, beginning about 1952, had reversed the hydraulic gradient in the Upper Floridan aquifer allowing relict brackish water from sources in the aquifer beneath Port Royal Sound to move southwest. Overlying sources of modern salt water in the sound also began to move downward into the aquifer where the upper confining unit was absent. Owing to greater density, modern salt water descended through the Upper Floridan aquifer to the top of the middle confining unit, diluting and moving laterally through the bottom of the aquifer toward the northeastern shoreline of Hilton Head Island near the Dolphin Head area and eventually into well BFT-315 (SCDHEC model; Appendix J14 and J15). Here, the toe of the brackish-water wedge was between the middle confining unit and the overlying Upper Floridan sampling point at 190 ft bgs. As the toe moved inland beneath BFT-315, modern brackish water moved closer to the sampling point where it moved upward during the sampling procedure, causing progressive increases in chlorides between 1974 and 1981. The greater chloride concentrations (averaging 1,611 mg/L) measured adjacent to the middle confining unit did not result from upward movement because the unit is believed to have a lower chloride concentration, averaging about 1,000 mg/L based on the point samples taken in 1982. Instead, they were probably caused by increasing chloride concentrations at the bottom of the Upper Floridan aquifer moving downward, owing to greater density, and amassing in the open borehole adjacent to the middle confining unit.

In 1986, the SCWRC and USGS constructed an Upper Floridan aquifer monitoring well (BFT-1810) about 1,800 ft northwest of well BFT-315. Well BFT-1810 was cased and grouted to the top of the Upper Floridan aquifer and completed as an open-borehole well to 202 ft bgs at the bottom of the aquifer. A comparison of water quality at wells BFT-315 and BFT-1810 shows that: (1) the1983 point sample at 200 bgs from well BFT-315 had a chloride concentration of 551 mg/L, similar to the approximately 800 mg/L computed for well BFT-1810 in 1986 (fig. 39); (2) specific-conductivity monitoring in well BFT-1810 between 1987 to 2014 (USGS data) indicate computed chloride concentrations increasing from about 1,000 to 6,500 mg/L (fig. 39), which are greater than the concentrations found in the middle confining unit.

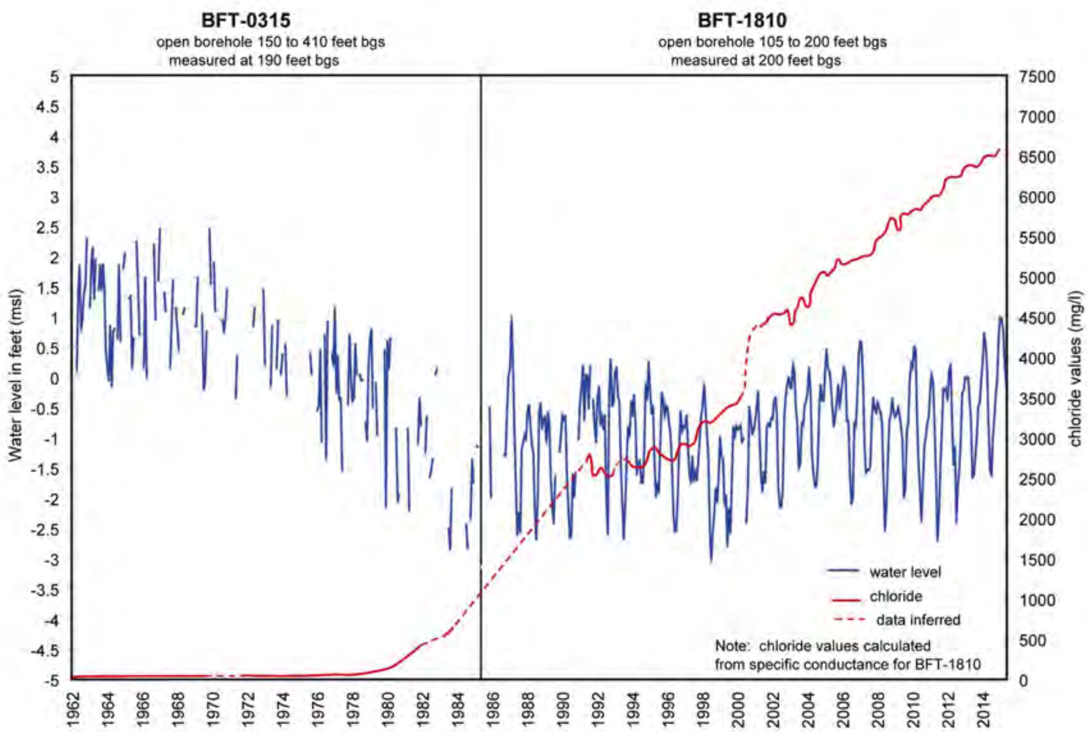


Figure 39. Water-level and computed chloride-concentration changes in BFT-315 and BFT-1810, 1962–2014, northern Hilton Head Island, S.C.

Sixteen Upper Floridan aquifer monitoring wells were constructed from 1995 to 2003 to further map chloride contamination in the Dolphin Head area; specific-conductance profiles in the open borehole of each well were used to compute chloride concentrations. The data delineate an area of approximately 8 mi^2 beneath northern Hilton Head Island where chloride concentrations at the bottom of the Upper Floridan aquifer exceeded 250 mg/L. The greatest computed chloride concentration, 10,900 mg/L, was present at well BFT-2201 on the shore of Port Royal Sound about 0.5 miles southeast of Dolphin Head. Computed chloride concentration decreased to about 150 mg/L at well BFT-2405, about 2 miles southwest of well BFT-2201. Owing to high-capacity pumping wells to the southeast since the early 1980’s, the direction of plume movement has a southeastern component, a departure from the southwestward regional groundwater gradient. The high concentration beneath the northwestern part of Hilton Head Island is herein named the Dolphin Head chloride plume (fig. 40).

Figure 40. Isochlors near the bottom of the Upper Floridan aquifer showing extent of the Dolphin Head chloride plume, 2003, northern Hilton Head Island, S.C.

The Dolphin Head chloride plume appears to be separate from the Port Royal Sound plume and originate near the northern shore of the island. These conclusions are based on the facts that: (1) computed chloride distribution along the northern shore of the island has both a southwestern and southeastern movement relative to the plume source area, the latter being influenced by pumping; (2) computed chloride concentrations near the aquifer bottom at well BFT-2201 that are greater than the concentrations measured in the leading edge of the Port Royal Sound chloride plume mapped after the1984 offshore drilling**;** (3) the landward extent of the Dolphin Head chloride plume is about 2 miles farther south than simulated by Smith (1984) for the Port Royal Sound chloride plume; (4) young age of groundwater samples are indicated by high DO concentrations (5.8 mg/L) at the bottom of the aquifer at well BFT-2201, indicating modern recharge, whereas DO concentrations in the seven Port Royal Sound test wells were negligible and indicated relict brackish to salt water; and (5) chlorofluorocarbon- and tritium-age analyses (discussed later) indicate water at the bottom of the aquifer at well BFT-2201 is less than 50 years old.

The chloride-distribution map prepared by Hayes (1979) for the Upper Floridan aquifer on Hilton

Head Island and nearby areas serves as a water-quality benchmark to evaluate subsequent changes and regional trends (fig. 41). Hayes' analyses were of composite water samples from production wells of differing depths relative to the depth of the aquifer, differing open-bore intervals, and differing pumping rates (100-1,000 gpm) collected from 1973 to 1976. Chloride concentrations were less than 50 mg/L on the western parts of the island; 50 to 100 mg/L on the eastern half bordering the Atlantic Ocean; and 50 to 100 mg/L at the northern-most part bordering Port Royal Sound. Chloride-concentration data collected from production wells also were mapped for 2010 (Groundwater Management Assoc., 2010). Chloride-concentration changes across Hilton Head Island during the 34-year period ending in 2010 can be seen by comparing the two chloride-distribution maps in figure 41. Differences between the 1976 and 2010 maps include: (1) the more recent data that define the Dolphin Head chloride plume; (2) the delineation of the Broad Creek plume; and (3) 50 to 100 mg/L chloride-concentration increases on the western side of the island. Many of the wells in the center, southern, and southwestern parts of the island did not penetrate to the bottom of the aquifer, which lies between about 250 ft and 300 ft bgs where greater chloride concentrations might be present.

Pinckney Island Chloride Plume

The Pinckney Island National Wildlife Refuge lies west of Hilton Head Island, separated by Skull Creek (fig. 42). It is bounded by the Chechessee River to the north, by Mackay Creek and Skull Creek to the west and east, and encompasses a main island, several small low-lying islands, hammocks, salt marsh and tidal channels. Small circular

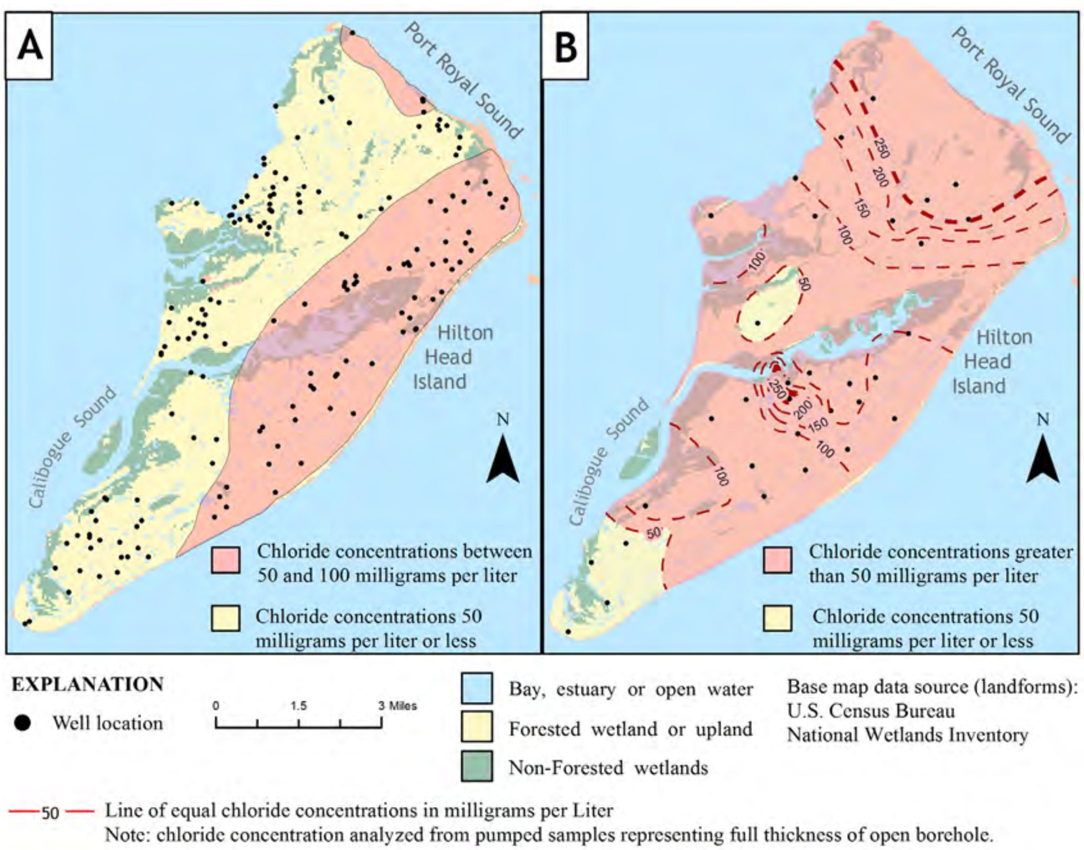


Figure 41. Chloride concentrations in Upper Floridan aquifer wells, Hilton Head Island, S.C., in (a) 1976 (Hayes, 1979) and (b) 2010 (Groundwater Management & Associates, 2010).

depressions and freshwater ponds formed by sinkholes are scattered across the refuge.

The original ranger-residence water supply at the northern part of the island, about 100 ft southwest of a saltwater marsh bordering the Chechessee River, was provided by an Upper Floridan aquifer well (BFT-401) drilled to 94 ft bgs. Well BFT-401 was abandoned in 1989 because of the water's salty taste (water-quality data were not available for well BFT-401) and a new well was completed farther south). Monitoring well BFT-2189 was drilled near well BFT-401 in 1999; the computed chloride concentration was about 1,000 mg/L at the top of the aquifer and increased to about 3,500 mg/L near the bottom of the aquifer (Appendix I).

Figure 42. Locations of Upper Floridan aquifer test wells at Pinckney Island, S.C.

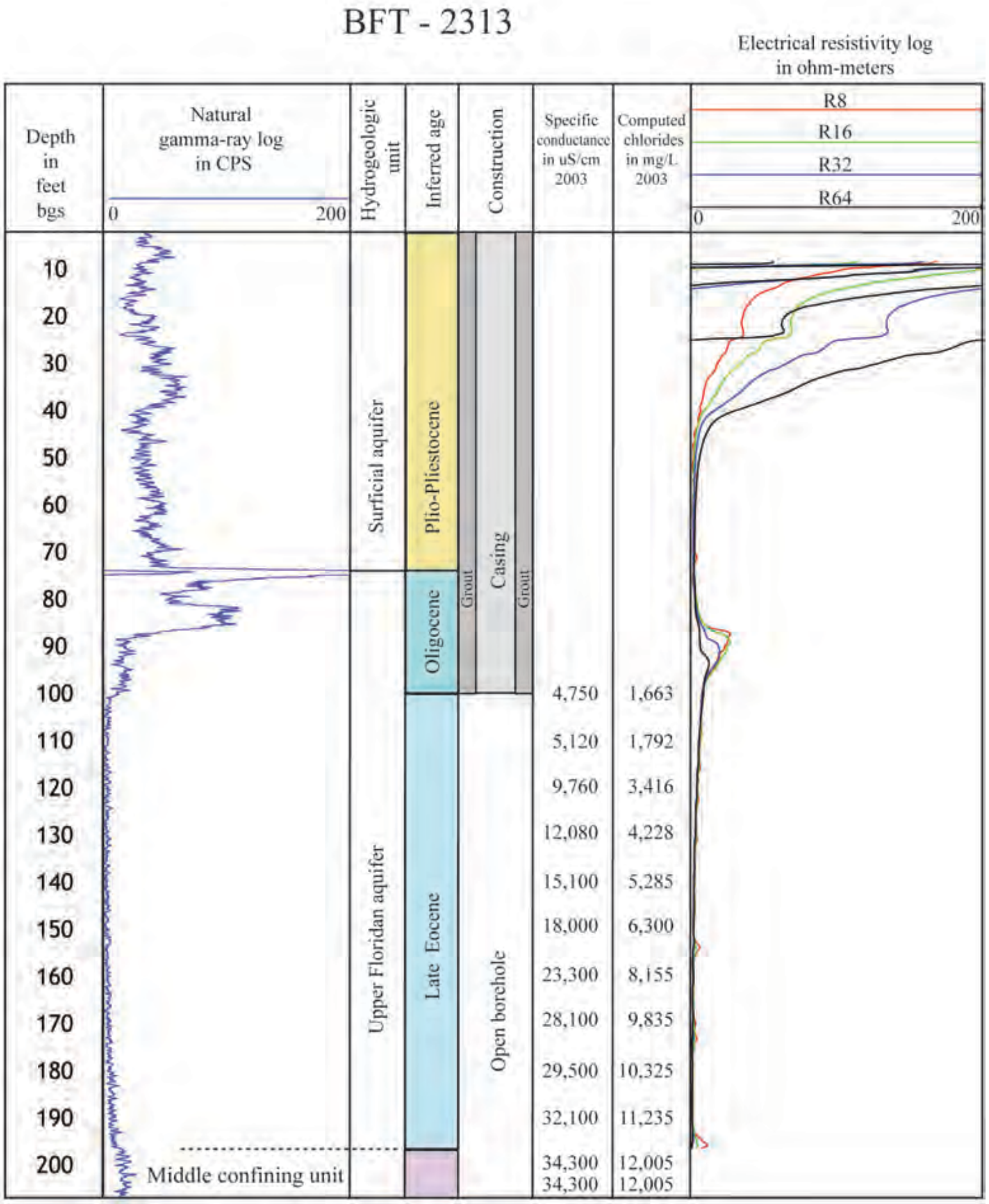


Figure 43. Hydrogeology, geophysical logs, chloride distribution, and well construction at well BFT-2313, Pinckney Island, S.C.

Six test wells were constructed on Pinckney Island to investigate the source and extent of salt water in the aquifer. Drill cuttings and geophysical logs from monitoring wells BFT-2312 and BFT-2313 indicate that the upper confining unit is thin on northwestern Pinckney Island near Mackay Creek. Only about 2 ft of the upper confining unit were observed during the drilling of well BFT-2312, and the upper confining unit was not encountered during the drilling of well BFT-2313 (fig. 43). Natural gamma-ray logs averaged about 20 cps between 0 and 70 ft bgs, indicating no significant presence of the upper confining unit, and the low electrical resistivity for the same interval suggests a high chloride concentration. Foyle and others (2001) conducted seismic surveys in Mackay Creek along the northwestern shoreline of Pinckney Island and concluded also that as little as 0 to 10 ft of the upper

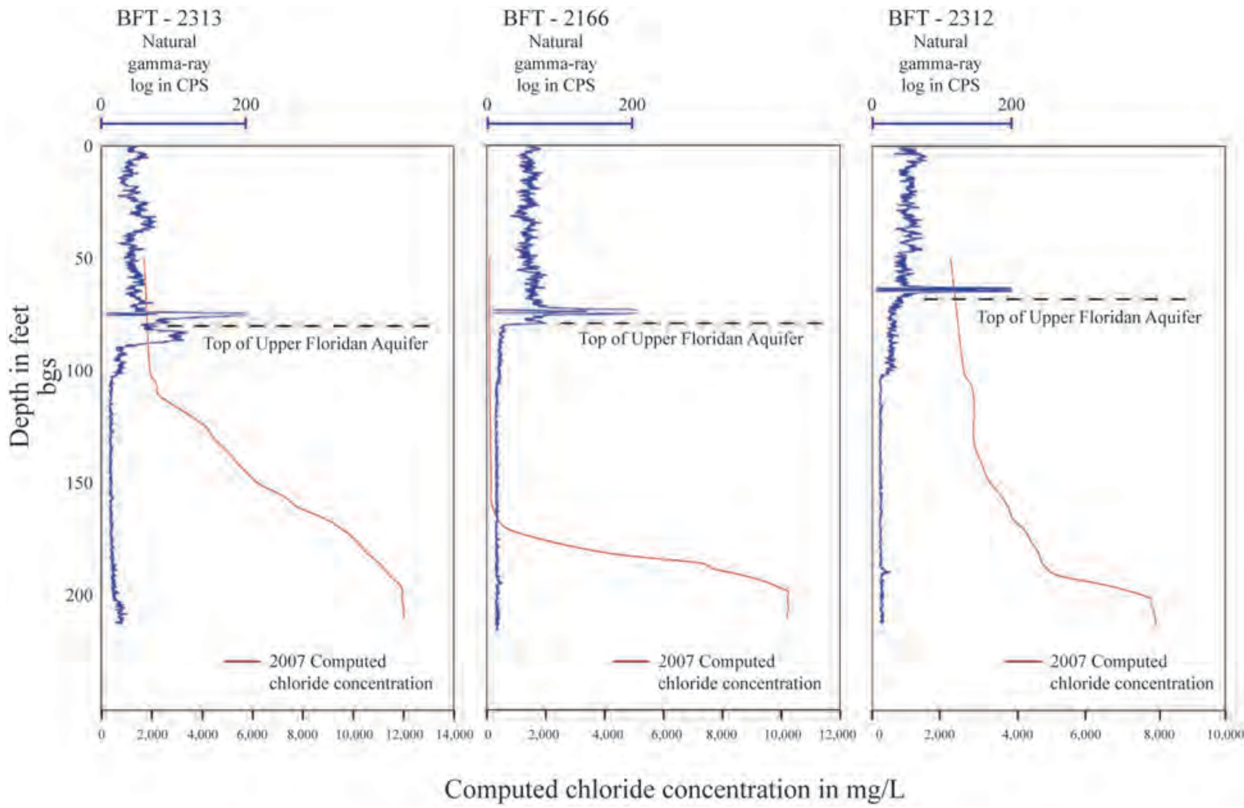


Figure 44. Chloride concentrations (red) and natural gamma-ray logs (blue) in Upper Floridan aquifer wells BFT-2313, BFT-2166, and BFT-2312, Pinckney Island, S.C., 2007. Concentrations computed from specific-conductance profiles.

confining unit remained above the aquifer in some areas.

Vertical specific conductance profiles were conducted in monitoring wells near Mackay Creek in 2003 (BFT-2313, BFT-2166, and BFT-2312; fig. 44). Computed chloride concentrations at well BFT-2313 increased with depth from 2,000 mg/L at the top of the Upper Floridan aquifer to 12,000 mg/L at the aquifer bottom. Well BFT-2166 contained fresh water between about 80 ft and 165 ft bgs with the greatest computed chloride concentration of about 10,000 mg/L near the bottom of the aquifer.

Computed chloride concentrations at well BFT-2312 increased from 2,300 near the top to 8,000 mg/L at the aquifer bottom. At the ranger residence, monitoring well BFT-2189 had a computed chloride concentration of about 1,000 mg/L near the top of the aquifer and about 5,500 mg/L near the bottom of the aquifer. The high computed chloride concentrations near the top of the aquifer at wells BFT-2313 and BFT-2312 indicate multiple nearby source areas of seawater breakthrough. Fresh water was present in the aquifer from top to bottom on the east (BFT-2190) and south end (BFT-2165) of the island.

To the west and southwest of Pinckney Island near the bottom of the Upper Floridan aquifer, computed chloride concentrations decrease (fig. 45). Here, computed chloride concentration in 2003 were between 1,000 and 2,300 mg/L at wells BFT-429, BFT-2304, BFT-1326, and BFT-2310. West of Pinckney Island, well BFT-1326 at Moss Creek Plantation is the only known Upper Floridan aquifer public supply well within the 2003 plume that was originally fresh. Well BFT-1326, constructed in

Figure 45. Isochlors near the bottom of the Upper Floridan aquifer centered near Pinckney Island, S.C. showing the extent of the Pinckney Island chloride plume, 2003.

1978, was taken out of service in 1991 because of increasing chloride concentration; the public supply system is now served by surface water from the Savannah River.

The Pinckney Island chloride plume (fig. 45), as designated in this report, underlies an area of about 10 mi^2. It is elongated southwest toward the center of pumpage at Savannah, Ga. and extends about 5 miles south-southwest of the confluence of Mackay Creek and the Chechessee River.

Colleton River Chloride Plume

Figure 46. Locations of Upper Floridan aquifer test wells in the Colleton River Plantation area, S.C. The Colleton River, about four miles northwest of Hilton Head Island, is a saltwater tidal stream that runs about 7 miles west from its confluence with the Chechessee River. The developed tracts of Colleton River Plantation, the SCDNR Waddell Mariculture Center, and Belfair Plantation border the river east to west. The area is part of the Beaufort County mainland and encompasses saltwater marsh, tidal channels, and sinkholes (fig. 13, 46, and front cover).

The first indications that high chloride concentrations were present in the Upper Floridan aquifer appeared in 1983 after wells were drilled at

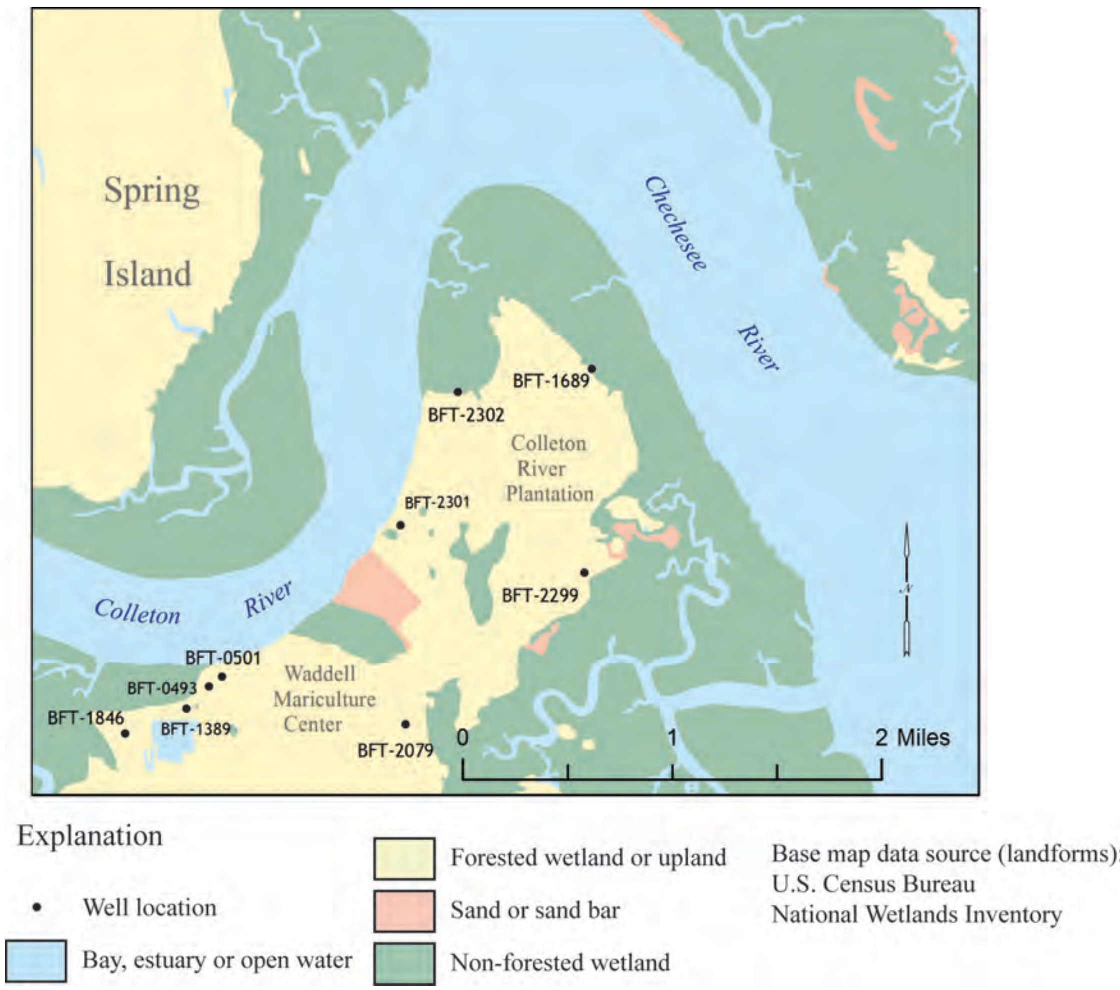


Figure 46. Locations of Upper Floridan aquifer test wells in the Colleton River Plantation area, S.C.

the newly developed Waddell Mariculture Center. An Upper Floridan aquifer pond-supply well, BFT-1389 (fig. 46), constructed near the river, had increasing chloride concentrations soon after the well began pumping. Water samples collected in the open-hole section contained chloride concentrations of about 140 mg/L near the aquifer top and about 1,800 mg/L at 150 ft bgs. Pumping well BFT-1389 at a rate of 1,600 gpm produced a composite chloride concentration of 2,400 mg/L, indicating that

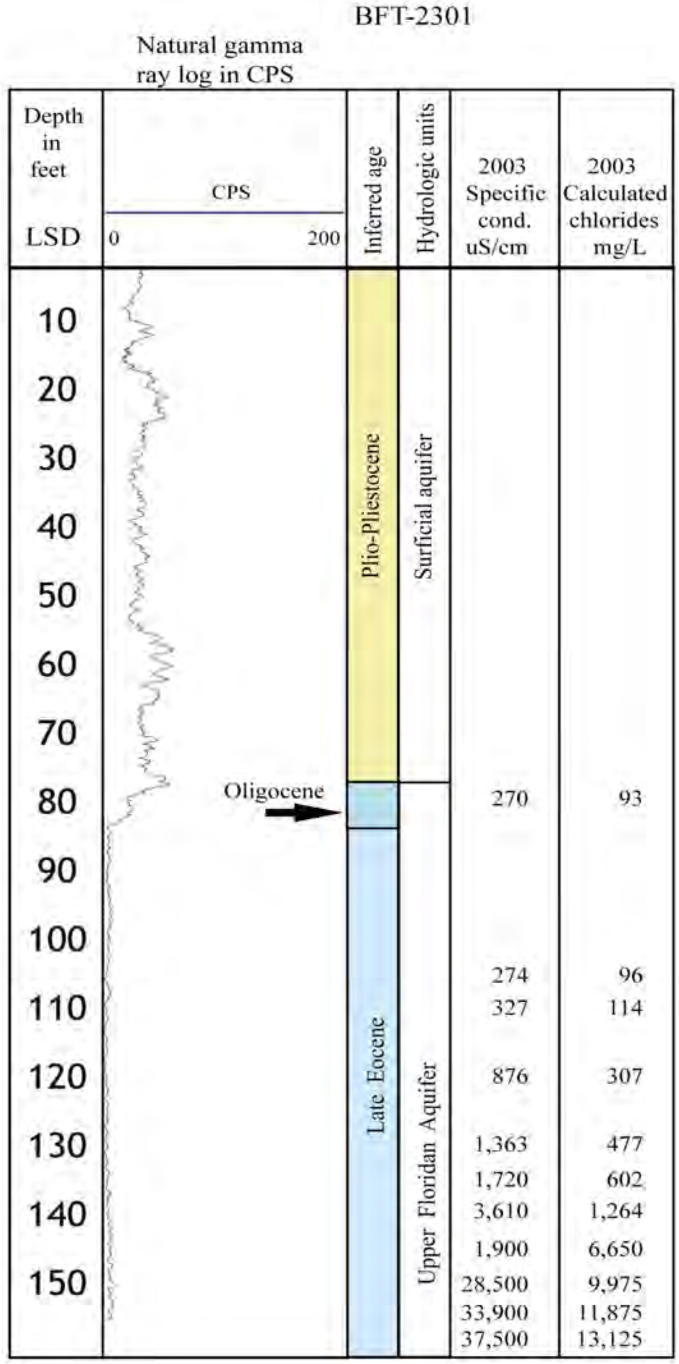


Figure 47. Hydrogeology, geophysical logs, specific conductance profile, and chloride distribution at well BFT-2301, near the Colleton River, S.C., 2003.

water having yet greater chloride concentrations was present near the bottom of the well bore at 192 ft bgs (Spencer and Park, 1984). Spenser and Park also compared 1970 and 1983 fluid-resistivity logs from well BFT-501, about 1,500 ft northeast of well BFT-1389, and found the elevation of the freshwater/brackish water contact in the wellbore had increased approximately 15 ft since 1970. Hughes and others (1989) later reported that public supply well BFT-493, drilled 300 ft northeast of well BFT-1389, produced water having a chloride concentration of 1,700 mg/L. The wellbore was plugged from -180 to -109 ft Msl and chloride concentration decreased to 83 mg/L: later sampling showed that chloride concentration had increased to 470 mg/L. They hypothesized that salt water in the mariculture center wells represented part of a localized plume drawn upward in pumping wells as it migrated toward Savannah, Ga.

Beginning in 2001, additional monitoring wells were drilled in the Colleton River area to investigate the chloride contamination. Well BFT-2301, completed to 162 ft bgs, was drilled at the southwestern edge of a sinkhole (see front cover) on the bank of the Colleton River (fig. 47). The presence of the sinkhole indicated collapse at the bottom of the upper confining unit and probable enhancement of the hydraulic connection between the aquifer and seawater in the Colleton River. This supposition was supported by (1) a cavern encountered at about 76 ft bgs during drilling, (2) the absence of confining-unit phosphate zones that are otherwise ubiquitous to the study area and easily identified in natural gamma-ray logs, (3) 2003 specific-conductance profiles in the open borehole that showed computed chloride concentrations from 100 mg/L near the top of the aquifer to about 13,000 mg/L at 162 ft bgs, and (4) consistent chloride concentrations of about 100 mg/L at the aquifer bottom in wells BFT-1689 and BFT-2302 (fig. 46), which lie up gradient and north to northeast of well BFT-2301. These wells have been monitored since 1986 and 2003, respectively. Seismic profiles (Foyle and others, 2001) also indicated the confining unit was thin or absent beneath the Colleton River opposite the sinkhole.

To the southwest, at the Waddell Mariculture Center, monitoring well BFT-1846 was drilled to a depth of 180 ft bgs in 1986; subsequent testing found freshwater near the aquifer bottom (SCDNR file data). A review of SCDNR file data (Gawne, 2008, unpublished SCDNR report) reported that, in 1991, a pumped sample taken at a depth of 178 ft had a chloride concentration of 475 mg/L, and a conductance profile 16 days later showed a computed chloride concentration of 748 mg/L at the bottom of the well. Gawne (2008) reported that chloride concentrations had increased by 1993 to an estimated 1,580 mg/L based on a fluid-resistivity log. Vertical specific-conductance monitoring by SCDHEC at well BFT-1846 began in 1999 and the computed chloride concentration near the aquifer bottom had increased to about 2,900 mg/L; by 2007 the chloride concentration had increased to 3,860 mg/L (Appendix I). Gawne (2008) reported that well BFT-502, a half mile southeast of well BFT-1846, showed a computed-chloride-concentration increase near the bottom of the Upper Floridan aquifer (185 ft bgs) from14 mg/L to 40 mg/L in 1983 and 1993, respectively. However, because two different instruments (logger truck vs. manual probe) were used and because chloride concentration was

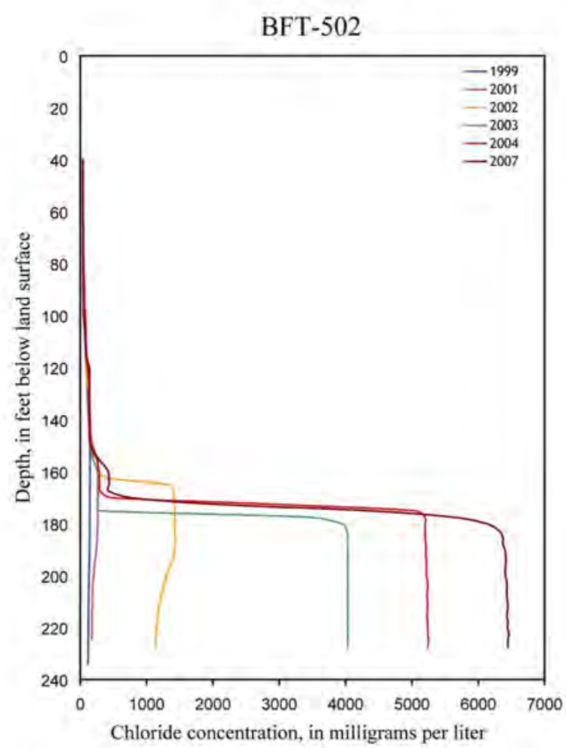


Figure 48. Computed chloride-concentration profiles in Upper Floridan aquifer well BFT-502, Colleton River area, S.C., 1999–2007.

low, the exact increase is uncertain. The most rapid increases occurred at well BFT-502 (fig.48), where computed chloride concentrations near the aquifer bottom increased from 114 to 6,450 mg/L between 1999 and 2007.

The southeastern position of the 4,000 mg/L isochlor in the Upper Floridan aquifer is partly inferred from middle Floridan wells in this area that have a background chloride concentration of about 10 mg/L. Well BFT-2039, an Upper Floridan aquifer irrigation well (fig. 46), was constructed in 1991 to a depth of 200 ft bgs but was later backfilled to 119 ft bgs to decrease chloride concentrations. The well was discontinued in September of 1991 after a pumped sample contained a chloride concentration of 1,291 mg/L (Gawne, 2008). In 1993, well BFT-2039 was replaced with middle Floridan aquifer well BFT-2079: however, in 2003, BFT-2079 also was abandoned after chloride concentrations increased to about 4,000 mg/L. A second replacement well BFT-2403 was drilled in 2004 with additional casing. A comparison of electrical-resistivity logs for BFT-2079 and BFT-2403 (fig. 73) indicated that the brackish water originated in the Upper Floridan aquifer migrated down the well bore through a casing leak (see **HYDROGEOLOGY - Middle Floridan Aquifer** section). Thus, the chloride concentration in the Upper Floridian aquifer is

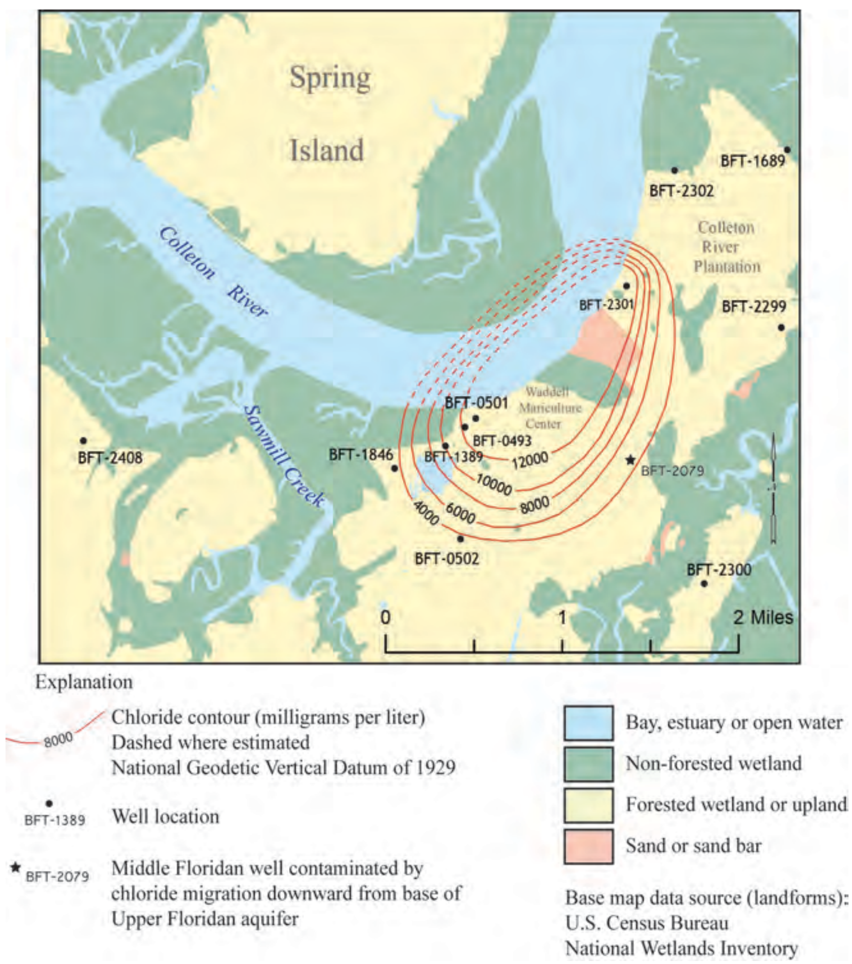


Figure 49.   Isochors near the bottom of the Upper Floridan aquifer showing the extent of the Colleton River chloride plume, 2003, Colleton River Plantation, S.C.

thought to be at least 4,000 mg/L (fig. 49).

Data were not available to evaluate the down-gradient extent of the 250 mg/L isochlor; however, compared to the isochlors for the nearby Pinckney Island plume, which developed under similar conditions, the southwestern position of the 250 mg/L isochlor for the Colleton River plume could lie as far as one mile southwest of the 4,000 mg/L isochlor. The estimated plume area inside the 4,000 mg/L isochlor encompassed about 1.8 mi^2 in 2003. The data indicate that brackish to salt water is moving downward toward the bottom of the aquifer from the estimated Colleton River source area. Thereafter, the contaminated water will move laterally down gradient to the southwest. Movement is principally influenced by groundwater withdrawals at Savannah, Ga. and probably began by the late 1950's (see potentiometric maps, Appendix D4) when the potentiometric head declined near mean sea level. The large area of brackish to salt water is named herein the Colleton River chloride plume (fig. 49).

Sawmill Creek Chloride Plume

Well BFT-2408 was constructed near Sawmill Creek at Belfair Plantation in June 2009 to evaluate the southwestern extent of the Colleton River chloride plume (fig. 50). The well site was about 3.2-miles

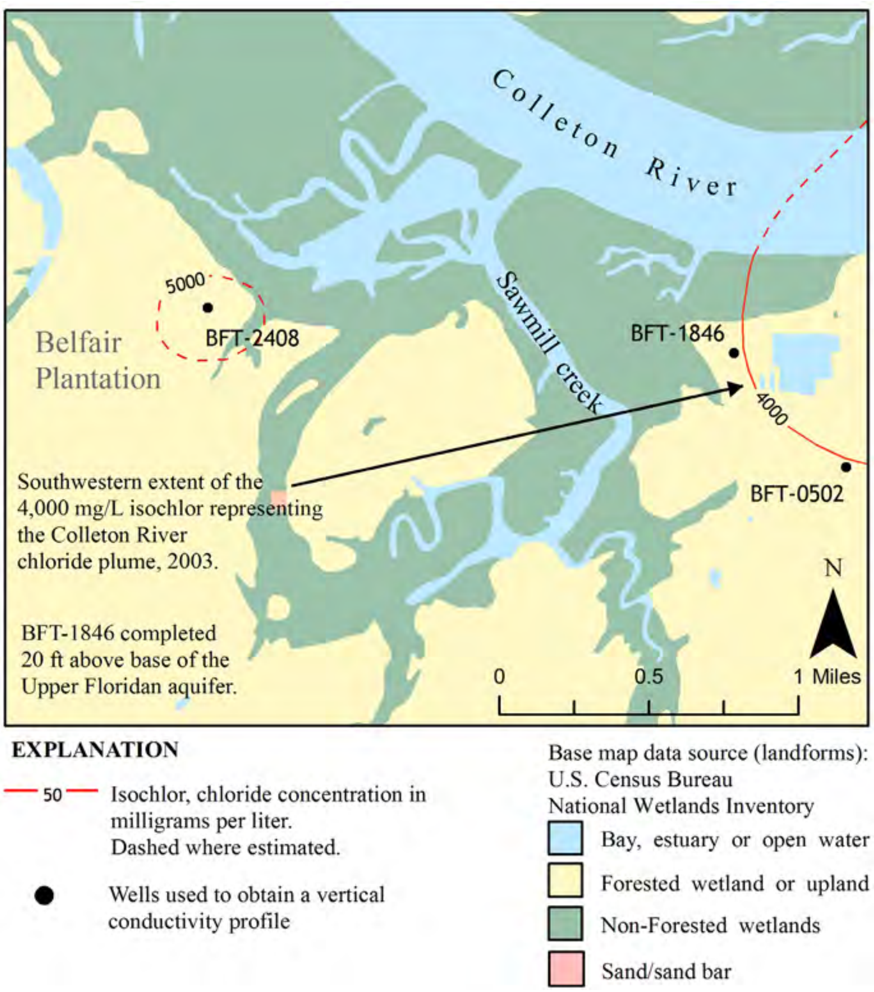


Figure 50. Locations of well BFT-2408, the 5,000-mg/L Sawmill Creek plume isochlor in 2013, and the 4,000 mg/L Colleton River plume isochlor in 2003, Colleton River area, S.C.

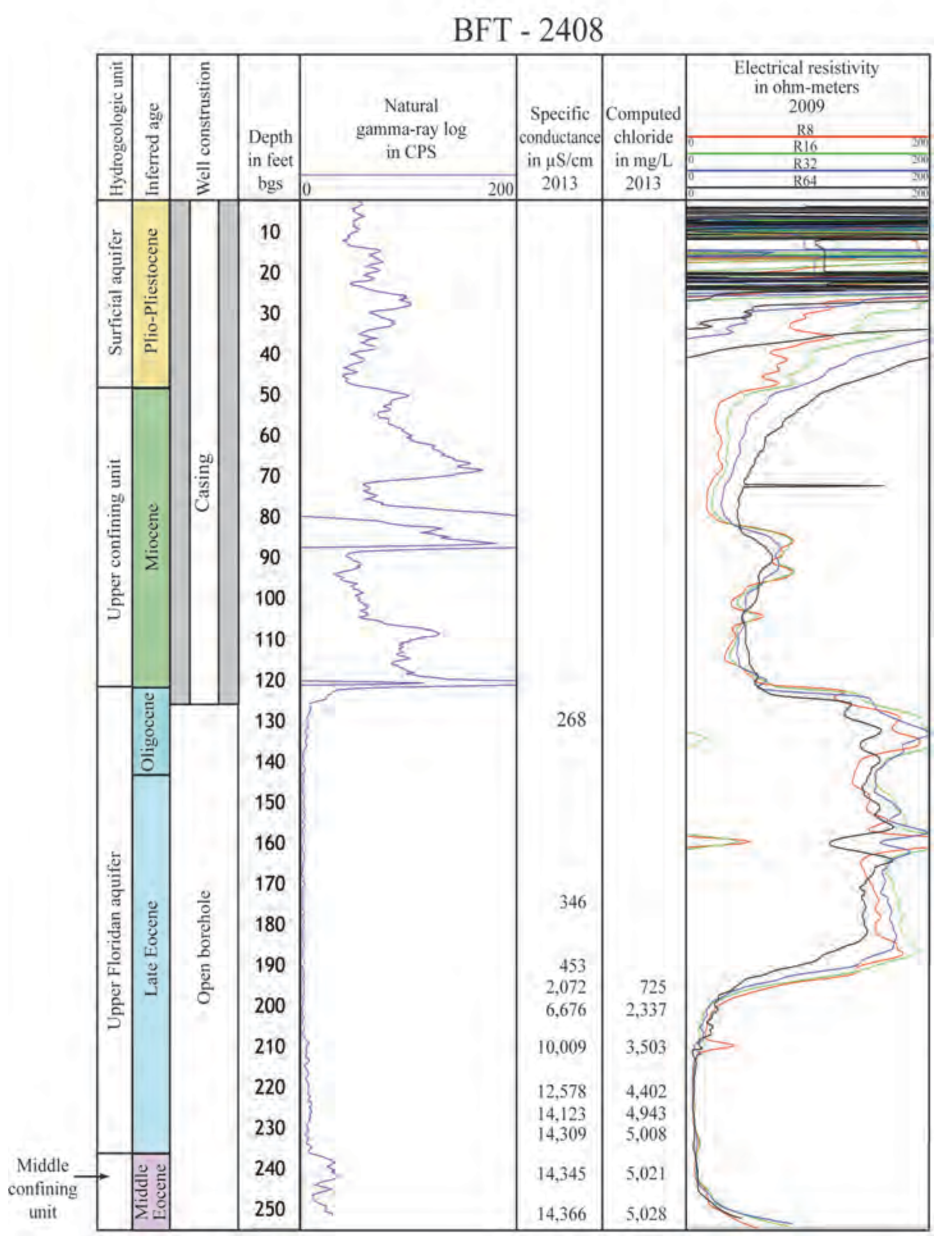


Figure 51. Hydrogeology, geophysical logs, chloride distribution, and well construction at well BFT-2408 near Sawmill Creek, S.C.

west-southwest and down gradient of well BFT-2301 (fig. 34: source area no. 5).

The natural gamma-ray log at well BFT-2408 indicated that the upper confining unit was present between 50 and 120 ft bgs and the Upper Floridan aquifer between 120 to 235 ft bgs (fig. 51). The electrical-resistivity log displayed high resistivity indicating fresh water in the upper confining unit and in the Upper Floridan aquifer to about 190 ft bgs. Electrical resistivity decreased between 190 and 235 ft bgs, near the aquifer bottom. Conductivity was within background limits (less than 500 µS/cm) at the top and middle of the aquifer but beginning about 200 ft bgs, specific conductance increased to 2,073 µS/cm and progressively increased toward the aquifer bottom where specific conductance was 14,309 µS/cm; computed chloride concentrations at the aquifer bottom (230 ft bgs) were about 5,000 mg/L. Electrical resistivity increased with depth below the top of the middle confining unit from 235 ft bgs to the bottom of the borehole at about 250 ft bgs. The increase probably indicating fresher water in the middle confining unit, although higher chlorides from above had amassed in the open borehole adjacent to the unit. The data suggest that the brackish water at the bottom of the Upper Floridan aquifer originated from a distant source area.

It is improbable that the 5,000 mg/L chloride concentration at the aquifer bottom in well BFT-2408 is part of the Colleton River chloride plume because the 5,000 mg/L chloride isochlor for the Colleton River chloride plume lies about 2 miles east of well BFT-2408. The brackish water at well BFT-2408 must instead originate near the confluence of Colleton River and Sawmill Creek or in the Sawmill Creek basin. While the geographic extent of the contamination is unknown, there are similarities to the Colleton River plume source area three miles to the northeast: (1) brackish water at the aquifer bottom, (2) comparable history of water-level elevations and pumping- induced water-level declines, and (3) the southwest-trending hydraulic gradients across both areas. Based on the similar conditions, the development of a separate plume is hypothesized and is designated herein as the Sawmill Creek chloride plume.

Jenkins Island Chloride Plume

Jenkins Island lies west of Hilton Head Island and south of the Pinckney Island Wildlife Refuge; it is

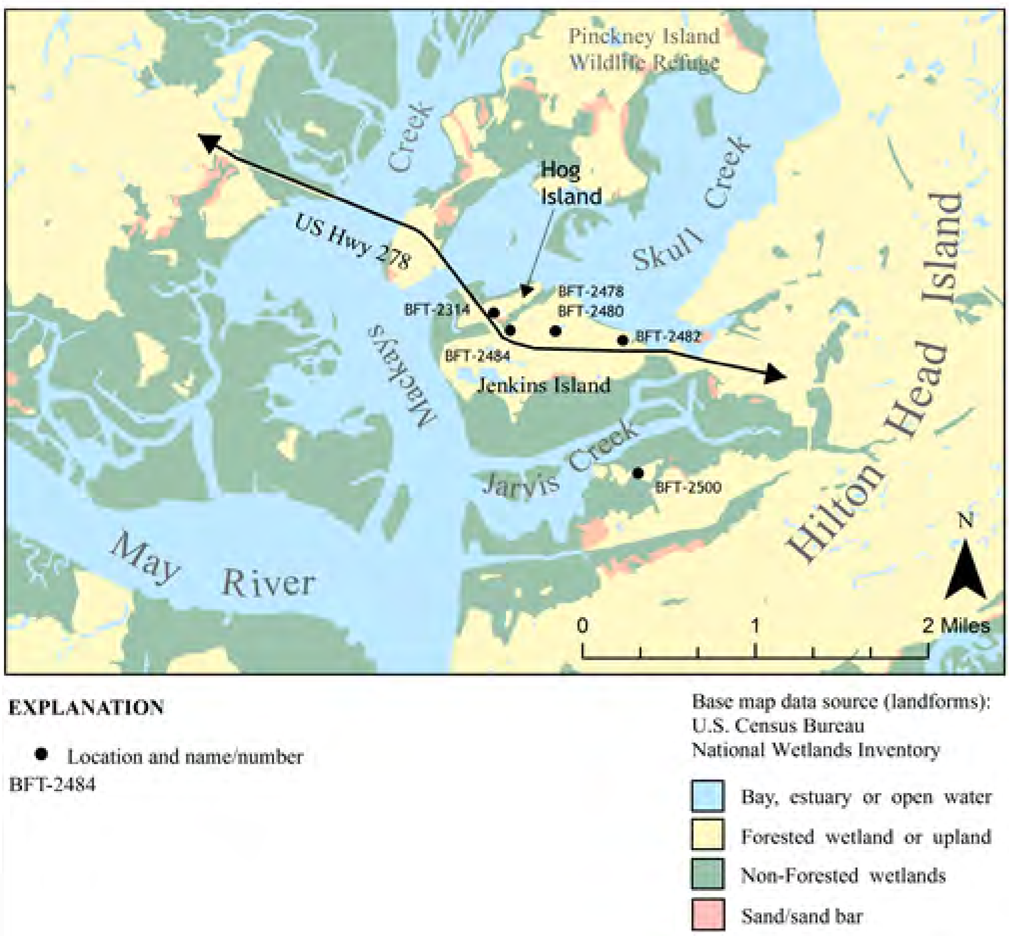


Figure 52. Locations of Upper Floridan aquifer and middle Floridan aquifer monitoring wells, Jenkins Island, S.C.

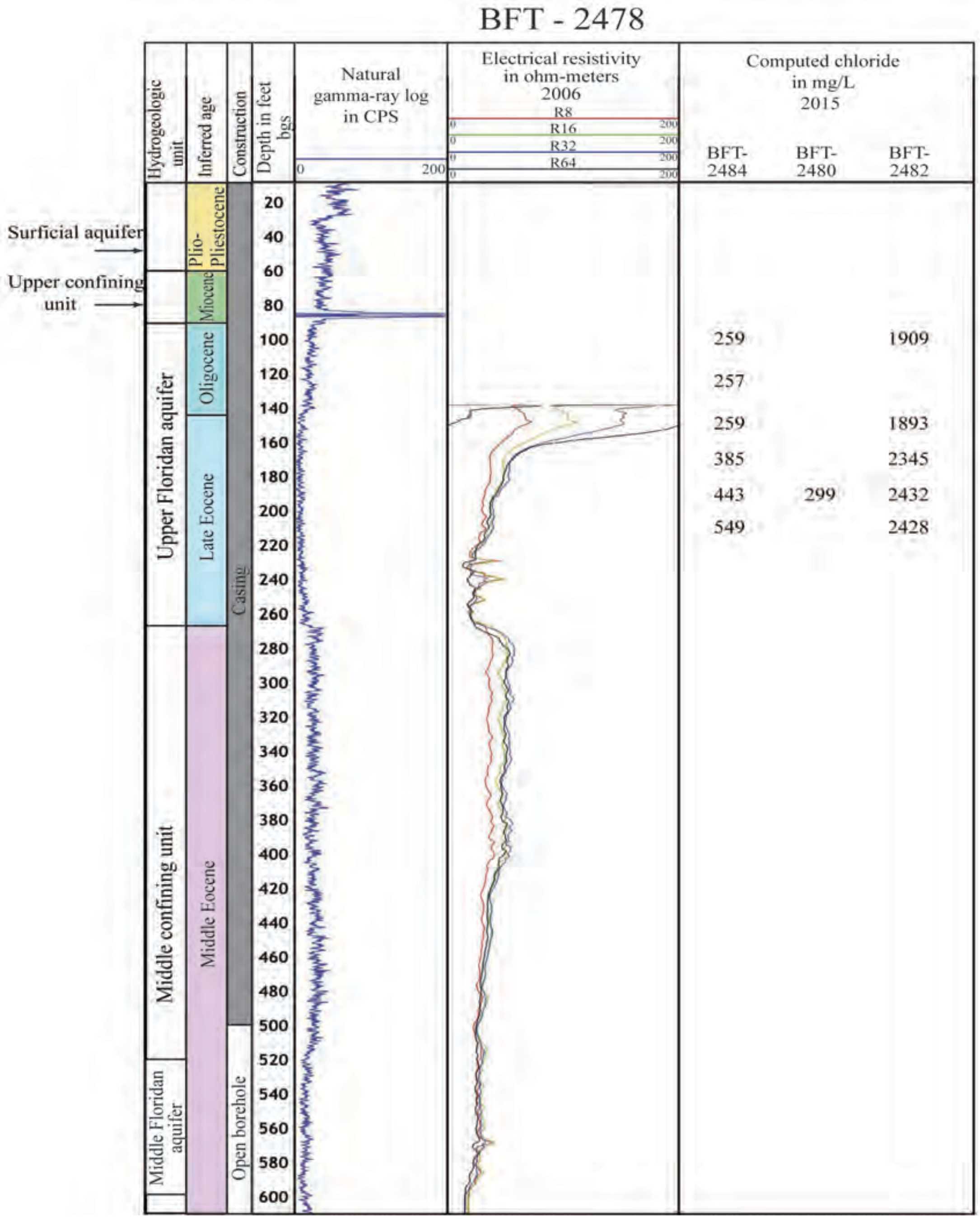


Figure 53. Hydrogeology, geophysical logs, chloride distribution, and well construction at well BFT-2478, Jenkins Island, S.C.

bordered by Skull Creek to the northeast, Mackay Creek to the west, and Jarvis Creek to the south. The Hilton Head Island Public Service District operates three middle Floridan aquifer wells and a reverse-osmosis plant on the island as part of its public supply system. Each of the three well sites include an Upper Floridan aquifer monitoring well completed to 200 ft bgs: they are locally known as the east site (well BFT-2482), the center site (well BFT-2480), and the west site (well BFT-2484); the center site also includes a middle Floridan aquifer monitoring well (BFT-2478). A fourth Upper

Floridan aquifer monitoring well (BFT-2314) was drilled on nearby Hog Island, northwest of Jenkins Island, as part of this study (fig. 52).

Geophysical logs of well BFT-2478 (fig. 53) indicated that the upper confining unit was thin, and that the Upper Floridan aquifer was present between 90 ft bgs and 260 ft bgs. The data support Foyle and others (2001) who conducted seismic surveys in nearby Skull Creek and Mackay Creek and concluded that the upper confining unit beneath channels north and west of Jenkins Island was between 0 and 10 ft thick.

Chloride concentrations were computed from specific-conductance profiles in the four Upper

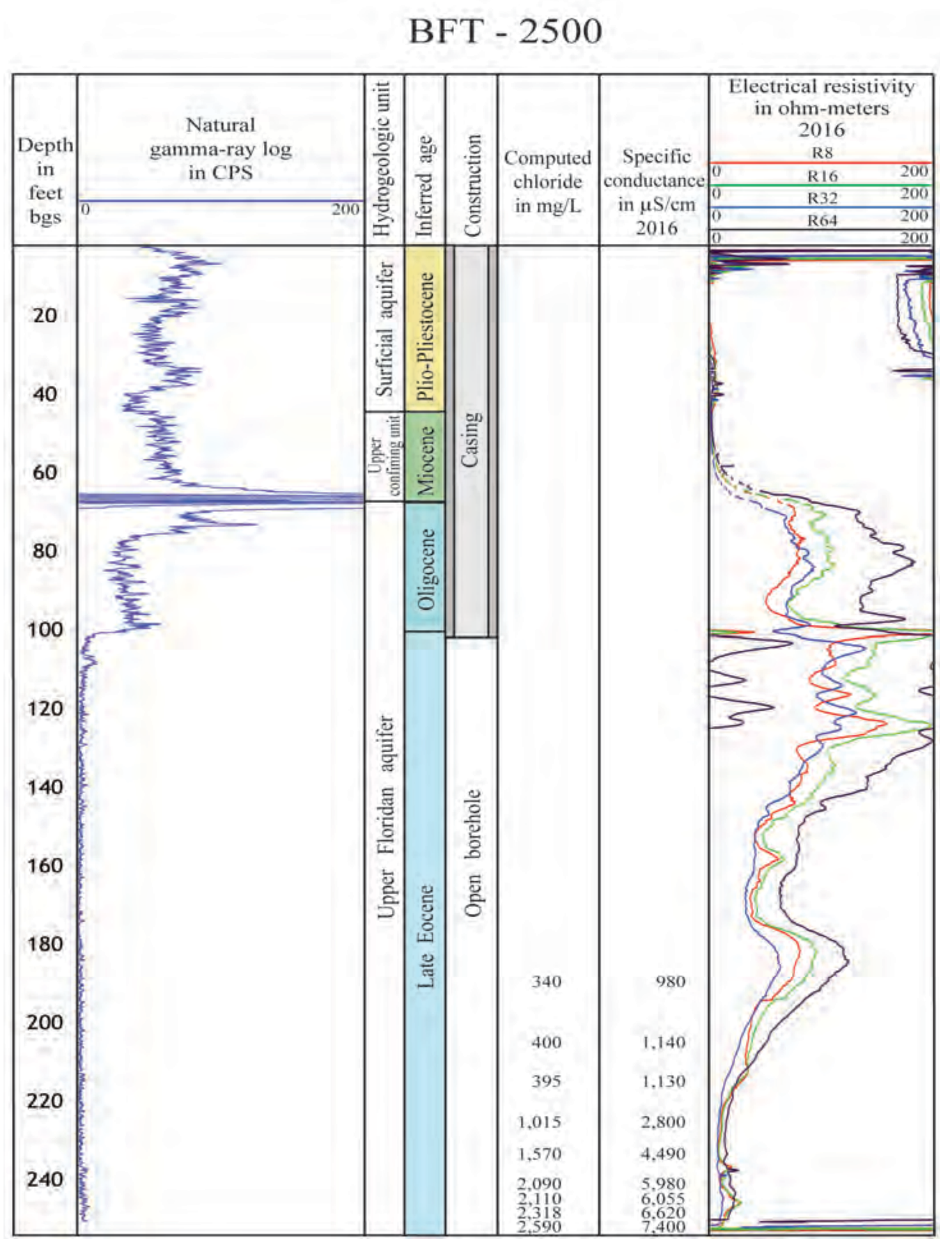


Figure 54. Hydrogeology, geophysical logs, chloride distribution, and well construction at well BFT-2500, near Jarvis Creek, Hilton Head Island, S.C.

Floridan aquifer monitoring wells in 2015. The greatest concentrations were found at well BFT-2482 near the eastern end of Jenkins Island where computed chloride concentrations increased with depth from 1,910 mg/L near the top of the aquifer (100 ft bgs) to 2,430 mg/L near the bottom of the borehole (200 ft bgs). At wells BFT-2480 and BFT-2484 computed chloride concentrations at the bottom of the boreholes (200 ft bgs) were 298 and 548 mg/L, respectively. Computed chloride concentrations at well BFT-2314, after the well was deepened from 225 to 250 ft bgs, were 700 mg/L near the aquifer bottom (the aquifer bottom may have been deeper). Geophysical logs at well BFT-2478 showed electrical resistivity decreasing with depth from 200 ft bgs to the bottom of the aquifer at about 260 ft bgs (fig. 53). The total depths of wells BFT-2482, BFT-2480, and BFT-2484 were about 60 ft above the bottom of the Upper Floridan aquifer. Therefore, the chloride concentrations at the bottom of the aquifer near these wells are unknown but are expected to be much greater than chloride concentrations at 200 ft bgs. Monitoring well BFT-2500, one mile southeast of Jenkins Island on the south side of Jarvis Creek, was drilled to 256 ft bgs in August 2015. Here, fresh water was present to 140 ft bgs; at about 210 ft bgs, the computed chloride concentration was about 400 mg/L and increased to about 2,550 mg/L at 256 ft bgs near the aquifer bottom (fig. 54).

The chloride contamination found in the Jenkins Island monitoring wells appears to originate near Skull Creek but also might originate from other nearby areas: reasons include (1) the poor confinement above the Upper Floridan aquifer reported by Foyle and others (2001) and observed in geophysical logs, (2) brackish water present in four wells drilled along the east-west axis of Jenkins Island with concentrations decreasing to the west, and (3) potentiometric data showing south to southwest-trending gradients beneath the area during the past 50 years. Brackish water at the top and bottom of the aquifer at well BFT-2482 indicates that seawater probably enters the aquifer from Skull Creek near the east end of Jenkins Island. Lesser chloride concentrations in the upper- and middle-aquifer sections occur west of well BFT-2482. The lowest chloride concentration at the middle section was found at BFT-2480 near the center of Jenkins Island at 200 ft bgs. Here, the lower chlorides might result from (1) greater distance from the chloride source area (Skull Creek), (2) freshwater recharge from the surficial aquifer, and (3) confining unit effectiveness. Well BFT-2500, one mile southeast of Jenkins Island, contained high chloride concentrations in the bottom 20 ft of the aquifer (fig.54); far lower than the expected chloride concentrations at the aquifer bottom beneath Jenkins Island. Here, brackish water at the aquifer bottom probably moved down gradient from the chloride source area near Jenkins Island; if not, another chloride-source area exists nearby.

Reasons for a chloride plume are: (1) a downward hydraulic gradient in the saltwater channels and estuaries overlying the Upper Floridan aquifer, (2) a lateral south to southwest-trending hydraulic gradient in the aquifer for the past 50 years , (3) brackish water at the bottom of the aquifer at both the east and west boundaries of the island, and (4) the southwestern extent of brackish water found one mile down gradient of the island at well BFT-2500. The saltwater plume originating near Jenkins Island and moving beneath Jenkins Island is named herein the Jenkins Island chloride plume.

Broad Creek Chloride Plume

Broad Creek forms a saltwater estuary that transects Hilton Head Island in a northeast-southwest direction and opens to Skull Creek on the western side of the island (fig. 55). Historically, wells completed in the Upper Floridan aquifer south of Broad Creek produce water with chloride concentrations less than 50 mg/L and between 50 and 100 mg/L near the Atlantic Ocean (fig. 41). However, public supply well BFT-678, about 0.4 mile south of Broad Creek, was removed from service in 2009 after chloride concentrations exceeded 250 mg/L: the well had pumped 1,000 gpm since 1981. Figure 55 shows the 2010 chloride concentration measured in pumped samples from southern Hilton Head Island (Groundwater Management Associates, 2010).

The possible occurrence of a chloride plume near Broad Creek was further investigated in 2009 by constructing test-well BFT-2410 on the south bank of the Broad Creek estuary (fig. 55). The borehole was advanced by roto-sonic method with continuous geologic core in sealed 5-foot sections to a depth of 198 ft bgs: afterwards, the well was cased and grouted to 130 ft bgs near the top of the Eocene limestone and completed as an open hole to the aquifer bottom at 283 ft bgs. Examination of the geologic core revealed that the upper confining unit was absent, and the surficial aquifer was in direct contact with the Upper Floridan aquifer (Oligocene limestone) at a depth of -60 ft bgs (fig. 56). Based on geophysical logs and structure-contour maps (Hayes, 1976; Hughes and others, 1989; Foyle and others, 2001; Falls and others 2005), the expected elevation for the top of the Upper Floridan aquifer would be about -80 ft Msl and the expected thickness of the overlying upper confining unit would be about 20 ft. Tectonic uplift and formation of the Beaufort Arch are probably responsible for the higher elevation of the Upper Floridan aquifer at well BFT-2410, designated herein the Broad Creek high.

Well BFT-2410 was constructed in 2009 on the bank of the Broad Creek estuary. Pore-water samples

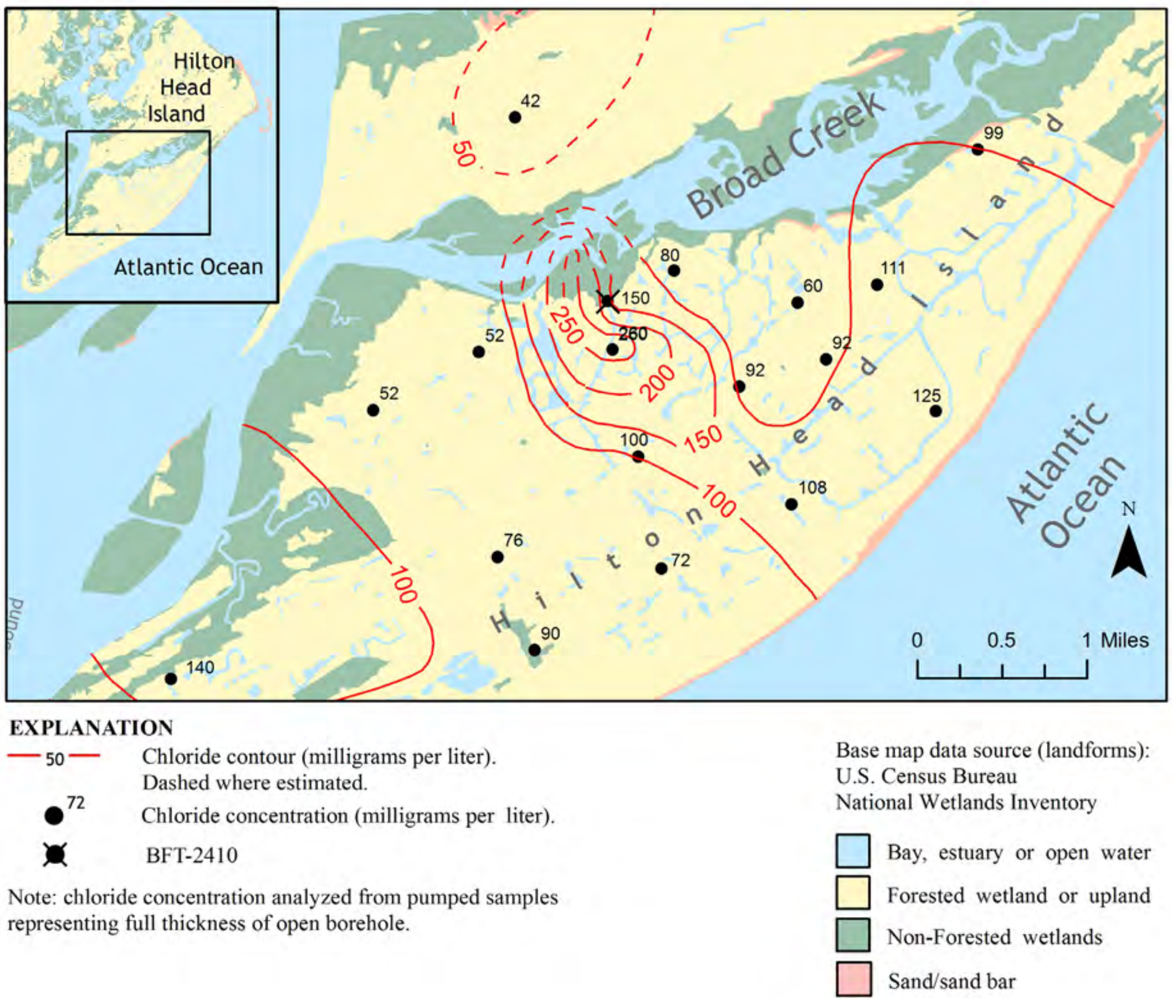


Figure 55. Location of test well BFT-2410 and isochlors showing the extent of the Broad Creek chloride plume, 2010, Hilton Head Island, S.C. (after Groundwater Management Associates, 2010).

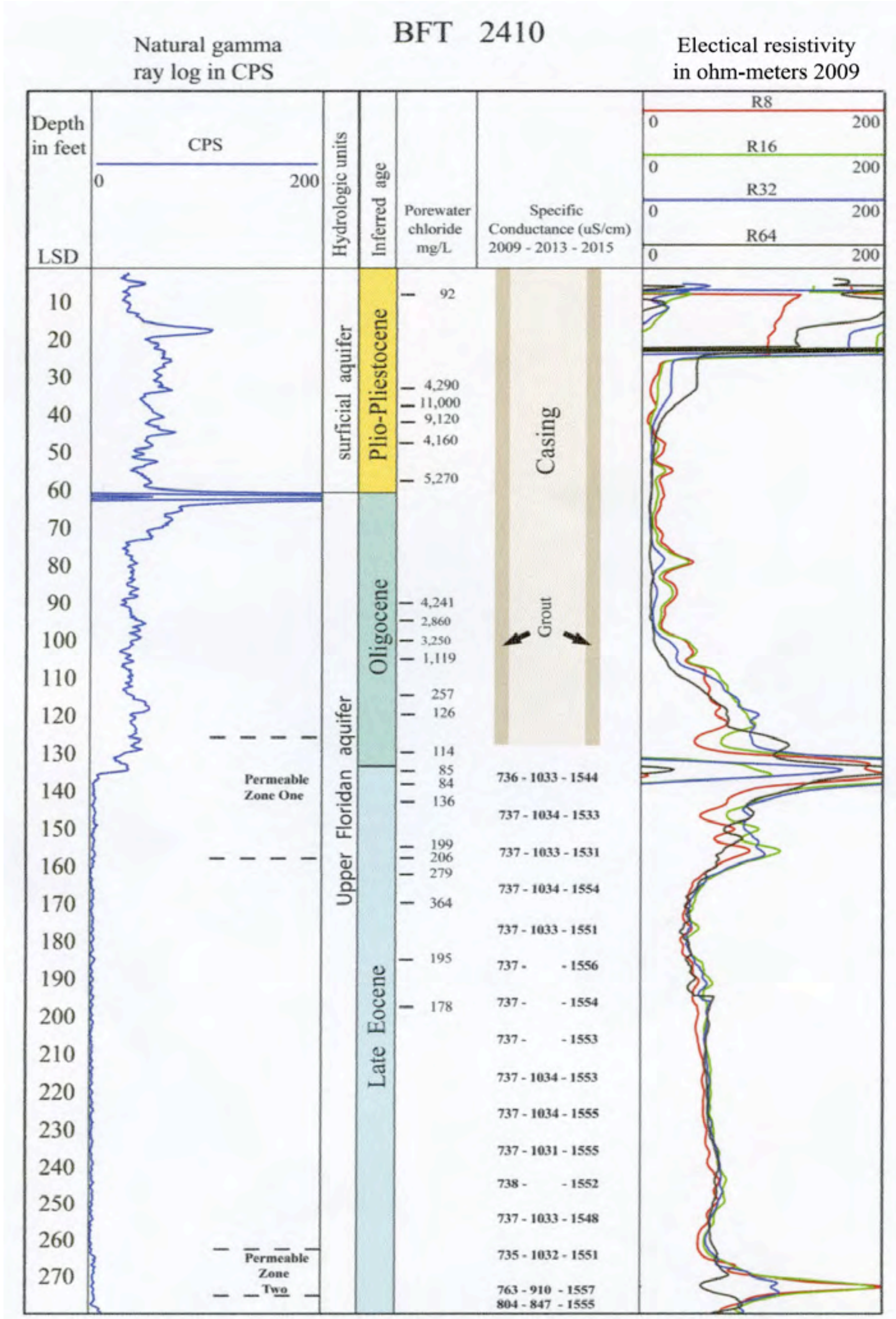


Figure 56. Hydrogeology, geophysical logs, specific-conductance profiles, chloride concentrations from pore-water, and well construction at well BFT-2410, Hilton Head Island, S.C., 2009–2015.

were extracted from the geologic core at selected depths to determine if chloride concentrations at well BFT-2410 were related to those found at well BFT-678. Chloride concentrations (analyzed by the USGS) ranged from 92 to 11,000 mg/L for six surficial-aquifer samples. The lowest chloride concentration of 92 mg/L was found near the top of the aquifer at 7.5 ft bgs (0.57 ft Msl) where fresh water would be expected. The remaining five samples from the brackish section of the surficial aquifer contained erratically distributed chloride concentrations that ranged from 4,160 to 11,000 mg/L; 5,270 mg/L was present near the bottom of the surficial aquifer at a depth of 57.5 ft bgs. The erratic chloride distribution can be attributed to heterogeneity in the sedimentary column, lateral freshwater discharge from the landmass, and variable freshwater heads resulting from artificial drainage, rainfall, and tides near the shore of the saltwater estuary. Near the top of the Upper Floridan aquifer (Oligocene limestone) pore water was extracted from seven samples beginning at 90 ft bgs near the middle of the Oligocene limestone to the bottom of the unit at 130 ft bgs. Chloride concentration was 4,241 mg/L at 90 ft bgs and, with one exception, progressively decreased with depth to 114 mg/L near the bottom of the Oligocene limestone: the progressive decrease in chloride concentration indicates vertical migration in response to a downward hydraulic gradient near the well site. Near the top of the underlying Eocene limestone the chloride concentration was 85 mg/L at 134 ft bgs and increased with depth though permeable zone 1 to 364 mg/L at 170 ft bgs: the lesser chloride concentrations near the top of the Eocene limestone were probably the result of higher concentrations moving downward and diluting into more permeable sediment. The progressive increase in chloride concentration that occurred at depth through permeable zone 1 suggests lateral migration of chloride from a more distant source area. Two pore-water samples were collected at 185 and 198 ft bgs; chloride concentrations were 195 and 178 mg/L, respectively. Here, the lower chloride concentrations probably are the result of overlying chlorides of greater concentration migrating downward in the open borehole, mixing with freshwater, and diluting.

Specific-conductance profiles at selected depths beneath the casing at well BFT-2410 were reasonably consistent throughout the open borehole for each sampling year. In 2009, specific conductance averaged 737 µS/cm: equivalent to a computed chloride concentration of about 200 mg/L and similar to concentrations at the abandoned down-gradient public supply well BFT-678. A second specific-conductance profile in 2013 had an average value of about 1,030 µS/cm; equivalent to a computed chloride concentration of about 350 mg/L. A third specific-conductance profile conducted in 2015 showed an average value of about 1,530 µS/cm; equivalent to a computed chloride concentration of about 540 mg/L. Computed chloride concentrations from specific-conductance profiles at well BFT-2410 in 2009 and 2015 indicated that the chloride concentration in the Eocene section of the Upper Floridan aquifer more than doubled in a span of five years.

The absence of the upper confining unit, the high elevation of the Upper Floridan aquifer surface, and the high chloride concentrations in the upper part of the sedimentary column indicate that the source of chloride contamination is modern seawater originating beneath the Broad Creek estuary near the well site. Saltwater migration from the Broad Creek estuary may have been retarded from moving into the Eocene limestone because: (1) the Oligocene limestone comprising the top of the Upper Floridan aquifer has a low hydraulic conductivity compared to the underlying Eocene limestone, (2) a thick Oligocene section of about 50 to 60 ft underlies the southwestern part of the Broad Creek estuary, and (3) a 70 ft thickness underlies the well BFT-2410 test site. Additionally, salt water at the bottom of the surficial aquifer is diluted because the estuary is long, narrow, and small relative to the length of its shoreline, and therefore receives an atypically large volume of subsurface discharge relative to estuary surface area. This hydrologic setting would explain the relatively low chloride concentrations (167 to 1,000 mg/L) measured by Ransom and Park (2011) in the surficial aquifer beneath Broad Creek (fig. 30).

The authors conclude, on the basis of data from monitoring well BFT-2410, that the high chloride concentrations found at well BFT-678 originate at a source area beneath the Broad Creek estuary owing to (1) the proximity to Broad Creek, (2) absence or thinning of the upper confining unit, (3) a potentiometric surface that ranged from 0 ft Msl since about 1957 to -10 ft Msl in 1998, (4) brackish water progressively moving downward and laterally into the aquifer at the monitoring well site, and (5) the overall isochlor pattern that indicate a source area to the north near Broad Creek. The plume is named herein the Broad Creek chloride plume.

Bull Island Chloride Plume

Bull Island is a relatively large Sea Island that lies between Hilton Head Island and the mainland and is surrounded by an expanse of saltwater marsh, small islands, and tidal channels. Potable water for two cottages on the island near the bank of Bull Creek was supplied from a domestic well completed in the

Upper Floridan aquifer; several larger wells were used seasonally for irrigation. This area was investigated after a report that an irrigation well drilled in about 2000, on the southeast side of the island, encountered brackish to salt water at the top of the aquifer. Later, in about 2009, the domestic well, that served the two cottages was reported to have unacceptable levels of chloride: a replacement well was attempted but also reported brackish water at the top of the aquifer**.** Access to the island was not possible and it was necessary to construct temporary offshore test wells BFT-2475 and BFT-2476 in channels along the east-central and southwest shores of the island in September 2011 (fig. 57).

Owing to the challenges of testing groundwater quality in wells constructed over saltwater channels, an account of well-construction and testing procedures follows. Well BFT-2475 was drilled in Bryan Creek bordering the eastern part of Bull Island (fig. 57). Construction began with the installation of a 6-inch surface casing lowered through the drill-rig-platform and positioned at about -10 ft Msl (sea level estimated from visual tidal observations) and extending to a depth 3 ft below the channel bottom; afterwards, a six-inch bit was advanced by mud-rotary drilling to the top of the Upper Floridan aquifer. Geologic cuttings and geophysical logs were obtained and used to determine the depths and thicknesses of hydrogeologic units prior to final casing installation. The surficial aquifer was present at about -7 ft Msl to -35 ft Msl; the upper confining unit was present between about -35 and -80 ft Msl; and the Upper Floridan aquifer lay below -80 ft Msl. Three-inch steel casing was installed by first lowering the drill rod to the top of the Upper Floridan aquifer (Oligocene limestone) and filling the borehole with neat cement grout pumped through the center of the drill stem. The 3-inch casing was fitted with a bottom plug and centralizers were installed at 20-ft

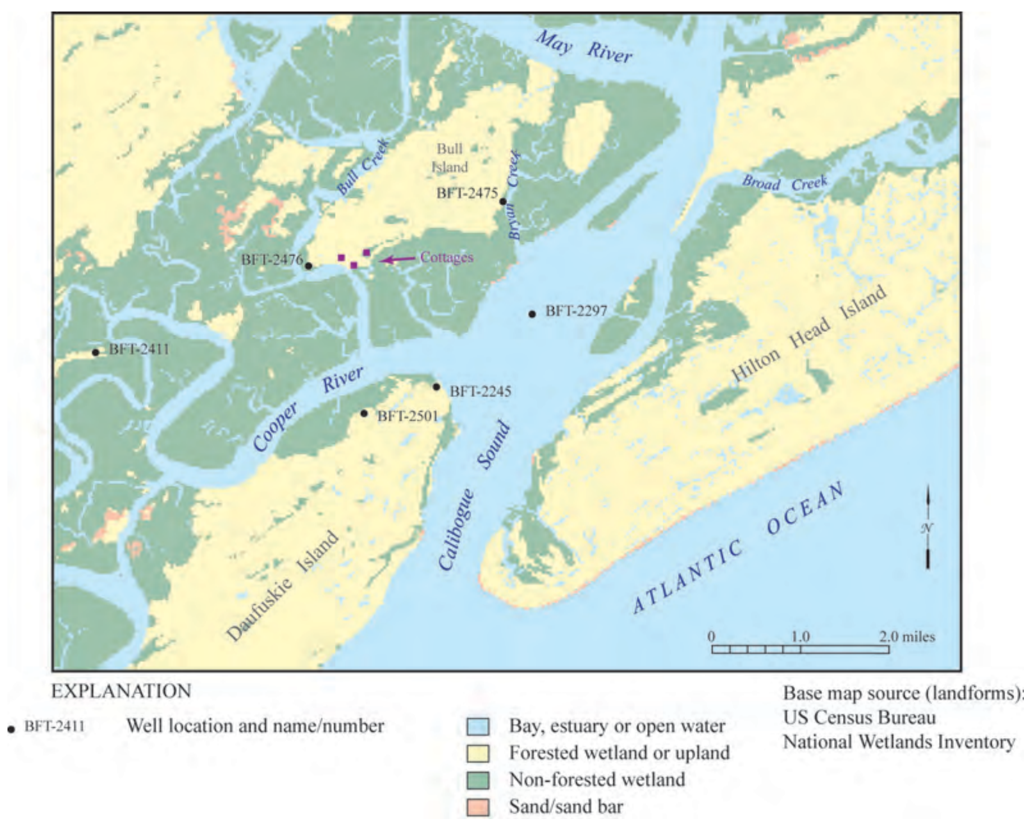


Figure 57. Location of test wells near Bull Island, S.C.

intervals, the casing was then floated to the bottom of the borehole and the 6-inch surface casing was removed. After 24 hours, a $2^{7}/_{8}$-inch diameter borehole was advanced through the grouted casing by mud rotary method to about -275 ft Msl, near the bottom of the aquifer; specific conductance of the drilling fluid was measured at selected depths as the borehole advanced. **N**ear the top of the Upper Floridan aquifer between -90 to -120 ft Msl specific conductance was field tested and found to be 1,300 µS/cm; at depths below -120 ft Msl, specific conductance was between 1,000 to 800 µS/cm. The specific conductance values were typical of the drilling fluid used. Prior to removing the drill stem, approximately 300 gallons of fresh water were injected through the drill stem at the aquifer bottom

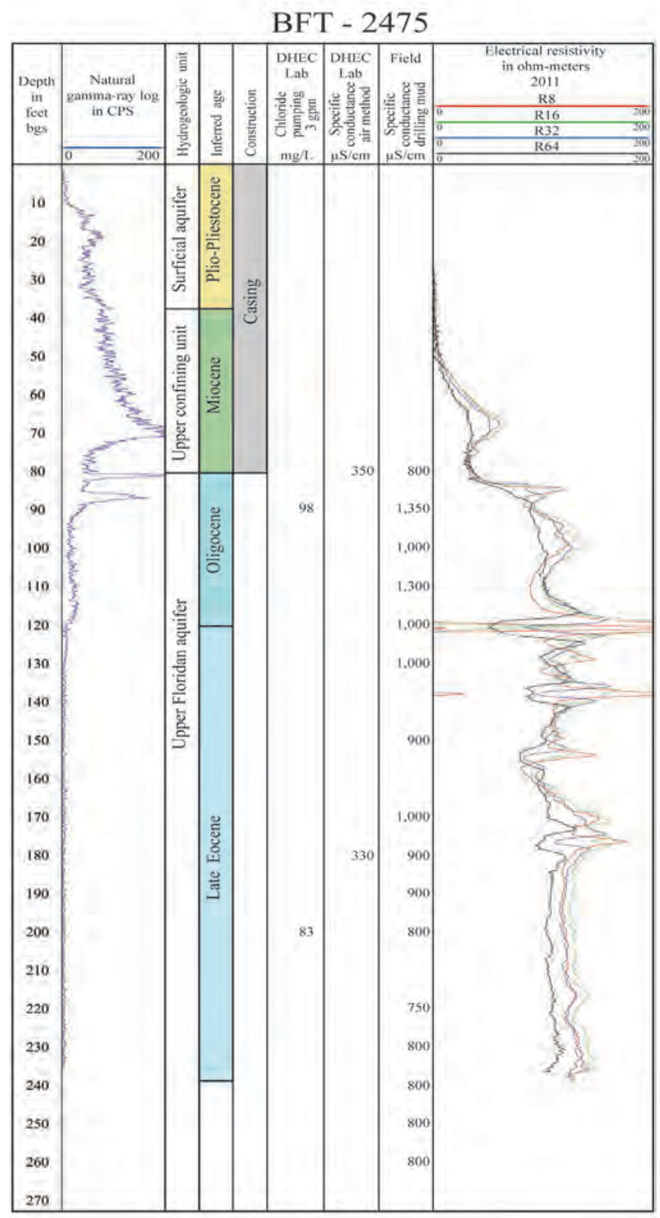


Figure 58. Hydrogeology, geophysical logs, specific conductance, chloride distribution, and well construction at well BFT-2475, Bull Island, S.C.

to remove drilling fluid from the well bore. Geophysical logs were run 16 hours later (fig. 58), afterwards a 3-gpm sampling pump was used to remove injected water from the borehole.

Specific conductance testing to assure that foreign water had been evacuated from the borehole prior to sampling began by setting the pump at -50 ft Msl and pumping for about 2.5 hours while slowly lowering the pump to -200 ft Msl. At depths of -100, -150, and -200 ft Msl, specific conductance stabilized at 400 µS/cm; the pump was then positioned at -85 and -195 ft Msl, and, after specific conductance stabilized, water samples were collected. Laboratory analyses (SCDHEC Lab) reported chloride concentrations of 98 and 83 mg/L, respectively. As a further precaution, an air compressor was attached to the drill stem on the final day and used to evacuate a far larger volume of water from the borehole at about -200 ft Msl. After purging the well for two hours at an estimated 40 gpm, the specific conductance at the well head was

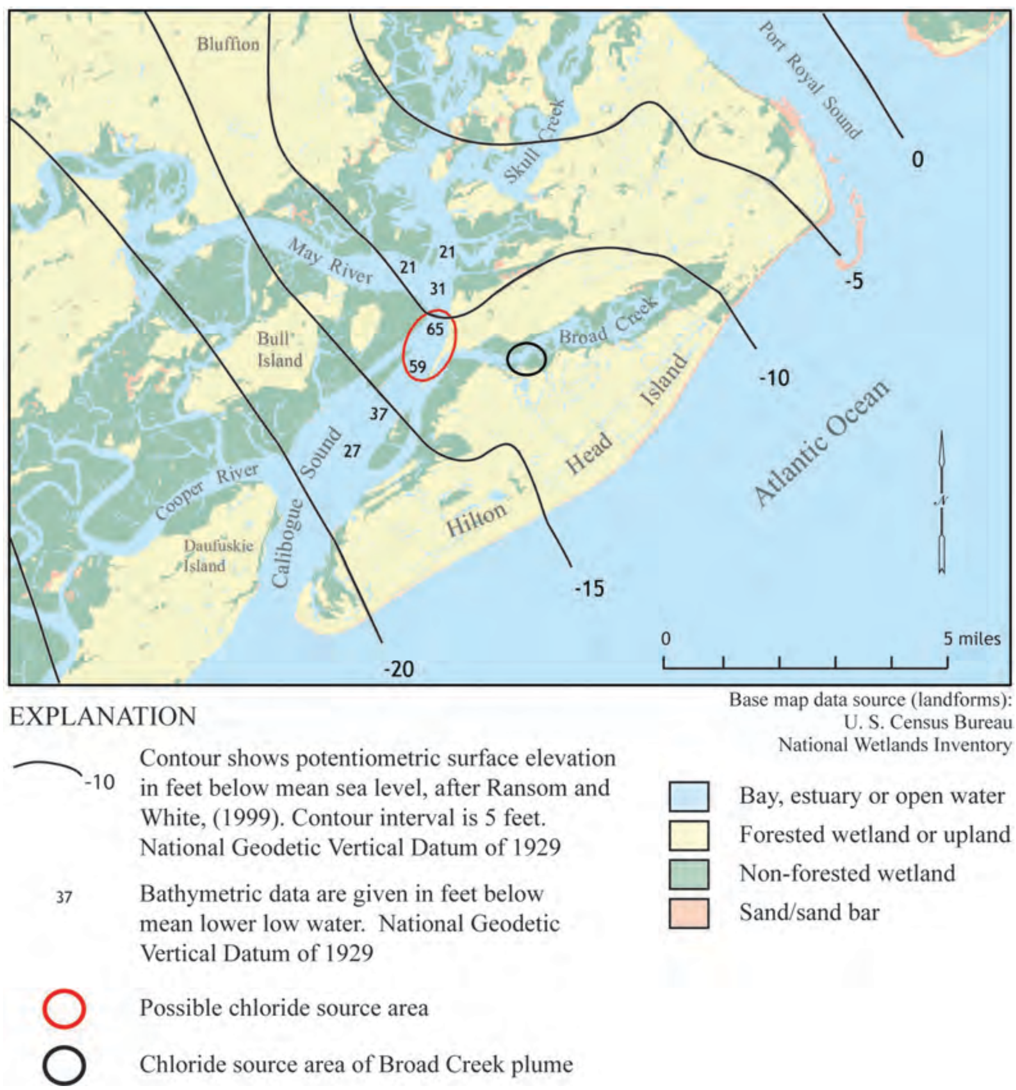


Figure 59. Bathymetry near the confluence of the May River and Skull Creek, S.C. (National Oceanic and Atmospheric Administration, 2013), and 1998 potentiometric surface of the Upper Floridan aquifer (after Ransom and White 1999).

330 µS/cm, and the estimated water level was -13 ft Msl. After specific conductance measurements proved the borehole was free of contamination, the well was abandoned with sand and filled with neat Portland cement from 10 ft below the casing to the top of the channel and the top casing joint (reverse threads) was removed (fig. 58).

Saltwater contamination, albeit comparatively minor, was present at the well BFT-2475 site where the predevelopment background chloride concentration in the Upper Floridan aquifer was less than 10 mg/L. The electrical-resistivity log suggested that chloride was present at higher concentrations in the top part of the upper confining unit (fig. 58), and laboratory analysis confirmed a chloride concentration of 98 mg/L at the top of the Upper Floridan aquifer. The data probably indicate that breakthrough has occurred at the top of the aquifer from chloride migrating downward through

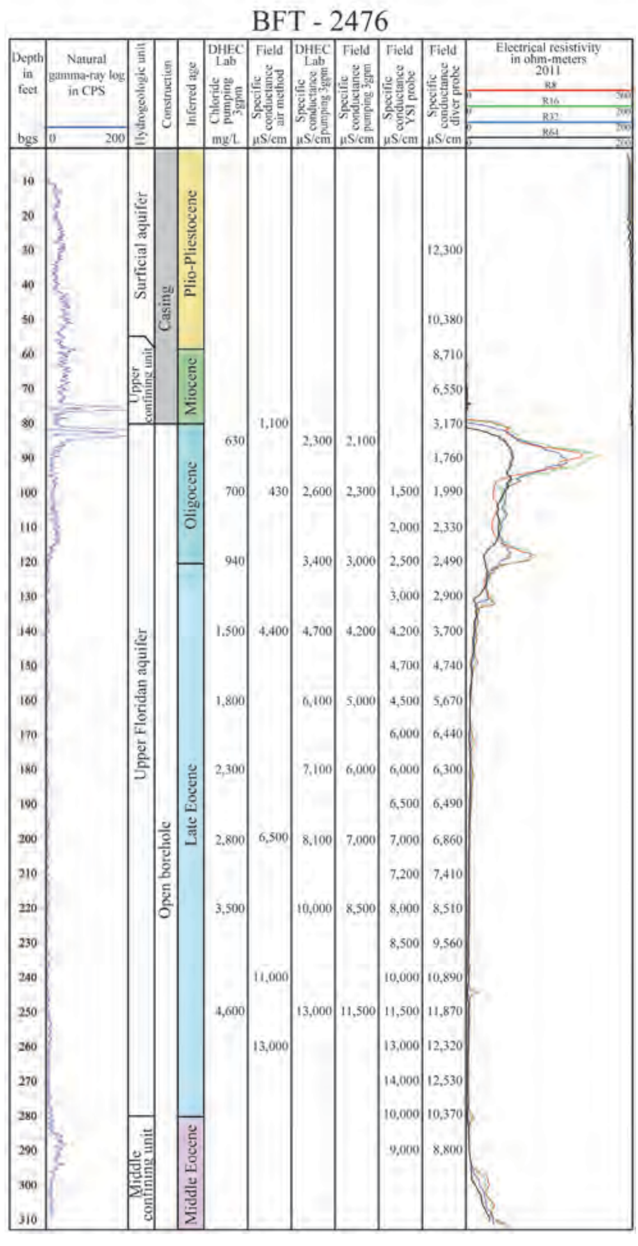


Figure 60. Hydrogeology, geophysical logs, specific conductance, chloride distribution, and well construction at well BFT-2476 near Bull Island, S.C. Bull Island, S.C.

the upper confining unit from overlying saltwater sources. Specific conductance measurements, laboratory analyses, and geophysical logs indicated that the Upper Floridan aquifer at well BFT-2475 contained fresh water relative to the EPA definition; however, chloride concentrations were about ten times greater than the background concentrations expected for the area. Warren's (1944) estimate of 1880 head near the test site was approximately 13 ft Msl (Appendix D1) and vertical head differences were probably higher during times of lower sea level, thereby providing greater opportunity to completely flush relict salt water. Ransom and others (2006) calculated that breakthrough time for 500-mg/L chloride concentrations could have occurred in 2004 near the northern part of Bull Island, and earlier in areas northeast and up gradient of well BFT-2475 (fig. 33).

The lower chloride concentration at the top of the aquifer, as opposed to that calculated for breakthrough, probably represents dilution after entering the top of the aquifer. Additionally, the chloride concentration for the source area is probably less than the 19,000 mg/L used by Ransom and others (2006) because dilution is taking place in the surficial aquifer beneath the intracoastal areas (Ransom and Park, 2011). Further support for downward migration is evident in pore water extracted from confining unit core from offshore well BFT-2297, drilled in 2001 about 1.5 miles south of offshore well BFT-2475 in Calibogue Sound. Here, Falls and others (2005) reported that the confining infill sediment had a chloride concentration of 1,300 mg/L near the top of the sediment at -44 Msl (NAVD88) and decreased to 360 mg/L near the bottom of the sediment at -79 ft Msl (NAVD88).

Evidence does not suggest that the computed chloride concentrations found in well BFT-2475 are associated with a specific source area. The contamination probably is related to a delayed seawater breakthrough in areas to the east and north where 20 to 30 ft confining unit thicknesses are thought to prevail but may be thinner in some areas. Near Bull Island, seawater has probably migrated through the upper confining unit for a longer timespan while driven by greater head differences across the unit. Indications of a thinner confining unit include: (1) the locally great channel depths noted on navigation charts (59 to 65 ft, mean lower-low water) between the May River and Broad Creek (fig. 59), (2) the potentiometric-surface mounding that indicates an atypically greater recharge rate northeast of Bull Island compared to surrounding areas and that is shown on potentiometric maps since 1961 and, (3) the general coincidence of the recharge mound with the shallow aquifer depth and confining-unit absence found at Broad Creek well BFT-2410, and (4) seismic profiles (Duncan, 1972; Foyle and others, 2001) that estimate confining-unit thicknesses less than 20 ft, and locally less than 10 ft, near the confluence of May River with northern Calibogue Sound. Thus, it seems probable that the chloride concentrations found in well BFT-2475 foretell of wide-spread breakthrough near Bull Island and the area to the east and northeast (fig. 33).

A second offshore test well (BFT-2476) was constructed near the southern part of Bull Island in Bull Creek about 0.3 miles southwest of the contaminated domestic wells at the cottages. Well-construction and water-quality sampling procedures were consistent with those described for well Bft-2475 with the exceptions that: (1) grout was allowed to set for 40 hours, (2) the borehole beneath the casing was drilled using the air-rotary method, and (3) the top of the confining unit was identified with core samples. The well was cased and grouted to about -76 ft Msl at the top of the Upper Floridan aquifer (Oligocene limestone) and completed as an open borehole beneath the casing to about -310 ft Msl, near the bottom of the aquifer. The upper confining unit was approximately 20 ft thick (fig. 60).

Water-quality data at well BFT-2476 (fig. 60) were collected by: (1) measuring specific conductance from composite water samples collected as the borehole was advanced by air-rotary drilling, (2) collecting 3-gpm pumped samples at selected depths for laboratory analysis, (3) measurements of specific conductance at selected depths in the open-borehole while pumping 3 gpm from within the casing to compensation for a small leak, and (4) measurements of specific conductance at selected depths under static conditions. Specific conductance measured in the casing with a Van Essen "CTD Diver" data logger at about -30 ft Msl was 12,300 µS/cm under static conditions and progressively decreased to 1,760 µS/cm at -90 ft Msl; below -90 ft

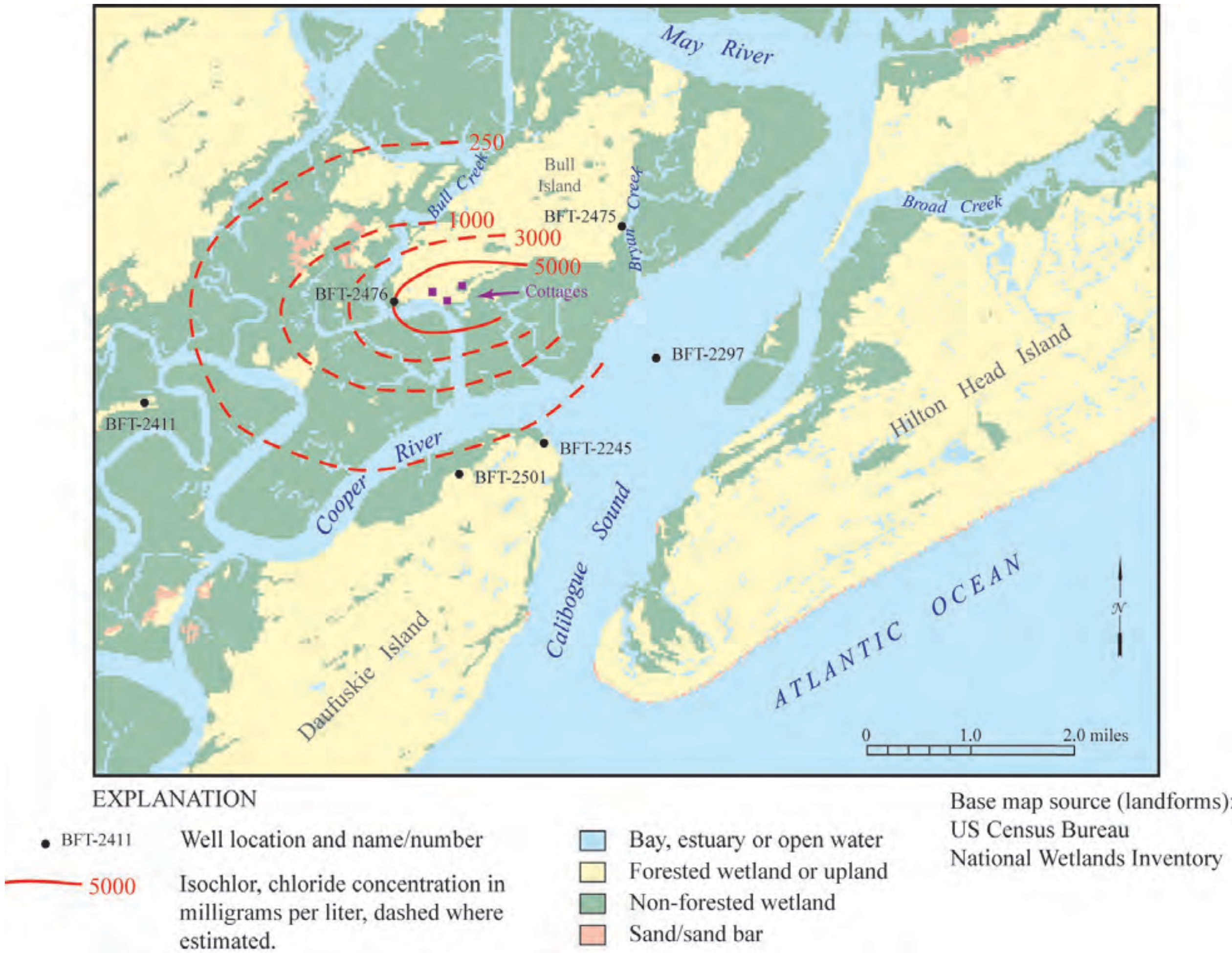


Figure 61. Location of test wells near Bull Island, S.C. and estimated position of the Bull Island chloride plume.

Msl specific conductance increased with depth. The high specific-conductance measurement at -30 ft Msl is attributed to a casing-joint leak. Beginning at -90 ft Msl, specific conductance progressively increased to the bottom of the Upper Floridan aquifer at a depth of about -280 ft Msl; here, specific conductance measured 12,530 µS/cm. Additionally, nine pumped samples from the Upper Floridan aquifer were taken at discrete depths in the open borehole and analyzed (SCDHEC laboratory) for chloride concentration; concentrations increased from 630 mg/L at -85 ft Msl to 4,600 mg/L at -250 ft Msl. Near the bottom of the Upper Floridan aquifer, at -270 ft Msl, the specific-conductance measurements taken with two probes, YSI and Diver, and were 14,000 and 12,530 µS/cm, respectively.

Electrical-resistivity logs and water-quality samples at well BFT-2476 show chloride contamination is present in the upper confining unit, the Upper Floridan aquifer, and the top of the middle confining unit. The relatively low electrical resistivity shown on the geophysical logs (fig. 60) is consistent also with the high specific-conductance values. The logs indicated resistivity was low at the top of the unit and increased with depth as fresh water was encountered. The electrical-resistivity logs corresponded also with the high specific conductance in the upper part of the middle confining unit; these data are interpreted to be chloride migrating downward from the Upper

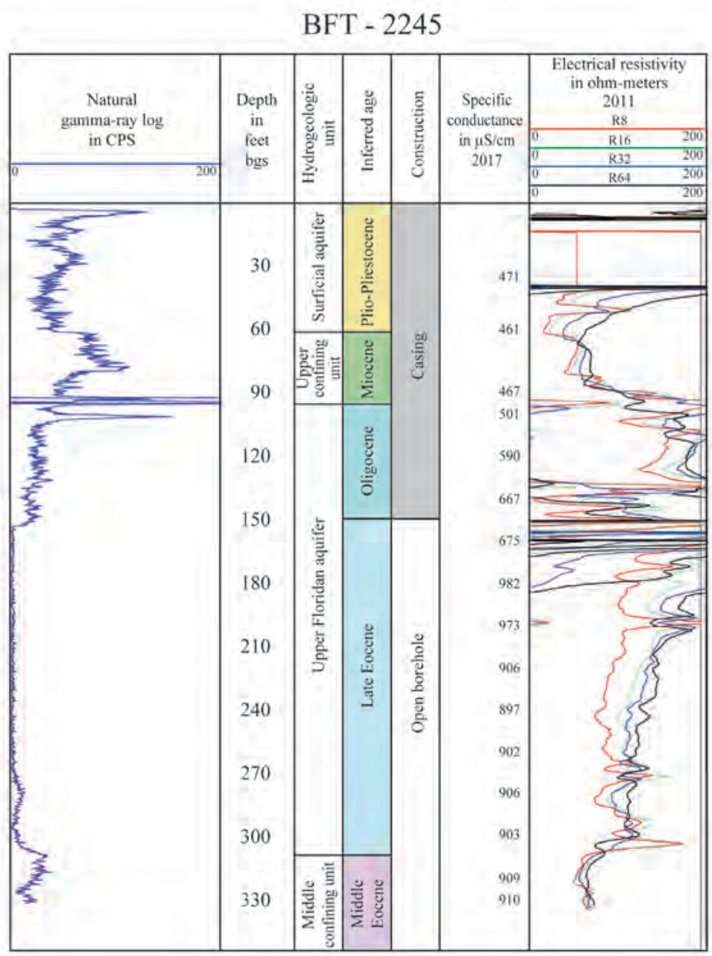


Figure 62. Geophysical logs and vertical specific-conductance profile at BFT-2245 on northern Daufuskie Island, S.C.

suggest chloride contamination from downward migration through the 20-ft thickness of the upper confining unit and brackish-water breakthrough that is diluted in the top of the Upper Floridan aquifer. Underlying the Upper Floridan aquifer, the electrical-resistivity log signature adjacent to the middle confining unit between 280 and 310 ft Msl Floridan aquifer and into the top of the previously freshwater middle confining unit.

The high chloride concentrations reported at the top of the aquifer near the domestic and irrigation wells on Bull Island (fig. 61) suggest a nearby direct chloride source area; other evidence that a more direct chloride-source area lies close to Bull Island also includes: (1) the vertical distribution of computed chloride concentrations at BFT-2476 with higher chloride concentrations near the bottom of the Upper Floridan aquifer that indicate a direct but more distant source to the northeast; (2) an upper confining unit thickness of 20 ft at the well that correlates with Foyle and others' (2001), who reported the unit's (Miocene) average thickness to be 10 to 20 ft beneath Bull Creek and part of Calibogue Sound near the southwestern tip of Daufuskie Island; (3) the missing upper confining unit near the mouth of the May River as mapped by Duncan (1972); (4) the thinning of the upper confining unit (Hawthorne Group, fig. 12) near the axis of the Beaufort Arch (fig. 13) at Bull Island; (5) the channel depths of 59 to 65 ft Mean Lower Low Water (about -62 to -68 ft Msl) east of Bull Island (Fig. 59), where less than 12 ft of sediment might overlie the top of the aquifer; (6) the area's proximity to the source area for the Broad Creek chloride plume where the top of the aquifer was -52 ft Msl or about -60 ft bgs; here, the upper confining unit was absent (figs. 55 and 56); and (7) the 360 mg/L chloride concentration near the bottom of the confining unit at offshore well BFT-2297 (Appendix I) in Calibogue Sound. The data indicate that a large saltwater plume (fig. 61), designated herein as the Bull Island chloride plume, is present in the Upper Floridan aquifer beneath the southern part of Bull Island and the surrounding saltwater wetlands.

The source area and extent of the Bull Island chloride plume are not well defined because few monitoring wells are available. However, the plume probably lies between wells BFT-2475 (eastern Bull Island), the western shore of Hilton Head Island, BFT-2245 and -2501 (Daufuskie Island), and BFT-2411 (Long Island). Well BFT-2475, located in Bryan Creek off the northern shore of Bull Island, produced water having chloride concentrations of 98 to 83 mg/L, probably the result of downward migration and are not believed to be a major contributor to the Bull Island chloride plume. Monitoring well BFT-2411 was constructed at the northern tip of Long Island about 2.7 mi. southwest of the cottages and lies within the southwestern flow path toward Savannah. Here, a specific-conductance profile conducted at selected intervals in 2014 measured about 200 µS/cm (Appendix I) and was consistent throughout the open borehole of the aquifer; estimated chloride concentration is expected to be about 10 mg/L. Monitoring well BFT-2245 is located at the northern tip of Daufuskie Island about 2 mi southeast of the estimated source area. Figure 62 shows the vertical specific-conductance profile taken in 2017 that ranged from about 500 µS/cm at the top of the aquifer to about 900 µS/cm near aquifer bottom. Here, a discrete water sample taken at 327 feet bgs found the chloride concentration to be 240 mg/L. Specific conductance at well BFT-2245 increased progressively downward from the top to the bottom of the aquifer and exceeded back-ground levels for the area. It is probable that the Bull River chloride plume may be contaminating the bottom of the aquifer at well BFT-2245 and that downward migration through the upper confining unit is contributing to an increase in chloride concentration near the top of the aquifer, similar to increases observed in well BFT-2475.

Atlantic Ocean Offshore Chloride Plumes

A large part of the cone of depression centered at Savannah extends offshore beneath the Atlantic Ocean where the potentiometric surface of the Upper Floridan aquifer is at or below mean sea level (Appendix D). Here, the thickness of the overlying upper confining unit was generally understood to vary and could be thin or absent in some areas and therefore allow salt water to enter the aquifer.

Seismic reflection surveys (Foyle and others; 1999, 2001) were conducted as part of the GSSI in the tidal channels of the study area and offshore in the Atlantic Ocean east of Hilton Head Island and Savannah to determine elevations of the Upper Floridan aquifer and overlying upper confining unit. The seismic surveys revealed an area three to seven miles offshore and southeast of central Hilton Head Island where the top of Upper Floridan aquifer occurred at an average elevation of -60 ft Msl, but elevations as shallow as -48 ft Msl were recorded. The area was designated the Hilton Head High by Foyle (1999) and could be both a structural sub-feature of the Beaufort Arch and an erosional remnant (fig. 13). Foyle interpreted three areas overlying the Hilton Head High where he believed the thickness of the upper confining unit was between 0 and 10 ft: the combined areas totaled about 3,700 acres. (fig. 63).

Six temporary Atlantic Ocean boreholes were drilled at four sites (fig. 63) to the south and southwest of the Hilton Head High as part of the CSSI (Falls and others, 2005). This offshore project was designed to corroborate the findings of the offshore seismic surveys where the upper confining unit was expected to be absent, to examine the geologic sediment, and determine water quality. Four of the six offshore boreholes were successfully completed as test wells between 1999 and 2001: BFT-2258 (15-mile site), BFT- 2251(10-mile site), BFT-2249 (7-mile site), and BFT-2295 (8-mile site). Boreholes identified as BFT-2257 and BFT-2250 (15- and 10-mile sites) were abandoned with incomplete data because of drilling difficulties. Two earlier offshore wells completed beneath the Atlantic Ocean near the Hilton Head High, BFT-1675 and BFT-1679, were part of the 1984 Port Royal Sound study (Burt and others, 1987; Hughes and others, 1989; Smith, 1988 and 1994). The offshore wells were constructed by the USACE using their offshore drilling platforms with specific attention given to preserving the integrity of sampling procedures and water quality testing according to project design. The well casings were seated and grouted in place to ensure that the wells remained free of overlying sources of saltwater

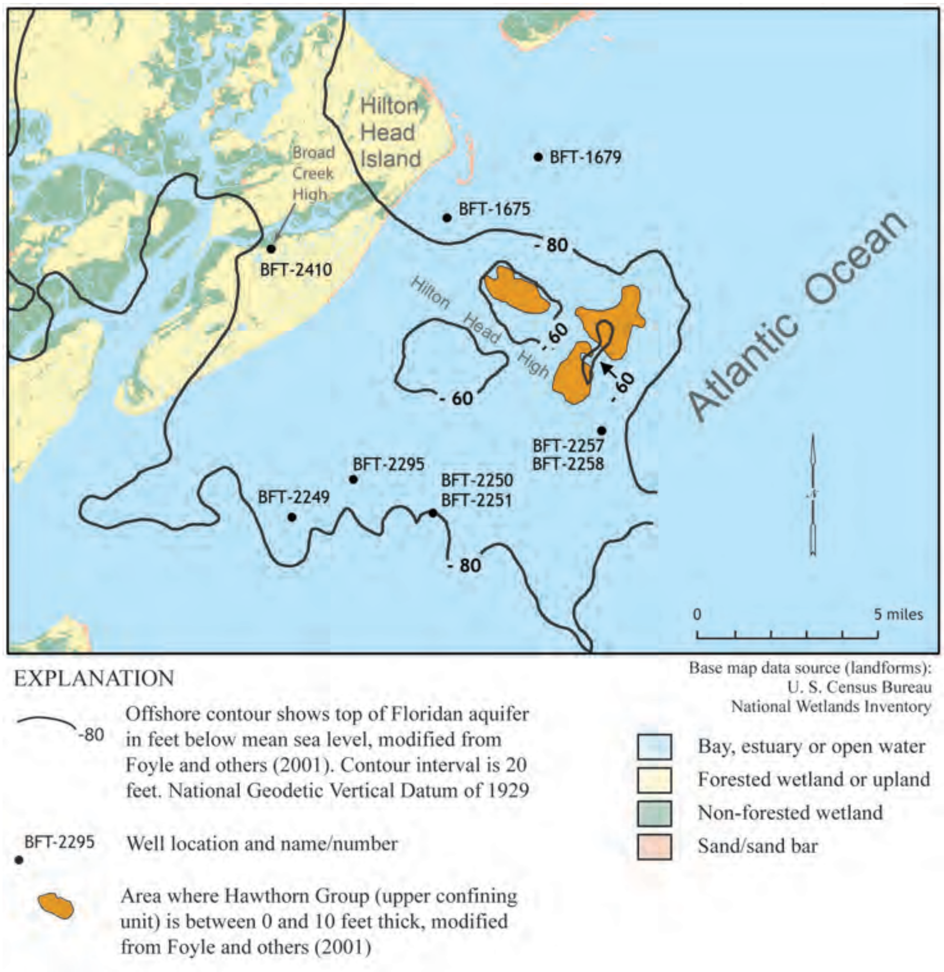


Figure 63. Locations of temporary offshore test wells near Hilton Head Island, S.C., surface contours on top of the Upper Floridan aquifer, and offshore areas where the Upper Floridan aquifer is overlain by less than 10 ft of the upper confining unit (after Foyle and others, 2001).

contamination; afterwards, the borehole was advanced using the air-lifted method to avoid the use of fresh water and drilling fluids. At sites where casing leaks were found above the sea floor, sampling procedures were adjusted to avoid contamination of water samples. Data from the Atlantic and Port Royal Sounds wells were referenced to NAV88 and NGVD29, respectively.

The possibility of the aquifer being directly exposed to seawater over a large area are discussed below and suggests that two chloride plumes, named herein the Hilton Head High and 8-mile chloride plumes, have developed. This section includes the authors' interpretations, and data and interpretations from Burt and others (1986), Hughes and others (1989), Foyle and others (1991 and 2001), Falls and others (2005), and the SCDHEC model (Appendix J).

Hilton Head High Chloride Plume

Offshore drilling has not been attempted above the Hilton Head High. However, a comparison can be inferred from similar hydrogeologic conditions at the Broad Creek High (Broad Creek chloride plume) to the west on Hilton Head Island. Here, continuous geologic core recovered from monitoring well BFT-2410 revealed that the upper confining unit was absent and the top of the Upper Floridan aquifer (Oligocene limestone) lay at -54 ft Msl, thereby allowing for a direct hydraulic connection between the surficial aquifer and underlying Upper Floridan aquifer. Given the similar elevations at the Hilton Head High, it is plausible that the upper confining unit could be absent over a significant area. As a result, conditions would be favorable for seawater to move downward into the aquifer as the potentiometric surface declined below Msl in the early 1950s. A review of the northernmost offshore test wells BFT-1679, BFT-1675, and BFT-2258 (fig. 63) and groundwater modeling (Appendix J) provide additional support for the presence and continued expansion of the Hilton Head High chloride plume.

Well BFT-1679 was constructed in 1984 (Burt and others, 1987) about 5 miles north of the Hilton Head High (fig. 63). Initially, the wellbore was advanced by mud-rotary method until the upper confining unit was encountered; here, the unit was continuously cored through a thickness of about 30 ft to the top of the Upper Floridan aquifer, encountered at -102 ft Msl; steel casing was installed and grouted to the sea floor (top of surficial aquifer). After 24 hours, the borehole was advanced by the air-lift method to -120 ft Msl, drilling was paused, and a packer was installed to seal the borehole at -108 ft Msl near the top of the Upper Floridan aquifer. Afterwards, a composite water sample was pumped from the open borehole between -108 ft and -120 ft Msl. The analyses revealed a DO concentration of 0.0 mg/L, a chloride concentration of about 260 mg/L, and a specific conductance of 1,450 μS/cm (computed chloride concentration was 507 mg/L). As the borehole advanced, composite water samples were air-lifted and collected at 10 ft intervals through the open borehole to a depth of -210 ft Msl. Chloride concentration progressively decreased with depth and was 220 mg/L at about -175 ft Msl; from -175 ft Msl chloride concentration increased to 270 mg/L near the bottom of the borehole. Specific-conductance measurements were made at 10-ft intervals on the following day and found to be 1,488 μS/cm at the top of the aquifer, progressively decreased to 1,423 μS/cm at about -175 ft Msl; below -175 ft Msl specific conductance increased to 1,517 μS/cm at -206 ft Msl. Because well Bft-1679 was near the predevelopment freshwater-saltwater interface, where heads were about -1 ft Msl in 1984 (Hughes and others, 1989), and DO was absent, the chloride contamination probably represented unflushed relict brackish water remaining in the in the bottom of the aquifer. The higher specific conductance and chloride concentration at the top of the aquifer were thought to indicate a casing-joint leak, but, with the potential threat of Tropical Storm Isidore, the well was abandoned with neat Portland cement without further testing.

Well BFT-1675, located about three miles southwest of well BFT-1679 and two miles northwest of the Hilton Head High, was completed in 1984 using construction methods similar to those for well BFT-1679 (fig.63). The upper confining unit was at -51 ft Msl and continuously cored through about 40 ft to the top of the Upper Floridan aquifer encountered at -91 ft Msl; afterwards, the well was cased and grouted to the top of the aquifer at -91 ft Msl. Drilling was paused at -103 ft Msl and a pumped water sample was collected near the top of the aquifer, between -91 and -103 ft Msl, prior to advancing the borehole. The analyses revealed a DO concentration of 0.0 mg/L, a chloride concentration of about 100 mg/L, and a specific conductance of 526 μS/cm. Air-lifted composite water samples were collected at 10 ft intervals as the borehole was advanced to -212 ft Msl near the bottom of the aquifer: chloride concentration at -97 ft Msl was 270 mg/L and progressively increased from 110 to 290 mg/L at depths from -113 to -212 ft Msl, respectively. The following day a Kemmerer-type point sampler was used to obtain discrete water samples at -50, -90, -130, and -200 ft Msl; chloride concentrations were found to be 2,320, 429, 154, and 160 mg/L, respectively. The high chloride concentrations present in the casing (2,320 and 429 mg/L) were thought to be caused by a casing-joint leak that might also have contaminated the two lower point samples. However, a pumped sample was later collected after isolating the interval between -186 and -212 ft Msl: DO concentration was found to be 0.0 mg/L, chloride concentration was 300 mg/L, and specific conductance was 838 μS/cm.

The hydraulic head at well BFT-1675 in August 1984 was -4.58 ft Msl (Burt and others, 1987) compared with a head of about -8 ft Msl measured by Crouch and others (1986, Appendix D13) on Hilton Head Island about 2 miles northwest of well BFT-1675. The lesser head at well BFT-1675 supports Foyle's (2001) interpretation that the upper confining unit may be absent in areas two to six miles southeast of well BFT-1675 near the Hilton Head High. Here, predevelopment heads were lowered by the upward discharge of fresh water into the Atlantic Ocean where the upper confining unit is thin or absent; the lower heads limited the northeastward movement of the predevelopment freshwater-to-saltwater interface as recharge/discharge reached equilibrium. However, during the early 1960's (see Appendix D6) the head was reversed by groundwater withdrawals and these areas are now presumed to be recharging the aquifer with modern seawater that is probably mixing with relict brackish water remaining in the aquifer as part of the freshwater/brackish water interface.

The low chloride concentration (100 mg/L) and absence of DO in the top of the aquifer at well BFT-1675 may denote unflushed relict brackish water migrating downward through the upper confining unit and breaking through at the bottom of the unit, whereas the higher concentrations near the bottom of the aquifer are thought to be relict-brackish to modern-brackish water that migrated from a more distant source nearer the Hilton Head High. The absence of DO in samples collected at the top and bottom of the aquifer as opposed to the presence of a tritium value of 4 TU at the bottom of the aquifer suggest that the water may be a mix of modern and relict brackish water.

Well BFT-2258, about one mile south-southeast of the Hilton Head high, was completed in 1999 and followed construction methods similar to those described for well BFT-1679). The well was cased and grouted to -89.4 ft Msl, placing the bottom of the casing about 9 ft into the Upper Floridan aquifer (Oligocene limestone) encountered at -80.7 ft Msl. The upper confining unit, encountered at -61.6 ft Msl in nearby well BFT-2257 was continuously cored and had a thickness of about 17 ft. Drilling continued to a depth of -154 ft Msl, and the well was completed as an open borehole in the Oligocene limestone. A composite water sample pumped from the open borehole revealed a chloride concentration of 5,800 mg/L, and the density-corrected mean daily water level measured in the open borehole was about 1 ft Msl (NAVD 88) in September 1999 (Falls and others, 2005). The 1885 predevelopment freshwater head in the Upper Floridan aquifer near well BFT-2258 (Appendix D1) was estimated to be about 8 ft Msl based on predevelopment potentiometric surface maps (Counts and Donsky, 1963, Appendix D1; Smith, 1988) but could have been less depending on the volume of freshwater discharge occurring near the Hilton Head High. It is plausible that some flushing occurred as the higher freshwater heads advanced the freshwater-to-brackish water boundary in the aquifer to the northeast and purged brackish to saltwater upward in the overlying upper confining unit. By the mid-1950s, offshore heads at well BFT-2258 were estimated to be about 0 ft Msl (Counts and Donsky, 1963; Appendix D4), thereby reversing the gradient and allowing (1) previously displaced relict brackish water in the Upper Floridan aquifer to advance toward the southwest, (2) relict and modern brackish to salt water to move downward though the upper confining unit, and (3) seawater to move directly downward into the top of the Upper Floridan aquifer (Oligocene limestone) where the upper confining unit was absent. Given that the -0.9 ft Msl (NAVD 88) head measured in 1999 showed little change from the estimated head since the mid-

1950s, it is probable that the aquifer is being recharged from a nearby source at or near the Hilton Head High.

Based on the data, the authors surmised that predevelopment discharge at the Hilton Head High lowered the local hydraulic head, thereby limiting the lateral northeast advancement of the freshwater-brackish water interface; after pumping began, the gradient eventually reversed to the southwest toward pumping centers. Owing to problems during the drilling of BFT-2258, DO was not measured, but the brackish water (5,800 mg/L chloride) found in the top of the Upper Floridan aquifer (Oligocene limestone) probably is relict brackish water displaced to the northeast prior to groundwater development (Falls and others, 2005): however, it is also possible that mixing with modern water from the upgradient areas is occurring where confinement is poor and absent. But considering the thickness, and the small 1-ft head difference across the upper confining unit, it is unlikely that there has been significant chloride breakthrough at the well site. The bottom of the Upper Floridan aquifer (Eocene limestone) was not penetrated in well BFT-2258, but chloride concentrations probably increased

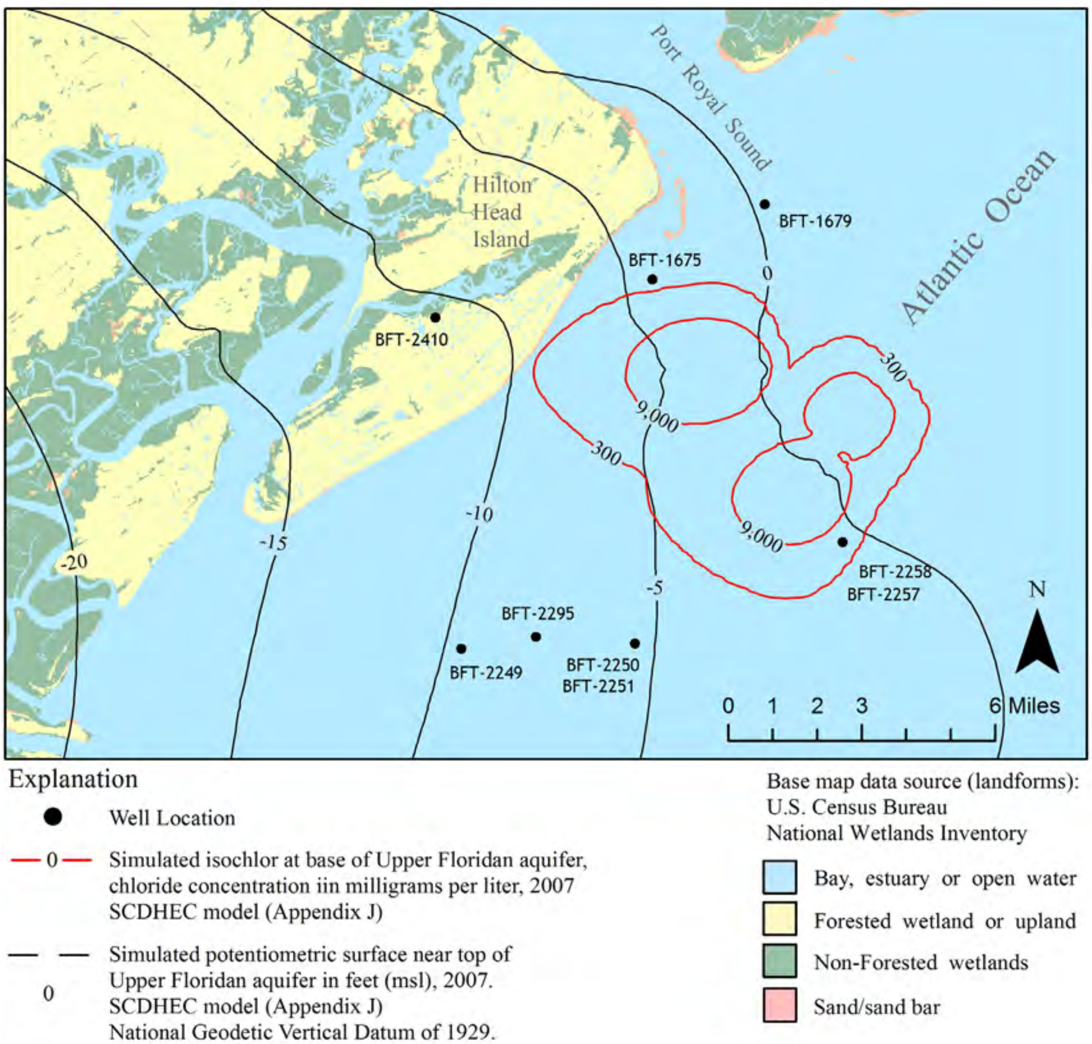


Figure 64. Simulated 2007 potentiometric surface contours and isochlors at the bottom of the Upper Floridan aquifer near the Hilton Head High, Port Royal Sound area, S.C.

progressively with depth.

The SCDHEC model was used to simulate direct downward saltwater movement above the Hilton Head High where the upper confining unit has been completely eroded. Estimated source areas were simulated by adjusting the conductivity of the unit to that of the overlying surficial aquifer to represent infill sediment for an area covering one model cell (40 acres). Three source areas were centered within the three areas of interest and represent about 3 % of the total area (3,700 acres) defined by Foyle and others (2001) where the upper confining unit was between 0 and 10 ft (fig. 63). The model simulated the possible position of the Hilton Head High chloride plume in 1998, 2007, and 2050 by projecting 2007 pumping (fig. 64; Appendix J18, J19, and J20).

The simulation for 2007 conditions showed that saltwater at the three source areas originating over the Hilton Head High moved downward and merged at the bottom of the Upper Floridan aquifer and are moving laterally down gradient to the west and southwest toward pumping centers at Hilton Head Island and Savannah, respectively. The model indicated a close relationship between the Hilton Head High and brackish water at well BFT-2258 (fig. 64); however, the model only simulated modern saltwater entering the aquifer. Relict salt water believed to be present, near and northeast of the high, was not inputted into the model.

8-Mile Chloride Plume

The southern offshore test well group was about 7 miles southwest of the Hilton Head High and included wells BFT-2251, BFT-2295, and BFT-2249. Here, the estimated 1880 predevelopment freshwater head was about 10 ft Msl in the Upper Floridan aquifer (Appendix D1) compared to the mean daily head of -13 ft Msl in June 2000 as measured in well BFT-2251, (Falls and others, 2005). It is plausible that the predevelopment freshwater heads in this area were sufficient to flush the Upper Floridan aquifer and overlying upper confining unit and move the freshwater-to-brackish water interface farther to the northeast. Test-well construction methods followed those previously described for well BFT-1679.

Well BFT-2251, constructed farthest to the east of the southern well group in 2000 (fig. 64), was cased and grouted to -92.5 ft Msl and penetrated 32 ft of the upper confining unit encountered between -56.0 ft Msl and -88.0 ft Msl. Pore-water samples extracted from geologic core at selected depths through the upper confining unit revealed chloride concentrations progressively decreasing with depth from 17,500 mg/L near the top to 510 mg/L at the bottom of the unit. The well penetrated the full thickness of the Oligocene limestone (uppermost part of the Upper Floridan aquifer) at about -170 ft Msl; here, pore water extracted from geologic core revealed chloride concentrations progressively decreasing from 88 mg/L near the top to 31 mg/L at the bottom (Appendix G). The borehole was advanced into the underlying late Eocene limestone (Ocala Limestone) to -221 ft Msl. A composite water sample pumped from -197 to -221 ft Msl revealed a chloride concentration of 25 mg/L compared to a pore-water sample extracted from -221 ft Msl that had a slightly greater chloride concentration of 47 mg/L. The open borehole was advanced to -699 ft Msl and a composite water sample pumped from middle Eocene limestone (middle confining unit) at -587 ft Msl had a chloride concentration was 740 mg/L.

Pore-water analyses at well BFT-2251 revealed high chloride concentration in the upper confining unit and lower chloride concentration at the top of the Upper Floridan aquifer (Oligocene and late Eocene limestone). The chlorides can be attributed to modern seawater migrating downward, under about a -10-ft head difference across the upper confining unit. Chloride concentrations determined from pore-water analysis increased from 31 mg/L near the bottom of the Oligocene limestone to 47 mg/L at -221 ft Msl in the late Eocene limestone, a departure from the decreasing trend measured for chloride concentrations in the overlying sediment. Concentrations might be higher near the bottom of the Upper Floridan aquifer, estimated to be at about -271 ft Msl. If so, the chlorides probably originated from a distant source. The greater chloride concentration at -587 ft Msl in the middle confining unit can be attributed to relict brackish water.

Well BFT-2295 was constructed in 2001, west of well BFT-2251, where the predevelopment head was about 10 ft Msl (Appendix D1). Here, pore water from the surficial sediment was extracted from geologic core at about -81 ft Msl (paleochannel infill); chloride concentration was found to be 15,300 mg/L. The well was cased and grouted to -99.3 ft Msl and completed as an open borehole to -208.4 ft Msl; the thickness of the upper confining unit was less than 1 foot, encountered between -78.6 ft and 79.4 ft Msl. A discrete, pumped water sample with a chloride concentration of 8,400 mg/L was obtained by isolating the Oligocene limestone between -99 to -111 ft Msl. Two pore-water samples were extracted from geologic core within the late Eocene carbonate sediment between -161 and -171 ft Msl. The chloride concentration of the upper sample was 600 mg/L and that of the lower sample 560 mg/L. A plausible explanation for the high chloride concentrations found in well BFT-2295 is downward migration of modern seawater. Given the virtual absence of the upper confining unit, it is probable that predevelopment heads flushed the aquifer with freshwater; and groundwater withdrawals later reversed the head creating a difference between heads in the surficial aquifer and the Upper Floridan aquifer that ranged between -14 ft and -10 ft Msl (Falls and others, 2005). The bottom of the Upper Floridan aquifer was not penetrated to the estimated depth of about -270 ft Msl, leaving about 100 ft of the aquifer untested. If chloride concentration is much greater near the bottom of aquifer, it is probable that brackish water is moving downward and laterally from a distant source area where the upper confining unit is absent.

Well BFT-2249 was constructed in 2000 to the west of well BFT-2295. Here, the predevelopment head was about 10 ft Msl (Appendix D1) and the average density-corrected mean daily water level taken from two measurements in June 2000 was -17.4 ft Msl (Falls and others, 2005). The well was cased and grouted into the top of the Upper Floridan aquifer to a depth of -78.4 ft Msl, penetrating 17 ft of the upper confining unit from -58.1 to -75.1 ft Msl. Pore water extracted from geologic core obtained from selected depths within the upper confining unit contained chloride concentrations of 7,030 mg/L near the top and progressively decreased to 2,600 mg/L near the bottom of the unit. A composite water sample collected from the top of the Upper Floridan aquifer (Oligocene limestone) between -79 to -136 ft Msl had a chloride concentration of 370 mg/L. Based on the relatively thin upper confining unit, the head difference of about -17.4 ft across the upper confining unit, and the progressively increasing chloride found in the upper confining unit, the high chloride concentrations found in the top of the Upper Floridan aquifer are the result of downward-migrating modern seawater.

The geographic extent of the 8-mile chloride plume has not been determined. However, the SCDHEC model (Appendix J) was used to simulate a source area near the 8-mile test well. The simulations (Appendix J18, J19, and J20) show that the plume could potentially cover a large area and is continuing to expand: a model simulation shown in Appendix J20 predicts that the Hilton Head High and 8-mile chloride plumes will merge before 2050.

ENVIRONMENTAL TRACERS – AGES AND SOURCES OF SALTWATER PLUMES

Environmental tracers were used to differentiate between relict and modern brackish to saltwater contamination near the bottom of the Upper Floridan aquifer. The presence of modern brackish to saltwater indicated that recent pumping-induced saltwater contamination had occurred. The four methods presented herein focused on modern water and relied on measurements of manmade chlorofluorocarbon (CFC) and tritium (^3H), naturally present dissolved oxygen (DO), and stable isotopes of hydrogen (δ^2H) and oxygen ($\delta^{18}O$). The apparent recharge date of the water samples, or time since seawater moved into the groundwater system were determined from four surface-water samples and 25 groundwater samples collected and analyzed by the USGS in cooperation with GaEPD and SCDHEC (Table 1).

Chlorofluorocarbons

Chlorofluorocarbons developed for use in refrigerants and solvents include 1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113), trichlorofluoromethane (CFC-11), and dichloro-difluoro-methane (CFC-12, Freon™). CFC-11 and CFC-12 were produced beginning in the 1940's and CFC-113 was produced beginning in the 1960's; production continued in developed countries until their ban in the 1995. During that period, CFC's were released into the atmosphere in overlapping cycles, dissolved in rainwater, and migrated through the hydrologic cycle.

The presence of CFC's in a groundwater sample indicate that the water might have been in contact with the atmosphere as early as the 1940's; the concentrations of CFC's can also indicate the apparent age and recharge date of groundwater (Plummer and Friedman, 1999). The total fraction of a groundwater mixture of modern CFC-contaminated water relative to older CFC-free water is determined with CFC-concentration ratios for each year since their introduction into the atmosphere: CFC-11/ CFC-12 for 1940 through about 1975 and CFC-113/CFC-12 for1970 through about 1994. The calculation of groundwater ratio age is possible because atmospheric ratios have changed through time and thereby are unique for each year (Happell and others, 2006), and are well documented. The correlation between atmospheric-CFC ratios and groundwater-CFC ratios establishes the apparent groundwater-recharge date (see Appendix H).

Tritium

Tritium (^3H) is produced naturally in the upper atmosphere and enters the hydrologic cycle as ^3HHO. The tritium concentration in a water sample is measured in units of picocuries per liter (pCi/L), or the more commonly used term Tritium Units (TU), where 1 TU = 1 atom of ^3H in 10^{18} atoms of non-tritium water: 3.19 pCi/L is equivalent to 1 TU. The input of naturally produced tritium was overshadowed during the production and release of weapons-related tritium during the 1950's and 1960's. Tritium concentrations in the northern hemisphere were greater than 2,000 TU at the peak of weapons testing and were between 5 and 30 TU in the year 2005. Relatively high concentrations might be present in the study area, which is less than 100 miles southeast of the Savannah River Site in Aiken County, S.C., a potential source of atmospheric tritium. The detection of tritium concentrations equal to or greater than the detection limit (0.003 to 10 TU, depending on method) indicates that the water was exposed to the atmosphere during or since the 1960's. Because tritium decays at a known rate, tritium concentrations can be used to estimate the age of groundwater in years since recharge using the following equation where: t = time in years since recharge; -17.93 *ln* = mean life of tritium; sample ^3H = measured tritium concentration in groundwater sample, and initial ^3H = measured tritium concentration of the surface-water samples.

$$t = -17.93\, ln\, (1+ \text{sample } {}^3H)/(\text{initial } {}^3H)$$

Dissolved Oxygen

The co-occurrence of high dissolved-oxygen concentrations and high specific conductance indicate also recent recharge from saline surface water because sulfate-reducing conditions typically predominate in the Upper Floridan aquifer and deplete oxygen over time (Landmeyer and Belval, 1996; Burt, 1993). For comparative purposes, background concentrations of DO in the aquifer are near 0 mg/L and specific conductance commonly is less than 300 µS/cm. The presence of both high DO concentrations and high specific conductance (salinity) indicates both local and recent recharge by saline surface water (Table 1).

Hydrogen and Oxygen Isotopes

The stable-isotope values of H and O (as δ^2H and $\delta^{18}O$) in a water sample can be used to determine the predominant source of that water: rainfall, surface water, or groundwater, or a mixture of water from multiple sources. In general, isotopic values of H and O are less negative, or heavier, in surface-water samples because evaporation preferentially removes the lighter ^1H and ^{16}O isotopes and leaves behind surface water that contains more of the heavier isotopes ^2H and ^{18}O.

Environmental Tracer Sampling

The ages of brackish water and salt water were determined for four surface water samples and for 25 groundwater samples collected at the bottom of the Upper Floridan aquifer in wells having chloride concentrations between 1,000 to 10,000 mg/L (fig. 65); exceptions where chloride concentration was lower occurred in six wells. Samples were analyzed for chloride, DO, specific conductance, tritium, CFC's, and for hydrogen and oxygen isotopes. These data were acquired during two sampling events.

The first sampling event, from December 2004 through March 2005, consisted of two surface-water samples, and eight groundwater samples collected near the northeastern part of Hilton Head Island, at Pinckney Island, and near Colleton River Plantation. Two surface water samples were collected from Port Royal Sound and Mackay Creek.

A second sampling event during 2009 consisted of surface water samples at Mackay Creek and Buckingham Landing and 17 groundwater samples. The groundwater sampling included three wells from the 2004-2005 sampling event, 11 additional wells from Hilton Head Island to the Colleton River, and three wells between Savannah and Tybee Island, Ga. No isotope samples were collected. Environmental tracers detected in groundwater and surface-water samples acquired during the 2004-2005 and 2009 sampling events, along with the absolute age (apparent age) and percent modern water are shown in table 1.

Environmental Tracers in Surface Water

Surface water samples were collected to provide background concentrations of CFC's, DO, and tritium in modern surface water (post 1940). Samples were collected in 2004-2005 from Mackay Creek west of Pinckney Island and from Port Royal Sound adjacent to Hilton Head Island, and in 2009 from Mackay Creek and at Buckingham Landing on the May River west of Hilton Head Island. Owing to seawater, surface-water samples had a specific conductance of about 48,000 µS/cm. These samples also had higher concentrations of CFC's, DO, and tritium relative to groundwater samples. Concentrations were greater than 200 pg/kg, 8.0 mg/L, and 10 TU, respectively. The evaporation-enriched surface-water samples were characterized by the heaviest (most positive, > 0 per mil) stable-isotope values of hydrogen and oxygen (table 1; fig. 66, 67, and 68) and provided the end member of heavier values that indicate saline surface-water mixing with other water.

Figure 65. Surface-water sites and Upper Floridan aquifer well sites sampled for geochemical analysis during the 2004-2005 and 2009 sampling event.

Table 1. Environmental tracers detected in surface-water and monitoring wells, calculated recharge dates, and percentages of modern water near Hilton Head Island, S.C. and Savannah, Ga. (USGS data)

							CFC concentration (pg/kg)			[3]Recharge date calculated from CFC ratios				Apparent recharge date		
Period	Sample location	Sample site	[1]Sample depth (ft bgs)	Sample date	[2]D. O. (mg/l)	Spec. Cond. (µS/cm)	CFC-11	CFC-12	CFC-113	CFC-11/12	CFC-113/12	CFC-113/11	Modern groundwater (percent)	CFC-11	CFC-12	CFC-113
2004-2005	Colleton River Plantation	BFT-2301	170	3/7/2005	2.01	22771	46.19	40.69	2.8	NP	1979	1981	25.7	1968	1967	1969
	Pinckney Island	BFT-2313	200	3/7/2005	3.87	36740	31.91	23.42	2.77	1969	1979	1983	34.5	1966	1966	1970
	Pinckney Island	BFT-2166	198	1/5/2005	NS	26678	56.17	72.18	11.28	NP	1984	1991	73.2	1974	1978	1970
	Pinckney Island	BFT-2312	200	1/5/2005	4.74	22799	178.94	105.49	17.05	NP	1982	NP	59.5	1966	1973	1977
	Hilton Head Island	BFT-2201	200	1/12/2005	5.8	32680	204.08	152	27.52	NP	NP	1991	78.8	1983	1990	1989
	Hilton Head Island	BFT-2200	210	3/14/2004	1.86	21418	86.36	36.9	6.35	1976	1984	1984	31.6	1968	1966	1973
	Hilton Head Island	BFT-2198	200	3/14/2004	3.48	15902	15.5	41.59	3.68	NP	1978	NP	36.9	1957	1967	1970
	Hilton Head Island	BFT-1591	248	9/19/2005	0.72	11455	40.71	7.69	7.26	NP	NP	NP	NP	1962	1953	1973
	Mackays Creek	Surface water	5	12/8/2004	8	47800	73.31	200.24	8.72	NP	NP	NP	74.5	1967	1998	1979
	Port Royal Sound	Surface water	5	1/12/2005	8.23	48863	91.36	216.94	31.71	NP	NP	NP	NP	1972	NP	1986
2009	Colleton River Plantation	BFT-2301	150	12/10/2009	4.49	6068	75.83	45.58	28.67	NP	NP	NP	NP	1968	1968	1984
	Pinckney Island	BFT-2313	206.5	12/11/2009	3.17	40368	60.99	42.32	19.86	1968	NP	NP	87.7	1967	1966	1980
	Pinckney Island	BFT-2312	205	12/8/2009	7.72	22458	53.57	20.19	12.18	NP	NP	NP	NP	1964	1959	1977
	Pinckney Island	BFT-2190	220	12/8/2009	0.48	713	50.83	18.62	11.43	NP	NP	NP	NP	1963	1958	1974
	Moss Creek	BFT-1326	195	12/16/2009	1.19	4545	37.23	19.71	28.48	1969	NP	NP	27	1961	1959	1980
	Hilton Head Island	BFT-1814	227	12/17/2009	1.4	4722	49.73	13.3	23.8	NP	NP	NP	NP	1963	1956	1979
	Hilton Head Island	BFT-2308	245	12/17/2009	3.47	496	85.99	108.34	31.11	1954	1991	NP	45	1967	1974	1982
	Waddell Mariculture Center	BFT-1846	178	12/16/2009	2.43	11627	70.75	28.17	29.23	NP	NP	NP	NP	1966	1963	1983
	Barker Field No. 2	BFT-2162	245	12/21/2009	3.65	13911	60.85	19.95	22.11	NP	NP	NP	NP	1965	1960	1980
	Cram Island	BFT-2300	164	12/10/2009	1.86	7892	75	23.21	20.05	NP	NP	NP	NP	1965	1959	1978
	Buckingham Landing	BFT-2310	192	12/9/2009	3.38	8220	44.23	15.84	19.49	NP	NP	NP	NP	1962	1958	1978
	Oyster Reef	BFT-2402	245	12/21/2009	4.5	15242	52.75	20.8	17.61	NP	NP	NP	NP	1964	1961	1979
	Belfair Plantation	BFT-2408	244	12/15/2009	0.71	12407	57.97	10.52	24.73	NP	NP	NP	NP	1964	1953	1979
	Wexford Plantation	BFT-2410	288	12/16/2009	0.6	879	91.9	36.88	27.92	NP	NP	NP	NP	1967	1964	1981
	Georgia	Bull River 2	123	12/15/2009	0.26	710	45.33	7.13	20.24	NP	NP	NP	NP	1962	1952	1977
	Georgia	Bull River 3	200	12/15/2009	0.74	223	34.48	6.77	13.68	NP	NP	NP	NP	1960	1950	1974
	Georgia	Tybee Island	205	12/14/2009	0.17	273	36.82	7.01	13.12	NP	NP	NP	NP	1962	1951	1975
	Buckingham Landing	Surface water	5	12/22/2009	7.68	44953	289.85	277.97	76.64	1956	1990	NP	93.8	1973	1986	1988
	Mackays Creek	Surface water	5	12/22/2009	8.61	44795	273.23	280.99	80.76	1955	1990	NP	82.5	1972	1984	1987

[1]In feet below land surface; [2]D.O., dissolved oxygen; [3]apparent age determined on the basis of piston-flow age, in which water containing CFC's moves through the aquifer as a plug with no mixing—derived from the absolute concentration of CFC-11, -12, and -113; NP, not possible to calculate.

The calculated age of local surface water, based on concentrations of CFC's, indicated that surface-water sources had apparent ages of 16 to 19 years relative to the same environmental tracers found at the bottom of the Upper Floridan aquifer. The younger age of surface water relative to groundwater is attributed to direct contact with the greater environmental-tracer concentrations in the atmosphere. The 2005 and 2009 tracer concentrations found in the surface-water samples are consistent with background concentrations for coastal South Carolina. The percent modern water in the surface-water samples ranged from 74.5 to 93.8 based on the CFC ratios.

Environmental Tracers in Groundwater

Dolphin Head Chloride Plume

The apparent ages of groundwater in the chloride plume beneath northern Hilton Head Island were determined from six groundwater samples collected along the shore of Port Royal Sound during the 2004-2005 sampling event (wells BFT-2200, BFT-2201, BFT-2198, BFT-1591, BFT-1814, and BFT-2308) and four samples collected along-shore and near-shore during the 2009 sampling event (wells BFT-2402, BFT-2162, BFT-1814, BFT-2308). Each well was sampled near the bottom of the Upper Floridan aquifer at about 200 ft bgs. At the northwestern part of the island, specific conductance measurements ranged from 13,911 to 32,680 µS/cm, and from 496 to 4,722 µS/cm for samples taken and at the northeastern part of the island (fig 65; table 1). All of the samples contained high DO concentrations (1.86 to 5.80 mg/L): in comparison, seven of the nine 1984 Port Royal Sound samples from the lower part of the aquifer contained DO concentrations of 0.0 to 0.2 mg/L and no DO concentration exceeded 0.9 mg/L (Burt and others, 1987, tbl. 6).

Calculations based on CFC data indicated the apparent age of groundwater in well BFT-2200 ranged from 21 to 39 years from 2005, indicating an apparent recharge date between the late 1960’s and early 1980’s: the percent modern water was about 32. The apparent age of the groundwater in well BFT-2201 ranged from 14 to 22 years, indicating an apparent recharge date between the early 1980’s and early 1990’s with modern groundwater contributing about 79 percent, which is approximately that of surface water in Port Royal Sound. The apparent age of the groundwater at well BFT-2198 ranged from 27 to 48 years, indicating an apparent recharge date between the late 1950’s and mid 1970’s with modern groundwater contributing about 37 percent. The apparent recharge date of the groundwater in well BFT-1814 ranged from the late 1950’s to the late 1970’s with modern groundwater from this well contributing 45 percent. The apparent recharge date for well BFT-2308 ranged from the late 1960’s to the early 1980’s. Wells BFT-2200 and BFT-2201, near the shore of Port Royal Sound, had heavier stable isotope values characteristic of surface water; these wells are near the 10,000 mg/L isochlor (fig.40). The least isotopically heavy water samples were those pumped from wells BFT-2198 and BFT-1591: BFT-1591 is farthest south from Port Royal Sound and lies nearest the 250 mg/L isochlor. Well BFT-2198 is one of five wells near the shoreline of Hilton Head Island adjacent to Port Royal Sound and is near the 10,000 mg/L isochlor. Generally, the isotopically heavy water samples were nearest Port Royal Sound; well BFT-2198 is an exception. Tritium was highest in well BFT-2201 (6.1 TU), and the concentrations in the aquifer decreased with increasing distance from Port Royal Sound.

Well BFT-1591 lies farthest from Port Royal Sound and produced the oldest groundwater. No detectable tritium was found in the groundwater sample and based on calculated dates from CFC concentrations, groundwater would have interacted with the air in the 1950’s and probably would have a recharge date prior to 1960 (table 1). The groundwater ages, or times elapsed since groundwater recharge, are plotted as isochronal contours in on figure 69.

Pinckney Island Chloride Plume

During the 2004-2005 sampling event, groundwater samples were collected on Pinckney Island at about 200 ft bgs near the bottom of the Upper Floridan aquifer (wells BFT-2313, BFT-2166, and BFT-2312). Samples again were collected from wells BFT-2313 and BFT-2312 during the 2009 sampling event. Dissolved-oxygen concentrations were between 3.87 to 4.74 mg/L, and specific conductance ranged from 22,799 to 36,740 µS/cm. Tritium concentrations in wells BFT-2313 and BFT-2166 were 8.8 and 7.8 TU, respectively, and were close to the 10.2 TU detected/measured in Port Royal Sound water (fig.68).

Calculations based on the CFC data indicated that the apparent age of the groundwater at well BFT-2313 near the northern tip of Pinckney Island ranged from 22 to 39 years, indicating an apparent recharge date between the mid 1960's and early 1980's for both the 2004-2005 and 2009 sampling event; modern groundwater from well BFT-2313 was 35 percent for the 2004-2005 sampling event and 88 percent for the 2009 sampling event. The apparent age of the groundwater at well BFT-2166 ranged from 14 to 31 years, indicating an apparent recharge date between the early 1970's and late 1980's; modern groundwater from this well was 73 percent. The apparent age of the groundwater at well BFT-2312 ranged from 23 to 39 years indicating an apparent recharge date between the mid 1960's and mid 1970's for the 2004-2005 and 2009 sampling events; modern groundwater from well BFT-2312 was approximately 60 percent for the 2004-2005 sampling event (table 1).

Samples from wells BFT-2313, -2166, and -2312 on Pinckney Island (fig. 65) found heavier H and O isotopes closer to saline surface water. The sample from the well closest to the presumed saline-water source, well BFT-2313, contained the heaviest stable isotope value and was located near the 12,000 mg/L isochlor (fig.45). Samples from wells Bft-2166 and BFT-2312, which are down gradient from well BFT-2313, contained lower chloride concentrations and less heavy isotope values (fig. 67).

Colleton River Chloride Plume

Groundwater samples were collected from well Bft-2301, adjacent to a sinkhole near the bank of the Colleton River. The sample from well BFT-2301 is upgradient of the 10,000 mg/L isochlor (fig. 49) for the Colleton River chloride plume. Sinkholes, common in the area, are geomorphic features wherein the upper confining unit might be breached, and, along with the confining-unit erosion in the river channel (see front cover image, page 2; fig. 12, Miocene isopachous), probably contribute to the formation of the Colleton River chloride plume. The samples were collected near the bottom of the well at 170 ft bgs during the 2004-2005 sampling event and at 150 ft bgs during the 2009 sampling event. At 170 ft bgs, the well water had a DO concentration of 2.01 mg/L and a high specific conductance of 22,771 µS/cm (table 1); computed chloride concentration was greater than 13,000 mg/L at -162 ft bgs. The CFC data suggested that the apparent age of the groundwater ranged from 24 to 37 years, for an apparent recharge date between the mid 1960's and late 1970's (fig. 69): modern groundwater from BFT-2301 was about 26 percent. During the 2009 sampling event well BFT-2301 was sampled at about 150 ft bgs, 20 ft shallower than when sampled during 2004-2005. The shallower 2009 sample also had a higher DO concentration (4.49 mg/L) and lower specific conductance (6,068 µS/cm). The apparent recharge date ranged from the late 1960's to early 1980's, slightly younger than the deeper, previous sample. The well sample also contained a heavy stable isotope value (fig. 67) and a tritium concentration of 8.7 TU (fig. 68): both values are attributed to interaction with saline surface water.

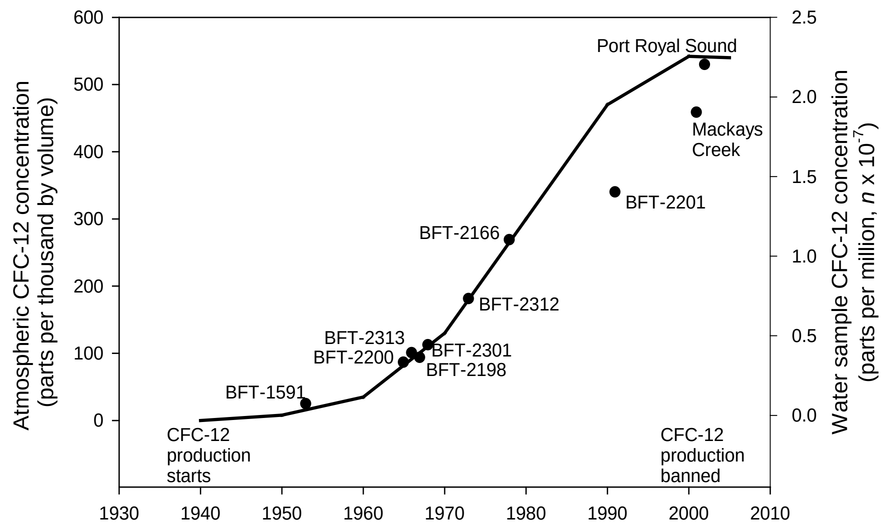


Figure 66. Atmospheric CFC-12 concentrations for the years, 1940–2005, and apparent recharge date of groundwater for selected wells.and surface-water CFC-12 concentrations and recharge dates.

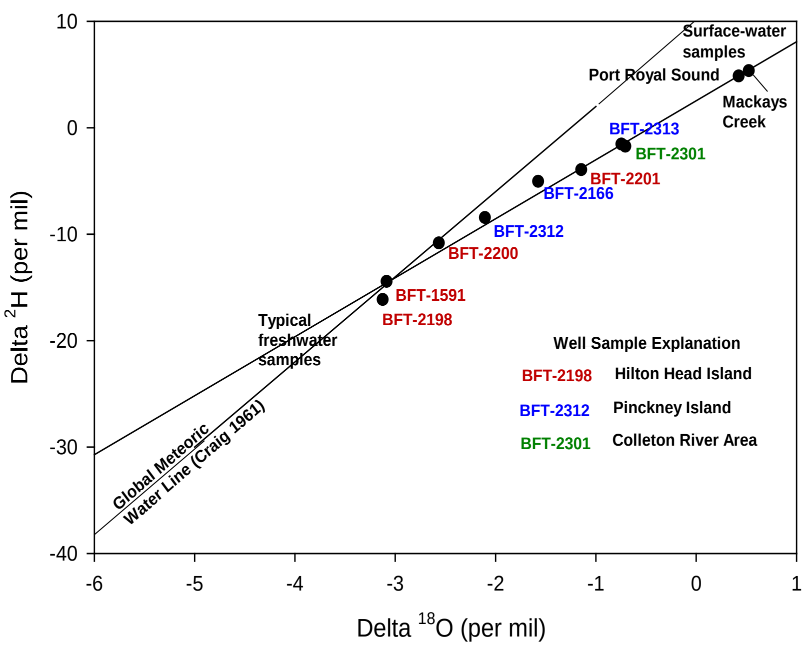


Figure 67. Stable isotopes in groundwater and surface water samples in southern Beaufort County, S.C., in relation to the Global Meteoric Water Line (Craig, 1961).

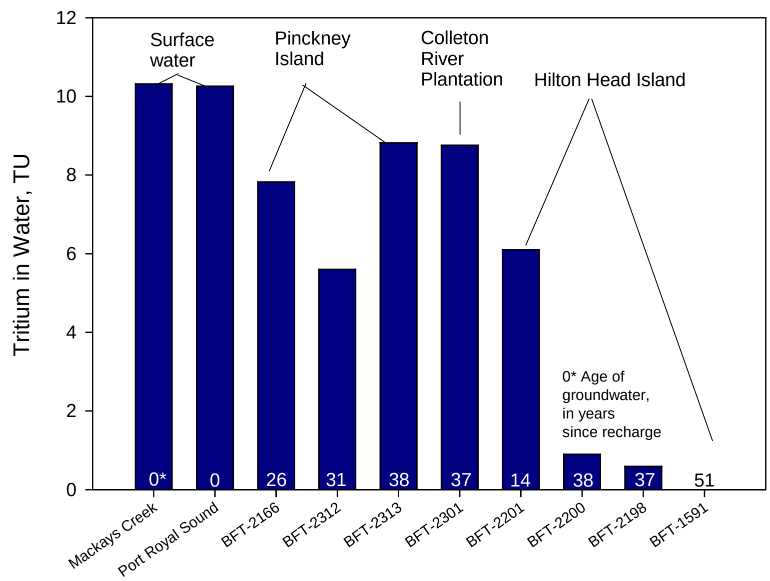


Figure 68. Recharge age computed from tritium concentrations in surface-water samples and Upper Floridan aquifer groundwater samples, southern Beaufort County, S.C., 2004–2005.

Summary Of 2004 - 2005 Sampling Event

The surface-water samples contained the highest concentrations of DO, CFC, and heavy isotopes, which reflected recent interaction with air. Groundwater samples also contained high concentrations of CFC-12, with their concentrations inversely related to distance from saline surface water.

Tritium concentrations above the method report level (MRL; 0.03 pCi/L, or 0.009 TU) were measured in two surface-water samples and seven of the eight groundwater samples collected during 2004 and 2005 (fig. 68). The surface-water samples contained the highest tritium concentrations, each greater than 10 TU. The high tritium concentration may reflect the high tritium background concentrations for coastal South Carolina. Brackish groundwater at the bottom of the Upper Floridan aquifer closest to saline surface-water bodies also contained high tritium concentrations; groundwater samples near Port Royal Sound and nearby channels contained the highest tritium concentrations. The tritium in those samples indicate a fractional component of post-1960 groundwater. Tritium and chloride concentrations decreased with increasing distance from recharge areas. Tritium was not detected in groundwater from well BFT-1591, farthest from the sound. The groundwater sample from this well was, therefore, recharged prior to the hydrogen-bomb tests of the late 1950's. The high tritium concentrations measured in the saline groundwater samples indicated that the water near the bottom of the aquifer contained a fraction of modern saline groundwater. The ages of groundwater, in years since recharge, also are shown in figure 68.

During 2004-2005 sampling, surface-water samples from Port Royal Sound north of well BFT-2201 and from Mackay Creek were characterized by the heaviest (most positive, > 0 per mil) stable-isotope values (fig. 67). These samples represent evaporation-enriched, saline surface water and provide the necessary end member needed to calculate a mixture of surface water and groundwater. Conversely, the least isotopically heavy water samples were those pumped from wells BFT-2198 and BFT-1591, farthest from saline surface water. For example, well BFT-1591 lies nearest the 250 mg/L isochlor for groundwater. Two wells sampled along the shore of Hilton Head Island, BFT-2200 and BFT-2201, had heavier stable isotope values characteristic of greater interaction with saline surface water. These wells are located between the 10,000 and 12,000 mg/L isochlors for the Dolphin Head chloride plume (fig. 40). The same pattern of heavier H and O isotopes in groundwater near saline surface water was observed in the three wells sampled on Pinckney Island (fig. 67). The sample from well BFT-2313, closest to the presumed source of saline water, contained the heaviest stable-isotope value and coincided with the 12,000 mg/L isochlor (fig. 45). Samples from the two down-gradient wells (BFT-2166 and BFT-2312) contained lower chloride concentrations and less heavy isotope values. The sample from well BFT-2301 at Colleton River Plantation near the bank of the Colleton River contained a heavy stable isotope value and plotted within the 10,000 mg/L isochlor of the Colleton River chloride plume (fig. 49).

The surface-water samples contained water with the highest concentration of CFC-12, indicating recent interaction with CFC-12 in the air. Conversely, groundwater samples contained lower concentrations of CFC-12, with concentration inversely related to distance from saline surface water. Figure 69 shows isochronal contours of saltwater at the bottom of the Upper Floridan aquifer in the Hilton Head Island, Pinckney Island, and Colleton River chloride plumes. The 1970 isochronal contour is closest to Port Royal Sound and the 1960 isochronal contour lies a greater distance from the sound. The wider separation between the isochronal contours may relate to more than one saltwater source area, freshwater recharge, or increased rate of groundwater movement from a source area.

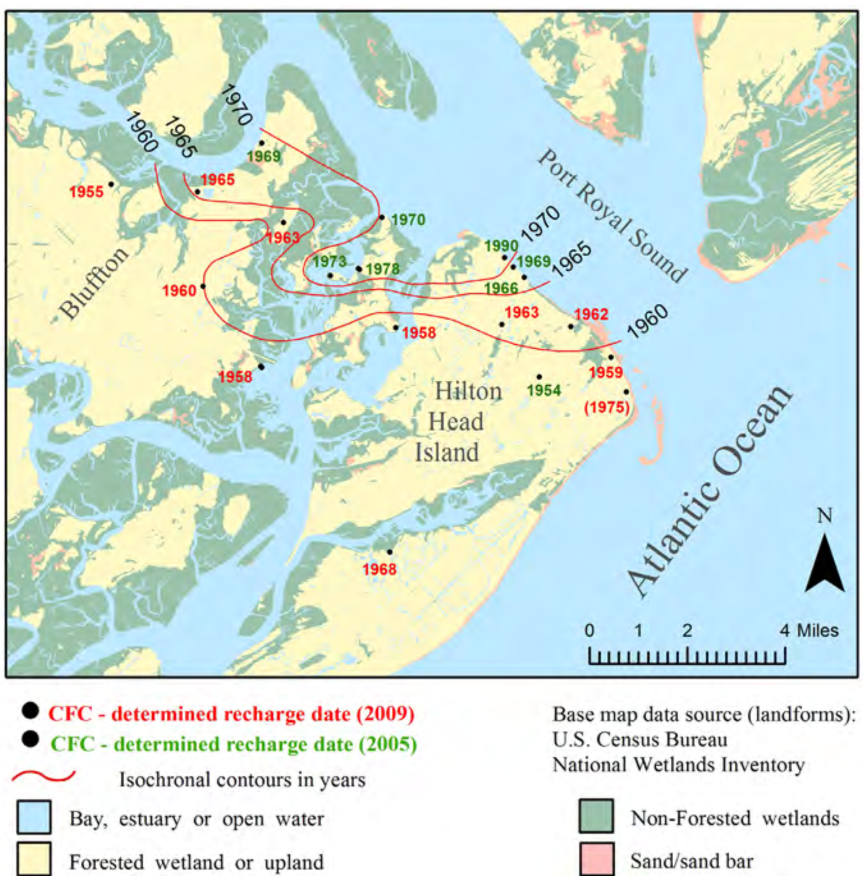


Figure 69. Isochronal contours representing equal saltwater recharge dates for water at the bottom of the Upper Floridan aquifer: determined by chlorofluorocarbon analyses (CFC-12), Port Royal Sound area, S.C.

Summary Of 2009 Sampling Event

The 2009 sampling event (table 1) included 17 groundwater samples and two surface-water samples. Three samples were taken from wells during the 2004-2005 sampling event; 11 additional wells were sampled in Beaufort County, S.C. near those wells sampled in 2004-2005, and three wells were sampled in Chatham County, Ga., between Savannah and Tybee Island (table 1; fig. 65). Consistent with the 2004-2005 sampling event, all wells in the 2009 sampling event were sampled near the bottom of the aquifer except for the three wells in Chatham County, Ga. Here, the sample was taken three feet below the casing at the top of the Upper Floridan aquifer (Oligocene limestone) for the wells Tybee Island South and Bull River 2. The third well, Bull River 3, was sampled at 200 ft bgs in the Upper Floridan aquifer (Eocene limestone).

The CFC data indicate the apparent recharge dates ranged from the late 1950's to the early 1980's for the eleven Beaufort County wells. The apparent recharge dates for the three Chatham County wells ranged from the early 1950's to the late 1970's and, because the sampling points were near the top of the aquifer, show downward migration of modern brackish and fresh water. Downard migration of modern water into the Upper Floridan aquifer was also seen in pore water samples extracted from Bull River 1 as evidenced by higher chloride concentrations (fig. 32 and Appendix G). In addition, like the 2004-2005 samples, most all the 2009 samples contained DO concentrations significantly greater than the DO-depleted background concentrations typical of the Upper Floridan aquifer (table 1).

The concentrations of CFC's are subject to vary from the mixing of two or more components and from other environmental factors that can affect the apparent age of groundwater (USGS, The Reston Groundwater Dating Laboratory). However, combining the results of the 2009 and 2004-2005 sampling events, high concentrations of CFC's and DO were present at each well site sampled. When interpreted together, these data indicated a component of modern water recharging the aquifer over a broad area.

SALTWATER MOVEMENT - THE GREATER PORT ROYAL SOUND CHLORIDE PLUME

Estimates of the rate and direction of movement for a solute such as chloride require data that include the source water concentration, aquifer properties, and hydraulic gradients which fluctuate in response to changes in groundwater withdrawals and distribution of pumpage. Predicting the behavior of a chloride plume is accomplished best by monitoring, and by developing a transient solute transport model that accounts for chemical diffusion and mechanical dispersion (which move contaminants transversely as well as longitudinally; Freeze and Cherry, 1979) to simulate future plume movement.

Specific-conductance profiles from selected wells (fig. 70) were used to determine the 2007 distribution of chloride concentrations in the bottom of the Upper Floridan aquifer and map the Parris Island, Port Royal Sound, Dolphin Head, Pinckney

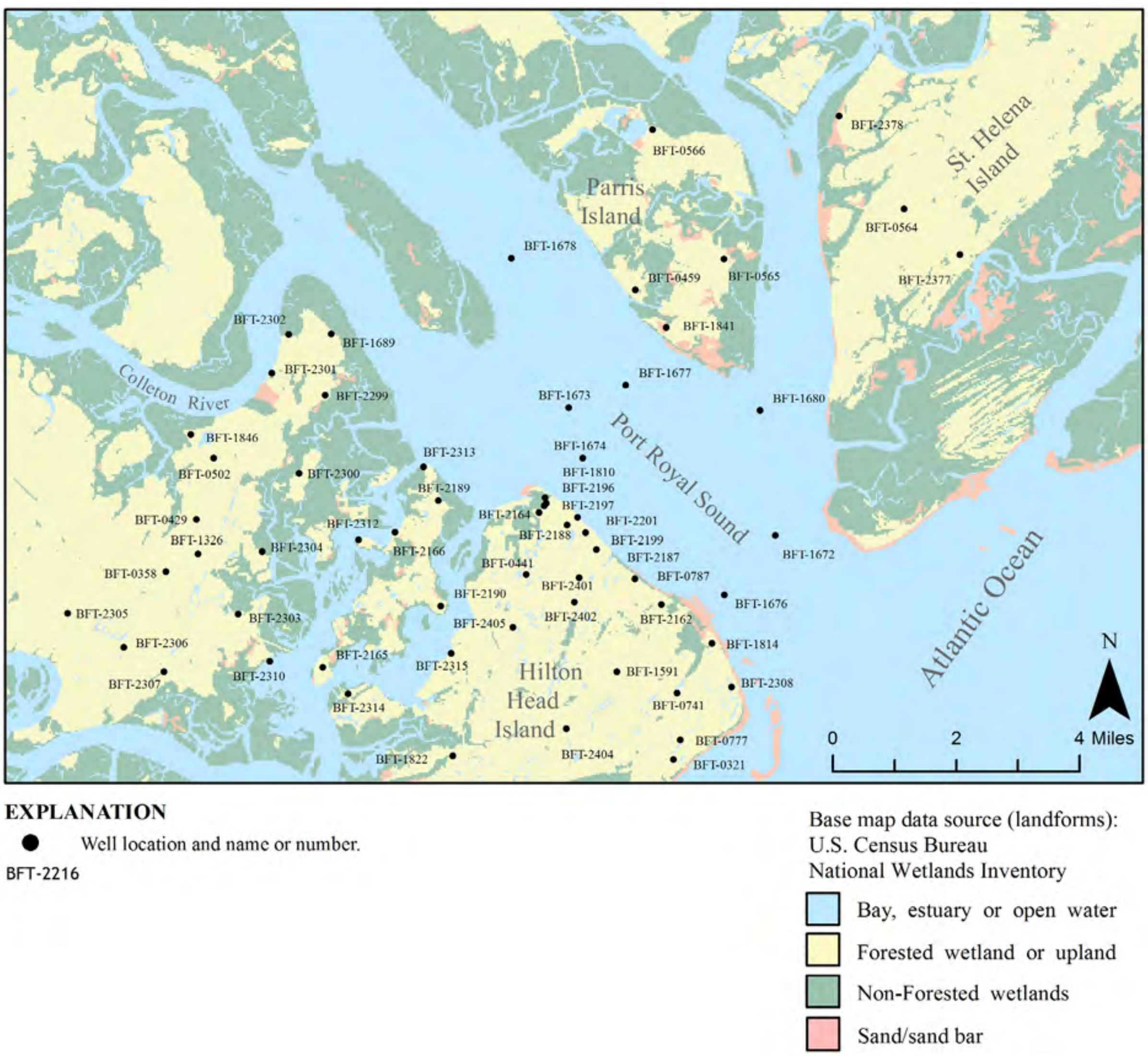


Figure 70. Location of wells measured for vertical specific conductance profiles to the bottom of the Upper Floridan aquifer, 2007 (offshore locations from Burt and others, 1987).

Island, and Colleton River chloride plumes. The distribution and pattern of chloride plumes was used also to estimate source-area locations (fig. 34). Seawater began to enter the groundwater system as early as 1952 based on interpretations of CFC, DO, and isotope data. This date generally corresponds with the estimated time that the declining potentiometric surface reversed the upward and northeasterly flow in the Upper Floridan aquifer beneath the Port Royal Sound area.

The relict freshwater-to-brackish water interface comprising the leading edge of the Port Royal Sound chloride plume was simulated by Smith's (1993 and 1994) two-dimensional solute transport model of the Upper Floridan aquifer to better determine the southwestward rate of movement. Figure 71 shows his simulated 1885 to 2032 progression of the relict brackish-freshwater interface through section A-A' across Port Royal Sound: the leading edge is represented by a 1,000 mg/L TDS concentration near the aquifer bottom. The 1885 simulated interface position corresponds to predevelopment conditions; the 1984 position is calibrated to Port Royal Sound well data; and the 2032 position is simulated and assumes a continuous 78-Mgal/d regional pumping rate from 1984 through 2032. Interface movement averaged 68 ft/yr from 1935 through 1976; 80 ft/yr from1976 through 1984; and 115 ft/yr during 1984. After 1984, the simulated interface moved approximately 3,000 ft and arrived beneath the Hilton Head Island shoreline in about 2008. By 2032, the simulated rate of movement was about 230 ft/yr and the interface was 4,000 ft southwest of the island's shoreline. If pumpage is removed at Hilton Head Island and the Bluffton area beginning in the year 2000, the model simulation shows that the relict freshwater-to-brackish water interface would continue to migrate approximately 65 ft/yr and arrived beneath the northern shore of the island in about 2016.

Brackish water arrived beneath the northeast shore of Hilton Head Island sooner than predicted by

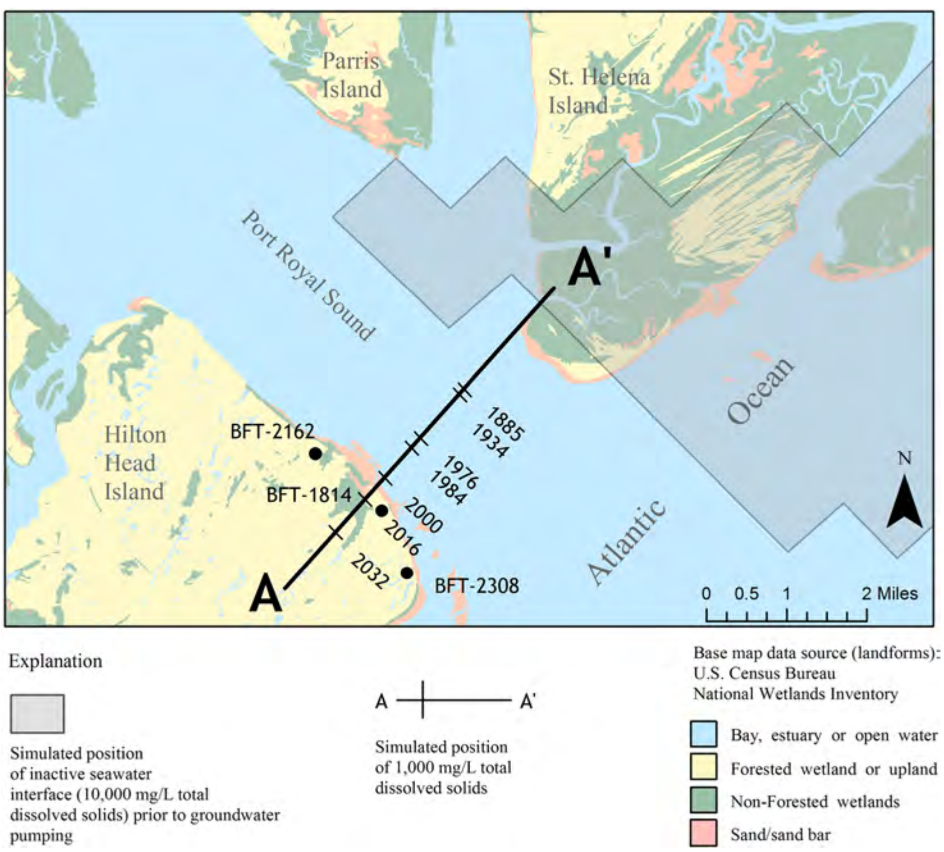


Figure 71. Simulated positions of the 1,000 mg/L total dissolved solids isopleth (saltwater-freshwater interface) beneath Port Royal Sound and Hilton Head Island, S.C. assuming 1984 pumpage, 1885–2032 (after Smith, 1988 and 1994).

Smith's solute-transport simulations, mostly because pumpage increased about 40 percent on the Hilton Head Island and about 30 percent regionally between 1984 and 1995 (fig. 19). Water samples from the aquifer bottom at well BFT-1814 contained chloride concentrations less than 200 mg/L in 1987 and 1995 (SCDNR file data), but computed concentrations of 800 to 1,500 mg/L were obtained by specific-conductance measurements between 1999 and 2007, respectively (Appendix I). In nearby wells BFT-2162 and BFT-2308, also on the northeast shore of the island, computed chloride concentrations near the aquifer bottom showed an increase of 4,500 and 700 mg/L in 2007, respectively.

The probable source of chloride contamination detected in specific-conductance profiles at wells BFT-1814 and BFT-2308, at the northeast corner of Hilton Head Island, is the southwestward encroaching Port Royal Sound plume. Supporting data include the: (1) thickness of the upper confining unit (30 - 40 ft) and small head differences across the confining unit in the area, which make modern, downward-migration of seawater an unlikely source of chloride contamination and (2) chloride concentrations that were much lower in the top and middle of the aquifer and therefore indicate that the chloride source area did not originate close to the two wells.

Chloride contamination at well BFT-2162 (referenced above), located midway between the northwest and northeast shoreline of the island (fig. 70), might be a mixture of relict and modern brackish water from the Port Royal Sound and Dolphin Head plumes, respectively, based on: (1) computed-chloride distribution near the north shore of Hilton Head Island (fig. 72); and (2) the rate of groundwater flow (fig. 71) and flow direction simulated by Smith (fig. 72) and the SCDHEC model (Appendix J).

Near the northwestern part of the island, modern seawater comprising the Dolphin Head chloride plume appears to have merged with the leading edge of relict brackish water from the encroaching Port Royal Sound chloride plume by 2007. Merging of the two plumes is consistent with: (1) the 1984 position of the Port Royal Sound chloride plume (fig. 36) mapped by Landmeyer and Belval (1996), and (2) the concentration of pumpage south southeast of Dolphin Head and the corresponding groundwater flow rate (fig. 71) and direction (fig.72) simulated by Smith (1994) and the SCDHEC model (Appendix J).

The Pinckney Island chloride plume developed along a southwesterly axis oriented toward Savannah, Ga. In 2007 the plume extended at least as far to the southwest as well BFT-2310, about five miles southwest of the estimated source area near the confluence of Mackay Creek and the Chechessee River (fig. 72). Given the history of the potentiometric declines in the area and the expansion of other nearby chloride plumes, the 2,300 mg/L chloride concentration found at well BFT-2310 near the bottom of the aquifer did not originate at the estimated source area near the northern part of Pinckney Island. Otherwise, the groundwater flow rates would have to average 400 to 500 ft/yr during a 50-year time span which cannot be supported by existing data. Furthermore, McCollum and Counts' (1964) 1961 potentiometric map (Appendix D6) shows a southwesterly dip in the 0-ft potentiometric surface contour, which indicates local recharge from Mackay Creek, Pinckney Island, and the surrounding area: thus, a downward gradient existed near well BFT-2310 by 1961. The onset of downward seawater migration in the late 1950's to early 1960's is consistent with the CFC recharge date of 1958 calculated for a water sample taken from well BFT-2310 at the bottom of the aquifer. Therefore, the brackish water entered the groundwater system in 1958 and occurred in an area where the potentiometric head was near mean sea level (fig 69). Thus, the source of chloride contamination in well BFT-2310 must lie close to the 0-ft contours mapped by Counts and Donsky, Siple, and McCollum and Counts in 1957, 1960, and 1961, respectively. The source area probably lies beneath the western shoreline of Pinckney Island. Recharge dates between 1970 and 1978 at three sample sites (wells BFT-2313, 2366, and 2312) on the western shoreline of Pinckney Island (fig. 69) indicate that seawater entered the groundwater system almost simultaneously along a 2-mile segment of the plume axis. Plume movement from well BFT-2312 to the southwestern edge of the 250-mg/L isochlor is about 2.7 miles along the groundwater flow path, approximating a rate of movement similar to the Colleton River and Dolphin Head chloride plumes. Therefore, it is plausible to assume that the greater expansion of the Pinckney Island chloride plume to the southwest is attributed to a second source area near well BFT-2312.

The Pinckney Island and Colleton River chloride plumes began to form at about the same time: the 250-mg/L isochlors for each plume are close to the same distances from their respective source areas, and they migrate at similar rates. Based on 2007 specific-conductance data, the plumes are merging as they migrate southwestward toward pumping wells at Savannah, Ga., and in response to diffusion and dispersion are moving perpendicular to their axes. The SCDHEC model simulations (Appendix J) show also that the two plumes have merged.

Greater Port Royal Sound Chloride Plume

Rationale that the five northeastern chloride plumes in the vicinity of Port Royal Sound merged at the bottom of the aquifer before 2007 and continue to expand include: (1) the merging of the eastern part of the Parris Island plume and the western part of the Port Royal Sound plume, (2) model simulations (Provost and others, 2006; SCDHEC model (Appendix J), and specific-conductance data that indicate the Port Royal Sound and Dolphin Head chloride plumes have migrated beneath most of the north shore of Hilton Head Island and also have merged with the Pinckney Island and Colleton River

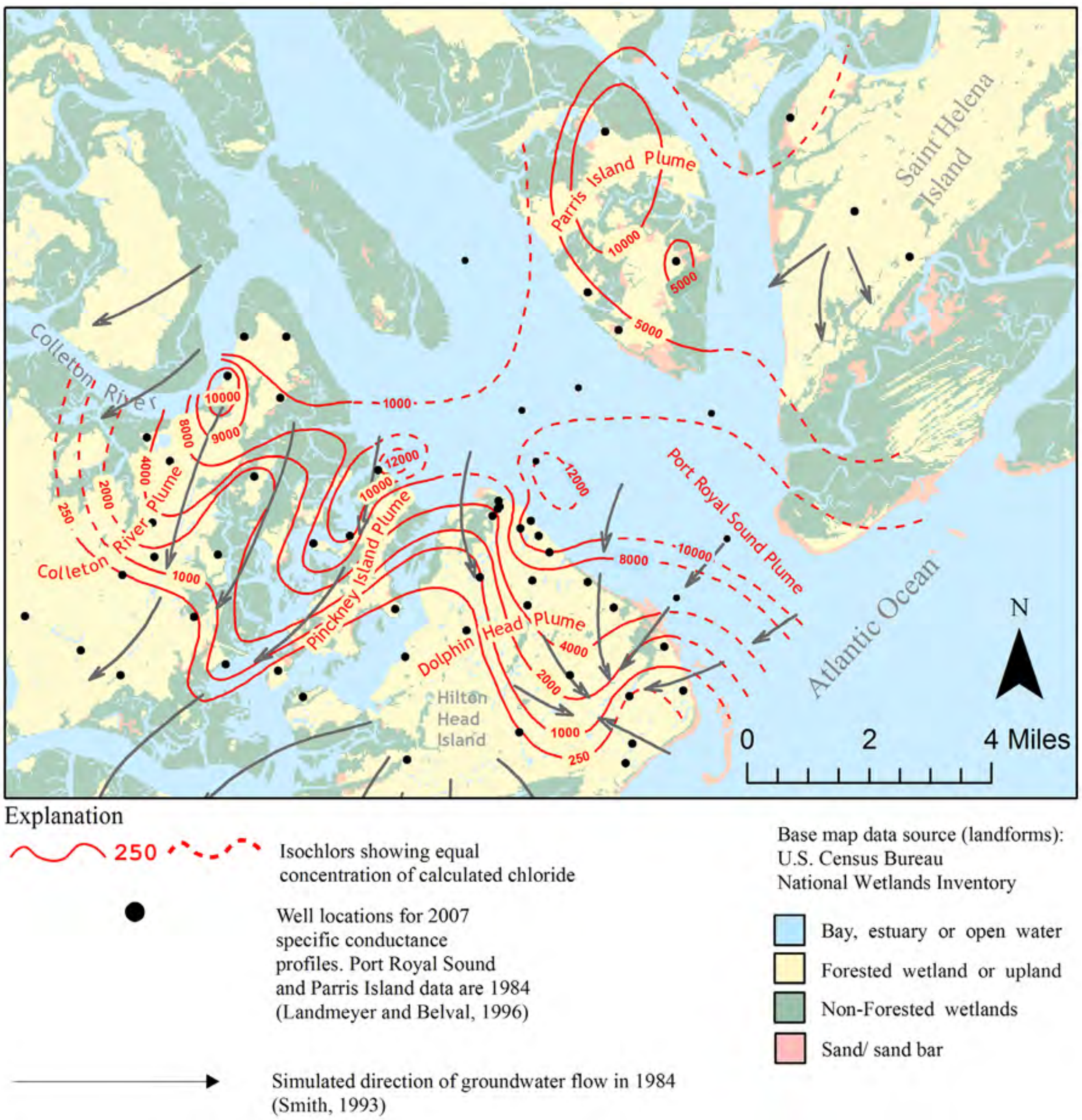


Figure 72. Isochlors map comprising the greater Port Royal Sound plume near the bottom of the Upper Floridan aquifer, Port Royal Sound area, S.C., 2007.

chloride plumes to the west, (3) the 1957 southwestward regional flow paths shown by Counts and Donsky (1963, Appendix D4)) and the 1984 southwestward and southeastward flow paths at the aquifer bottom simulated by Smith (1994) near Port Royal Sound, S.C. (fig. 72), (4) the specific-conductance data and isochlor-map changes (see **SALT WATER CONTAMINATION** section) that indicate continued plume expansion southwest and west between Hilton Head Island and the Colleton River, and (5) chloride distribution, that is consistent with a single large plume.

The 2007 isochlor map (fig 72) shows that the Parris Island, Port Royal Sound, Dolphin Head, Pinckney Island, and Colleton River chloride plumes had merged and are designated herein the greater Port Royal Sound chloride plume. Smith's simulated 1984 flow lines at the bottom of the aquifer were superimposed over the 2007 isochlors and found to coincide with the direction of plume movement. The southwest direction of groundwater flow near the source areas of the Pinckney Island and Colleton River chloride plumes is most influenced by Savannah's pumpage; part of the Dolphin Head chloride plume reflects the influence of local pumpage at northeastern Hilton Head Island superimposed on the greater regional southwesterly trend. The plumes emanate from discrete source areas shown by isochlor saddles wherein chloride concentrations increase to the north northeast toward Port Royal Sound between the Dolphin Head and Pinckney Island chloride plumes and between the Pinckney Island and Colleton River chloride plumes.

The greater Port Royal Sound chloride plume encompasses approximately 80 mi^2 and is advancing southwestward along a 15-mile front between the Colleton River and the northeast shoreline of Hilton Head Island. Onshore, part of the plume is driven downward toward permeable zone 2 by the greater density of salt water, recharge from higher heads in the overlying surficial aquifer, and by pumping from permeable zone 2; it then moves laterally along the bottom 20 to 30 ft of the aquifer. Upward migration of relict brackish water in the middle confining unit near Port Royal Sound does not appear to significantly contribute to the chloride plumes in the overlying Upper Floridan aquifer because of: (1) the lower hydraulic conductivity and small head difference across the middle confining unit, (2) the generally greater chloride concentrations at the Upper Floridan aquifer bottom compared to those found in the middle confining unit, (3) the overall pattern of the greater Port Royal Sound chloride plume, which is consistent with the plume originating from three source areas contributing modern brackish to salt water and two larger plumes contributing relict brackish to salt water in the aquifer beneath Port Royal Sound and Parris Island, and (4) the absence of detectable brackish-water upconing at northern Hilton Head Island in wells pumping less than 1,000 gpm on the northern part of Hilton Head Island (Hayes, 1979). The greater density of brackish to salt water comprising the greater Port Royal Sound chloride plume also causes brackish to salt water from the aquifer bottom to penetrate downward into the underlying middle confining unit (SCDHEC model simulations J16 and J17).

The average yearly linear velocity for the period 1952 through 2007 is computed for the brackish water comprising the greater Port Royal Sound chloride plume using the total estimated travel distance and time since movement began for the Colleton River, Pinckney Island, and Dolphin Head chloride plumes. The average travel distances for each estimated source area and the respective down-gradient 250 mg/L isochlor. The travel times, beginning in 1952, are estimated from the calculated CFC recharge dates and historical potentiometric maps that approximate the year that the potentiometric surface declined to near mean sea level at the estimated chloride source areas. The plumes have moved an average of about 3 miles from their initial source areas, and the travel times of each plume was about 55 years; thus, the average yearly linear velocity of brackish and salt water comprising the greater Port Royal Sound plume for this time span was approximately 288 ft/yr. The greater Port Royal Sound chloride plume will eventually merge with the Sawmill Creek, the Jenkins Island, the Broad Creek, and the Bull River chloride plumes. In the future, downward migration of chloride from the upper confining unit will increase and eventually make a greater contribution to plume development, movement, and regional distribution of chlorides in the aquifer beneath offshore areas.

MIDDLE CONFINING UNIT

The middle confining unit contains mostly relict brackish water in the coastal part of the study area. Water quality, geophysical logs, and specific conductance profiles (SCDNR and SCDHEC) in the middle Floridan aquifer and the middle confining unit indicate that chloride concentration decreases west and southwest of northern Hilton Head Island and increases to the northeast. Increases in chloride concentration moving into the top of the confining unit might to be occurring beneath several Upper Floridan aquifer chloride plumes (SCDHEC model, Appendix J).

Back and others (1970, Table 2) obtained a sample from 483 ft bgs in BFT-315 on northwestern Hilton Head Island: the sampling point was open to the bottom of the middle confining unit and top of the middle Floridan aquifer. Based on a water sample in 1965 they calculated an adjusted carbon-14 age of 20,000 years and reported a chloride concentration of 1,180 mg/L. 1n 1983 six discrete water samples were collected from middle confining unit in well BFT-315 between -210 and -410 ft Msl (SCDNR, file data), chloride concentrations in the upper 164 ft of the middle confining unit ranged from 1,490 to 1,671 mg/L (fig. 37).

Specific conductance profiles were run in five wells open to both the middle confining unit and the middle Floridan aquifer during 2008. Two wells (BFT-1809 and BFT-2185) at the northern part of Hilton Head Island indicated maximum chloride concentrations in the middle confining unit of about 1,000 mg/L. Wells on the northeastern part of the island (well BFT-1813 and well BFT-786), also open to the middle confining unit, showed chloride concentrations of about 500 mg/L. Well BFT-1840, at Parris Island, showed chloride concentrations of 4,000 mg/L. On the mainland, northwest of Hilton Head Island, middle Floridan aquifer irrigation wells are constructed with casing installed to about 350 ft bgs, leaving an open borehole opposite the lower section of the middle confining unit and the middle Floridan aquifer. These wells typically have chloride concentrations of less than 50 mg/L, indicating that the middle confining unit and the middle Floridan aquifer follow a similar trend of decreasing chloride concentrations toward the west.

Changes in pumping patterns since the early 1990's have altered the vertical hydraulic gradients across the middle confining unit and, coincident with the spread of Upper Floridan aquifer salt-water plumes, have begun to noticeably influence confining-unit water quality. Gawne and Park (1992) reported small head differences across the middle confining unit for February 1991, with upward gradients at mid Hilton Head Island and the Colleton River area and downward gradients at the northeast shore of Hilton Head Island: head differences were between 0.7 and -0.7 ft, respectively. A downward gradient probably developed in the Skull Creek-Colleton River-Bluffton area after 1990 after: (1) golf courses on the mainland turned to the middle Floridan aquifer for irrigation water, (2) surface water became available, in about 2000, for public supply use and to replace Upper Floridan public supply wells threatened by the Colleton River, Pinckney Island, and Dolphin Head chloride plumes, (3) Upper Floridan pumpage at Hilton Head Island subsequently was reduced to 9.7 Mgal/d, and (4) Hilton Head Island PSD began using middle Floridan aquifer wells at Jenkins Island in 2013 to replace Upper Floridan wells contaminated by the Dolphin Head plume. The upward gradient at northern Hilton Head Island and the Bluffton area probably reversed as middle Floridan pumpage increased to about 7 Mgal/d (fig. 27) and Upper Floridan aquifer pumage decreased.

Modern saltwater plumes in the Upper Floridan aquifer can also migrate downward and contaminate the middle confining unit. As an example, well BFT-2079 was completed as a middle Floridan irrigation well at Colleton River Plantation in 1993: the well was cased to 290 ft bgs and completed as an open borehole to 497 ft bgs. The electrical-resistivity logs obtained in 1993 (SCDNR) indicate low resistivity between 110 and 210 ft bgs, the interval corresponding to the Colleton River chloride plume in the lower 70 ft of the Upper Floridan aquifer and extending 30 ft (180 to 210 ft bgs) into the underlying middle confining unit (fig 73). At depths greater than 210 ft bgs, electrical resistivity increased and indicated fresh water in the lower part of the middle confining unit and in the middle Floridan aquifer: the latter yielded water containing a chloride concentration of 7 mg/L in 1993 (SCDNR files).

In 2004, a specific conductance profile and geophysical logs completed in well BFT-2079 (SCDHEC files) revealed that the chloride concentration had increased to more than 4,000 mg/L in the middle confining unit. The only documented chloride source near the well was the Colleton River chloride plume moving through the bottom of the overlying Upper Floridan aquifer. It is plausible that the chloride contamination in well BFT-2079 was attributed, in part, to interconnection with the plume through corroded casing or grout failure, which combined with pumpage from well BFT-2079, created a greater downward gradient at the well site. Well BFT-2079 was abandoned, and replacement-well BFT-2403 was constructed about 50 ft from well BFT-2079 in 2004. Electrical-resistivity logs at well BFT-2403 showed low resistivity between about 110 to 300 ft bgs, indicating that brackish water from the Colleton River plume had migrated about 90 ft further into the middle confining unit between 1993 and 2004 and was below the casing at well BFT-2079 (fig. 73).

Downward saltwater migration into the upper 30 feet of the middle confining unit at well BFT-2079 prior to 1993 indicates that the migration was probably driven by density and pumping from the water-bearing unit equivalent to the middle Floridan aquifer (permeable zone 4) at Savannah, Ga., that, in turn further increased the rate of downward migration from the Colleton River plume at the well site.

Regionally, downward migration of brackish water toward the middle Floridan aquifer will be less extreme than in the Colleton River Plantation case. The contamination of well BFT-2079 by brackish water at Colleton River Plantation occurred beneath an area of the Colleton River chloride plume and at the center of a cone of depression created by pumping well BFT-2079. The potential for downward saltwater intrusion through the middle confining unit will increase if middle Floridan aquifer withdrawals increase and as the greater Port Royal Sound chloride plume encroaches farther to the southwest.

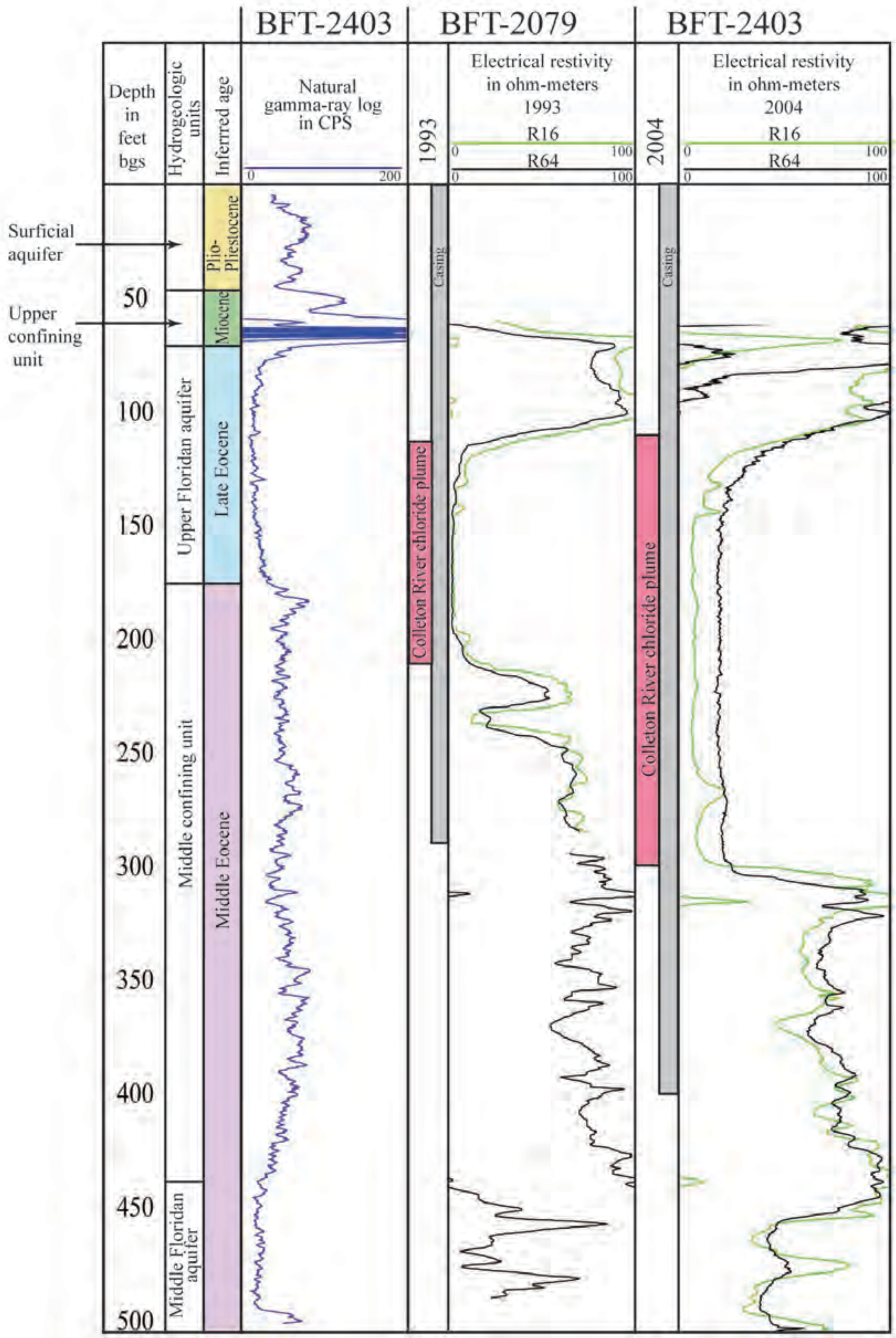


Figure 73. Changes in electrical resistivity (showing decreasing resistance) in the middle confining unit between 1993 and 2004 at Colleton River Plantation, S.C.

MIDDLE FLORIDAN AQUIFER

The informally named middle Floridan aquifer (Gawne and Park, 1992) was first identified in South Carolina as zone 4 by Counts and Donsky (1963) in three test wells (BFT-304, BFT-101, and BFT-315; fig. 15) on Daufuskie and Hilton Head Islands. The distribution of chloride in the middle Floridan aquifer from Parris Island through Hilton Head Island toward Daufuskie Island (fig. 74) shows chloride concentrations decreasing to the south and west of the Port Royal Sound area. The area of brackish groundwater generally coincides with the area where fresh water reached equilibrium with relict brackish water prior to groundwater development. Carbon-14 analyses of samples from the middle Floridan aquifer beneath central and northern Hilton Head Island from 543 ft bgs at well BFT-101 and 483 ft bgs at well BFT-315 indicate brackish-groundwater ages of 25,000 and 20,000 years B.P., respectively (Back and others, 1970, table 2). These dates support earlier reference (see **SALTWATER CONTAMINATION** section) to the ancient shoreline where sea level was about 400 ft lower than present before beginning to advance about 19,000 years B.P. Increased development of fresh water from the middle Floridan aquifer northwest of Hilton Head Island will likely reverse the upward leakage into the overlying Upper Floridan aquifer and increase the lateral movement of relict brackish water toward Bluffton, S.C.

Monitoring of middle Floridan aquifer sampling points in two of these wells, beginning about 1960, found chloride concentrations of 1,120 mg/L at BFT-315 on the northwestern part of Hilton Head Island and 480 mg/L at well BFT-101 midway on Hilton Head Island. Chloride concentrations in well BFT-101 have not changed significantly since measurement began but increases of about 620 mg/L (table 2) have been measured at well BFT-315 dating from 1963 to 2013 (table 2); the increased chloride concentrations may have been caused by relict brackish water moving laterally from Parris Island where middle Floridan wells have much higher chloride concentrations (table 2). South of well BFT-315, the middle Floridan aquifer test well (well BFT-985) was constructed at Bear Creek Golf Course in 1979 on the northern part of Hilton Head Island for irrigation. Well BFT-985 was cased to 542 ft bgs (top of middle Floridan aquifer) and completed as an open borehole to 550 ft bgs. Samples collected for chloride analyses from 1979 to 1993 (SCDNR files) showed that chloride concentrations ranged from 510 to 547 mg/L, respectively. However, the well was removed from service after several years because chloride concentrations were too great for golf course irrigation. In 1993, middle Floridan aquifer well BFT-2079 was completed in Colleton River Plantation west of Hilton Head Island (fig. 26) and

Bft-101				*BFT-315*			
Pumped sample interval	Chloride concentration (mg/L)			Pumped sample interval	Chloride concentration (mg/L)		
ft below ground surface	USGS 1958-1975	USGS 1965	GMA 2010	ft below ground surface	USGS 1963-1983	USGS 1965	PSD#1 2013
585-635	495-570	580	480	450-510	1,060-1,300	1,180	1,683

Table 2. Chloride concentrations from middle Floridan aquifer samples at BFT-101, and BFT-315 (data from Counts and Donsky, 1963; Back, Hanshaw, and Rubin, 1970; Groundwater Management & Associates, 2010; and Hilton Head Island Public Service District No. 1, 2013).

marked the beginning of regional development for the aquifer in South Carolina.

The highest chloride concentrations for the middle Floridan aquifer were at wells BFT-2248 and BFT-2255 on Parris Island. These wells were cased to about 300 ft bgs and completed to a depth of about 600 ft bgs, leaving the borehole open to the middle confining unit. The wells were used for golf course irrigation; however, chloride concentrations were more than 4,000 mg/L. Similar observations were made on Parris Island earlier at well BFT-1840, for which Gawne and Park (1992) reported 4,250 mg/L. On the northern and northeastern part of Hilton Head Island, chloride concentrations are about 1,400 mg/L and decrease to the southwest where concentrations are about 500 mg/L. West of Hilton Head Island, chloride concentrations generally are less than 30 mg/L, and at Daufuskie Island, chloride concentrations decrease southwestward from 170 to 160 mg/L. Three middle Floridan wells, BFT-2481 (east), BFT-2479 (center), and BFT-2483 (west), were constructed on Jenkins Island beginning in 2006 as part of a public supply reverse-osmosis system (Groundwater Management & Associates, 2009). The well field produced about 3 Mgal/day until 2015 when withdrawals increased to 4 Mgal/day. Chloride concentrations remained stable through 2015 (fig 75).

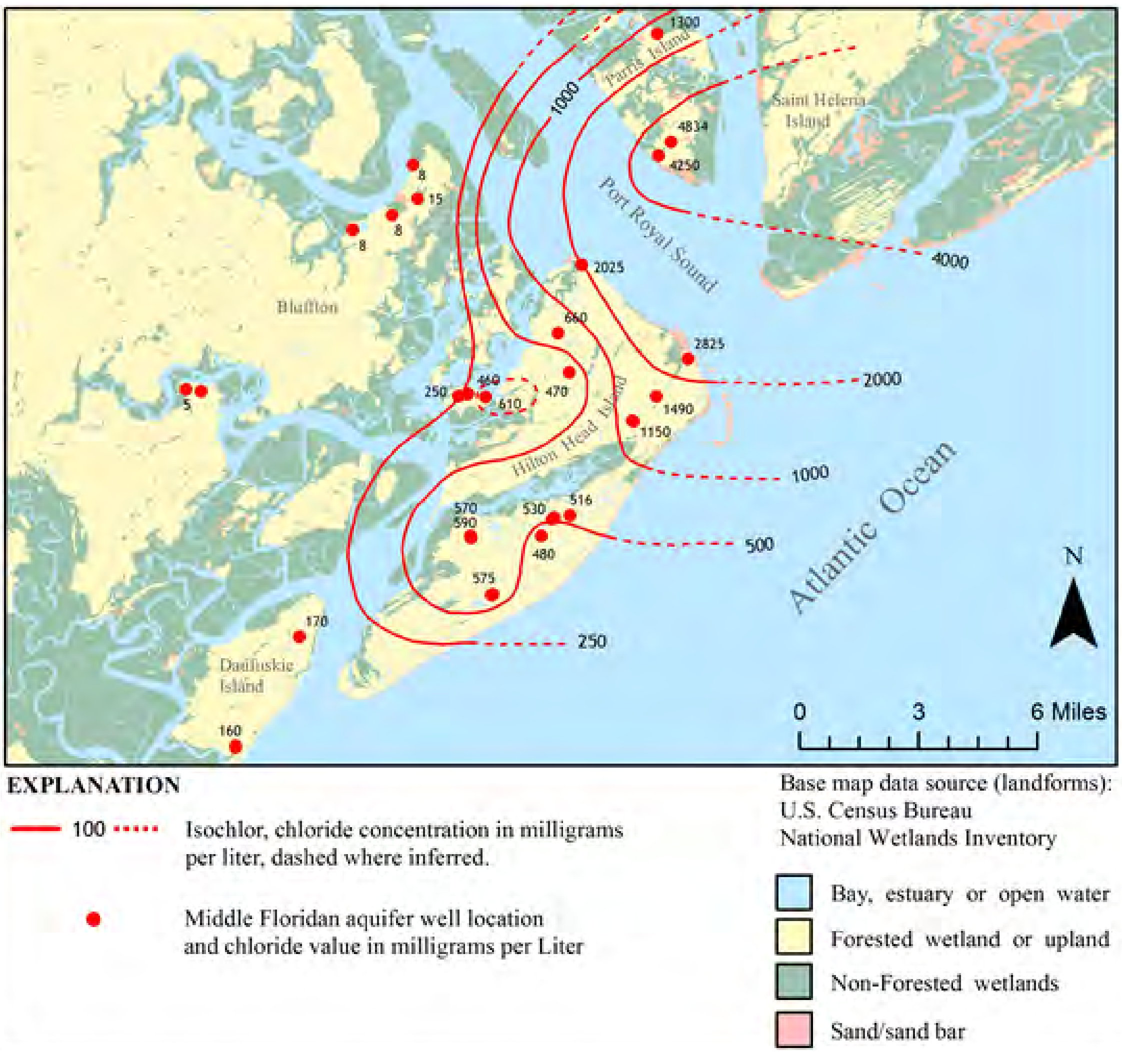


Figure 74. Chloride concentrations in pumped water samples from the middle Floridan aquifer, southern Beaufort County, S.C., 1962–2015 (data from Counts and Donsky, 1963; Back, Hanshaw, and Rubin, 1970; Gawne and Park, 1999;Groundwater Management & Associates, 2010 and 2014; and Hilton Head Island Public Service District , 2013).

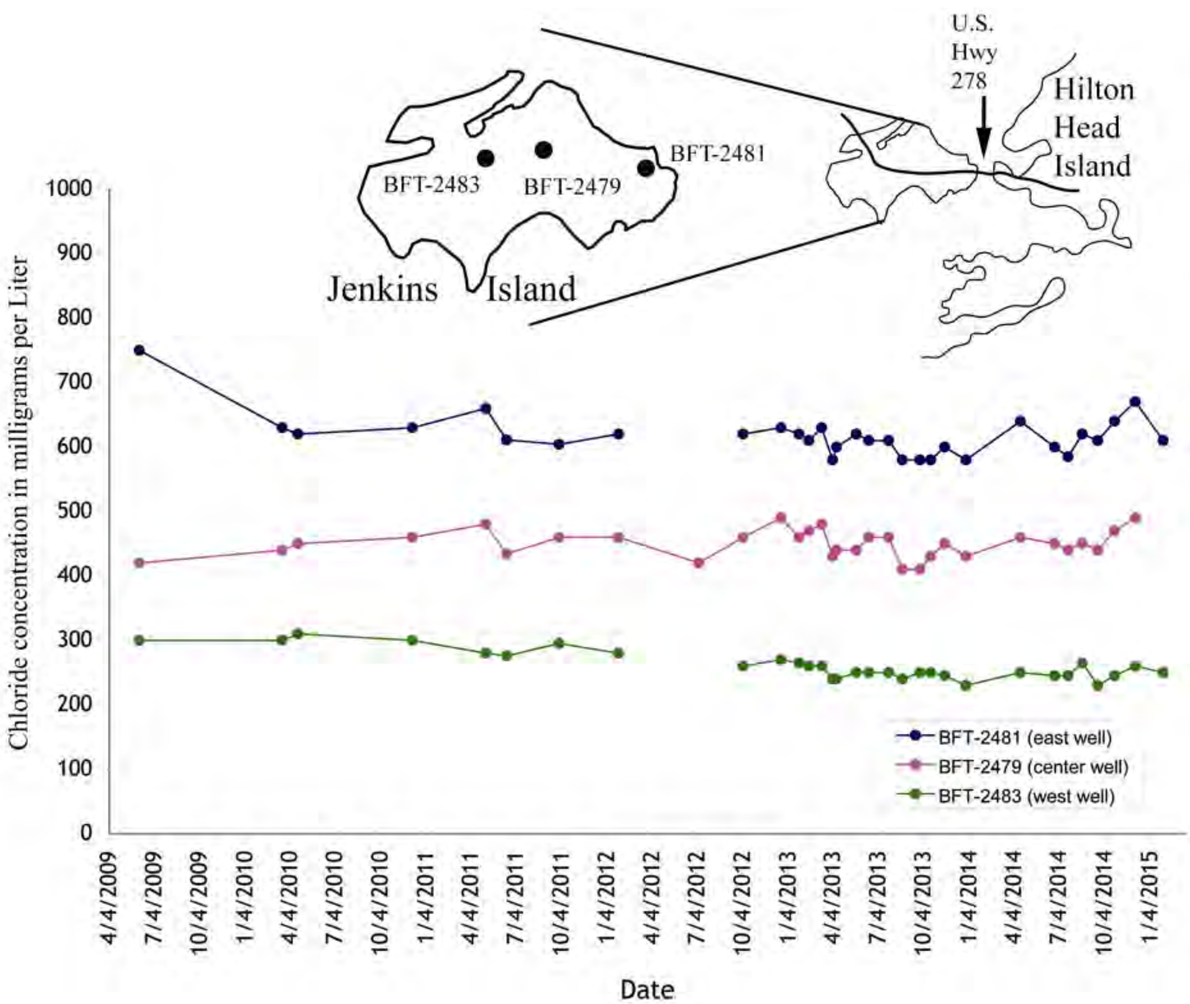


Figure 75. Chloride concentrations in middle Floridan aquifer wells at Jenkins Island, S.C, 2009–2015 (Hilton Head PSD data).

LOWER CONFINING UNIT AND LOWER FLORIDAN AQUIFER

The Lower Floridan aquifer as interpreted by Williams (2010) includes McCollum and Counts' (1964) permeable zones 4 and 5 and several smaller composite zones in the Savannah, Ga. area. These zones lie within the lower confining unit of the Floridan aquifer system: in South Carolina permeable zone 5 has not been confirmed and permeable zone 4 is considered the middle Floridan aquifer. McCollum and Counts reported on seven wells in Chatham County, Ga., and two wells in southern South Carolina that penetrated at least part of the Lower Floridan aquifer. Two other wells (BFT-2485, BFT-2473) drilled at Hilton Head Island between 2012 and 2013 penetrated most of the lower confining unit (fig. 76). Well BFT-2485 was completed as an open borehole between 1,103 and 1,145 ft bgs; the well yielded only 2 gpm with a chloride concentration that exceeded 7,000 mg/L (Groundwater Management & Associates, 2014). Point samples (SCDHEC) from selected depths in the open borehole of USGS test-well BFT-2473 contained 1,100 mg/L at 881 ft bgs and 4,400 mg/L at 1,200 ft bgs. Chloride concentrations in the lower confining unit are expected to be greatest near Port Royal Sound and to decrease southwest and west toward the mainland. Table 3 shows water quality with respect to depth, but differences in well construction, sampling methods, and hydrologic correlations among wells generally do not permit direct comparison.

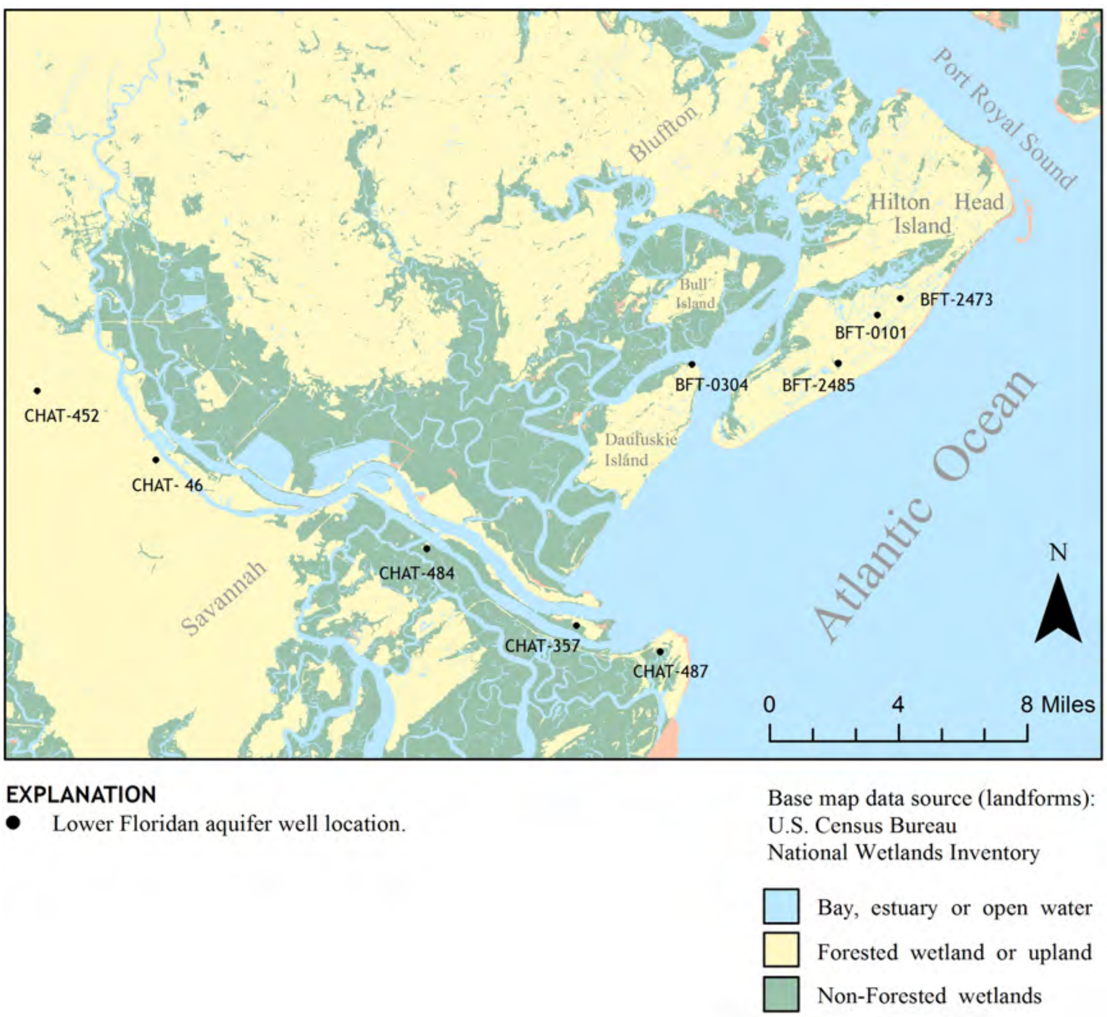


Figure 76. Locations of wells open to Lower Floridan aquifer and lower confining unit in the Hilton Head Island, S.C. – Savannah, Ga., area.

Table 3. Chloride concentrations in Lower Floridan aquifer/lower confining unit at wells Chatham-487, BFT-304, BFT-101, BFT-2485, and BFT-2473.

Chatham-487		BFT-304		BFT-101				BFT-2485		BFT-2473*	
Pump sample interval	Chloride (mg/L)	Pump sample interval	Chloride (mg/L)	Pump sample interval	Chloride (mg/L)			Pump sample interval	Chloride (mg/L)	Discrete sample interval*	Chloride (mg/L)
ft below ground surface	USGS 1960	ft below ground surface	USGS 1960-1983	ft below ground surface	USGS 1958-1982	USGS 1965	GMA 2010	ft below ground surface	GMA 2013	ft below ground surface	SCDHEC 2012
	423	693-706	478-500	665-745	1918-2030	2020	1899	1103-1145	7141	640	840
										881	1100
										1200	4300

* Open borehole 200-1258 feet

SUMMARY AND CONCLUSIONS

The Floridan aquifer system in the study area is composed of carbonate sediment that range from early Eocene to Oligocene and include up to five principle permeable zones. The aquifer is confined above by the low permeability Miocene upper confining unit consisting of very-fine sand, silt, phosphate, and clay that is overlain by Plio-Pliesticene and Holocene sediment that form a surficial aquifer. The most productive part of the aquifer system is the upper unit of the Ocala Limestone, comprised of late Eocene sediment that include permeable zones 1 and 2, and forms the Upper Floridan aquifer in South Carolina. The lower unit of the Ocala Limestone acts as the middle confining unit, except for a thin permeable zone 3 identified in the Savannah, Georgia, area. Underlying the middle confining unit are middle Eocene carbonate sediment that include permeable zone 4, informally known as the middle Floridan aquifer in South Carolina, but considered the top of the Lower Floridan aquifer in Georgia. Except for the fifth permeable zone identified only in Georgia, the remaining middle to early Eocene carbonate rock form the lower confining unit of the Floridan aquifer system.

The Beaufort Arch, an area of tectonic uplift, is the dominant structural feature in the study area. The arch trends along a northeast-southwest axis with the greatest uplift present northeast of Beaufort, South Carolina; here, the Upper Floridan aquifer lies close to the surface and overlying sediment are thin owing to lack of deposition or erosion during episodes of lower sea level. Sinkholes are present near the northeast and southwest borders of Port Royal Sound along the axis of the Beaufort Arch, where the overlying confining unit locally can be less than 10 feet thick. To the southwest, toward Tybee Island, Ga., the arch dips downward and the sediment generally thicken except above isolated areas of uplift.

The predevelopment potentiometric heads in the Upper Floridan aquifer near Savannah, Georgia were between 35 and 40 feet mean sea level and dipped northeastward to about 5 feet mean sea level near the northern shoreline of Hilton Head Island, South Carolina. The heads began to decline in 1888 after

municipal groundwater withdrawals began at Savannah. By 1960, total groundwater withdrawals were about 62 million gallons per day at Savannah and groundwater withdrawals was just beginning at Hilton Head Island. As the potentiometric surface continued to decline with increased withdrawals, the cone of depression expanded northeastward from Savannah, and, by the early 1970's, heads were below mean sea level near Port Royal Sound. Groundwater withdrawals reversed the hydraulic gradient toward Savannah and captured freshwater that previously discharged toward Port Royal Sound. Groundwater development peaked between 1992 and 1998 with withdrawals in the Savannah, Georgia - Hilton Head Island, South Carolina, area reaching approximately 100 and 14.5 million gallons per day, respectively. During peak pumpage, potentiometric heads declined at the northern part of Hilton Head Island to about -4 feet mean sea level, about -10 feet mean sea level near the center, and about -20 feet mean sea level at the southern part of the island. Near the center of the cone of depression at Savannah, heads declined to about -150 feet mean sea level. Heads in the underlying middle Floridan aquifer (lower Floridan aquifer in Georgia) were similar and changed in response to pumpage from the Upper Floridan aquifer owing to a hydraulic connection through the middle confining unit and response to pumping wells in Georgia that penetrated the middle Floridan aquifer.

The high predevelopment freshwater heads originating from the southwest flushed salt water, remaining since the last post-glacial sea level rise, from the aquifer. Relict brackish to salt water remained in the Upper Floridan aquifer near Parris Island and Port Royal Sound because of low freshwater heads. High chloride concentrations were also present in the underlying middle confining unit and the middle Floridan aquifer in the coastal part of the study area. Here, chloride concentrations were about 170 milligrams per liter on Daufuskie Island, South Carolina and increased to about 4,000 milligrams per liter toward the northeast at Parris Island, South Carolina. West of Hilton Head Island, chloride concentrations were typically less than 10 milligrams per liter.

As heads in the Upper Floridan aquifer declined near and below mean sea level, downward migration of modern seawater began, probably in the 1ate 1930’s, near Savannah, Georgia and during the 1950’s in the Port Royal Sound area. Here, modern seawater migrated into the surficial aquifer and into the underlying upper confining unit, and where the unit is absent, modern seawater moved directly from the surficial aquifer into the unprotected Upper Floridan aquifer. Sampling at the bottom of the surficial aquifer beneath tidal channels in southern Beaufort County, South Carolina and Chatham County, Georgia found chloride concentrations between 160 and 18,500 milligrams per liter at 27 sites. Generally, chloride concentration at the bottom of the surficial aquifer decreased with depth and increased with distance from major landmasses that supplied freshwater to the bottom of the aquifer but were dependent also on heterogeneous sediment that vary over relatively short distances. As part of this report and other investigations, pore water was extracted from the upper confining unit at 16 tests well sites to evaluate the downward movement of brackish to salt water from the bottom of the surficial aquifer beneath offshore areas; high chloride concentrations were detected at each site and decreased with depth, indicating progressive downward movement. The source areas for modern saltwater contamination of the Upper Floridan aquifer were found where the upper confining unit is absent beneath tidal channels and offshore areas near the axis of the Beaufort Arch: the greatest number of source areas lies between St. Helena Sound and Daufuskie Island, South Carolina.

Eleven chloride plumes are documented in the study area and are recognized herein as: the Parris Island, the Port Royal Sound, the Dolphin Head, the Pinckney Island, the Colleton River, the Sawmill Creek, the Jenkins Island, the Broad Creek, the Bull Island, the Hilton Head High, and the 8-mile chloride plumes. The plumes are near the axis of the Beaufort Arch and have formed over an area extending about fifteen miles southwest from the Parris Island and Port Royal Sound area to areas near Daufuskie Island. The highest computed (from vertical specific-conductance profiles) and laboratory analyzed chloride concentrations were found near the bottom of the aquifer in monitoring wells closest to the estimated source areas; here chloride concentrations were as high as 10,000 milligrams per liter.

The predevelopment positions of the Parris Island and Port Royal Sound chloride plumes were near the northeastern shore of Port Royal Sound; these plumes are comprised of relict brackish to salt water. The Parris Island chloride plume may also include modern seawater induced by minor pumpage on the island between 1899 and 1926. The Parris Island and Port Royal Sound chloride plumes were mapped in 1984 after the completion of nine temporary offshore test wells.

Southwest of Parris Island and Port Royal Sound, along the northern shoreline of Hilton Head Island and extending to the Colleton River about fifteen miles to the northwest, are the Dolphin Head, Pinckney Island, and Colleton River chloride plumes. The saltwater source areas lie beneath Port Royal Sound, the Chechessee River, and the Colleton River, respectively. Here, test wells yielded geologic samples and geophysical logs and were monitored by conducting vertical specific-conductivity profiles. The data show that the highest chloride concentrations, near the bottom of the aquifer, occur in the northernmost monitoring wells nearest to saltwater bodies and suggest that modern brackish to salt water is migrating directly downward into the aquifer from nearby areas where the upper confining unit is absent.

To verify the presence of modern brackish to salt water and identify the source of high chloride concentrations comprising the Hilton Head Island, Pinckney Island, and Colleton River chloride plumes, water samples were collected at the bottom of the Upper Floridan aquifer. The samples were analyzed for environmental tracers, including chlorofluorocarbon, tritium, and dissolved-oxygen concentrations to determine the time salt water entered the aquifer. These data show that the northern-most samples, where chloride concentrations are 8,000 to 12,000 mg/L, contained the highest concentrations of chlorofluorocarbon, dissolved oxygen, and tritium: groundwater recharge dates calculated with the chlorofluorocarbon measurements were about 1970. Samples collected southwest and down gradient of the estimated saltwater source areas dated between 1970 and 1960. The sample farthest down gradient, at the toe of the Dolphin Head chloride plume, dated to about 1954 or about the same time potentiometric heads declined to about sea level near the estimated source areas. Dissolved oxygen was about 8 milligrams per liter in surface-water control samples and is typically near 0 milligrams per liter for relict Upper Floridan aquifer groundwater because dissolved-oxygen is depleted by the sulfate-reducing conditions. Dissolved oxygen in groundwater samples collected from offshore at the top and bottom of the aquifer beneath Port Royal Sound in 1984 were between 0.0 and 0.2 milligrams per liter indicating relict groundwater. Monitoring wells on the northwest shoreline of Port Royal Sound near source areas for the Dolphin Head, Pinckney Island and Colleton River chloride plumes had dissolved-oxygen measurements as high as 7.7 milligrams per liter for groundwater samples collected near the bottom of the aquifer, indicating modern saltwater intrusion from Port Royal Sound and nearby channels. Generally, the greatest concentrations of environmental tracers were found closest to saltwater source areas near the bottom of the aquifer, and concentrations decreased with increasing distance from the source areas.

An average plume migration rate was computed by establishing the estimated year of seawater entry at the source areas (about 1950) and the estimated distances between the source areas and the 2007 positions of the 250 milligrams per liter isochlors for the Dolphin Head, Pinckney Island, and Colleton River chloride plumes. The computations show that the three plumes traveled approximately 3 miles over a time span of 55 years or, an average of about 288 feet per year. The computations underestimate average migration rates because the saltwater-recharge dates are estimates for seawater entering the groundwater system and do not account for travel time through the surficial aquifer. Monitoring data indicated that the Parris Island, Port Royal Sound, Dolphin Head, Pinckney Island, and Colleton River chloride plumes continued to expand and merged by about 2007. Plume merging is driven by a regional southwest hydraulic gradient, chemical diffusion, lateral dispersion from plume axes, and increasingly density-driven head changes at the centers of the source areas and along the axes of their plumes. The five combined plumes recognized herein form the greater Port Royal Sound chloride plume and encompass approximately 80 square miles.

Farther to the southwest, the remaining six chloride plumes mainly lie beneath large expanses of saltwater estuary and the Atlantic Ocean where data principally were obtained from temporary and widely spaced test wells; plume properties are not well mapped by direct observation, and plume characteristics and behavior must be inferred from groundwater models. The Sawmill Creek chloride plume lies southwest of the Colleton River chloride plume near the confluence of the Colleton River and Sawmill Creek, and its presence is based on an Upper Floridan aquifer monitoring well having a computed chloride concentration of 5,000 mg/L at the aquifer bottom. Here, the chloride concentration was much higher than at the southwestern extent of the Colleton River Chloride plume and suggests another nearby source area. The Jenkins Island chloride plume, west of Hilton Head Island, has a source area near the eastern part of the island based on four monitoring wells completed in the Upper Floridan aquifer. The monitoring well closest to the estimated source area had a computed chloride concentration of about 2,500 milligrams per liter at 200 feet below ground surface, 60 feet above the bottom of the aquifer where chloride concentrations are expected to be much higher. A second monitoring well 0.7 miles south of Jenkins Island had a computed chloride concentration of 2,590 milligrams per liter at a depth of 230 feet below ground surface near the aquifer bottom, indicating that the plume 250-milligrams-per-liter isochlor has migrated even farther to the southwest.

The Broad Creek chloride plume near and southwest of Broad Creek on Hilton Head Island was investigated after a public supply well was taken out of service because of chloride contamination. As part of the mapping, monitoring well BFT-2410 was constructed on the bank of Broad Creek: the data showed that the upper confining unit was absent and that the top of the Upper Floridan aquifer was present at -54 feet mean sea level. Analyses of pore water from geologic core showed chloride concentrations generally decreasing with depth through the surficial aquifer and into the top of Upper Floridan aquifer, where the chloride concentration was about 5,000 milligrams per liter. Specific-conductance profiles conducted in the Upper Floridan aquifer at well BFT-2410 measured a chloride concentration of about 800 milligrams per liter throughout the depth of the open borehole in 2009 and exceeding 1,500 milligrams per liter by 2015. The plume is small partly because the Oligocene limestone (the upper unit of the Upper Floridan aquifer) acts as a semi-confining unit; here the Oligocene limestone has a relatively lower permeability and a thickness of about 70 feet. The chloride source area lies to the north beneath the Broad Creek estuary.

The Bull Island chloride plume is the southwestern most plume identified in the study area and is about 2.5 miles west of southern Hilton Head Island and about 14 miles northeast of Savannah, Georgia. The plume was investigated after several domestic and irrigation wells on the island were reported to produce high chloride concentrations from the top of the aquifer. Two temporary Upper Floridan aquifer test wells were constructed offshore in 2011; well BFT-2475 beneath Bryan Creek east of the island and well BFT-2476 beneath Bull Creek southwest of the island. Well BFT-2475 contained fresh water but chloride concentrations were above background level at 100 mg/L; however, well BFT-2476 contained high chloride concentrations that increased with depth through the thickness of the Upper Floridan aquifer, and a concentration of about 4,600 mg/L was found near the aquifer bottom. Well BFT-2245, one and a half miles southeast of well BFT-2476 at the most northeastern tip of Daufuskie Island, had greater chloride concentrations at the top of the aquifer based on a vertical specific-conductance profile. Here, the specific conductance ranged from 500 to 670 microsiemens per centimeter. The high chloride concentrations are thought to originate from a broad source area to the north where brackish water migrates downward through the upper confining unit and into the top of the aquifer. As an example, pore water near the bottom of the upper confining unit at the temporary offshore well BFT-2297, about one-mile northeast of Daufuskie Island in Calibogue Sound, had a chloride concentration of 360 milligrams per liter. The highest specific conductance at BFT-2245 was encountered at the middle of the aquifer and was about 1,000 microsiemens per centimeter, decreasing slightly to about 900 microsiemens per centimeter near the bottom of the aquifer. A discrete sample taken at the bottom in 2017 had a chloride concentration of about 240 milligrams per liter. Chloride contamination at the middle and bottom of the aquifer may have been caused by the southwestern movement and expansion of the Bull Island chloride plume. Well BFT-2411 is located at the northeastern tip of Long Island, two and a half miles southwest and down gradient of well BFT-2476. Specific-conductance profiles remained unchanged between 2012 and 2016 and, showed 200 microsiemens per centimeter throughout the open borehole to a depth of 337 feet near the bottom of the Upper Floridan aquifer. Because of the large expanse of saltwater marsh, data were not available to map the geographical extent of the plume: however, given the high concentration of chloride at well BFT-2476 and the historical hydraulic gradient, the plume is believed to be large.

The Hilton Head High chloride plume is tentatively identified from seismic surveys and test-well data and is centered about six miles east of Hilton Head Island. The plume was not specifically identified by offshore test wells but is hypothesized based on a structural high (Hilton Head High) associated with the Beaufort Arch. The Hilton Head High was discovered and mapped as part of an offshore seismic survey to map the surface and thickness of the overlying upper confining unit. Here, the top of the Upper Floridan aquifer was mapped at about -60 feet mean sea level at the crest of the high at three separate areas, and the thickness of the upper confining unit was estimated between 0 and 10 feet for areas associated with the high.

The 8-mile chloride plume lies beneath the Atlantic Ocean approximately seven miles southwest of the Hilton Head High near the 8-mile offshore test well (BFT-2295). Here, the thickness of the upper confining unit was only 1 foot and chloride concentration at the top of the aquifer was 8,400 milligrams per liter and decreased with depth to 560 mg/L at -171 ft mean sea level; however, the estimated depth to the bottom of the aquifer was -271 ft mean sea level. Chloride concentrations might be greater near the aquifer bottom if the upper confining unit is absent some distance upgradient of BFT-2295 and allows seawater to move downward and thence laterally along the bottom of the aquifer. The offshore data giving credence for the existence of the Hilton Head High and the 8-mile chloride plumes includes geologic core, pore-water chloride analyses, chloride concentrations computed from specific-conductance profiles, geophysical logs, and multiple tracks of seismic data.

The middle confining unit underlies the Upper Floridan aquifer, has a thickness of about 300 feet in the study area, and is known to contain chloride concentrations as great as 1,500 milligrams per liter at the northern shore of Hilton Head Island. The chloride concentrations are attributed to relict brackish water unflushed by freshwater discharge prior to groundwater development owing to the relatively low hydraulic conductivity of the unit. Water is slowly transmitted through the middle confining unit in response to downward or upward hydraulic gradients between the overlying Upper Floridan and underlying middle Floridan aquifers. The relict brackish water is present in the middle confining unit between southern Hilton Head Island and areas north of St. Helena Sound.

The middle Floridan aquifer (informally used in South Carolina) underlies the middle confining unit at a depth of 450 ft to 600 feet below ground surface between northern Hilton Head Island and Chatham County, Georgia, respectively. On Paris Island, a flow-meter test at BFT-1840 showed a permeable-zone thickness of about 7 feet and a well specific capacity of about 1 gallon-per-minute/foot. North of Paris Island, the aquifer pinches out. Where present, the aquifer has a maximum thickness of about 60 feet and can produce as much as 1,400 gallons per minute from a single well. Middle Floridan aquifer chloride concentrations range between 160 milligrams per liter on the southwestern part of Daufuskie Island, where it is used for golf-course irrigation; to about 1,500 milligrams per liter on the northeastern part of Hilton Head Island, where it is used for aquifer storage and recovery; a concentration of about 4,000 milligrams per liter is reported at two Parris Island irrigation wells. West of Hilton Head Island, the middle Floridan aquifer has low chloride concentrations and is principally used for golf-course irrigation.

Permitting policy required golf courses to use irrigation-supply sources other than the Upper Floridan aquifer after 1992, and the number of middle Floridan aquifer wells subsequently increased along a corridor extending 15 miles west of Hilton Head Island. Withdrawals from the aquifer for irrigation averaged about 3 million gallons per day by 2007. Total pumpage increased to about 6 million gallons per day in 2013, after three middle Floridan aquifer public supply wells (treated by reverse osmosis) at Jenkins Island were placed in operation to serve the northern part of Hilton Head Island, and again in 2015 when pumpage at the well field increased to 4 million gallons per day. Water pumped from the Jenkins Island well field is projected to meet future demand and to replace Upper Floridan aquifer water supplies lost to saltwater contamination. Several middle Floridan aquifer wells also are used on the island for aquifer storage and recovery of potable surface water and treated wastewater for irrigation. In northeast Georgia, the middle Floridan contains fresh water, and some wells withdraw from both the middle and Upper Floridan aquifer.

The South Carolina Department of Health and Environmental Control constructed a three-dimensional variable-density groundwater-flow and solute-transport model using Visual MODFLOW. The model was used to evaluate the potentiometric surface and saltwater intrusion in the Upper Floridan aquifer from 1885 through 2050 for the Savannah, Georgia and Hilton Head Island, South Carolina area. Model simulations corresponded closely to the published potentiometric-surface maps for the years 1885, 1957 and 1998 and the chloride-concentration distribution for 2007. Eleven chloride plumes were simulated using average water-use data inputted by year through 2007 and projecting 2007 average yearly pumpage through 2050. Except for the Parris Island and Port Royal Sound chloride plumes, the model only considered direct downward migration of modern salt water through the upper confining unit and through areas where the unit is absent. The 2050 model simulation indicated that the combined area of the eleven saltwater plumes might underlie an area of almost 300 square miles.

Unless groundwater withdrawals in the Upper Floridan and middle Floridan aquifers are reduced in the vicinity of Savannah, Georgia, and Hilton Head Island, South Carolina, seawater will continue to migrate into the Upper Floridan aquifer, and relict and modern salt water now in the Upper Floridan and middle Floridan aquifers aquifer will continue to migrate toward pumpage in southern Beaufort County, South Carolina, and Savannah, Georgia. The sustainability of potable groundwater in the Hilton Head Island, South Carolina - Savannah, Georgia area will depend on the reduction of Floridan aquifer groundwater use.

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Appendix A1.

History of Water Supply for Parris Island

1899 - 1949

T.L. Burnett, Mechanical Engineer

1952

Department of Public Works

U.S. Navy, Parris Island, South Carolina

INTRODUCTION TO THE HISTORY OF PARRIS ISLAND’S WATER SUPPLY

Parris Island's quest for a permanent supply of potable water dates from 1899 to the present day. This brief history was compiled from existing records of the Public Works Department (including old drawings, land records contract records, inspector's reports, well log data, and such reports as Mundorff's "Ground Water in the Beaufort Area" dated 10 May 1944; David A. Kendall's "Comprehensive Plan for the Development of an Adequate Water Supply for the Marine Corps Recruit Depot, Parris Island, S. C." dated 30 June 1948, and G. E. Siple's "Ground Water Investigations in South Carolina"), and from the files and help of Mr. S. F. Williams, Master Mechanic for Parris Island.

All of the wells that supply Parris Island with potable water, with the exception of Parris Island's deep well, obtain water from the limestone formation at the top of the Ocala Strata. This Ocala Strata or formation is the equivalent of Cooper marl and Santee limestone and outcrops chiefly in Allendale, Bamberg, Orangeburg, Dorchester and Berkeley counties.

The various well numbers referred to in the following history are the numbers that were assigned to these wells at the time of drilling. These numbers were used to avoid confusion and contradiction with the old records. A conversion table of the old numbers to the new (existing) well numbers is submitted as follows:

Old Well Number	New Well Number
Deep Well No. 1	1
Deep Well No. 2	2
Jericho Well No. 1	3
Jericho Well No. 2	4
Jericho Well No. 3	Jericho Well No. 4
Jericho Well No. 5	5
Burton Well No. 1	6
Burton Well No. 2	7
Burton Well No. 3	8
Burton Well No. 4	9
Beaufort Naval Air Station No. 1	11
Beaufort Naval Air Station No. 2	12
Beaufort Naval Air Station No. 3	13
6 New Wells on 12” & 16” Water Pipe Line Right-of—Way	(21 (22 (23 (24 (25 (26

Until the U. S. Government constructed a dry dock at Parris Island, the potable water supply was adequate for the local inhabitants whose demands were few. These people, mostly small farmers, used "pitcher pumps" and shallow hand-dug wells which collected only surface water and which did not disturb the water reserve in the Ocala Strata below.

During the year 1899, there were three 5-inch wells located in the vicinity of the Wet Slip. The lives of these wells were short, however, since in 1903 there was only one remaining in operation. This was an artesian well, located approximately 80 ft. west of Building No. 11. When this remaining well was ruined by salt intrusion is not known, but records indicate that it was connected to an elevated water storage tank which was constructed sometime between 1899 and 1903 and that the well and this tank were, for many years, connected to a salt water fire protection system.

In addition to the above wells, there were also in operation at that time several civilian-owned wells which were supplying potable water. During the year 1903, a project was proposed and submitted for the purchase of two fresh water wells located in what is now the Forestry Area. This new supply was stated to be potable and ample for the Station's needs. The wells were purchased in 1906, three years later.

During the next few years, various 6-inch wells were drilled in different locations on Parris Island to augment the Station's dwindling supply. Three water storage tanks, a reservoir and a water pumping station were also constructed in the area of the two new wells, giving the Station its first water plant.

World War I brought with it the need for a greatly increased potable water supply. Two wells were drilled and a 35,000 gallon elevated water tank constructed in the Rifle Range area and six wells were drilled approximately 500 ft. north of the present Golf Clubhouse to supply "Seagoing", a newly established area consisting of an encampment and docks from which small tugs and personnel barges transported men to awaiting transport ships in Port Royal Sound.

By this time, the supply of potable water beneath Parris Island was rapidly becoming exhausted. The salt count was steadily rising, making the water unfit for consumption, and it became necessary to leave Parris Island for a potable supply.

From 1916 to 1919 the fresh water for this Depot was purchased from the C&WC Railroad and from the town of Port Royal, S. C. The water was pumped through a 6-inch pipeline to the dock at Port Royal, thence into a water barge, which was towed to Parris Island and anchored in the river opposite the Power Plant. The water was then pumped into two underground cisterns of 130,000 gallons capacity each, located in the vicinity of the Power Plant. These cisterns had formerly been used to store rainwater collected from the building roofs for domestic purposes. From these cisterns the water was then pumped to a number of buildings in the Main Station Area and to some officers' quarters. The remainder of the Post had their water delivered in containers. Salt water was used for sanitary purposes, for bathing and for laundering. Sometimes it was even used for making coffee.

In the year 1919, eight 6-inch wells were drilled approximately 3/4 of a mile north of the existing intersection of the C&WC Railway and the State highway at Port Royal. These wells were drilled to a depth of 86 feet; the Ocala Strata was encountered at a depth of 60 to 65 feet. A pumping station, a 6-inch universal joint pipeline and accessories were constructed to carry the new water supply to Parris Island. The salt count in these new wells ranged from 16 ppm to 226 ppm in their period of use. The water, however, was very hard and records indicated the presence of a large amount of Hydrogen Sulfide. Hydrogen Sulfide is a substance, which has a very disagreeable odor and taste and is usually found in artesian wells in this district. These wells were abandoned in the year 1930.

The first well in the Jericho Point area was drilled during June 1927. Although its size is not known, the casing was seated in the Ocala Strata at 62 feet and the well extended to 68 ft. On 7 July 1927 a test was made of this well by pumping it at 147 gpm for five hours. The salt count was then 18 ppm. The well was capped until 14 March 1929 when it was re-opened and for some unknown reason was drilled to a new depth of 131 ft. The static level of the water was 106 ft. and the salt count had risen to 59.6 ppm. This well was abandoned because it had no flow and because the salt count had risen. It was located in Lot 22 on the property of H. H. Lake.

Jericho Well #4, drilled by Station Forces, was completed 1 May 1929. An 8-inch casing extended 100 feet beneath the surface of the ground while the well proper extended to 125 feet. The salt count, upon its completion, was 34 ppm. The well was then capped for approximately ten years, when reopened. It was abandoned in February 1943 because of salt intrusion.

Jericho Well #1, drilled by the Layne-Atlantic Company and completed 12 December 1929, was a typical Layne-Atlantic gravel well with an 18-inch casing which extended 139 feet beneath the ground surface. This casing was equipped with screens set at the most desirable elevation as predetermined while sinking the 36-inch outer casing. The space between the inner and outer casing was filled with gravel and the outer casing then removed. This gravel protects the screens and acts as a filter. The gravel-type well is especially successful in sandy soil areas. Until Jericho Well #2 was complete on 18 March 1930, this well was Parris Island's only source of potable water.

During the period in which the drilling of Jericho Wells Nos. 1 and 2 was contracted; Station Forces installed a 10-inch east iron water line from Jericho Point to Parris Island, thus making it possible to open up the Jericho Well Field.

Jericho Well #2, drilled by the Layne-Atlantic Company, was completed 18 March 1930. It was an 18-inch casing and was drilled to a depth of 190 feet. Salt count averaged 23 ppm during test pumpage.

Jericho Well #3, drilled by Station Forces and WPA labor, has a 12” casing and is 87 feet deep. There are no records to indicate when this well was drilled, but it was abandoned in September 1942 because of salt intrusion. "Ground Water Investigations in South Carolina" by G. B.

Siple, states that its yield was 500 gpm.

Jericho Well #5, drilled by Station Forces and WPA labor, has a 10-inch casing and is 90 feet deep.

Jericho Well Field supplied Parris Island with potable water until completion of the 16-inch water line from the newly developed Burton Well Field in December 1942. Since that time, the Jericho Well Field has been used in a stand-by capacity only.

Burton Well #1, drilled by Station Forces with the help of WPA labor in the year 1941, has a 12-inch casing and is 64 feet deep. At the time of drilling its yield was 1400 gpm, with a salt count of 14 ppm. As a point of interest, when this well started pumping, it dried up all of the local wells for a radius of approximately 3,000 feet.

Burton Well #2, was drilled in 1944 by Station Forces and with the help of WPA labor. Pumping tests indicated a yield of 350 gpm, with a 40 foot drawdown. It has a 12" casing and is 84 feet deep.

Parris Island Deep Well #1, drilled by Layne-Atlantic Co. and completed on 5 March 1940, was a flowing well 2811 feet in depth, with a yield of 120 gpm. The temperature of the water was 90°F, and the static head at the top of the casing was 46 psi. Pumping increased the flow to only 160 gpm, with a drawdown of 155 feet. The screens for this well were set from 2500 to 2700 feet and the water is allowed to flow directly into the reservoir.

Parris Island Deep Well #2, drilled by the Layne-Atlantic Company and completed in April 1941, was 3430 feet in depth. As the salt content of this well increased with depth, below 2500 feet it was plugged at the 2500 feet level. The yield from this well is 80 gpm; however, because of the high Fluorine and Alkaline content of the water, this well is used to supply the Rifle Range indoor swimming pool and is not a part of the potable water supply for Parris Island.

The Beaufort Naval Air Station Well Field was obtained by the Marine Corps from War Assets Administration in 1947. A 12-inch east iron water line between Beaufort Naval Air Station and the Burton Well Field was completed 13 December 1948, thus tying the Beaufort Naval Air Station Wells into the 16inch wrapped steel pipe line leading to Parris Island.

BNAS Well #1 was drilled in 1942 by Station Forces. It is 80 ft. deep and has a 12-inch casing. Its salt count at the time of drilling was 12 ppm.

BNAS Well #2 was drilled in 1942 by Station Forces. Its original depth was 62 feet, with a 12-inch casing and a salt count of 12 ppm. This well sanded down in 1949, however, and was re-drilled by Station Forces. An 8-inch casing was installed to a depth of 92 ft., while the well proper was extended to 117 ft. The new yield was 250 gpm, with a salt count of 22 ppm.

BNAS Well #3 was drilled in 1942 by Station Forces. It is 98 ft. deep and has an 8-inch casing. The high iron content of its water has made this well useless for anything but a standby supply since it was drilled. At the time of drilling its yield was 300 gpm, with a salt count of 12 ppm.

Burton Well #3 was drilled in 1949 by Station Forces. It is 93 ft. deep and has a 10-inch casing. At the time of drilling, the yield was 560 gpm, with a salt count of 19 ppm.

Burton Well #4 was drilled in 1949 by Station Forces. It is 96 ft. deep and has a 10-inch casing. At the time of drilling, its yield was 800 gpm, with a salt count of 20 ppm.

There are six wells located along the 16-inch and 12-inch water line right-of-way. The drilling of these wells was begun on 17 May 1951 and the last one completed 13 September 1951. Although drilled by the Layne-Atlantic Company, they are straight casing wells and not the gravel type usually drilled by this company.

Well #21 was drilled to a depth of 103 ft. and has a 10-inch casing. On test this well produced 390 gpm, with a salt count of 16 ppm.

Well # 22 was drilled to a depth of 100 ft. and has a 10-inch casing. During testing, this well produced 390 gpm, with a salt count of 20 ppm.

Well #23 was drilled to a depth of 101 ft. and has a 10-inch casing. On test this well produced 300 gpm with a salt count of 26 ppm.

Well #25 was drilled to a depth of 108 ft. and has a 10-inch casing. On test it produced 340 gpm, with a salt count of 32 ppm.

Well #26 was drilled to a depth of 100 ft. and has a 10-inch casing. On test it produced 330 gpm, with a salt count of 20 ppm.

From time to time, numerous other wells were drilled in various localities by Station Forces in an effort to locate a supply of potable water, preferably on Parris Island. Warrant Officer Feltwell drilled a test well on Horse Island during the year 1924. He reached a depth of 635 ft., but found no potable water. In 1941 he drilled a test well, approximately one mile south of the Burton Well site, but found only water with a very high salt content, unfit for consumption.

On 30 June 1938, Mr. W. S. Beiser, Layne-Atlantic Company's representative in Savannah, Ga. stated in a letter to Major J. W. Flett, Post Quartermaster, " .... the possibilities for good water on Parris Island have far from been exhausted". He suggested that a well be driven to a 2000 ft. depth. The two deep wells drilled by that company on Parris Island were undoubtedly a result of this letter, but did not prove Mr. Beiser's theory. In his letter, however, Mr. Beiser also made it clear that such a suggestion was merely theory, as no scientific investigation has ever been made of the water supply in this area. This experiment cost the Government $144,478.16 and it is not recommended that such an experiment again be undertaken.

At the request of the Bureau of Yards and Docks, Mr. M. J. Mundorff, Assistant Geologist of the Department of the Interior, submitted a report entitled "Ground Water in the Beaufort Area, South Carolina." This report was very thorough and discussed every phase of the ground water situation. His conclusions were: "It appears that the limestone in the upper part of the Ocala formation is permeable enough to transmit large quantities of water. If the head available were 40-50 feet, probably many millions of gallons of water a day could be safely withdrawn. However, the salt water in Beaufort River, Battery Creek and other channels has access to the Ocala limestone at many places, so the peizometric surface can be lowered generally only a few feet without danger of salt water contamination."

There is no way to prevent salt water intrusion into the Ocala strata from the surrounding rivers and creeks; therefore, it is impossible to get the 40 to 50 ft. head Mr. Mundorff states would be necessary to obtain an ample supply of water.

On 30 June 1948, Mr. David A. Kendall of the Bureau of Yards and Docks submitted a report, "Comprehensive Plan for the Development of an Adequate Water Supply for the Marine Corps Recruit Depot, Parris Island, S. C." This report described the existing water supply, outlined the water supply sources, estimated the Station's requirements and formulated and made recommendations for a comprehensive plan for the development of an adequate water supply. Although short, this report was thorough.

It is recommended that an investigation be made and that a chart similar to the one prepared by Mr. Mundorff in his report dated 11 May 1944, giving the location, flow and chloride content of most of the major wells in the Beaufort County be prepared for comparison. This comparison should prove most valuable in making future decisions regarding Parris Island's water supply.

T.L. Burnett, Mech. Engineer

Appendix A2.

City of Savannah Mayor's Annual Report

Excerpts from

Report of the Superintendent of Water Works

and

other related reports

1887-1894

Water Department

The receipts from this department have been $49,174.33, and the expenditures $49,803.40; $48,033.47 is chargeable to the water works proper.

The supply of water has been changed from the river to artesian water. This work was commenced in 1886, and considerable progress was made during the year 1887. The work has been so far completed by the sinking of additional wells and deepening the others, that an ample supply of artesian water is now furnished. The amount of money expended for this has been $16,586.83 in addition to $3,232.68 expended in 1886.

In addition to this $8,141.94 has been expended for enlarging the pumps, making the sum of $24,738.77 extraordinary expenditures. The consumption of water had increased so much that it became necessary to increase the pumping capacity. This has been done at an expense of $8,141.94. The capacity of the pumps is now estimated by the Superintendent to be 12,500,000 gallons a day.

In changing from the river to the artesian wells the connections with the river have not been disturbed, and the river water may be used in case of necessity.

The water works has been a source of net revenue to the city, and its receipts this year have been in excess of former years, but the expense of procuring artesian water and the alteration of the pumps, have caused extraordinary expenditures, yet all the expenses, including these extraordinary items, have not exceeded the earnings.

Respectfully submitted,

RUFUS E. LESTER,
Mayor.

City of Savannah Mayor's Annual Report.
December 31, 1887.

Excerpts from the

REPORT OF THE SUPERINTENDENT OF WATER WORKS.

A. N. Miller, Superintendent

Hon. Rufus E. Lester,
Mayor:

SIR—I have the honor to respectfully present my annual report of the Water Works Department. The year has been quite an eventful one, the supply of water having been changed from the river to that of artesian well water, and now deriving a full supply from wells bored at and in the vicinity of the works, affording an ample supply of pure and wholesome water. Beyond contamination, with the only fear that the wells in disgust of the wilful waste of the water, may contract in their delivery. And also increasing the pumping capacity from eight (8) million to twelve and a half (12|) million gallons per day, with this advantage that either pump, singly, can supply the wants of the community.

ENGINES AND MACHINERY.

The engines are now in good order, having been thoroughly overhauled, and I anticipate but a small outlay for repairs during the next year. There has been pumped during the year two billion, eighty-six million, three hundred and sixty-one thousand and fifty-three (2,086,361,053) gallons of water, exceeding in amount the year previous by two hundred and four million, thirty-three thousand and two hundred and fifty-three (204,033,253) gallons, to accomplish which additional pumping force was needed.

ARTESIAN WELLS.

There has been bored and completed fifteen (15) artesian wells, of the following dimensions:

2.................................... 10 inch.
12.... .... 6 inch.
1. .... 4 inch.
15

All of the wells are connected (with the exception of the last six inch well bored) and delivering directly into the mains leading to the pumps without the intervention of basins or reservoir. The pumps drawing from the wells to that extent as to create from two (2) to four (4) pounds vacuum in the mains. The water of the wells is impregnated with sulphurious gas, which on exposure to the atmosphere escapes, leaving a very feint odor and taste of sulphur. The water being confined, is conveyed to the consumer in its natural state, encountering the atmosphere and light only when drawn from the hydrants for use. Many evidences have presented themselves of the curative properties and healthfulness of the water, and which is attested by the analysis made by the Geological Survey at Washington, and Dr. C. F. Chandler, of New York, accompanying this report.

CITY WELL PUMPS.

The pumps and wells have been kept in good order. The removal of old wooden pumps and substituting iron pumps has been continued with satisfaction. Seventeen (17) iron pumps have been put in this year replacing wooden pumps. There are ten (10) new pumps on hand, purchased during the year and reported in expenses under account of bills paid for this branch of the department. These pumps, it is more than likely, will be all that will be needed next year.

LEAKS.

There has been no leaks in the main water pipes. But quite a large number have occurred in the supply pipes to houses,' caused by defective plumbing work, and brought to light by the use of the artesian water. Being very small the defect was hid by the mud accumulating in the opening while using river water.

WASTE.

The waste of water continues at a fearful rate, entailing a heavy expense. The many appeals for its correction to consumers have met with little consideration. The Committee, as well as myself, indulged the hope that in the change from river to artesian water—being so much the more acceptable—they would appreciate sufficient to induce less waste. Our hopes, however, where not realized. It would be greatly to the advantage of the consumer as well as to the works if meters were introduced on all applications in the future. Meters have been very much improved in their construction and correctness of measurement with little liability of derangement of late, as also in price, being now generally adopted in other cities.

Respectfully submitted.

A. N. MILLER,
Superintendent.

REPORT OF SUPERINTENDENT WATER WORKS
City of Savannah Mayors Report
1890

Hon. John Schwarz,
Mayor:

SIR—I respectfully submit the following report of the Water Works Department, for the year ending December 31st, 1890: The number of gallons of water pumped during the year, as shown by the record, has been two billion, four hundred and twenty-six million, six hundred and forty-six thousand, five hundred and sixty (2,426,646,- 560) gallons, being nine million, thirty-seven thousand, three hundred and forty-nine (9,037,349) gallons less than for the year 1889- From these figures it would appear that the consumption of water for the past year has not been as great as heretofore. Such, however, is not the truth, and is accounted for by the fact that during the month of February the small engine was in operation while the large one was being repaired and did not pump by upward of thirty million (30,000,000) gallons as much as the general monthly average.

ARTESIAN WELLS.

In consequence of the increasing demand for water in the city. The twenty-three artesian wells in operation had for sometime failed to yield an adequate supply and the deficiency was made up of river water which gave general dissatisfaction.

To obviate this it was decided to sink some of the wells at the present works to a depth of one thousand feet, hoping by so doing to increase the flow. Consequently the boring on the deep twelve inch well on Springfield plantation was stopped on February 3d, at a depth of fifteen hundred and fifty (1,550) feet, and the machinery moved from there to the works, where boring was commenced on a ten (10) inch well on February 12th and continued until a depth of one thousand and nine (1,009) feet was reached on April 9th, but the increase in the quantity of water gained was so trifling compared to the expense of sinking them that this plan was abandoned.

Several suggestions were offered and plans proposed to improve the water supply, both in quantity and quality. Among others, a plan advanced by Civil Engineer T. T. Johnston, of Chicago, Ill., who was invited to come here and assist in settling the matter, he having had large experience in water works building and artesian wells supply.

Mr. Johnston came here and looked over the situation and his proposition was to erect an entire new plant on the Springfield Plantation and build a brick conduit from the present works to the new plant, cut off the wells in use, to increase the flow, bore more wells at intervals along the line of conduit and convey all the water from all the wells through such conduit to a cistern, to be located near the new pump house, from whence the pumps would draw and force it to a stand pipe, higher up in the city.

Mr. Johnston, as Chief Engineer, had just completed at Memphis, Tenn., a system of water works upon this plan, and said to be one of the best in the country. But after careful surveys, and estimates being made by Col. W. J. Winn, City Engineer, this plan was considered somewhat too extensive and expensive for the present. Finally, at a special meeting of City Council on the llth of June, it was decided to proceed at once to bore two or more 10-inch wells for immediate relief at the present works, and as soon as those were finished and sufficient water obtained to warrant the river being shut off, a number of wells should be bored on Springfield Plantation, to furnish water for a fifteen million gallon engine, and it, with the necessary attachments and connections, be contracted for, and erected with all possible despatch. Accordingly, on or about June 24th, a contract was signed with Mr. James Mulligan, a well-borer, of this city, to bore two or more 10-inch wells at the present works, each of which he agreed to complete in about forty days. But on account of improper tools he was unable to finish the contract, and abandoned it. It was then required of his sureties to complete it. They gave the contract to Mr. E. F. Joyce, of St. Augustine, Fla., who commenced work on well number 25, as soon as he could move his machinery upon the ground, and completed that well at a depth of five hundred and two (502) feet. This well was connected to the system on December 29tb, and increased the supply of artesian water to such an extent that it was unnecessary to continue the use of the river water any longer, and the river connection was accordingly shut off the same day.

Mr. Joyce is now at work on well number 24, which it is expected will be finished in a very short time, when it is hoped the supply of pure artesian water will equal the capacity of the pumps. In making the necessary alterations to allow the increased quantity of water, furnished by 'the two new wells, to reach the pumps, the suction main had to be enlarged and extended. This involved the laying of three hundred and twenty (320) feet of twenty-four (24) inch pipe, and eight hundred and eighty (880) feet of sixteen (16) inch pipe, a total length of twelve hundred (1200) feet of suction main, together with all necessary valves and connections. The artesian wells in operation at this time are:

3 ten (10) inch wells.
20 six (6) inch wells.
1 four (4) inch well.
Total, - 24

And one ten (10) inch well in process of boring, which, when completed and connected, will make a total of twenty-five (25) wells.

The experiment of " shooting " or " torpedoing " the wells for the purpose of increasing the flow was tried. An agreement with Mr. Elisha Gregory, of New York, to do the work being made. He came on in July, and torpedoed three (3) wells. It is done by sinking a tin case or shell charged with explosives to the bottom of the well, which is ignited and fired by means of a fuse. The result of the experiment was not sufficiently successful to warrant the farther prosecution of the work.

Recommendations.

In conclusion, I would say that while the present machinery is in good order and is working well, it is being forced beyond its legitimate capacity, and cannot reasonably be expected to keep in repair, or to last as long as if it were not so overloaded. And I very respectfully suggest, that it would be prudent and wise to avoid any delay in setting on foot active preliminaries for the erection of the new works. That an expert hydraulic engineer be selected, and that his services be secured to give early attention to the matter, as consulting engineer; and he be requested to come to the city to get the work properly formulated and arranged. Bearing in mind from the beginning that the lowest priced article, be it men or material, is not by any means the cheapest.

Very respectfully submitted,
JAMES MANNING,
Superintendent.

REPORT OF SUPERINTENDENT OF WATER WORKS.
City of Savannah Mayor's Report
1891

Hon. John J. McDonouyh,
Mayor.

Sir:— In accordance with the regulation of the ordinances, I respectfully submit the annual report of the condition and workings of the Water Works Department of the City, for the year ending December 31, 1891. The gallons of water pumped during the year, as shown by the record, has been two billion, three hundred and ninety-four million, six hundred and forty-five thousand, six hundred and eighty (2,394,645,680) gallons.

ARTESIAN WELLS AT WORKS.

Well No. 24. ten-inch bore, was completed at a depth five hundred and five (505) feet, and connected to the system on January 27, this well making a total of twenty five artesian wells. Sizes as follows :

4 ten (10) inch wells.
20 six (6) inch well?
1 four (4) inch well.
Total, - - 25

With the addition of the No. 24 well the quantity of water secured was very materially increased, and it was thought that no more would be required for at least some time. But as the year advanced and the warm season set in, the demand for water increased to such an extent, that although the engines were working up to their full speed, they failed to furnish a satisfactory pressure in the city, and many complaints were heard from those who could not obtain a supply of water in the upper stories of the high buildings. From observations and approximate measurements, it was evident that the engines were drawing more water from the wells near the engine house than from those at a distance, and to ascertain with certainty an exact and actual survey and measurement was made with instruments on June 13th, and found a variation in elevation of water in the different wells on the main suction line of nine (9) feet, that is to say, number one (1) well, which is close by the engine house, was pumped nine (9) feet below the level of cumber twenty-five (25) well, which is sixteen hundred (1,600) feet farther away. This shows that with the arrangement of the present system additional wells would be of little service, because it would be necessary to locate them at a still greater distance, and the pumps would not draw the water from them. The lack of water from the wells caused the engines to labor greatly and pound badly. And was the principal cause of the stop of the large engine in August for repairs. This great labor and pounding of the engines continued until the fifth (5th) of November, when, fearing greater injury to the machinery, and as a last resort, the river water was turned on to the pumps, which gave some relief. And it is the only means, in my opinion, by which a satisfactory supply of water can be obtained, until the new works now being constructed, or a part at least, can be put in operation. The large engine, upon which the supply depends, will not work with any reasonable degree of safety without the aid of the river water.

Very Respectfully submitted,
JAMES MANNING,
Superintendent.

REPORT ON NEW WATER WORKS.
City of Savannah Mayor's Report
SAVANNAH, GA., December 31st, 1891.

Hon. John ,T. McDonough,
Mayor:

SIR—In accordance with instructions received from your Honor, I herewith present a report on New Water Works, to accompany the report of the workings of the department on the present water supply. The erection of new works having been undertaken during the year, the preparation consumed much of the time, but some progress has been made which will be shown in this report. The number and character of contracts awarded for furnishing material and construction and the advancement of them. Also including the expenditures on New Water Works account to date. The pressing necessity of immediate action upon the matter of providing additional or new waterworks, having been presented to Council in former reports, and there having been plans suggested, and some preliminary survey sand estimates made, it was decided to build an entirely new plant and to commence work upon it at as early a date as possible; accordingly, on February 26th proposals were advertised for boring a number of artesian wells to be twelve (12) inches in diameter, and to be situated on the Springfield plantation north of Gwinnett street and immediately west of West Boundary street.

Before the beginning of any work upon the erection of new works, the services of Mr. Thomas T. Johnston 'of Chicago, Illinois, was secured, and an engagement entered into with him as consulting engineer, he having had large experience, and having been in charge of the building of a waterworks plant of the same, or like character, only a short time previous at Memphis, Tenn., with eminent success. Proceedings were at once entered upon, maps and surveys made, test pits dug in the ground and a most thorough examination and investigation into the subject in order to collect information and obtain all the advantages, and the most suitable location.

After carefully viewing the surroundings of the portion of the Springfield plantation on which one (12) inch Artesian well had been bored and completed at a depth of fifteen hundred and fifty(1,550) feet, objections were presented, and it was deemed inadvisable to build the new works and to bore other artesian wells at that point. That location was abandoned and a new site was selected on the west side of the Springfield plantation, at the intersection of Gwinuett street and Stiles avenue. Negotiations were opened with the owners of the land, and the lots numbers fifty-seven (57), fifty-eight(58), and fifty-nine (59), lying north of Gwinnett street and east of Stiles avenue on the Springfield plantation, and containing thirty-one(31) acres, was secured by purchase from the Savannah Brick Manufacturing Company, for the sum of Seventeen Thousand and Fifty Dollars ($17,050). Eight and one-third (8*) acres of the tract purchased to be reserved as a site for Water Works, and the remainder to be placed in the hands of a committee of City Council to be disposed of to the best advantage.

The site selected is favorably and conveniently situated for the purpose and the character of the work contemplated. It being near the city and far enough removed from any contaminating influences.

After examination of the plans and consultation with the engineer upon them, they were approved by the Committee, and authority was given by Council to proceed to advertise for bids for furnishing and constructing new Water Works.

On May 21st, proposals were called for furnishing and constructing machinery and boilers as follows: Two high duty pumping engines, each having a capacity often million (10,000,000) U.S. gallons per day, and the necessary boilers.

On July 14th, for the construction of a water conduit of masonry, or masonry and timber, having an internal diameter of (approximate) six (6) feet, and a length of three thousand (3,000) feet, more or less, only this length of the conduit to be built at this time.

On July 30th, for furnishing cast-iron water pipes and special castings.

On October 21st, for furnishing valves or water gates, and for furnishing sixty thousand (60,000) pounds of lead, for drayage of pipes, for laying pipes in the ground, also for constructing subwork of pumping station, and for building railroad trestle for a track to extend from the track of the Central Railroad Company to the site of the new works.

Contracts for furnishing and constructing the works have been awarded as follows:

For boring a number of twelve (12) artesian wells, to E. F. Joyce, of St. Augustine, Florida, at four dollars and fifty cents, to a depth of four hundred and thirty feet (430 feet) at $4 50 per foot, and any greater depth at five dollars per foot '($5per foot) over 430 feet.

For constructing and furnishing two (2) high duty pumpage engines, to the Holly Manufacturing Company, of Lockport, New York, for the sum of ninety-two thousand four hundred dollars ($92,-400).

For constructing and furnishing the necessary boilers, to John Rourke & Son, of Savannah, Ga., for the sum of thirteen thousand eight hundred and seventy-five dollars (813,875).

On August 26th, bids were received and opened for the construction of a water conduit, and the contract was awarded to Robertson & Weaver, of Baltimore, Maryland, for the sum of twenty-seven thousand five hundred dollars ($27,500).

The work of boring the artesian wells has progressed as rapidly as possible. Two gangs of men with derricks and full set of boring apparatus have been at work all the time. Eight wells have been completed, each having a diameter of twelve (12) inches, and bored to the depth of from five hundred (500) to six hundred (600) feet. They are located along the line of Stiles avenue, on which line the Conduit will be built. Each well has been cased down to a depth of about two hundred and twenty-five (225) feet. The flow of water from all the completed wells has proven exceedingly satisfactory, each well discharging about a half million (500,000) gallons per day, and it may reasonably be expected that a sufficient quantity will be obtained for a full and ample supply when all the wells are completed.

Very respectfully submitted.
JAMES MANNING,
Superintendent.

REPORT OF THE SUPERINTENDENT OF WATER WORKS.
City of Savannah Mayor's Report
SAVANNAH, GA., December 31st, 1892.

Honorable John J. McDonough, Mayor:

SIR—I have the honor herewith to present report, showing the operation of the Water Works Department, during the year ending December 31st, 1892. The record, as shown below, presents a total of two billion, three hundred and forty-seven million, one hundred and nineteen thousand, three hundred and forty gallons of water pumped during the year:

RECORD.

MONTHS.	
January...............	198,648,000
February.......	185,063,040
March.."...................................	201,980,160
April..............................	198,263,520
May...	212,361,120
June...................	204,415,200
July...	201,566,880
August......................................	206,337,600
September...............................	188,779,680
October............................	196,469,280
November......	195,572,160
December................................	157,662,700
	2,347,119,340

On the morning of the ninth (9th) day of December, at twenty-five minutes past nine o'clock, water was pumped into the city from the new water works. One Gaskill engine having been put in operation, and since that date there has been pumped from that station ninety-eight million, three hundred and eighty-three thousand, nine hundred and twelve (98,383,912) gallons of water, which, added to the record for December, gives a grand total of two hundred and fifty-six million, forty-six thousand, six hundred and twelve (256,046,612) gallons of water pumped into the city during the month of December.

ARTESIAN WELLS.

As stated in last year's report, the artesian wells did not furnish a sufficient quantity of water to keep up the supply demanded and the addition of river water has been necessary. The mixing of artesian and river water has been pronounced as unhealthy, or at least injurious to health. But no proof has been advanced to sustain the imputation. The analysis of the mixed water has been declared fit and wholesome by the Geological Survey Department at Washington, D. C., after a proper test of samples sent to them. There has been no river water pumped since December 19th.

LEAKS.

There has been very few leaks in the main pipes, and none of very serious consequence. The four-inch main in alley running from Zubly to Harrison street broke in half, but was repaired without damage. Soon after the new Gaskill engine was started a break was discovered in the sixteen-inch main on Abercorn street near New Houston street. It was found to be a crack and it is supposed was defective when laid, but was not observed. Another break was found in the ten-inch main on Anderson street and West Broad street of the same nature. All were repaired promptly.

Very respectfully submitted by
Your obedient servant,
JAMES MANNING,
Superintendent.

WATER WORKS.
City of Savannah Annual Mayor's Report
1893

The new water works have been finished, and a splendid supply of water is now furnished. In a former report the Mayor has already called attention to the able work of the Water Committee having in charge the improvements, and, as a matter of information, adds the following report of Alderman Cann, Chairman, which will be presented to Council:

SAVANNAH, GA., January 2, 1894.

Hon. J. J. McDonough, Mayor of Savannah, Ga.:

SIR: I beg to submit herewith a final report upon the new water works. The total cost of the works complete is §410,660.21; this is exclusive of interest on deferred payments and cost of widening Styles avenue, neither of which do I consider a proper charge against the construction of the works, the first named item being in lieu of a bond issue, and the latter for permanent widening of a street. The original estimate was 8364,500. The scope of ' the work was subsequently enlarged, causing an increase in the cost of the wells, buildings and forcing main. The other items have been completed within the original estimates. There remains unpaid a balance of $2,896.19 on the roof, the contractors not yet having completed it according to the contract. The balance of the amouut due ($58,665.10) is represented by notes given the Holly Manufacturing Company and John Rourke & Son, for deferred payments on engines and boilers.

The main features of the works were completed some time since. In fact, the city has been supplied from these works exclusively since April last. There remained, however, several details in connection with the building and machinery, which have prevented a complete report until the present time. It gives me great pleasure to be able to report that in every respect the desires and hopes of your committee have been fulfilled by the system of water supply I now officially turn over to you as completed. We went into office with an insufficient supply of artesian water, pumping machinery both incompetent to perform the work required and expensive as to operation, an undesirable location of woi-ks necessitating a force main of great length, causing serious loss of pressure from frictional resistance, and of insufficient size to properly meet the demand of our city. We now beg to present you one of the best and most complete water works of its size in this country. An abundant supply of artesian water, duplicate pumping machinery of the most improved and economical pattern, a forcing main of ample size, not only for our immediate, but future wants, entering our city near its center, furnishing a uniform and desirable distribution, and commodious buildings, well arranged and of sufficient size to permit the addition of double the present pumping capacity. It is a source also of congratulation that the work has been completed without the issuing of a single bond, and without preventing or interfering with any other improvement desired by the city. I am indebted for the technical portion of the attached report to Mr. Thomas T. Johnson, of Chicago, HI., who has been our consulting engineer during the entire progress of the work, and in this connection I think it proper to congratulate him upon the results obtained through his plans.

In conclusion, I thank Your Honor for many favors and valuable assistance received during the progress of this work, and also tender my colleagues on the present, as well as preceding, committee my sincere appreciation of their aid and many courtesies. Your committee is also indebted to the Superintendent of the Water Works, Capt. James Manning, for his cheerful assistance and faithful services rendered them.

Respectfully submitted,
W. G. CANN,
Chairman Committee on Water.

REPORT OF SUPERINTENDENT WATER WORKS.
City of Savannah Mayor's Report
1893

Hon. John J. McDonough, Mayor :

SAVANNAH, GA., January 1st, 1894.

SIR—In accordance with custom and requirement, I herewith submit the annual report of the Water Works Department for the year ending December 31st, 1893.

The new works having been completed with increased pumping capacity of high order, I am pleased to say that the service has been very satisfactory and that the outlook for the future is exceedingly encouraging.

One of the new Gaskill pumping engines was put in operation on the 9th of December, 1892, as mentioned briefly in the report of that year, and during the twelve months ending on December 8th, 1893, the new pumps have been in operation three hundred and sixty-two (362) days, during which time there has been pumped two billion, two hundred and fifty-seven million, nine hundred and forty-one thousand, five hundred and ninety-five (2,257,941,595) gallons of water, an average per day of six million, two hundred and thirty-seven thousand, four hundred and eight (6,237,408) gallons.

The new Gaskill pumpage engines are numbered as No. 410 and No. 411 by the builders, the Holly Manufacturing Company of Lockport, N. Y. During the year Engine No. 410 has run one hundred and twenty-three (123) days and Engine No. 411 has run two hundred and thirty-nine (239) days. Both engines have performed their work exceedingly well.

The engines and boilers were run upon a duty test on the 27th and 28th days of March and came fully up to the requirements of the contract.

The total quantity of coal consumed has been two thousand and twenty-seven (2,027) tons, an average of five six-hundredths (5 6/100) tons per day, for which was pumped one million, one hundred and thirteen thousand, nine hundred and thirty-three (1,113,933) gallons of water per ton of coal.

The total cost of fuel has been six thousand, five hundred ($6,500) dollars, which, compared with the cost of fuel at the old works, is very favorable, the annual cost for fuel at the old works having been about ten thousand ($10,000) dollars.

The whole number of the artesian wells not having been completed or connected when the new pump was placed in operation, and when completed the bulkheads inside conduit having to be removed in order to obtain the use of the wells, it became necessary to shut down the pumps and return to the old works for furnishing the supply of water during the progress of the work. As soon as this was completed the new pumps were again placed in service and have been at work continuously since March 26th.

For a statement of the service performed and water pumped during the year refer to the following :

RECORD.

New Works.

1803.	Gallons.
January	184,773,374
February	177,993,476
March	175,451,607
April	213,607,137
May	216,525,650
June	188,927,847
July	187,918,782
August	180,370,687
September	191,753,662
October	201,747,621
November	189,415,323
December	192,741,027
Total New Works	2,301,226,193

Old Works.

January	109,555,200
February	8,637,300
March	28,820,170
Grand Total	2,448,238,863

Two billion, four hundred and forty-eight million, two hundred and thirty-eight thousand, eight hundred and sixty-three gallons.

LEAKS.

There has been only two leaks in the main pipes, one in the 6-inch main on Henry street, near Montgomery street, and one on south Broad street, corner of Whitaker street, both of which were repaired promptly and without inconvenience to the consumers. The old mains have withstood the increase in pressure much better than was expected.

Very respectfully yours,

JAMES MANNING,

Superintendent

REPORT OF SUPERINTENDENT OF WATER WORKS.

OFFICE SUPERINTENDENT OF WATER WORKS,
SAVANNAH, GA., Jan. 1, 1894.

Hon. John J. McDonough, Mayor:

SIR—I have the honor to submit the following report of the Water Works Department for the year ending Dec. 31, 1894:

The record of the pumpage, HS shown below, presents an apparent decrease from the quantity pumped the previous year, which is accounted for by the use in 1893 of the engines at the old works, which, in conjunction with the new, pumped during the month of January, 1893, 294,328,574 gallons, or about 90,000,000 gallons above the average for a month. This unusual demand for water was principally caused by severe cold weather,
a snowstorm having visited our locality on Jan. 18,1893, the cold continued for some days, when the quantity of water furnished reached the unprecedented amount of 10,700,000 gallons per day.

For a detailed account of the pumping, the quantity furnished monthly during the year, I refer to the following table:

RECORD OF WATER PUMPED.

1894	Gallons
January	188,320,474
February	173,840,548
March	204,115,444
April	201,901,639
May	211,137,602
June	208,944,239
July	197,967,300
August	198,549,172
September	202,300,917
October	210,653.335
November	199,922,708
December	205,040,330
Total	2,402,693,708

Two billion, four hundred and two million, six hundred and ninety-three thousand, seven hundred and eight gallons.

Premising that the city has a population of sixty thousand (60,000) inhabitants the quantity of water consumed would allow forty thousand and forty-one (40,041) gallons per capita per annum, or one hundred and nine (109) gallons per day.

LEAKS.

There have, been no leaks in the mains during the year and only a few leaks at pipe joints, which were repaired immediately after being discovered. It has been a matter of surprise that the old mains have stood so well, those in the older parts of the city being quite aged, having been in the ground since the year 1853, at which time the original works were built—a period of forty-one (41) years.

WASTE.

There has been discovered by inspection eleven hundred and seventy-five (1,175) leaking fixtures and supply pipe and fixtures left running, and notices sent to owners and agents.

It has become manifest, both from observation and computation, that a large proportion of the total pumpage is wasted, and that it is a heavy, additional and unnecessary expense to the city, since the expenditure of fuel and ware and tear of machinery are directly proportionate to the pumpage, and have no relation to the use or misuse of the water after delivery.

There being no arrangement for the determination of the locations of the waste, except by inspections and the casual information from citizens, it is not possible to correct the many leaking and flowing hydrants, water closets, wash basins, etc. by the system heretofore in use. That there should be some waste not due to ignorance and a want of a just and proper comprehension of the subject is, of course, unavoidable, but whatever the cause or nature of the waste, it is a fact that it has now assumed proportions that are very great, and which makes the matter a very serious one to be considered. The quantity consumed at this time is at the rate of one hundred and nine (109) gallons per day for every man, woman and child in the city. This is at least double the quantity necessary for purposes of utility, comfort or health.

The matter of the waste of water is one I think it my duty to bring to the notice of your Honor and the board, that some measures be instituted to check the enormous waste, which is largely wilful waste. All other means having failed here as well as elsewhere, I know of no other plan to suggest than the introduction of the meter system. This has been adopted in other cities with good effect, and is gaining favor with water departments.

I am very respectfully yours,

JAS. MANNING,

Superintendent

Appendix B.

Well locations in Beaufort and Jasper County, S.C., and Chatham County, Ga. used for this report, and

Test-well construction data.

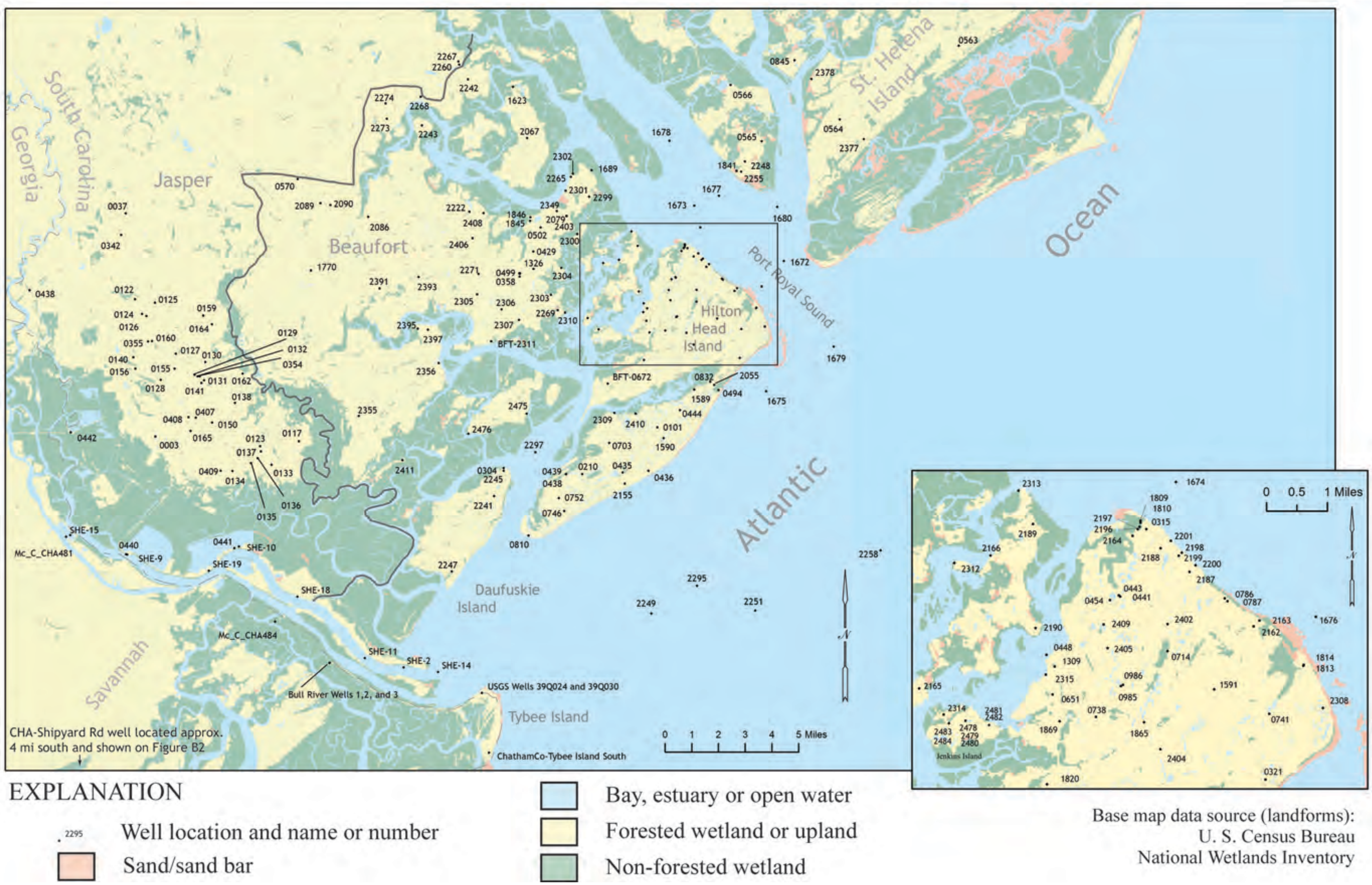


Figure B1. Locations of wells completed in the Upper Floridan aquifer used for this report

Figure B2. Locations for monitoring wells constructed in the Upper Floridan aquifer for this report.

County Well no.	Longitude NAD83	Latitude NAD83	Elev. (ft) land surface	Elev. (ft) top of casing	Casing dia.	Casing depth bgs	Well depth bgs	Year Installed
BFT-2162	-80.691104	32.242206		13.77	4	121	220	2002
BFT-2163	-80.689485	32.243614		13.97	4	123	221	2002
BFT-2164	-80.724982	32.263852		9.84	4	104	210	2003
BFT-2166	-80.764861	32.259273		9.65	4	76	210	1998
BFT-2187	-80.709036	32.255262		20.61	4	124	222	2002
BFT-2188	-80.717155	32.260896		18.09	4	116	217	2002
BFT-2189	-80.752876	32.266758		15.4	4	94	192	2002
BFT-2190	-80.752231	32.241971		9.86	4	90	225	2002
BFT-2196	-80.72299	32.266033	14.2	15.3	4	100	210	1996
BFT-2197	-80.723524	32.265477	14.58	15.92	4	102	212	1996
BFT-2198	-80.71118	32.259863	17.14	18.33	4	123	240	1996
BFT-2199	-80.712047	32.259128	17.47	18.74	4	122	238	1996
BFT-2200	-80.707354	32.256796	17.8	19.04	4	123	220	1997
BFT-2201	-80.714263	32.262662	13.16	14.45	4	102	235	1996
BFT-2245	-80.837874	32.147984	11.4	13.1	4	152	335	2000
BFT-2247	-80.872035	32.090203	8.6	10.1	4	165	263	2000
BFT-2299	-80.783982	32.293546		10.7	45	75	164	2001
BFT-2300	-80.791483	32.273267		13.16	4.5	80	164	2001
BFT-2301	-80.798983	32.296877		15.38	4.5	85	162	2002
BFT-2302	-80.794253	32.306046		13.02	4.5	75	176	2001
BFT-2303	-80.808423	32.240205		18.19	4.5	100	198	2001
BFT-2304	-80.801753	32.254936		13.84	4.5	94	197	2002
BFT-2305	-80.855644	32.240487		27.77	4.5	95	217	2001
BFT-2306	-80.840094	32.232437		23.57	4.5	94	217	2001
BFT-2307	-80.828984	32.226597		11.35	4.5	80	218	2001
BFT-2308	-80.671749	32.222707		11.87	4.5	118	244	2001
BFT-2309	-80.767872	32.177986		9.99	4.5	144	226	2001
BFT-2310	-80.79944	32.23055		9.81	4.5	85	196	2002
BFT-2311	-80.84666	32.215		7.54	4.5	85	236	2002
BFT-2312	-80.775	32.2575		9.02	4.5	100	216	2002
BFT-2313	-80.75694	32.27472		15.04	4.5	100	207	2002
BFT-2314	-80.77805	32.22138		9.26	4.5	100	258	2002
BFT-2315	-80.74944	32.23083		14.59	4.5	102	216	2002
BFT-2355	-80.931111	32.174444		24.52	4.5	181	306	2002
BFT-2356	-80.880278	32.203056		17.1	4.5	112	206	2002
BFT-2377	-80.6081110	32.2411390			4.5	100	216	2002

County Well no.	Longitude NAD83	Latitude NAD83	Elev.(ft) land surface	Elev. (ft) top of casing	Casing dia.	Casing depth bgs	Well depth bgs	Year Installed
BFT-2378	-80.6414720	32.3574440			4.5	75	156	2002
BFT-2402	-80.715261	32.242842	14.1	15.3	4.5	120	250	2004
BFT-2405	-80.73205	32.237144	16.4	18.9	4.5	110	250	2004
BFT-2408	-80.851444	32.284583		23 T	4.5	125	256	2009
BFT-2410	-80.754444	32.175333	8.07	11.67	4.5	130	286	2009
BFT-2411	-80.903583	32.150694	5.29	7.11	4.5	160	300	2008
Bft-2473	-80.7282190	32.1757430			8	200	1249	2011
Bft-2474	-80.7282180	32.1758380			8	80	240	2011
BFT-2475*	-80.8232220	32.1756390	Msl	Msl	4.5	80	280	2011
BFT-2476*	-80.8620560	32.1641940	Msl	Msl	4.5	76	311	2011
BFT-2500	-80.7642500	32.2080280			4.5	100	256	2015
BFT-2501	-805105.40	320826.40			4.5	140	316	2016
JAS-442	-81.1156110	32.1655830		8.89	4.5	221	396	2002
CHA-Bull River 2	-80.9500990	32.0405040	6.22	7.73	4.5	122	125	2009
CHA-South Tybee Island	-80.8513330	31.9875560	8.31	10.31	4.5	200	207	2009
CHA-Shipyard Rd	-81.1001110	31.9342220	5.36	7.33	4.5	137	140	2009

* Temporary offshore well

Table B1. Well construction data for Upper Floridan aquifer wells constructed by SCDHEC for this report.

Appendix C.

Elevation at the top of hydrogeologic units for selected wells and auger boreholes in Beaufort and Jasper Counties S.C., and Chatham County, Ga.

Elevations are based on geophysical logs and lithologic samples, reported in NGVD29. NAVD88 data are converted to NGVD29 by adding -0.9 ft (rounded).

Top of hydrogeologic units (ND = not determined)

County well no.	Long.-DD NAD83	Lat.-DD NAD83	Surface elev. NGVD29	Upper confining unit	Oligocene limestone	Late Eocene limestone	Middle confining unit	Upper Floridan aquifer
BFT-0101	-80.74056	32.16806	14.31	ND	ND	-127	-277	-127
BFT-0121	-80.73472	32.46333	31.25	ND	-35	-55	ND	-35
BFT-0210	-80.78861	32.14306	7.1	-59	-81	-123	ND	-81
BFT-0315	-80.72109	32.26548	16.06	-55	-82	-134	-172	-82
BFT-0321	-80.68789	32.20569	7.33	-47	-96	-126	ND	-96
BFT-0358	-80.82842	32.25021	20.15	-22	-65	-82	-174	-65
BFT-0429	-80.81972	32.26389	21.56	-33	-70	-102	-166	-70
BFT-0435	-80.76278	32.14389	12.26	-53	-78	-136	ND	-78
BFT-0436	-80.74636	32.14477	11.19	-47	-87	-134	ND	-87
BFT-0438	-80.79889	32.14306	7.68	-55	-74	-121	ND	-74
BFT-0439	-80.79917	32.14306	6.95	ND	-75	-122	ND	-75
BFT-0441	-80.72851	32.24944	10.15	-56	-71	-125	ND	-71
BFT-0443	-80.72889	32.24972	11.83	ND	-67	-124	-198	-67
BFT-0448	-80.74917	32.23556	ND	ND	-64	-106	ND	-64
BFT-0454	-80.73139	32.24861	ND	ND	-63	-101	-144	-63
BFT-0494	-80.70139	32.18833	6.98	-41	ND	-91	ND	-91
BFT-0502	-80.81509	32.27688	23.3	-24	-65	-76	-167	-65
BFT-0563	-80.54691	32.37498	17.38	ND	-52	-67	-88	-52
BFT-0564	-80.62340	32.33522	18.05	-24	ND	-77	-127	-77
BFT-0565	-80.67342	32.32355	15.77	-44	ND	-76	ND	-76
BFT-0566	-80.69314	32.35410	13.08	ND	ND	-69	-117	-69
BFT-0570	-80.97038	32.30327	17.3	-31	ND	-133	-247	-133
BFT-0651	-80.74750	32.22611	10.06	ND	-64	-82	ND	-64
BFT-0672	-80.77222	32.19194	15	-52	-78	-132	ND	-78
BFT-0703	-80.77139	32.15972	6	-54	-70	-125	ND	-70
BFT-0738	-80.73537	32.22077	10	-60	-72	-99	ND	-72
BFT-0741	-80.68680	32.22136	10	-46	-99	-130	ND	-99
BFT-0746	-80.80025	32.12297	12.5	-68	-74	-124	-283	ND
BFT-0752	-80.80361	32.13000	11.87	-43	-62	-124	ND	-62
BFT-0786	-80.69917	32.24889	12.14	ND	-108	-112	-228	-108
BFT-0787	-80.69841	32.24827	11.89	-51	-108	-114	-228	-108
BFT-0810	-80.82306	32.10972	12.02	-51	-83	-108	ND	-86
BFT-0832	-80.70667	32.19278	12.02	ND	-90	-103	ND	-90
BFT-0834	-80.69722	32.50500	11.15	ND	-19	-29	ND	-19
BFT-0845	-80.65222	32.36750	10	-18	ND	-56	ND	-56
BFT-0985	-80.72833	32.22806	19.12	ND	-69	-81	-226	-69
BFT-0986	-80.72778	32.22833	17.86	ND	-77	-122	ND	-77
BFT-1211	-80.74139	32.56917	23.06	ND	-75	-86	-108	-75
BFT-1326	-80.81953	32.25438	23.5	ND	-59	-64	ND	-59
BFT-1589	-80.71694	32.18861	9	-58	-100	-116	ND	-100

County well no.	Long.-DD NAD83	Lat.-DD NAD83	Surface elev. NGVD29	Upper confining unit	Oligocene limestone	Late Eocene limestone	Middle confining unit	Upper Floridan aquifer
BFT-1590	-80.73667	32.16222	10	-57	-80	-139	ND	-80
BFT-1591	-80.70222	32.22722	21	-57	-76	-107	ND	-76
BFT-1623	-80.83250	32.35333	20	-35	ND	-94	ND	-94
BFT-1672	-80.65944	32.25833	10.76	-56	ND	-98	-205	-98
BFT-1673	-80.71667	32.28861	11.67	-60	ND	-84	-181	-84
BFT-1674	-80.71278	32.27667	15.45	-56	ND	-102	ND	-102
BFT-1675	-80.67111	32.18750	10.26	-42	ND	-91	ND	-91
BFT-1676	-80.67361	32.24444	13.25	-61	ND	-97	-180	-97
BFT-1677	-80.70083	32.29389	13.06	-80	ND	-95	ND	-95
BFT-1678	-80.73250	32.32389	11.16	-62	ND	-77	-158	-77
BFT-1679	-80.62778	32.21167	12.77	-56	ND	-106	ND	-106
BFT-1680	-80.66361	32.28778	14.28	-64	-101	-103	-182	-103
BFT-1689	-80.78231	32.30799	9.16	-36	-67	-80	-153	-67
BFT-1770	-80.96194	32.25361	35	-29	-141	-152	-255	-141
BFT-1809	-80.72278	32.26750	12	-58	ND	-86	-208	-86
BFT-1810	-80.72273	32.26705	13.52	-55	-81	-106	ND	-80
BFT-1813	-80.67722	32.23278	11.42	ND	-100	-107	-222	-100
BFT-1814	-80.67709	32.23300	11.7	-52	-100	-114	ND	-100
BFT-1820	-80.74917	32.20472	10	-53	-73	-120	-260	-73
BFT-1840	-80.68953	32.30739	10	-47	-84	-94	-260	-84
BFT-1841	-80.68953	32.30744	10	-47	ND	-94	-260	-94
BFT-1845	-80.82167	32.28056	13	-36	-69	-77	-179	-69
BFT-1846	-80.82148	32.28244	13	-57	-69	-77	ND	-69
BFT-1861	-80.72000	32.46167	16.36	ND	-29	-35	ND	-29
BFT-1865	-80.72194	32.21944	16	ND	-89	-94	-241	-89
BFT-1869	-80.74556	32.21972	10	ND	-80	-130	-246	-61
BFT-1952	-80.73750	32.47472	36.26	ND	-43	-53	ND	-43
BFT-2067	-80.82361	32.32556	20	-46	-86	-98	-172	-86
BFT-2079	-80.79833	32.28306	15.24	ND	-47	-56	-167	-47
BFT-2086	-80.92528	32.28278	18	ND	ND	-114	-280	-114
BFT-2089	-80.95583	32.29028	15	-25	ND	-137	-255	-137
BFT-2090	-80.94944	32.28917	15	-23	ND	-142	-253	-142
BFT-2162	-80.69110	32.24221	13.77	-52	-107	-110	-220	-107
BFT-2163	-80.68948	32.24361	13.97	ND	-108	-111	-220	-108
BFT-2164	-80.72498	32.26385	9.84	-60	-85	95	ND	-85
BFT-2165	-80.78496	32.22761	13.48	-49	-71	-90	ND	-74
BFT-2166	-80.76486	32.25927	9.65	ND	-62	-90	ND	-62
BFT-2187	-80.70904	32.25526	20.61	-63	ND	-99	ND	-99
BFT-2188	-80.71715	32.26090	18.09	ND	-89	-102	ND	-89
BFT-2189	-80.75288	32.26676	15.4	-62	ND	-75	ND	-75

County well no.	Long.-DD NAD83	Lat.-DD NAD83	Surface elev. NGVD29	Upper confining unit	Oligocene limestone	Late Eocene limestone	Middle confining unit	Upper Floridan aquifer
BFT-2190	-80.75223	32.24197	9.86	-66	-73	-81	ND	-73
BFT-2196	-80.72299	32.26603	15.3	-59	-77	-87	ND	-77
BFT-2197	-80.72352	32.26548	15.92	-52	ND	-87	ND	-87
BFT-2198	-80.71118	32.25986	18.33	ND	ND	-105	-200	-105
BFT-2199	-80.71205	32.25913	18.74	-50	ND	-104	-203	-104
BFT-2200	-80.70735	32.25680	19.04	ND	ND	-104	ND	-104
BFT-2201	-80.71426	32.26266	14.45	ND	-94	-100	-202	-94
BFT-2222	-80.86056	32.28556	20	-20	ND	-104	-208	-104
BFT-2241	-80.84500	32.13111	21	-34	-82	-137	-276	-91
BFT-2242	-80.86139	32.35750	25	-53	-96	-110	-202	-96
BFT-2243	-80.89083	32.33250	15	ND	ND	-112	-236	-112
BFT-2245	-80.83681	32.14517	21	-41	-75	-132	ND	-75
BFT-2247	-80.87204	32.09020	15	-42	-88	-155	ND	-88
BFT-2248	-80.68417	32.31250	10	-46	ND	-89	-179	-89
BFT-2249	-80.74472	32.06722	19.3	-57	-75	-121	ND	-75
BFT-2251	-80.67833	32.06861	16.78	-54	-89	-170	-270	-89
BFT-2255	-80.68664	32.30694	10	-43	-73	-87	-172	-73
BFT-2258	-80.59833	32.10111	17.71	-64	-81	ND	ND	-81
BFT-2260	-80.86694	32.36550	15	ND	-110	-119	-212	-110
BFT-2267	-80.86750	32.36720	15	-52	-116	-128	ND	-116
BFT-2268	-80.89167	32.34806	22	-68	-114	-120	ND	-114
BFT-2269	-80.80417	32.23194	10	ND	-67	-72	ND	-67
BFT-2271	-80.85472	32.25167	24	-20	ND	-75	ND	-75
BFT-2273	-80.91333	32.33611	15	-68	-118	-122	-236	-118
BFT-2274	-80.91417	32.34444	18	-69	ND	-121	-238	-121
BFT-2295	-80.71556	32.08222	16	-77	-78	-147	ND	-78
BFT-2297	-80.81861	32.15472	18.2	ND	-82	-129	ND	-82
BFT-2299	-80.78398	32.29355	10.7	-45	-54	-66	ND	-54
BFT-2300	-80.79148	32.27327	13.16	-56	-57	-62	ND	-57
BFT-2301	-80.79898	32.29688	15.38	ND	ND	-69	ND	-69
BFT-2302	-80.79425	32.30605	13.02	-37	ND	-63	-148	-63
BFT-2303	-80.80842	32.24021	18.19	-49	-70	-85	ND	-70
BFT-2304	-80.80175	32.25494	13.84	-51	-68	-79	ND	-68
BFT-2305	-80.85564	32.24049	27.77	-21	-61	-76	ND	-61
BFT-2306	-80.84009	32.23244	23.57	-24	-53	-60	ND	-53
BFT-2307	-80.82898	32.22660	11.35	-27	-56	-62	ND	-56
BFT-2308	-80.67175	32.22271	11.87	-53	-94	-104	ND	-94
BFT-2309	-80.76800	32.17606	9.99	-46	-72	-129	ND	-72
BFT-2310	-80.79944	32.23055	9.81	ND	-66	-78	ND	-66
BFT-2311	-80.84666	32.21500	7.54	-26	-66	-79	-231	-66

County well no.	Long.-DD NAD83	Lat.-DD NAD83	Surface elev. NGVD29	Upper confining unit	Oligocene limestone	Late Eocene limestone	Middle confining unit	Upper Floridan aquifer
BFT-2312	-80.77500	32.25750	9.02	ND	-59	-94	ND	-59
BFT-2313	-80.75694	32.27472	15.04	ND	-62	-85	-181	-62
BFT-2314	-80.77805	32.22138	9.26	-64	-72	-80	ND	-72
BFT-2315	-80.74944	32.23083	14.59	-58	-65	-87	ND	-65
BFT-2349	-80.80472	32.28583	23.5	ND	-52	-56	-163	-52
BFT-2355	-80.93136	32.17455	24.52	-38	-121	-151	-242	-121
BFT-2356	-80.88027	32.20325	17.1	-32	-79	-94	ND	-79
BFT-2368	-80.73528	32.48861	34.35	ND	-47	-49	ND	-47
BFT-2370	-80.72778	32.48222	28.31	ND	-43	-45	ND	-43
BFT-2372	-80.72472	32.47972	26.79	ND	-45	-48	ND	-45
BFT-2374	-80.71056	32.46750	20.36	ND	-34	-42	ND	-34
BFT-2375	-80.71306	32.46944	20.51	ND	-32	-38	ND	-32
BFT-2377	-80.60805	32.32444	11.49	-26	ND	-83	-136	-83
BFT-2378	-80.64138	32.35722	9.43	-19	ND	-60	-112	-60
BFT-2391	-80.91806	32.24389	18	-24	-113	-118	ND	-113
BFT-2393	-80.89306	32.25000	28	-26	ND	-100	ND	-100
BFT-2395	-80.89361	32.22194	13	-23	-88	-92	-234	-88
BFT-2397	-80.88722	32.22139	13	-26	-88	-91	-233	-88
BFT-2402	-80.71526	32.24284	17	-53	-92	-104	-225	-92
BFT-2403	-80.79861	32.28306	18.19	-29	-50	-62	ND	-50
BFT-2404	-80.71733	32.21298	17	-49	-92	-109	-231	-92
BFT-2405	-80.73205	32.23714	15	-45	-72	-87	ND	-72
BFT-2406	-80.85861	32.27111	26	-20	-81	-91	ND	-81
BFT-2408	-80.85158	32.28469	22	-26	-115	-105	-213	-115
BFT-2409	-80.73314	32.24274	12	-46	-80	-108	-240	-80
BFT-2410	-80.75450	32.17556	8.07	ND	-54	-128	ND	-54
BFT-2411	-80.90359	32.15069	5.29	-42	-99	-150	ND	-99
BFT-2474	-80.72806	32.17556	16.51	-38	-64	-134	ND	-64
BFT-2475	-80.82418	32.17563	ND	-37	-80	-120	ND	-80
BFT-2476	-80.86138	32.16483	6	-52	-70	-112	-275	-70
BFT-2477	-80.87250	32.09111	10	-47	-95	-157	-330	-95
BFT-2500	-80.76425	32.20803	6	-39	-63	-95	ND	-63
BFT-2501	-80.85150	32.14067	10	-62	-90	-125	-283	-90
CHA-39024	-80.85295	32.02410	12	-45	-115	-180	ND	-115
CHA-481	-81.11567	32.10995	40	ND	-220	-315	-433	-290
CHA-484	-80.98494	32.06304	10	ND	-130	-220	-330	-210
CHA-Bull River well 1	-80.95003	32.04057	7	-67	-113	-184	-325	-113
CHA-Shipyard Rd	-81.10002	31.93389	5.36	-52	ND	ND	ND	ND

County well no.	Long.-DD NAD83	Lat.-DD NAD83	Surface elev. NGVD29	Upper confining unit	Oligocene limestone	Late Eocene limestone	Middle confining unit	Upper Floridan aquifer
CHA-Tybee Island South	-80.84855	31.99171	8.31	-52	-119	-183	ND	-119
JAS-0003	-81.06139	32.16333	10	-36	-190	ND	ND	-190
JAS-0037	-81.08045	32.28467	23	-12	-153	-185	-253	-153
JAS-0117	-80.96972	32.16083	13	-42	-155	-163	ND	-155
JAS-0122	-81.07444	32.23806	15	-24	-202	-234	-300	-202
JAS-0123	-80.99444	32.15806	23	-37	-171	ND	ND	-171
JAS-0124	-81.07000	32.23000	15	-29	-209	ND	ND	-209
JAS-0125	-81.06167	32.23611	10	-22	-220	ND	ND	-220
JAS-0126	-81.06722	32.22889	10	-34	-190	-238	ND	-190
JAS-0127	-81.04833	32.20833	18	-33	-184	-228	ND	-184
JAS-0128	-81.05806	32.19417	15	-45	-203	ND	ND	-203
JAS-0129	-81.03639	32.19694	17	-31	-185	-232	ND	-185
JAS-0130	-81.02944	32.20389	12	-31	-172	-228	ND	-172
JAS-0131	-81.03028	32.19389	13.5	-35	-172	-234	ND	-172
JAS-0132	-81.03444	32.19611	18	-22	-178	-227	ND	-178
JAS-0133	-80.98722	32.14833	14	-57	-178	-209	ND	-178
JAS-0134	-81.01210	32.14493	16	-49	-178	ND	ND	-178
JAS-0135	-81.00028	32.14917	22	-38	-182	-226	ND	-182
JAS-0136	-80.99611	32.15194	22.9	-41	-173	ND	ND	-173
JAS-0137	-80.99389	32.15528	22	-42	-174	ND	ND	-174
JAS-0138	-81.01056	32.18167	12	-20	-172	-214	-284	-172
JAS-0140	-81.07556	32.20639	13	-14	-193	ND	ND	-193
JAS-0141	-81.03194	32.19250	13	-44	-189	-256	ND	-189
JAS-0150	-81.02513	32.17092	26	-28	-147	ND	ND	-147
JAS-0155	-81.04917	32.20028	16	-34	-188	ND	ND	-188
JAS-0156	-81.07417	32.20028	16	-24	-128	ND	ND	-128
JAS-0159	-81.03083	32.22917	13	-32	-121	ND	ND	-121
JAS-0160	-81.06361	32.21528	16	-24	-200	-224	-299	-200
JAS-0162	-81.00556	32.19750	15	-27	-177	-205	ND	-177
JAS-0164	-81.02528	32.22444	7	-33	-173	-197	ND	-173
JAS-0165	-81.03889	32.16639	16	-24	-192	ND	ND	-192
JAS-0166	-80.91056	32.56000	14	11	-19	-97	ND	-19
JAS-0342	-81.08334	32.27298	21	-65	-187	ND	ND	-187
JAS-0354	-81.03306	32.19611	18	-50	-174	-202	ND	-174
JAS-0355	-81.06611	32.21500	15	-27	-191	-208	ND	-191
JAS-0407	-81.03556	32.17361	19	-26	-191	ND	ND	-191
JAS-0408	-81.04028	32.17389	20	-25	-190	ND	ND	-190
JAS-0409	-81.01972	32.14500	16	-32	ND	ND	ND	ND

County well no.	Long.-DD NAD83	Lat.-DD NAD83	Surface elev. NGVD29	Upper confining unit	Oligocene limestone	Late Eocene limestone	Middle confining unit	Upper Floridan aquifer
JAS-0438	-81.14194	32.24278	5	-32	-244	-325	-420	-244
JAS-0440	-81.07944	32.09944	10.8	-29	-205	-297	ND	-205
JAS-0441	-81.00806	32.10389	19.1	-37	-185	-250	ND	-185
JAS-0442	-81.11555	32.16555	8.89	-23	-195	-276	ND	-195
SHE-10	-81.01093	32.10295	ND	-35	-166	-204	ND	ND
SHE-11	-80.92765	32.04314	ND	-66	-112	ND	ND	ND
SHE-14	-80.88096	32.03560	ND	-47	-94	ND	ND	ND
SHE-15	-81.11836	32.10914	ND	-52	-198	ND	ND	ND
SHE-18	-80.97061	32.07657	ND	-49	-115	ND	ND	ND
SHE-19	-81.02722	32.09067	ND	-52	-198	ND	ND	ND
SHE-2	-80.90284	32.03812	ND	-45	-102	ND	ND	ND
SHE-9	-81.08010	32.09951	ND	-28	-192	ND	ND	ND

SC Geological Survey borehole terminated at top of upper confining unit
(Elevations estimated from USGS topographic maps)

Augered borehole county no.	Long.-DD NAD83	Lat.-DD NAD83	Est. topo elev.	Upper confining unit
Beaufort - 070	-80.61500	32.32625	10	-30
Beaufort - 071	-80.61910	32.33150	15	-30
Beaufort - 072	-80.62069	32.31167	8	-42
Beaufort - 073	-80.48900	32.41933	15	-34
Beaufort - 074	-80.61833	32.31717	8	-52
Beaufort - 076	-80.59700	32.33467	12	-58
Beaufort - 079	-80.46733	32.40833	5	-38
Beaufort - 083	-80.94047	32.25861	6	-33
Beaufort - 084	-80.53222	32.39236	20	-48
Beaufort - 089	-80.54100	32.37500	11	-45
Beaufort - 091	-80.55383	32.43117	7	-36
Beaufort - 093	-80.53517	32.44733	11	-24
Beaufort - 095	-80.58933	32.39283	10	-40
Beaufort - 098	-80.57067	32.39883	16	-35
Beaufort - 099	-80.52347	32.41028	15	-35
Beaufort - 101	-80.51767	32.41200	20	-31
Beaufort - 102	-80.51233	32.41367	22	-36
Beaufort - 103	-80.71667	32.41444	15	-49
Beaufort - 104	-80.48833	32.41483	8	-37
Beaufort - 105	-80.50833	32.40000	28	-46
Beaufort - 106	-80.59683	32.39767	5	-40
Beaufort - 107	-80.53317	32.40550	15	-37
Beaufort - 108	-80.46017	32.34833	4	-56
Beaufort - 109	-80.45700	32.35367	4	-55
Beaufort - 111	-80.44150	32.38483	4	-60
Beaufort - 112	-80.44800	32.37083	4	-52
Beaufort - 113	-80.50883	32.40183	12	-56
Beaufort - 114	-80.50083	32.40800	12	-48
Beaufort - 115	-80.51483	32.42967	12	-38
Beaufort - 116	-80.51983	32.39217	12	-40
Beaufort - 117	-80.55636	32.36758	15	-50
Beaufort - 118	-80.47133	32.42183	14	-50
Beaufort - 119	-80.50183	32.41783	11	-49
Beaufort - 120	-80.46733	32.42083	5	-65
Beaufort - 121	-80.47417	32.43600	14	-36
Beaufort - 122	-80.47600	32.42700	8	-56
Beaufort - 123	-80.49733	32.42583	11	-47
Beaufort - 124	-80.56883	32.46617	4	-28

Augered borehole county no.	Long.-DD NAD83	Lat.-DD NAD83	Est. topo elev.	Upper confining unit
Beaufort - 125	-80.48650	32.43550	8	-64
Beaufort - 126	-80.59967	32.38033	8	-44
Beaufort - 127	-80.61350	32.38300	12	-33
Beaufort - 128	-80.60050	32.46933	12	-30
Beaufort - 129	-80.59750	32.37200	12	-44
Beaufort - 130	-80.63733	32.36283	9	-23
Beaufort - 131	-80.61750	32.44181	9	-33
Beaufort - 140	-80.64017	32.33767	4	-41
Beaufort - 141	-80.82447	32.26039	19	-21
Beaufort - 142	-80.82308	32.26411	19	-24
Beaufort - 143	-80.82183	32.26775	19	-28
Beaufort - 144	-80.82058	32.27106	19	-30
Beaufort - 145	-80.81914	32.27483	19	-29
Beaufort - 146	-80.80736	32.28133	22	-41
Beaufort - 147	-80.90833	32.26783	17	-23
Beaufort - 148	-80.93067	32.27411	32	-16
Beaufort - 149	-80.78758	32.22783	7	-48
Beaufort - 150	-80.79997	32.23042	4	-52
Beaufort - 151	-80.83244	32.35481	5	-31
Beaufort - 152	-80.81342	32.31769	22	-41
Beaufort - 153	-80.84100	32.30661	17	-64
Beaufort - 154	-80.70844	32.25067	12	-59
Beaufort - 155	-80.71569	32.26139	20	-47
Beaufort - 157	-80.68481	32.23983	12	-60
Beaufort - 158	-80.71819	32.19972	5	-52
Beaufort - 159	-80.69797	32.19339	4	-50
Beaufort - 160	-80.77167	32.15167	11	-50
Beaufort - 161	-80.78042	32.13564	8	-65
Beaufort - 165	-80.77769	32.14136	9	-62
Beaufort - 166	-80.76678	32.14619	9	-53
Beaufort - 167	-80.79989	32.14453	3	-64
Beaufort - 168	-80.81064	32.11533	4	-45
Beaufort - 169	-80.81436	32.12347	8	-49
Beaufort - 170	-80.82672	32.11797	7	-74
Beaufort - 171	-80.75183	32.14228	8	-43
Beaufort - 172	-80.76981	32.17617	5	-51
Beaufort - 173	-80.76031	32.15328	17	-34
Beaufort - 174	-80.77372	32.22094	10	-71
Beaufort - 175	-80.90925	32.28783	26	-16

Augered borehole county no.	Long.-DD NAD83	Lat.-DD NAD83	Est. topo elev.	Upper confining unit
Beaufort - 176	-80.91103	32.28294	23	-3
Beaufort - 177	-80.95525	32.25792	40	-21
Beaufort - 178	-80.94533	32.26106	38	-13
Beaufort - 179	-80.94400	32.26044	30	-16
Beaufort - 180	-80.94256	32.25972	20	-18
Beaufort - 181	-80.93394	32.24925	22	-32
Beaufort - 182	-80.93861	32.25575	18	-17
Beaufort - 183	-80.94047	32.25861	21	-14
Beaufort - 184	-80.95186	32.26531	40	-22
Beaufort - 185	-80.82736	32.24139	22	-23
Beaufort - 186	-80.80831	32.28842	17	-33
Beaufort - 187	-80.81711	32.27831	20	-30
Beaufort - 188	-80.81083	32.28011	21	-53
Beaufort - 189	-80.82944	32.25000	19	-15
Beaufort - 190	-80.82706	32.25328	19	-27
Beaufort - 191	-80.82569	32.25750	17	-25
Beaufort - 192	-80.83394	32.33503	8	-43
Beaufort - 193	-80.76692	32.23225	6	-42
Beaufort - 194	-80.76583	32.25897	6	-49
Beaufort - 196	-80.83011	32.24656	22	-18
Beaufort - 197	-80.85100	32.25825	22	-19
Beaufort - 198	-80.87072	32.27581	31	-13
Beaufort - 199	-80.89786	32.31769	10	-70
Beaufort - 260	-80.71394	32.32324	15	-1
Beaufort - 262	-80.68438	32.57271	11	-17
Beaufort - 263	-80.67010	32.57795	4	-27
Beaufort - 264	-80.73913	32.52337	5	-15
Beaufort - 265	-80.99546	32.25318	15	-40
Beaufort - 266	-80.99131	32.26114	15	-21
Beaufort - 267	-81.00676	32.23331	10	-49
Beaufort - 268	-81.00320	32.23790	15	-44
Beaufort - 269	-80.69581	32.56898	7	-33
Beaufort - 270	-80.70908	32.56421	12	-29
Beaufort - 271	-80.71895	32.56106	18	-20
Beaufort - 272	-80.72511	32.57850	21	-15
Beaufort - 273	-80.74196	32.57716	24	-23
Beaufort - 274	-80.73450	32.61877	17	-11
Beaufort - 275	-80.72260	32.61998	15	-4
Beaufort - 276	-80.71764	32.50789	8	-20

Augered borehole county no.	Long.-DD NAD83	Lat.-DD NAD83	Est. topo elev.	Upper confining unit
Beaufort - 279	-80.71917	32.52156	12	-43
Beaufort - 280	-80.74126	32.59482	20	-12
Beaufort - 281	-80.72211	32.60269	16	-3
Beaufort - 282	-80.70984	32.60814	12	-7
Beaufort - 283	-80.70222	32.59798	12	-5
Beaufort - 284	-80.69268	32.61267	9	-8
Beaufort - 285	-80.70137	32.63471	11	-34
Beaufort - 286	-80.71428	32.57987	17	-4
Beaufort - 287	-80.70697	32.61418	14	-7
Beaufort - 288	-80.68402	32.65289	10	-5
Beaufort - 289	-80.55436	32.60158	35	-47
Beaufort - 290	-80.69839	32.38096	12	-41
Beaufort - 294	-80.62963	32.47407	21	-15
Beaufort - 295	-80.64059	32.48167	21	-12
Beaufort - 297	-80.71844	32.37773	12	-20
Beaufort - 299	-80.63298	32.45103	18	-25
Beaufort - 303	-80.63061	32.48344	22	-18
Beaufort - 309	-80.64034	32.44469	24	-25
Beaufort - 311	-80.68210	32.40047	20	-21
Beaufort - 314	-80.75000	32.47666	25	-45
Beaufort - 315	-80.77530	32.39190	6	-36
Beaufort - 316	-80.75748	32.54996	18	-15
Beaufort - 318	-80.63091	32.53192	7	-7
Beaufort - 319	-80.66302	32.53037	8	-12
Beaufort - 321	-80.57956	32.52704	7	-31
Beaufort - 323	-80.74715	32.55140	16	-21
Beaufort - 324	-80.75068	32.49249	35	-33
Beaufort - 327	-80.71484	32.41508	21	-30
Beaufort - 329	-80.73972	32.46611	35	-34
Colleton - 47	-80.55733	32.56786	10	-51
Colleton - 48	-80.55904	32.57300	14	-49
Colleton - 49	-80.55985	32.57412	25	-45
Colleton - 51	-80.58795	32.58740	11	-48
Colleton - 52	-80.58418	32.60687	12	-15
Colleton - 53	-80.55008	32.59459	25	-37
Colleton - 54	-80.55035	32.58722	20	-41
Colleton - 55	-80.56129	32.61475	13	-38
Colleton - 56	-80.56969	32.61135	20	-26
Colleton - 57	-80.60486	32.61032	8	-23

Augered borehole county no.	Long.-DD NAD83	Lat.-DD NAD83	Est. topo elev.	Upper confining unit
Colleton - 58	-80.59153	32.62382	28	-27
Colleton - 59	-80.57574	32.59984	30	-16
Colleton - 60	-80.55960	32.59221	29	-42
Colleton - 61	-80.45399	32.55885	10	-38
Colleton - 62	-80.46811	32.57214	8	-36
Colleton - 63	-80.46049	32.58406	8	-28
Colleton - 64	-80.45278	32.58505	4	-36
Colleton - 65	-80.45018	32.65252	12	-44
Colleton - 66	-80.44634	32.61450	8	-35
Colleton - 67	-80.43262	32.61282	8	-60
Colleton - 68	-80.44054	32.59961	6	-55
Colleton - 69	-80.47559	32.59000	6	-37
Colleton - 70	-80.48217	32.61410	8	8
Colleton - 71	-80.41394	32.53554	10	-73
Colleton - 72	-80.42157	32.56127	10	-29
Colleton - 73	-80.44245	32.56478	7	-37
Colleton - 74	-80.49708	32.63300	31	-17
Colleton - 75	-80.58727	32.63389	6	-30
Colleton - 76	-80.62814	32.59199	12	-29
Colleton - 77	-80.65490	32.59611	8	-36
Charleston - 174	-80.37638	32.60446	6	-34
Charleston - 175	-80.36900	32.59224	10	-66
Jasper - 112	-81.01340	32.23647	5	-35
Jasper - 113	-81.07896	32.18322	13	-49
Jasper - 114	-81.06165	32.22263	12	-30
Jasper - 115	-81.12130	32.36567	28	-1
Jasper - 116	-81.10961	32.36836	31	-12
Jasper - 117	-81.10189	32.37476	22	-8
Jasper - 126	-81.11625	32.23898	5	-26
Jasper - 128	-81.05989	32.37436	18	-8
Jasper - 129	-81.06946	32.36447	16	-19
Jasper - 130	-81.08120	32.35229	18	-41
Jasper - 132	-81.09726	32.33465	20	-19
Jasper - 133	-81.12495	32.31179	8	-12
Jasper - 134	-81.02164	32.23379	9	-40
Jasper - 139	-81.03858	32.36581	15	-19
Jasper - 140	-81.05682	32.32822	12	-57
Jasper - 141	-81.06522	32.31101	14	-20
Jasper - 142	-81.07258	32.27960	21	-27

Augered borehole county no.	Long.-DD NAD83	Lat.-DD NAD83	Est. topo elev.	Upper confining unit
Jasper - 143	-81.07740	32.27499	18	-20
Jasper - 144	-81.05395	32.29965	20	-11
Jasper - 145	-81.06868	32.29293	20	-33
Jasper - 150	-81.04745	32.30348	15	-16
Jasper - 151	-81.07499	32.19697	15	-34
Jasper - 152	-81.07209	32.23302	20	-26
Jasper - 153	-81.03253	32.30373	19	-16
Jasper - 154	-81.01947	32.26889	18	-20
Jasper - 155	-81.02998	32.27100	19	-29
Jasper - 158	-81.02958	32.37683	16	-19
Jasper - 160	-81.02855	32.36521	19	-11
Jasper - 163	-81.03147	32.35163	16	-20
Jasper - 165	-81.02010	32.31633	9	-60
Jasper - 166	-81.01096	32.30957	11	-22
Jasper - 167	-81.01322	32.34579	13	-12
Jasper - 169	-81.00993	32.33660	12	-20
Jasper - 170	-81.00323	32.32434	11	-21
Jasper - 171	-81.02020	32.32651	14	-21
Jasper - 173	-81.05626	32.16845	10	-21
Jasper - 174	-81.04908	32.17801	13	-23
Jasper - 176	-81.11860	32.28737	8	-39

Appendix D.

Maps showing the potentiometric surface in the Upper Floridan aquifer for the Savannah Ga., area and adjacent parts of S.C., 1880 to 1998.

Figures D1 – D20

Note: D14 – D20 reference specific water-level measurements on original maps (Gawn,1994).

Figure D1. The estimated 1880 potentiometric surface of the Upper Floridan aquifer in the Savannah, Ga. area and adjacent parts of South Carolina (Warren, 1944 and Counts and Donsky, 1963).

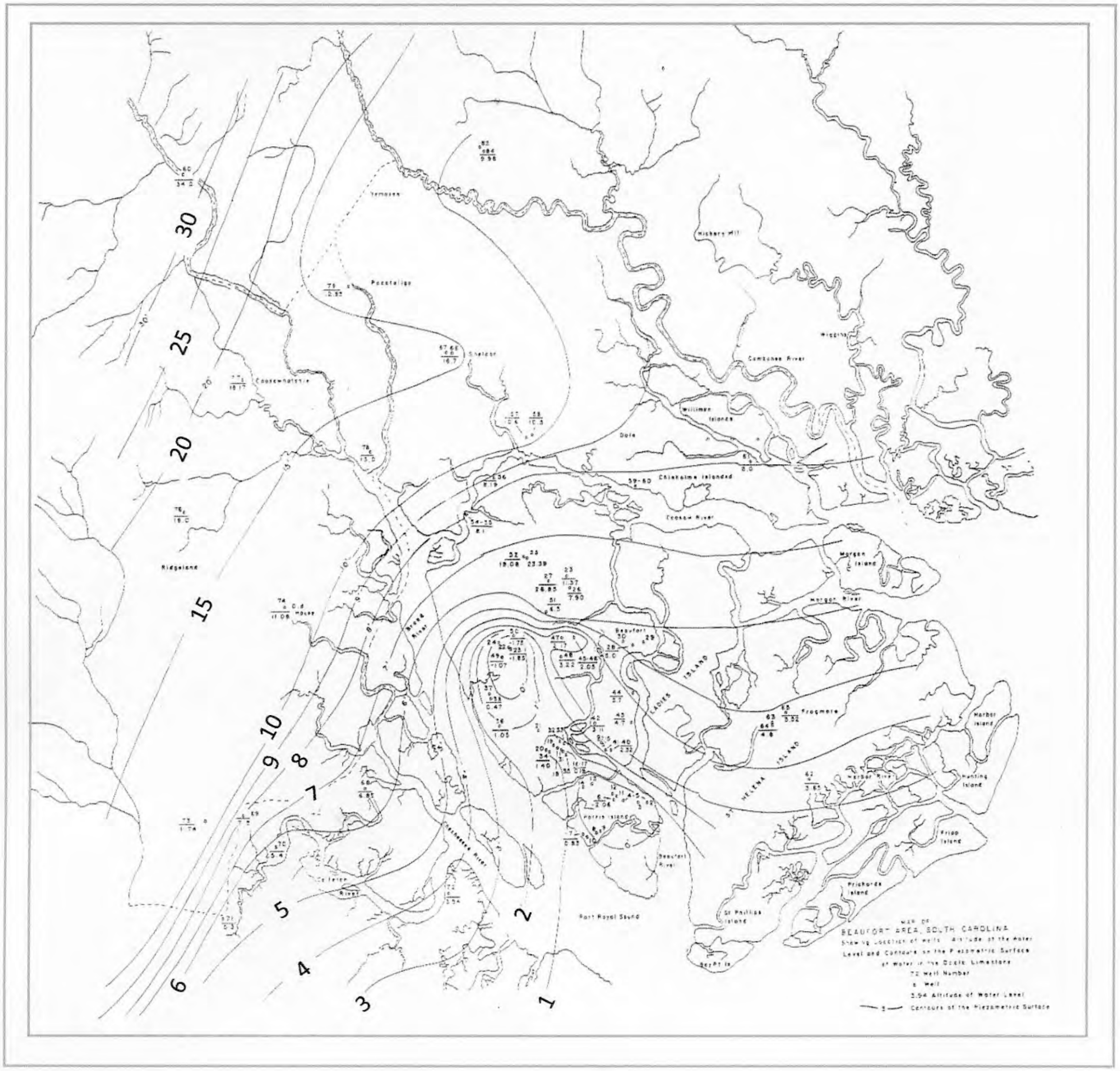


Figure D2. The 1942 potentiometric surface of the Upper Floridan aquifer in southern Beaufort and Jasper Counties, S.C. (Mundorff, 1944).

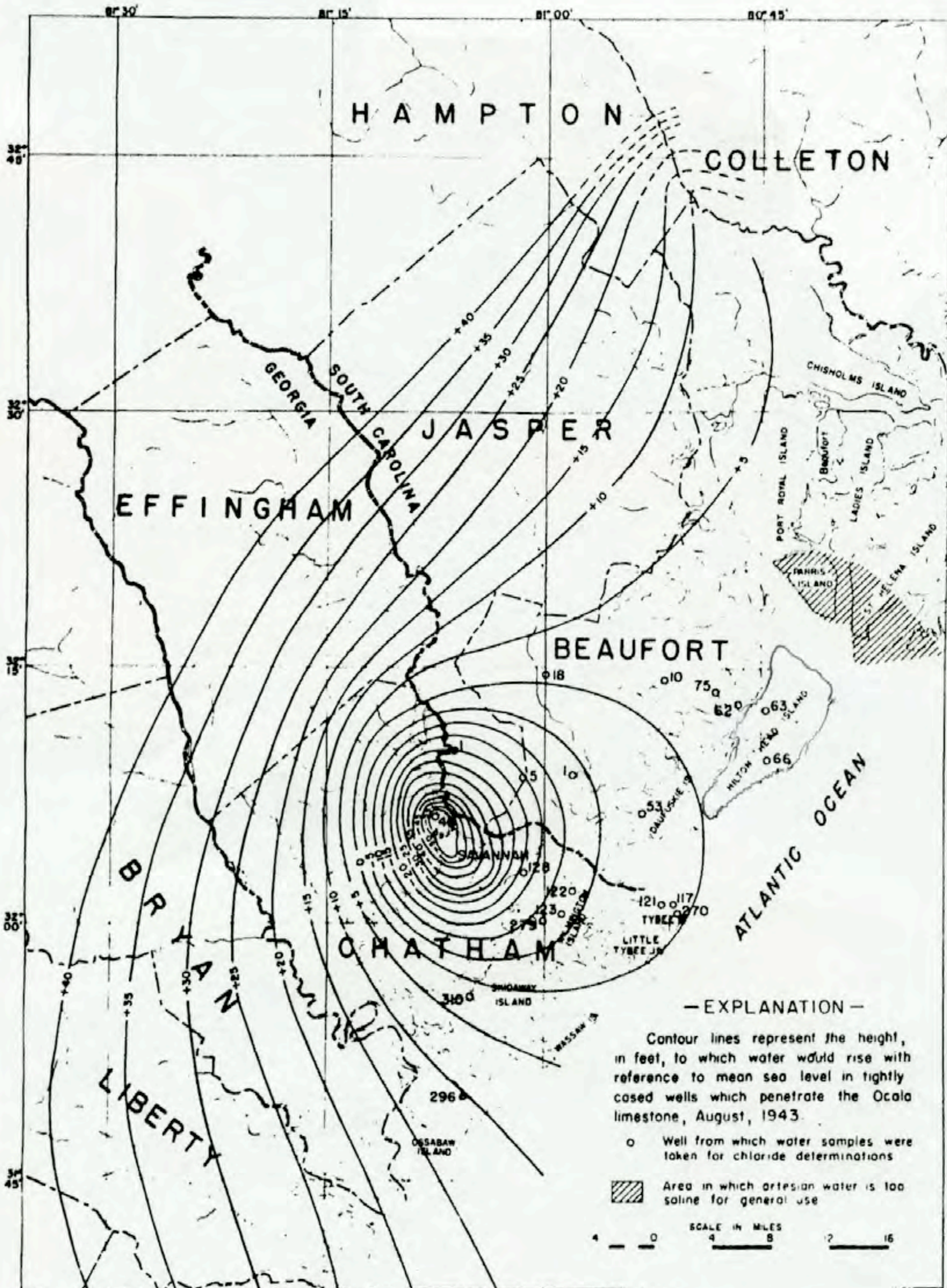


Figure 31. Map showing piezometric surface of artesian water in Savannah and adjacent areas during August, 1943, and location of wells from which water samples were taken for chloride determination.

Figure D3. The 1943 potentiometric surface of the Upper Floridan aquifer beneath the surrounding area of Savannah, Ga., and adjacent parts of South Carolina (Warren, 1944).

EXPLANATION

—10– - Potentiometric contour. Shows altitude in feet above and below sea level. Dashed where approximate. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

→ Groundwater-flow path.

● Well Location

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D4. The December 1957 potentiometric surface of the Upper Floridan aquifer in the Savannah, Ga. area and adjacent parts of South Carolina (Counts and Donsky, 1963).

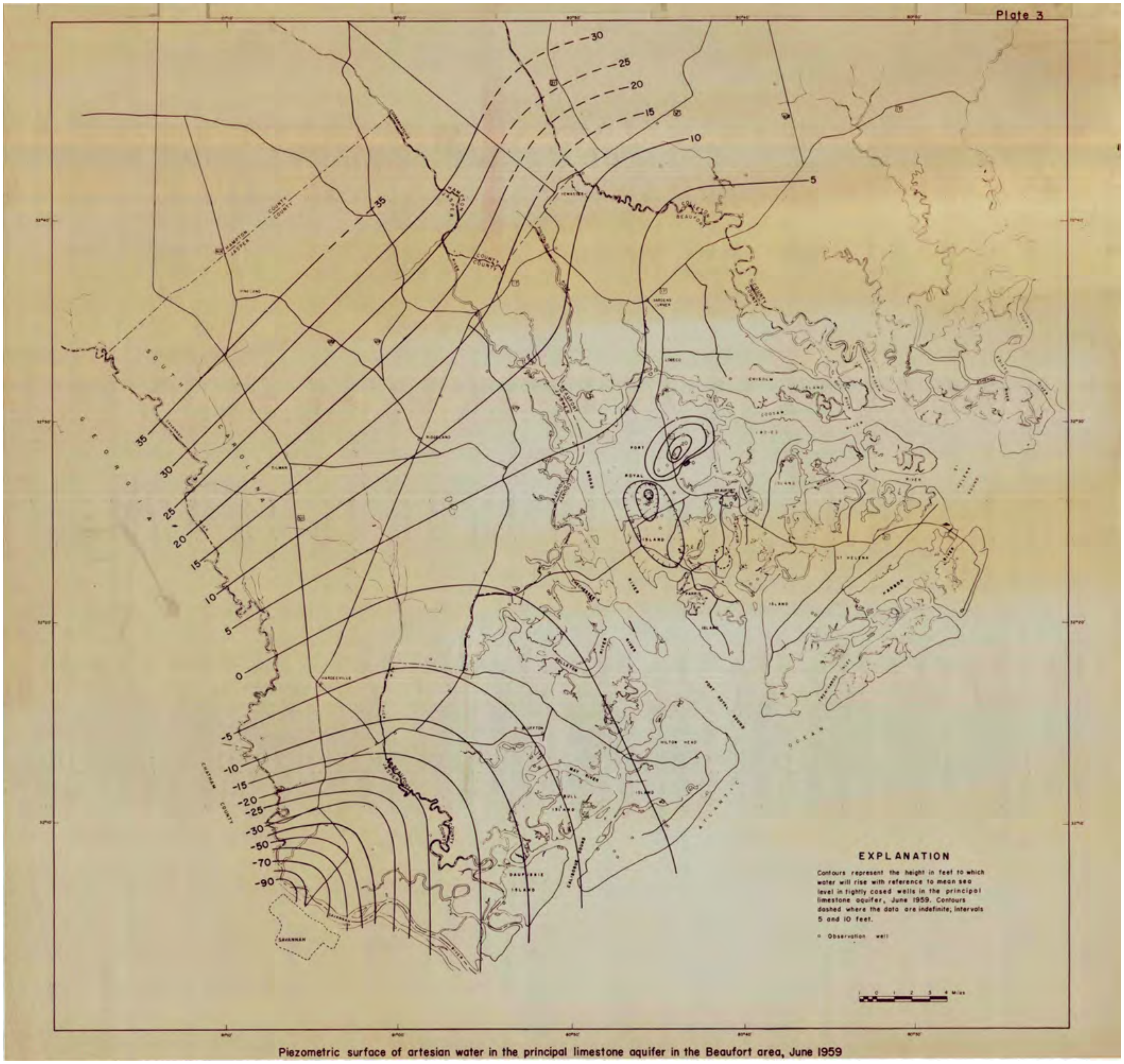
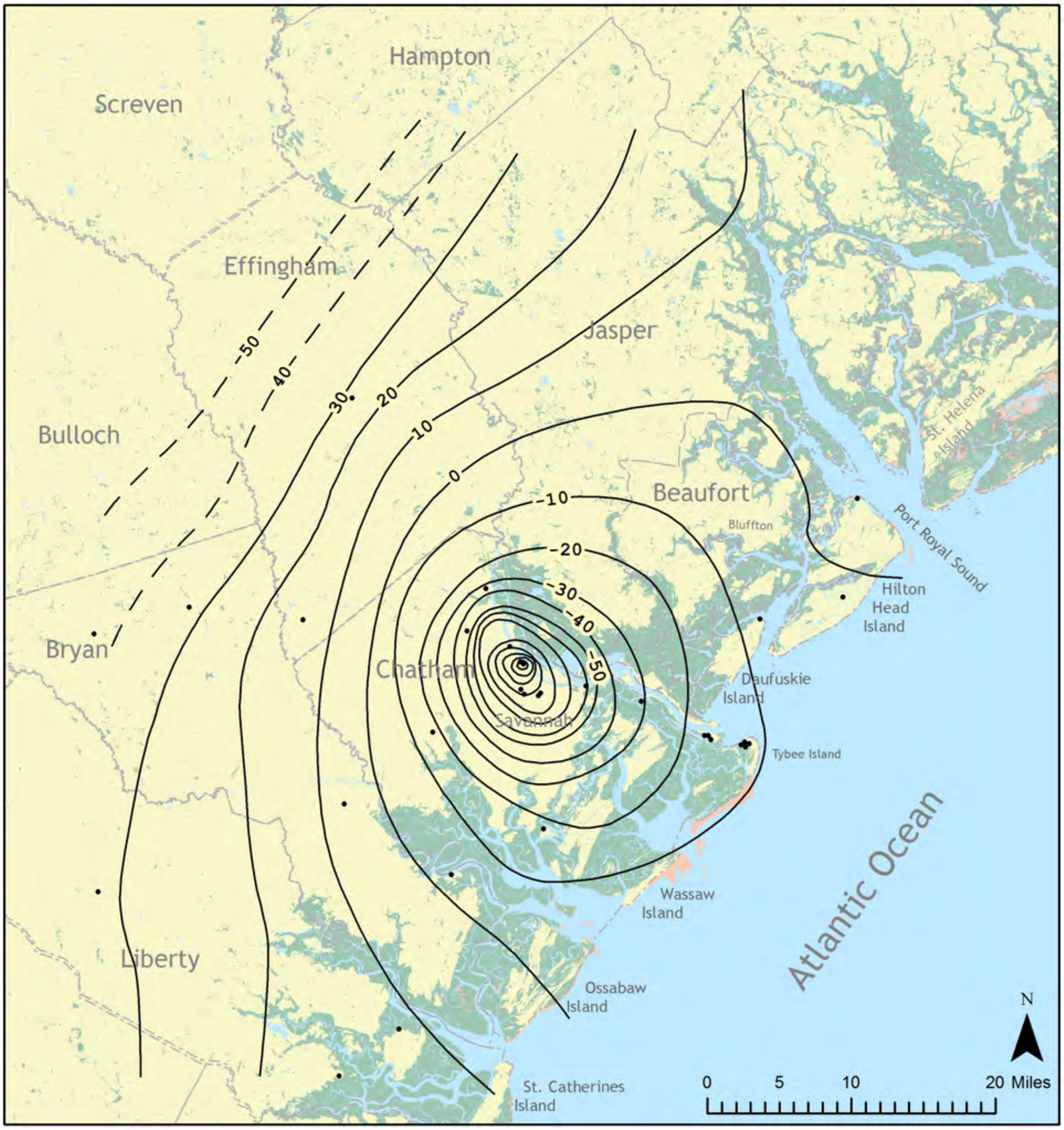


Figure D5. The 1959 potentiometric surface of the Upper Floridan aquifer in Beaufort and Jasper Counties, S.C. (Siple, 1960).



EXPLANATION

—10— - Potentiometric contour. Shows altitude in feet above sea level. Dashed where approximate. Contour interval 10 feet. National Geodetic Vertical Datum of 1929.

● Well Location

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D6. The 1961 potentiometric surface of the Upper Floridan aquifer in the Savannah, Ga. area and adjacent parts of South Carolina (McCollum and Counts, 1964).

EXPLANATION

—10 - - Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 10 and 20 feet. National Geodetic Vertical Datum of 1929.

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D7. The 1970 potentiometric surface of the Upper Floridan aquifer in the Savannah, Ga. area and adjacent parts of South Carolina (Counts and Krause, 1976).

EXPLANATION

—10— - Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

● Well Location

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D8a. The December 1976 potentiometric surface of the Upper Floridan aquifer in Beaufort, Jasper, Hampton, and Colleton Counties, S.C. (Hayes, 1979).

Figure D8b. The December 1976 potentiometric surface of the Upper Floridan aquifer at Hilton Head Island, S.C. (Hayes, 1979).

EXPLANATION

—10— · contour interval 10 feet. Dashed where inferred. (after Mitchell, 1979) National Geodetic Vertical Datum of 1929.

● Well Location

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D9. The November 1979 potentiometric surface of the Upper Floridan aquifer in Chatham County, Ga. and adjacent parts of South Carolina (Mitchell, 1980)

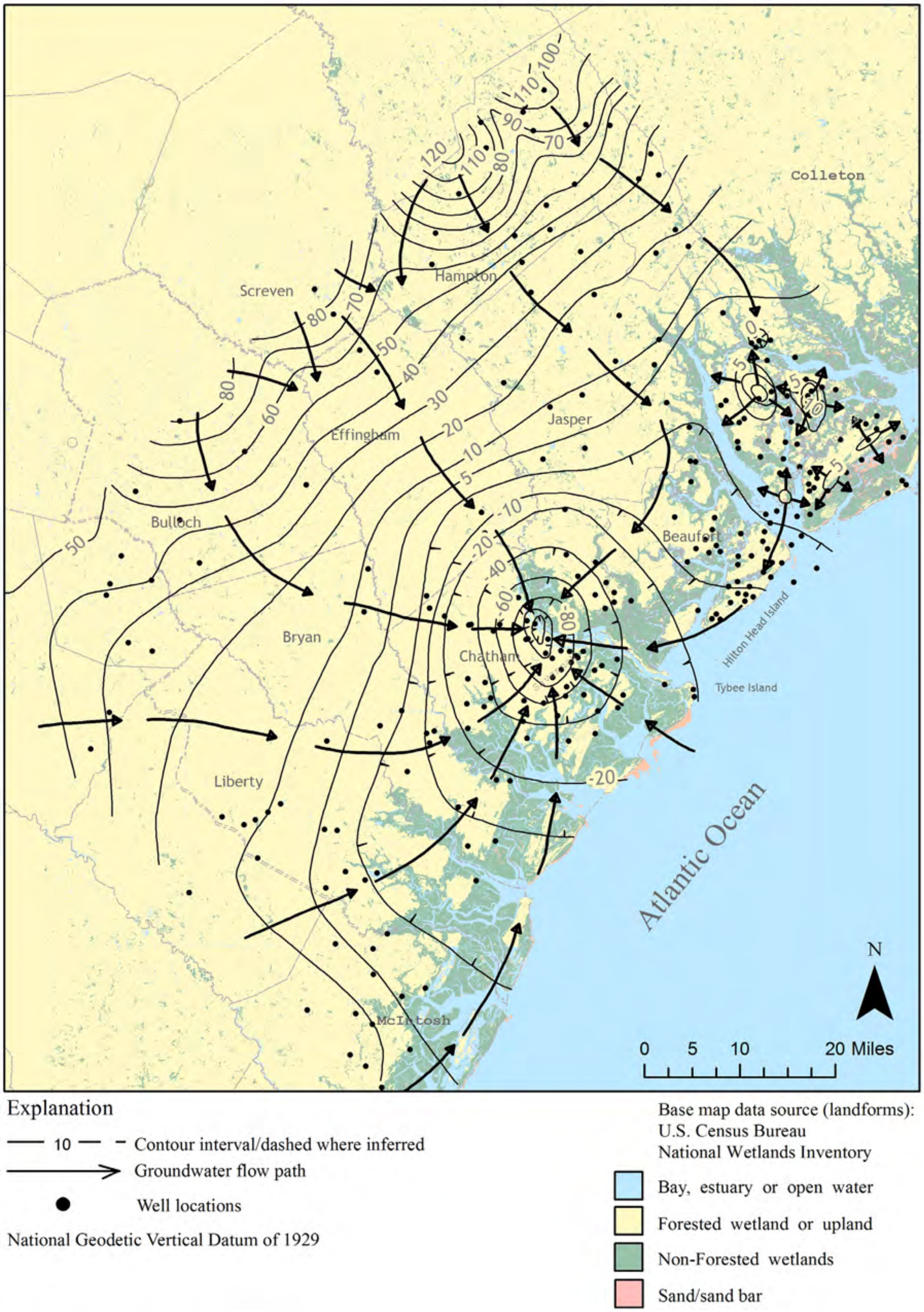
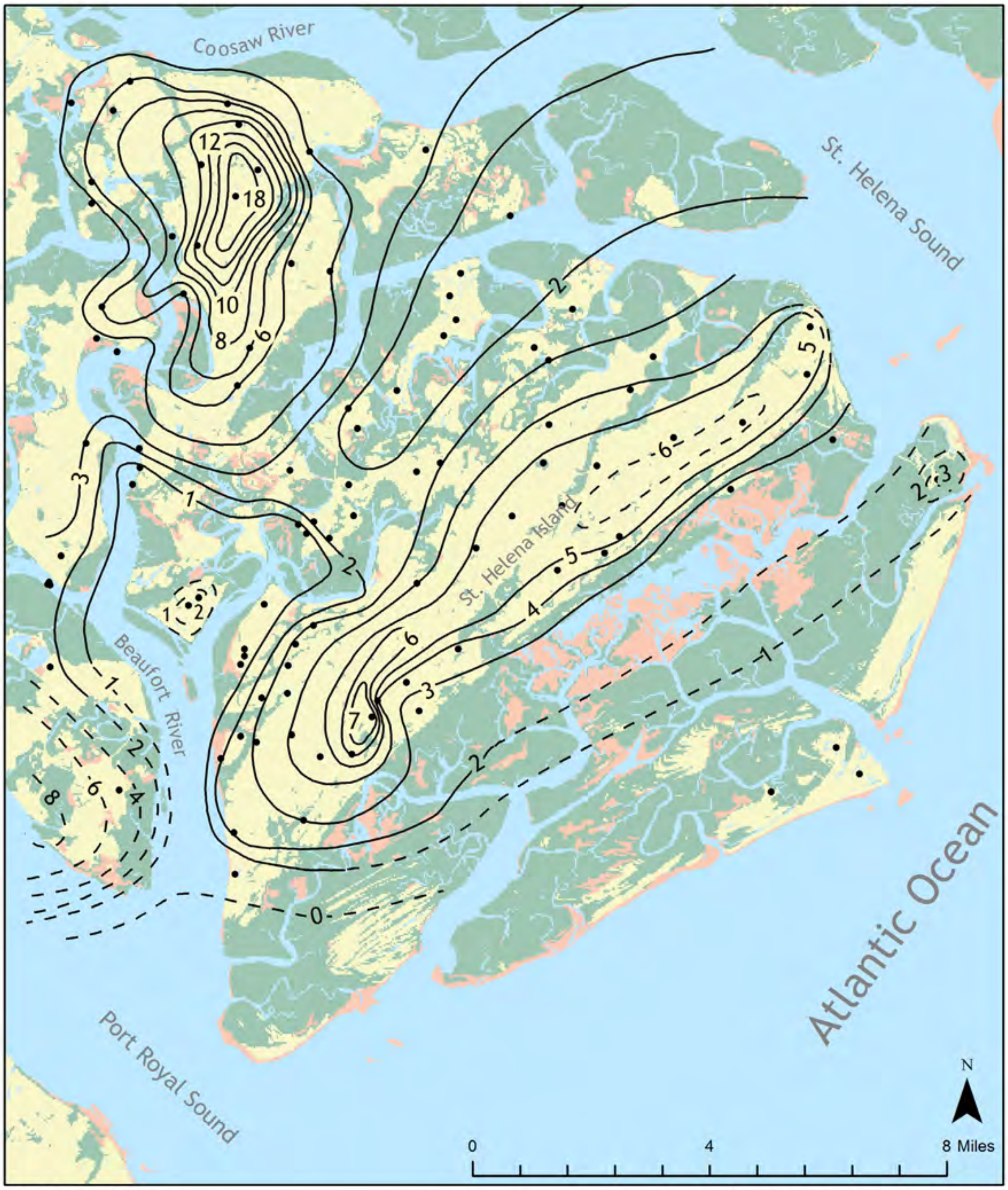


Figure D10. The 1984 potentiometric surface of the Upper Floridan aquifer in Chatham County, Ga. and adjacent parts of South Carolina (from Smith, 1988).



EXPLANATION

— 2 - - Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 1,and 2 feet. National Geodetic Vertical Datum of 1929.

● Well Location

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

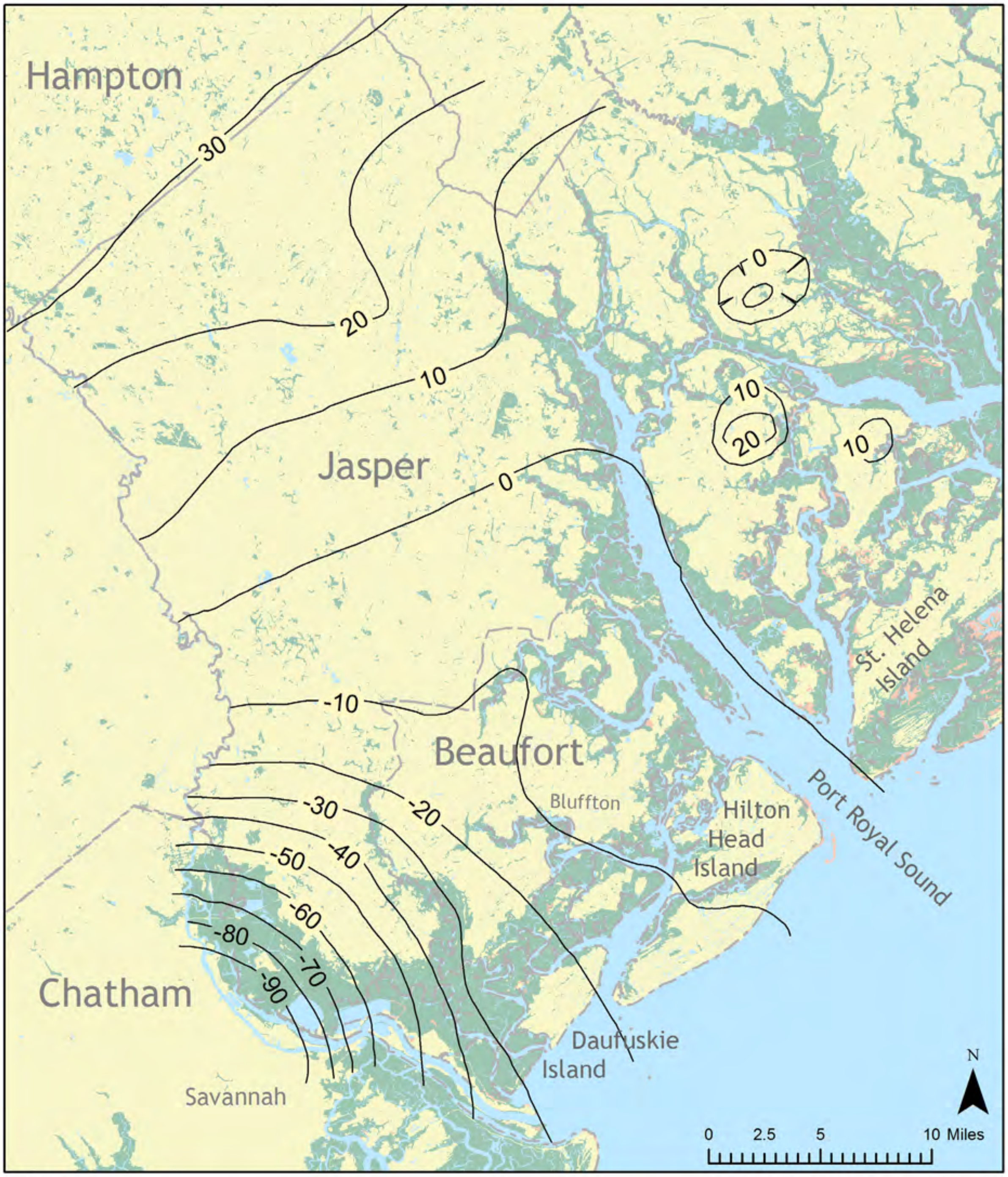
Bay, estuary or open water

Forested wetland or upland

Non-Forested wetlands

Sand/sand bar

Figure D11. The March 1984 potentiometric surface of the Upper Floridan aquifer beneath Lady's and St. Helena Islands, S.C. (Hassen, 1985).



EXPLANATION

—10— · Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 1,5, and 10 feet. National Geodetic Vertical Datum of 1929.

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D12. The 1985 potentiometric surface of the Upper Floridan aquifer in Beaufort and Jasper Counties, S.C. (Hughes and others, 1989).

Figure D13. The 1986 potentiometric surface of the Upper Floridan aquifer at Hilton Head Island, S.C. (Crouch and others, 1987).

EXPLANATION

—10— · Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

——— Approximate updip divide of the upper and lower Floridan aquifers.

● Well locations

Base map data source (landforms): U.S. Census Bureau National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D14. The March 1991 potentiometric surface of the Upper Floridan aquifer in Beaufort, Jasper, Hampton, and Colleton Counties, S.C. (Gawne, 1994).

EXPLANATION

—10— - Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

Approximate updip divide of the upper and lower Floridan aquifers.

● Well locations

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

Bay, estuary or open water

Forested wetland or upland

Non-Forested wetlands

Sand/sand bar

Figure D15. The July 1991 potentiometric surface of the Upper Floridan aquifer in Beaufort, Jasper, Hampton, and Colleton Counties, S.C. (Gawne, 1994).

EXPLANATION

—10— · Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

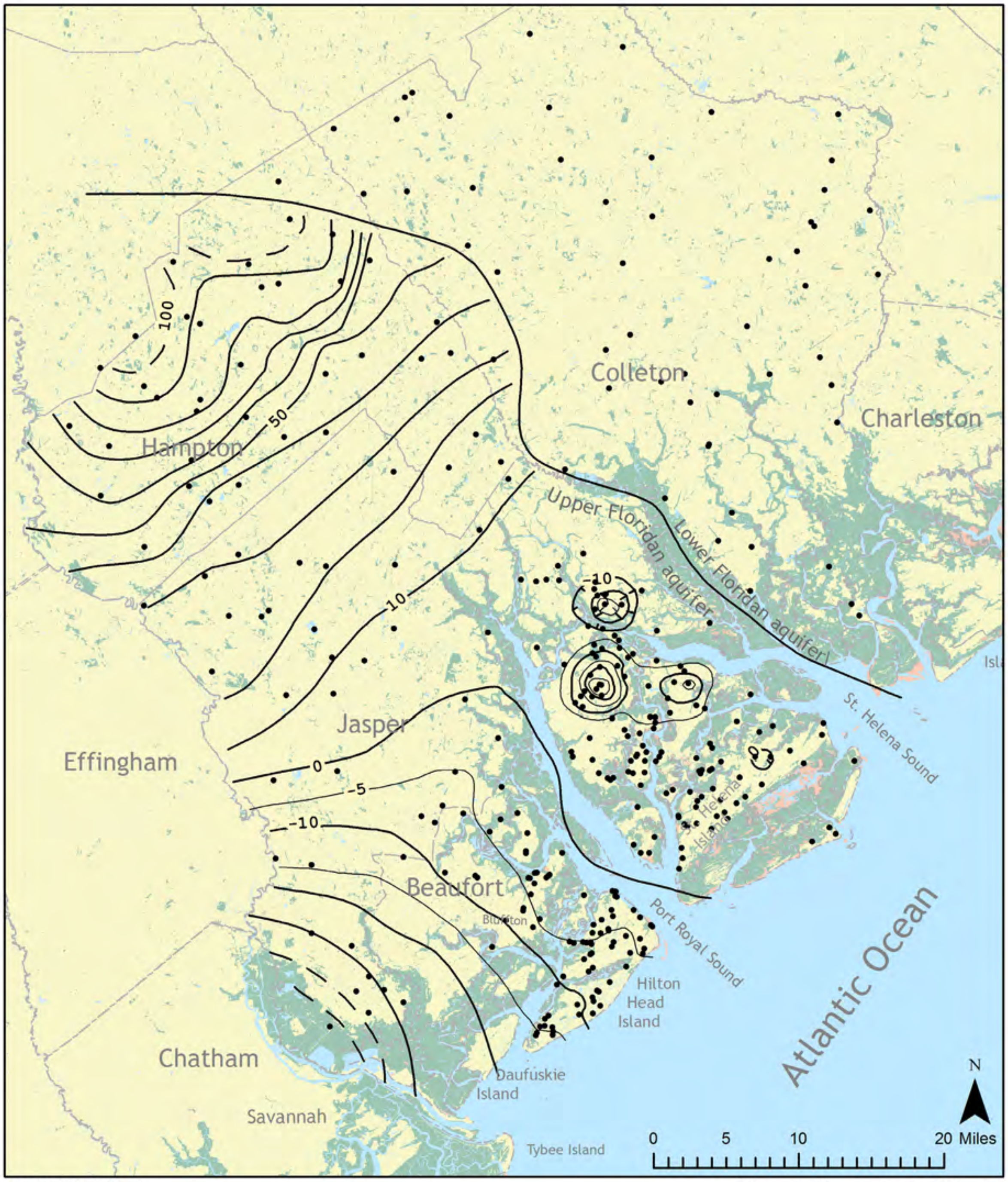
——— Approximate updip divide of the upper and lower Floridan aquifers.

● Well locations

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D16. The February 1992 potentiometric surface of the Upper Floridan aquifer in Beaufort, Jasper, Hampton, and Colleton Counties, S.C. (Gawne, 1994).



EXPLANATION

—10 – · Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

Approximate updip divide of the upper and lower Floridan aquifers.

● Well locations

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D17. The May 1992 potentiometric surface of the Upper Floridan aquifer in Beaufort, Jasper, Hampton, and Colleton Counties, S.C. (Gawne, 1994).

EXPLANATION

—10— · Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

—— Approximate updip divide of the upper and lower Floridan aquifers.

● Well locations

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D18. The November 1992 potentiometric surface of the Upper Floridan aquifer in Beaufort, Jasper, Hampton, and Colleton Counties, S.C. (Gawne, 1994).

EXPLANATION

—10— - Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

Approximate updip divide of the upper and lower Floridan aquifers.

● Well locations

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

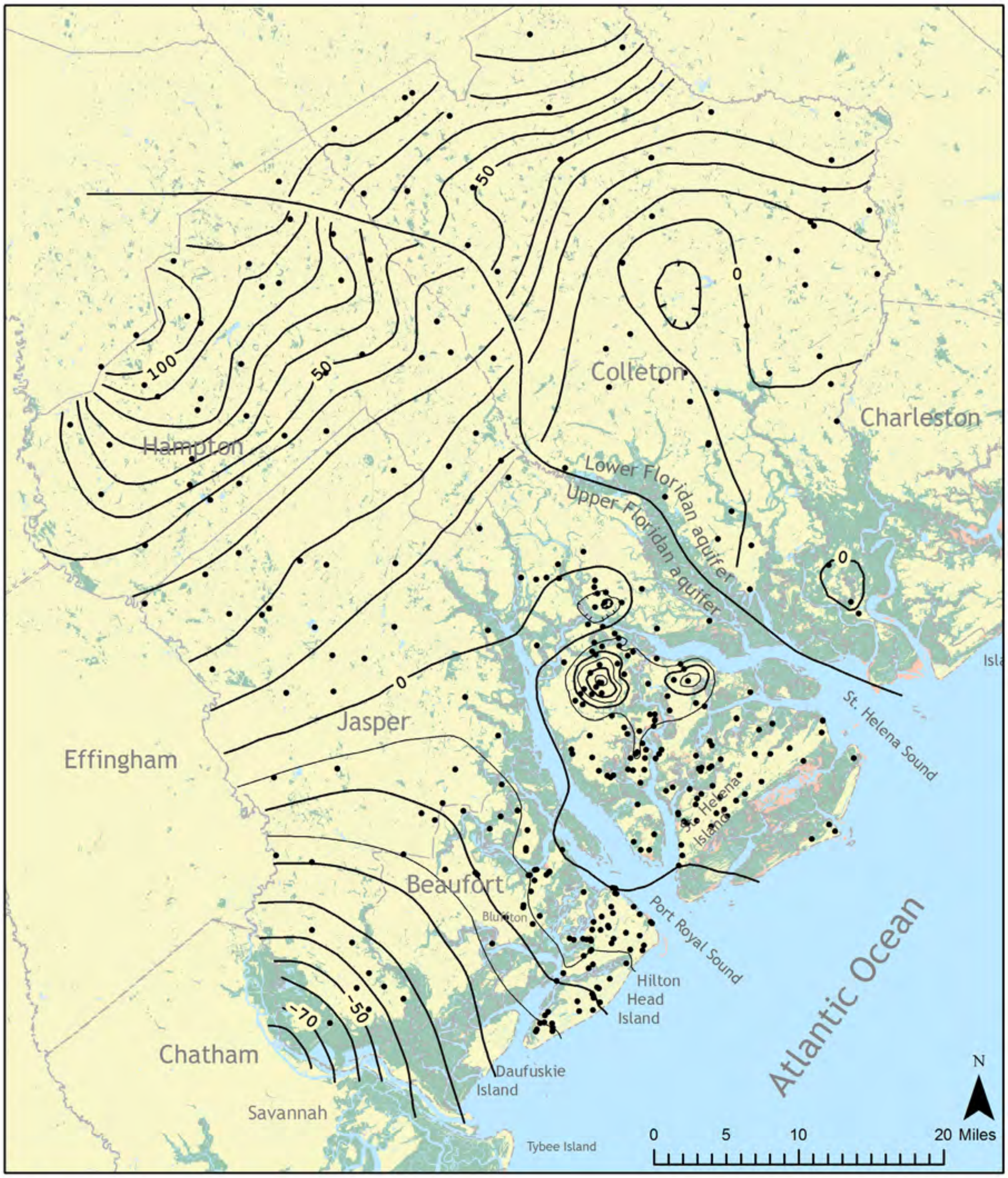
Bay, estuary or open water

Forested wetland or upland

Non-Forested wetlands

Sand/sand bar

Figure D19. The March 1993 potentiometric surface of the Upper Floridan aquifer in Beaufort, Jasper, Hampton, and Colleton Counties, S.C (Gawne, 1994).



EXPLANATION

—10 – - Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

—— Approximate updip divide of the upper and lower Floridan aquifers.

● Well locations

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D20. The November 1993 potentiometric surface of the Upper Floridan aquifer in Beaufort, Jasper, Hampton, and Colleton Counties, S.C. (Gawne, 1994).

EXPLANATION

—10— · Potentiometric contour. Shows altitude in feet above and below sea level. Contour interval 1,5, and 10 feet. Nation Geodetic Vertical Datum of 1929

—— Approximate updip divide of the upper and lower Floridan aquifers.

● Well locations

Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

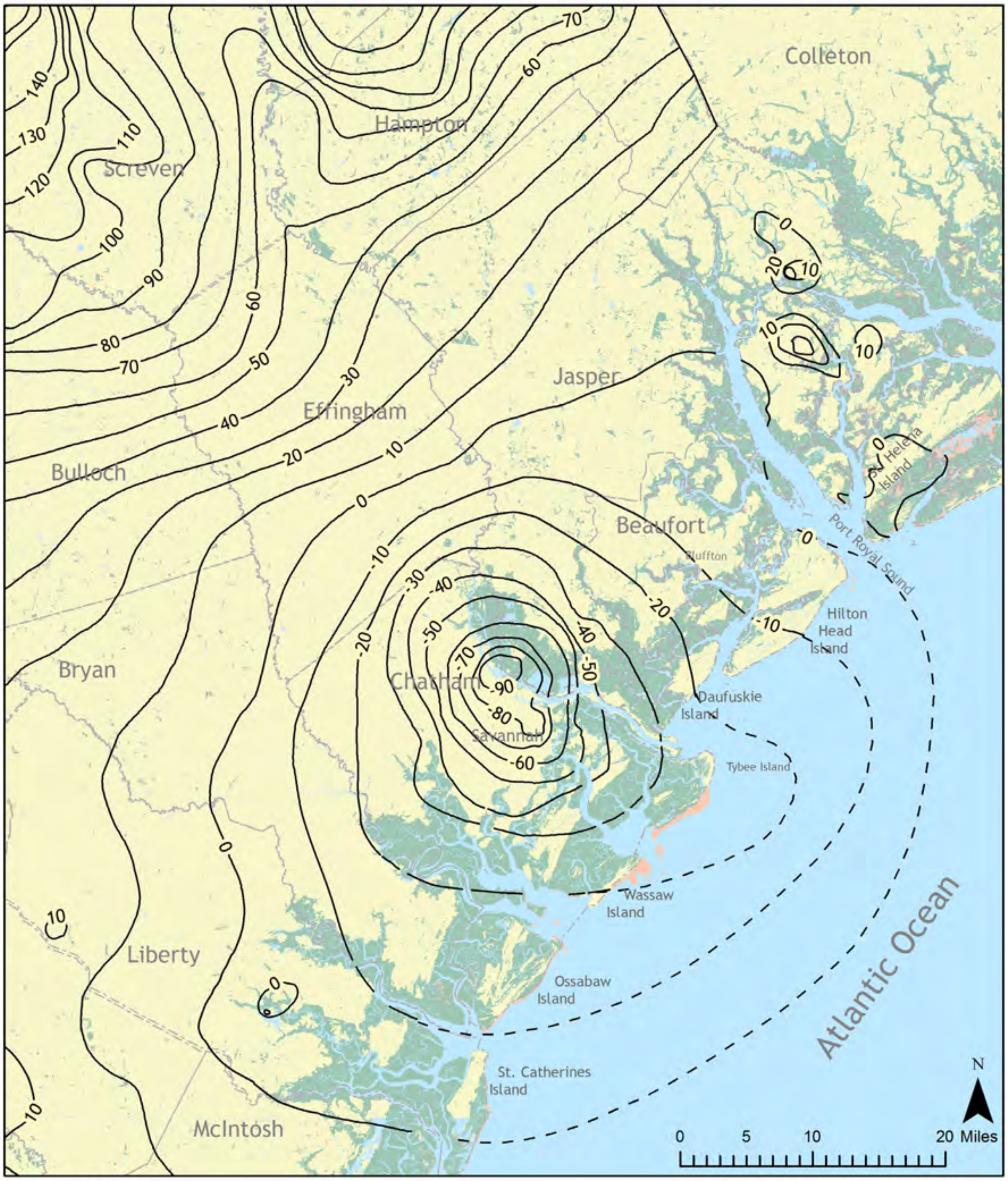
Bay, estuary or open water

Forested wetland or upland

Non-Forested wetlands

Sand/sand bar

Figure D21. The September 1998 potentiometric surface of the Upper Floridan aquifer in Beaufort, Jasper, Hampton, and Colleton Counties, S.C. (Ransom and White, 1999).



EXPLANATION

—10— · Potentiometric contour. Shows altitude in feet above and below sea level. Dashed where approximate. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

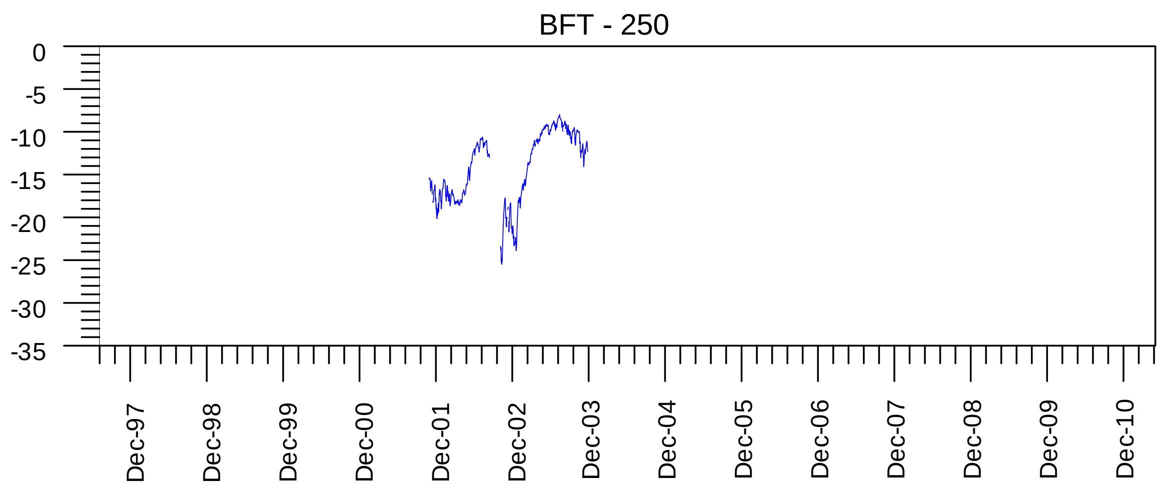
Base map data source (landforms):
U.S. Census Bureau
National Wetlands Inventory

- Bay, estuary or open water
- Forested wetland or upland
- Non-Forested wetlands
- Sand/sand bar

Figure D22. The May 1998 potentiometric surface of the Upper Floridan aquifer in the Savannah, Ga. area and adjacent parts of South Carolina (modified from Peck and others, 1999).

Appendix E.

Hydrographs for selected wells completed in the Upper Floridan aquifer.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-15
-20
-25
-30
-35
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Dec-98
Dec-99
Dec-00
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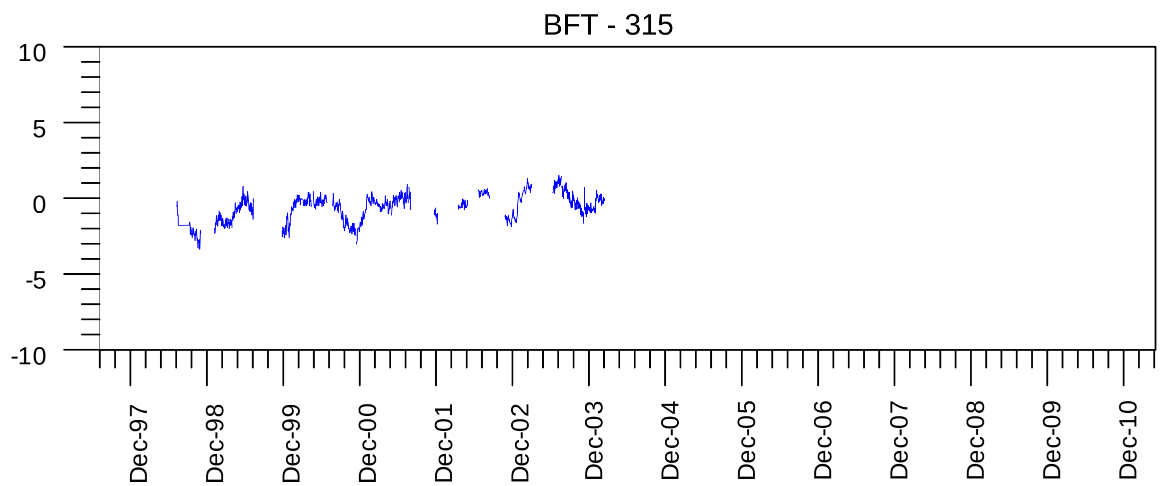
Dec-08
Dec-09
Dec-10


BFT - 315
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-10
Dec-97
Dec-98
Dec-99
Dec-00
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Dec-02
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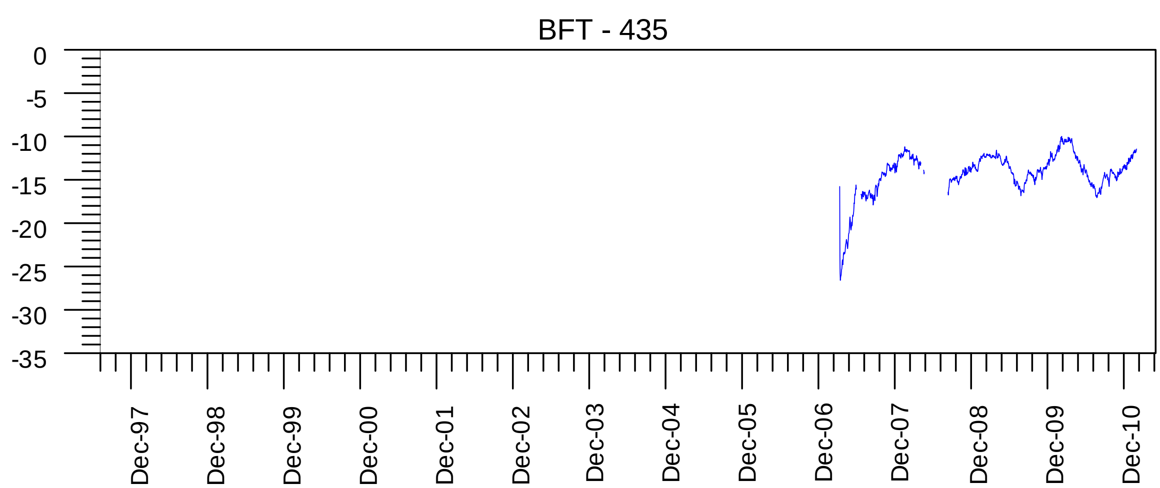
Dec-08
Dec-09
Dec-10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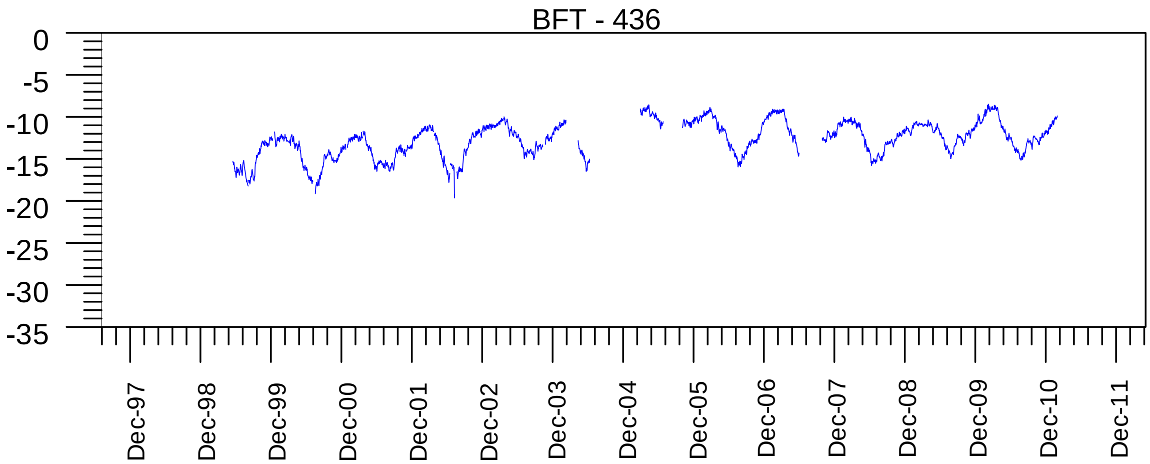
Dec-08
Dec-09
Dec-10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Dec-99
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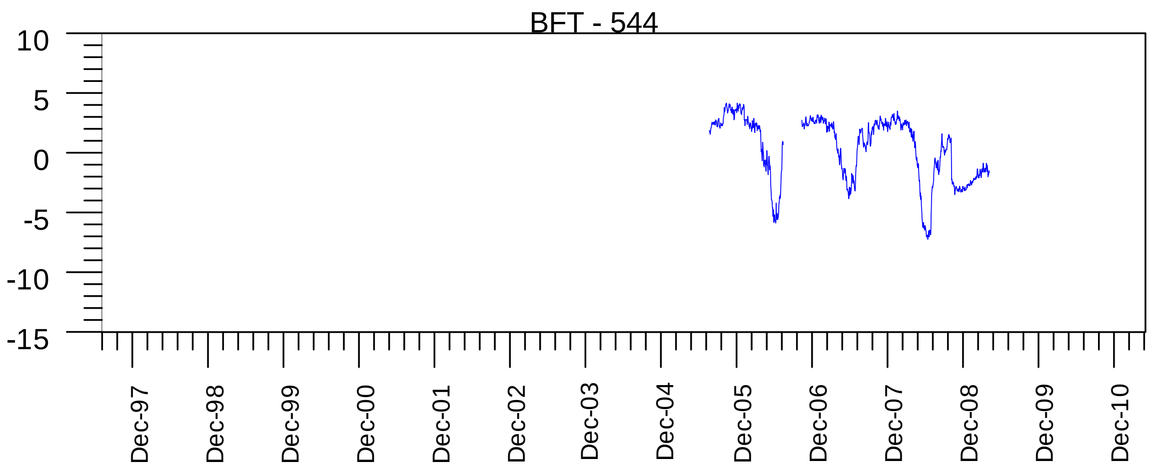
Dec-09
Dec-10
Dec-11


BFT - 544
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-10
-15
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Dec-98
Dec-99
Dec-00
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Dec-02
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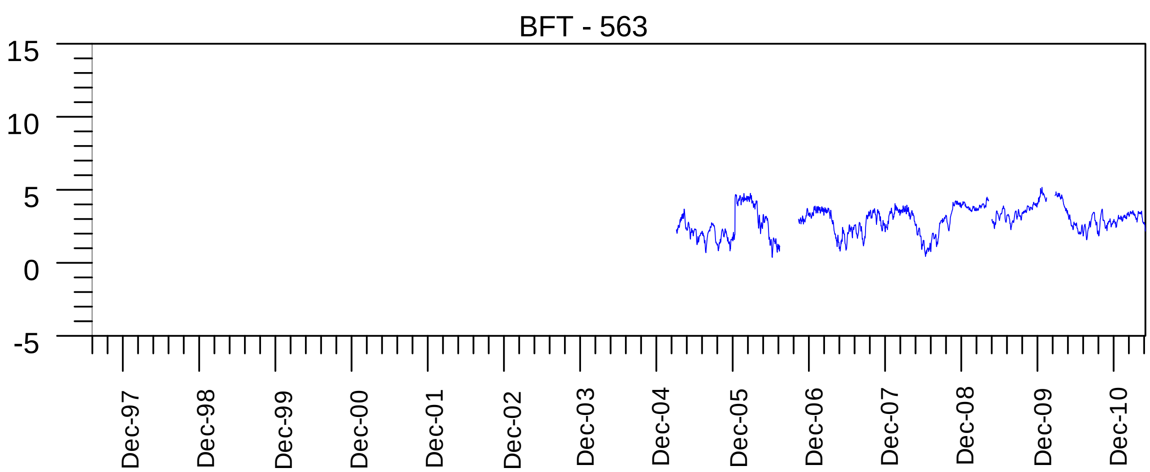
Dec-08
Dec-09
Dec-10


BFT - 563
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10
5
0
-5
Dec-97
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Dec-02
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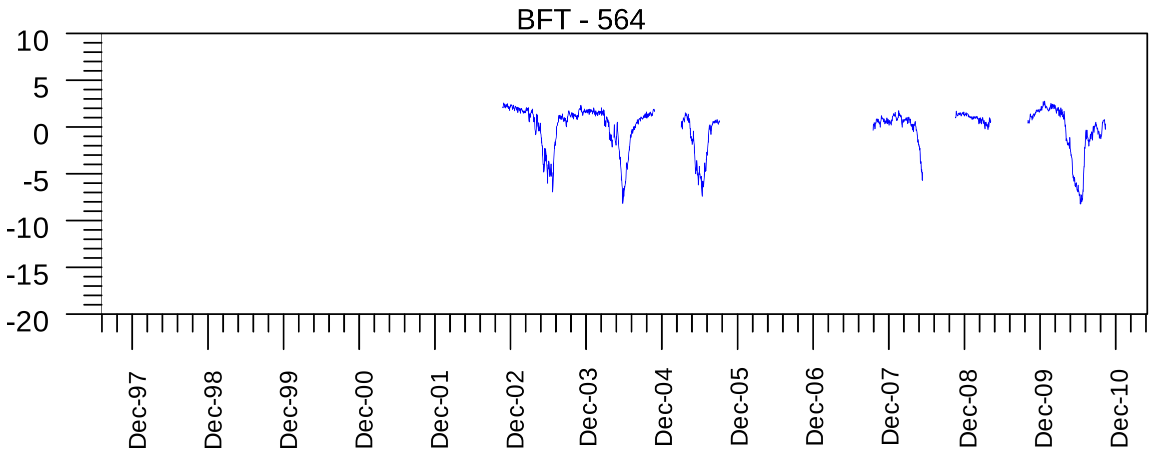
Dec-08
Dec-09
Dec-10


BFT - 564
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0
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Dec-06
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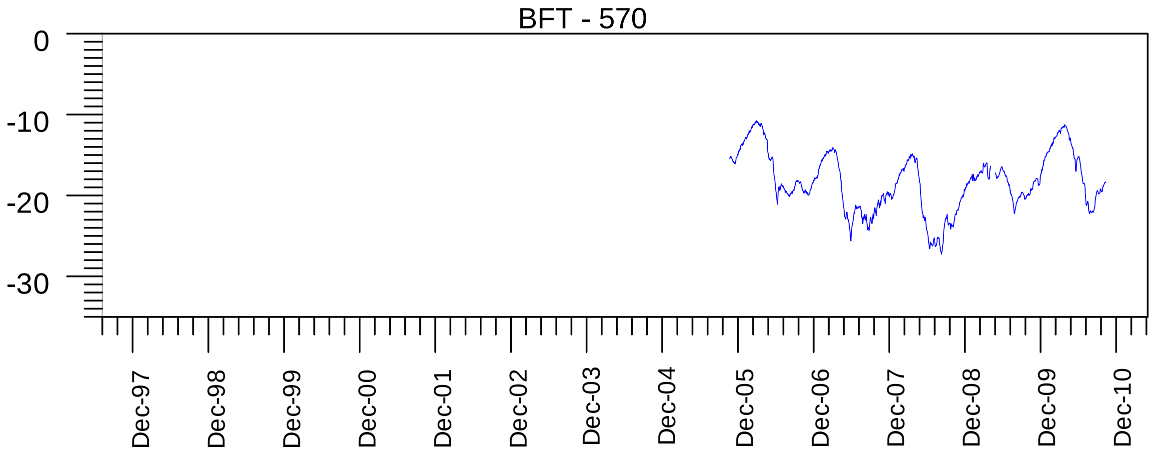
Dec-08
Dec-09
Dec-10


BFT - 570
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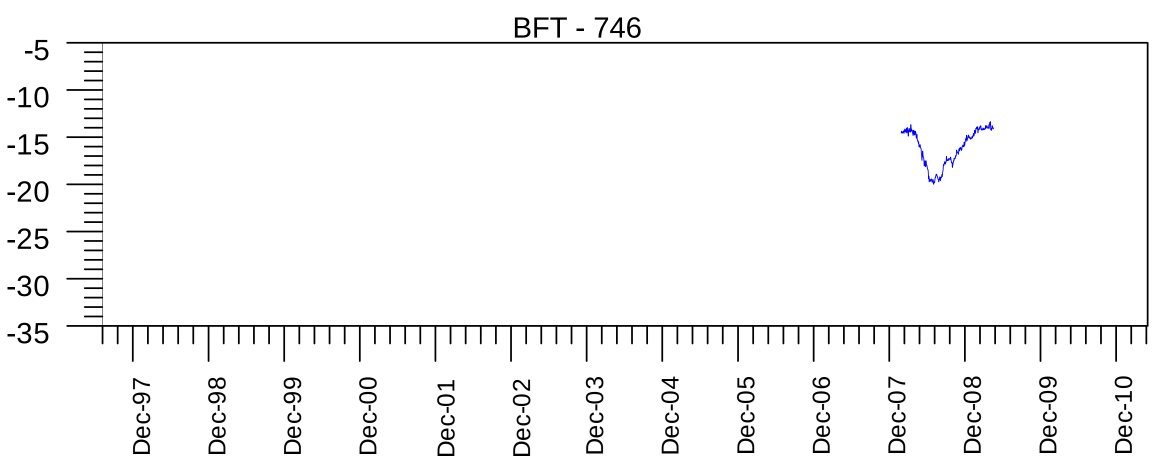
Dec-08
Dec-09
Dec-10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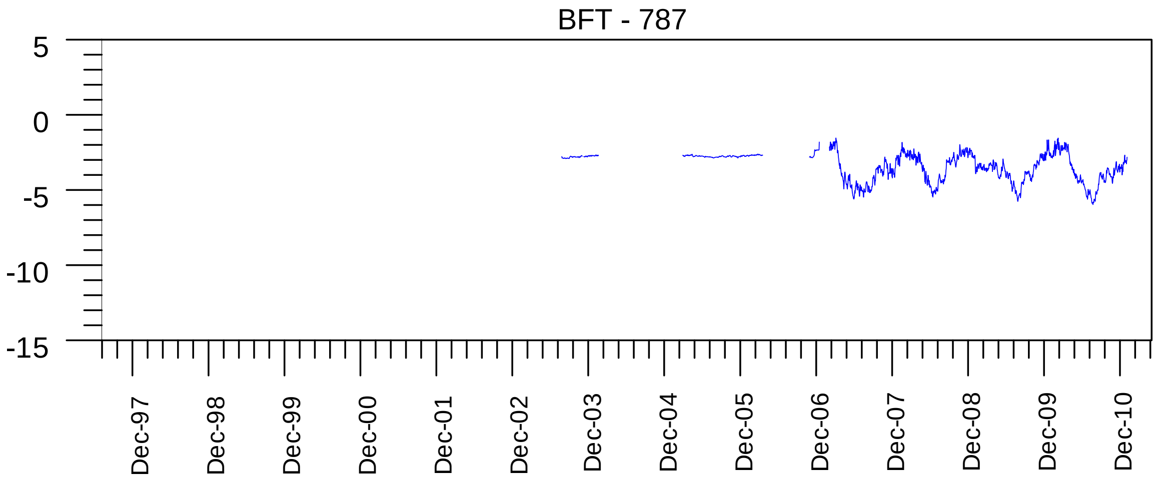
Dec-08
Dec-09
Dec-10


BFT - 787
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-5
-10
-15
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Dec-98
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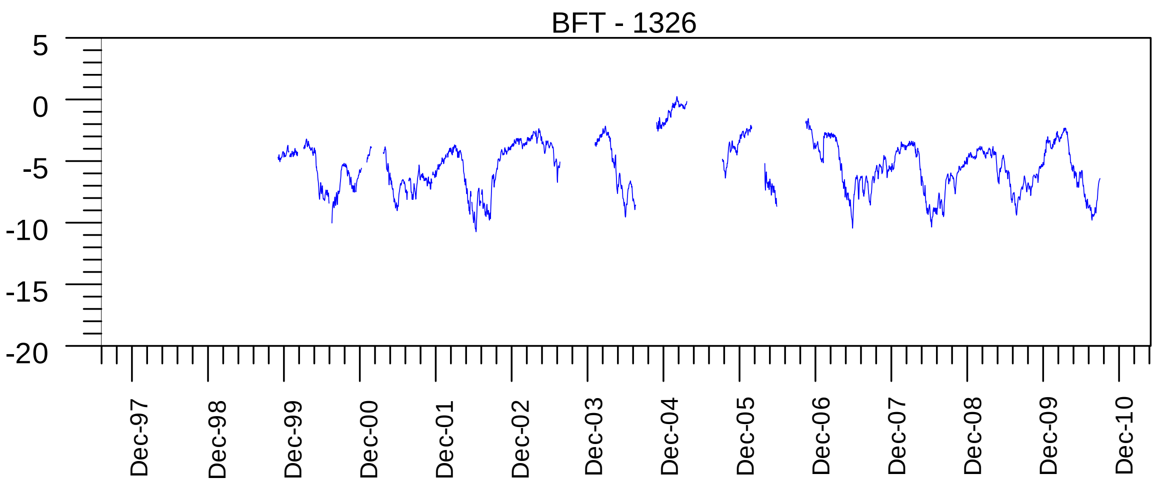
Dec-08
Dec-09
Dec-10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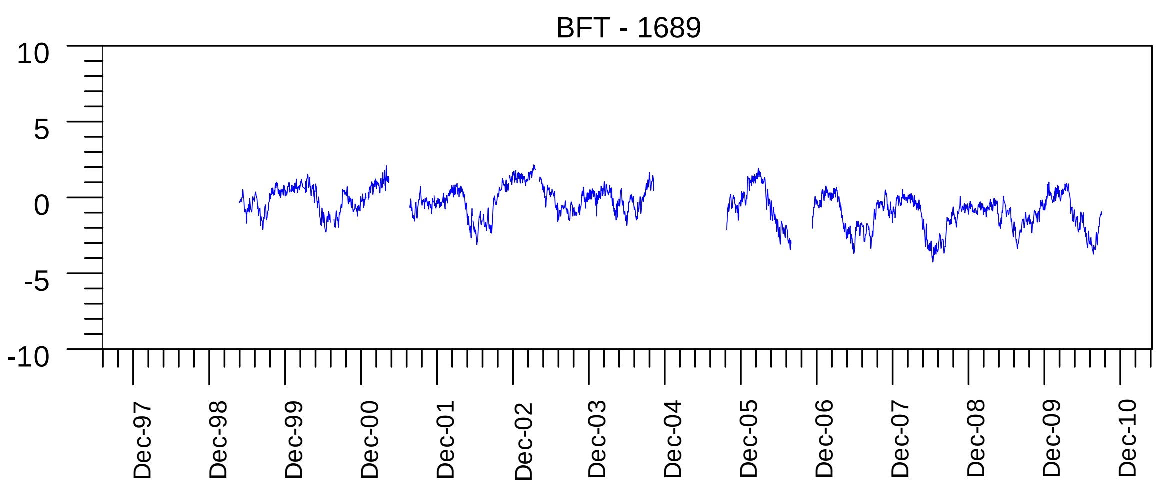
Dec-08
Dec-09
Dec-10


BFT - 1689
10
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0
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Dec-98
Dec-99
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Dec-01
Dec-02
Dec-03
Dec-04
Dec-05
Dec-06
Dec-07
Dec-08
Dec-09
Dec-10

Appendix F.

USGS laboratory derived porosity and hydraulic conductivity values from core samples in cooperation with SCDHEC from selected wells in Beaufort County, S.C., and Chatham County, Ga.

Tybee Island Core

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective porosity (m3/m3)	Saturated hydraulic conductivity (cm/s)	Saturated hydraulic conductivity (cm/day)
46.5 - 47.0	Surficial aquifer	0.69		2.5E-08	
47.0		0.69	0.63	1.4E-06	0.12
47.0				2.2E-07	0.02
47.0				2.5E-08	0.00
68.5 - 69.0					
72.0	Upper confining unit	0.44	0.42	6.3E-06	0.54
72.0				6.3E-06	0.55
72.0				6.5E-06	0.56
72.0				7.0E-06	0.60
72.0 - 72.5		0.44		7.0E-06	
76.5		0.49	0.46	5.2E-06	0.45
76.5				4.9E-06	0.43
76.5 - 77.0		0.49		4.9E-06	
77.5 - 78.0					
79.6 - 80.1		0.47		6.1E-06	
80.1		0.47	0.43	5.6E-06	0.49
80.1				6.1E-06	0.52
84.0 - 84.5		0.50		7.6E-07	
84.5		0.5	0.46	6.2E-07	0.05
84.5				7.6E-07	0.07
87.0 - 87.5		0.46		2.1E-07	
87.5		0.46	0.41	2.0E-07	0.02
87.5				2.2E-07	0.02
87.5				2.1E-07	0.02
87.5 - 88.0					
92.0 - 92.5		0.56		5.4E-07	
92.5		0.56	0.54	5.4E-07	0.05
96.5		0.53	0.5	1.1E-06	0.10
96.5				1.9E-06	0.17
96.5				7.4E-07	0.06
96.5 - 97.0		0.53		7.4E-07	
97.5 - 98.0					
106.5	Upper Floridan aquifer (Oligocene)	0.46	0.45	1.5E-04	12.80
106.5				1.5E-04	12.63
106.5 - 107.0		0.46		1.5E-04	
107.5 - 108.0					
112.0 - 112.5		0.35		9.9E-04	
112.5		0.35	0.35	1.1E-03	90.82
112.5				9.9E-04	85.85
117.5 - 118.0					
127.5 - 128.0					
138.0 - 138.5					

Tybee Island Core (cont'd)

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective porosity (m3/m3)	Saturated Hydraulic Conductivity (cm/s)	Saturated Hydraulic Conductivity (cm/day)
139.6	Upper Floridan aquifer (Oligocene)	0.32	0.31	2.2E-04	
139.6 - 140.1		0.32			
145.0 - 145.5					
156.0 - 156.5				4.5E-05	
164.6 - 165.1		0.28		4.5E-05	3.85
165.1		0.28	0.28		
167.5 - 168.0					
176.25 - 176.75				1.1E-04	
189.6 - 190.1		0.41		1.2E-04	10.45
190.1		0.41	0.4	1.1E-04	9.52
195.5 - 196.0					
197.5 - 198.0					

Long Island Core

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective Porosity (m3/m3)	Saturated Hydraulic Conductivity (cm/s)	Saturated Hydraulic Conductivity (cm/day)
44.0 - 44.5	Upper confining unit	0.47		1.2E-05	
44.5		0.47	0.43	1.2E-05	1.08
44.5				1.2E-05	1.03
54.6 - 55.0				3.7E-05	
55.0				3.7E-05	3.17
57.0 - 57.5		0.45		1.5E-07	
57.5		0.45	0.40	1.5E-07	0.01
61.5 - 62.0				2.6E-06	
66.5 - 67.0					
74.5 - 75.0		0.49		2.6E-06	
75.0				3.0E-06	0.26
75.0				2.6E-06	0.22
75.0 - 75.5		0.49		7.9E-06	
75.5		0.49	0.47	7.9E-06	0.68
96.5 - 97.0				3.2E-07	
97.0		0.49	0.47	3.2E-07	0.03
99.5				5.5E-08	0.00
99.5				5.2E-08	0.00
99.0 - 99.5	Upper Floridan aquifer (Oligocene)			5.2E-08	
167.5 - 168.0		0.15		3.0E-05	
168.0		0.15	0.15	2.6E-05	2.28
168.0				3.0E-05	2.63

Bull River 2 Core

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective Porosity (m3/m3)	Saturated Hydraulic Conductivity (cm/s)	Saturated Hydraulic Conductivity (cm/day)
2.5-3	Surficial aquifer	0.37		3.5E-05	
3.0		0.37	0.36	3.5E-05	3.00
3.5-4		0.35		5.2E-04	
4.0		0.35	0.35	5.2E-04	44.92
5.5-6		0.38		1.7E-04	
6.0		0.38	0.37	1.7E-04	15.09
6.0				1.7E-04	14.93
7.5-8		0.36		5.6E-04	
8.0		0.36	0.35	5.5E-04	47.92
8.0				5.6E-04	47.97
9.0		0.33	0.32	9.2E-04	79.33
9.0				1.1E-03	93.63
10-10.5		0.32		2.2E-03	
10.5		0.32	0.32	2.2E-03	185.95
11-11.5		0.56		9.7E-06	
11.5		0.56	0.54	1.1E-05	0.96
11.5				9.7E-06	0.84
12.5-13		0.53		8.7E-05	
13.0		0.53	0.49	8.7E-05	7.52
14-14.5		0.43		6.5E-04	
14.5		0.43	0.41	6.5E-04	56.09
15-15.5		0.73		5.9E-06	
15.5		0.73	0.69	5.9E-06	0.51
15.5-16					
18.0		0.44	0.43	8.3E-05	7.21
18.18.5		0.44		8.3E-05	
20.5-21					
23.0		0.35	0.34	3.6E-04	30.75
23.0				3.6E-04	30.70
23-23.5		0.35		3.6E-04	
29-29.5		0.66		1.8E-06	
29.0		0.66	0.63	3.0E-06	0.26
29.0				2.3E-06	0.20
29.0				1.8E-06	0.16
30-30.5				3.4E-05	
31.5		0.51	0.49	1.5E-04	13.36
31.5-32		0.51		1.5E-04	
35-35.5					
37.5		0.53	0.51	3.1E-04	27.90
37.5-38		0.53		3.1E-04	
40-40.5				2.0E-04	
43.0		0.47	0.45	3.7E-05	3.28

Bull River 2 Core (cont'd)

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective Porosity (m3/m3)	Saturated Hydraulic Conductivity (cm/s)	Saturated Hydraulic Conductivity (cm/day)
43-43.5	Surficial aquifer	0.47		3.7E-05	
45.25-45.75				1.8E-06	
47.5 - 48.0					
50.5 - 51.0				1.7E-05	
53.0 - 53.5				1.1E-07	
57.0 - 57.5	Paleo-channel			8.0E-05	
70.5 - 71.0				9.9E-05	
75.0		0.38	0.36	9.6E-05	8.70
75.0				8.1E-05	7.36
75-75.5		0.38		8.1E-05	
75.5 - 76.0	Upper confining unit				
78.0 - 78.5				1.1E-04	
80-80.5				1.5E-06	
80.5 - 81.0				6.4E-04	
83.0 - 83.5				8.7E-08	
86.0		0.45	0.43	1.6E-06	0.15
86-86.5		0.45		1.6E-06	
87.75 - 88.25				9.4E-08	
90-90.5				1.8E-06	
90.5 - 91.0					
93.5 - 94.0				3.1E-07	
95.5 - 96.0				2.5E-05	
98.0 - 98.5				1.9E-04	
100.0 - 101.5					
105.5 - 106.0				2.9E-06	
108.0 - 108.5				3.4E-06	
110.5 - 111.0					
112.5 - 113.0					
115.5 - 116.0				3.1E-06	
118.5 - 119.0				3.1E-05	
125.5 - 126.0				4.3E-05	

Bull River 3 Core

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective Porosity (m3/m3)	Saturated Hydraulic Conductivity (cm/s)	Saturated Hydraulic Conductivity (cm/day)
120.5 - 121.0	Upper Floridan aquifer (Oligocene)			1.2E-05	
122.5		0.41	0.41	7.1E-05	6.16
122.5 - 123.0		0.41		7.1E-05	
126.0 - 126.5				8.8E-05	
127.5		0.27	0.27	2.2E-06	0.19
127.5 - 128.0		0.27		2.2E-06	
131.0 - 131.5				6.1E-05	
132.5		0.25	0.25	1.4E-05	1.19
132.5 - 133.0		0.25		1.4E-05	
135.5 - 136.0				1.3E-04	
138.0		0.24	0.23	2.8E-05	2.43
138.0 - 138.5		0.24		2.8E-05	
141.7 - 142.2				2.3E-05	
142.7		0.27	0.27	2.3E-05	1.99
142.7 - 143.2		0.27		2.3E-05	
146.5 - 147.0				2.2E-05	
148.3		0.27	0.27	1.9E-05	1.62
148.3 - 148.8		0.27		1.9E-05	
151.0 - 151.5				7.0E-05	
152.5		0.28	0.27	3.0E-05	2.60
152.5 - 153.0		0.28		3.0E-05	
156.6 - 157.1				6.7E-04	
158.5		0.32	0.32	1.3E-04	11.13
158.5 - 159.0		0.32		1.3E-04	
163.0 - 163.5				3.2E-04	
163.5 - 164.0				4.9E-05	
166.5		0.34	0.34	1.3E-03	115.74
166.5 - 167.0		0.34		1.3E-03	
168.0 - 168.5		0.37		4.6E-04	
168.5		0.37	0.36	4.6E-04	39.85
171.5 - 172.0					
173.25 - 173.75		0.36		4.6E-05	
173.8		0.36	0.36	4.6E-05	4.01
176.5 - 177.0				3.9E-05	
177.5		0.35	0.34	9.2E-05	7.97
177.5 - 178.0		0.35		9.2E-05	

Bull River 3 Core (cont'd)

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective Porosity (m3/m3)	Saturated Hydraulic Conductivity (cm/s)	Saturated Hydraulic Conductivity (cm/day)
181.5 - 182	Upper Floridan aquifer (Oligocene)			2.3E-04	
183.5 - 184.0		0.31		4.5E-04	
184.0		0.31	0.31	4.5E-04	39.24
186.5 - 187.0				5.3E-05	
188.5 - 189.0				8.0E-06	
192.5 - 193.0	Upper Floridan aquifer (Eocene)			7.3E-05	
208.0 - 208.5				5.6E-05	
214.0 - 214.5				1.1E-05	
217.5 - 218.0					
222.5 - 223.0				6.7E-05	
227.0 - 227.5				5.1E-04	
238.0 - 238.5				3.7E-04	

Wexford Plantation Core

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective Porosity (m3/m3)	Saturated Hydraulic Conductivity (cm/s)	Saturated Hydraulic Conductivity (cm/day)
6.0 - 6.5				6.0E-04	
7.5 - 8.0				2.9E-04	
11.5 - 12.0					
12.0		0.44	0.42	2.9E-04	24.80
12.0 - 12.5		0.44		2.9E-04	
13.5 - 14.0				4.1E-04	
16.0		0.39	0.37	1.3E-04	11.16
16.0 - 16.5		0.39		1.3E-04	
21.5 - 22.0				1.3E-04	
27.0		0.40	0.39	8.8E-05	7.64
27.0 - 27.5		0.40		8.8E-05	
27.5 - 28.0					
28.0 - 28.5					
31.0	Surficial aquifer	0.49	0.46	1.3E-04	11.12
31.0 - 31.5		0.49		1.3E-04	
32.5 - 33.0		0.51		1.8E-06	
33.0		0.51	0.46	2.7E-06	0.24
33.0				1.8E-06	0.15
37.0 - 37.5				3.1E-06	
38.0 - 38.5				2.4E-08	
42.0 - 42.5				8.2E-05	
43.0 - 43.5				7.5E-05	
47.0		0.31	0.31	4.0E-04	34.28
47.0 - 47.5		0.31		4.0E-04	
48.0 - 48.5				4.7E-04	
52.0		0.30	0.30	3.2E-04	27.32
52.0 - 52.5		0.30		3.2E-04	
53.0 - 53.5				3.8E-04	
57.0 - 57.5					
58.0 - 58.5				2.0E-04	
62.0 - 62.5				3.1E-06	
67.0	Upper Floridan aquifer (Oligocene)	0.29	0.28	2.2E-06	0.19
67.0 - 67.5		0.29		2.2E-06	
72.0		0.26	0.25	1.1E-04	9.74
72.0 - 72.5		0.26		1.1E-04	
82.0		0.27	0.26	5.3E-04	45.58
82.0 - 82.5		0.27		5.3E-04	
87.0		0.33	0.32	1.4E-05	1.21

Wexford Plantation (cont'd)

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective Porosity (m3/m3)	Saturated Hydraulic Conductivity (cm/s)	Saturated Hydraulic Conductivity (cm/day)
87.0 - 87.5	Upper Floridan aquifer (Oligocene)	0.33		1.4E-05	
87.0		0.38	0.36	1.4E-05	1.22
92.0		0.25	0.25	5.6E-06	0.48
92.0 - 92.5		0.38		5.6E-06	
93.0 - 93.5				5.1E-05	
97.0 - 97.5				6.5E-06	
98.0 - 98.5				3.6E-04	
102.0 - 102.5				4.7E-04	
107.0		0.27	0.26	2.4E-04	21.05
107.0 - 107.5		0.25		2.4E-04	
111.0 - 111.5				2.9E-04	
117.0		0.36	0.36	4.1E-06	0.35
117.0 - 117.5		0.27		4.1E-06	
118.0 - 118.5					
122.0 - 122.5				1.4E-04	
124.0 - 124.5				3.7E-05	
127.0 - 127.5				4.3E-04	
138.0 - 138.5	Upper Floridan aquifer (Eocene)			1.6E-03	
141.0		0.39	0.38	1.2E-04	10.37
141.0 - 141.5		0.36		1.2E-04	
142.5 - 143.0		0.39		2.0E-04	
143.0		0.28	0.27	2.0E-04	16.89
147.0 - 147.5				2.5E-03	
148.0 - 148.5				4.5E-05	
152.0		0.35	0.35	1.8E-04	15.58
152.0 - 152.5		0.28		1.8E-04	
153.0 - 153.5				4.2E-06	
157.0 - 157.5				2.0E-04	
158.0 - 158.5				1.4E-04	
162.0 - 162.5					
167.0 - 167.5		0.35		3.2E-03	
171.5 - 172.0		0.26		4.9E-05	
172.0		0.26	0.26	4.9E-05	4.20
177.0 - 177.5					
178.7 - 179.3				6.5E-04	
182.0 - 182.5					
183.0 - 183.5					
187.0 - 187.5				1.0E-03	
188.0 - 188.5					
192.0 - 192.5					
197.5 - 198.0		0.42		3.6E-04	
198.0		0.42	0.42	3.6E-04	30.79

Shipyard Road Core

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective Porosity (m3/m3)	Saturated Hydraulic Conductivity (cm/s)	Saturated Hydraulic Conductivity (cm/day)
12.0		0.36	0.33		
12.0 - 12.5		0.36		2.5E-03	
14.0		0.44	0.40		
14.0 - 14.5		0.44		1.7E-06	
17.0				5.6E-07	0.05
17.0 - 17.5				5.6E-07	
18.0 - 18.5					
22.0		0.58	0.50		
22.0 - 22.5		0.58		3.0E-07	
23.0				3.9E-08	0.00
23.0 - 23.5				3.9E-08	
27.0		0.54	0.47		
27.0 - 27.5		0.54		3.8E-04	
28.0 - 28.5	Surficial aquifer				
32.0 - 32.5					
33.0 - 33.5					
37.0				6.3E-07	0.05
37.0 - 37.5				6.3E-07	
38.0				5.0E-07	0.04
38.0 - 38.5				5.0E-07	
42.0		0.46	0.43		
42.0 - 42.5		0.46		4.7E-05	
43.5 - 44.0					
47.0				6.0E-05	5.19
47.0 - 47.5				6.0E-05	
48.0				1.5E-04	12.71
48.0 - 48.5				1.5E-04	
52.0				5.8E-04	50.29
52.0 - 52.5				5.8E-04	
53.0 - 53.5					
57.0		0.36	0.31		
57.0 - 57.5		0.36		6.6E-04	
58.0				6.5E-07	0.06
58.0 - 58.5				6.5E-07	
62.0	Upper confining unit	0.49	0.44		
62.0 - 62.5		0.49		5.6E-06	
63.5 - 64.0					
67.0		0.54	0.50		
67.0 - 67.5		0.54		3.5E-05	
69.0 - 69.5					
72.0 - 72.5					

Shipyard Road Core (cont'd)

Depth (ft bgs)	Hydro-geologic units	Porosity (m3/m3)	Effective Porosity (m3/m3)	Saturated Hydraulic Conductivity (cm/s)	Saturated Hydraulic Conductivity (cm/day)
74.0 - 74.5	Upper confining unit				
77.0		0.50	0.48		
77.0 - 77.5		0.50		5.0E-05	
78.0				2.7E-05	2.35
78.0 - 78.5				2.7E-05	
82.0		0.56	0.47		
82.0 - 82.5		0.56		1.2E-06	
83.0				2.8E-07	0.02
83.0 - 83.5				2.8E-07	
87.0 - 87.5					
88.0 - 88.5					
92.0		0.76	0.70		
92.0 - 92.5		0.76		2.5E-05	
93.5 - 94.0					
97.0 - 97.5					
98.0 - 98.5					
100.7		0.62	0.59		
100.7 - 101.3		0.62		4.9E-06	
103.0 - 103.5					
107.0 - 107.5					
108.0 - 108.5					
110.5		0.63	0.58		
110.5 - 111.0		0.63		5.4E-06	
113.0 - 113.5					
117.0 - 117.5					
118.0 - 118.5					
124.0 - 124.5					
128.0 - 128.5					
132.0		0.61	0.57		
132.0 - 132.5		0.61		4.5E-06	
133.0 - 133.5					
137.0 - 137.5					
138.0 - 138.5					

Hydrogeological unit	Tybee Island Savannah GA	BFT - 2411 Long Island	Bull River 2 Savannah GA	Bull River 3 Savannah GA	BFT - 2410 Wexford Plant	Shipyard Road Savannah GA	Total Average
Average Porosity							
Surface aquifer	69.1%	NS	46.1%	NS	40.5%	46.4%	45.8%
Channel deposits	NS	NS	37.8%	NS	NS	NS	37.8%
Upper confining unit	49.3%	47.6%	45.1%	NS	NS	57.7%	51.9%
Upper Floridan aquifer (Oligocene)	36.4%	15.4%	NS	31.1%	29.8%	NS	31.2%
Upper Floridan aquifer (Eocene)	NS	NS	NS	NS	34.0%	NS	34.0%

Hydrogeological unit	Tybee Island Savannah GA	BFT - 2411 Long Island	Bull River 2 Savannah GA	Bull River 3 Savannah GA	BFT - 2410 Wexford Plant	Shipyard Road Savannah GA	Total Average
Average hydraulic conductivity (cm/s)							
Surface aquifer	4.1E-07	NS	3.2E-04	NS	2.1E-04	2.4E-04	2.6E-04
Channel deposits	NS	NS	8.8E-05	NS	NS	NS	8.8E-05
Upper confining unit	3.1E-06	8.1E-06	6.7E-05	NS	NS	5.6E-05	2.9E-05
Upper Floridan aquifer (Oligocene)	3.4E-04	2.2E-05	4.3E-05	1.8E-04	1.4E-04	NS	1.9E-05
Upper Floridan aquifer (Eocene)	NS	NS	NS	1.8E-04	5.9E-04	NS	4.9E-04

NS = Not sampled

Appendix G.

Chloride concentration (mg/L) in pore water extracted from the surficial aquifer, upper confining unit, and Upper Floridan aquifer at test wells in Beaufort County, S.C., and Chatham County, Ga.

Laboratory analysis for chloride concentrations were determined by the USGS in cooperation with SCDHEC and by USACE as part of the Savannah Harbor Expansion (SHE) Project

Refer to figures 31 and 63 for locations of test wells.

Bull River 1 2001				Bull River 2 2009		Bull River 3 2009		BFT - 2411 2008		Shipyard Road 2009	
ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)
-1.28	121	-126.28	30	3.22	285	-70.53	6150	-10.31	2180	-2.14	2810
-6.28	878	-146.28	40	-1.78	2960	-113.53	88.4	-15.31	1442.3	-4.64	10700
-11.28	5323	-166.28	32	-6.28	7140	-118.53	24.9	-20.31	4609.4	-29.64	21100
-16.28	12520			-16.28	15400			-25.31	7644.5	-32.14	21200
-21.28	17088			-36.28	8420			-39.31	11114	-37.14	19000
-26.28	12779			-51.28	13200			-44.31	6188.1	-52.14	28600
-31.28	12653			-56.28	2360			-54.31	1904	-57.14	24200
-36.28	11246			-61.28	301			-59.31	995.3	-62.14	15000
-41.28	11890			-66.78	7280			-64.31	539.9	-67.14	10200
-46.28	8953			-67.28	8150			-69.31	244.2	-72.14	7080
-51.28	8300			-67.78	2260			-74.31	103.2	-82.14	3010
-56.28	8000			-71.28	6280			-79.31	58.8	-87.14	2110
-61.28	8200			-81.28	2260			-84.31	61.8	-97.14	345
-66.28	8200			-91.28	263			-94.31	45.7	-117.14	60.1
-68.78	7898							-99.31	36.8		
-71.28	6339							-104.31	27.3		
-76.28	4496							-109.31	22.4		
-81.28	1833							-114.31	26.6		
-86.28	524							-119.31	21.5		
-91.28	180							-124.31	21.6		
-96.28	134							-129.31	16.08		
-101.28	65							-139.31	18.7		
-106.28	70							-144.31	18.5		
-111.28	50							-149.31	34.2		
-116.28	17										
-121.28	95										

Explanation

Surficial aquifer
Paleo-channel

Upper Floridan aquifer (Oligocene)

Upper confining unit

Upper Floridan aquifer (Eocene)

99 Chloride concentration

Tybee Island 2009		BFT - 2410 2009		SHE - 9 2004		SHE - 10 2004		SHE - 11 2004		SHE - 13 2004	
ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)
-2.19	200.69	0.57	91.6	-1.8	4212	13.5	5086	-48.1	5195	-50.9	17423
-7.29	49.9	-24.43	4290	-5.8	5421	3.5	4374	-56.1	3572	-52.4	19760
-12.19	71.3	-29.43	11000	-9.8	4201	-6.5	331	-58.6	5210	-56.4	16518
-17.29	115.8	-34.43	9120	-13.8	4871	-10.5	1769	-66.6	7879	-62.9	9972
-22.29	2961.4	-39.43	4160	-20.1	901	-40.5	820	-79.1	1418	-73.1	7677
-27.29	9261.5	-49.43	5270	-21.8	1212	-50.5	809	-90.6	971	-78.7	4484
-32.29	8984.5	-81.93	4241	-24.8	1264	-55.5	755	-97.3	936	-82.9	1760
-42.29	3688.2	-86.93	2860	-29.2	2154	-68.5	761	-100.6	782	-86.9	1062
-47.29	1835.8	-91.93	3250	-29.8	1298	-76.5	453	-106.3	501	-91.9	492
-51.19	1801.9	-96.93	1119	-44.4	1523	-83.5	451			-97.6	281
-63.19	5560.4	-106.93	257	-52.7	1542	-91.5	220			-104.4	153
-66.19	3062.9	-111.93	126	-71.1	910	-98.5	179				
-71.19	1908.8	-121.93	114	-87.7	917	-104.5	141				
-76.19	633	-125.93	85	-97.8	901	-112.5	130				
-81.19	279.1	-129.43	84	-112.7	987	-128.5	76				
-86.19	92.4	-134.43	136	-115.9	904						
-97.29	31.3	-146.93	199	-119.3	2189						
-101.29	54.8	-149.43	206	-128.2	1847						
-121.29	44.4	-154.43	279	-130.9	910						
-131.29	50.3	-161.93	364	-149.2	961						
-136.29	29.6	-176.93	195	-164.7	910						
-146.29	57.4	-189.93	178	-175.8	480						
-151.29	31.2			-184.6	310						
-156.29	39.6										
-161.29	61										
-166.29	29.7										

Explanation

Surficial aquifer

Upper Floridan aquifer (Oligocene)

Upper confining unit

Upper Floridan aquifer (Eocene)

99 Chloride concentration

SHE - 14 2004		SHE - 15 2004		SHE - 16 2004		SHE - 17 2004		BFT - 2249 2000		BFT - 2295 2001	
ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)
-45.2	14405	-41.1	4296	-41.8	12381	-39.5	15601	-54	7030	-43	13800
-52.9	5198	-48.7	3237	-46.6	5252	-39.5	15655	-59	6060	-78	15300
-56.6	6570	-52.3	7209	-51.6	2810	-44.2	6548	-62	4290	-164	600
-65.6	14687	-53.1	3573	-56.6	1245	-51.8	2666	-69	2150	-173	540
-65.6	15916	-57.7	1400	-61.6	629	-51.8	3044	-71	2610	-176	580
-66.1	13334	-64.1	279	-69.6	176	-57.6	2791				
-71.6	2709	-74.7	130	-79.6	66	-58.7	1663				
-76.7	462	-89	91	-89.6	24	-68.2	680				
-81.6	186	-101.6	45	-97.6	16	-82.2	74				
-87.1	256	-111.5	192	-99.6	24	-90.9	39				
-92.8	69	-114.1	172			-97.2	28				
-96.1	151	-120.6	50								
		-120.6	49								
		-123.4	50								
		-135.6	18								
		-145	12								
		-154.8	22								
		-170.8	11								
		-180.3	14								
		-193.4	24								

Explanation

Surficial aquifer

Upper Floridan aquifer (Oligocene)

Upper confining unit

Upper Floridan aquifer (Eocene)

99 Chloride concentration

BFT - 2250 2000		BFT - 2297 2001		JAS-0500 2012			
ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)	ft Msl	Cl (mg/L)
-55	17500	-56	1300	-0.5	1100	-100.5	14
-56	15900	-61	320	-5.5	5600	-105.5	13
-68	3730	-62	140	-10.5	6900	-110.5	55
-74	1850	-70	120	-15.5	6700	-115	11
-76	1260	-75	360	-20.5	6000	-117	16
-84	510			-25.5	6000	-121.3	37
-116	88			-30.5	5800	-125.5	22
-124	57			-35.5	8200	-130.5	47
-135	33			-36.4	8000	-135.5	14
-167	23			-40.6	6300	-140.5	13
-219	47			-45.5	6700	-181.5	47
				-50.5	3400		
				-55.5	1200		
				-60.5	350		
				-65.5	270		
				-70.5	150		
				-73	130		
				-80.5	37		
				-85.5	17		
				-91.5	29		
				-95.5	12		

Explanation

Surficial aquifer

Upper Floridan aquifer (Oligocene)

Upper confining unit

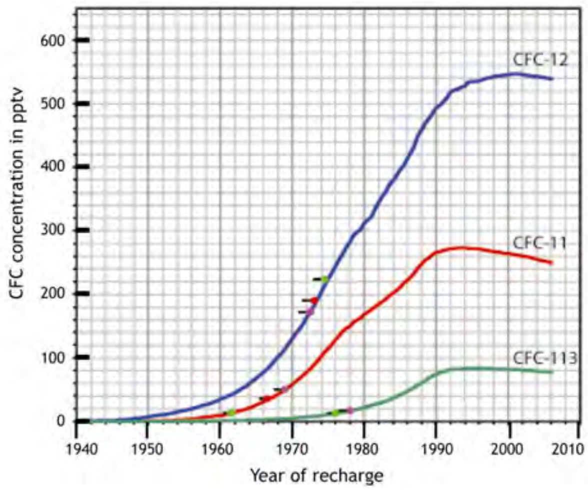
Upper Floridan aquifer (Eocene)

99 Chloride concentration

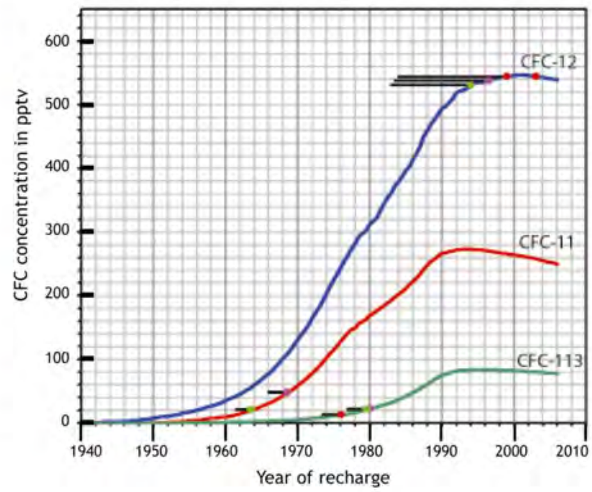
Appendix H.

Graphs (USGS) showing residual atmospheric concentrations of chlorofluorocarbons at selected wells, 1940 to 2006.

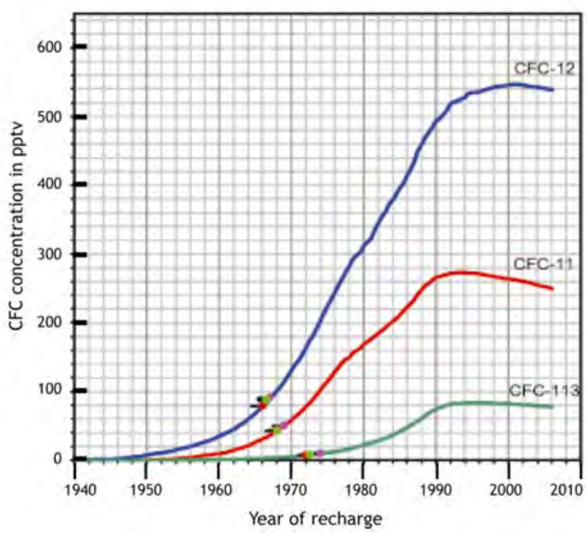
Pinckney Island (BFT - 2312)



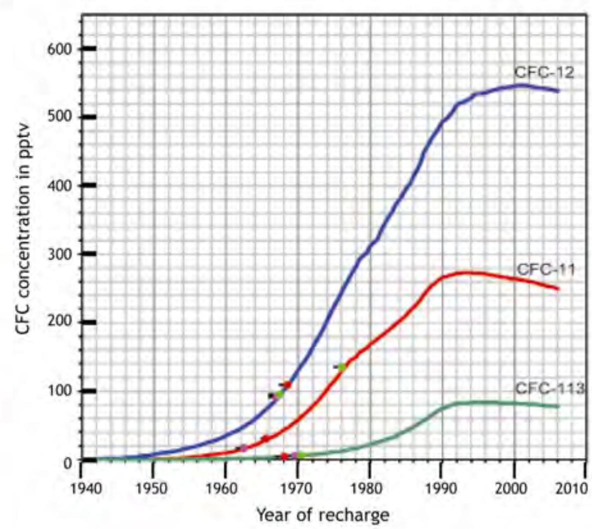
Pinckney Island - MacKay Creek

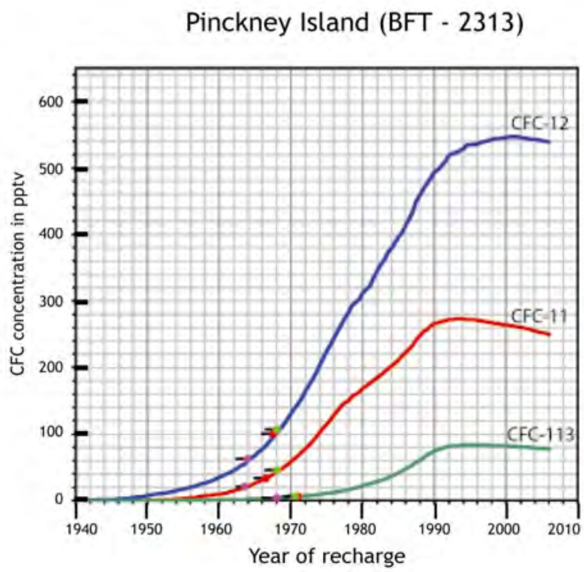


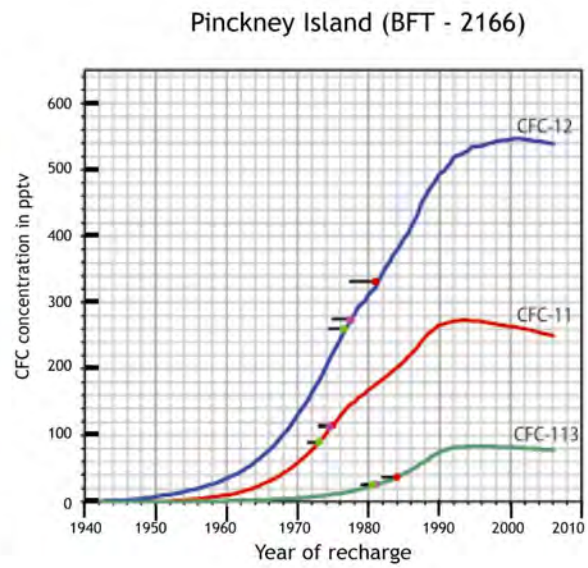
Hilton Head Island (BFT - 2200)

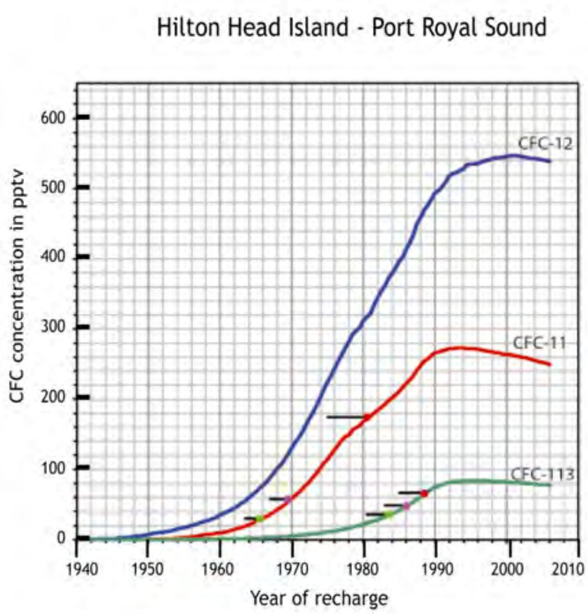


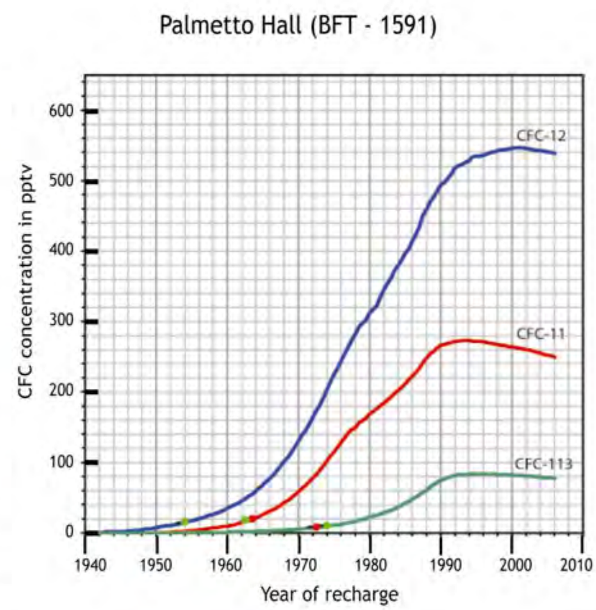
Colleton River Plantation (BFT - 2301)




Pinckney Island (BFT - 2313)
CFC concentration in pptv
Year of recharge
CFC-12
CFC-11
CFC-113

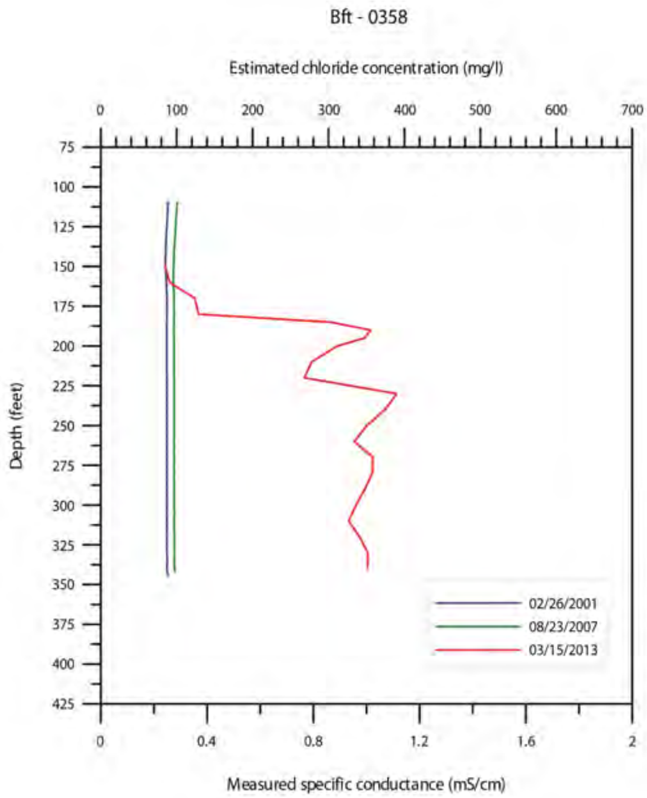

Pinckney Island (BFT - 2166)
CFC concentration in pptv
Year of recharge
CFC-12
CFC-11
CFC-113

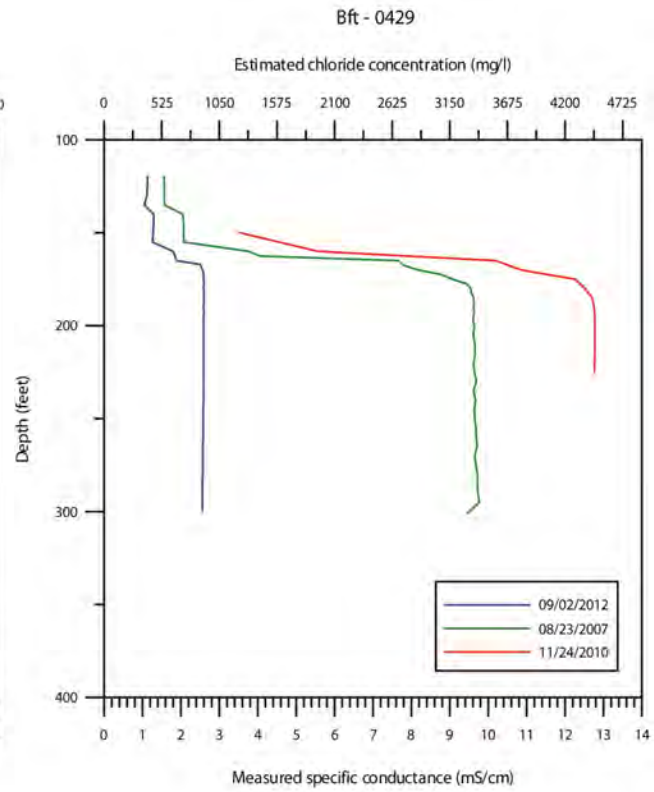

Hilton Head Island - Port Royal Sound
CFC concentration in pptv
Year of recharge
CFC-12
CFC-11
CFC-113

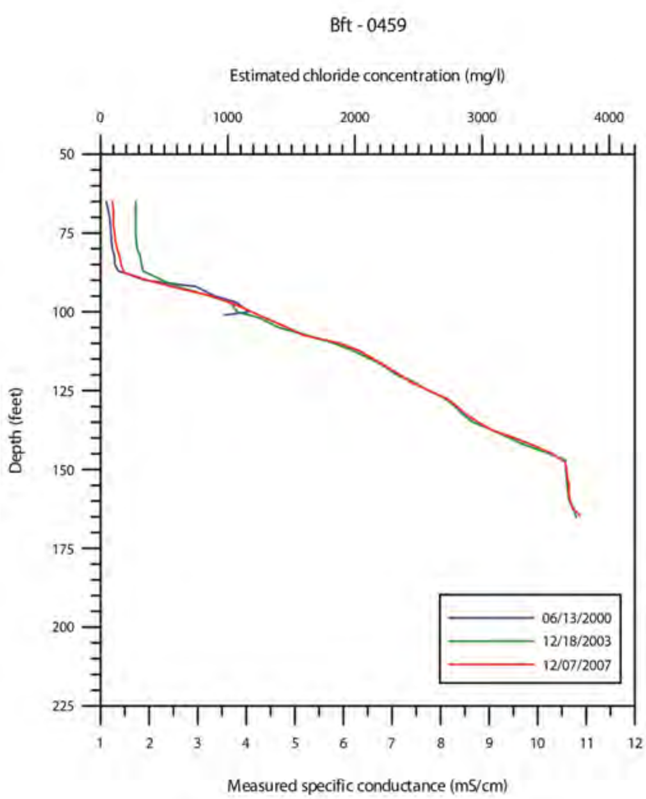

Palmetto Hall (BFT - 1591)
CFC concentration in pptv
Year of recharge
CFC-12
CFC-11
CFC-113

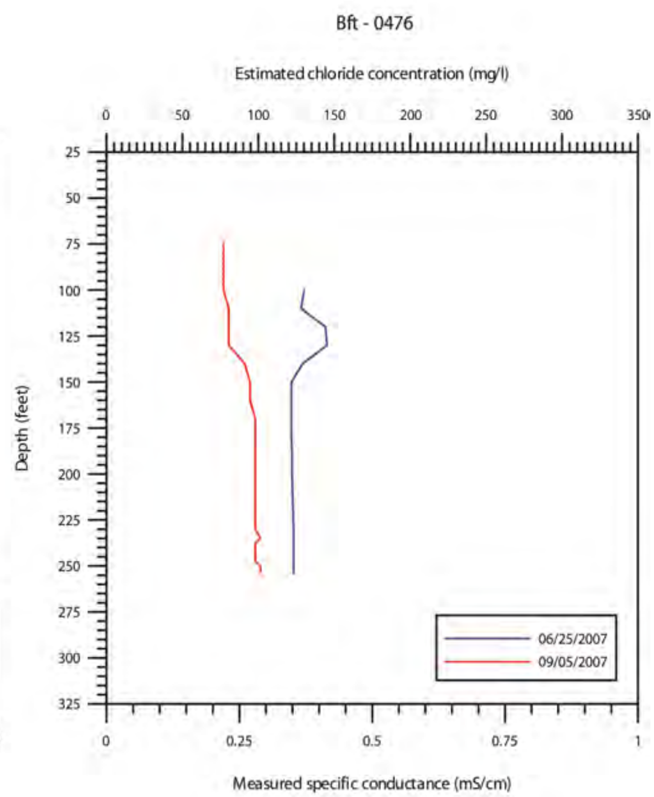
Appendix I.

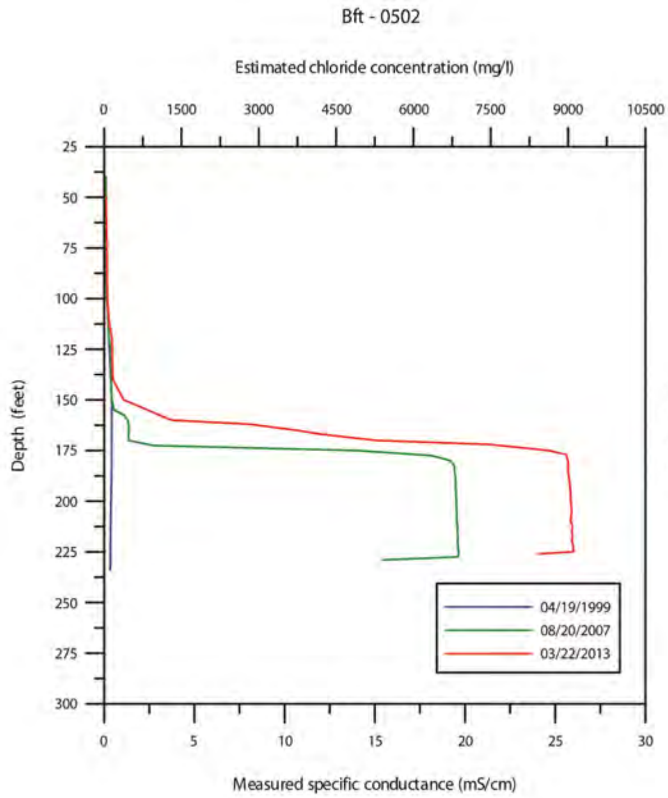
Specific conductance vertical profiles with computed (estimated) chloride concentration in mg/L (fig. 5). Where specific conductance is less than 1,000 μS/cm, chloride concentration will be less than estimated in this section.

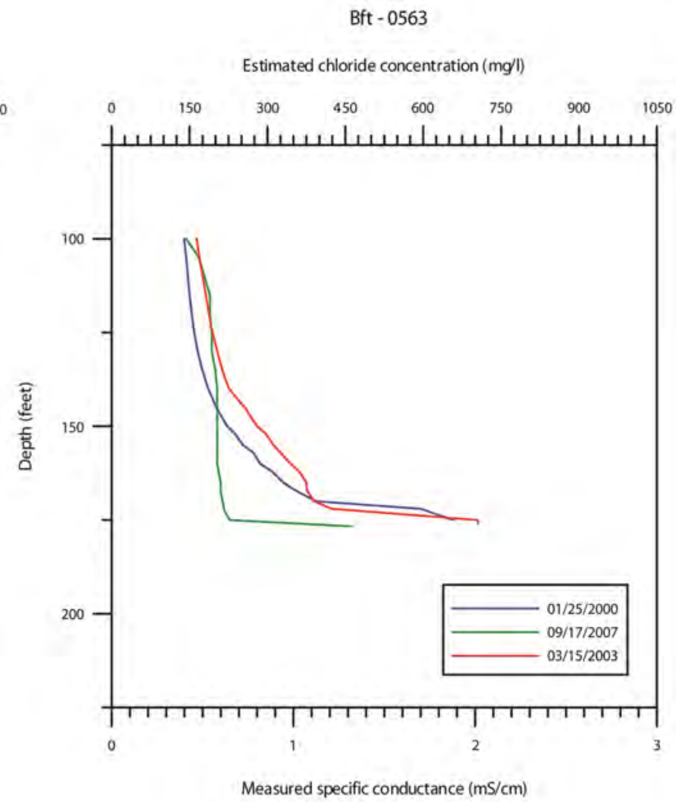

Bft - 0358
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
02/26/2001
08/23/2007
03/15/2013

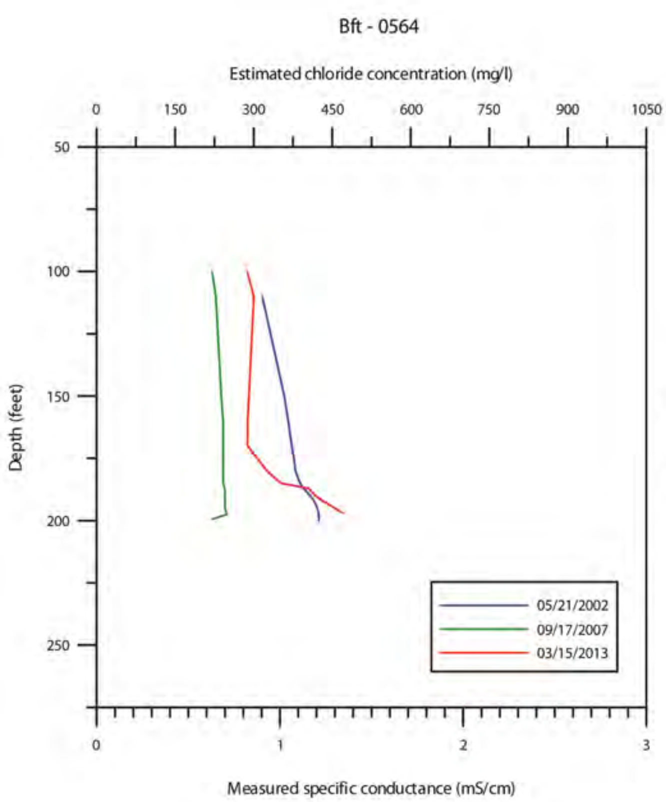

Bft - 0429
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
09/02/2012
08/23/2007
11/24/2010

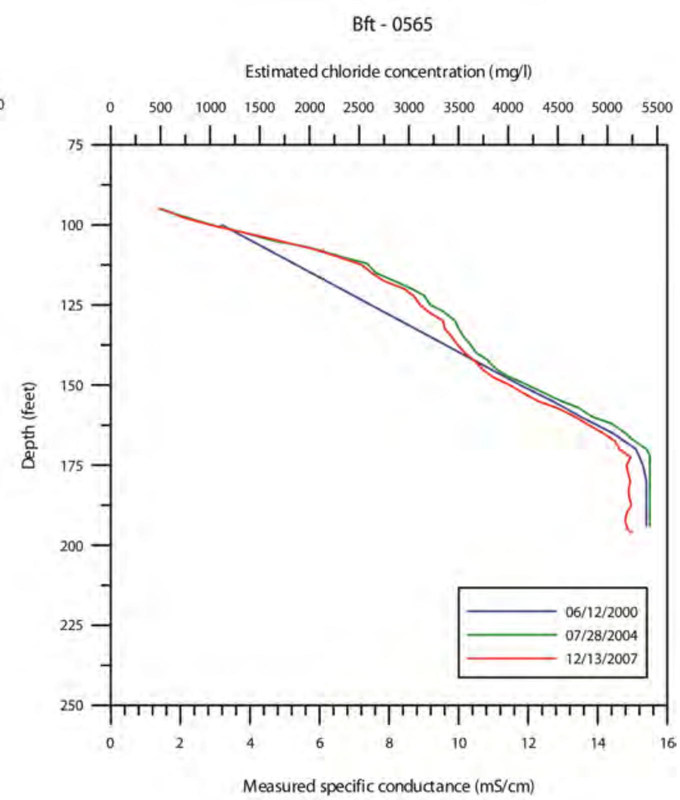

Bft - 0459
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
06/13/2000
12/18/2003
12/07/2007

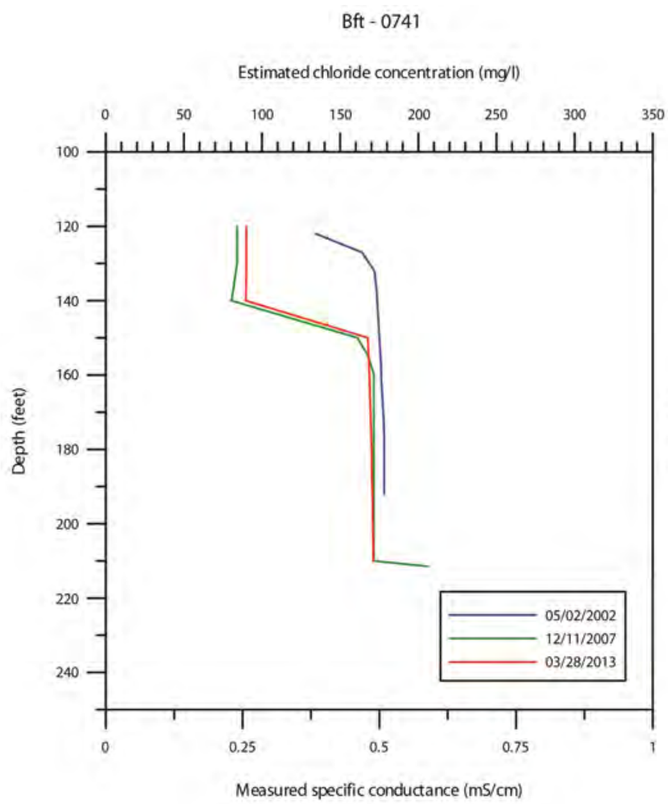

Bft - 0476
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
06/25/2007
09/05/2007

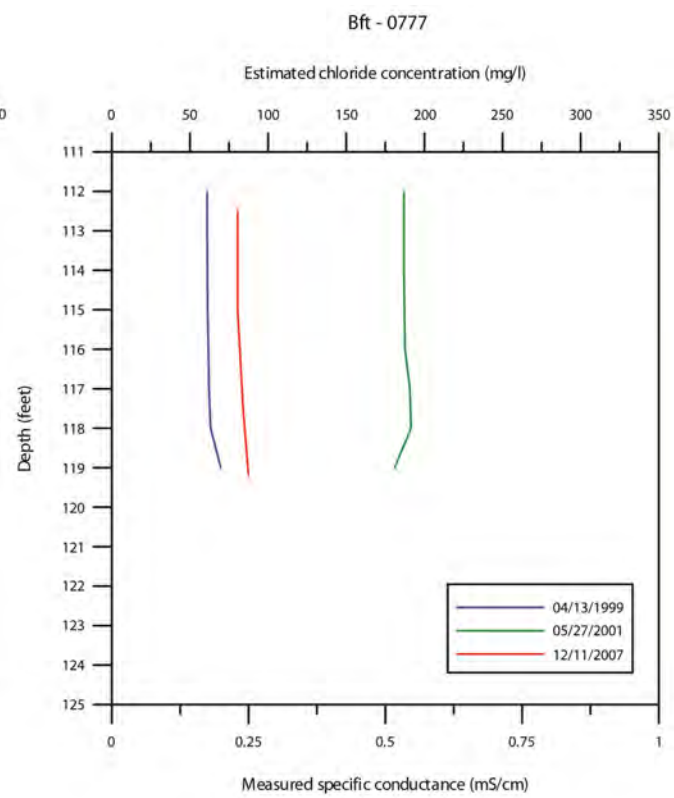

Bft - 0502
Estimated chloride concentration (mg/l)
0 1500 3000 4500 6000 7500 9000 10500
25 50 75 100 125 150 175 200 225 250 275 300
Depth (feet)
0 5 10 15 20 25 30
Measured specific conductance (mS/cm)
04/19/1999
08/20/2007
03/22/2013

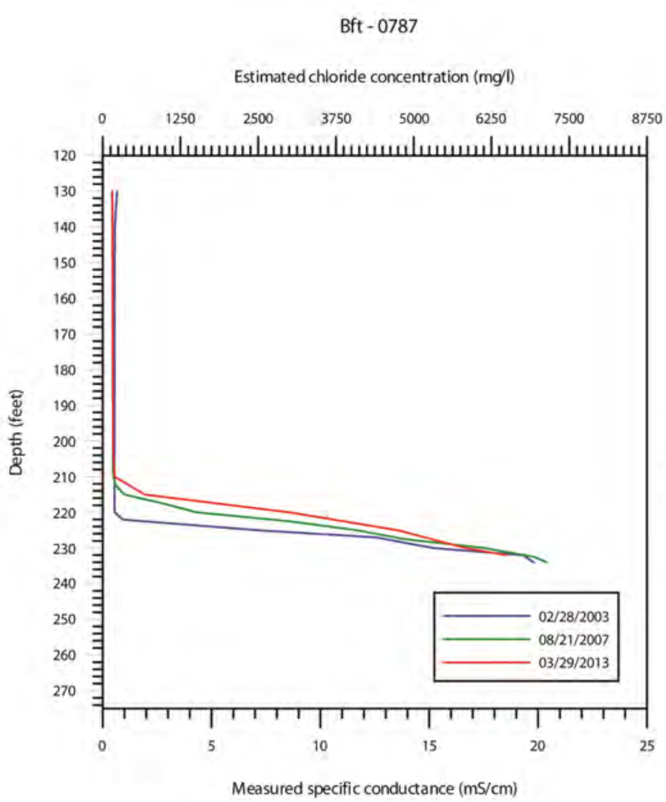

Bft - 0563
Estimated chloride concentration (mg/l)
0 150 300 450 600 750 900 1050
100 150 200
Depth (feet)
0 1 2 3
Measured specific conductance (mS/cm)
01/25/2000
09/17/2007
03/15/2003

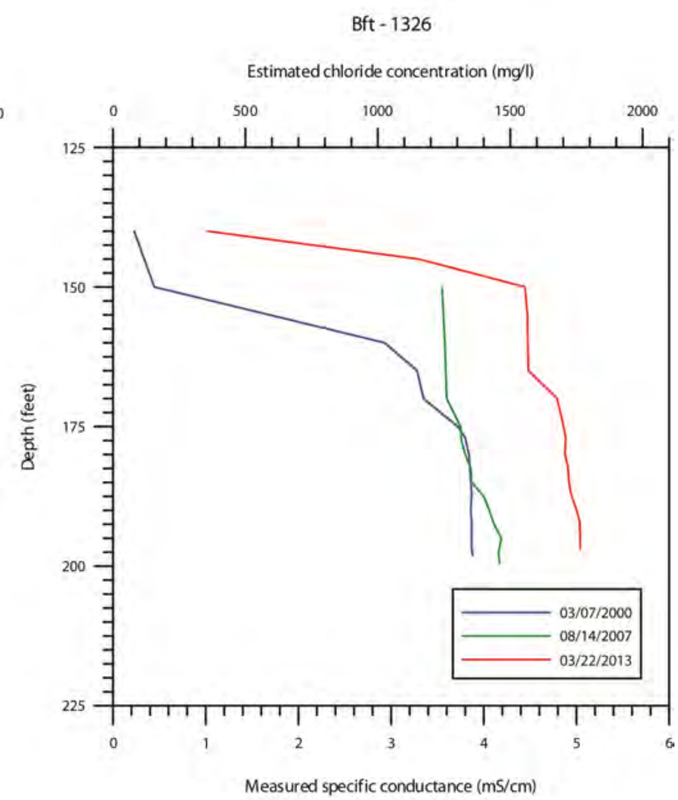

Bft - 0564
Estimated chloride concentration (mg/l)
0 150 300 450 600 750 900 1050
50 100 150 200 250
Depth (feet)
0 1 2 3
Measured specific conductance (mS/cm)
05/21/2002
09/17/2007
03/15/2013

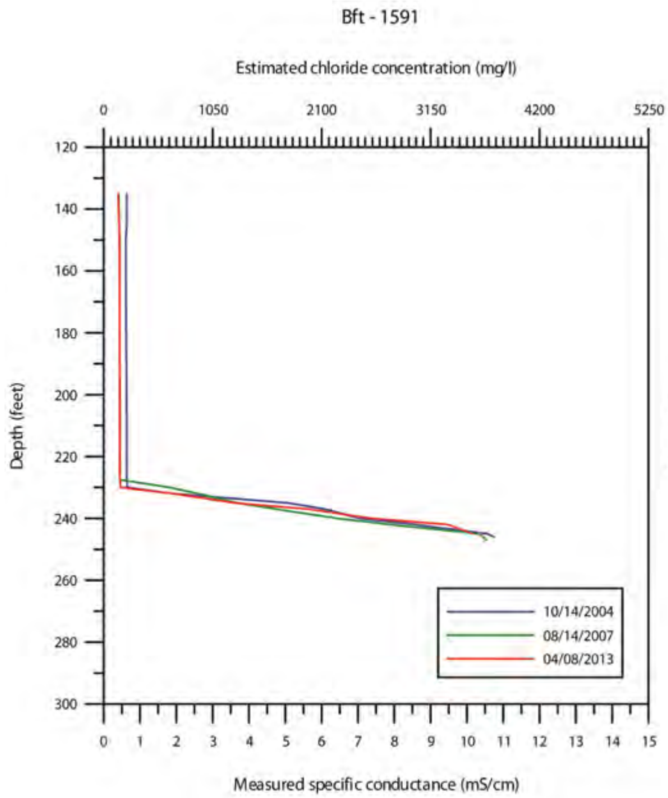

Bft - 0565
Estimated chloride concentration (mg/l)
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500
75 100 125 150 175 200 225 250
Depth (feet)
0 2 4 6 8 10 12 14 16
Measured specific conductance (mS/cm)
06/12/2000
07/28/2004
12/13/2007

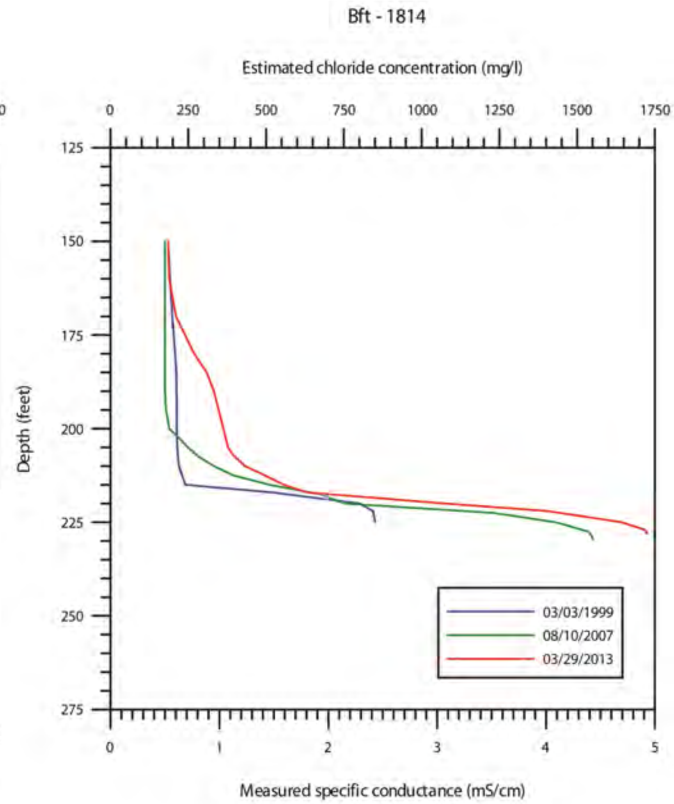

Bft - 0741
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
05/02/2002
12/11/2007
03/28/2013

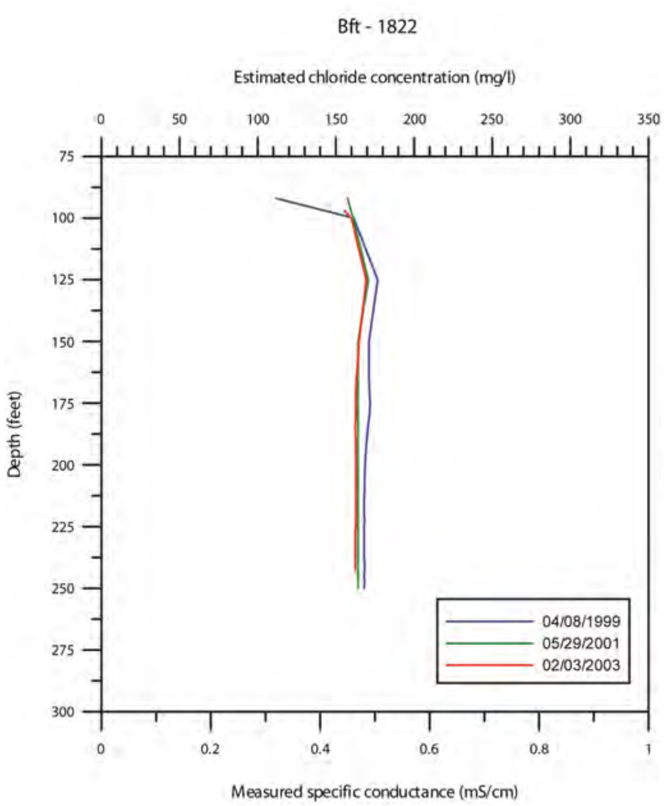

Bft - 0777
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
04/13/1999
05/27/2001
12/11/2007

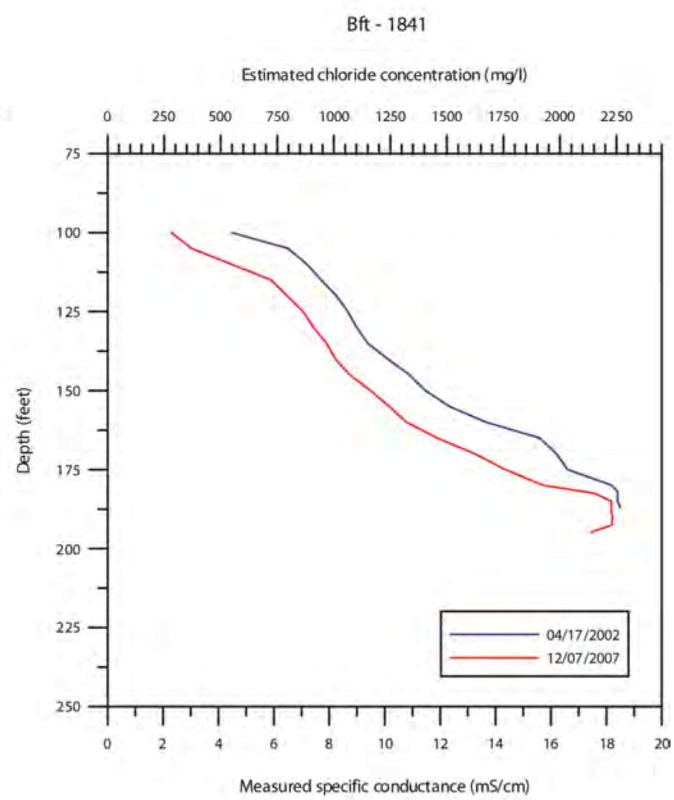

Bft - 0787
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
02/28/2003
08/21/2007
03/29/2013

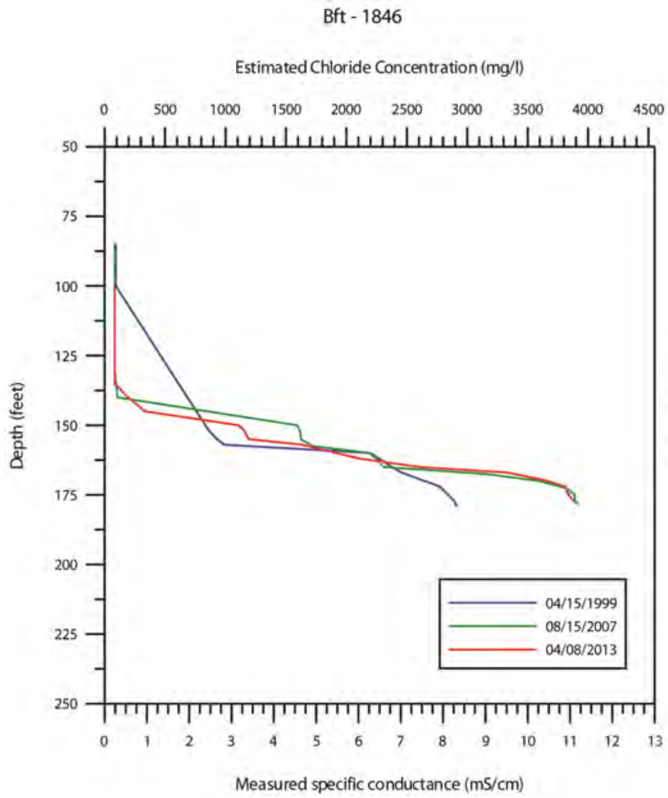

Bft - 1326
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
03/07/2000
08/14/2007
03/22/2013

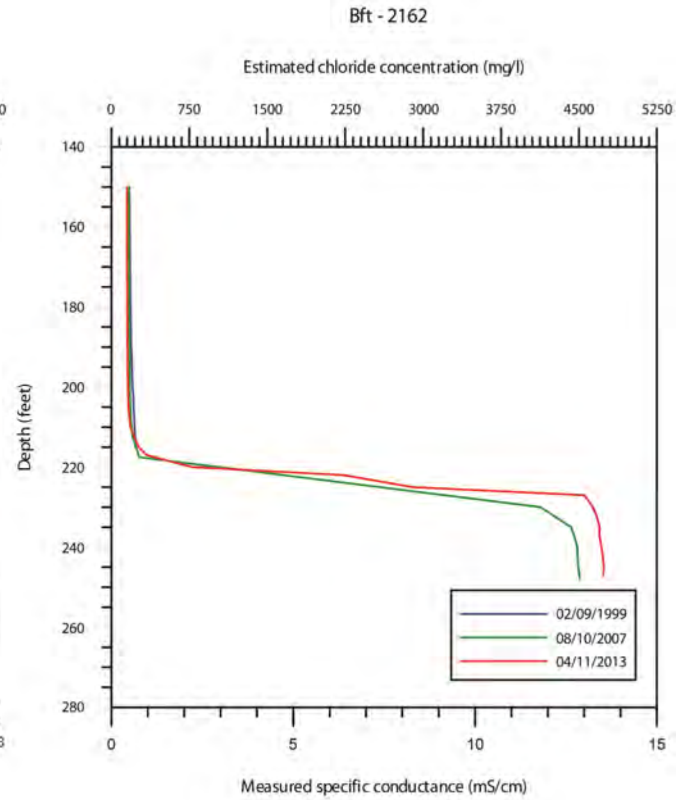

Bft - 1591
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
10/14/2004
08/14/2007
04/08/2013

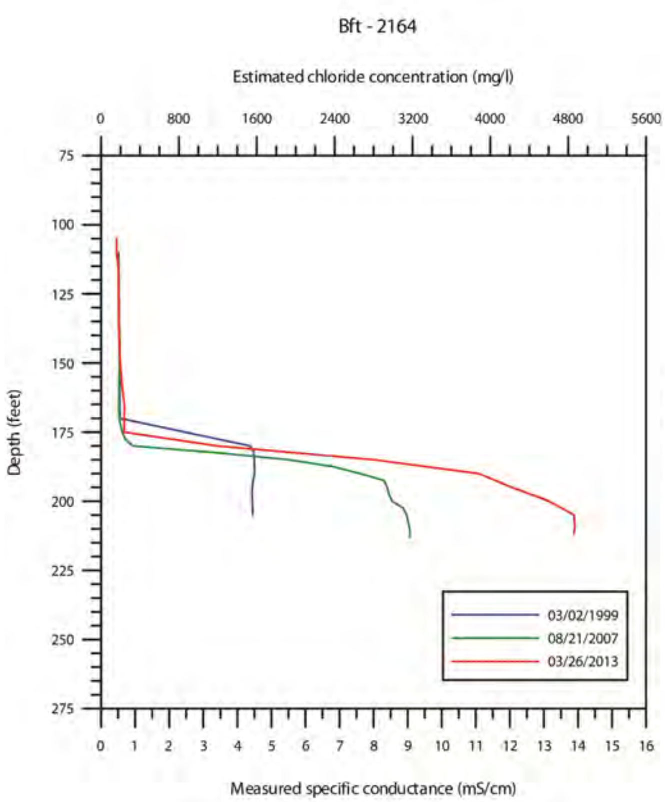

Bft - 1814
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
03/03/1999
08/10/2007
03/29/2013

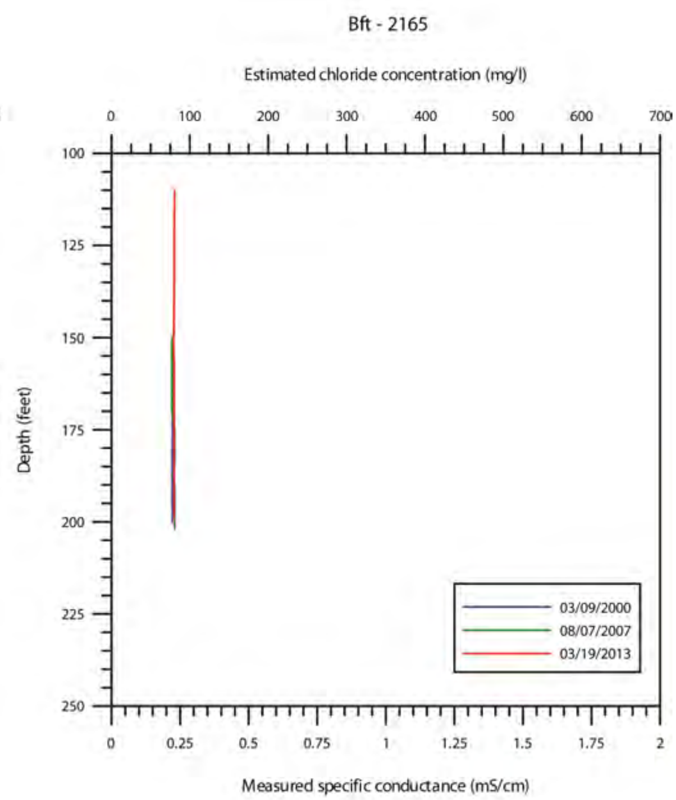

Bft - 1822
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
04/08/1999
05/29/2001
02/03/2003

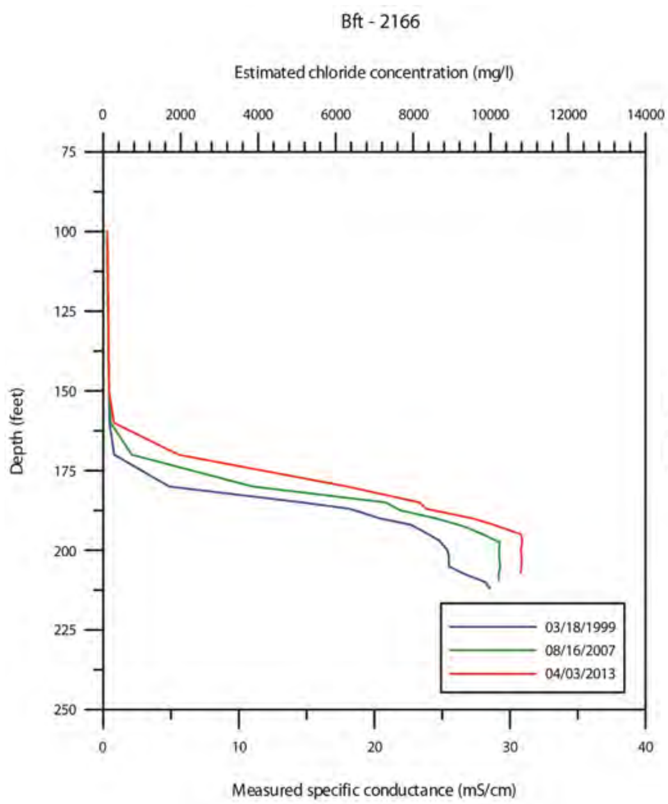

Bft - 1841
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
04/17/2002
12/07/2007

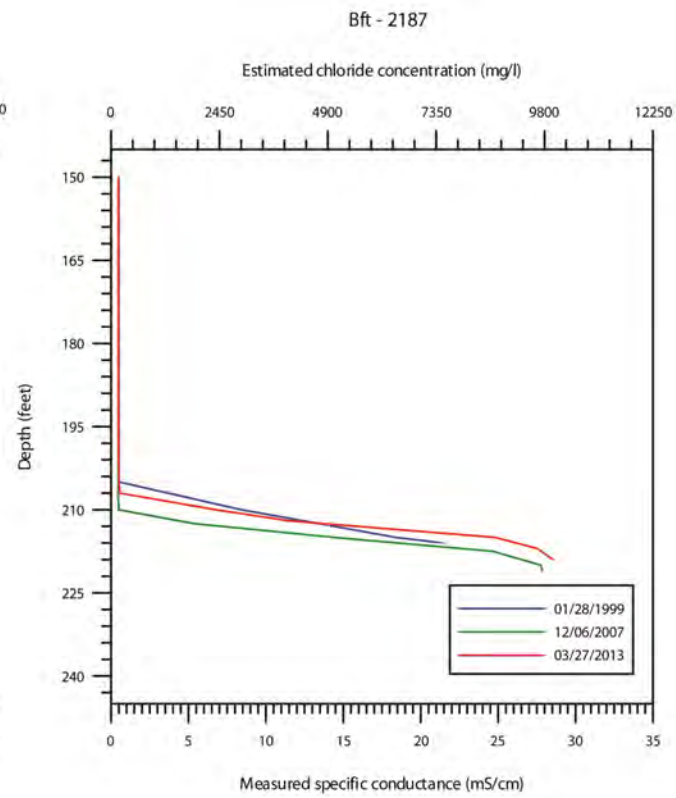

Bft - 1846
Estimated Chloride Concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
04/15/1999
08/15/2007
04/08/2013

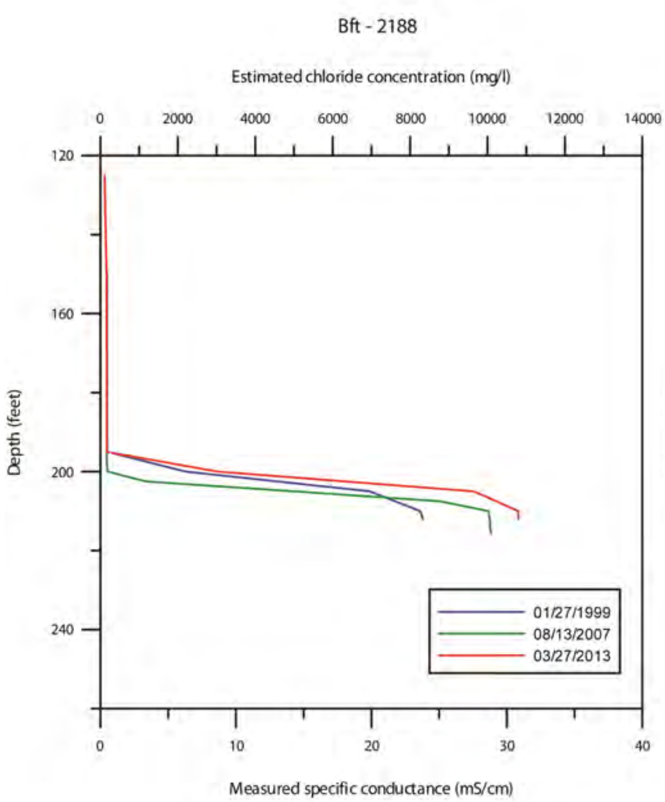

Bft - 2162
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
02/09/1999
08/10/2007
04/11/2013

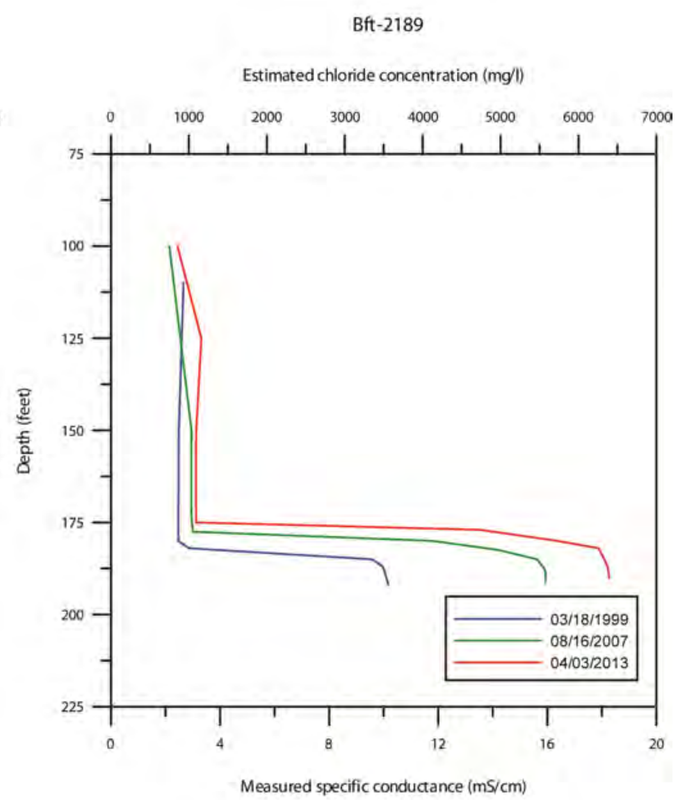

Bft - 2164
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
03/02/1999
08/21/2007
03/26/2013

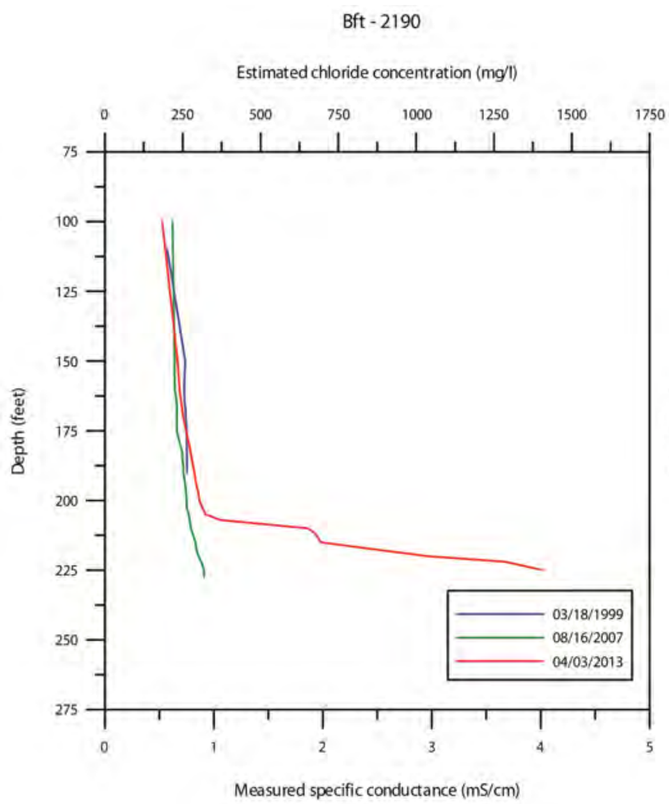

Bft - 2165
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
03/09/2000
08/07/2007
03/19/2013

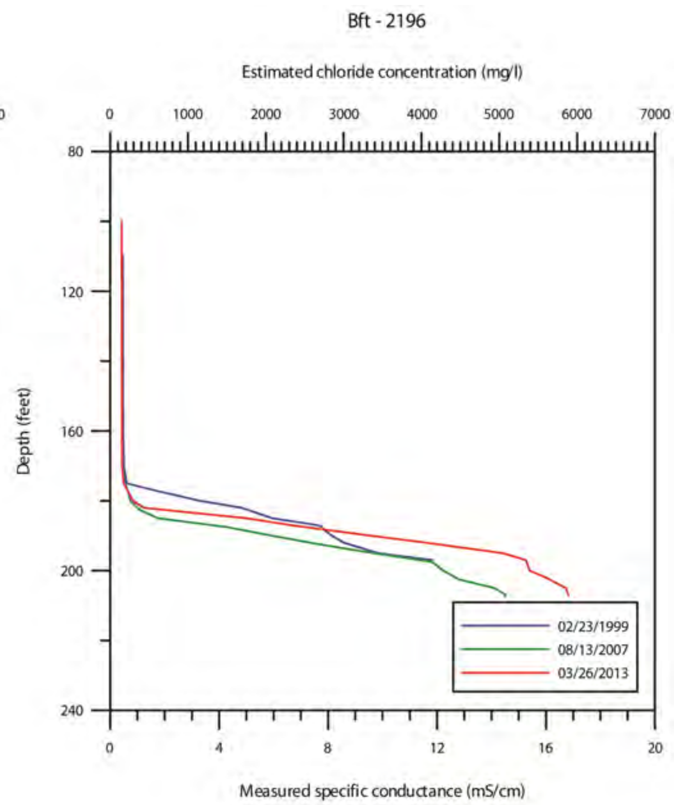

Bft - 2166
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
03/18/1999
08/16/2007
04/03/2013

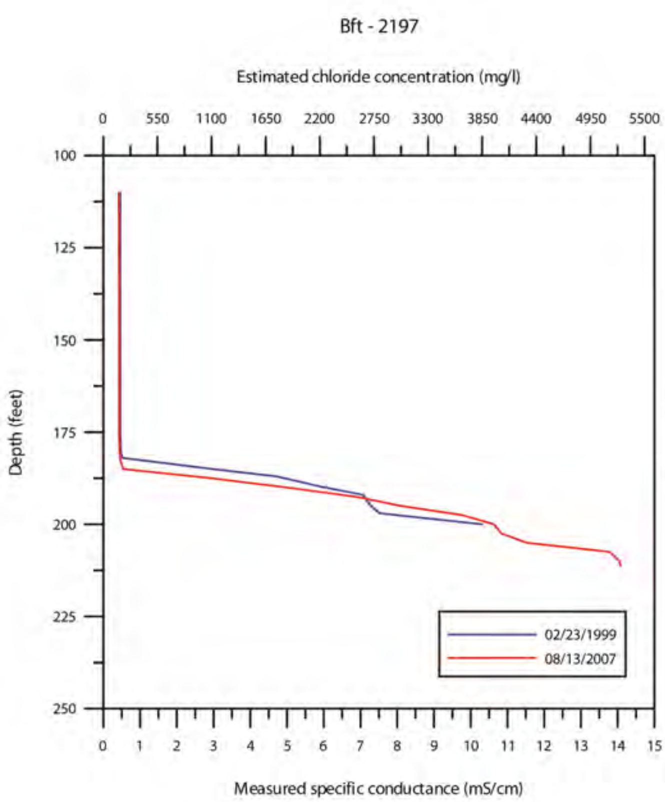

Bft - 2187
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
01/28/1999
12/06/2007
03/27/2013

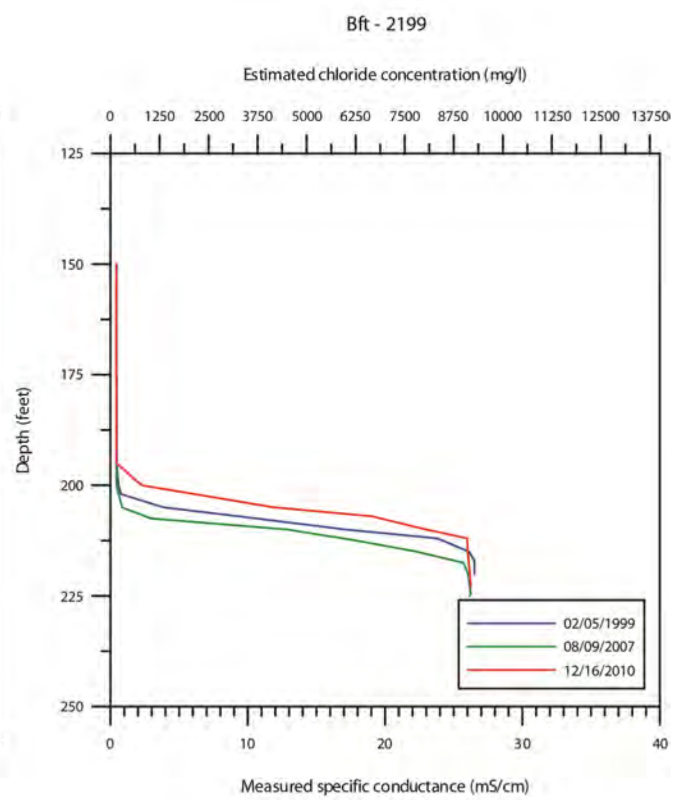

Bft - 2188
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
01/27/1999
08/13/2007
03/27/2013

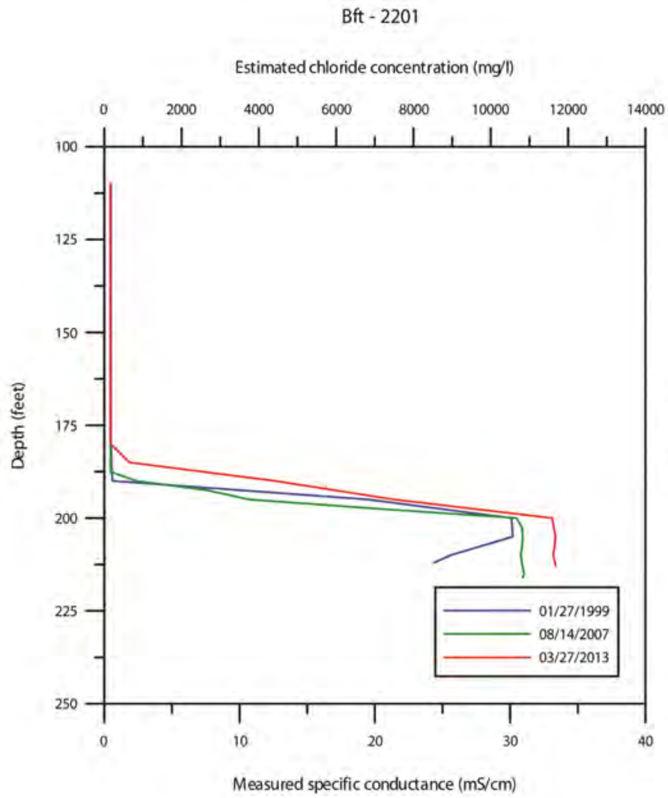

Bft-2189
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
03/18/1999
08/16/2007
04/03/2013

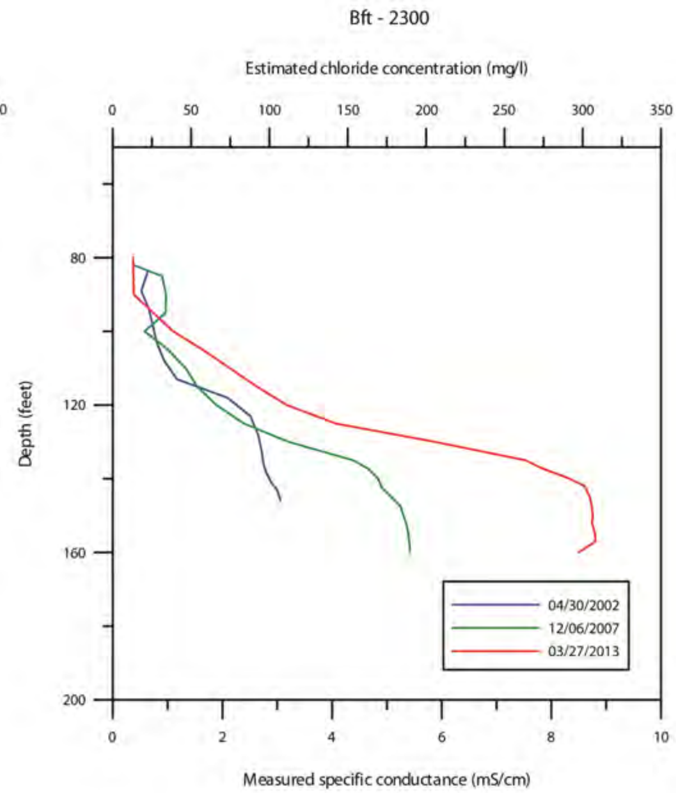

Bft - 2190
Estimated chloride concentration (mg/l)
0 250 500 750 1000 1250 1500 1750
Depth (feet)
75 100 125 150 175 200 225 250 275
0 1 2 3 4 5
Measured specific conductance (mS/cm)
03/18/1999
08/16/2007
04/03/2013

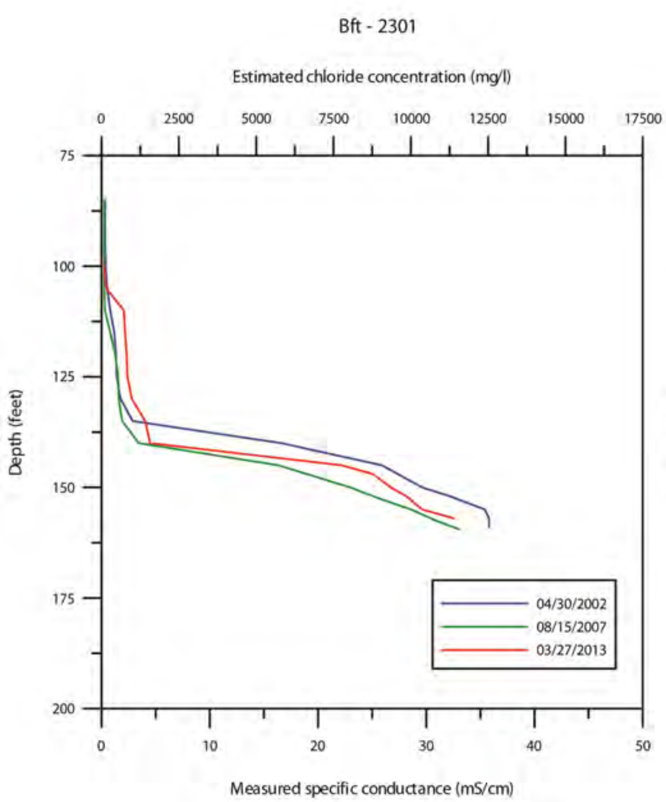

Bft - 2196
Estimated chloride concentration (mg/l)
0 1000 2000 3000 4000 5000 6000 7000
Depth (feet)
80 120 160 200 240
0 4 8 12 16 20
Measured specific conductance (mS/cm)
02/23/1999
08/13/2007
03/26/2013

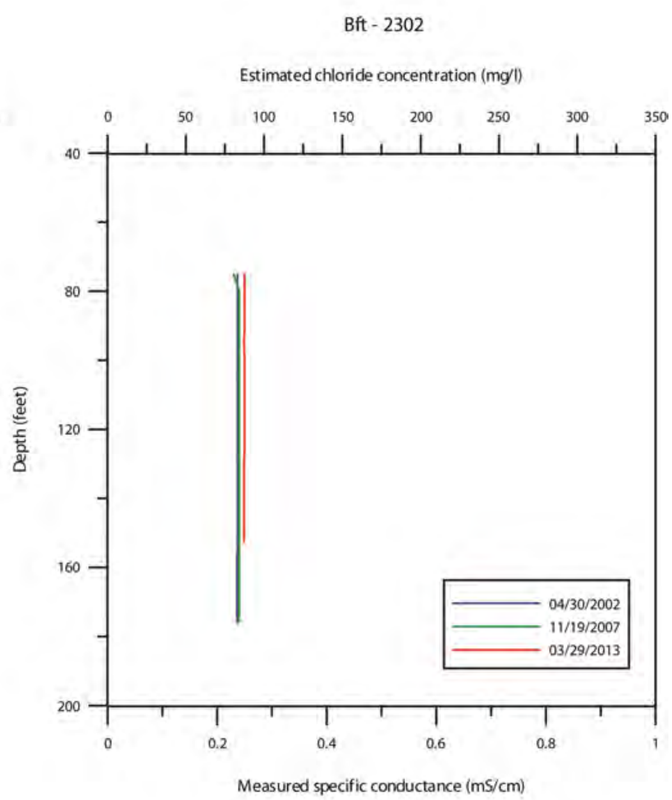

Bft - 2197
Estimated chloride concentration (mg/l)
0 550 1100 1650 2200 2750 3300 3850 4400 4950 5500
Depth (feet)
100 125 150 175 200 225 250
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Measured specific conductance (mS/cm)
02/23/1999
08/13/2007

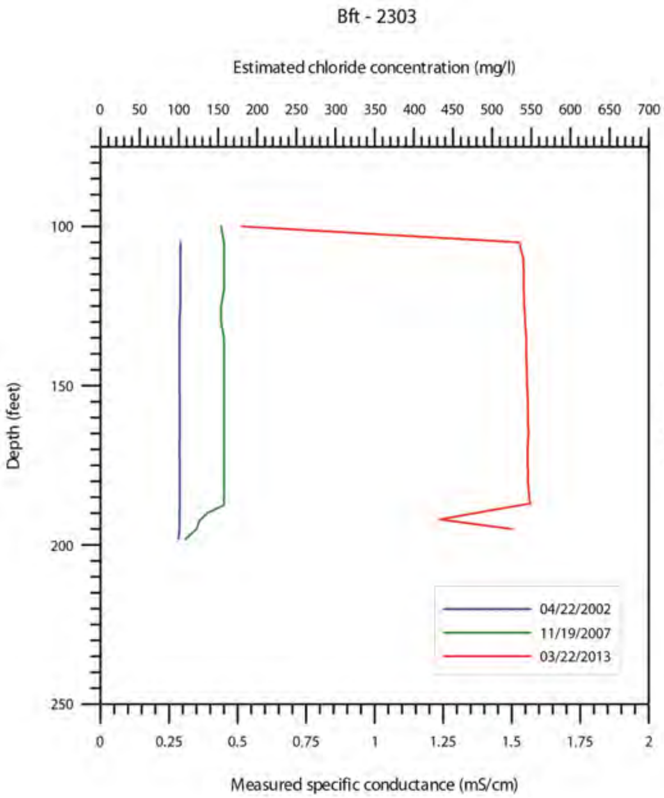

Bft - 2199
Estimated chloride concentration (mg/l)
0 1250 2500 3750 5000 6250 7500 8750 10000 11250 12500 13750
Depth (feet)
125 150 175 200 225 250
0 10 20 30 40
Measured specific conductance (mS/cm)
02/05/1999
08/09/2007
12/16/2010

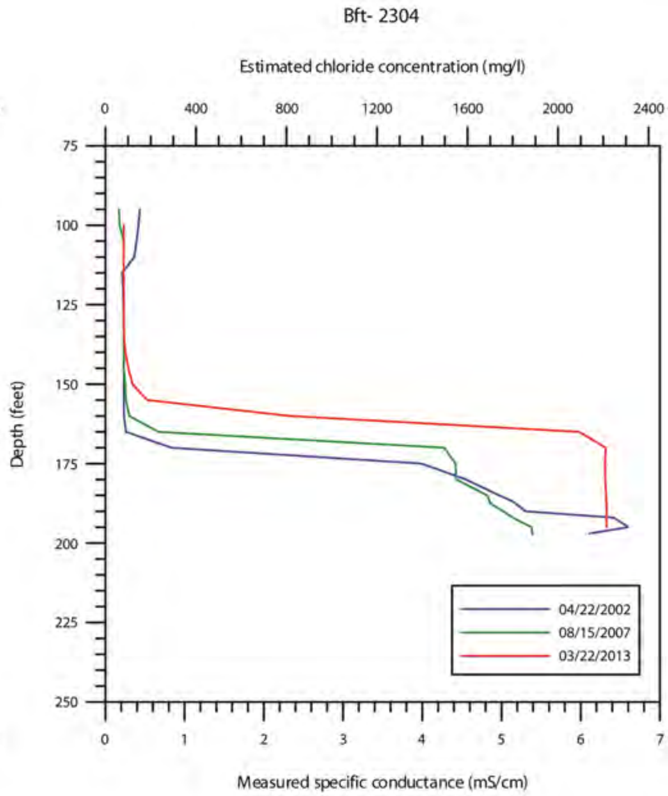

Bft - 2201
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
01/27/1999
08/14/2007
03/27/2013

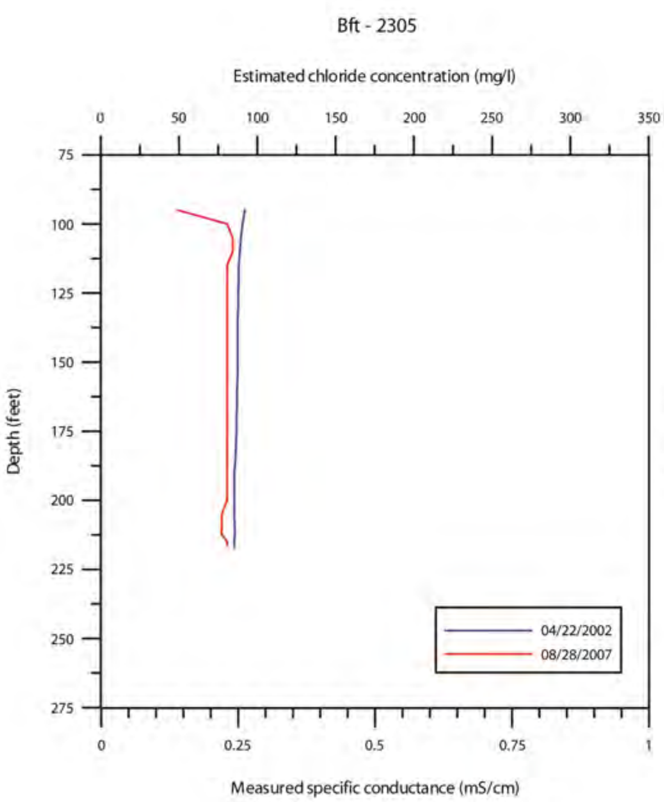

Bft - 2300
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
04/30/2002
12/06/2007
03/27/2013

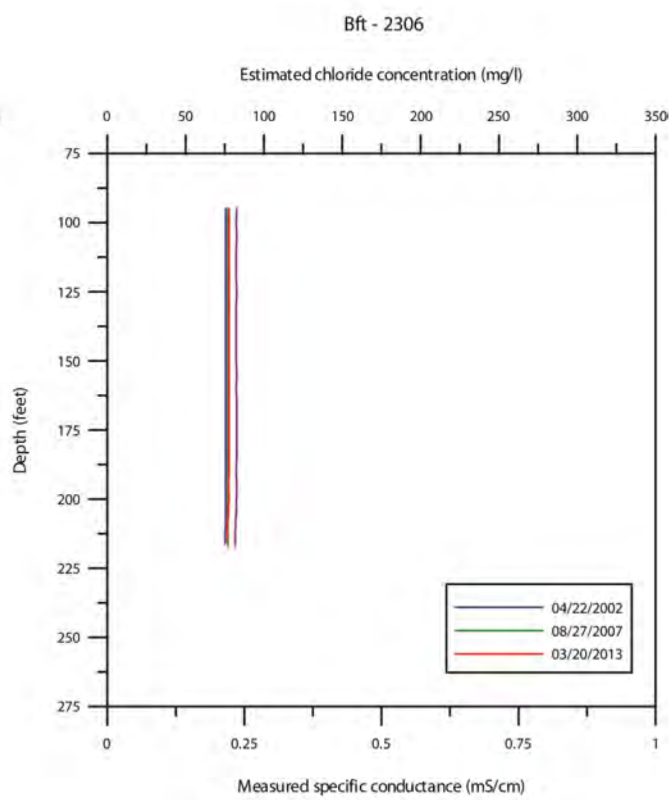

Bft - 2301
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
04/30/2002
08/15/2007
03/27/2013

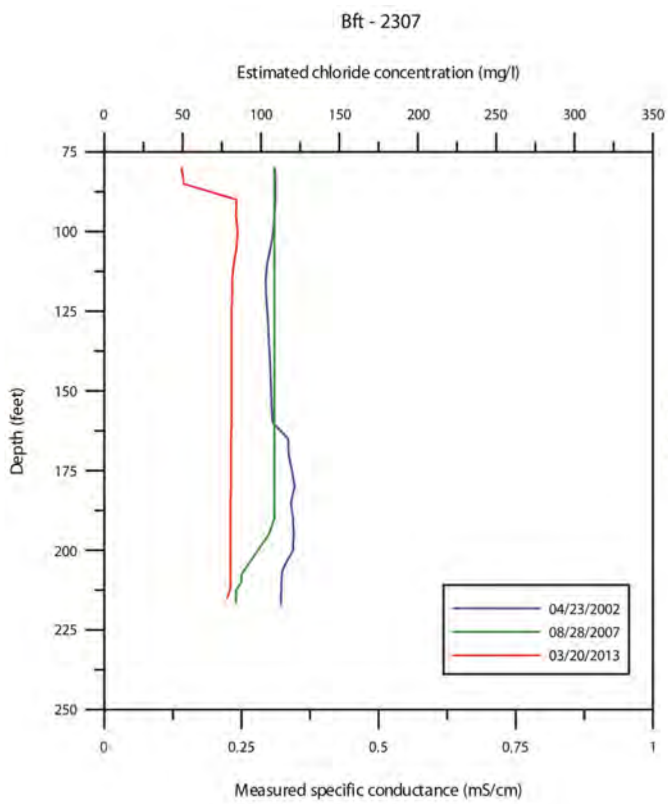

Bft - 2302
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
04/30/2002
11/19/2007
03/29/2013

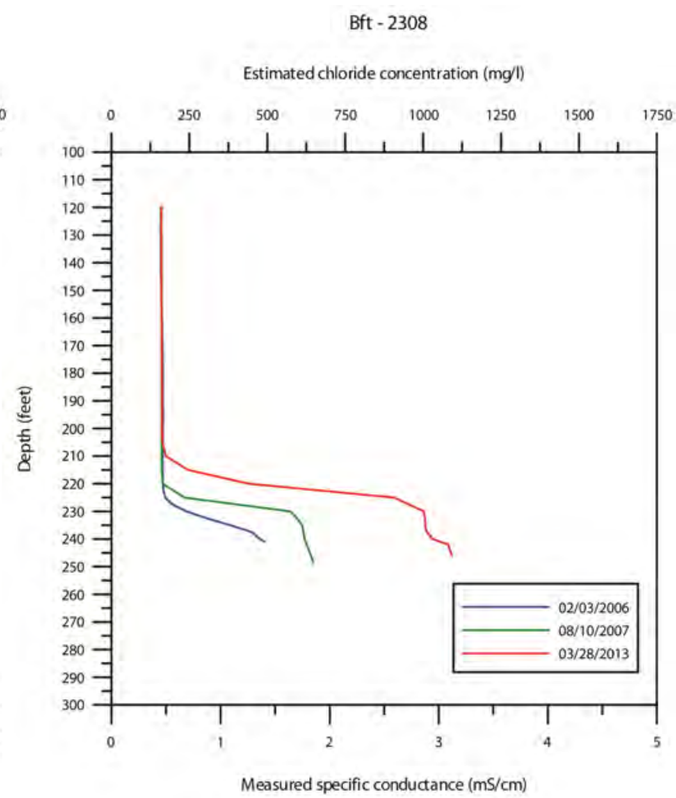

Bft - 2303
Estimated chloride concentration (mg/l)
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Depth (feet)
100
150
200
250
04/22/2002
11/19/2007
03/22/2013
0 0.25 0.5 0.75 1 1.25 1.5 1.75 2
Measured specific conductance (mS/cm)

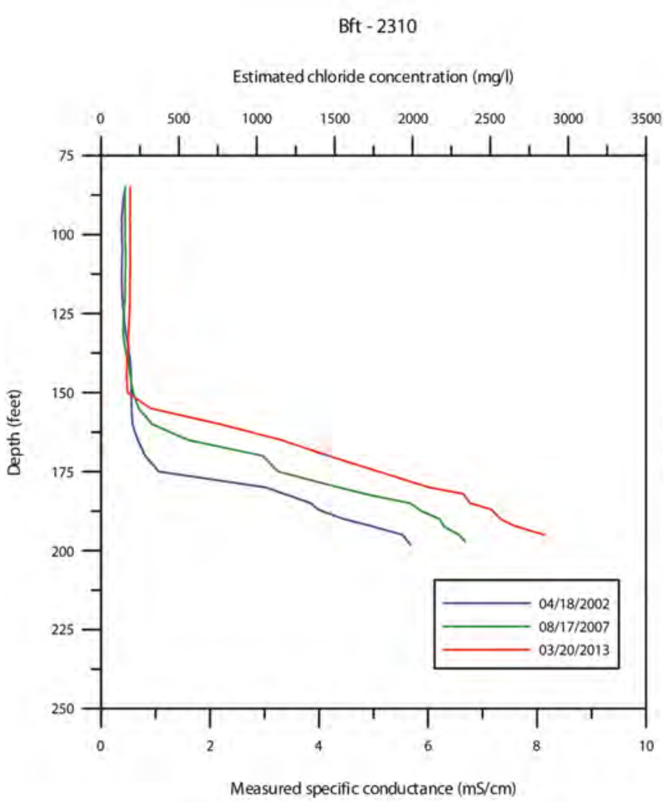

Bft- 2304
Estimated chloride concentration (mg/l)
0 400 800 1200 1600 2000 2400
Depth (feet)
75
100
125
150
175
200
225
250
04/22/2002
08/15/2007
03/22/2013
0 1 2 3 4 5 6 7
Measured specific conductance (mS/cm)

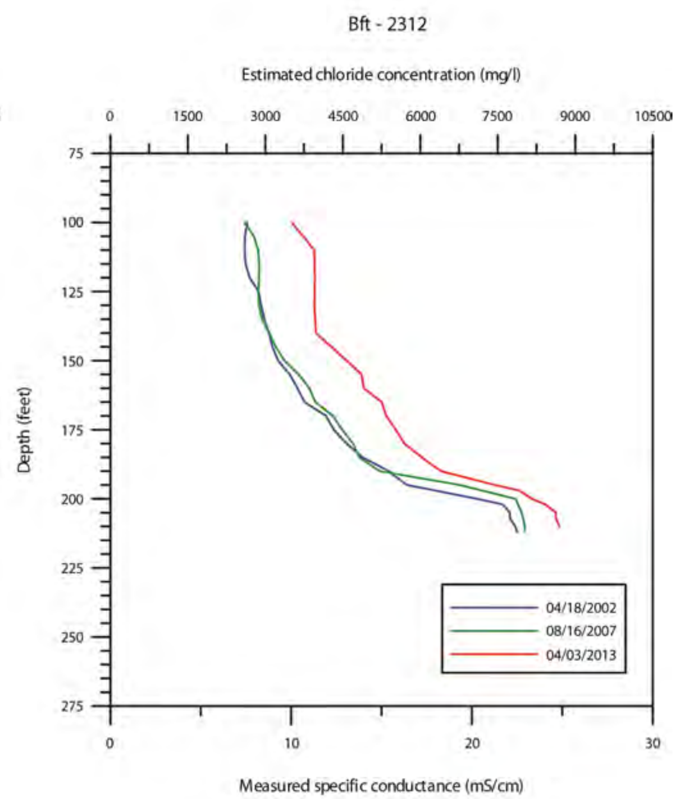

Bft - 2305
Estimated chloride concentration (mg/l)
0 50 100 150 200 250 300 350
Depth (feet)
75
100
125
150
175
200
225
250
275
04/22/2002
08/28/2007
0 0.25 0.5 0.75 1
Measured specific conductance (mS/cm)

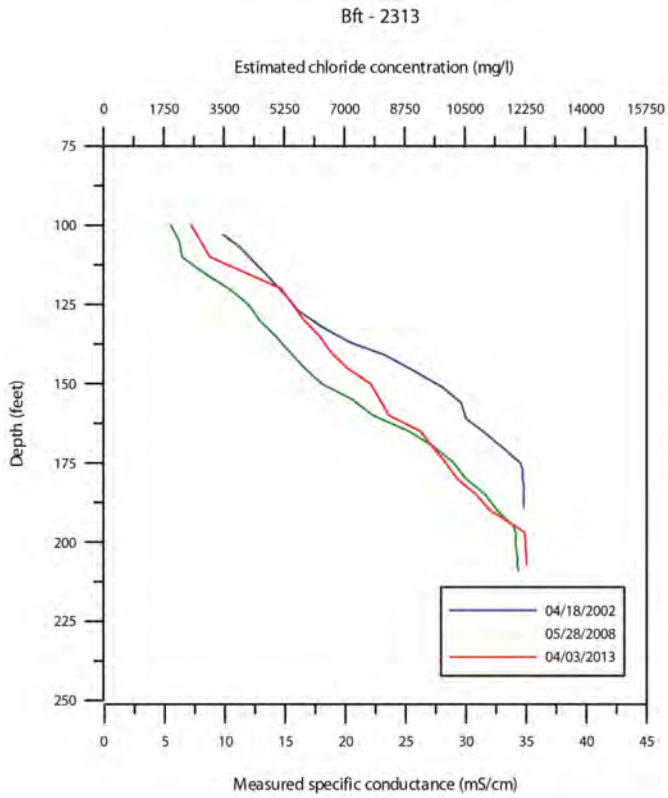

Bft - 2306
Estimated chloride concentration (mg/l)
0 50 100 150 200 250 300 350
Depth (feet)
75
100
125
150
175
200
225
250
275
04/22/2002
08/27/2007
03/20/2013
0 0.25 0.5 0.75 1
Measured specific conductance (mS/cm)

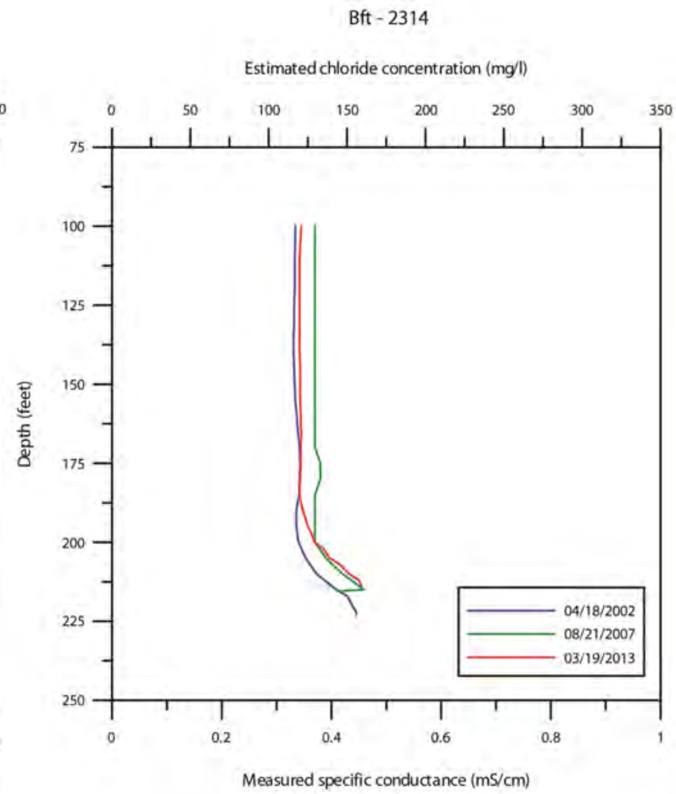

Bft - 2307
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
04/23/2002
08/28/2007
03/20/2013

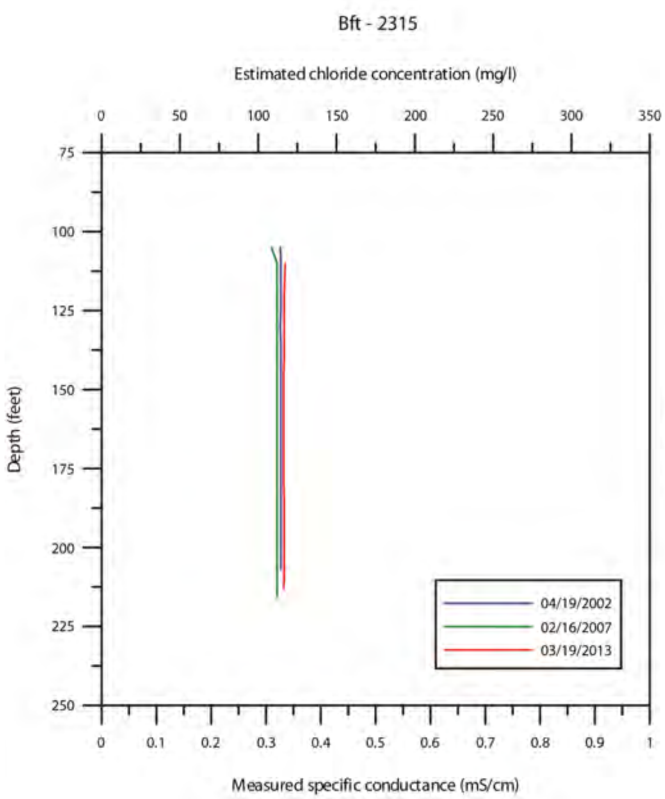

Bft - 2308
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
02/03/2006
08/10/2007
03/28/2013

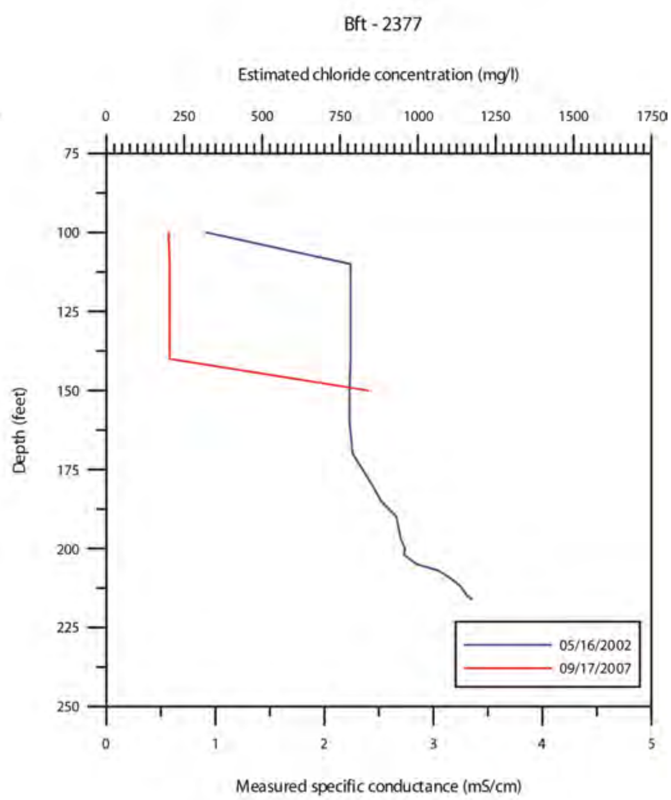

Bft - 2310
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
04/18/2002
08/17/2007
03/20/2013

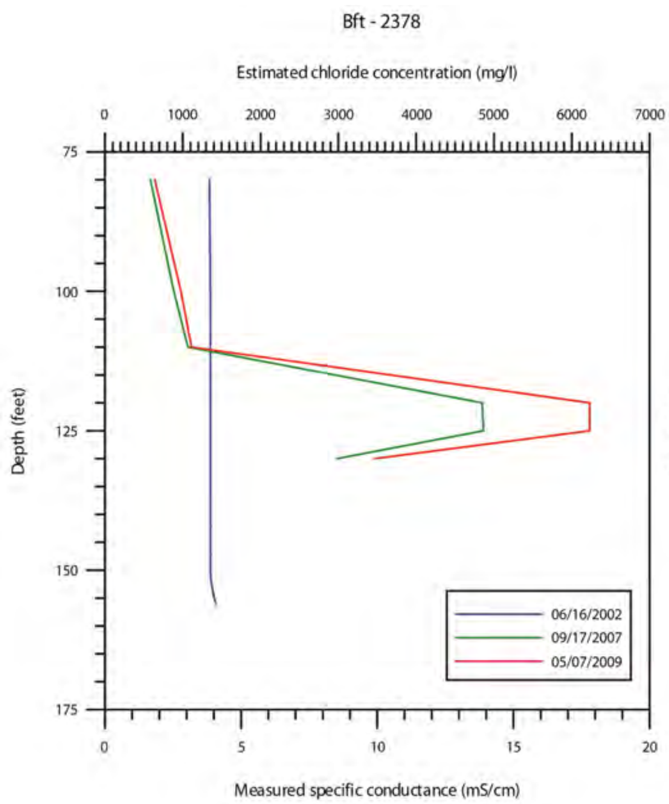

Bft - 2312
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
04/18/2002
08/16/2007
04/03/2013

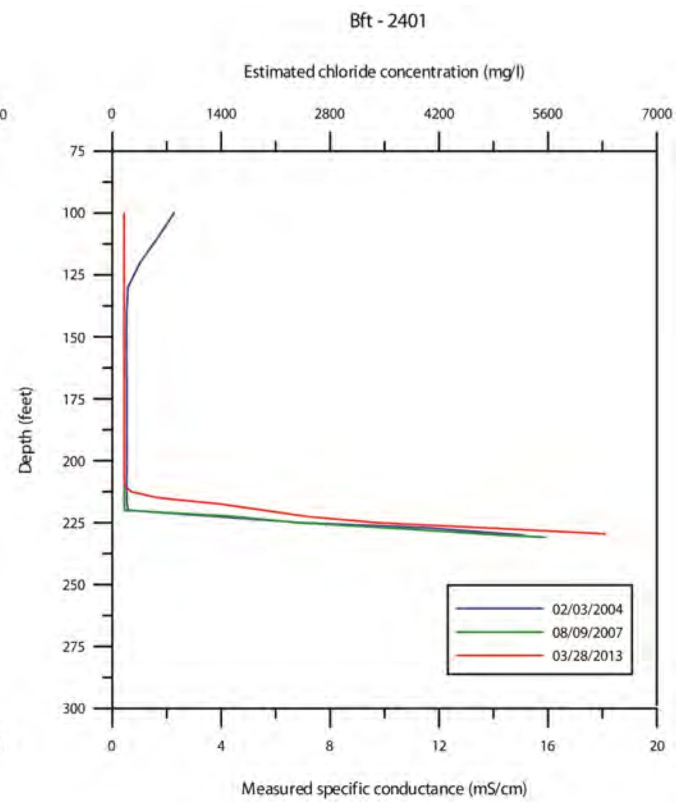

Bft - 2313
Estimated chloride concentration (mg/l)
0 1750 3500 5250 7000 8750 10500 12250 14000 15750
Depth (feet)
75 100 125 150 175 200 225 250
0 5 10 15 20 25 30 35 40 45
Measured specific conductance (mS/cm)
04/18/2002
05/28/2008
04/03/2013

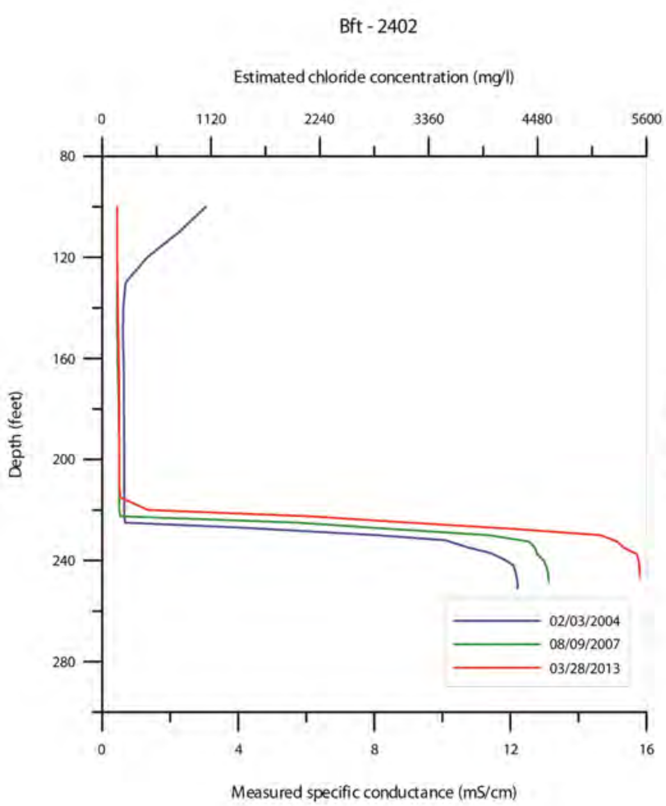

Bft - 2314
Estimated chloride concentration (mg/l)
0 50 100 150 200 250 300 350
Depth (feet)
75 100 125 150 175 200 225 250
0 0.2 0.4 0.6 0.8 1
Measured specific conductance (mS/cm)
04/18/2002
08/21/2007
03/19/2013

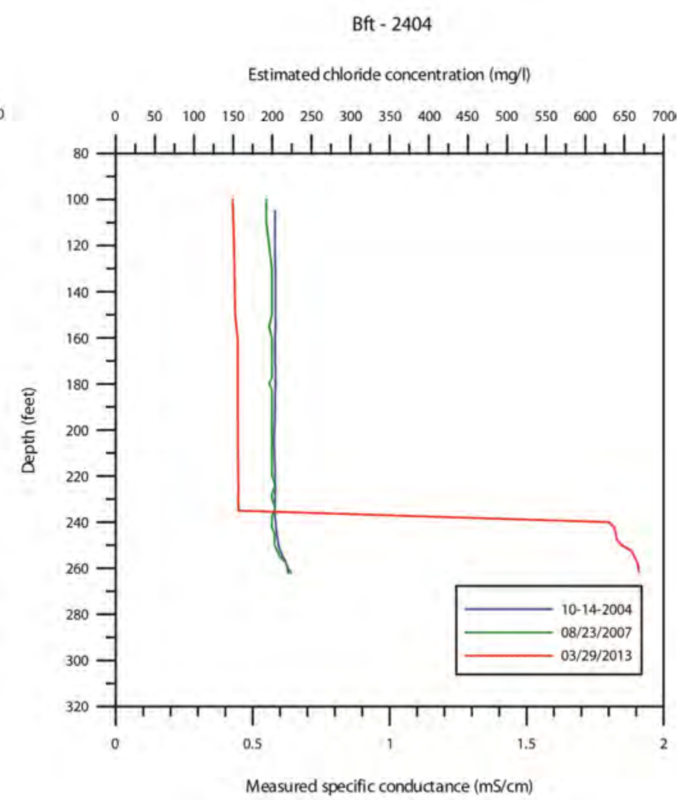

Bft - 2315
Estimated chloride concentration (mg/l)
0 50 100 150 200 250 300 350
Depth (feet)
75 100 125 150 175 200 225 250
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Measured specific conductance (mS/cm)
04/19/2002
02/16/2007
03/19/2013

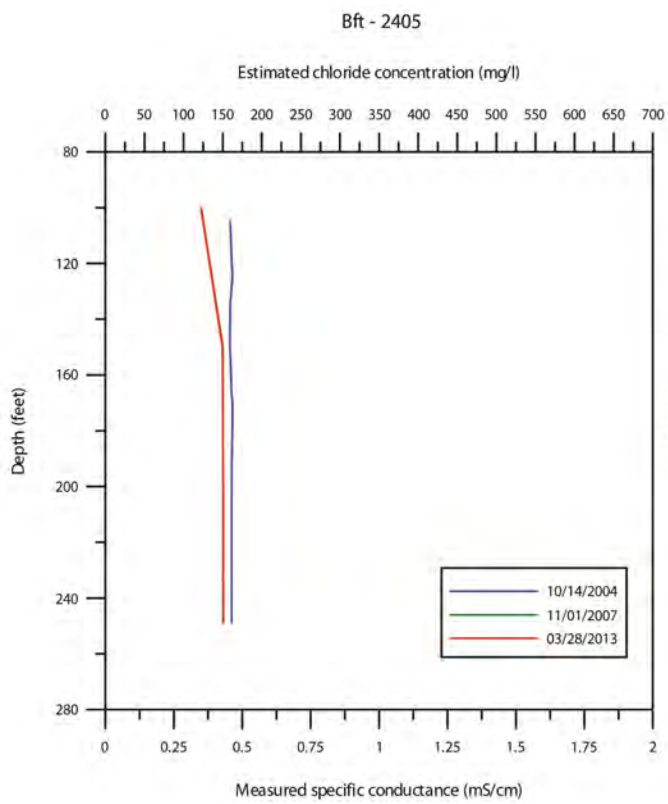

Bft - 2377
Estimated chloride concentration (mg/l)
0 250 500 750 1000 1250 1500 1750
Depth (feet)
75 100 125 150 175 200 225 250
0 1 2 3 4 5
Measured specific conductance (mS/cm)
05/16/2002
09/17/2007


Bft - 2378
Estimated chloride concentration (mg/l)
0
1000
2000
3000
4000
5000
6000
7000
Depth (feet)
75
100
125
150
175
0
5
10
15
20
Measured specific conductance (mS/cm)
06/16/2002
09/17/2007
05/07/2009

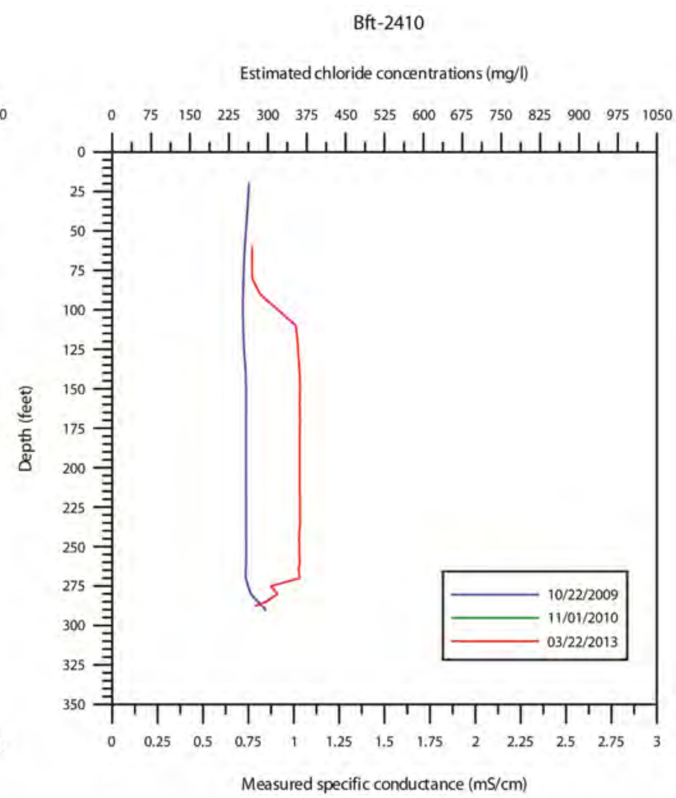

Bft - 2401
Estimated chloride concentration (mg/l)
0
1400
2800
4200
5600
7000
Depth (feet)
75
100
125
150
175
200
225
250
275
300
0
4
8
12
16
20
Measured specific conductance (mS/cm)
02/03/2004
08/09/2007
03/28/2013


Bft - 2402
Estimated chloride concentration (mg/l)
0
1120
2240
3360
4480
5600
Depth (feet)
80
120
160
200
240
280
0
4
8
12
16
Measured specific conductance (mS/cm)
02/03/2004
08/09/2007
03/28/2013

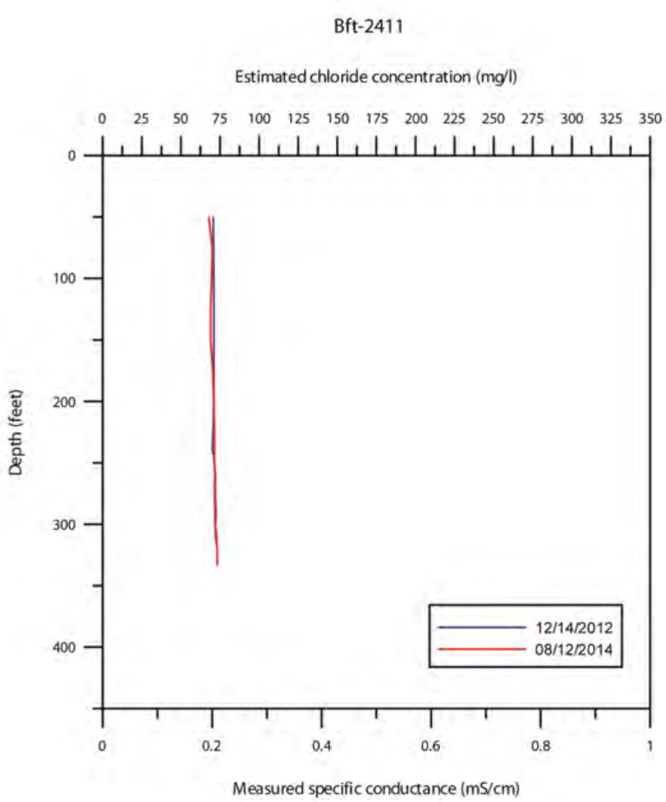

Bft - 2404
Estimated chloride concentration (mg/l)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Depth (feet)
80
100
120
140
160
180
200
220
240
260
280
300
320
0
0.5
1
1.5
2
Measured specific conductance (mS/cm)
10-14-2004
08/23/2007
03/29/2013



Bft - 2405
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
10/14/2004
11/01/2007
03/28/2013



Bft-2410
Estimated chloride concentrations (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
10/22/2009
11/01/2010
03/22/2013



Bft-2411
Estimated chloride concentration (mg/l)
Depth (feet)
Measured specific conductance (mS/cm)
12/14/2012
08/12/2014

Appendix J

A three-dimensional variable-density groundwater-flow and solute-transport model to evaluate saltwater intrusion in the Upper Floridan aquifer from 1885 through 2050 for the Savannah, Georgia and Hilton Head Island, South Carolina area.

By

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Bureau of Water

INTRODUCTION

The conceptual model was constructed using a three-dimensional variable-density groundwater flow and solute-transport software (Visual MODFLOW) developed by Waterloo Hydrogeologic, Inc. The project was part of SCDHEC's continuing contribution to the GSSI's understanding of saltwater-plume movement through the Upper Floridan aquifer for the Savannah, Ga. – Hilton Head Island, S.C. area. Selected model simulations demonstrate how pumpage-induced water-level declines have led to the initial development and expansion of eleven chloride plumes from 1885 to 2050.

Previous models include Counts and Krause, 1976; Garza and Krause, 1992; Bush, 1988; Smith, 1988 and 1994; Payne and others, 2005; Provost and others, 2006; and Camp Dresser & McKee, 2009. Supporting data for the SCDHEC model are included in the preceding parts of this report: Geology, Hydrology, and Saltwater Contamination sections and in the Appendices. Note: this report references computed chloride concentrations (see **METHODS** section) whereas model values are referenced as total salt (sodium chloride).

ACKNOWLEDGEMENTS

Appreciation is extended to the South Carolina State Legislature for special funding and also to Dr. John Shafer, Director, University of South Carolina Earth Sciences Resource Institute, who provided training in the navigation and use of model software and data input, and for technical discussions.

MODEL AREA

The model area extends from Savannah, Ga. northeastward about 50 miles, near Edisto Island, S. C.; southward about 50 miles to Sapelo Island, Ga.; westward about 30 miles, near Hinesville, Ga.; and eastward about 50 miles, encompassing part of the Atlantic Ocean: total model area is about 8,000 square miles. The primary study area of Savannah, Ga. and Hilton Head Island, S.C. covers an area of about 2,500 square miles (fig. J1).

MODEL DESIGN

The model is based on data presented in previous sections of this report including the selected references from the period 1885 to 2015. Model design as discussed herein includes boundary conditions, grid density, and hydrogeologic units represented by model layers, and the position and movement of relict and modern brackish to salt water in the surficial aquifer, the upper confining unit, and the Upper Floridan aquifer. Relict brackish-to-saltwater concentrations were assigned only to the lower part of the Upper Floridan aquifer and, in areas where modern brackish to salt water is known to be moving vertically downward, a constant concentration was estimated and assigned to cells at the bottom of the surficial aquifer. Elevations assigned to hydrogeologic units are referenced to NGVD29.

Hydrogeologic Layers and Grid Density

Model layers were constructed to simulate the principle hydrogeologic units discussed earlier in this report (see **HYROGEOLOGY** section). Depths and thicknesses of units were inputted into the model based on elevations; the highest elevations were assigned to units in the northeast where tectonic uplift (Beaufort Arch) had occurred. Where data were not available, elevations were interpolated. The units were further distinguished by changes in their respective hydraulic conductivities (fig. J5).

The model grid consisted of approximately 140,000 1/4^{mi2} cells for each of 30 layers totaling 4,200,000 cells distributed homogeneously through the model grid (fig. J2). Hydrogeologic unit assignments are; layers 1 and 2 for the surficial aquifer; layers 3 through 12 for the upper confining unit; layers 13 through 22 for the Upper Floridan aquifer, inclusive of the Oligocene limestone (layers 13-15), permeable zone 1 (layers 16-17), a relatively less permeable strata of carbonate limestone (layers 18-20), and permeable zone 2 (layers 21-22); layers 23 through 25 for the middle confining unit; layers 27 and 28 for the middle Floridan aquifer; and layers 29 and 30 for the lower confining unit (fig. J5, see table).

Boundary Conditions

Constant-head boundary conditions are inputted throughout layer 1 for the surficial aquifer beneath landmasses and for offshore areas that include estuaries, saltwater channels, and the Atlantic Ocean. Constant heads for the surficial aquifer beneath landmasses were computed by multiplying the land-surface elevation by 0.66 and assigning the resulting value to each cell in layer 1 (fig. J8). For offshore areas, constant heads were assigned a value of 0.5 ft Msl (NGVD29) for each cell in layer 1 to allow for an approximate average rise in sea level. Boundary conditions were not assigned to layers 3 through 12 for the upper confining unit. General-head boundaries were assigned to the model boundaries for layers 13 through 30, which represent the Floridan aquifer system in the model area. Here, the western boundary was assigned a constant head of 75 ft Msl that approximates the predevelopment heads published by Counts and Donsky (1963; Appendix D1) and simulated by Gaza and Krause (1992). For the northern and southern borders, general-head boundaries progressively decreased from 70 ft Msl at the northwest and southwest boundaries to 20 ft Msl at the northeastern and southeastern boundaries (fig. J7).

Constant-concentration boundary conditions for salt were assigned to surficial-aquifer cells in layer 2 for offshore areas in the Atlantic Ocean, saltwater marshes, and channels. Beneath the Atlantic Ocean, cells were assigned a constant salt concentration of 31,000 mg/L; for intracoastal areas (other than landmasses) cells were assigned an estimated constant concentration for salt based on a water-quality investigation (Ransom and Park, 2011) discussed previously in this report (fig. 30). Here, depending on estimated freshwater discharge from landmasses and distance from landmasses, constant concentrations for salt were assigned a value that ranged from 1,200 to 31,000 mg/L (fig. J4). Where the upper confining unit is interpreted to be absent, constant concentrations for salt were estimated at the source areas with computed chloride concentrations from specific-conductance profiles in nearby monitoring wells.

Constant concentrations for salt were assigned to cells at the bottom of the Upper Floridan aquifer to simulate relict brackish to salt water in the vicinity of the Port Royal Sound and Parris Island chloride plumes (fig. 71). Initial concentrations were assigned to cells adjacent and down gradient of cells assigned constant concentrations to assist the simulated predevelopment saltwater wedge to reach equilibrium under steady-state conditions after running the model for the years 1800 – 1884.

Hydraulic Conductivity

Hydraulic conductivity (x, y, and z) inputted into the model was generally consistent except for the upper confining unit (layers 3 through 12) and the Upper Floridan aquifer (layers 13 through 22). Conductivities in the upper confining unit were divided into four zones distributed laterally through the full thickness of the unit: conductivities for each of the four zones increased from the southwest toward areas northeast of Port Royal Sound. For the Upper Floridan aquifer, conductivities were divided into nine separate zones distributed laterally and vertically through the thickness of the aquifer. Conductivities in the aquifer generally increased from the southwest to the northeast toward Port

Royal Sound and are highest in Upper Floridan aquifer permeable zones 1 and 2 (fig. J5). Permeable zone 1 was removed (conductivity lowered) in the northeastern part of the study area after model simulations showed that a higher conductivity normally associated with permeable zone 1 also allowed for movement of brackish to salt water through the zone. Vertical specific-conductance profiles in monitoring wells near the Port Royal Sound area did not show high chloride concentrations in permeable zone 1 near the top of the aquifer except where the monitoring well was near a chloride source area, e.g., well BFT-2313 (Appendix I; and figs. J5 and J6).

Pumpage

Water-use data for the Upper Floridan aquifer and middle Floridan aquifer were obtained from published reports and from water use reports for permitted wells maintained by the GaEPD and SCDHEC. Simulated pumping wells from the Upper Floridan and middle Floridan aquifers were assigned coordinates within the model grid, withdrawals (Mgal/day) for each well were inputted as total yearly pumpage (Mgal/yr) from 1885 to 2015. Unpermitted Upper Floridan aquifer pumpage was estimated from referenced reports and simulated by pumping wells inputted randomly throughout the study area. Based on potentiometric maps, simulated water levels in the primary study area were not sensitive to the relatively small groundwater withdrawals northeast of Port Royal Sound, and those withdrawals were not included in the model (figs. 19 and J3).

MODEL CALIBRATION

The SCDHEC model was calibrated to closely match published potentiometric surface maps for the years 1880, 1957, and 1998 (Appendix D) and to match vertical specific-conductance profiles for the years 1984 and 2007 in wells open through the full thickness of the Upper Floridan aquifer (fig. 72). Where mapped, the profiles show the vertical and lateral distribution of computed chloride concentration. The model did not consider the relict brackish to salt water present in the middle confining unit and middle Floridan aquifer. Calibration of the model was accomplished by adjusting the most sensitive hydraulic parameters for each layer that, in turn, corresponded to hydrogeologic units in the study area (fig. J5). The hydraulic parameters included conductivity, porosity, and estimated position and concentration of saltwater source areas inputted as constant and initial concentrations. Adjustments were made after each model run until a close match was achieved between simulated maps and the above referenced measured potentiometric surface and isochlor maps.

Water-Table and Potentiometric Surfaces

The largest Sea Islands northeast of Port Royal Sound, S. C., include Port Royal Island, Parris Island, Lady's Island, and St. Helena Island. Here, seasonal domestic and agricultural irrigation pumpage from the Upper Floridan aquifer principally has been the largest use of groundwater. The effectiveness of the upper confining unit in the vicinity of these islands is diminished owing to thinning, absence and, where present, the unit has a relatively greater hydraulic conductivity that allows interconnection between the surficial aquifer and the Upper Floridan aquifer (see **HYDROGEOLOGY - Upper Confining Unit** section and fig. J5). Evidence for the interconnection between the surficial aquifer and the Upper Floridan aquifer is shown by the similarity between the estimated high water-table elevation (surficial aquifer) and the potentiometric surface of the Upper Floridan aquifer (mostly unconfined). Downward recharge from the surficial aquifer to the Upper Floridan aquifer is greatest in the central parts of the islands where topographic elevations are highest and is lowest near island perimeters where elevations are near sea level, as demonstrated by potentiometric maps for the Upper Floridan aquifer (Appendix D).

For the Sea Islands northeast of Port Royal Sound, Upper Floridan aquifer pumping wells were not used to calibrate the model because: (1) measured water-table elevations and potentiometric maps for the Upper Floridan aquifer are not available for predevelopment conditions, (2) the model input can only accept average yearly water use as opposed to seasonal irrigation use, and (3) water use reporting is less reliable because groundwater withdrawals for irrigation are not metered. However, it is plausible that measured potentiometric surface maps constructed during the winter season would approximate the natural predevelopment potentiometric surface for the aquifer. This reasoning is based on the higher water-table elevations in the surficial aquifer contributing local recharge to the underlying Upper Floridan aquifer in combination with low groundwater withdrawals from the aquifer during the winter season. However, measured potentiometric surface maps for the aquifer northeast of Port Royal Sound will differ from the simulated predevelopment map where (1) measurements were not taken during the winter season and (2) recharge to the aquifer is above or below normal owing to drought or above average rainfall.

Water-table elevations for the surficial aquifer were computed by first assigning topographic elevations, using light detection, and ranging (LIDAR) data, for each cell in layer 1. Afterwards, a multiplier of 0.66 was applied to the elevations and the computed values were inputted as a constant-head boundary for each cell in the overlying surficial aquifer (fig. J8); the same multiplier was used for the remaining cells in layer 1 throughout the model area. For areas northeast of Port Royal Sound, hydraulic conductivity for the upper confining unit was adjusted (0.03 ft/d; fig. J5) until the computed water-table elevations (constant heads: fig. J8) were slightly higher than the simulated predevelopment heads in the Upper Floridan aquifer (Appendix J9). The resulting simulated heads for the predevelopment surface allow sufficient margin to match the lower heads measured during irrigation pumping season as evidenced from potentiometric-surface maps that date from 1984 to 1998 (Appendix D).

To the southwest of Port Royal Sound, the Upper Floridan aquifer potentiometric surface maps selected for model calibration represented the years circa 1880, 1957, and two maps in 1998 (Appendix D1, D4, D21, and D22). The referenced dates cover the progressive declines in the potentiometric surface and include: (1) the estimated 1880 predevelopment potentiometric-surface map (Warren, 1944; Counts and Donsky, 1963); the 1957 potentiometric map for Savannah pumpage prior to development at Hilton Head Island (Counts and Donsky, 1963); and (3) the 1998 potentiometric map for Savannah and Hilton Head Island pumpage (Ransom and White, 1998; Peck and others, 1998). After initial model design and input of hydraulic parameters, the model was run for 85 years (1800 to 1884; pumpage began about 1885) under steady-state conditions to allow the predevelopment potentiometric surface to reach equilibrium. The simulated 1884 predevelopment potentiometric surface (fig. J7) was compared to the 1880 predevelopment potentiometric maps: hydraulic conductivities of the Upper Floridan aquifer and upper confining unit were then adjusted until a close match was achieved. The simulated 1957 and 1998 potentiometric maps (Appendix J11 and J12) were calibrated in a similar manner. Afterwards, the model was run to simulate the 1943 potentiometric surface (Warren, 1944). The published 1943 map and the 1943 model simulation are shown in Appendix D3 and fig. J10: a close match was achieved without further adjustment.

Saltwater Movement

The model was calibrated to simulate the movement of chloride plumes created by: (1) relict brackish-to-saltwater movement near the bottom of the Upper Floridan aquifer that applies to the Parris Island and Port Royal Sound chloride plumes, (2) modern brackish-to-salt water moving directly downward from source areas where the upper confining unit is absent beneath the Atlantic Ocean, saltwater marshes and channels that applies to the Parris Island chloride plume and areas southwest of Port Royal Sound (the Dolphin Head, Pinckney Island, Colleton River, Sawmill Creek, Jenkins

Island, Broad Creek, Bull Island, Hilton Head High, and Eight-Mile chloride plumes (fig. 34)) and, (3) modern brackish-to-salt water moving vertically downward through the upper confining unit over an area that includes approximately 1,200 mi^2 beneath the Atlantic Ocean, saltwater marshes, and tidal channels.

The 1880 predevelopment position of the relict saltwater plume (fig. 71) at the bottom of the Upper Floridan aquifer beneath Port Royal Sound was simulated by Smith (1988), who used data from the 1984 Port Royal Sound drilling project completed by the SCWRC, USGS, and the USACE (Burt and others, 1987). He also simulated the rate of movement of the relict freshwater to brackish-water interface at the leading edge of the predevelopment plume across a transect that extended from an area near the southern end of St. Helena Island to an area of heavy pumpage on northern Hilton Head Island, S.C. Landmeyer and Belval (1996) used more recent data, in addition to data from the Port Royal Sound drilling project, to construct a 1984 isochlor map (fig. 36) for the top and bottom of the Upper Floridan aquifer beneath Port Royal Sound and Parris Island. Data from the above referenced reports were used in this model to simulate the estimated 1880 predevelopment position of the brackish-to-saltwater interface: the low pumpage and short duration of groundwater withdrawals in this area prior to 1984 would have done little to change the 1884 predevelopment position of the Parris Island and Port Royal Sound plume (Bush 1988). Construction of the predevelopment plume involved (1) assigning constant concentrations to cells where relict salt water was present near the bottom of the Upper Floridan aquifer and initial concentrations for cells at the leading edge of the interface where relict brackish water was present, and (2) removing the upper confining unit in areas near Parris Island (fig. 34) where data from monitoring wells and offshore seismic profiles indicated that the unit was thin or absent, allowing a vertical path for modern brackish to salt water to move downward and mix with relict brackish to salt water in the Upper Floridan aquifer (fig. J13). Afterwards, the model was run at steady-state conditions for 85 years (model years 1800 to 1884) to allow the simulated relict freshwater-to-saltwater interface to reach equilibrium. Calibration of the simulated predevelopment chloride plumes was achieved by repeating model runs and adjusting conductivity, constant concentrations, initial concentrations, and the estimated areas where the upper confining unit was eroded near Parris Island to obtain a close match with the 1984 Port Royal Sound isochlor map (figs. 36 and J14).

Modern brackish to saltwater will move directly downward from surface sources into the Upper Floridan aquifer where the upper confining unit is absent, and the potentiometric surface is near or below sea level. Here, the model simulated direct source areas by increasing the conductivity to 20 ft/d of the upper confining unit (layers 3 through 12), thereby creating a vertical column of cells in, that is characteristic of infill originating from overlying surficial sediment (fig. J6). Direct-source areas were assigned an estimated constant concentration for salt at the bottom of the surficial aquifer (layer 2) by evaluating the computed chloride concentrations at the bottom of the Upper Floridan aquifer in monitoring wells closest to the estimated source area. The value for salt was based on the belief that a relatively large volume of modern brackish to salt water moving downward and laterally toward Upper Floridan aquifer monitoring wells would be similar if the monitoring wells were not too distant from the source area. The values assigned for constant concentrations in layer 2 were adjusted for cells above the designated direct brackish-to-salt water source areas.

At Parris Island, the potential was great for downward movement of modern brackish to salt water, but regional downward movement would have been minor because the potentiometric surface was rarely depressed below mean sea level: exceptions may have occurred near pumping wells. However, nine offshore source areas were discovered southwest of Port Royal Sound where the potentiometric surface was much lower. Here, the direct downward movement of modern brackish to salt water at source areas created large chloride plumes near the bottom of the Upper Floridan aquifer.

Nearest to Port Royal Sound are the Dolphin Head, Pinckney Island, and Colleton River chloride plumes. The simulated movement of these three chloride plumes was calibrated by adjusting the regional porosity of the aquifer, estimated location of the source areas, and constant concentration for salt at each source area. Model runs continued until a close match was achieved with the 2007 isochlor map, which showed that the Parris Island, Port Royal Sound, Dolphin Head, Pinckney Island, and Colleton River chloride plumes had merged at the bottom of the Upper Floridan aquifer. These five combined plumes are designated in this report as the greater Port Royal Sound chloride plume (figs. 70 and 72; fig. J19).

Farther to the southwest and southeast of Port Royal Sound, offshore data were not available to map the full extent of the Sawmill Creek, Jenkins Island, Broad Creek, Bull Island, Hilton Head High, and Eight-Mile chloride plumes. Here, model calibration to estimate plume expansion was primarily limited to comparing simulated concentration of salt at the bottom of the Upper Floridan aquifer with computed chloride concentration from the aquifer bottom at the nearest monitoring well. After each model run, the location of the source area, the constant concentration of salt assigned to the source area, and the conductivity of the channel infill that replaced the upper confining unit were adjusted until a close match was achieved with computed chlorides at the nearest monitoring well. The parameters inputted to calibrate the potentiometric maps were not adjusted and remained similar to those used throughout the model area: therefore, the model simulations showing plume expansion for the six plumes located southwest and southeast of the sound should be a close approximation (fig. J19).

Downward migration of modern brackish to salt water through the upper confining unit has been verified by chemical analyses of pore water extracted from geologic core (fig. 32; Appendix G). The migration began about 100 years ago, has expanded with increased pumpage (fig. 19), and covers approximately 1,200 mi^2 beneath the Atlantic Ocean, saltwater marshes, and tidal channels where water levels are at or below sea level. Pore-water quality is site specific and will vary greatly over small distances depending on: (1) the thickness of the upper confining unit, (2) the heterogeneity of the surficial sediment, and (3) the source concentrations of modern brackish to salt water near the bottom of the surficial aquifer (layer 2) that vary with (a) distance from landmasses, (b) size and elevation of nearby landmasses, (c) rainfall, and (d) the parameters that control the dynamic mixing between lateral freshwater discharge from landmasses with overlying sources of salt water moving toward the bottom of the surficial aquifer (Ransom and Park, 2011) (fig. 30). Although interpolation of pore-water concentration for mapping remains impractical, the model can provide insight by leaving the calibrated model parameters unchanged and assigning an estimated constant concentration for brackish to salt water for each cell in layer 2 at the bottom of the surficial aquifer beneath surface sources of salt water (fig. J4). Estimates were based on Ransom and Park (2011) who published water-quality data from 27 temporary offshore boreholes sampled at discrete depths from the channel bottom to the bottom of the surficial aquifer (fig.30). The model simulation (fig. J16 for example section) was compared with chloride concentrations found in pore water extracted from the upper confining unit (Appendix G) to determine if the downward movement of brackish to salt water simulated by the model was reasonable. Given the variation in source concentration and thickness of the upper confining unit, a direct comparison was not feasible. However, the model simulations did demonstrate the regional downward movement of brackish to salt water relative to variations in thickness of the upper confining unit, head difference across the confining unit, and approximate concentration of salt overlying source areas (bottom of surficial aquifer).

MODEL RESULTS

The credibility of the model is dependent on accurately simulating the relationship between pumpage and the potentiometric surface of the Upper Floridan aquifer between 1884 and 1998 and simulating the corresponding changes in the vertical and lateral distribution of chlorides (salt) in the aquifer.

The model simulations for Upper Floridan aquifer potentiometric-surface maps dated 1880, 1943, 1957, and 1998 (figs. J7, J11, J10, and J12) compared favorably to corresponding published data after adjusting conductivity in the upper confining unit and the Upper Floridan aquifer (Appendix D1, D3, D4, D21, and D22). Differences in the measured and simulated potentiometric surface are present near Hilton Head Island after the island developed because the average yearly pumpage input into the model was not representative of seasonal irrigation and public-supply demand near Hilton Head Island: published potentiometric surface maps typically were constructed using data collected during periods of low or high groundwater demand. Potentiometric-surface maps of the Upper Floridan aquifer showing variations caused by seasonal pumpage in the four South Carolina counties adjoining the Savannah, Ga. area were constructed by Gawne for 1991, 1992, and 1993 (Appendix D12-18). The six-map series illustrates the range of seasonal water levels that were measured as opposed to average-yearly levels that that were simulated, and the difference must be considered where judging the fit of modeled and measured potentiometric surfaces.

The model simulation for 1884 predevelopment conditions suggests that the relict brackish to salt water at the bottom of the Upper Floridan aquifer in the vicinity of Parris Island and Port Royal Sound had already merged with modern brackish to salt water near the Dolphin Head plume source area (fig. J14). Geochemical analyses (fig. 69) to determine the date of saltwater intrusion indicated that modern salt water migrated downward into the groundwater system at the Dolphin Head source area by the mid 1950's (fig. 69) and that southwestward plume movement began before 1969 (fig. J16). The USGS monitoring well BFT-315, on the northwestern edge of Hilton Head Island began to show small increases in chloride concentration soon after 1974 (fig. 38). These data correspond closely to the 1977 model simulation wherein chloride concentration increased 15 mg/L at the aquifer bottom near BFT-315 (fig. J15) and marked the onshore arrival of the Dolphin Head chloride plume. The southwest-southeast advancing Dolphin Head chloride plume, shown on the 1977 model simulation, suggests that the remaining plumes shown, in part, on the model simulation were also advancing toward the southwest near the bottom of the aquifer during this time and earlier (fig. J15).

Three model simulations shown in Figures J18, J19, and J20 depict the progressive growth of the eleven chloride plumes at the bottom of the Upper Floridan aquifer in 1998, 2007, and 2050. The simulation showing plume growth by 2007 approximates the pattern of the 2007 isochlor map derived from computed chloride concentrations at the bottom of the aquifer for the greater Port Royal Sound chloride plume (fig. 72). A simulated 2007 vertical section (fig. J17) through the greater Port Royal Sound chloride plume and traversing the Dolphin Head chloride plume source area, simulates the pattern of modern saltwater entering the Upper Floridan aquifer. In the simulated section, high chloride concentrations move to the bottom of the aquifer first, and afterwards move laterally to the southwest; simultaneously, a component of the chloride plume moves downward from the bottom of the Upper Floridan aquifer into the top of the middle confining unit. The 2050 model simulation represents a projection of plume growth assuming no change in 2007 groundwater withdrawals. Here, most of the chloride plumes have combined at the bottom of the Upper Floridan aquifer and cover a combined area of about 300 mi^2.

The general pattern of downward migration of modern brackish to salt water was modeled for the full thickness of the upper confining unit, represented by ten model layers. Model simulations predict the widespread occurrence of brackish to salt water in the upper confining unit beneath saltwater estuaries, channels, and the Atlantic Ocean. Two simulations are presented in Figures J21 and J22 and illustrate salt water in the middle (layer 7) of the upper confining unit and at the bottom of the unit (layer 12), respectively. The simulations show salt at the bottom of the unit mostly to the west of Hilton Head Island and near the mouth of Port Royal Sound. Sharp differences in the simulated salt concentration are present in some areas and are attributed to abrupt changes in input parameters: conductivity; salt concentration in overlying sources; upper confining unit thickness; and potentiometric-surface changes. There also are differences between the chloride breakthrough times calculated by Ransom and others (2006; fig. 33) and those simulated by this model (fig. J22). The analytical model used by Ransom and others showed a greater rate of downward migration that is attributed to (1) a source concentration equivalent to seawater rather than varied concentrations resulting from lateral freshwater discharge from the surficial aquifer beneath nearby landmasses as reported by Ransom and Park (2011), and (2) a single and greater conductivity value for the upper confining unit as opposed to variable conductivities input into this digital model. Initial breakthrough concentration will be diluted by the greater flow through the Upper Floridan aquifer, but chloride concentrations in the aquifer will increase with time.

Explanation

Base map: USGS 7 ½ minute topographic quadrangles.

Map scale: ¼-inch equals approx. 4 miles.

Figure J1. Map showing extent of model boundaries and primary study area of Savannah, Ga. and Hilton Head Island, S.C.

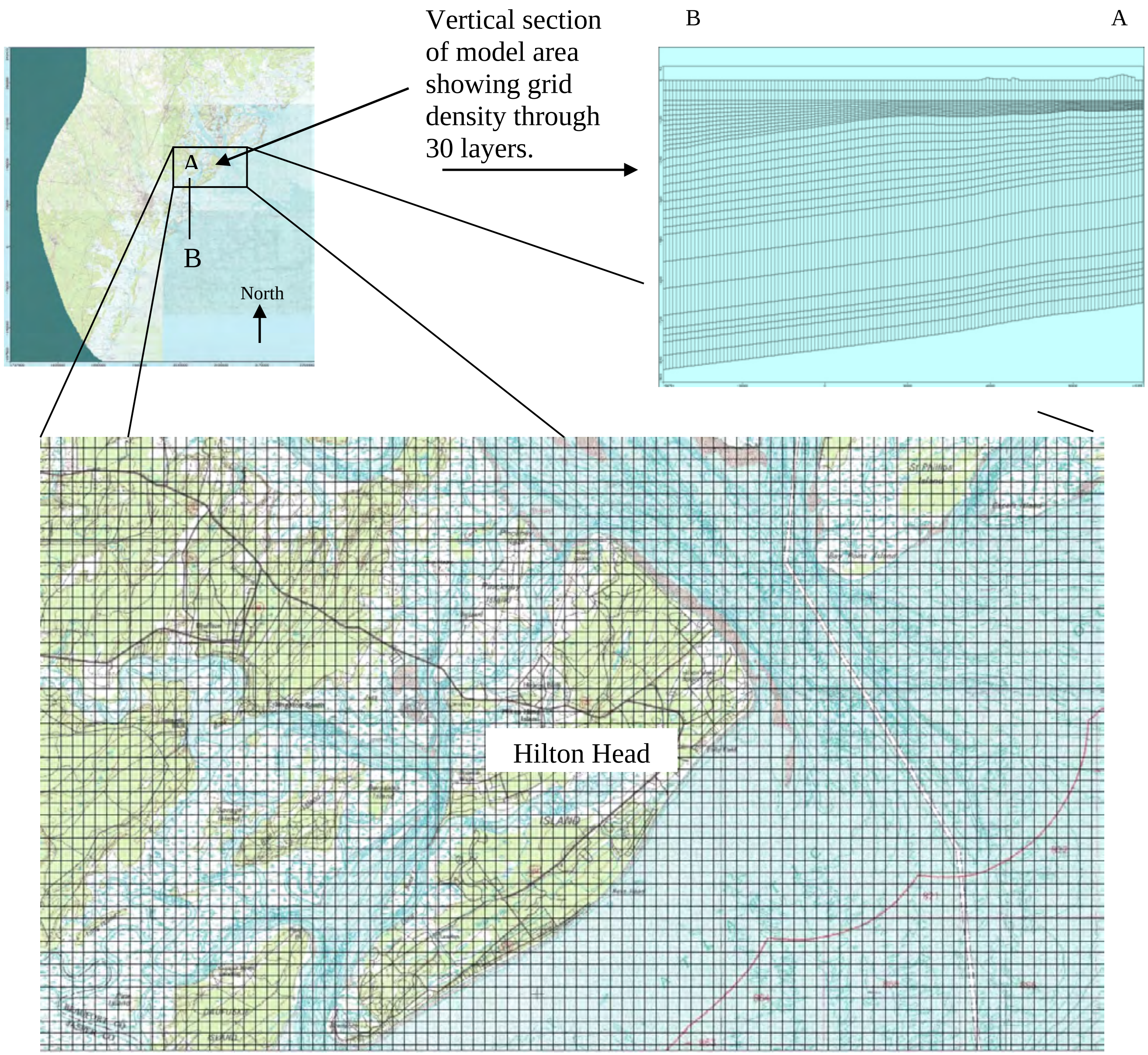
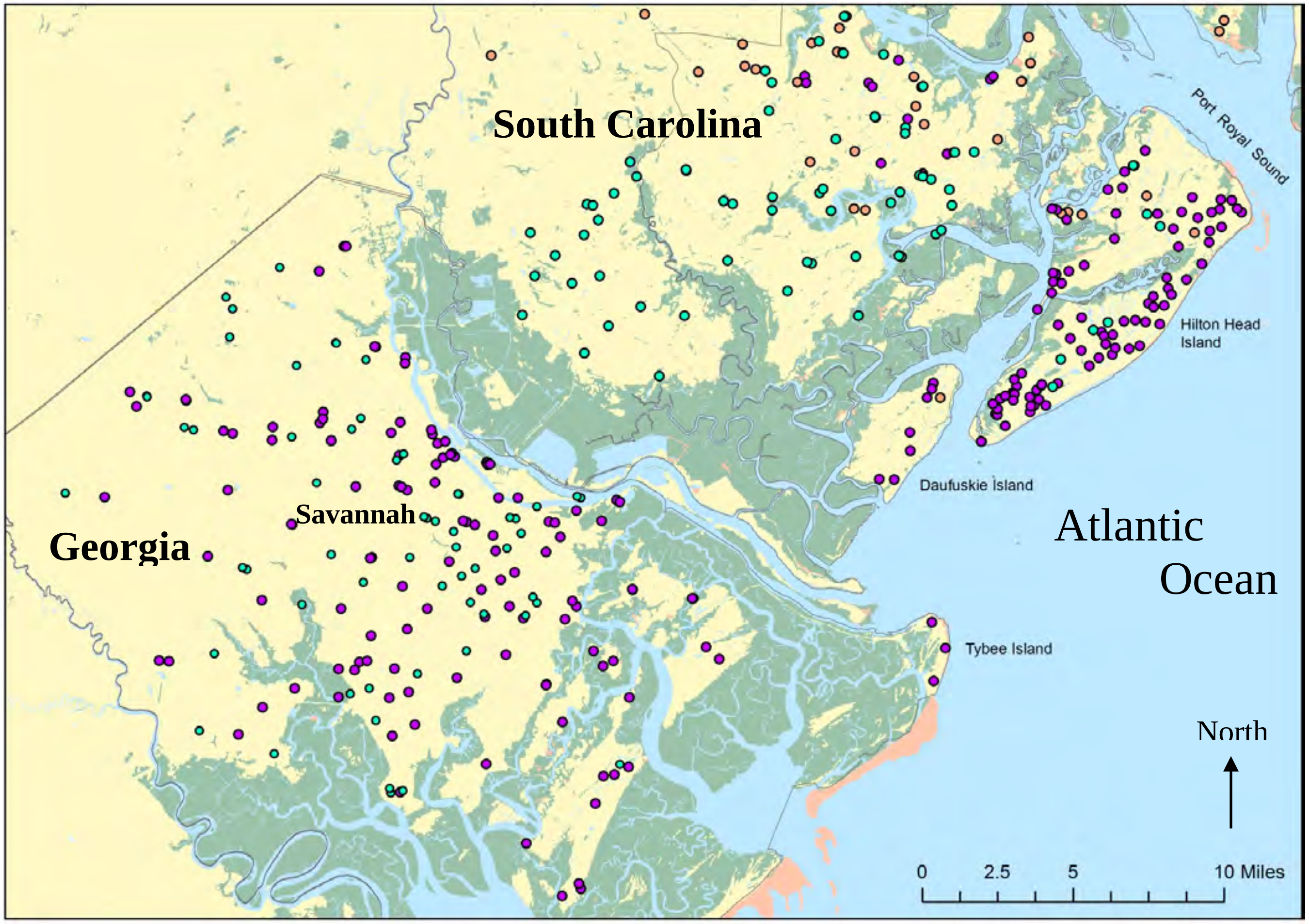


Figure J2. Map and section showing grid density for x, y, and z planes with ¼ mi^2 cells, in part, for the model area in the vicinity of Hilton Head Island, S.C.

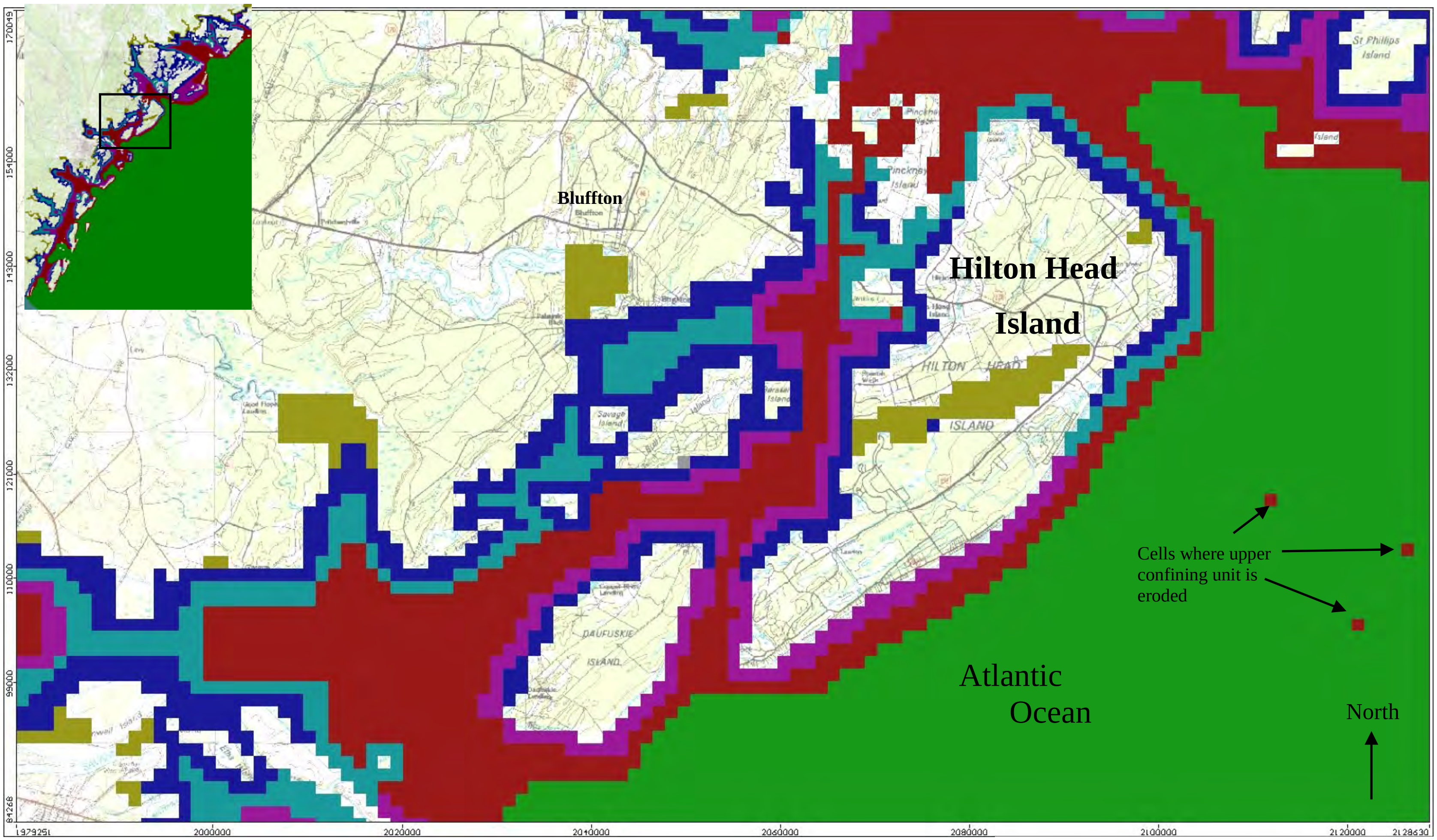


Explanation

- Permitted Upper Floridan aquifer pumpage.
- Permitted middle Floridan aquifer pumpage.
- Unpermitted Upper Floridan aquifer pumpage (locations random).

Base map: U.S. Census Bureau –national wetlands inventory

Figure J3. Location of simulated pumping wells assigned to the model area near Savannah Ga. and Hilton Head Island, S.C.



Explanation

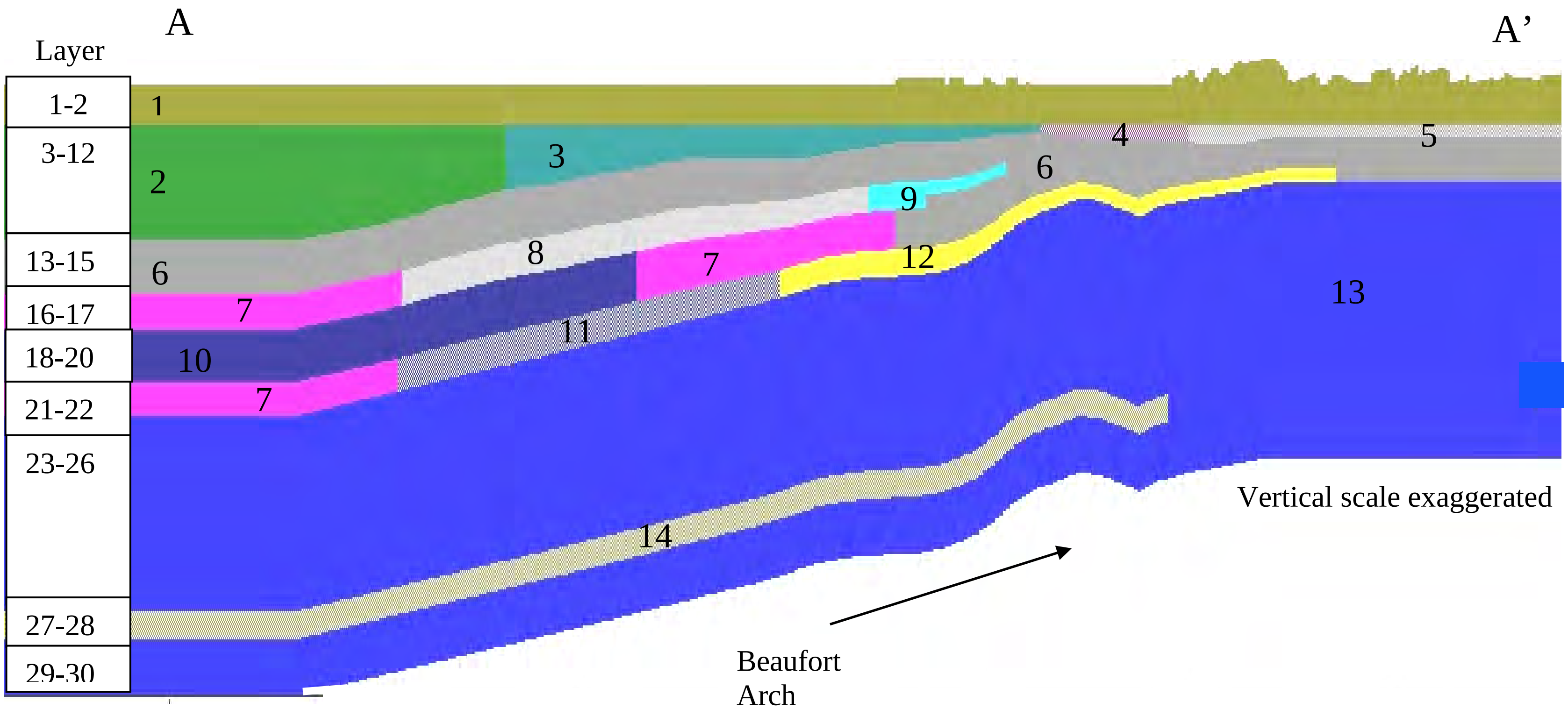
Model cell: ¼ square mile.

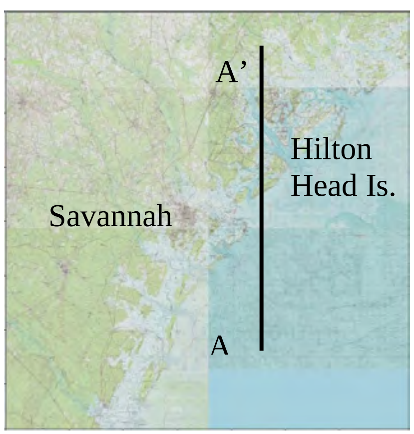
Salt, as sodium chloride.

Base map: USGS 7 ½ minute topographic quadrangle.
1/2-inch equals approx. 1 mile.

31,000 mg/L	20,000 mg/L	13,500 mg/L	10,000 mg/L	2,000 mg/L	1,200 mg/L

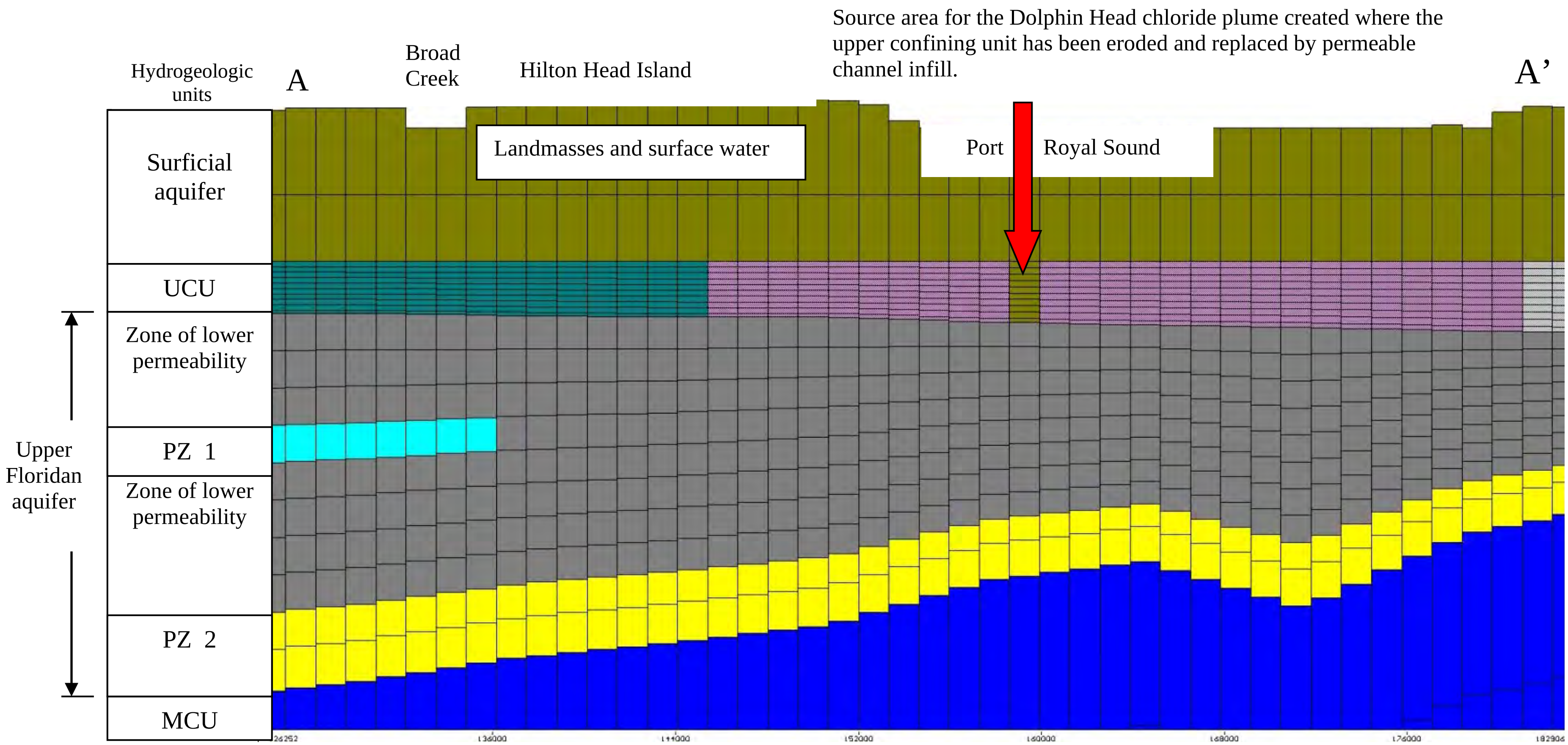
Figure J4. Distribution of brackish to salt water assigned as a constant concentration at the surficial aquifer bottom (layer 2) in the vicinity of Hilton Head Island, S.C area (only part of model area shown).

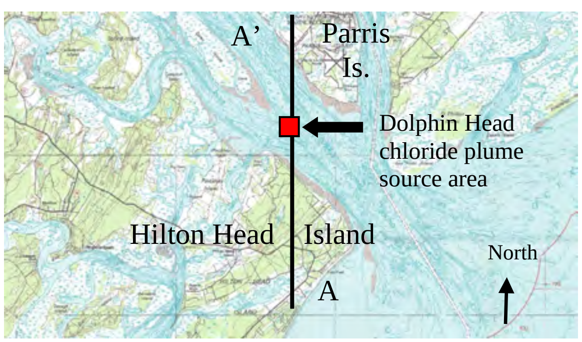




Hydrogeologic unit	Model Layers	No.	Conductivity (ft/d)
Surficial aquifer	1 - 2	1	20
Upper confining unit	3 - 12	2,3,4,5	6e-6, 8e-5, 0.0025, 0.03
Upper Floridan aquifer – Oligocene limestone – zone of lower permeability	13 - 15	6	50
Upper Floridan aquifer – permeable zone 1	16 - 17	7,8,9	200, 350, 600
Upper Floridan aquifer – zone of lower permeability	18 - 20	10, 7, 6	25, 200, 50
Upper Floridan aquifer – permeable zone 2	21 - 22	7, 11, 12	200, 250, 500
Middle confining unit	23 - 30	13	x and y = 0.5, z = 0.05
Middle Floridan aquifer	26-28	14	25

Figure J5. Hydraulic conductivity assigned to hydrogeologic units in the model area are depicted in section A – A’ traversing offshore of Savannah, Ga., through Hilton Head Island, S.C.





Explanation

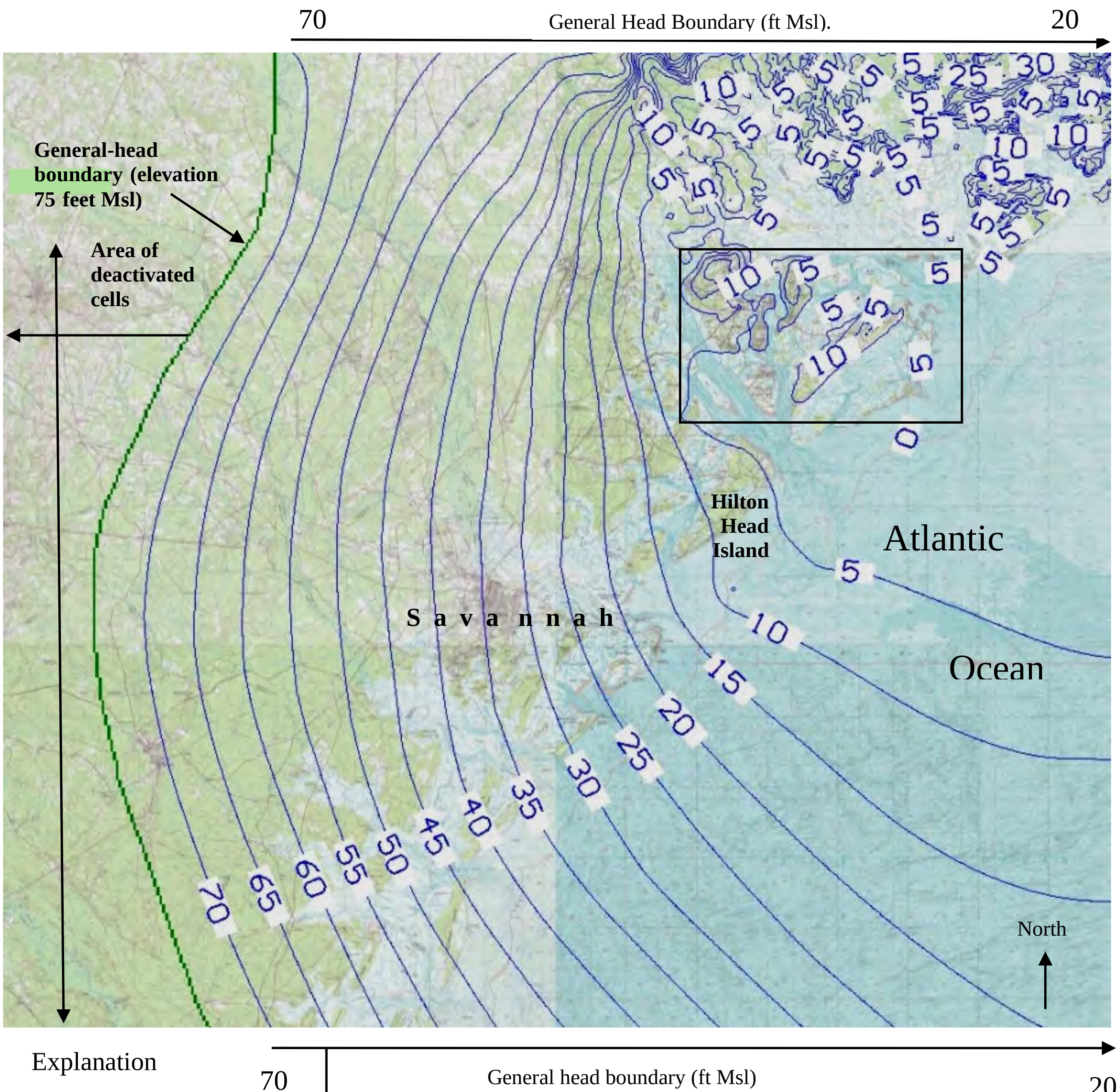
Cell color depicts changes in conductivity of hydrogeologic units.

UCU – upper confining unit
PZ 1 – permeable zone 1
PZ 2 – permeable zone 2
MCU – middle confining unit

Horizontal scale: one cell equals ¼-mile.

Vertical scale: exaggerated.

Figure J6. Generalized model section showing permeability change where the upper confining unit has been eroded, replaced by overlying sandy infill, and serves as a source area for salt water to enter the Upper Floridan aquifer from Port Royal Sound, S.C.



Explanation

Note: General-head boundaries are constant for layers 13 through 30.

Southern part of model area cropped – General-head boundary (ft Msl) are for southern boundary of model (Appendix J1).

Base map: USGS 7 ½ minute topographic quadrangles.

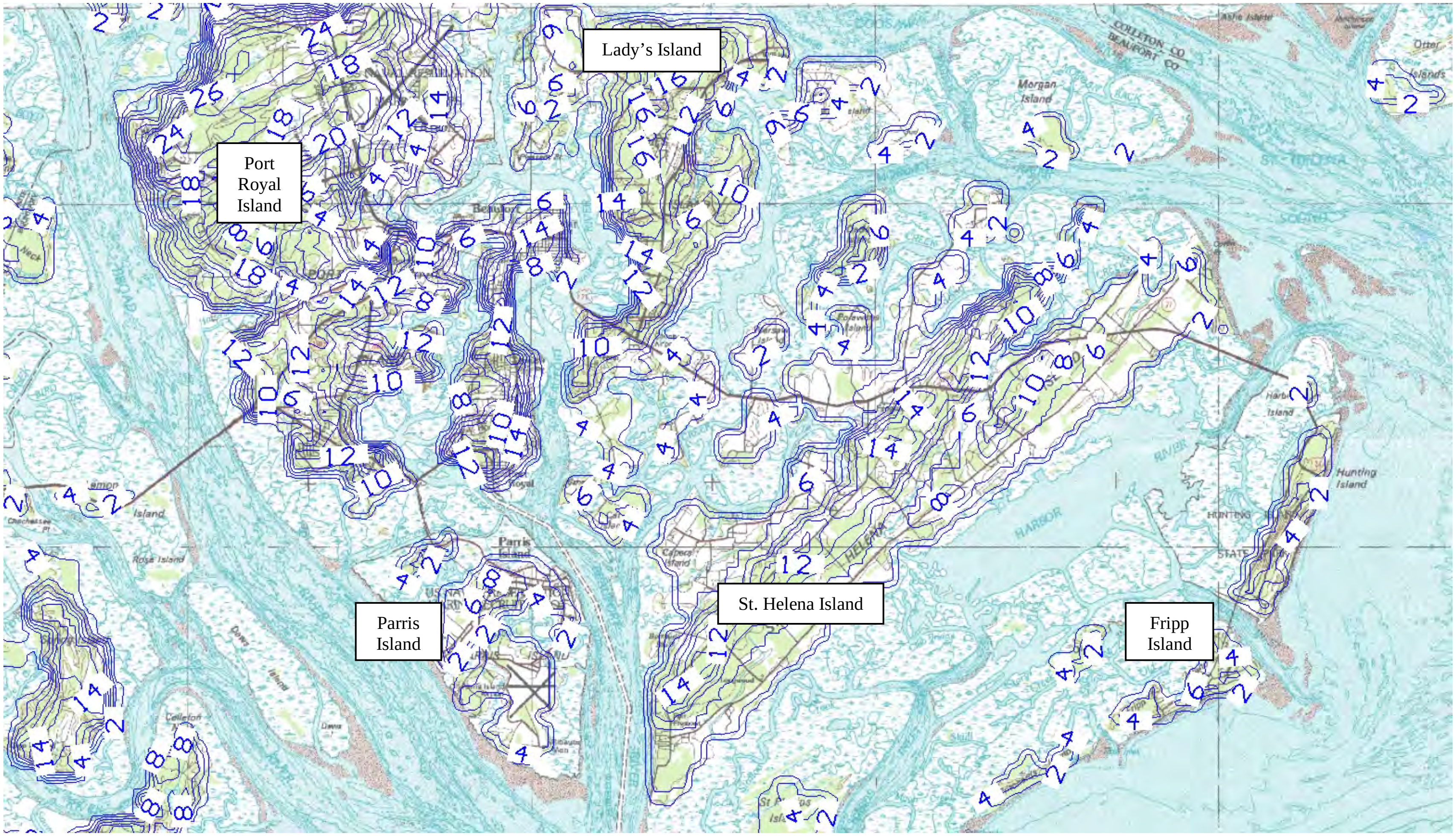
Map scale: ¼-inch equals approx. 4 miles.

Potentiometric contours are lines of equal elevation – contour interval is 5 feet. Contour labels represent approx. location of contours in some areas.

INSET

Refer to figures J8 and J9 for enhanced predevelopment water-level elevations for the surficial and Upper Floridan aquifers.

Figure J7. Simulated 1884 predevelopment potentiometric-surface map of the Upper Floridan aquifer in the Savannah, Ga. southern Beaufort County, S.C. area showing boundary conditions.

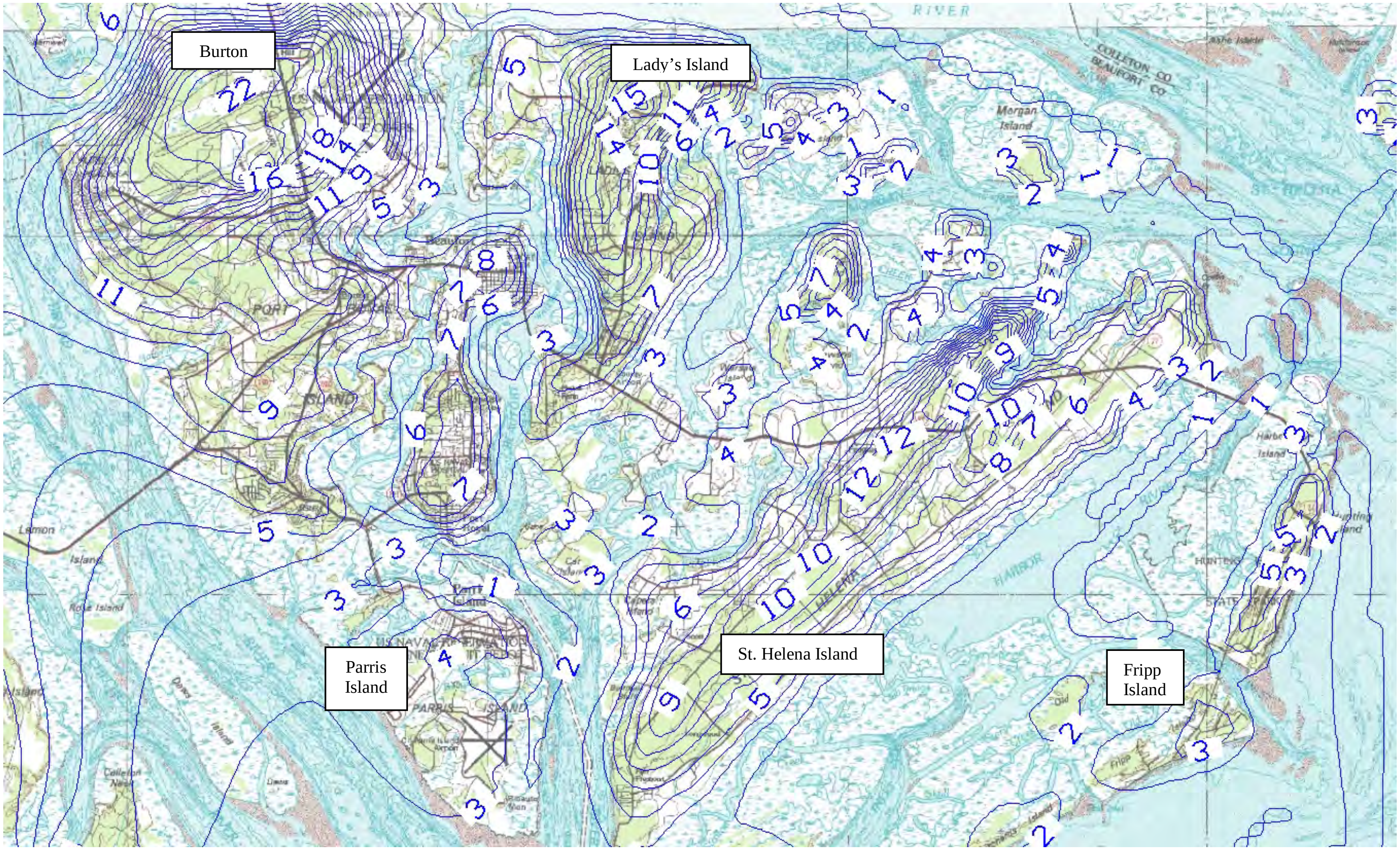


Explanation

Potentiometric contours are areas of equal elevation – contour intervals are 2 feet. **Note:** Contour labels represent approx. area of contour.

Base map: USGS 7 ½ minute topographic quadrangles.
Map scale: ¾-inch equals approx. 2 miles.

Figure J8. Map of Port Royal Island, Parris Island, Lady's Island, and St. Helena Island S.C. (Appendix J7, see inset) showing example area for computed average annual water-table elevations (surficial aquifer) input into model as constant heads.



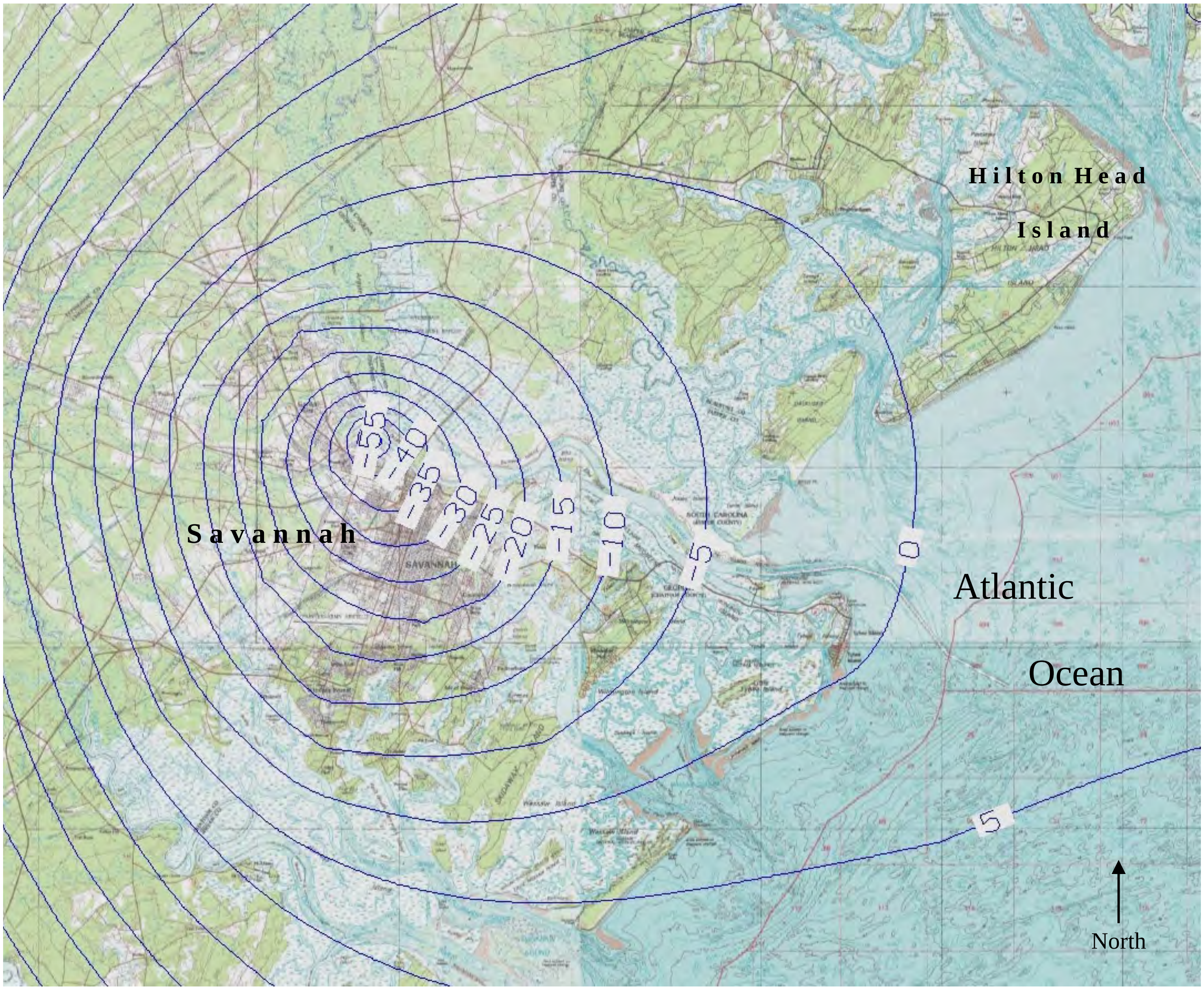
Explanation

Water-table contours are areas of equal elevation – contour intervals are 2 feet. **Note**: Contour label represent approx. area of contour.

Base map: USGS 7 ½ minute topographic quadrangle.

Map scale: ¾-inch equals approx. 2 miles.

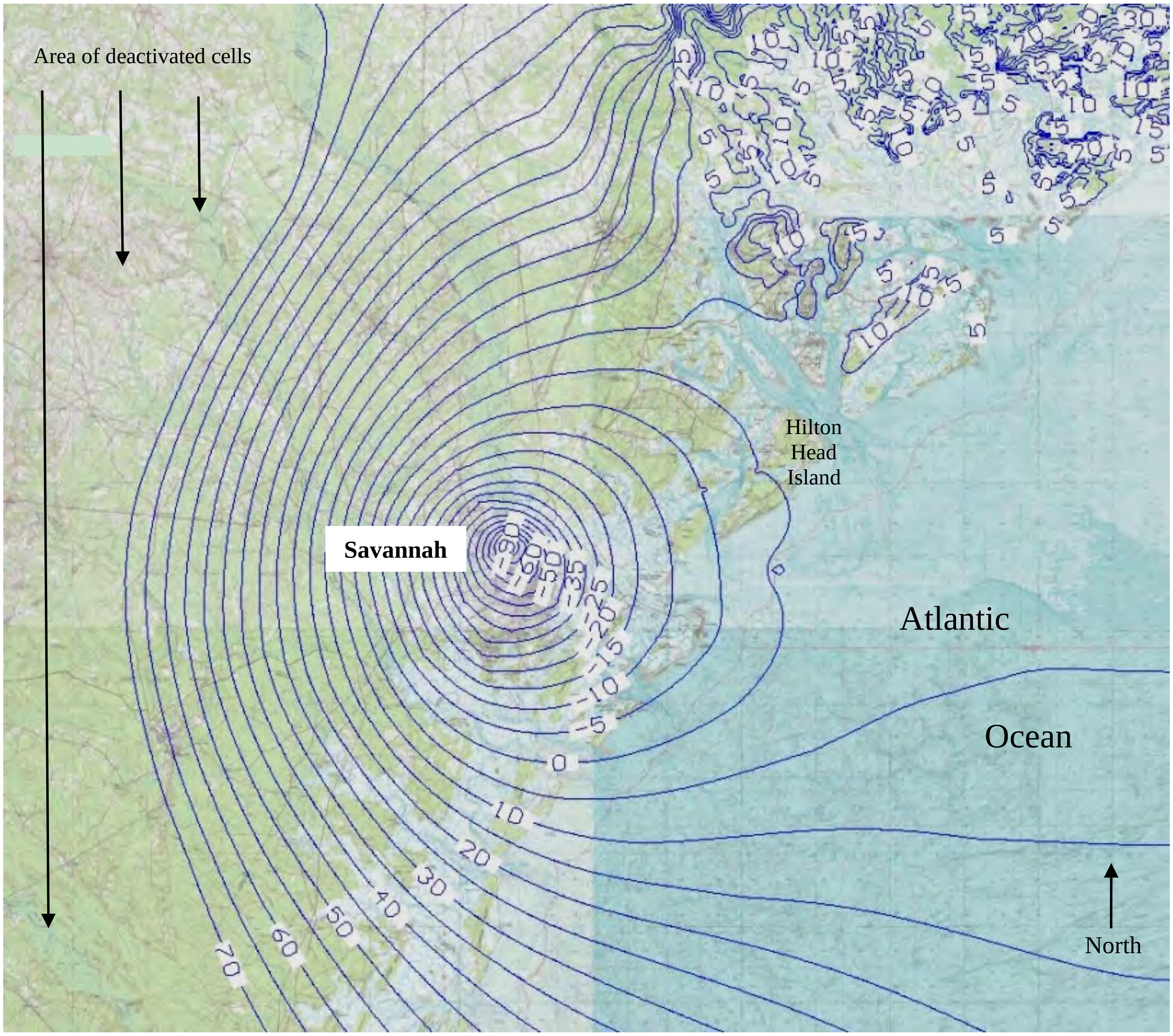
Figure J9. Map of Port Royal Island, Parris Island, Lady's Island, and St. Helena Island S.C. (Appendix J7, see inset) showing simulated 1880 predevelopment surface (unconfined) of the Upper Floridan aquifer.



Explanation — Potentiometric contours represent lines of equal elevation – contour interval is 5 feet. Some contour labels may indicate approximate location of contours.

Base map: USGS 7 ½ minute topographic quadrangles.
Map scale: one inch equals approx. 6 miles.

Figure J10. Simulated 1943 potentiometric-surface map of the Upper Floridan aquifer for the Savannah, Ga. – Hilton Head Island, S.C. area.



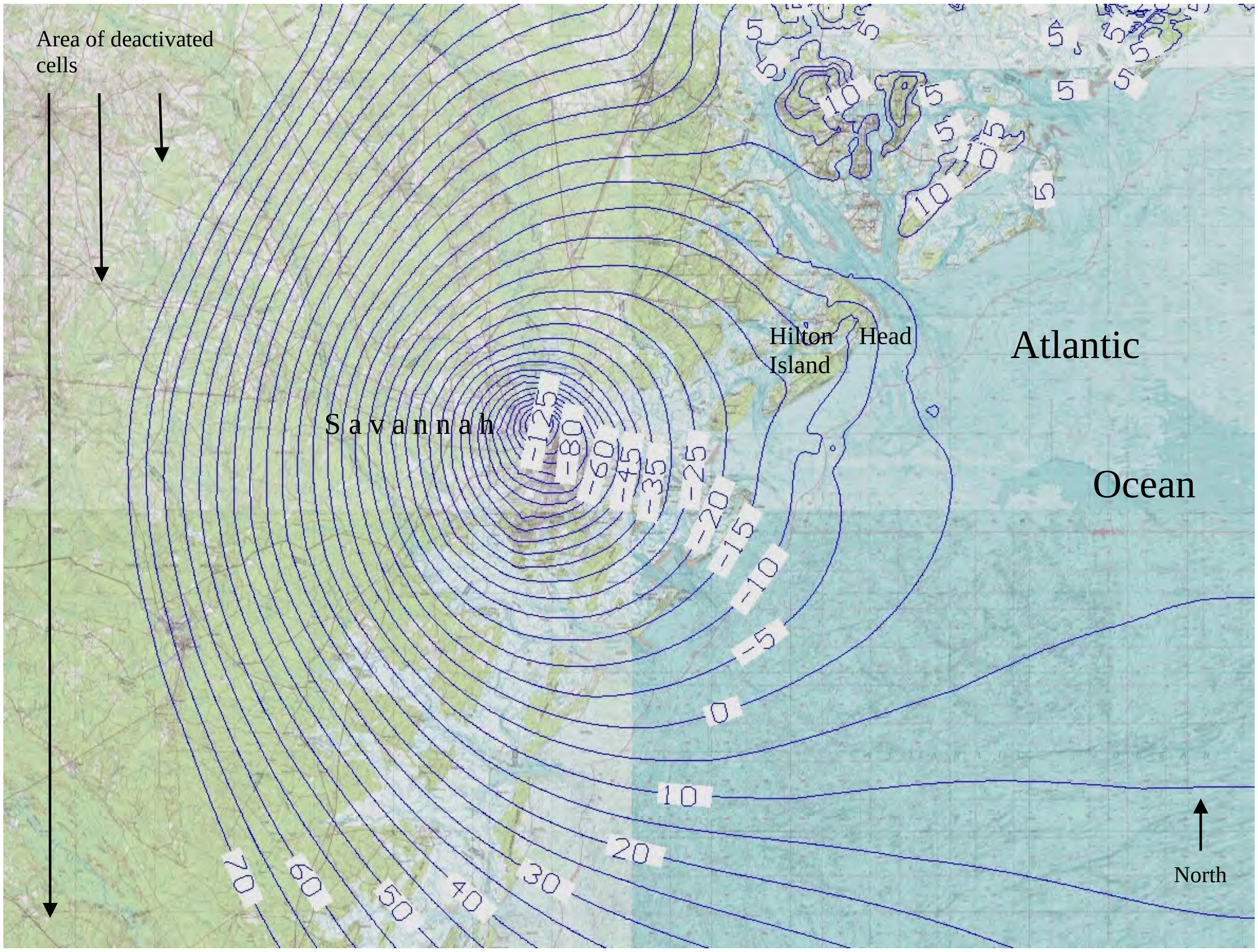
Explanation

Potentiometric contours are lines of equal elevation – contour interval is 5 feet. Some contour labels may indicate approximate location of contours.

Base map: USGS 7 ½ minute topographic quadrangles.

Map scale: one-inch equals approx. 12 miles.

Figure J11. Simulated 1957 potentiometric-surface map of the Upper Floridan aquifer for the Savannah, Ga. – Hilton Head Island, S.C. area.



Explanation

Potentiometric contours represent lines of equal elevation – contour interval is 5 feet Msl. Note: some contour labels may indicate approx. location of contours.

Base map: USGS 7 ½ minute topographic quadrangles.

Map scale: one inch equals approx. 10 miles.

Figure J12. Simulated 1998 potentiometric surface map of the Upper Floridan aquifer for the Savannah, Ga. – Hilton Head Island, S.C. area.

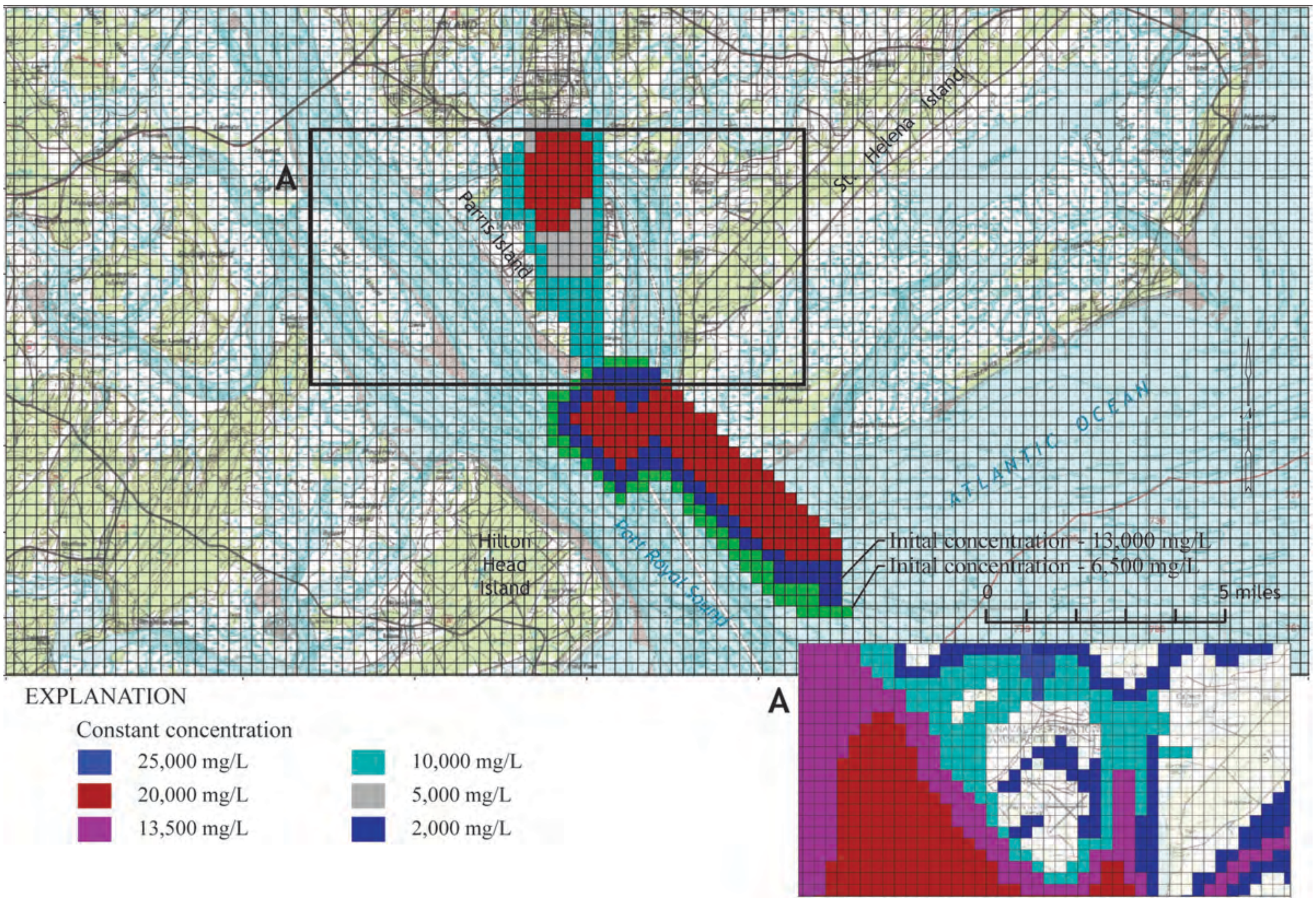
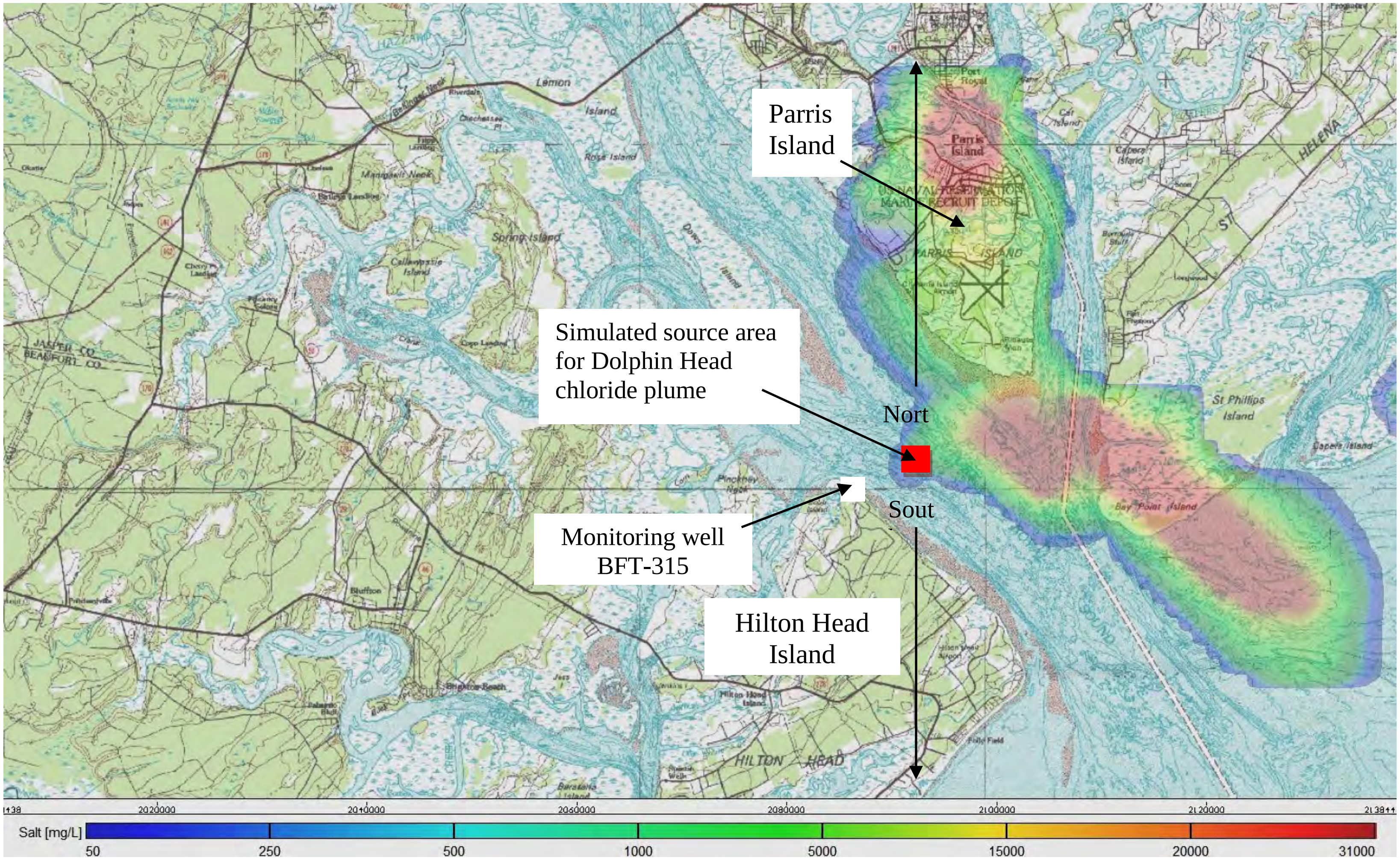


Figure J13. Initial and Constant concentrations assigned to the bottom of Upper Floridan aquifer and bottom of surficial aquifer for predevelopment conditions beneath Port Royal Sound and Paris Island, S.C.

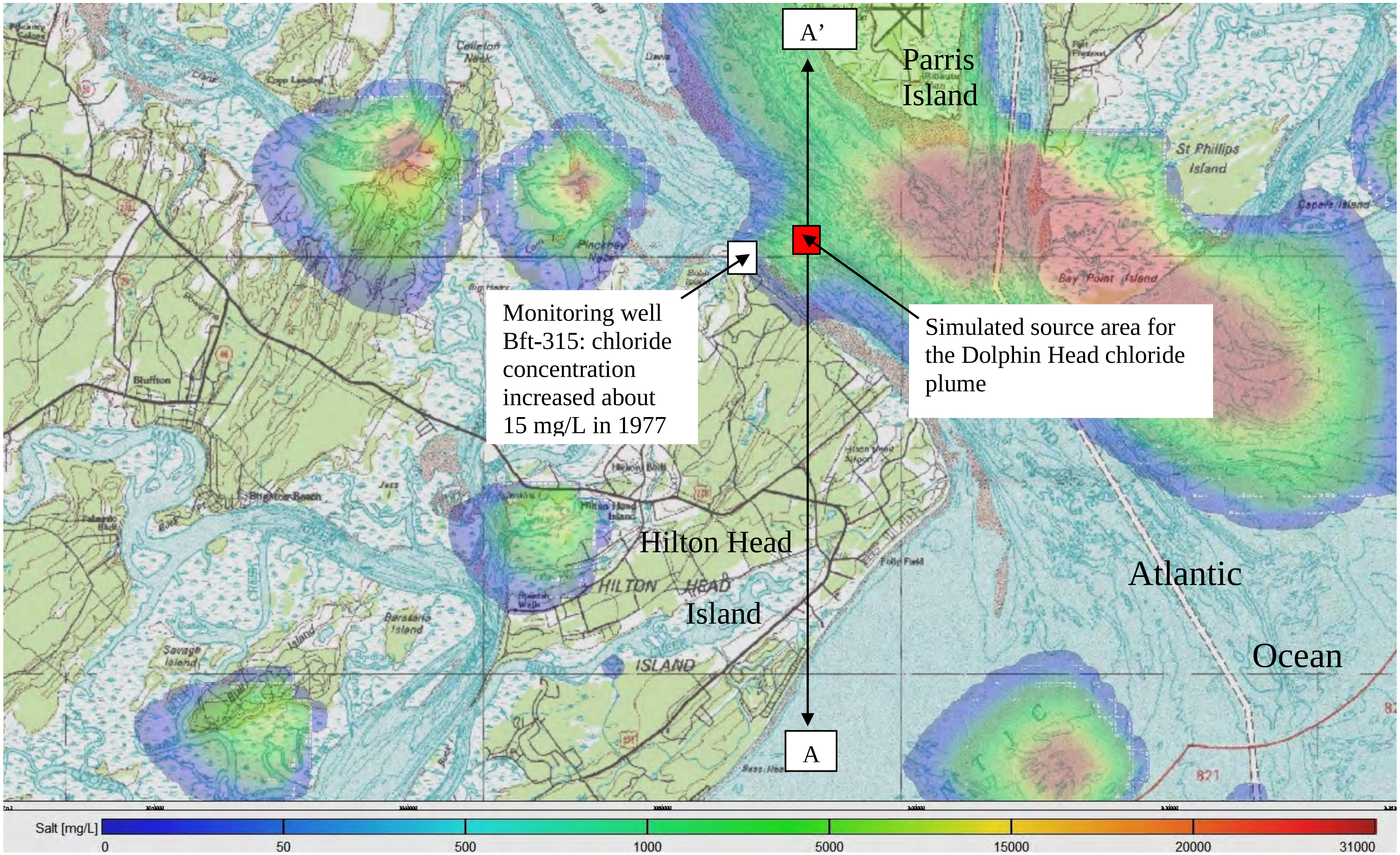


Explanation

Base map: USGS 7 ½ minute topographic quadrangles.

Map scale: one inch equals approx. 3 miles.

Figure J14. Simulated 1884 predevelopment position of brackish to salt water at the bottom of the Upper Floridan.aquifer at Port Royal Sound, S.C.

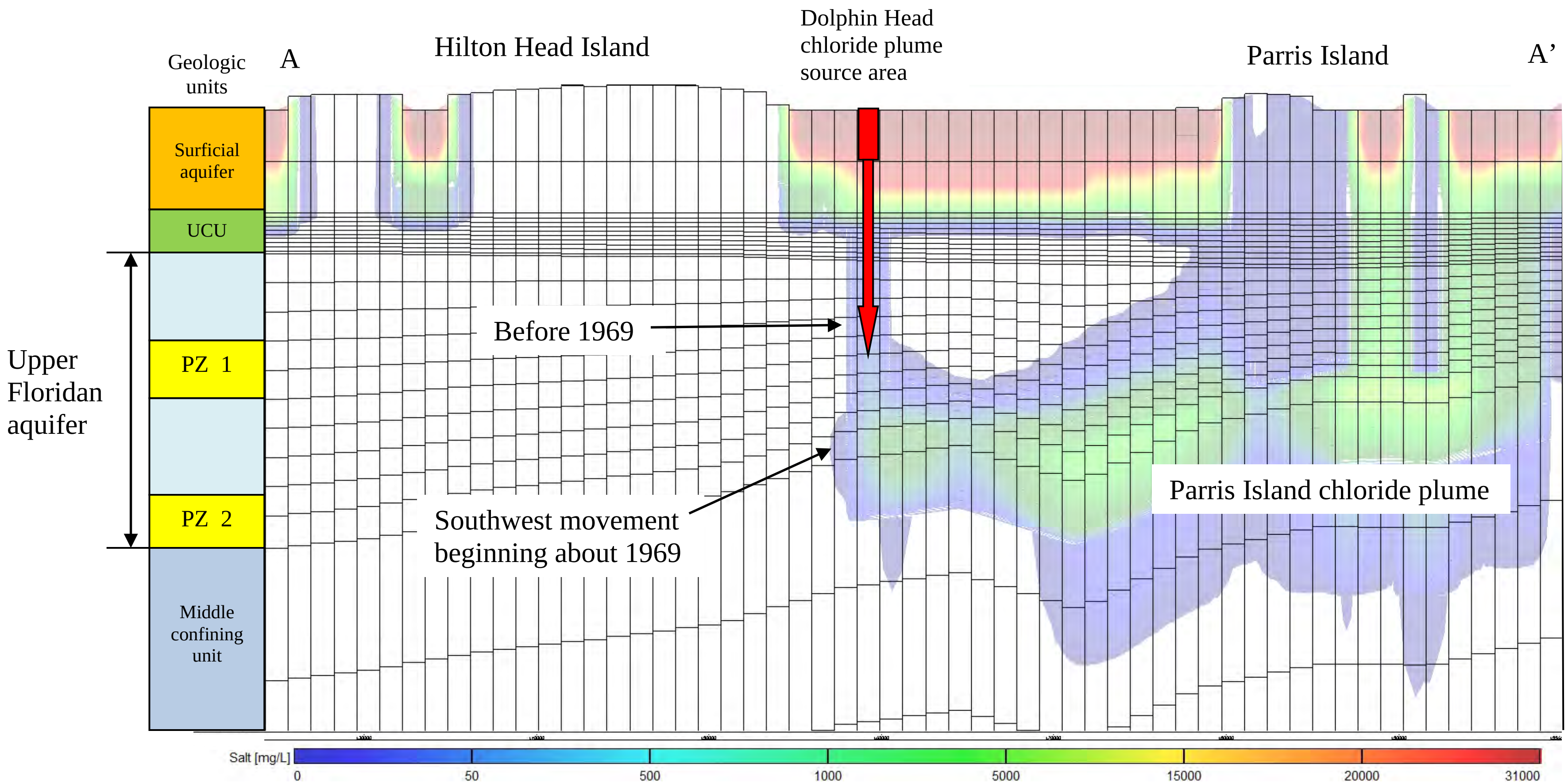


Explanation

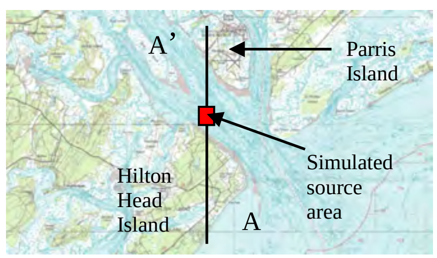
Base map: USGS 7 ½ minute topographic quadrangles.

Map scale: one inch equals approx. 2.5 miles.

Figure J15. Simulated 1977 position of brackish to salt water at the bottom of the Upper Floridan aquifer and coinciding increase in chloride concentration reported for monitoring well BFT-315 near Port Royal Sound, S.C.



Explanation

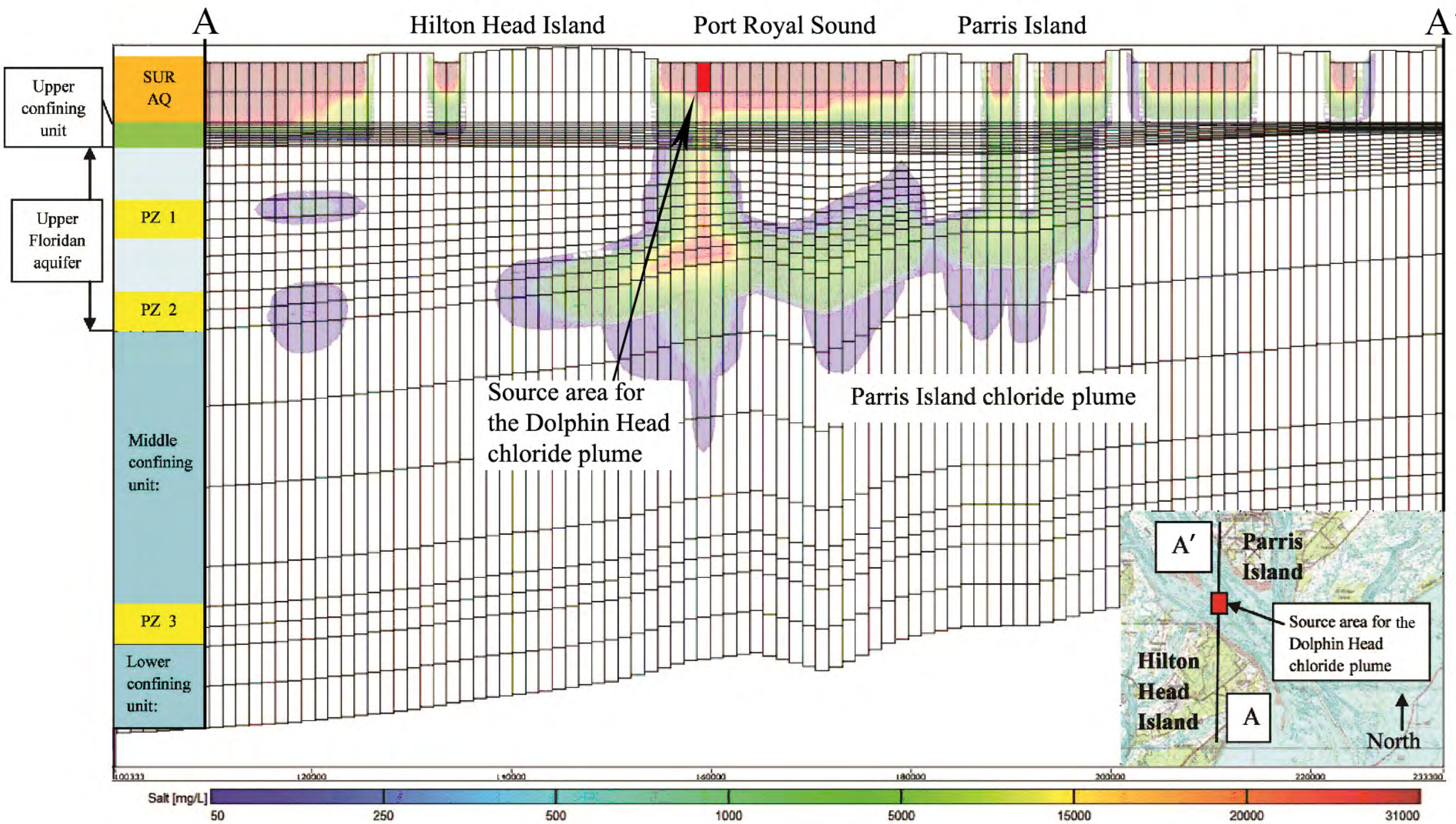


Horizontal scale: one cell equals ¼ mile.

Vertical scale: exaggerated.

UCU – upper confining unit
PZ 1 – permeable zone 1
PZ 2 – permeable zone 2
MCU – middle confining unit

Figure J16. Simulated 1969 section through source area of the Dolphin Head chloride plume and the onset of southwest plume movement, Port Royal Sound, S.C.

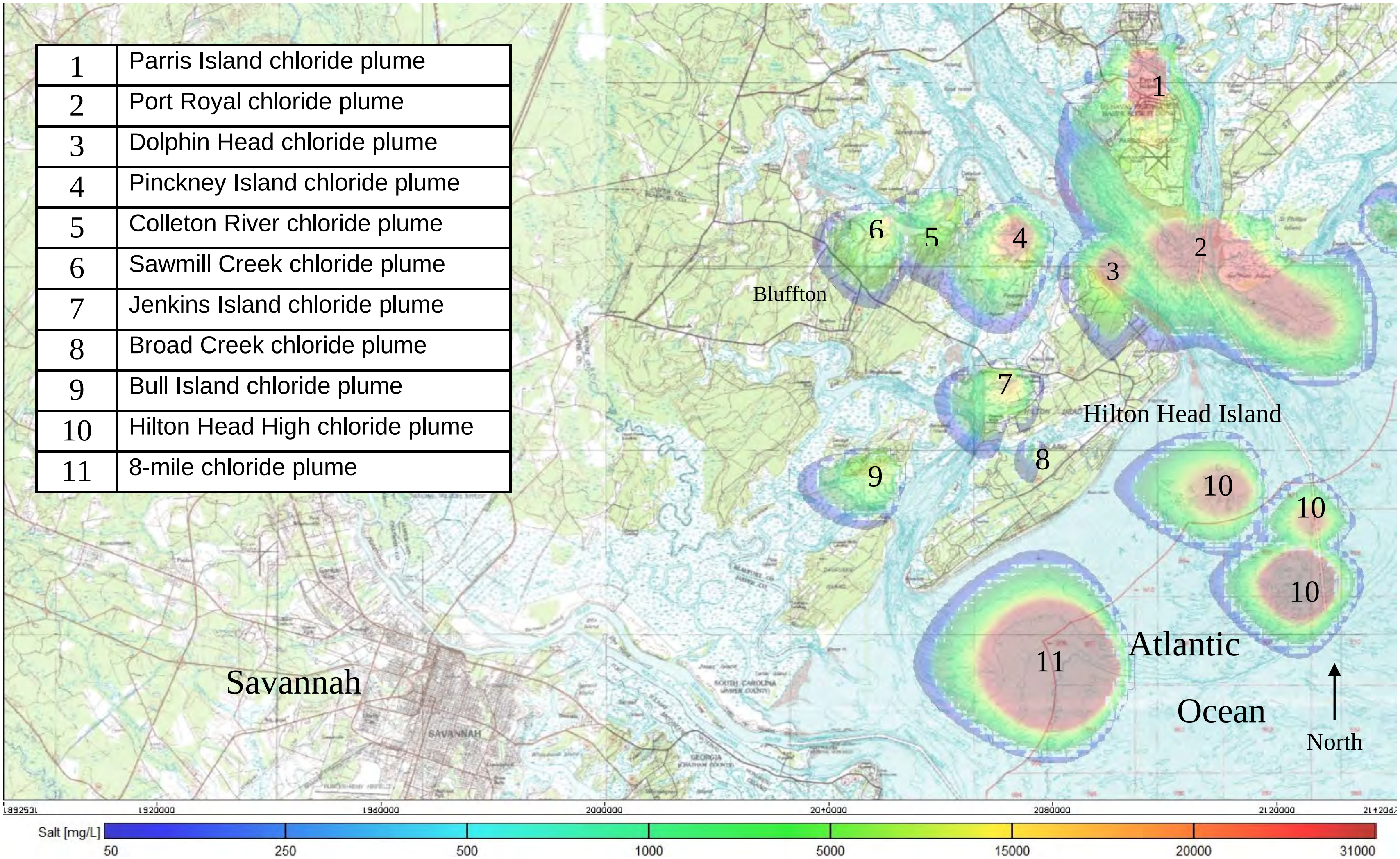


Explanation

UCU – upper confining unit
PZ 1 – permeable zone 1
PZ 2 – permeable zone 2
MCU – middle confining unit

Horizontal scale: one cell equals ¼ mile.
Vertical scale: exaggerated.

Figure J17. Section A-A' showing the simulated 2007 positions of the Dolphin Head and Parris Island chloride plumes, Port Royal Sound, S.C.

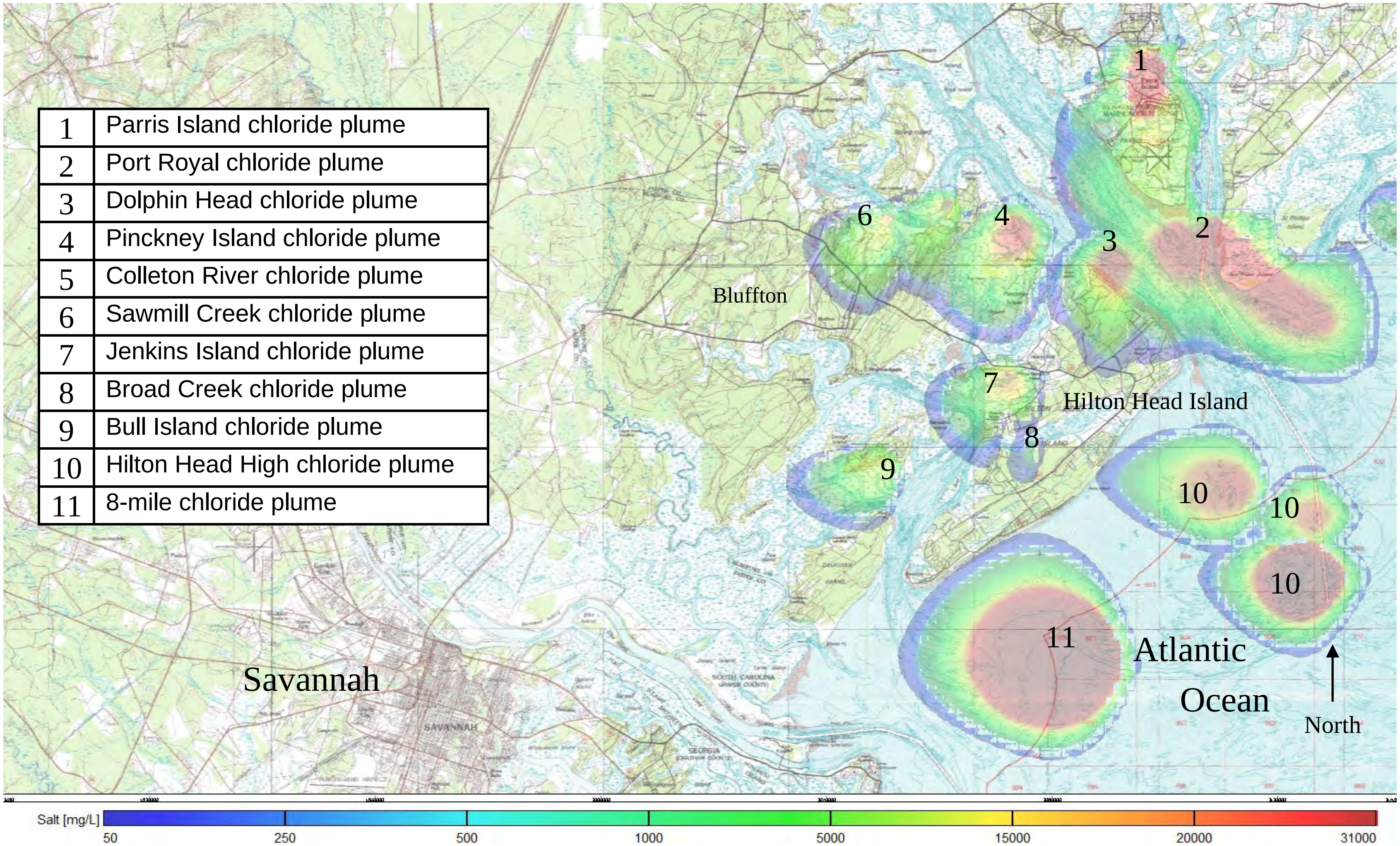


Explanation

Base map: USGS 7 ½ minute topographic quadrangles.

Map scale: One inch equals approx. 6 miles.

Figure J18. Simulated 1998 brackish-to-saltwater plumes at the bottom of the Upper Floridan aquifer (permeable zone 2), Hilton Head Island, S.C. – Savannah, Ga. area.

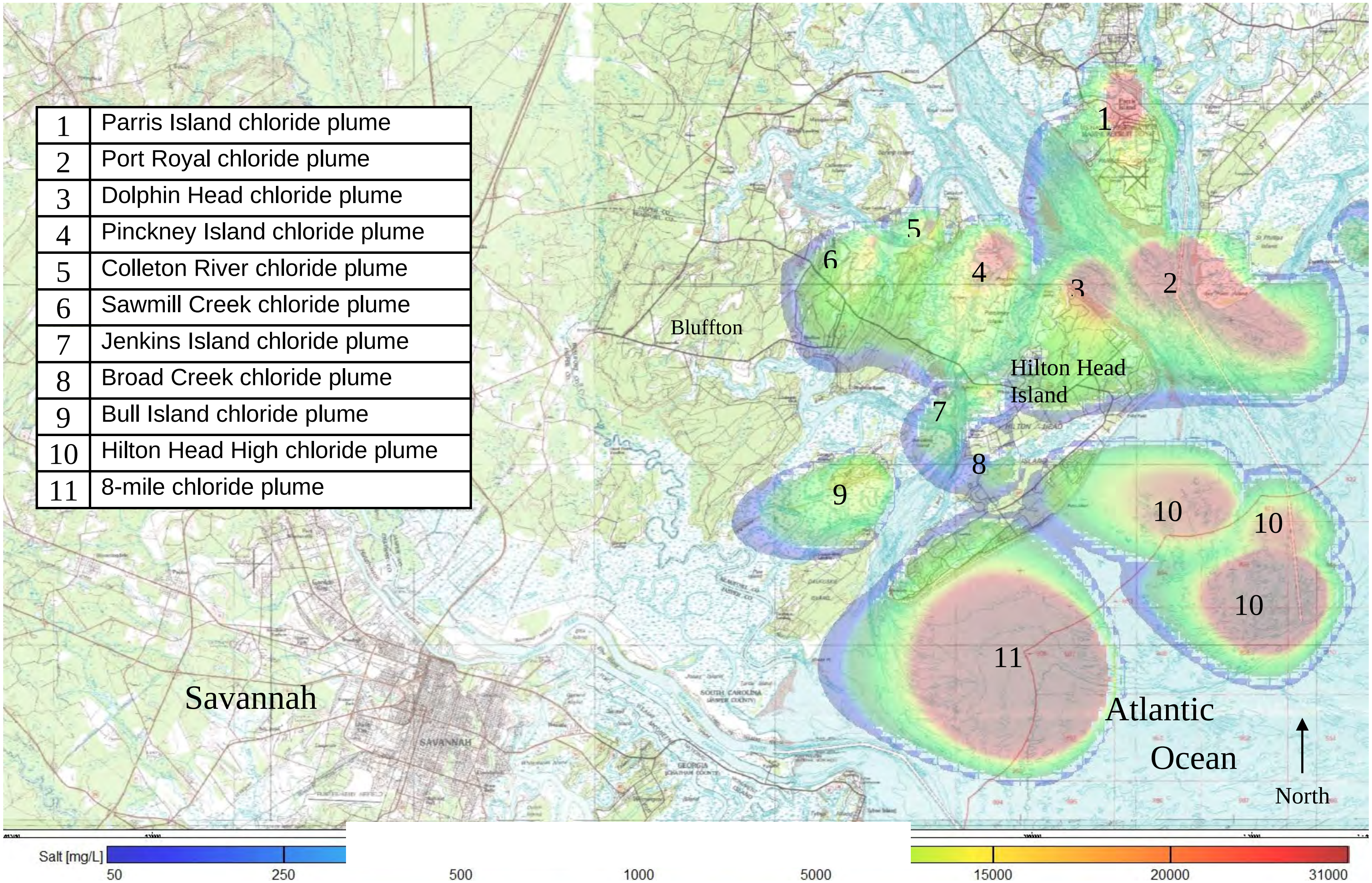


Map scale: One inch equals approx. 6 miles.

Explanation

angles.

Figure J19. Simulated 2007 positions of brackish to saltwater plumes at the bottom of the Upper Floridan aquifer (permeable zone 2,), Hilton Head Island S.C. – Savannah, Ga. area.

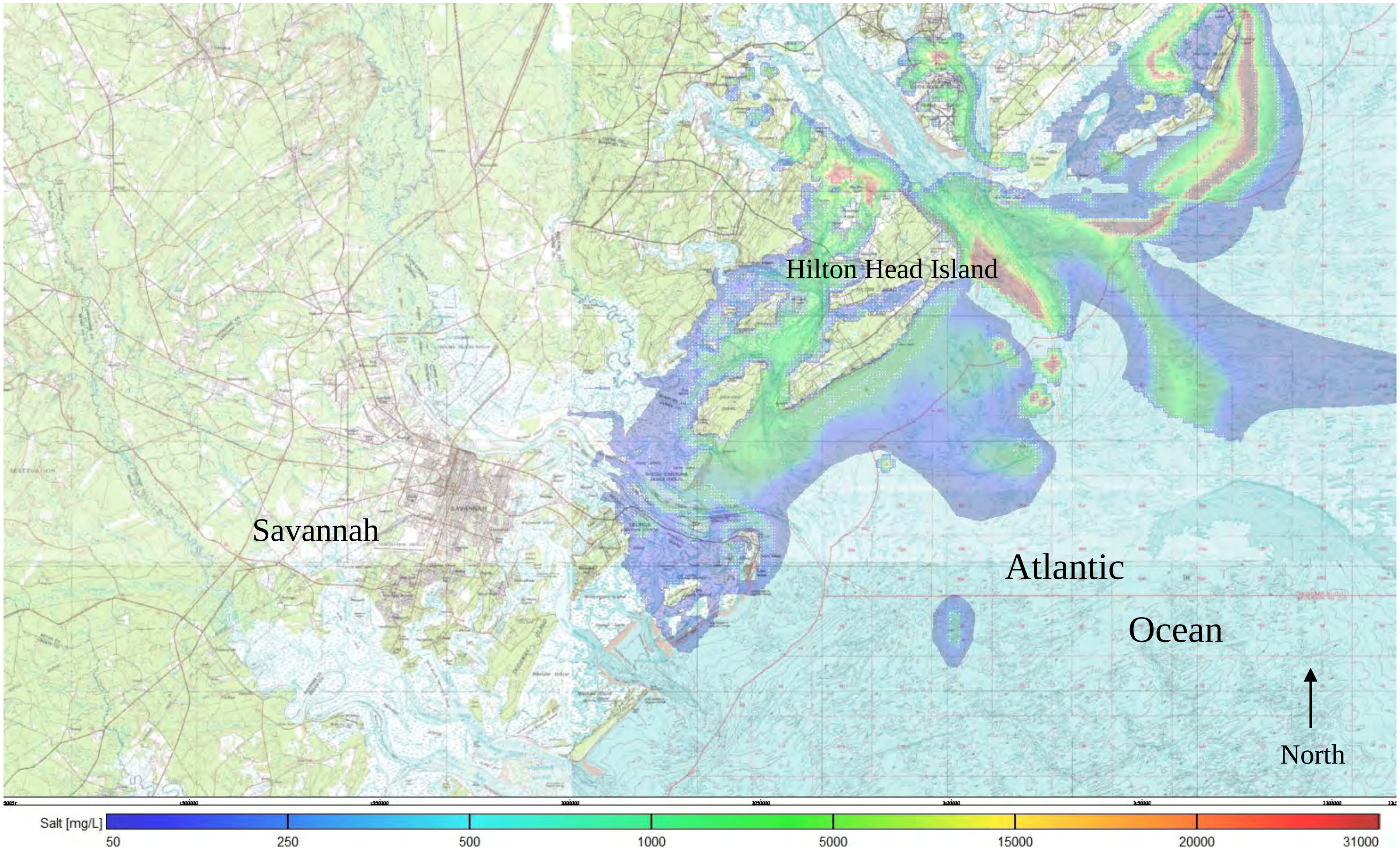


Explanation

Base map: USGS 7 ½ minute topographic quadrangles.

Map scale: One inch equals approx. 6 miles.

Figure J20. Simulated 2050 positions of brackish to saltwater plumes at the bottom of the Upper Floridan aquifer (permeable zone 2), Hilton Head Island, S.C. – Savannah, Ga. area.

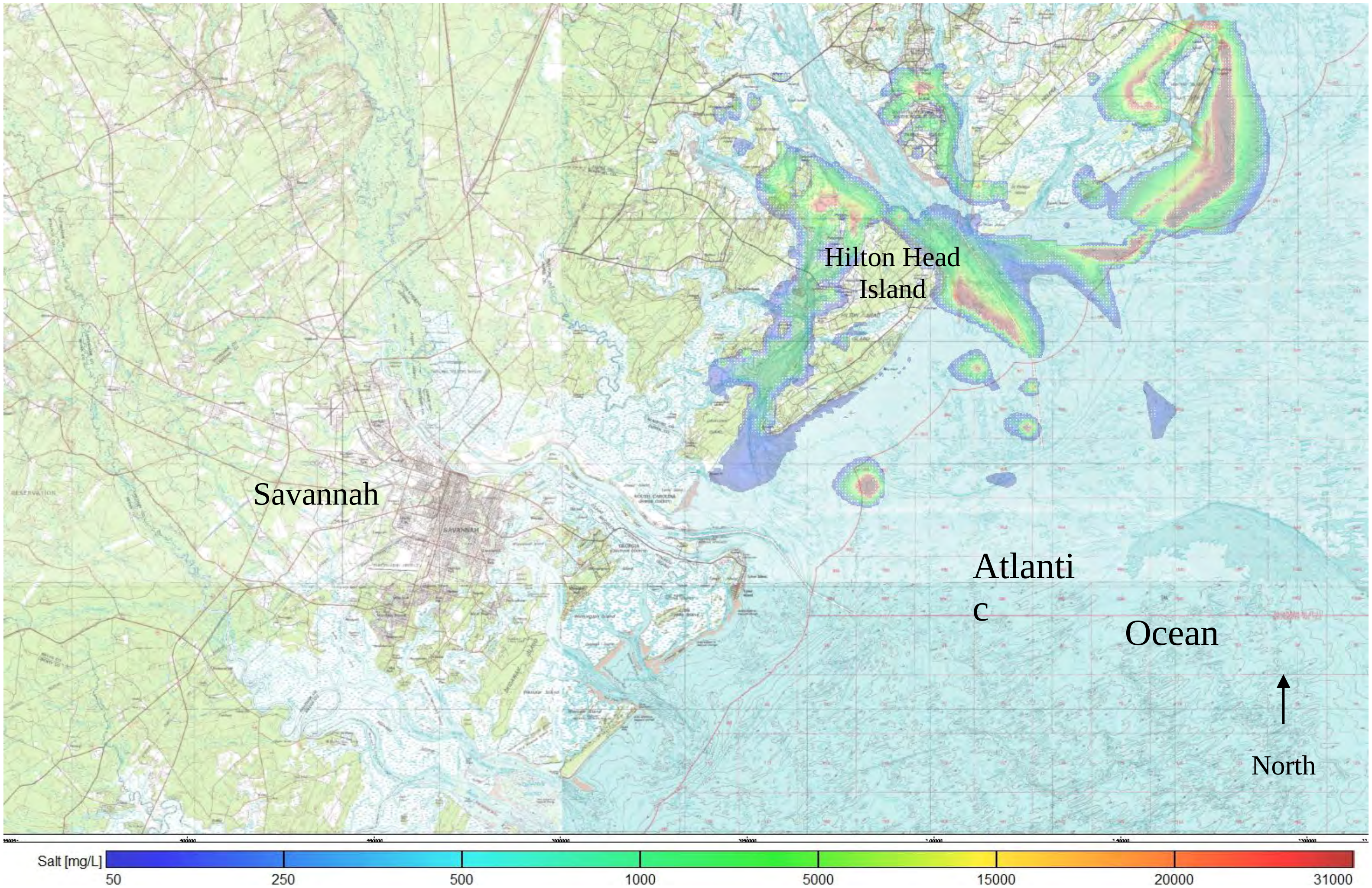


Explanation

Base map: USGS 7 ½ minute topographic quadrangles.

Map scale: One inch equals approx. 8 miles.

Figure J21. Simulated 2007 position of brackish to saltwater in middle of the upper confining unit, Hilton Head Island S.C. – Savannah, Ga. area.



Explanation

Base map: USGS 7 ½ minute topographic quadrangles.

Map scale: One inch equals approx. 8 miles.

Figure J22. Simulated 2050 position of brackish to salt water at the bottom of the upper confining unit, Hilton Head Island, S.C. – Savannah, Ga. area.

Downrigger with attached minisonde positioned on northern shore of Hilton Head Island with Port Royal Sound in background – equipment used to conduct vertical specific-conductance profiles in Upper Floridan wells aquifer. Photography by Camille Ransom, III.

Drennan Park conducting vertical conductance profile at well BFT-2411 on Long Island, S.C. Photography by Camille Ransom, III, December 15,1012.

SCDHEC's geophysical logger developed by Mount Sopris Instrument Company preparing to log USACE's monitoring well located on McQueens Island, Chatham County, Ga. Photography by Camille Ransom, III, August 14, 2012.

Mid-Atlantic Drilling, Inc. preparing to construct the temporary offshore well BFT-2476 near the southern part of Bull Island, S.C. Photography by Camille Ransom, III, October 1, 2011.