European Water 58: 359-364, 2017.

Influence of clay lens on contaminant transport in unconfined coastal aquifers

B. Sharma*, D.S. Rishi, B.K. Mudai and R.K. Bhattacharjya
Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India
* *e-mail: bhrigumanisharma@yahoo.com*

Abstract: Groundwater serves as the most reliable source of freshwater for domestic, industrial and agricultural purposes in most of the coastal areas of the world. However, the freshwater aquifers hydraulically connected with the sea or ocean has been deteriorating day by day due to different anthropogenic activities. Therefore, a better understanding of contaminant transport processes in coastal aquifers is highly important to prepare and implement proper water resources planning and management policies for coastal environment. The coastal groundwater flow is very complex due to the occurrence of a freshwater-saltwater diffusion zone and the tidal variation of sea level at the seaward end also contributes to the complexity of coastal groundwater flow. In this study, an experimental investigation has been carried out to understand the behavior of contaminant plume in unconfined coastal aquifers under the influence of horizontal clay lens. The laboratory experiment is conducted in a rectangular flow tank filled with glass beads as the porous medium. A constant head was maintained on the freshwater and saltwater boundary using respective chambers during the experiment. A colored dye with the salt solution was used to differentiate the saltwater from the freshwater. This also helps in visualization of the contaminant. The experimental results show that there are two saltwater wedges developed, one at the base of the aquifer and the other one is above the clay lens. Experimental results also show that the contaminant travels slightly along the saltwater wedge towards the seaward boundary. This experimental study helped us to better understanding of contaminant transport processes occurring in coastal aquifers.

Key words: Contaminant Transport, Unconfined Coastal Aquifer, Laboratory Experiments, Saltwater Interface, Clay Lens

1. INTRODUCTION

Coastal groundwater contamination is a very serious environmental problem throughout the world that threatens the human health and the integrity of aquatic ecosystems in coastal areas. The interest in understanding the mechanism of contaminant transport in coastal groundwater systems is garnering increased attention worldwide with the growing population and rapid development of coastal areas since about 70% of the world's population lives in coastal zones (Bear et al., 1999). However, coastal aquifers play a vital role all over the world due to the availability as well as high quality of groundwater resources they provide. The freshwater aquifers hydraulically connected with the sea or ocean have been deteriorating day by day due to different anthropogenic activities and natural events such as climate change and sea level rise. Once it is highly contaminated, it is very challenging and expensive to remediate contaminated aquifers. Therefore, a quantitative understanding of contaminant transport dynamics in coastal aquifer systems is indispensable with regard to water resources planning, development and management in coastal and island environments.

In the past, numerous scientific investigations related to contaminant transport in coastal aquifers have been conducted. Various approaches, including numerical and experimental studies have been carried out to investigate the contaminant transport patterns in coastal aquifers. For example, Zhang et al. (2002) who experimentally investigated the migration of a contaminant plume of different densities in a coastal aquifer system. They performed a series of laboratory experiments in a rectangular flow tank filled with glass beads as the homogeneous porous medium. Based on the experimental results, they hypothesized that the less dense contaminant plume had less diffusive front than the dense contaminant plume in the seaward direction towards the coastline. As pointed out by them, the contaminant plume became more diffusive when it approached the saltwater-freshwater interface. A numerical study was conducted by Volker et al. (2002) using a two-dimensional variable-density flow and transport model, 2DFEMFAT to investigate the movement of a dense contaminant plume in an unconfined coastal aquifer. They concluded that neglect of seawater density results in the underestimation of solute mass rate exiting around the shoreline. More recently, Chang and Clement (2013) conducted both experimental and numerical studies to quantify the contaminant plume migration processes occurring within and above the saltwater wedge. Their experimental datasets were numerically simulated by SEAWAT model and they found that numerical prediction matches well with the experimental results. They reported that the contaminant transport dynamics occurring above the saltwater-freshwater interface are much faster than the contaminant migration processes occurring within the interface.

However, as per the author's knowledge, this is the first time an experimental study has been conducted to investigate the contaminant transport dynamics in presence of a horizontal clay lens in an unconfined coastal aquifer system. In this effort, we have successfully completed a laboratory experiment to investigate the influence of a horizontal clay lens on the behavior of contaminant plume patterns in an unconfined coastal aquifer. The experiment was carried out in a laboratory-scale flow tank model with constant head boundary conditions.

2. LABORATORY METHODS

2.1 Experimental setup and measurements

The laboratory experiment was conducted in a rectangular flow tank made of 6 mm thick glass, simulating a two-dimensional flow system in a homogenous and unconfined coastal aquifer (Figure 1). The internal dimensions of the flow tank used was 55.6 cm (length) × 40 cm (height) × 6.8 cm (width).

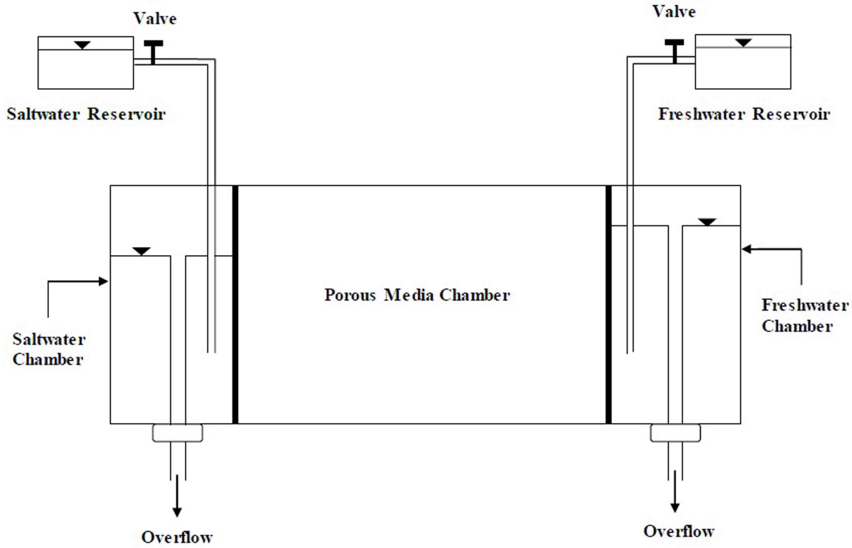


Figure 1. Schematic diagram of experimental setup.

As shown in Figure 1, the flow tank was divided into three distinct chambers and the central flow chamber contains the porous medium (the aquifer). The other two side chambers were used for maintaining constant water heads at the boundary. The left hand and the right hand side constant-head chambers represent the seaward and landward boundary respectively. The constant-head chambers are of length 5.3 cm each and are separated from the central porous media chamber by 7 mm thick Plexiglas plate, which contains 120 holes of 0.7 cm diameter each. The holes are provided to allow the flow through the chamber into the porous media. These two Plexiglas plates were then wrapped by 500-micron stainless steel meshes in order to prevent the passage of granular material from the central chamber to the side ones. Moreover, thin strips of foam were attached to seal the sides of the wrapped Plexiglas plate to prevent any kind of leakage. In this study, we have used glass beads as a porous media as used by many researchers in their study (Volker et al., 2002; Zhang et al., 2002; Goswami and Clement, 2007; Abarca and Clement, 2009; Chang and Clement, 2013 etc.). The central porous media chamber (45 cm × 40 cm × 6.8 cm) was filled with uniform glass beads of an average diameter of 0.57 mm to a height of 31.5 cm. Both freshwater and saltwater were supplied at constant flow rates to the respective chambers from two overhead chambers whose outlets were attached by PVC pipe with adjustable valve for adjusting the discharge. The overflow from both the freshwater and saltwater chambers were released by PVC pipes diameter of 2.5 cm. Printable rulers were attached on the sides and at the bottom of the flow tank to allow quick measurements.

In this study, tap water was used as freshwater and saltwater was prepared by dissolving 35 g of commercial salt (NaCl) in 1L of deionized water, yielding an effective concentration of 35 g/L. A red color dye was mixed at a ratio of 100 ml per 32 liters of saltwater to differentiate the saltwater from freshwater. The density of the dyed saltwater was measured by using the G8030@JAPSINR specific gravity hydrometer and its value was estimated to be as 1.025 g/cm^3. We also measured the density of freshwater as 0.9943 g/cm^3 using the aforementioned hydrometer. The saturated hydraulic conductivity (K) of the flow tank was measured using the in-situ method described by Goswami and Clement, 2007 and the average value was estimated as 0.251 cm/s. The main geometrical and hydraulic properties of the porous medium are listed in Table 1.

Table 1. Properties of the Porous Medium

Parameter	Value
Average grain size, mm	0.57
Average bulk density, g/cm^3	1.443
Specific gravity	2.49
Average saturated hydraulic conductivity, cm/s	0.251
Porosity	0.43

2.2 Experimental procedures

Prior to the experiment, the flow tank was packed with glass beads in layers of about 5 cm under fully saturated condition to prevent entrapment of air bubbles inside the flow tank. The glass beads were prudently compressed by hand pressure after each layer was completed. To replicate a horizontal clay lens, we placed an approximately 3 cm thick layer of bentonite clay at a certain height inside the flow tank. It was covered the entire width of the flow tank.

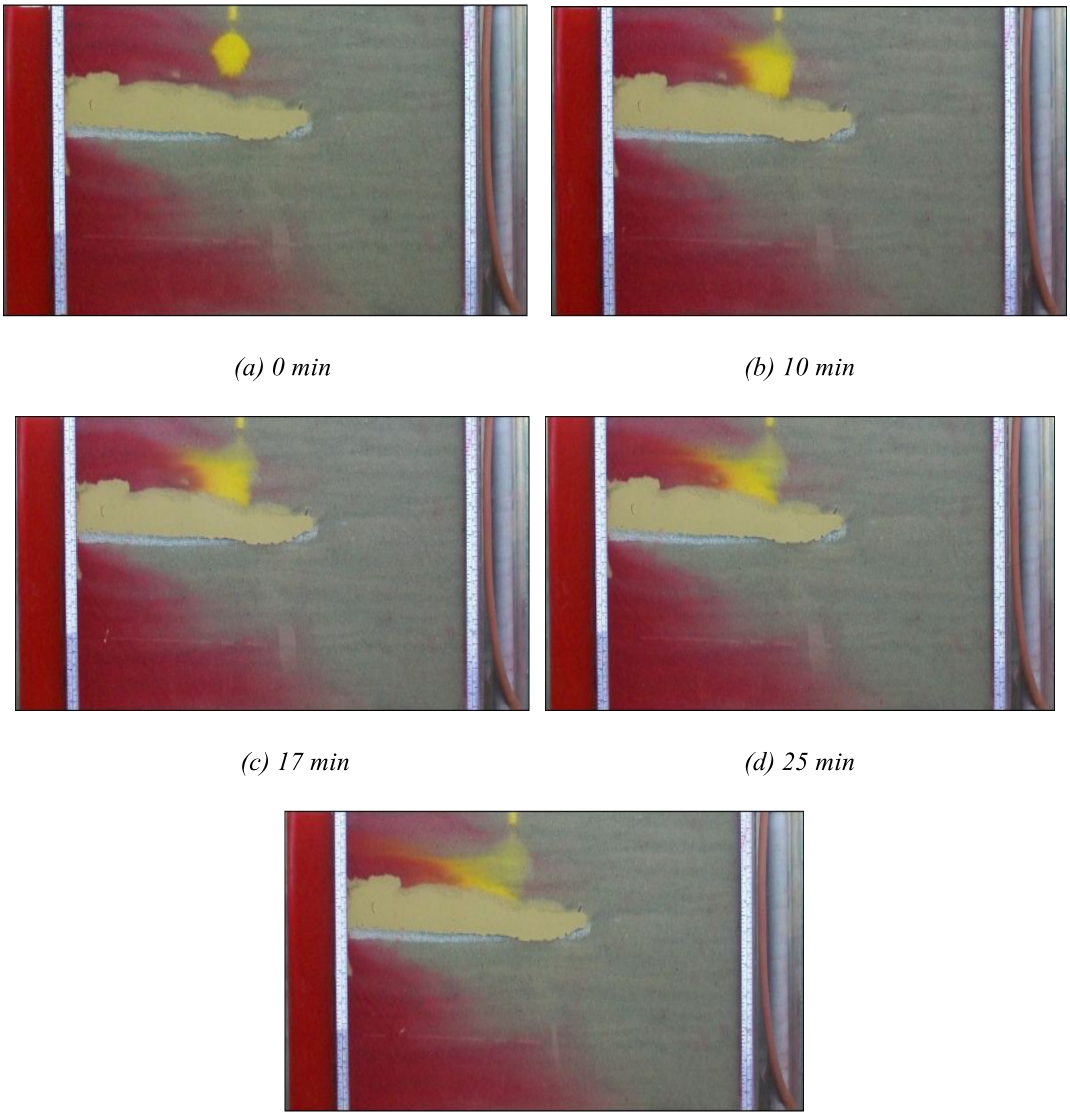
Before starting the contaminant transport experiment, the flow tank was initially flushed with freshwater towards the left side from the right side through a fixed gradient condition until it reaches steady state flow. After establishing steady state flow, the left side chamber was fed quickly with dyed saltwater and when the saltwater in the left side chamber attained a constant level, the saltwater began to intrude the porous media. After a certain duration of time, a steady state saltwater wedge was achieved. After achieving a steady state saltwater wedge position, the contaminant was injected at a specific location of the porous media through a pipette of length 43.8 cm diameter of 1.4 cm. A constant rate of injection of the contaminant into the porous medium was maintained. The pipette was buried in the main flow tank when the porous media was wet packed and contaminant was poured into the pipette using a syringe. A yellow color dye was used as the contaminant in this study to visualize the behavior of the contaminant plume. The left bottom corner of the central flow chamber was considered as the origin to record experimental observations. A Nikon digital camera was used to record images of the behavior of contaminant plume during the experiment. The recorded images were cropped and presented at a suitable scale to provide better visualization.

2.3 Laboratory-scale experiment

This experiment was performed to study the influence of a horizontal clay lens on the behavior of contaminant plume patterns in an unconfined coastal aquifer system. The height of the freshwater level and saltwater level at the respective chambers were fixed at 28.5 cm and 27.5 cm respectively. The clay lens was prolonged horizontally from the left side of the flow tank to a distance of about 28 cm and at a height of 20 cm from the bottom of the tank. After developing a steady state saltwater wedge, the contaminant about 5 ml in volume was injected and the location of the injection point was: x = 20 cm, y = 0.7 cm and z = 13.5 cm. The contaminant plume was allowed to migrate with the freshwater flow and the images were taken at different times. The time of injection of the contaminant was recorded as 35 minutes from starting the experiment.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental data of the contaminant transport patterns under the influence of a clay lens are shown in Figure 2. The digital images were recorded to examine the contaminant migration patterns and photographs were taken at 0, 10, 17, 25 and 37 min after injecting the contaminant.



(a) 0 min *(b) 10 min*

(c) 17 min *(d) 25 min*

(e) 37 min

Figure 2. Contaminant transport experimental results.

Figure 2 shows photographs of the contaminant plume as it moved from the injection point towards the saltwater boundary. From the experimental results, we observed that there are two saltwater wedges developed, one below and the other above the clay lens. Because of the presence of a horizontal stratified layer, it was observed that in addition to the formation of the usual saltwater wedge, there was an additional wedge formed on top of the clay lens. Figure 2(a) was recorded instantly after injection and it indicates that the initial shape of the injected contaminant plume was nearly circular. As time advanced, the plume transported in downward direction towards the saltwater wedge and eventually attained an elongated shape when it came closer to the saltwater wedge. Due to higher level of mixing occurring near the interface, the plume formed an elongated shape as it approached the freshwater-saltwater interface. The shape of the migrating plume was elongated as shown in Figures 2(b), 2(c), 2(d), and 2(e). It was also observed that the contaminant plume moved along the top surface of the saltwater wedge and eventually discharged at the saltwater boundary.

4. CONCLUSIONS

Groundwater contamination in coastal aquifers has been an ongoing and most challenging environmental management problem faced by water resources planners worldwide. Therefore, understanding of contaminant transport patterns in coastal aquifers is an important subject of research work in the field of contaminant hydrology. In this effort, an experimental study was conducted in a laboratory-scale flow tank model to investigate the contaminant plume patterns under the influence of a horizontal clay lens in an unconfined coastal aquifer. The experimental results indicate that there are two saltwater wedges developed, one at the base of the aquifer and the other one is above the clay lens. Experimental data also indicate that the contaminant plume moves along the top surface of the saltwater-freshwater interface towards the seaward boundary and then exits around the shoreline. Due to dispersion effects, the contaminant plume attains an elongated shape as it approaches the interface. Higher velocities occurring near the interface creates a rapid transport of contaminant plume mass along the mixing zone forming this elongated shape. This experimental study helps us to better understanding of contaminant transport dynamics occurring in an unconfined coastal aquifer system.

REFERENCES

Abarca, E., Clement, T. P., 2009. A novel approach for characterizing the mixing zone of a saltwater wedge. Geophysical Research Letters; 36 (6), L06402.

Bear, J., 1972. Dynamics of Fluids in Porous Media. American Elsevier Publishing Company, Inc., New York; 764.

Bear, J., 1979. Hydraulics of Groundwater. McGraw-Hill Publishing Company, Inc., New York; 569.

Bear, J., Cheng, A. H., Sorek, S., Quazar, D., Herrera, I., 1999. Seawater intrusion in coastal aquifers, concepts, methods and practices, Kluwer Academic publisher, Dordrecht, The Netherlands.

Brovelli, A., Mao, X., Barry, D. A., 2007. Numerical modeling of tidal influence on density-dependent contaminant transport. Water Resources Research; 43 (10), W10426.

Chang, S. W., Clement, T. P., 2012. Experimental and numerical investigation of saltwater intrusion dynamics in flux-controlled groundwater systems. Water Resources Research; 48 (9), W09527.

Chang, S. W., Clement, T. P., 2013. Laboratory and numerical investigation of transport processes occurring above and within a saltwater wedge. Journal of Contaminant Hydrology; 147, 14-24.

Goswami, R. R., Clement, T. P., 2007. Laboratory-scale investigation of saltwater intrusion dynamics. Water Resources Research; 43 (4), W04418.

Goswami, R. R., Clement, T. P., Hayworth, J. H., 2012. Comparison of numerical techniques used for simulating variable-density flow and transport experiments. Journal of Hydrologic Engineering; 17 (2), 272-282.

Kuan, W. K., Jin, G., Xin, P., Robinson, C., Gibbes, B., Li, L., 2012. Tidal influence on seawater intrusion in unconfined coastal aquifers. Water Resources Research; 48 (2), W02502.

Lu, C., Chen, Y., Zhang, C., Luo, J., 2013. Steady-state freshwater-seawater mixing zone in stratified coastal aquifers. Journal of Hydrology; 505, 24-34.

Todd, D. K., 1980. Ground-Water Hydrology. John Wiley and Sons, New York; 535.

Volker, R. E., Zhang, Q., Lockington, D. A., 1999. Simulation of contaminant transport in unconfined coastal aquifers, In: Oxley, L., Scrimgeour, F. (Eds.), MODSIM'99, Proceedings of International Congress on Modelling and Simulation, Hamilton, New Zealand, 6^{th}-9^{th} Dec. 1999; 1, 13-18.

Volker, R. E., Zhang, Q., Lockington, D. A., 2002. Numerical modelling of contaminant transport in coastal aquifers. Mathematics and Computers in Simulation; 59, 35-44.

Zhang, Q., Volker, R. E., Lockington, D. A., 2001. Influence of seaward boundary condition on contaminant transport in unconfined coastal aquifers. Journal of Contaminant Hydrology; 49, 201-215.

Zhang, Q., Volker, R. E., Lockington, D. A., 2002. Experimental investigation of contaminant transport in coastal groundwater. Advances in Environmental Research; 6 (3), 229-237.