Physical and Numerical Modeling of Buoyant Groundwater Plumes

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ABSTRACT
In coastal states, the injection of treated wastewater into deep saline aquifers offers a disposal alternative to ocean outfalls and discharge directly into local waterways. The density of treated wastewater is similar to that of freshwater, but is often much lower than the ambient density of deep aquifers. This density contrast can cause upward buoyant movement of the wastewater plume during and after injection. Because of large injection volumes at some wastewater treatment plants (WWTP), it is important to be able to determine the fate and transport rates of the plume. In this study, both physical and numerical modeling were undertaken to investigate and understand buoyant plume behavior and transport.

INTRODUCTION
Because more than 98 percent of the Earth's potable water supply comes from groundwater (Fetter 1988), underground sources of drinking water (USDW) need protection from possible contamination, especially in urban areas where wastewater production is high. In southeastern Florida, the sizeable population produces large amounts of wastewater, which must be properly disposed of. A viable option for disposal of this treated wastewater is deep-well injection. As part of the U.S. Environmental Protection Agency's Underground Injection Control Program (UIC), injection wells have been classified into five major types. The first type (Class I) is used for injection of municipal wastewater beneath the lowermost USDW. In southeastern Florida, the total daily injection rate for all wells is ~265 Mgal/d (Muniz et al. 2005). The high injection rate has led to concerns over the safety of the local USDW; therefore, it is important to determine the fate and transport of the resulting waste plumes.

Because injected water undergoes primary and secondary treatment at a WWTP, the density of the water is close to that of freshwater (~1.000 g/cc). In contrast, an ambient density of about 1.025 g/cc is typical for saline aquifers used for waste disposal in Florida. This density difference causes buoyant upward movement of the plume during and after injection. The objective of the current study is to investigate the fate and transport of freshwater buoyant plumes in saline aquifers under hydrostatic conditions. This objective was accomplished using both physical and numerical modeling.

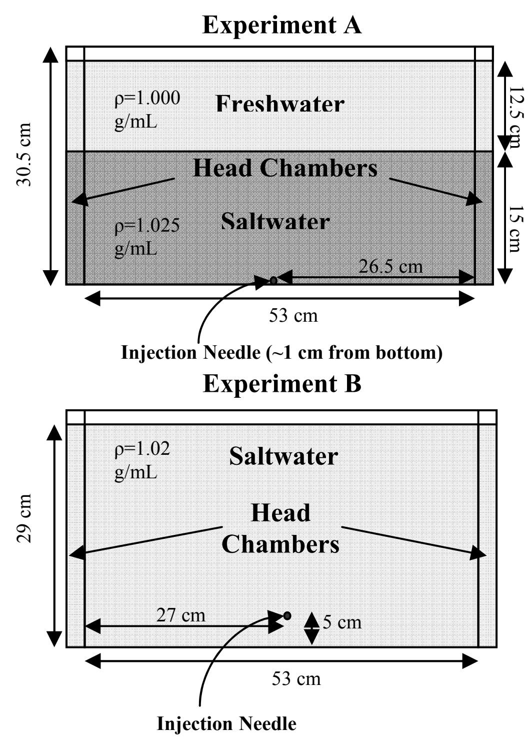

Figure 1 (A and B). Physical model set-up for experiments A and B

METHODOLOGY

Physical Modeling

A 2-D transparent flow tank (53 cm × 30.5 cm × 2.7 cm) was used as the physical model (Figure 1). The tank consists of two lateral head chambers and a central porous media chamber that was carefully packed with glass beads (~1 mm) under saturated conditions to avoid air entrapment and layering. Syringes fastened to two holes (~1 cm diameter), drilled at different heights, were used for injection. The saltwater was prepared using sodium chloride and de-ionized water. The density was measured using an ASTM 111H hydrometer. Three food coloring dyes were used for plume visualization. Digital images of the experiments were captured using time-lapse photography.

Physical models were designed to replicate real-world buoyant groundwater plume problems and allow for easy visualization under controlled laboratory conditions. Furthermore, the experimental results were used later for comparison to numerical modeling results for code validation. In this study, two physical experiments (A and B) were carried out using the same tank. Experiment A was conducted to mimic a scenario in which the saline aquifers used for disposal are overlain by freshwater layers representing the USDW. In this exercise, a 24-mL freshwater slug was injected over a 14-second period into a static, density-stratified system of saline water overlain by freshwater (Figure 1A). Experiment B was designed to investigate plume behavior in a confined system. The zero-pressure upper air boundary was used to conceptually model a non-leaky, impermeable confining unit. In this exercise, 60 mL of freshwater was injected over a 41-second period into the static, fully saline, confined system (Figure 1B). Experiment B utilized an injection point 5 cm from the bottom of the tank, which allowed for better plume visualization than the injection point used in Experiment A.

Numerical Modeling

Experiment B was modeled numerically using SEAWAT Version 4 and compared to laboratory data. SEAWAT couples a modified version of the MODFLOW code with the MT3DMS transport code through the density term in order to solve the variable density flow and transport equations (Langevin et al. 2008). The grid resolution was 0.1 cm × 0.1 cm × 2.7 cm. The MOC (Method of Characteristics) was used to solve the advective part of the transport equation. Time stepping was determined using a Courant number of 0.25. A hydraulic conductivity value of 1.0995 cm/sec was shown to give the best matching qualitative results when compared to Experiment B. Longitudinal dispersivity was calibrated to a value of 0.01 cm, with a transverse to longitudinal dispersivity ratio of 1:10. The low dispersivity values were required to replicate the fingering patterns in the physical experiment (Liu and Dane 1997). Initial heads in the model were 29 cm. Only two zero-pressure boundary conditions were added, at the left and right top corners, to allow fluid and salt to exit the domain while maintaining a hydrostatic system (Voss and Souza 1987). The injection point was modeled using a well boundary condition. Two species were simulated in the model, allowing use of both molecular diffusivities; species 1 was used to represent total dissolved solids of sodium chloride in the water, and species 2 was a tracer representing the dye injected in the well.

RESULTS

Results from Experiment A show a freshwater plume that develops fingers as it migrates upwards (Figure 2). These fingers are presumably caused by small-scale porous media heterogeneities and by dense fluid sinking into the rising relatively lighter fluid. The fingers appear to rise at similar rates until they reach the overlying freshwater layer. However, the

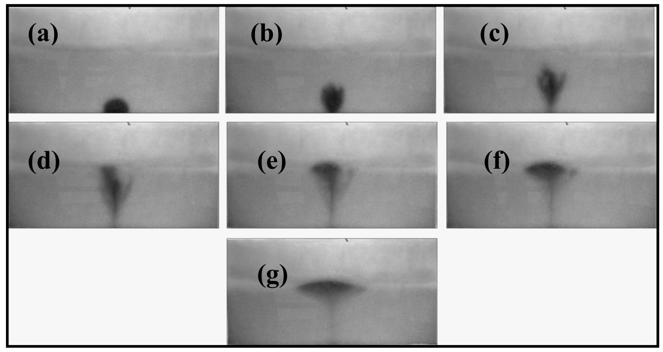

Figure 2. Experiment A results: [times are from end of injection (sec)] (a) 0, (b) 90, (c) 210, (d) 330, (e) 510, (f) 750, (g) 1410

middle finger advection is slightly faster than that of the outer two fingers. As the plume rises, hydrodynamic dispersion causes mixing between the plume and the ambient saltwater along the boundary of the two fluids. As fingering becomes more complex, the surface area of the plume in contact with the ambient water increases, thereby increasing mixing and salt entrainment into the plume. Saltwater entrainment can be visualized by a dilute concentration of the tracer being left behind in a "tail" as the plume rises (Figure 2). As mixing increases, the density contrast between the plume and the ambient water decreases, which lessens the uplifting buoyant force. With decreasing buoyancy, vertical velocities diminish. This cycle continues as the vertical velocity decreases, declining rapidly when the plume makes contact with the freshwater layer. When the boundary is reached, the average plume density is greater than the freshwater, resulting in only some of the injectate entering the bottom of the freshwater layer while the rest spreads out laterally along the boundary. Thus, the freshwater layer behaves similar to a confining unit in that vertical transport is considerably reduced.

The results from experiment B are shown in Figure 3 (left-hand column). As with the results from Experiment A, the plume also rises vertically and fingers until it reaches the boundary. In this case, the boundary is the top of the tank open to the atmosphere, which simulates a confining unit. The fingering between plumes in Figures 2 and 3 is similar early in the experiments as slight instabilities form due to small-scale heterogeneities and the density difference between the injected and ambient water. In addition, the initial instabilities later develop into distinct fingers, or pathways for flow. Upon reaching the upper boundary, both plumes exhibit similar behavior in that vertical advection decreases and the plume begins to spread laterally along the boundary. The complex fingering pattern also evolves into a cone-shaped formation at the upper boundary.

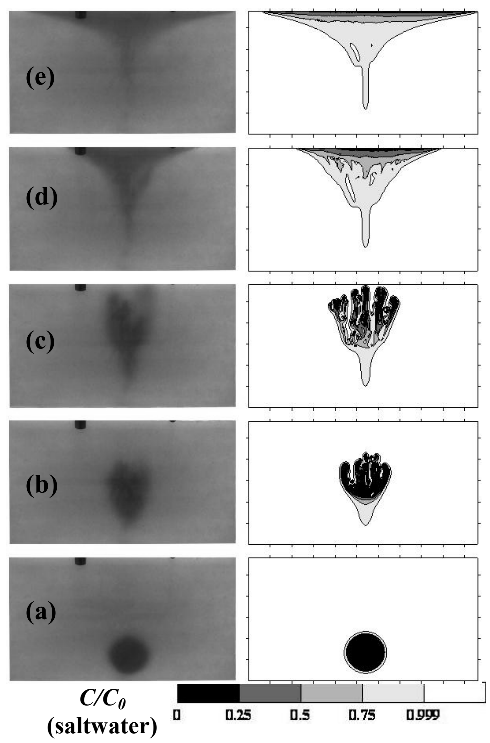

Figure 3. Experiment B and SEAWAT results: [times are from end of injection (sec)] (a) 27, (b) 369, (c) 685, (d) 1385, (e) 2631

One main difference between results from these two physical experiments is the variation in plume behavior that occurs when the plumes reach their respective overlying boundaries, due to the inherent differences between the boundaries themselves. Even though both plumes begin an outward lateral migration after reaching the boundary, the plume underneath the confining unit (Figure 3) laterally expands faster than the plume underneath the freshwater layer (Figure 2). In Experiment A, when the freshwater plume makes contact with the boundary, the plume pushes up into the freshwater layer, displacing some of the overlying water and mixing with it. In Experiment B, however, the freshwater plume cannot continue its vertical path once in contact with the confining layer, resulting in immediate outward expansion.

Because Figure 3 displays results from the numerical modeling effort in the right-hand column, the results of Experiment B and the SEAWAT simulation can be compared at specific times. The shape of the experimental plume appears to be matched well by the SEAWAT simulation results. As with the physical model, the plume in the SEAWAT simulation contains initial instabilities that develop into preferential pathways and elongated fingers. The fingers reach the confining unit at slightly different times and join to form a conical shape beneath the boundary, leaving a tail created by saltwater entrainment. The experimental and simulated plumes have a similar bulk vertical velocity as well as similar lateral spreading once the boundary is reached. Fingering in the simulated plume was more complex than in the experimental results. Because concentration contours were not obtained from the experiment, the numerical model reveals more quantitative information in regards to concentration stratification and the degree of mixing occurring between the plume and the ambient water. Results from the numerical model show that freshwater begins mixing with the saline water at injection. This mixing appears to increase as the plume moves vertically upward, causing saltwater entrainment and creating a tail of brackish water behind the plume. However, relatively freshwater does appear to have reached the confining layer. Although it cannot be determined how fresh this water is, Figure 3 indicates that the relative concentration of salt is between 0 to 0.25, which represents ”relatively fresh” water.

DISCUSSION AND CONCLUSIONS

Experiments A and B show that a buoyant plume will experience more lateral spreading once it makes contact with a confining unit than when it makes contact with an overlying freshwater layer of the same permeability. Overall, the buoyant plumes in both scenarios exhibited similar behavior in terms of fingering and transport dynamics. The numerical simulation results show that SEAWAT (with MOC as the advection solver) is capable of modeling these types of scenarios, and that mixing of the plume with the ambient water increased with vertical transport. Further experiment and numerical details can be found in Brakefield (2008).

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