EVALUATION OF THE DOWNWARD MIGRATION OF SALTWATER TO THE UPPER FLORIDAN AQUIFER IN THE SAVANNAH, GEORGIA, AND HILTON HEAD ISLAND, SOUTH CAROLINA, AREA

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Abstract. The Upper Floridan aquifer underlies all of Florida, most of the Georgia and Alabama Coastal Plain, and large parts of coastal South Carolina. The aquifer is composed primarily of carbonate rock of varying permeability that ranges in age from middle Eocene to early Miocene. In the study area, the Upper Floridan aquifer is confined above by the upper confining unit of Miocene age that, in turn, is overlain by more recent undifferentiated surficial sediments.

Prior to groundwater development, potentiometric heads in the Upper Floridan aquifer ranged between 5 and 35 feet above mean sea level throughout most of the study area until about 1888 when groundwater withdrawals began in the vicinity of Savannah, Georgia. By 1998, withdrawals totaled approximately 80 million gallons per day in the Savannah, Georgia and Hilton Head Island, South Carolina, area. The cone of depression created by the 1998 pumpage lowered the potentiometric surface below mean sea level over an area greater than 2,300 square miles, of which about 1,200 square miles (53 percent) are overlain by saltwater marshes, rivers, and the Atlantic Ocean.

To determine if saltwater was migrating downward through the confining unit, onshore and offshore locations were selected to collect core samples from the upper confining unit to extract and analyze pore water for dissolved chloride concentration. Pore-water analyses indicated a trend of high chloride concentrations near the top of the upper confining unit that decreased with depth at both the offshore and onshore locations. The results of the pore-water analyses indicated the downward migration of surficial saltwater through the upper confining unit overlying the Upper Floridan aquifer.

Darcy's Law was used to estimate the volume of downward flow of saltwater through the upper confining unit. This approach indicated that an area of approximately 382 square miles east and northeast of Savannah, Georgia, may be contributing 7.7 million gallons per day of downward flow to the Upper Floridan aquifer. Because this area may affect water quality in the Upper Floridan aquifer in the future, it is considered to be an area of concern.

To further evaluate the area of concern, a one-dimensional solute-transport equation was used to simulate the future arrival times for a given concentration of chloride to reach the top of the Upper Floridan aquifer through the upper confining unit. These simulations, conducted on 110 cells each having an area of 4 square miles, predicted that the arrival times for saltwater having a chloride concentration of 500 milligrams per liter ranged from as early as 25 years ago to 113 years from 2005, with an average arrival time of approximately 36 years from 2005 within the area of concern.

THE STUDY AREA

The study area is located in the Coastal Plain physiographic province of southern South Carolina and northeastern Georgia (fig.1). To the northeast, the study area is bounded by Port Royal Sound, S.C., to the southwest by Ossabaw Sound, Ga., and to the southeast by the Atlantic Ocean. The main metropolitan areas are Hilton Head Island, S.C., and Savannah, Ga. Hilton Head Island has been developed primarily as a resort community for retirees and tourism whereas the City of Savannah has promoted tourism and industrial development. The topography is generally flat and geographic features include the Atlantic Ocean, saltwater marshes, rivers, estuaries, and freshwater wetlands.

GEOLOGY

Sediments that originated from terrestrial, marginal marine, and marine environments underlie the study area; these sediments consist of sands, clays, clayey sands, shells or shell fragments, and carbonates. The unconsolidated sediments form a stratigraphic wedge that thins to a few feet (ft) near the Fall Line and

Figure 1. Location of study area showing landform classifications, geographic features, and drill sites.

thickens toward the coast, where the sediments extend to a depth of 3,800 ft below ground surface (bgs) at the southern end of Hilton Head Island (Temples and Waddell, 1996). This investigation focused on the sedimentary deposits that include the undifferentiated surficial sediments of Pleistocene and Holocene age, the Hawthorn Group of Miocene age, the Tiger Leap, Suwannee, and Lazaretto Creek Limestones of Oligocene age, and the Ocala Limestone of late Eocene age.

HYDROGEOLOGY

The geologic strata in the South Carolina and Georgia Coastal Plain are grouped into aquifers and confining units based on their ability to transmit water. The primary hydrogeologic strata for this study include the surficial aquifer, the upper confining unit, and the Upper Floridan aquifer.

Surficial Aquifer

The surficial aquifer consists of sands and clays in the upper 50 to 70 ft of sediments in the study area. The quality of water in the aquifer is generally fresh where the landforms are above sea level. In areas where landforms are below mean sea level, such as saltwater marshes, tidal rivers, and the Atlantic Ocean, the aquifer contains saltwater. Recharge to the surficial aquifer is by local precipitation, and discharge occurs both downward to underlying sediments and laterally to adjacent surface-water bodies.

Upper Confining Unit

The upper confining unit is present throughout the study area and includes the relatively impermeable sediments of the Hawthorn Group and also may include part of the Oligocene carbonates (Miller, 1986). The term "relatively" is used because these sediments slow but do not impede the flow of water. When the hydraulic gradient across the upper confining unit becomes greater than a few feet over large geographical areas, the sediments are sufficiently permeable to transmit large volumes of water either upward or downward, depending on the magnitude and direction of the hydraulic gradient. Further support of the upper confining unit's capability to transmit water can be seen in regional groundwater flow models used to simulate groundwater levels in response to pumping patterns in the study area. The model designs require large volumes of groundwater to move downward through the upper confining unit for simulated heads to obtain a close match with observed heads occurring in the Upper Floridan aquifer.

Upper Floridan Aquifer

The Upper Floridan aquifer underlies the upper confining unit and includes parts of Oligocene carbonates and the Ocala Limestone of Eocene age. The aquifer is the primary source of groundwater supply in the Savannah – Hilton Head Island area for domestic, industrial, and municipal needs.

Warren (1944) estimated the potentiometric surface of the Upper Floridan aquifer in the Savannah – Hilton Head Island area in 1880 prior to development. The predevelopment map shows that groundwater levels ranged from about 35 ft above mean sea level (MSL) in the vicinity of Savannah to about 10 ft above MSL near the center of Hilton Head Island.

In the Savannah area, pumping began in the early 1880's, and by 1888, pumping had increased to 7 million gallons per day (Mgal/d) (Counts and Donsky, 1963). Peak withdrawals occurred in 1990 when the reported permitted use was 88 Mgal/d (Clarke and others, 2004). By 2000, groundwater withdrawals had decreased to approximately 70 Mgal/d (Fanning, 2003).

The 1998 potentiometric map (Peck and others, 1999) shows that the potentiometric surface had declined below mean sea level for an area covering approximately 2,300 square miles (mi^2) (fig.2). Within the influence of the cone of depression, these water-level declines have reversed the natural groundwater gradient. Groundwater in the Upper Floridan aquifer now flows toward the center of the cone of depression at Savannah, Georgia from all directions. The original upward component of flow from the aquifer through the upper confining unit into the overlying surficial sediments has also reversed and is now downward toward the Upper Floridan aquifer.

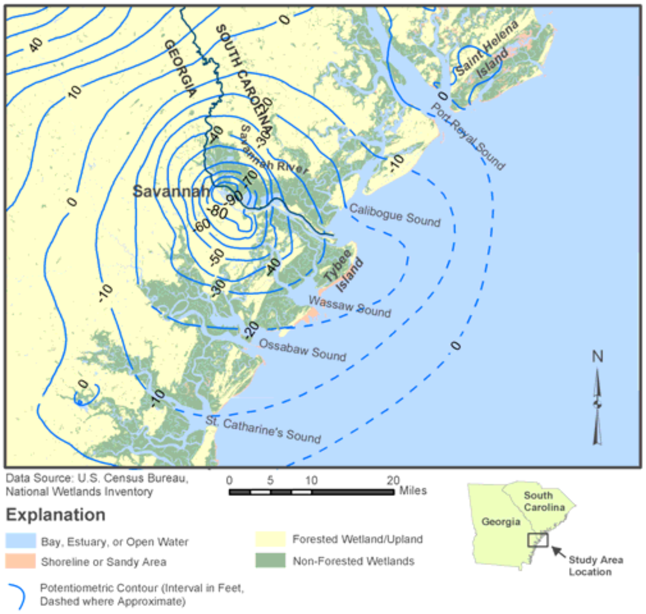


Figure 2. The potentiometric surface of the Upper Floridan aquifer, May 1998 (modified from Peck and others, 1999).

PORE-WATER ANALYSES

The 7-mile offshore site and the Bull River onshore site (fig. 1) were chosen for study because these sites provided the most ideal conditions to investigate the potential for saltwater migration through the upper confining unit. The geology at the Bull River onshore site is used herein to describe the sediments that characterize both sites and most of the study area. Analysis of continuous geologic core obtained at the Bull River onshore site indicates that the upper section of surficial sediments consists of alternating beds of sand, clay, and shell fragments to a depth of 55 ft bgs. The surficial sediments are underlain by 20 ft of coarse quartz sand that extends to a depth of 75 ft bgs. This coarse sand deposit is interpreted as a paleochannel that incised through part of the underlying upper confining unit during a period of low mean sea level. Paleochannels are common throughout the coastal area of Georgia and South Carolina (Foyle and Henry, 2001). The upper confining unit underlies the paleochannel and consists mostly of very fine to medium sand interbedded in a matrix of silt and clay to a depth of 120 ft bgs. The undifferentiated limestone of Oligocene age was found beneath the upper confining unit at 120 ft bgs and consisted of unconsolidated medium to coarse quartz sand interbedded with limey clay and shell fragments and extended to a depth to 192 ft bgs. The Ocala Limestone, found at 192 ft bgs, consisted of large, consolidated shell fragments in a lime matrix that extended to the base of the borehole, which totaled 200 ft bgs.

The pore-water analyses from selected core samples at the Bull River onshore site and the 7-mile offshore site were studied to determine to what depth chloride concentrations were present through the thickness of the upper confining unit. Chloride concentrations theoretically are dependent on several hydraulic properties that affect the rate and volume of saltwater migration through the upper confining unit. These properties include (1) the thickness of the upper confining unit, (2) the vertical hydraulic conductivity of the upper confining unit, (3) the average head difference across the upper confining unit, (4) the concentration of saltwater present in the sediment overlying the upper confining unit, (5) the effective porosity of the upper confining unit, and (6) the effects of dispersion and diffusion.

At the 7-mile offshore site, located in the Atlantic Ocean, five pore-water samples were collected at selected depths from a 20-ft-thick section of the upper confining unit. The chloride concentration in the sediments overlying the upper confining unit was assumed to be that of saltwater (19,000 milligrams per liter (mg/L)). The results of pore-water sample analyses (fig. 3a) indicate that chloride concentrations decreased from 7,034 mg/L near the top of the upper confining unit at -55.5 ft below msl to 2,612 mg/L near the bottom of the upper confining unit at -72.0 ft below msl. After the well was completed in the Upper Floridan aquifer, a water sample was collected 10 ft below the upper confining unit in the Oligocene limestone using a pump rated at 7.5 gallons per minute (gpm). After pumping for 3 hours, the chloride concentration was 370 mg/L (Falls and others, 2005). The pumped sample indicates that saltwater present in the upper confining unit has migrated downward into the top of the Upper Floridan aquifer.

At the Bull River onshore site, 23 pore-water samples were collected at 5-ft intervals from the surficial sediments to the top of the Upper Floridan aquifer at 120 ft bgs (fig. 3b). Six samples were collected in the aquifer between depths of 122.5 ft and 195 ft bgs. Chloride concentrations in the surficial sediments ranged from 121 mg/L near the surface at a depth of 7.5 ft bgs and increased to the maximum concentration of 17,088 mg/L at a depth of 27.5 ft. The low chloride concentrations near the surface are likely the result of freshwater from recent rainfall overlying the more dense saltwater at depth. From a depth of 27.5 ft bgs, chloride concentrations gradually decreased to 8,953 mg/L at a depth of 52.5 ft. An exception occurred in the coarse-grain paleochannel located between depths of 55 ft and 75 ft bgs. Within this interval, the chloride concentration of pore water ranged between 709 mg/L and 3,751 mg/L, much lower than those concentrations present above and below the paleochannel.

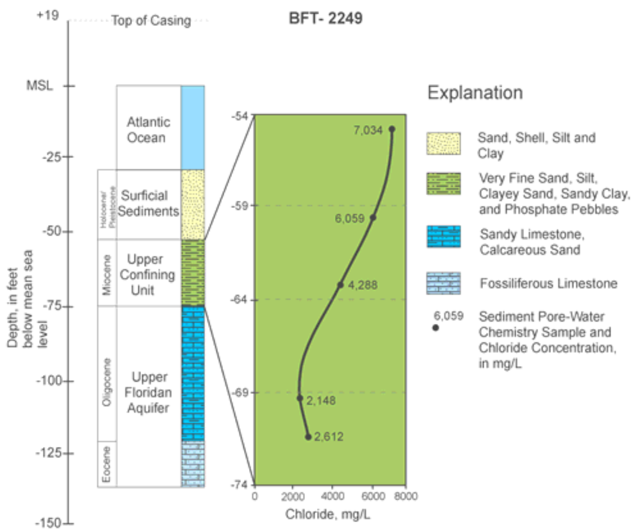


Figure 3a. Pore-water chloride concentrations with depth through the upper confining unit at the 7-mile offshore site (Bft-2249).

The lower concentrations may have been the result of contamination by freshwater used to prevent the casing from overheating during drilling operations. The freshwater could possibly have migrated through the more porous paleochannel deposits and diluted the in-situ water with a lower chloride concentration. Locating a new hole 20 ft from the original core site provided an opportunity to test this theory, by using the U.S. Geological Survey (USGS) direct-push rig to advance an open drill rod into the paleochannel sediments. Afterwards, a peristaltic pump was used to extract a sample of groundwater from the bottom of the drill rod at a depth of 62.5 ft bgs. Prior to sampling, water quality was monitored using a specific conductance probe to ascertain that the water was representative of the paleochannel. The laboratory analysis of the sample yielded a chloride concentration of 8,200 mg/L, closely matching the concentrations above and below the paleochannel. Beneath the paleochannel, chloride concentrations decreased with depth through the thickness of the upper confining unit from 7,898 mg/L at a depth of 75 ft bgs near the top of the upper confining unit to 50 mg/L at a depth of 117.5 ft bgs near the bottom of the upper confining unit. Six pore-water samples obtained from the top of the Upper Floridan aquifer between depths ranging from 122.5 ft and 195 ft bgs indicated that chloride concentrations ranged from 17 mg/L to 95 mg/L with an average concentration of 40 mg/L.

It is important to document the complete flushing of saltwater in the upper confining unit resulting from an upward hydraulic gradient prior to groundwater development. Evidence can be obtained by comparing the pore-water chloride profile at the Bull River site with the chloride profile obtained by the U.S. Army Corps of Engineers (US ACE) and the USGS at SHE-15 (H. Cardwell Smith, written commun., 2006) located in the Savannah River approximately 1 mile northwest of the Talmadge Bridge (fig.1). Both wells used pore-water analyses to obtain water-quality data at selected depths within the upper confining unit. The chloride profile at the Bull River site showed higher concentrations than the chloride profile at the SHE-15 site on the Savannah River. This fact is important, because predevelopment estimates of the upward hydraulic gradient across the upper confining unit at the Bull River onshore site and SHE-15 were 0.63 and 0.23, respectively. If saltwater had remained in the upper confining unit because of incomplete flushing, then higher concentrations of chloride would be expected in areas where the predevelopment gradient across the upper confining unit was less. Instead, these data indicate the opposite.

The patterns shown in figures 3a and 3b provide the first evidence that present-day saltwater from surficial

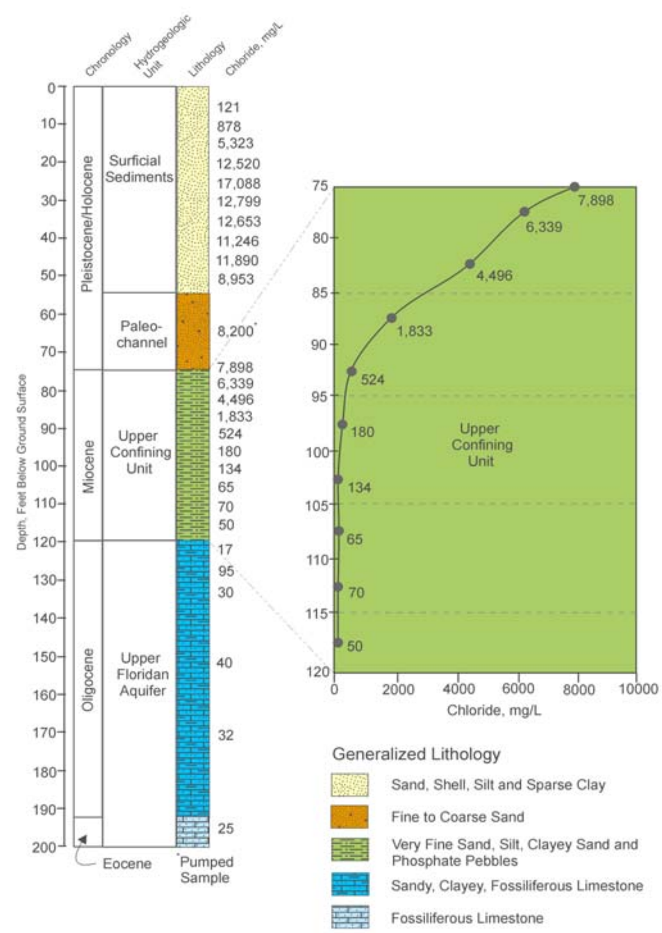


Figure 3b: Pore-water chloride concentrations with depth at the Bull River site.

sources has moved through the upper confining unit and entered the top of the Upper Floridan aquifer.

DOWNWARD SALTWATER MIGRATION

The estimated rate (in gallons per day) of downward saltwater migration from surficial sources was calculated by applying Darcy's Law to each 4-mi^2 cell superposed over approximately 1,255 mi^2. The calculated area included only those parts overlain with saltwater within the 0-ft potentiometric contour of the cone of depression. To apply Darcy's Law, vertical hydraulic gradients for each cell were based on the hydraulic heads estimated from the1998 potentiometric map constructed by Peck and others (1999) and the upper confining unit thickness determined from isopach maps constructed by Miller (1986), Hughes and others (1989), and Foyle and others (2001). A constant value for the estimated average vertical hydraulic conductivity of 2.4x10^{-3} gallons per day per square foot (gal/d/ft^2) was assigned to each cell. These calculations indicated that an area totaling 382 mi^2 near Hilton Head Island and Tybee Island, accounted for 7.7 Mgal/d, or 50 percent of the 15 Mgal/d moving downward through the upper confining unit within the 1255 mi^2 area. The relatively large volume of downward recharge to the Upper Floridan aquifer in the 382 mi^2 is predominately the result of a thin upper confining unit that contributes to a high downward hydraulic gradient.

Measurements of chloride concentration in the upper confining unit at the Bull River onshore site were used to calibrate a Base Case analytical model based on a one-dimensional advective-dispersive solute-transport equation (Van Genuchten and Alves, 1982). Values for vertical hydraulic gradient, vertical hydraulic conductivity, time (years), effective porosity, dispersion, and diffusion, were adjusted to simulate the measured chloride concentrations for selected depths at the Bull River onshore site. The root-mean square error was less than 5 percent of the source concentration (8,200 mg/L).

The calibrated model, Base Case model was applied to each 4-mi^2 cell within the 382-mi^2 area overlain by saltwater to simulate arrival times for chloride concentrations of 500 mg/L to reach the top of the Upper Floridan aquifer, assuming 1998 pumping conditions. The calibrated parameters of the Base Case model remained unchanged except for the vertical hydraulic gradient, vertical hydraulic conductivity, and the source concentration. The vertical hydraulic gradient in the Base Case model was the gradient previously assigned at each cell to accommodate Darcy's Law to compute the downward flow through the upper confining unit. The vertical hydraulic conductivity was changed slightly from 1.5x10^{-3} gal/d/ft^2 in the Base Case to 2.4x10^{-3} gal/d/ft^2 to represent the average value previously calculated for the Darcy Law computations. The concentration of the source (saltwater) was assumed to be 19,000 mg/L chloride (Hem, 1970). The simulated results are shown on figure 4.

The red-shaded cells (fig. 4) total 382 mi^2 and represent those areas where the simulated arrival time for chloride with a concentration of 500 mg/L to reach the top of the Upper Floridan aquifer is 113 years or less. Arrival times in the red-shaded cells ranged from 25 years ago (negative values in fig. 4) to 113 years into the future from 2005. Outside of the red-shaded cells, simulated arrival times are much later because of decreasing head differences across the upper confining unit, increasing thickness of the upper confining unit, or a combination of both. The 382 mi^2 area is considered an area of concern, because of the high downward flow rates and the relatively short arrival time for water containing 500 mg/L of chloride to enter the top of the Upper Floridan aquifer.

The simulated arrival time for water with an average chloride concentration of 500 mg/L to enter the top of the Upper Floridan aquifer beneath the area of concern is about 36 years from 2005. Assuming that 50 percent of the total flow is from downward leakage and that the remaining 50 percent is from lateral flow within the aquifer, then mixing would result in a total flow of about 15.4 Mgal/d with an average chloride concentration of 250 mg/L. The

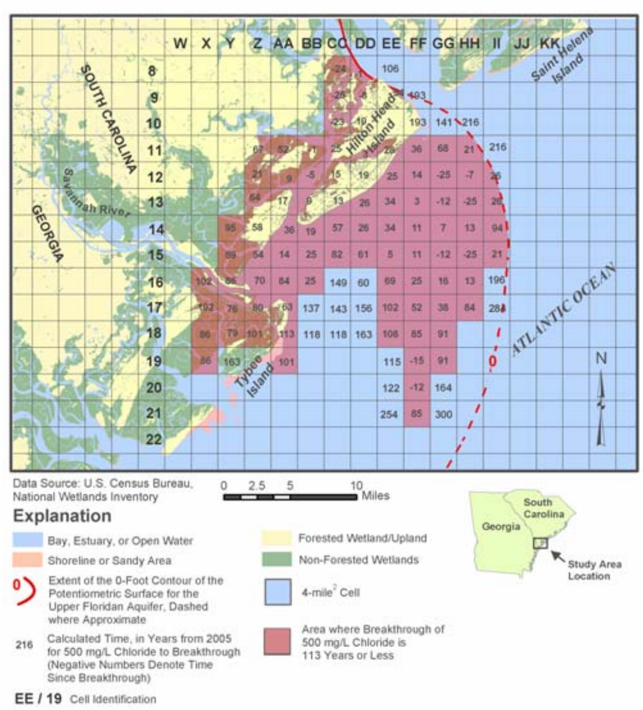
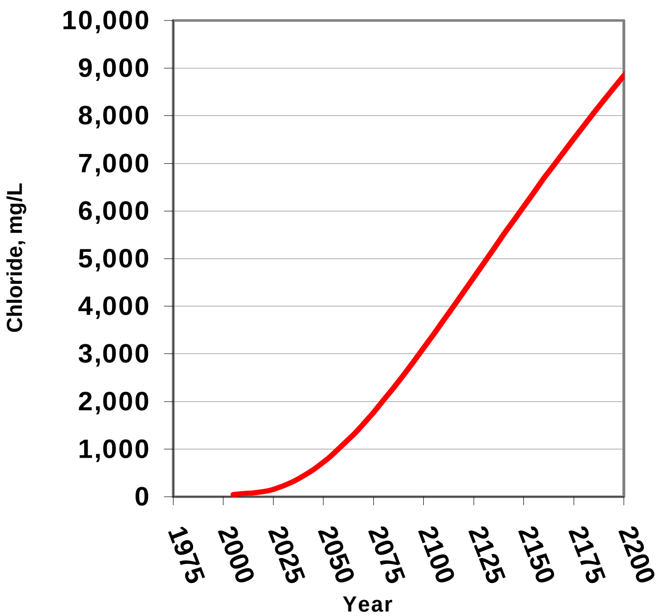


Figure 4. Estimated time, in years from 2005, for 500 mg/L chloride concentration to arrive at the top of the Upper Floridan aquifer.

simulation results indicate that chloride concentrations will continue to increase and at a more rapid rate with respect to time (fig. 5). For example, the average chloride concentration will increase to 1,000 mg/L in 48 years and to 2,000 mg/L in 72 years from 2005.

Figure 5. Simulated arrival time for average chloride concentrations to enter the top of the Upper Floridan aquifer from the upper confining unit beneath the area of concern northeast of Savannah, Ga.



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