A MODEL OF SEAWATER INTRUSION IN SURFICIAL AND
CONFINED AQUIFERS OF NORTHEAST FLORIDA

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ABSTRACT

The freshwater-seawater interface is affected by groundwater extraction by public supply, irrigation wells, and domestic wells in coastal communities. The position of the interface is controlled by several factors including precipitation, recharge, evapotranspiration, hydraulic conductivity, hydraulic head, etc. Landward migration of the interface often results in a significant decrease in the water resources available to coastal communities. Modeling the coastal groundwater-seawater flow system enables the evaluation of the potential for seawater intrusion into surficial and confined aquifers as a result of artificial extraction of groundwater.

The two-dimensional, density-dependent, fluid flow and mass-transport numerical model SUTRA was used to model the coastal surficial and confined aquifers of Flagler County and the freshwater-seawater interface. The hydrogeology of this area consists of the surficial aquifer system, the underlying intermediate confining unit, and the Floridan aquifer. The effects of groundwater withdrawals from this area have been documented enabling dynamic conditions to be used to calibrate the model and to approximate the position of the seawater-freshwater interface. Optimum groundwater withdrawal rates are proposed, based on aquifer safe yield, in order to minimize the migration of the interface. Artificial aquifer recharge and other measures are considered as potential means of restoring the position of the interface to its pre-pumping position.

Introduction

Seawater intrusion results in the contamination of coastal aquifers and, therefore a reduction in the available water for human consumption and agriculture. The withdrawal of groundwater by public supply wells and numerous irrigation wells has resulted in the increased intrusion (encroachment) of seawater inland. The United States Environmental Protection Agency (USEPA) standards for Total Dissolved Solids (TDS) and chlorides are 500 milligrams per liter (mg/L) and 250 mg/L, respectively. In comparison, the concentrations of TDS and chlorides in seawater are approximately 35,700 mg/L and 19,400 mg/L, respectively.

A preliminary evaluation of the effects of sea-water intrusion in the surficial and the confined Floridan aquifer in northeast Florida (Figure 1) was conducted by constructing a 2-dimensional, cross-sectional model from approximately Flagler Beach to...
Figure 1. Map of general study area.

Figure 2. Map of cross-section and distribution of pumping.
Bunnell, Florida. The cross-section represents a distance of 12,000 meters (overland) and a distance of 160 meters offshore into the Atlantic Ocean. The approximate location of the model cross-section and the areas of major groundwater withdrawals are shown in Figure 2. The results of investigations of the groundwater resources and salt-water intrusion in northeast Florida conducted by the St. Johns River Water Management District (Frazee and McClaugherty, 1979) were used to evaluate and simulate the approximate pre-pumping distribution of salinities. The finite element, variable-density, groundwater flow and solute transport model SUTRA (Saturated Unsaturated Transport; Voss, 1984) was used to simulate the regional pre-pumping distributions of hydrostatic pressure and salinity throughout the model.

Intrusion into the Upper Floridan aquifer occurs as a result of upward leakage of connate water from the Lower Floridan and lateral intrusion of the freshwater-seawater interface, which occurs at varying distances from the northeast Florida coast. This study evaluated the potential sources of saltwater intrusion into the Upper Floridan aquifer by determining the potential flux across the semi-confining layer overlying the Lower Floridan aquifer and comparing this flux to the effects of lateral seawater intrusion. Pumping scenarios were then simulated to demonstrate the effects of pumping groundwater from the Upper Floridan aquifer in locations susceptible to seawater intrusion.

**Hydrogeology**

The study area modeled is located in southeastern Flagler County. The physiography (Figure 3) from east to west includes the Atlantic Beach Ridge associated with a barrier island, the intracoastal water way and bounding salt marshes, Silver Bluff Terrace, Atlantic Coastal Ridge, Pamlico Terrace, and Eastern Valley. The climate is humid subtropical and the area receives approximately 1.33 m (52 in) of rainfall annually.

The general hydrogeology of the study area modeled includes the undifferentiated surficial deposits of Pleistocene and recent age consisting of sand, coquina, and sandy clay lenses from land surface to 8.0 meters below land surface. These deposits form shallow sand
Figure 3. Map of major physiographic provinces.

Figure 4. Map showing distribution of chlorides in March 1975.
shell-sand, and coquina aquifers. The transmissivity of the shell-sand aquifer was determined to be 271 m²/day or 21,400 gallons per day per foot [(gpd/ft); Frazee and McClaugherty, 1979]). The transmissivity of the Anastasia coquina aquifer was determined to be approximately 101 m²/day (8,000 gpd/ft). Underlying the surficial clastics are Miocene deposits of the Hawthorne Group consisting of clay, sandy clay, sand, interbedded shell, and weathered sandy limestone. The unit is approximately 9.2 m thick in the study area and its base is comprised of hard, dolomitic limestone. Groundwater is obtained from this unit, which is also referred to as the secondary artesian aquifer. Underlying the Hawthorne Group sediments are the limestones of the Eocene Ocala Limestone Formation consisting of chalky to granular, fossiliferous, massive limestone with dolomite beds in the lower part of the formation. The Ocala Limestone is approximately 165 m thick and represents the Upper Floridan aquifer in this area. The transmissivity of the Upper Floridan aquifer in Flagler County ranges from 2405 m²/day to 3545 m²/day [190,000 to 280,000 gpd/ft (Frazee and McClaugherty, 1979)]. The Ocala limestone is underlain by the Middle semi-confining unit. This unit separates the Upper and Lower Floridan aquifers and consists of soft chalky limestones ofocene age in the area modeled. The Lower Floridan aquifer consists of upper Paleocene to early middle Eocene carbonates. The Lower Floridan contains predominantly brackish and saline water of connate origin.

The surficial aquifers along the northeast Florida coast exhibit seawater intrusion due to pumping. The barrier islands have limited freshwater aquifers. The Upper Floridan aquifer of northeast Florida extends offshore greater than [80 km (50 miles)] and exhibits negligible seawater intrusion as a result of lateral migration. The presence of the Hawthorne Group sediments overlying the Upper Floridan restricts vertical migration and enables the preservation of the potentiometric surface above sea level. However, inland significant chloride concentrations have been documented, suggesting an upward migration from the Lower Floridan. In Duval and St. Johns County, wells located [22 km (14 miles)] inland have exhibited chloride concentrations exceeding 250 mg/L (Spechler, 2001). In coastal Volusia County, lateral seawater intrusion does occur in both the surficial and Upper Floridan aquifers due to pumping; however, it is believed that most of the saltwater contamination in the Upper Floridan aquifer is due to the upconing of brackish water caused by deeper wells designed to pumped at higher rates for longer periods of time (Rutledge, 1985).

Although the Upper Floridan aquifer extends approximately 20 km offshore in this study area (Bush and Johnston, 1988), measurements of salinity from the general area represented by this model indicate that chloride concentrations greater than 1,000 mg/L existed approximately 5.5 kilometers inland in March (Figure 4) and 4.5 km in July 1975 (Munch et al., 1979). Similar conditions existed in 1980 (Mercer et al., 1984). The vertical distribution of salinity, near the section modeled, is shown Figure 5. This figure represents the partial results of an investigation of the groundwater resources and saltwater intrusion in northeast Florida conducted by the St. John’s River Water Management District (Frazee and McClaugherty, 1979) and was used to simulate the approximate pre-pumping distribution of salinity. This boundary shifts seasonally (in response to recharge) depending on the elevation of the potentiometric surface. During
periods of increased recharge, the transition zone migrates seaward. Agricultural pumping also tends to increase migration inland of this transition zone.

In the vicinity of the coast both the surficial and Upper Floridan aquifers typically exhibit seawater intrusion with chloride concentrations exceeding 1000 mg/L. Inland the salinity of the surficial aquifer decreases to less than 250 mg/L. Salinity in the upper part of the Floridan aquifer also decreases inland; however, in the vicinity of Bunnell [approximately 12 kilometers (7.5 miles)] from the coast) salinity increases to between 250 and 1,000 mg/L chlorides due to vertical migration from the Lower Floridan. This has resulted from natural leakage through the middle semi-confining unit and from upconing associated with pumping wells installed near the lower boundary of the Upper Floridan. Although intensive agriculture takes place in the vicinity of Bunnell, the area between Bunnell and the coast is also significantly developed for its groundwater resources.
Figure 5. Geologic cross-section and distribution of chlorides in the study area.
Prior to 1979, the City of Flagler Beach abandoned 32 shallow wells along the central ridge and initiated its groundwater supply from the Upper Floridan aquifer in the vicinity of Bunnell.

Model Design

The model domain represents dimensions of 12,150 m by 205 m. The coastal area of the model grid is shown on Figure 6 (as part of a simulation) and the parameters are presented in Table 1. Due to the horizontal dimension of the model, the entire grid was not shown. The model begins 160 m offshore and includes three elements with horizontal dimensions of 75 m, 50 m, and 35 m. The seaward side of the barrier island includes four elements of 12.5 m each in order to model the concentration gradient associated with the transition zone. Inland the elements were gradually expanded to the western edge of the model. The vertical dimensions of the elements were also expanded with depth. The vertical dimensions of the three elements representing the surficial aquifer, below sea-level, were kept constant at 8.3 m each. In order to account for the topography and extent of the surficial aquifer above sea level, two elements of 6 m each were included. The upper confining unit was represented by elements with a constant thickness of 10 m. The upper Floridan aquifer was represented by 10 elements with a constant thickness of 16.5 m each.

The western model boundary was simulated with flux boundaries. Given the elevations of the water table of the unconfined aquifer and potentiometric surface of the confined aquifer, the hydraulic conductivities, porosities, and the dimensions of the model cross-section, fluxes were calculated with Darcy’s Law. The fluxes assigned to the model for the unconfined and confined aquifers were 0.203 and 0.195 m³/day, respectively. Recharge [0.013 m (0.5 in)] and discharge [-0.03 m (-1.25 in.)] fluxes to and from the Upper Floridan aquifer as leakage were obtained from Bush and Johnston, 1988. The surface of the model was simulated with varying recharge rates. The rates varied from [0.36 m (14 in)] inland, [-0.13 m (-5.0 in)] in the vicinity of the intracoastal waterway, and [0.26 m (10.0 in)] on the barrier island. These rates were estimated from the average annual precipitation rate of [1.33 m (52 inches) per year], an evapotranspiration rate of [0.97 m (38 inches) per year], and negligible runoff. The presence of the intracoastal waterway was simulated by assigning two nodes, along the surface boundary of the model, a total fluid flux of 0.432 m³/day with a concentration of 35,700 mg/L (seawater). Since the vertical migration of saline water occurs near the base of the Upper Floridan, a flux boundary of 0.0075 m³/day with a concentration of seawater, was assigned based on the calibration of the model to coincide with measured concentrations. The eastern edge of the model was assigned a specified pressure boundary for the surficial and Upper Floridan aquifers. Since the transition zone, apparently, extended inland significantly from 1975 to 1980, setting the specified boundary along the eastern edge of the model would simulate the general location of the transition zone. In order to simulate the part of the transition zone present along the model boundary, the concentration of the specified pressure boundary was varied until a fit was observed to measured chloride concentrations.
<table>
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<th>Parameter</th>
<th>Value</th>
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<td>Horizontal longitudinal dispersivity (maximum, m)</td>
<td>6 surficial; 12 Floridan</td>
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<tr>
<td>Vertical longitudinal dispersivity (minimum, m)</td>
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<tr>
<td>Transverse dispersivity (m)</td>
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<td>Concentration of recharge (kg/kg)</td>
<td>6.6 x 10^{-6} Barrier Island</td>
</tr>
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<td>Concentration of sea water (kg/kg)</td>
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<tr>
<td>Fluid viscosity (kg/m/s)</td>
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<td>Molecular diffusivity (m^2/s)</td>
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<tr>
<td>Gravitational acceleration (m/s^2)</td>
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</table>

Key to simulation salinity contours
Figure 6a. Simulation with 100% seawater boundary.  
Horizontal scale  1cm = 98m  
Vertical scale    1cm = 36m
Figure 6b. Simulation with 100% seawater boundary.

Figure 7. Simulation with 50% seawater boundary.
Since the lithologies of the surficial and Upper Floridan aquifers varied, the dispersivities used in the model were varied by calibrating the model to generally agree with the salinity distributions measured between 1975 and 1980. The Upper Floridan aquifer was assigned a longitudinal dispersivity of 12 m and the surficial materials were assigned a longitudinal dispersivity of 6.0 m. These values are within the range of field-scale dispersivity measurements (Fetter, 1999).

Groundwater Model Simulations

Since seawater intrusion occurs inland at significant distances and a progressive increase in concentrations exists inland from the coast, it was assumed that upward leakage and lateral seawater intrusion had occurred. In order to determine the potential position of the transition zone along the coast, simulations were conducted by varying the specified pressure boundary concentration along the coast at 100%, 50%, 25%, and 10% seawater. The specified pressure concentration of the surficial aquifer was maintained at 100%. These simulations are represented by Figures 6, 7, 8, and 9. The simulations were run as transient simulations until approximate steady state conditions had been attained. The results indicate that the simulations with boundary concentrations of 100%, 50%, and 25% do not match the observed concentrations of Figure 5. The simulation using a concentration of 10% matched the observed data closely. These results indicate that saline water occurs generally in the vicinity of the coast and the inland salt marsh area. These results therefore do not appear to account for the presence of saltwater intrusion farther inland. Since upward leakage from the Lower Floridan is known to occur, the flux was estimated by adjusting the upward flux until a reasonable fit to the observed data was simulated. An upward flux of 0.19 m/yr (7.6 in/yr) yielded a reasonable fit to the observed data. The results of this simulation are presented in Figure 10.
Figure 8. Simulation with 25% seawater boundary.

Figure 9. Simulation with 10% seawater boundary.
**Figure 10a.** Simulation with 10% seawater boundary and vertical flux.

**Figure 10b.** Simulation with 10% seawater boundary and vertical flux (cont.).
Groundwater Extraction Simulations

Since groundwater is a renewable natural resource, the proper management of groundwater supplies can ensure continued supplies. The safe yield of an aquifer is “the amount of water which can be withdrawn without producing undesirable effects” (Walton, 1970). In the vicinity of Bunnell, the recommended pumping rate is approximately 1121 m³/day [250 gallons per minute (gpm)]. Between Bunnell and Flagler Beach, the recommended rate is 841 m³/day (150 gpm), due to the thinning of the Upper Floridan aquifer. Irrigation wells in the study area have been installed as close as ten feet apart. Since the drawdowns from multiple wells are cumulative due to well interference effects, well spacing must be considered. The models with the specific boundary set at 50% and 10% seawater were used to simulate various effects of pumping from the area between Bunnell and Flagler Beach.

A total pumping rate of [4,488 m³/day (800 gpm)] was assigned to four wells [1122 m³/day (200 gpm each)] simulated in the upper part of the Upper Floridan aquifer. In order to simulate pumping wells, the Theis equation was used to calculate the drawdown for various pumping rates. Based on these calculations, a capture zone radius of 3,000 m was used for wells pumping [1122 m³/day (200 gpm)]. With the volume represented by the diameter of the capture zone, width of the model cross-section (1.0 m), and the thickness of the aquifer being pumped, the proportion of the total volume of a vertical cylinder of the aquifer affected was determined. This fraction of the estimated total aquifer impacted also represented the fraction of the total pumping rate. The pumping rate assigned to each well was 0.238 m³/day. In order to minimize well interference effects, the wells simulated were spaced approximately 1000 m apart from 4,600 to 7,800 m from the eastern edge of the barrier island. The simulations were run to approximately steady state. The results (Figures 11 and 12) indicate that lateral intrusion occurs under these scenarios. The west edge of the transition zone appears to have migrated approximately 500 m in response to the pumping. This is evident by comparing the pre-pumping simulations [Figure 7 (50% seawater) and Figure10 (10% seawater)]. The simulation with the 10% seawater concentration boundary did not exhibit any vertical migration of salinity from the Lower Floridan, as a result of upconing.
Figure 11. Simulation of pumping scenario with 50% seawater boundary.

Figure 12. Simulation of pumping scenario with 10% seawater boundary.
Conclusions

The results of this preliminary evaluation of seawater intrusion into the surficial and Upper Floridan aquifers indicate that lateral seawater intrusion has occurred in the surficial aquifer and that both lateral and vertical intrusion into the Upper Floridan aquifer have occurred. The decrease in water quality in both the surficial and Upper Floridan aquifers have been due to excessive pumping. These results indicate that the near-seawater concentrations associated with the transition zone are not present in the vicinity of the coastal area modeled. Although excessive pumping has reduced the potentiometric surface elevation compared to the pre-development elevations, the constant potentiometric surface elevation above sea level decreases lateral migration. In contrast, the existence of vertical leakage associated with fractures, collapse features, faults, structural anomalies (Spechler, 2001), facilitated by pumping, increases saltwater intrusion into the Upper Floridan aquifer.

References


