Saltwater/Freshwater Interface Movement in Response to Deep-Well Injection in a Coastal Aquifer

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ABSTRACT

Southeastern Florida has disposed of secondarily treated, low total dissolved solids (TDS), wastewater by injecting it into a saltwater aquifer more than 2500 ft below land surface (BLS) since the 1950s. In theory, a confining unit above the zone of injection prevents less dense effluent from migrating vertically upward toward protected drinking water (< 10,000 mg/L TDS) sources at depths of about 1200 ft BLS. However, ammonia concentrations indicative of effluent have been observed in monitoring wells open in and above the confining unit. Water levels, in the protected drinking water aquifer above the zone of injection at a wastewater treatment plant, have increased over 20 ft in the last 30 years. The increased water levels and ammonia concentrations, from vertical migration of effluent, could potentially affect the location of the saltwater interface (the transition from freshwater to saltwater in the aquifer). A variable-density groundwater flow and solute transport model was created and calibrated to better understand the system. Future injection scenarios were simulated to observe the long-term effects of deep-well injection, including the migration of effluent and prediction of interface movement. Results show that long-standing increased water levels at the site with freshwater injected into the ground could affect movement of the interface downward and seaward in southeastern Florida. Based on the Ghyben-Herzberg principle, the interface transition zone could move from about 1700 ft below sea level (BSL) to over 2500 ft BSL at the injection site.

INTRODUCTION

The Florida peninsula is the emergent part of the Florida Platform, containing the Floridan aquifer system (FAS). The FAS consists of the Upper, middle, and Lower Floridan aquifers (UFA, MFA, LFA; Figure 1; Reese and Richardson, 2008). In southeastern Florida, the UFA is an artesian aquifer about 1000 ft BSL and is about 100-200 ft thick. Background water levels in the UFA range from about 30 ft above sea level (ASL) at the coast to about 55 ft ASL inland (Meyer, 1989). The UFA contains mostly brackish groundwater, defined by a TDS concentration of less than 10,000 mg/L. The brackish-water zone is about 1200 ft thick near the coast and thickens toward the center of the platform. The depth to the base of brackish water generally follows the Ghyben-Herzberg principle (Herzberg, 1901; Reese, 1994). The transition zone (referred to herein as the interface) from brackish water (defined above) to seawater (35,000 mg/L TDS) is about 150 ft thick in southeastern Florida. Just below the UFA lies the middle confining unit 1 (MCU1) and the MFA, which has properties similar to those of the UFA. The MFA, however, is slightly more brackish than the UFA. The native

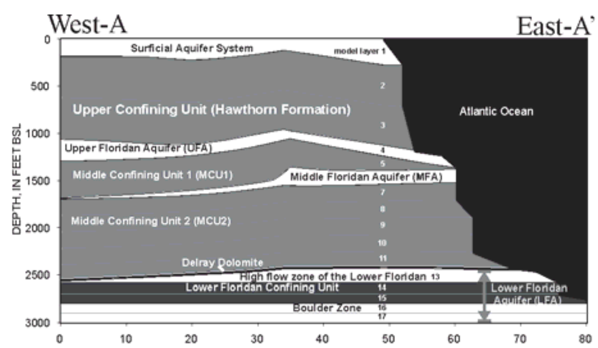

Figure 1: Cross section showing hydrogeologic units along the eastern margin of the Florida Platform in southeastern Florida (Reese and Richardson, 2008; McNeill, 2002), geologic units and layering scheme used for numerical modeling. Location shown in Figure 2.

waters of the LFA have TDS concentrations equal to seawater. The LFA is not artesian and has water levels near sea level.

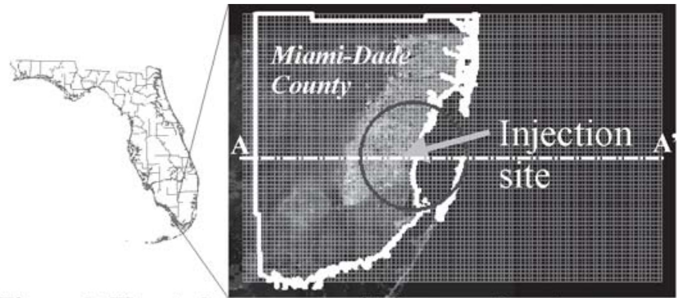

Figure 2: The study area and grid from southeastern Florida. A-A' cross section line shown for Figure 1.

The largest capacity deep-well injection plant in the United States, constructed in southeastern Florida during the 1970s, injects about 100 Mgal/d of secondarily-treated effluent into the saline and highly-transmissive parts of the LFA (Figures 1 and 2). The Delray Dolomite and middle confining unit 2 (MCU2) separate the zone of injection from the overlying UFA and MFA, which are protected under the U.S. Environmental Protection Agency's (USEPA) Safe Drinking Water Act (SDWA). The SDWA stipulates that aquifers containing groundwater with TDS less than 10,000 mg/L are "protected by law" (contamination by effluent is illegal). However, ammonia concentrations exceeding ambient conditions have been observed in monitoring wells open in and above the MCU2 and MFA (Figure 1), suggesting effluent has migrated upward (Maliva et al., 2007). Vertical migration is probably due to salinity-induced buoyancy effects created by injection of the low-TDS effluent into the saline native waters of the LFA.

Historical site records indicate injection of effluent into the LFA has caused more than a 20-ft increase in UFA groundwater levels; pre-injection water levels average about 42 ft ASL, whereas current water levels are about 65 ft ASL. Although the increase in heads is pervasive at the site, no nearby offsite monitoring wells are available to determine the aerial extent of the water-level increase. Some onsite monitoring wells show an increase in effluent concentration, indicated by anomalously high ammonia concentrations, or a decrease in TDS, caused by freshening of the well from effluent migration. An increase in effluent concentration, however, is not observed in all onsite monitoring wells. At present, the decrease in TDS in some of the wells with the increased water levels may indicate localized upward vertical migration of effluent.

The State permit for deep-well injection requires facility upgrades to be completed by 2010; effluent will be treated to drinking water standards prior to injection. This decreases the potential for contamination and allows deep-well injection to continue. The purpose of this study is to use groundwater modeling to address the following questions concerning deep-well injection. First, has the water injected over the past 25 years (~ 700 billion gallons) migrated (1) horizontally within the LFA towards the Atlantic Ocean, or (2) vertically towards the MFA/UFA? Second, if the majority of low-TDS injectate is migrating vertically upward, could it affect the overall location of the interface in the MFA/UFA? Finally, if the injectate is treated to drinking water standards, could it be considered future "recharge" to the UFA as a result of vertical migration?

MODELING APPROACH

The U.S. Geological Survey is developing a variable-density groundwater flow and solute transport model of southeastern Florida using SEAWAT (Version 4; Langevin et al., 2008). The numerical model is designed to assess (1) the fate and transport of injectate in the UFA and LFA, and (2) the movement of the brackish-water/freshwater interface in response to injection. The domain of a three-dimensional model spans the boundaries of Miami-Dade County (Figure 2). The top boundary is at sea level and the bottom is 3000 ft BSL. The model grid consists of 17 layers (Figure 1), 66 rows, and 104 columns (covering an area of about 57 by 89 miles, Figure

2). The interface depth was estimated using salinity data from Reese (1994) in combination with an automated parameter estimation program (PEST; Doherty, 2004). PEST is also used to calibrate model parameters, including hydraulic conductivity, porosity, and storage, by matching model output to water levels measured in the field. All estimated parameters are within realistic ranges of reported values. The injection rate into the LFA was obtained from historical records; current injection rates were used to estimate future injection rates. The model simulation period begins in January of 1983 and extends 148 years. Three "solute" species are simulated by the model: TDS (species 1), the relative concentration of injectate prior to 2010 (species 2), and the relative concentration of injectate after 2010 (species 3). A high level disinfectant (HLD) upgrade to the treatment facility is estimated to be complete by 2011.

MODEL RESULTS

The model predicts that after 148 years of injection, heads in the MFA and UFA will reach over 70 ft ASL at the site (Figure 3). Over the 148-year simulation, species 1, 2, and 3 continue to migrate upward at the site toward the UFA, as well as horizontally towards the coast in the LFA. Although effluent will migrate both horizontally and vertically upward in the FAS; the UFA is not contaminated with species 2 at the end of the simulation. Results also suggest that the injectate never reaches the Atlantic Ocean (Figures 3 and 4). By the year 2131, 120 years after the injectate is treated to drinking water standards, the secondarily-treated effluent represented by species 2 is well mixed and diluted. Low concentrations of species 2 (less than 5% of the original) still remain in some of the area (Figure 3). After 120 years, the injectate treated to drinking water standards (species 3) extends outward about 13 miles from the site in the MFA, just beneath the UFA (Figures 1, 3, and 4). The overall interface location in the MFA around the site shifts landward a few miles, with the brackish-water zone being “recharged” with injectate by 2031 (Figure 3). Model results suggest that injection has a local effect on the interface position within the MFA near the site (the interface moves in several miles by 2031). Injection does not appear to have had a regional effect on the interface position.

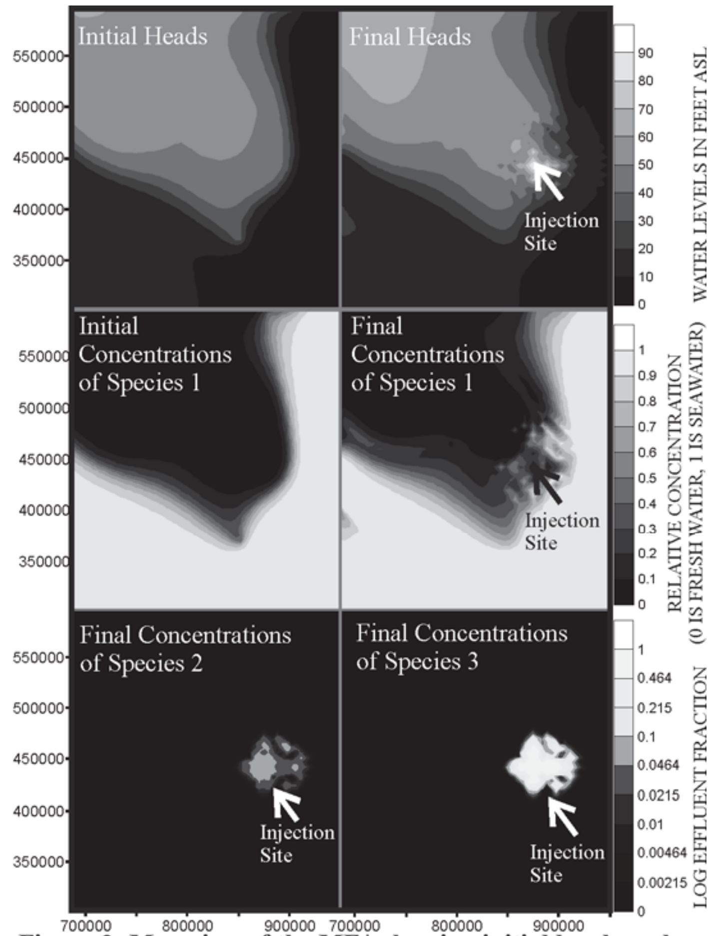

Figure 3: Map view of the MFA showing initial heads and concentrations, and final heads and concentrations of species 1, 2, and 3 after 148 years of injection. Coordinates are in feet, State Plane 83.

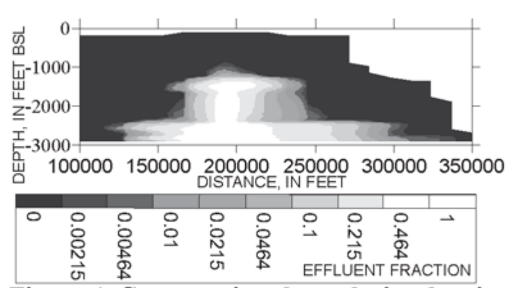

Figure 4. Cross section through site showing species 3 after 120 years of injection.

DISCUSSION AND CONCLUSIONS

The observed local freshening of certain monitoring wells at the site coincides with an increase in ammonia, although this is probably caused by the vertical upward migration of effluent over the last 25 years, rather than overall seaward movement of the interface. Over a longer, 148-year time period, however, the predicted increase in water levels at the site may affect the interface location in Miami-Dade County, depending on the areal extent of the increased water levels in the MFA and UFA. Based on the Ghyben-Herzberg principle, the interface transition zone could move from about 1700 ft BSL to over 2500 ft BSL at the injection site. The model results suggest that residual secondarily-treated effluent remains in the aquifer system as a result of 28 years of injection. This residual effluent, however, appears to be diluted over time due to the injection of higher quality water and mixing with native groundwaters.

The model presented here is a first step in understanding the long-term effects of a deep-well injection facility; a higher resolution model of the same area is being developed. This more refined model could provide additional insight in the localized vertical migration of effluent, as well as the long-term movement of the interface and injectate in the Floridan aquifer system.

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