Understanding the Flow and Mixing Dynamics of Saline Water Discharged into Coastal Freshwater Aquifers

M. B. Hogan, R. R. Goswami, K. G. Villholth, T. H. Illangasekare, and T. P. Clement

Abstract In the traditional conceptual models, the origin of saltwater intrusion into coastal aquifers has been attributed to the reduction of freshwater flux (or head) in the aquifer which allows the saltwater wedge to migrate laterally inland. Although this process is the most common natural source of saltwater contamination in coastal aquifers, it is not the only source. Other sources of saltwater contamination, including saltwater deposition caused by tsunamis and hurricanes have been observed. The country of Sri Lanka was devastated by the 2004 Asian tsunami, event which also caused large scale saltwater contamination. In this study, laboratory experiments were performed, using a physical two dimensional groundwater model, to observe the subsurface saltwater transport patterns in a coastal aquifer after a large scale inundation event.

Index Terms groundwater, tsunami, saltwater intrusion, density coupled flow

I. Introduction

The Sumatra-Andaman earthquake, which occurred on December 26, 2004 in the Indian Ocean, was considered the worst tsunami catastrophe in history according to a report published by UNESCO (UNESCO-IOC 2006). The tsunami was the result of a magnitude 9.3 earthquake, which occurred near the west coast of Indonesia. The earthquake produced an ocean-wide tsunami event that devastated many countries including Indonesia, Sri Lanka, India, and Thailand. An estimated 230,000 people were killed and more than 1.5 million were displaced (Wikipedia 2006).

In Sri Lanka alone, approximately 85,000 homes were damaged, and 400,000 jobs were lost (Illangasekare et al. 2006). Despite being located 1600 km from the earthquake's epicenter, Sri Lanka experienced the second most casualties of any of the affected countries. In addition to the damaged homes and loss of life, an estimated 40,000 freshwater supply wells, mostly open wells, were contaminated due to inundation caused by the tsunami's run-up water level along the coast. These open wells were used to serve as the main freshwater supply for local residents. A preliminary site investigation concerning the potential sources and related processes of groundwater contamination was published in Villholth et al. (2005). This experimental work is based on some of the field observations summarized in this report.

Figure 1 shows the devastation of the tsunami and the presence of a high density of open dug wells (concrete cylinders and open excavations) in the coastal town of Maruthumunai on the eastern coast of Sri Lanka. Reports indicated that the maximum water level during wave inundation was about 10 meters at this site which is higher than the top of the palm trees shown in the figure. The United States Geological Survey, USGS provide a detailed report of water elevation measurements (Liu et al. 2005). Since many coastal villages in Sri Lanka are no more than 10 – 15 meters above sea level the impact of the tsunami-impacted devastation at these places was enormous.Many coastal residents accessed water through open wells which are hand dug in the shallow fresh unconfined aquifer. The saline tsunami waters entered and contaminated these aquifers via three main sources: Source 1) water filtrating or seeping from inundated land depressions and ponds located along the coastal zone; Source 2) water infiltrating from the land surface along the beach face; and Source 3) water discharging from flooded open dug wells (Villholth et al. 2005). These sources of saltwater contamination are identified in the conceptual diagram shown in Figure 2.

Figure 1 Picture illustrating the high density of open wells in the coastal town of Maruthumunai, Sri Lanka (concrete cylinders shown here are open wells)

It is important to understand the mechanism contributing to the entrapment and deposition of large quantities of seawater

Manuscript received September , 2006

M. B. Hogan and R. R. Goswami are with Auburn University, Department of Civil Engineering, Auburn, AL USA (email: hoganmb@auburn edu, goswarr@auburn.edu)

K. G. Villholth is with International Water Management Institute Colombo, Sri Lanka (email: k.villholth@cgiar.org)

T. H. Illangasekare is with CESEP at Colorado School of Mines, Department of Environmental Engineering, Golden, CO 80401; (email: tillanga@mines.edu)

Corresponding author: T. P. Clement is with Auburn University, Dept. of Civil Engineering, 238 Harbert Engineering Center, Auburn, AL 36849 USA (phone: 334-844-6268); email: clement@eng.auburn.edu).

at great distances inland.

Typically, sand dune developments are influenced by a continuous cycle of erosion and deposition that depend heavily on wind. Energy from wind traveling over the sea will decrease once it encounters the elevated land surface with obstructions such as vegetation. When the wind energy is reduced, dust and sand particles are deposited which creates a topographical high point or mound, commonly known as a sand dune. Sand dunes serve as a natural energy dissipater against storm waves, surges, and wind.

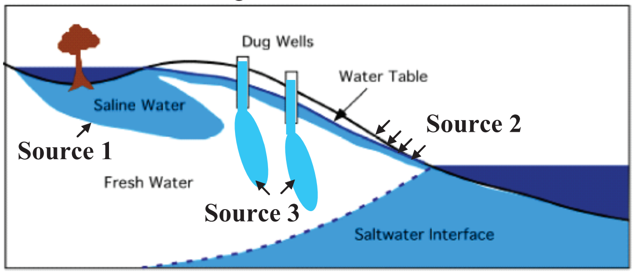


Figure 2 Conceptual diagram illustrating the three sources of saltwater contamination of the aquifer due to the tsunami

However, if run-up water levels exceed the height of the sand dune then the seawater becomes trapped on the other side of the sand dune and can become a longer-term contaminant source (source 1) for coastal aquifers. Typically sand dune formations run parallel to the coastline which means that the aquifer of the region can be conceptualized as a series of two-dimensional strips running perpendicular to the sea. Furthermore, the sediment sequences can often be assumed to be uniform across cross-sections perpendicular to the coast and hence the profile of an infiltrating saltwater plume can be assumed to be the same at any cross-section along the coast. Therefore, the plume movement can be conceptualized in a two-dimensional domain.

The combination of contamination from open wells and infiltration from the land surface coupled with potential effects of saltwater intrusion from below created a unique variable-density groundwater flow and mixing problem with multiple fronts. In the past, the effects of dense contaminant plumes emanating from point sources have been studied (e.g., Oostrom et al. 1992). In Sri Lanka, contamination from multiple point as well as areal sources occurred simultaneously. A detailed fundamental experimental study concerning this type of complex system is lacking in the literature.

Currently, there are no guidelines available for the decontamination of aquifers and open wells that have been contaminated by saltwater. One strategy applied was to pump the contaminated water out of the wells to avoid a contaminant source to the aquifer. However, any increase in the drawdown of the groundwater table due to pumping would increase the likelihood of secondary contamination of the well and aquifer, via upconing of the underlying saltwater or from remnant tsunami water in other parts of the aquifer. Another possible decontamination strategy is to allow the aquifer to remediate itself naturally through recharge from natural rainfall. The later approach appears to be a pragmatic solution because the hydraulic conductivity is relatively high in the coastal sandy aquifers (10-500 m/day) and Sri Lanka experiences a relatively high annual rainfall of 1000 – 1700 mm (Villholth 2005), which are concentrated during the monsoon season. However, more information is required to propose best practices for well decontamination and to accurately predict the length of time required for natural remediation of the contaminated aquifers.

II. Objectives of the Study

The overall goal of this study was to investigate the migration of infiltrated seawater in an unconfined aquifer, and also to gain a qualitative understanding of the fate of saltwater discharged into open dug wells. This was achieved by performing laboratory experiments in a small scale two-dimensional physical model to mimic and visually demonstrate the saltwater migration patterns in a simulated tsunami-impacted coastal aquifer. Our first objective was to experimentally simulate the deposition of saltwater by the three distinct sources identified in the conceptual model presented in Figure 2. To accomplish this, three separate experiments were performed. The first experiment focused on the behavior of a type 1 source, continuous infiltration of saltwater from a shallow saltwater pond. A second experiment simulated a type 2 source, large scale groundwater infiltration along the beach face. The final experiment investigated a combination of type 2 and type 3 sources, the latter being infiltration through open wells.

III. Experimental Setup

This section of the paper describes the experimental setup used to create a physical model for saltwater contamination processes occurring at a tsunami-impacted field site. The experiment descriptions are presented in three parts. Part A and B concern the behavior of source-1 and source-2, respectively (see Figure 2). Part C describes an experiment involving a combination of sources 2 and 3.

A. Saltwater Pond Infiltration Experiment (Source 1)

Experiments were conducted in a thin transparent rectangular flow container constructed from Plexiglass™. The dimensions of the flow container were 53 cm × 30.5 cm × 2.7 cm. The container was filled with homogeneous glass beads (1.1 mm average diameter) to simulate a coastal aquifer system with an intrinsic permeability of 1.4×10^{-9} m^2 measured using a constant head permeameter. The flow container has three sections: a porous media flow chamber filled with glass beads, and two constant head chambers (reservoirs) at both ends as shown in Figure 3. In all experiments the ambient fresh groundwater flowed from right to left. Seawater was prepared by dissolving NaCl in de-ionized water. The average density of saltwater used in the experiments was 1025 kg/m^3, which is representative of sea water. A small amount of red food coloring was added to the saltwater to differentiate the injected tsunami water from the freshwater. The saltwater was supplied as a continuous point source to the surface of the porous media through a continuous volume displacement peristaltic pump at a constant rate (Q_L=8.9 mL/min). The flow rate was sufficiently low to prevent any ponding effects. The system was used to simulate a leaking saltwater pond. Three experiments were performed to study the effects of different ambient groundwater flow rates. The rates were controlled by varying the hydraulic gradient in the flow direction by adjusting the water levels in the end reservoirs. Digital data was collected with a 7.1 mega-pixel camera.

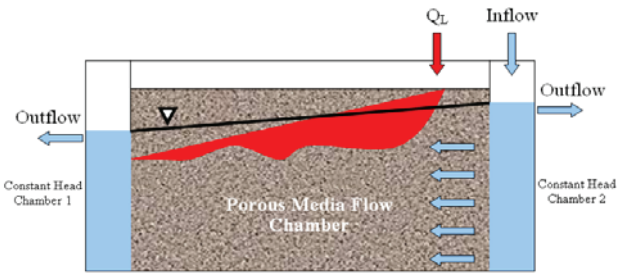


Figure 3 Generalized schematic of experimental setup illustrating saltwater contaminant from Source-1 type region infiltrating into an aquifer

B. Beach Face Infiltration Experiment (Source 2)

The flow container described above was also used for the beach face infiltration (source-2) experiment. However, for this experiment, the left freshwater boundary was replaced with a saltwater boundary, to represent the coastal interface, by injecting saltwater at a constant rate from a saltwater supply reservoir as illustrated in Figure 3. The saltwater from the boundary was allowed to intrude into the aquifer from the left to form a stable saltwater wedge.

The steady initial condition was attained when the saltwater wedge reached a steady position and the lateral movement of the wedge ceased to penetrate further into the porous medium. Furthermore, this initial steady condition, representing the pre-tsunami scenario was attained by setting up a regional hydraulic gradient across the length of the model that would force the uncolored freshwater to flow from right to left (see Figure 4). The inundation caused by the tsunami wave was simulated by instantaneously discharging approximately 500 mL of saltwater at the top surface of the model. The freshwater flow was continuously supplied to the model from the constant head boundary at the right side.

To avoid any variation in density or chemical composition, the same batch of saltwater was used in a particular set of experiments to supply both the saltwater boundary in the left reservoir and the tsunami water from above. Again, experiments were performed for different ambient groundwater flow rates.

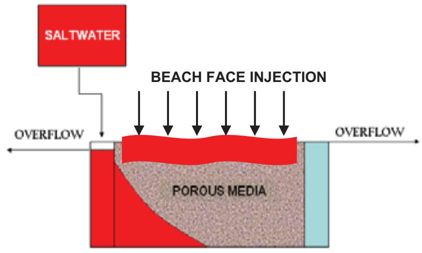


Figure 4 Generalized schematic of experimental setup illustrating saltwater contamination from Source-2 type region infiltrating through the beach face

C. Beach Face Infiltration with Well Experiment (Sources 2 and 3)

For the combined Source-2 and Source-3 case, the tsunami water entered the freshwater flow region by injection through an open well (Source 1), in addition to the beach face infiltration (Source 2). A 2-cm diameter impermeable glass tube, open at both ends, was inserted into the top of the porous media model to represent an open dug well as shown in Figure 5. Due to density differences, the saltwater from the left boundary intruded the porous medium, as described in the previous section, creating a wedge. Beach face infiltration was simulated by applying a volume of the denser saltwater to the surface (top) of the porous medium as described in Part B. Input to the well was achieved by a simultaneous and instantaneous filling of saltwater in the empty head space above the groundwater table in the well.

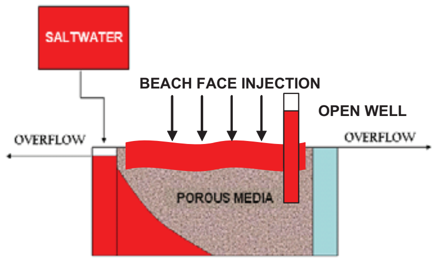
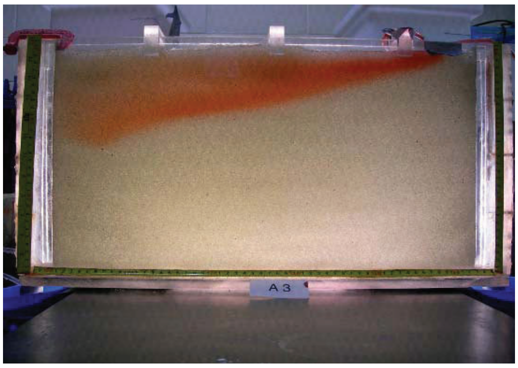


Figure 5 Generalized schematic of experimental setup illustrating the combined Source-2 and Source-3 saltwater discharges into an aquifer

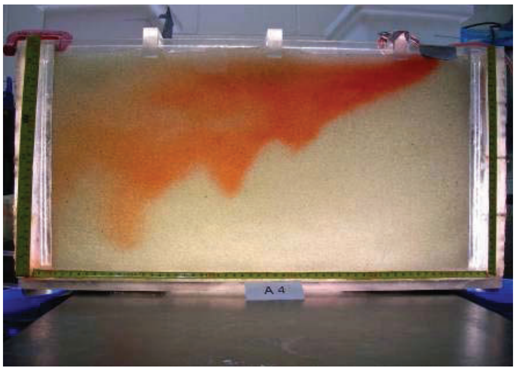
IV. Results and Discussion

A. Results of Saltwater Pond Infiltration Experiment (Effects of Source 1)

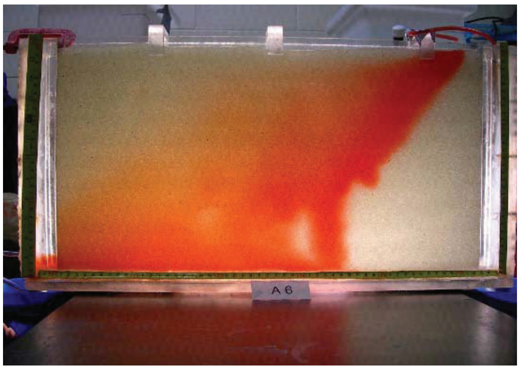
In the physical model study of Source 1, the plume behaved considerably different for different groundwater velocity scenarios. Transport observed under low, medium, and high flow scenarios are shown in Figure 6a, 6b, and 6c, respectively. The saltwater water loading rate of 8.9 mL/min was used in all the experiments. Our preliminary experiments indicated that the loading rate has much less effect on the plume's migratory patterns when compared to other parameters such as groundwater velocity and density differences. However, further field studies are required to determine acceptable values for loading rate emanating from the ponded sources in Sri Lanka.



6a: High Flow (stable plume)



6b: Medium Flow (unstable plume)



6c: Low Flow (highly unstable plume)

Figure 6 Source-1 experimental results for low, medium, and high ambient flow scenarios after 28 minutes of transport

The groundwater flux in this experiment was measured to be 36 m^3/m^2/day (average linear velocity, v = 97 m/day) for the high flow (stable plume) experiment. The velocity was then decreased to 16 m^3/m^2/day (v = 43 m/day) and 6 m^3/m^2/day (v = 15 m/day) to create medium (Figure 6b) and low flow (Figure 6c) scenarios, respectively.

Stable saltwater plumes can be characterized by their tendency to remain concentrated near the top of the aquifer and their smooth continuous interface with the ambient fresh groundwater below. Plume behavior in low flow groundwater systems (unstable environment) is characterized by a tendency of the saltwater to penetrate deeper into an aquifer and their shape tends to be erratic with fingering patterns along the plume-ambient freshwater interface (Schincariol and Mendoza 1994). These plumes are of concern because they mix heavily with the aquifer and can contaminate a large volume of freshwater resources. So, the plume stability is strongly governed by the ambient groundwater flow velocity. A detailed modeling analysis of this dataset is discussed in Hogan (2006).

The saltwater wedge was not present in this experiment because the saltwater infiltration of Source 1 occurred at greater distances inland. In the field case, where it was reported that the tsunami traveled up to a 1.5 km inland (Villholth et al 2005), the saltwater wedge would have much less impact on the migration patterns of plume emanating from a source-3 plume.

B. Results of Beach Face Infiltration Experiment (Effects Source 2)

As discussed in the methods section the tsunami source (source-2) was created by instantaneously depositing a fixed volume of saltwater over the model. Figure 7 shows the transport of this dense saltwater slug over a time period of 11 minutes. Under high flow conditions the saltwater slug was transported fast and formed a rather shallow contamination zone. On the other hand, when the ambient flow was low, the slug of saltwater migrated downward and contaminated larger volume of aquifer. In addition, the low flow case also indicated more intense fingering effects. An important observation made in these experiments is that tsunami water (red-colored salt water) always remained above the regional seawater interface. This should be expected because the density of the tsunami water decreased due to dilution as it migrated through the aquifer and mixed with freshwater. Therefore, the tsunami water would never be able to penetrate the regional seawater wedge. Instead, it will remain floating above the wedge and will eventually be advected by the regional freshwater flow along the wedge.

C. Results of Beach Face Infiltration and Well Experiment (Effects Sources 2 and 3)

Figure 8a illustrates the initial condition of a steady state saltwater wedge. The flow rate used here corresponds to the flow rate used for the low flow rate case in Part B. This figure is followed by a series of pictures (Figures 8b –8f) of the transport and mixing patterns at 1, 4, 9, 14 and 19 minutes after the simulated inundation by a tsunami wave. The experimental results demonstrate that within a short period of time the tsunami water that flooded the well descended as a large slug and contaminated the deeper aquifer (see Figure

8c). The infiltrated tsunami water eventually merged with seawater from the flooded well.

Another major observation was that the open well remained contaminated for a relatively long period. As shown in Figures 8-b through 8-e, the bulk of the tsunami water injected into the well moved downward as a blob within about five minutes. However, a small amount of seawater remained trapped inside the well, and this remnant saltwater acted as a continuous source of saline water that discharged from the well. After about 19 minutes, a syringe was used to extract three storage volumes directly from the open well thereby removing the remnant saltwater from the well..

These simulation results provided a conceptual basis for understanding the saline water transport processes from both surface infiltration and from direct injection into the wells These results demonstrate the mixing processes that would have occurred in flooded open dug wells. It is important to note that this physical experiment was completed in a homogeneous system. Under field condition, subsurface heterogeneities and the coastal topography would play a larger role in mixing different water. However, these conceptual experiments provide insight into the density driven transport processes that would have occurred in Sri Lankan coastal aquifers immediately after the December 2004 tsunami event.

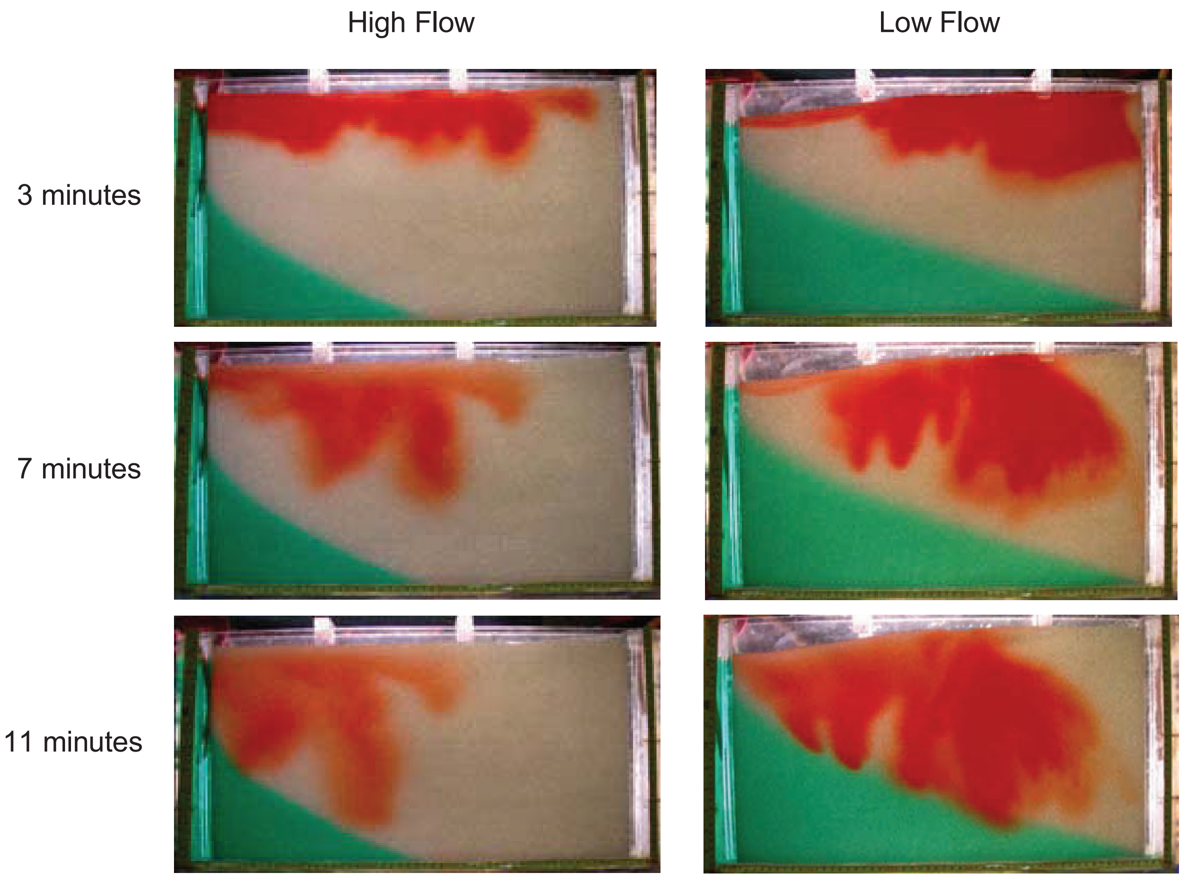


Figure 7 Source-2 experimental results for high and low ambient flow scenarios

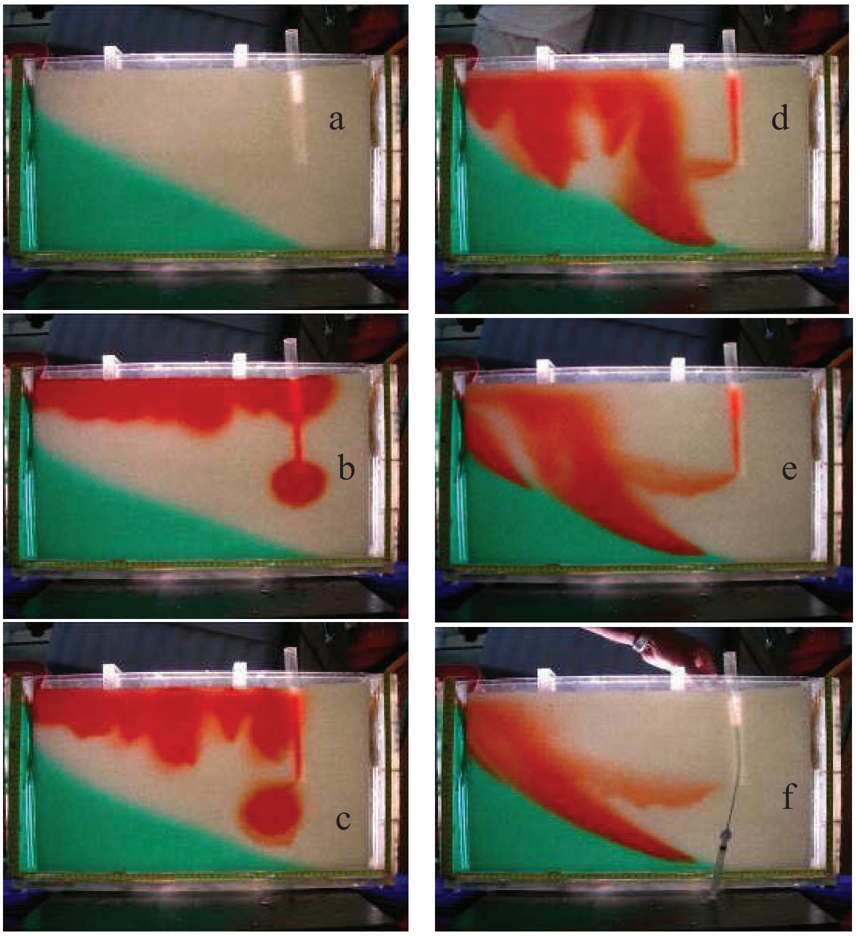


Figure 8 Combined Source-2 and Source-3 scenario experimental results (Times: 0, 1, 4, 9, 14, 19 minutes, respectively

V. Summary and Conclusions

This paper presents the results of a set of laboratory experiments completed to investigate the fate and transport of saltwater deposited by a tsunami wave into a coastal aquifer system. The study included three types of contaminant sources: (i) a pond-type source, (ii) a beach infiltration source, and iii) a well source. These sources were specifically used to model the contamination scenarios that could have occurred in the coastal regions of Sri Lanka during the December 2004 tsunami event.

Among the three plume types (stable, unstable, and highly unstable), the highly unstable plume, which is also the slower moving plume, appears to be the most hazardous because it will penetrate the deepest into an aquifer and contaminate a relatively larger aquifer volume. A stable plume will only exist in the subsurface when groundwater velocities are large.

The open wells may remain contaminated by a tsunami event and may remain contaminated until the hydraulic gradient is increased (due to regional recharge via rainfall events) and the aquifer is flushed.
However, if sufficient time passes before a monsoon season the contaminant may have the time to sink deep enough into the aquifer so that a large portion of the contaminant might be lost to deeper formations. However, the migration pattern from a well can be greatly disturbed by pumping and cleaning actions. Simply purging the well a few times, as done in this experiment, might significantly improve the salinity levels. However, further experimental work is required to investigate various pumping/cleaning strategies under different source and flow conditions.

The experimental data provides a preliminary conceptual model for saltwater transport in tsunami-impacted coastal aquifers. The developed model, however, should be carefully interpreted based upon actual field observations and further investigated by dedicated well cleaning experiments before implementing it to develop remediation strategies.

ACKNOWLEDGEMENTS

This experimental study was completed at Auburn University, Alabama, USA. Hogan and Clement were, in part, supported by a grant (Grant no: USGS-06-HQGR0020) from the Alabama State Water Resources Competitive Grants Program administered by the Alabama Water Resources Research Institute. The field visits to Sri Lanka was funded by the US National Science Foundation grant EAR-0519409.

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