

Tracing Vertical and Horizontal Migration of Injected Fresh Wastewater into a Deep Saline Aquifer using Natural Chemical Tracers

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ABSTRACT

The Miami-Dade Water and Sewer Department (MDWASD), Miami-Dade County, Florida, operates two deep-well injection facilities which inject an average of 430 million liters per day of fresh treated wastewater into a deep saline aquifer approximately 900 meters below land surface. Although this deep aquifer is separated from overlying brackish aquifers by a confining unit 150 meters thick, evidence of migration of injected wastewater has been detected in the overlying aquifers. This injected fresh water is a source of freshwater recharge chemically distinct from the native brackish aquifer water. Ammonium contained in the injected wastewater is higher than native aquifer water background levels, and exhibits a high seasonal variability in response to the wet and dry climatic conditions in south Florida. Geochemical data indicate that the injected ammonium behaves conservatively when mixed with native water, and thus can be used as a tracer of injected wastewater. Ammonium data, in conjunction with major ion chemistry and stable isotope data, were used to identify source and pathways of the recharge. Data indicate multiple pathways that are chemically distinct depending on their pathway to the aquifer, and suggest vertical migration a result of either natural or anthropogenically-induced fractures. Once introduced into the overlying aquifer, horizontal migration appears to be the result of natural advection/diffusion through a highly heterogeneous carbonate aquifer with little mixing of native waters.

INTRODUCTION

South Florida has experienced rapid urban growth in the past several decades, which has placed extraordinary demands on the management of ground-water resources in southern Florida. Potable water has been produced from the Biscayne aquifer, a pristine karst surficial aquifer that has supplied an average of 1300 million liters per day (MLD). Due to restrictions on increased allocations from the Biscayne aquifer, the underlying Floridan aquifer in south Florida is becoming an alternate water supply source. Historically, the Floridan aquifer in south Florida has been used for aquifer storage and recovery (ASR) in the Upper Floridan aquifer, and for industrial and treated domestic wastewater disposal in a highly permeable zone in the Lower Floridan aquifer. Increasingly the Upper Floridan aquifer is used as becoming a source of brackish water to blend with Biscayne aquifer water.

The Floridan aquifer system in south Florida lies approximately 300 meters below land surface (BLS), and consists of heterogeneous permeability carbonate layers of Oligocene to Paleocene in age. The Upper Floridan aquifer (UFA) is an artesian aquifer and is used for ASR and a source of water for blending. Water quality is brackish, with total dissolve solids (TDS) averaging less than 10,000 milligrams per liter (mg l^{-1}), (Reese, 1994). The UFA is underlain by the middle confining unit 1 (MCU1) and the Middle Floridan aquifer (MFA) at approximately 420 m below land surface (BLS), with water quality becoming increasing saline (Reese et al, 2008). Beneath the MCU1 and the MFA is the Lower Floridan aquifer (LFA), which consists of water quality close to seawater, with TDS concentrations over $33,000 \text{ mg l}^{-1}$. The LFA outcrops along the Florida Straits, with water levels in the LFA near sea level.

MDWASD began injecting treated domestic wastewater in the early 1980's, and currently is injecting an average of 430 MLD into the highly permeable boulder zone 900 m BLS in the LFA. Domestic wastewater is treated to secondary drinking water standards, with TDS levels of 375 mg l^{-1} , and ammonia concentrations ranging from 15 to 35 mg l^{-1} , in response to the wet and dry seasons in south Florida. Evidence of upward migration of ammonia was observed at 440 m BLS in the UFA, as concentrations of 7 mg l^{-1} were detected above reported background levels of 0.05 mg l^{-1} (BC&E, 1977), with the implication that the MCU1 is actually not confining. The authors of this paper and others (Maliva et al, 2007) have suggested that the vertical migration pathway may most likely be along fractures. The purpose of this research is to determine the transport mechanisms and migration pathways of freshwater injectate into a highly saline aquifer.

METHODS

Historical water quality data for the FAS were collected and analyzed from utility, state and federal sources. Water quality samples were collected from following standard protocols from on-site dual-zone monitoring wells, representing the 300 m zone, 440 m zone, and the 550 m zones. The 300 m and 440 m zones are located in the UFA; the 550 m zone lies in the MCU1 and MFA. Samples were analyzed for major ions, pH, temperature, stable isotopes, and chemical parameters including ammonium, nitrate and nitrite. Ammonium was evaluated for use as a conservative tracer. As part of the nitrogen cycle, ammonium is oxidized to NO_3^- (nitrification) in the presence of O_2 , and therefore ammonium reacts non-conservatively. Water quality data at the project site suggests otherwise, as dissolved O_2 values are $< 1 \text{ mg l}^{-1}$, and nitrate values for all zones monitored on site in the Floridan aquifer, including wells with high ammonium concentrations, are typically less than 0.05 mg l^{-1} . Ammonia levels have remained constant over time in several wells, further suggesting a conservative nature. Therefore, mixing and ratio models of ammonium to major ions were developed to determine chemical evolution of the injected freshwater.

RESULTS

Time series historical ammonium and chloride water quality data were analyzed to determine if any patterns could be distinguished. Ambient levels of ammonium at the 300 m, 440 m, and 550 m zones typically are $> 0.2 \text{ mg l}^{-1}$. Ammonium concentrations as high as 15 mg l^{-1} have been observed in wells in the 440 m zone on the west side of the site, and as high as 20 mg l^{-1} in the 550 m zone on the south side of the site. Two patterns were observed in the time-series analysis. Ammonium concentrations above ambient levels were observed in MWs in the UFA, however, they were at ambient levels in the monitoring zones beneath. Ammonium concentrations increased sharply, and exhibited apparent seasonal variation, very similar to the seasonal variations observed in the injected freshwater (Figure 1). Once ammonium was detected above ambient levels, data show relatively stable concentrations, with very slight increases. Levels in wells exhibiting this trend average $2 - 5 \text{ mg l}^{-1}$. Ammonium levels were compared to chloride levels for each monitoring zone. Ambient chloride levels were 750 mg l^{-1} for the 300 m, 3700 mg l^{-1} for the 440 m, and $19,000 \text{ mg l}^{-1}$ for the 550 m zones. It was assumed that chloride and ammonium are conservative tracers, and ammonium/chloride mixing models were developed for each well, compared to ammonium concentration trends over time. End members of the mixing model were the ambient concentrations of chlorides and ammonium of each monitored zone. Several distinct mixing models were observed (Figure 1). Mixing models that showed strong increasing trend of ammonium concentrations comparative to freshwater injectate concentrations plot with time indicated relatively rapid mixing with the freshwater end member (well IDs 6U and 12L). This mixing model at the 440 m zone (well ID 6U) also showed no mixing with the

550 m zone. The models that showed ammonium concentrations to have slowly increased with time, or that have remained relatively static with time (well ID 10L) indicated slow progression of water chemistry evolution towards the freshwater end member.

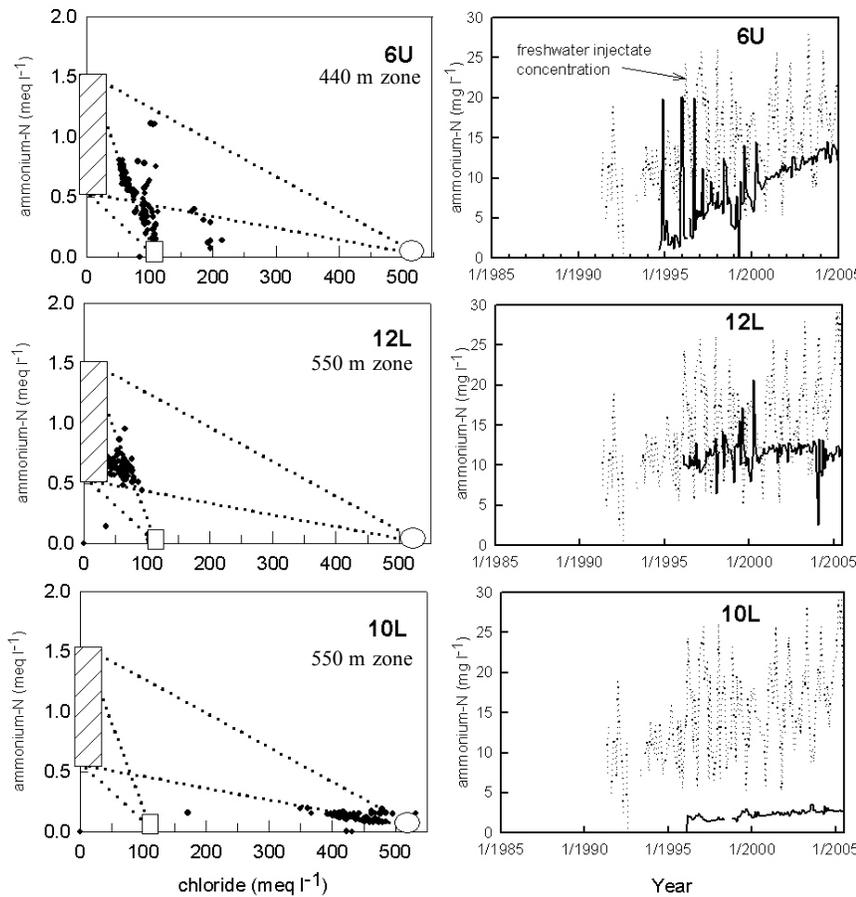


Figure 6. Graphs on the left are ammonium/chloride mixing end member models for the 440 m and 550 m zones. 6U, 12L and 10L are wells IDs. Hatched rectangle is injected freshwater end member, indicating the seasonal range in concentrations. Square is 440 m zone (brackish water) ambient water end member; circle is 550 m zone (saline water). Graphs on the right are ammonium concentrations over time. Solid black lines are concentrations from each well site; dotted line is injected freshwater concentration.

DISCUSSION AND CONCLUSIONS

Possible migration pathways of freshwater injectate were determined using chlorides, major ions, and ammonium. Analysis of time-series ammonium data shows two distinct ammonium patterns. The first pattern indicates a sharp increase of ammonium above ambient levels, with a strong seasonality component that closely matches the seasonality component of the freshwater injectate. The second pattern shows once ammonium appears in the water above ambient levels, concentrations remain static, or exhibit very small increasing concentration trends. This suggests that there are multiple pathways of

Calcium/chloride ion ratios analysis show a similar effect (Figure 7). The freshwater injectate calcium ion concentrations average 59 mg l⁻¹; calcium concentrations in the 440 m zone 176 mg l⁻¹, and at the 550 m zone 436 mg l⁻¹. When plotted against ambient ratios, chloride/calcium ratios for the 440 m and the 550 m impacted zones showed groundwater evolution towards the freshwater injectate (Figure 2). As with the ammonium/chloride end member model, the 440 m zone does not show any mixing with the underlying 550 m zone.

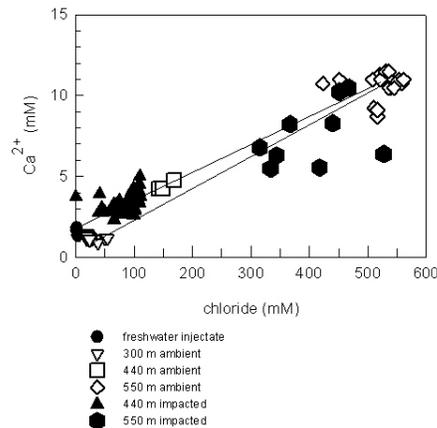


Figure 7. Chloride/calcium ion ratios.

migration of ammonium in the aquifers. Mixing models developed using ammonium/chloride end members and ion ratios as conservative tracers also suggest different migration pathways of freshwater injectate. In the 440 m zone where ammonium concentrations in the aquifer water closely follow the same concentration trends as the injectate, mixing models show no mixing with 550 m zone. This suggests that freshwater injectate is migrating directly to the 440 m zone, with little to no mixing of underlying highly saline water. If freshwater injectate were migrating up through the MCU1 it would be expected to exhibit a mixing line from the 550m to the 440 m zone. Both the end member and ion ratio models do not show such a mixing line. It appears that the freshwater injectate is traveling up through the MCU1 via natural or anthropogenically-induced fracturing, (possibly as a result injection well construction); and is probably vertically migrating due to the buoyancy effect of injecting freshwater into the highly saline LFA. Where ammonium concentrations are slowly increasing in time or remaining static, mixing and ratio models suggest that once the freshwater is introduced into the aquifer, it slowly advects/diffuses through the aquifer, with a slow groundwater evolution over time from brackish to gradual freshening, and remaining geochemically distinct. On-going research on this project includes helium/tritium dating and ¹⁵Nitrogen isotope analysis to further differentiate freshwater injectate migration pathway.

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