Impacts of the 2004 tsunami on groundwater resources in Sri Lanka

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[1] The 26 December 2004 tsunami caused widespread destruction and contamination of coastal aquifers across southern Asia. Seawater filled domestic open dug wells and also entered the aquifers via direct infiltration during the first flooding waves and later as ponded seawater infiltrated through the permeable sands that are typical of coastal aquifers. In Sri Lanka alone, it is estimated that over 40,000 drinking water wells were either destroyed or contaminated. From February through September 2005, a team of United States, Sri Lankan, and Danish water resource scientists and engineers surveyed the coastal groundwater resources of Sri Lanka to develop an understanding of the impacts of the tsunami and to provide recommendations for the future of coastal water resources in south Asia. In the tsunami-affected areas, seawater was found to have infiltrated and mixed with fresh groundwater lenses as indicated by the elevated groundwater salinity levels. Seawater infiltrated through the shallow vadose zone as well as entered aquifers directly through flooded open wells. Our preliminary transport analysis demonstrates that the intruded seawater has vertically mixed in the aquifers because of both forced and free convection. Widespread pumping of wells to remove seawater was effective in some areas, but overpumping has led to upconing of the saltwater interface and rising salinity. We estimate that groundwater recharge from several monsoon seasons will reduce salinity of many sandy Sri Lankan coastal aquifers. However, the continued sustainability of these small and fragile aquifers for potable water will be difficult because of the rapid growth of human activities that results in more intensive groundwater pumping and increased pollution. Long-term sustainability of coastal aquifers is also impacted by the decrease in sand replenishment of the beaches due to sand mining and erosion.

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1. Introduction

[2] On 26 December 2004, a magnitude 9.3 earthquake off the south coast of Sumatra generated tsunami waves that left over 280,000 people dead or missing in Asia and Africa. Hundreds of thousands of homes were destroyed resulting in a humanitarian crisis in the hardest hit countries. From February through September 2005, a team of United States, Sri Lankan and Danish water resource scientists and engineers surveyed the impacts of the tsunami on the coastal groundwater resources of Sri Lanka. Sri Lanka was chosen for study as it was one of the hardest impacted by the tsunami. Further, the coastal aquifers found in Sri Lanka are similar to those found in parts of Indonesia, Thailand and India. The objectives of the survey team were (1) to investigate the impacts of the tsunami on coastal groundwater resources and review well cleaning methods and their impacts, (2) to develop a conceptual understanding of the seawater mixing phenomenon in coastal aquifers after the

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Figure 1. Photograph of the coastal area near Maruthumunai, Sri Lanka, showing the near complete destruction of homes along the coast. The photographer is standing about 150 m from the coastline, and it was reported to the team that the maximum wave height at this site reached high into the palm trees shown in the background. Note the high density of domestic open dug wells (typically short vertical circular structures), many of which were not destroyed by the wave but were inundated and flooded by seawater and debris.

tsunami event, (3) to investigate the medium and long-term impacts of the tsunami on coastal groundwater resources, (4) to develop a joint program to study the regional aquifer hydrology and hydrogeology of Sri Lanka, and (5) to transfer knowledge about coastal aquifer vulnerability to other south Asian nations.

[3] We begin with a review of the tsunami and its impacts in Sri Lanka along with a brief overview of Sri Lankan groundwater in the tsunami-impacted areas. We then discuss the major processes that occurred in the aquifers with an emphasis on salinity changes caused by the tsunami. We conclude with a preliminary estimate of the recovery and long-term sustainability of coastal aquifers in densely populated countries such as Sri Lanka.

[4] The tsunami first impacted Sri Lanka along its eastern coastline and during a period of about 90 min, swept along the southern and southwestern and northern coasts. Inundation distances varied significantly because of the angle of wave incidence and the local shore and coast configurations, but in places wells up to 1.5 km inland were flooded [*Villholth et al.*, 2005]. The height of the tsunami waves in Sri Lanka ranged from 3–8 m, with runup heights as much as ~15 m [*Liu et al.*, 2005].

[5] Although Sri Lanka is approximately 1600 km from the epicenter, it still suffered catastrophic losses that include over 35,000 people known dead or missing. In addition, more than 85,000 homes were destroyed or severely damaged along the coast of Sri Lanka and over 400,000 jobs were lost as a result of the devastation (Joint Asian Development Bank (ADB), Japan Bank for International Cooperation, and World Bank, Sri Lanka–2005 Post-Tsunami Recovery Program: Preliminary Damage and Needs Assessment, Colombo, Sri Lanka, 10–28 January 2005, available at http://www.adb.org/Tsunami/sri-lanka-assessment.asp, hereinafter referred to as ADB report, 2005). The magnitude of the tragedy continued to dominate the social and political structure of the region at the time this paper was written.

[6] In most areas of Sri Lanka, the availability of potable drinking water quickly became a major concern for relief efforts, both from the perspective of life requirements and from concerns over the potential spread of waterborne diseases from contaminated water supplies. The largest coastal urban communities of Sri Lanka are supplied by treated and piped surface and groundwater supplies managed by the National Water Supply and Drainage Board (NWSDB). The primary damage to the treated water supply involved breaks in pipelines which were completely destroyed at several river and estuary crossings. Additional leaks were caused when the force of tsunami waves sheared off the water connections to individual dwellings. Repairs to the distribution system began soon after the tsunami event, and as of September 2005, piped water service had been restored to most areas previously served and plans were underway to expand the distribution system.

[7] While the NWSDB served about 30% of the country's general population via 287 water supply systems (www.waterboard.lk) using tube wells and surface water systems,

many of the coastal areas rely on individual or community wells for potable water. Typically, these wells are of large diameter (1–2 m) and 3–8 m deep and are designed to tap the shallow parts of the fresh groundwater lens found in most of the coastal aquifers. Figure 1 shows the remains of many of these wells following the destruction of the tsunami. They are dug manually and/or with explosives and excavators. These shallow wells are termed as ''open dug wells'' in this communication. The density of open dug wells in Sri Lankan coastal villages is very high in heavily populated or cultivated areas with well densities of approximately 90–125 wells km^{-2} [*Nadarajah*, 2001; *Villholth et al.*, 2006]. Figure 1 shows both the devastation of the tsunami at the coastal town of Maruthumunai on the eastern coast of Sri Lanka, and also the high density of domestic open dug wells (concrete cylinders and open excavations) typically used along the coast of Sri Lanka. Generally, each of the wells shown in Figure 1 may have been used by several individual households that were totally destroyed by the tsunami wave. The local villagers reported that the water level reached close to the top of the coconut palm trees shown in Figure 1. Over one thousand lives were lost when the wave completely inundated this coastal village.

[8] The tsunami immediately inundated and contaminated more than 40,000 of these wells in Sri Lanka [*United Nations Environment Programme*, 2005; ADB report, 2005], primarily close to the coastline. Because many of the coastal villages are no more than 10–15 m above sea level, an enormous area was affected by this inundation. In most affected areas, the open dug wells were instantly filled with the seawater and large volumes of saltwater were injected into the freshwater lens. Many wells were also contaminated with organic and inorganic debris from the flood waters, rendering them unusable until they were cleaned and disinfected. In addition, the seawater inundated low-lying areas resulting in infiltration of saline water into the aquifers.

[9] During the post-tsunami clean up, government, non-governmental organizations (NGOs), foreign and local voluntary groups and local citizens began pumping contaminated wells and treating them with chlorine disinfectant. Fears of waterborne disease outbreaks were not realized in the coastal regions of Sri Lanka affected by the tsunami partly because there was public awareness of the need for well disinfection in addition to personal and food hygiene. Although emergency well cleaning advice and instructions are now available from various sources (e.g., http://www.who.int/water_sanitation_health/hygiene/envsan/technotes/en/, http://www.ngwa.org/presscenter/pr2005/01-02-05emerwelldisinfection.pdf, and http://www.bt.cdc.gov/disasters/wellsdisinfect.asp), no widely accepted guidelines were available at the time for decontaminating wells affected by tsunami-related seawater, let alone guidelines relevant for conditions specific to coastal aquifers such as those found in Sri Lanka and other portions of south Asia. From the perspective of removing saltwater and restoring potable drinking water quality, the emergency procedures used may not have been effective. The excessive pumping may have caused more seawater intrusion from below rather than its removal from the upper part of the saturated zone. In addition, the purged well water was often discharged on the land surface close to the wells, allowing the contaminated water to reenter the aquifer and the wells after vadose zone infiltration.

2. Summary of the Coastal Hydrogeology of Sri Lanka

[10] In order to better understand the nature of the tsunami impacts on the coastal aquifers of Sri Lanka, the major aquifer characteristics are summarized below from the work of *Panabokke* [2001]. While generalizations can be made, there also exist many site-specific attributes that produced a wide variety of aquifer responses to the tsunami.

[11] While confined Miocene age limestone aquifers exist along the northern and northwest coast and throughout the Jaffna Peninsula [*Lawrence and Dharmagunawardena*, 1983], groundwater resources across most of the Sri Lankan coast are dominated by the ''coastal sand'' aquifers, which consist primarily of spits and bars, coastal dunes, raised beaches and paleobeach deposits [*Panabokke*, 2001]. The total area of these aquifers has been estimated to be 1,800 km^2 [*Somasiri*, 2001] and are tapped by shallow open dug wells and occasionally by deeper, wells (termed ''tube wells''). The shallow open dug wells are usually manually pumped whereas the deeper tube wells use electric pumps and are typically managed by the NWSDB or by private agricultural enterprises.

[12] Although the configuration and the hydrologic properties of coastal sandy aquifers varies substantially, several broad generalizations can be made. The aquifers along the eastern coastline tend to be parallel to the coast and often have a brackish or saltwater lagoon just behind the beach ridge or rice paddy fields that extend inland from the coast. A limited freshwater lens, ranging in thickness up to more than 10 m [*Villholth et al.*, 2005] and varying seasonally, is maintained above the seawater wedge by the northeast monsoon (''maha'') rains. Approximately 75% of the 1,000–1,700 mm annual coastal rainfall along this coastline occurs from October to February. The thickness of the freshwater lenses varies seasonally, and may range from as much as 10 m to as little as tens of centimeters at the end of the dry season. *Panabokke* [2001] suggested that recharge may be as much as 50% of the net precipitation. Along the eastern coast, precipitation may be as low as 1000 mm yr^{-1}, and assuming a typical sand porosity of 30%, a preliminary estimate of the seasonal fluctuation of the water table is between 1.5 and 2 m. The thickness of the vadose zone is poorly documented, but the study team typically observed water table depths of 2–6 m at most field sites visited in February and September of 2005.

[13] Data on groundwater quality from coastal sand aquifers have been collected in a number of studies, which have shown that salinity (as measured by specific conductance) in the coastal sand aquifers can range from a minimum of 400 $\mu S\ cm^{-1}$ to as high as that of seawater [*Panabokke*, 2001]. However, most wells used for drinking water or agriculture do not exceed 2000 $\mu S\ cm^{-1}$. While there are no strict health-based drinking water quality standards for salinity, levels below 1000 $\mu S\ cm^{-1}$ are considered to be palatable, that is, not giving objectionable taste. Coastal aquifer wells have shown seasonal water quality variations, with an increase in salinity following the onset of the monsoon rains, believed to be the result of leaching of solutes from the vadose zone built up during the dry season. Increasing salinity is generally

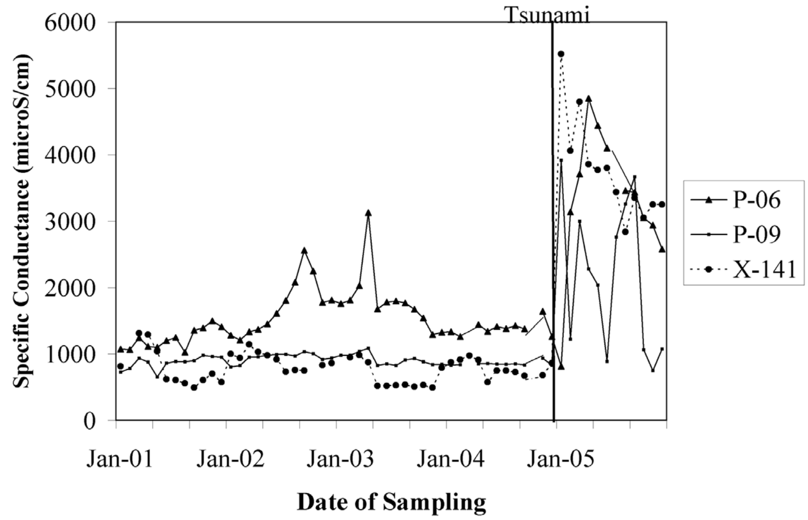

Figure 2. Specific conductance of groundwater from three tube wells in Kaggola, Sri Lanka. These wells were inundated to various degrees by the tsunami; however, it is not believed that significant volumes of seawater entered these wells directly during overtopping. All wells show a rapid rise in specific conductance following the tsunami and have not yet returned to background levels.

observed during the dry season and has been attributed to the evapotranspiration and possible upconing of the fresh/saline water interface caused by pumping during this period. *Panabokke* [2001] reported that nitrate concentrations often exceed the World Health Organization standards of 10 mg L^{-1} as nitrate-N and also showed a seasonal fluctuation, with maximum values occurring before or at the onset of rainy seasons. The likely sources of the elevated nitrate are domestic septic tank systems and fertilizer application.

3. Observations of Tsunami Effects on Groundwater

[14] Across much of Sri Lanka, the earthquake produced as many as four large tsunami waves [*Liu et al.*, 2005]. Where multiple direct waves hit the shore, the second wave was generally the largest and most devastating. Eyewitnesses reported the appearance of gas bubbles in wells long before the arrival of the tsunami; this may be related to the arrival of the earthquake-generated energy rather than the tsunami. The onshore extent and timing of inundation varied substantially depending upon shoreline geometry, bathymetry, and local topography. In some areas, flooding of low-lying areas behind the shoreline and raised beaches and associated back lagoons continued for extended periods. Over much of the area, however, inundation by the seawater did not last more than a few hours.

[15] Immediately after the tsunami waters retreated, efforts were initiated to clean and pump contaminated wells. Verbal reports indicated that at the time of first pumping (within hours or days), many flooded wells had already developed a sharp seawater/freshwater interface, with a stable seawater configuration, that is, at the bottom of the well. Salinity stratification in open dug wells was observed up to one month after the tsunami as indicated by increases of up to one order of magnitude in specific conductance from the water surface to the bottom of the well [*Villholth et al.*, 2005].

[16] Several monitoring programs have documented salinity changes in wells affected by the tsunami, although these programs began several months after the tsunami. Monitoring of flooded open dug wells between March and July 2005 at Kallady, Kaluthavalai and Oluvil on the eastern coast of Sri Lanka [*Villholth et al.*, 2005] showed large variability of impacts from the tsunami and the subsequent well cleaning. The data showed that changes in salinity over time were highly variable from well to well, with some wells actually showing an increase in salinity long after the tsunami. Several factors may be responsible for the observed variations including (1) the amount of seawater that initially entered the wells directly through the well opening, (2) the amount of seawater that infiltrated through the vadose zone, (3) the volume and frequency of water that was pumped from each well after the tsunami, (4) well interference and recontamination through the vadose zone due to pumping from closely spaced wells, and (5) variations in monsoon recharge. In this case, the mean distance between wells in the monitoring transects was approximately 100–150 m. In the study, flooded wells maintained a higher average salinity for seven months after the tsunami compared to salinity in nearby wells that were not flooded [*Villholth et al.*, 2005].

[17] While a large amount of seawater was injected through open dug wells, there is also strong evidence that substantial volumes of seawater infiltrated through the vadose zone. Figure 2 shows a 5 year salinity record from three high-capacity tube wells in the Koggala Free Trade Zone region (maintained by the Water Resources Board of Sri Lanka) on the southeastern coast of Sri Lanka. These wells were inundated by the tsunami, but it is believed that in most cases seawater either did not directly enter the well bores, or did so less rapidly than open wells that have less of a surface seal. Two of these wells still showed a rapid increase in salinity, with well P-06 showing a delayed response but eventually increased to high specific conductance values. The gradual increase may also be due to lateral migration of infiltrated seawater.

[18] Contamination of coastal aquifers has added a substantial burden to the relief and resettlement efforts in Sri

Lanka. In some cases, potable water is now supplied by tanker trucks to roadside tanks; in a few other cases, portable reverse osmosis units have been set up to produce fresh water from contaminated wells. Neither provides a sustainable system of water delivery, and an improved understanding of the mechanism of coastal aquifer contamination is clearly needed to assess and identify long-term solutions for drinking water. In the next section, we develop a conceptual model of the fate and transport of tsunami water in the permeable coastal aquifers common in Sri Lanka and other low-lying coastal areas for the evaluation of both well cleaning efforts and water resource planning.

4. Conceptual Model of Groundwater Impacts

[19] Seawater entered the coastal aquifers from three possible sources: (1) direct introduction through the opening of the dug wells, (2) infiltration through the vadose zone during inundation of seawater over the land, and (3) additional subsequent recharge of the groundwater by seawater from back lagoons and surface depressions. Of these three mechanisms, infiltration through the vadose zone is likely to have injected the largest volume of seawater into the coastal aquifers because of their highly permeable sands and large areal extent of inundation, while direct injection into the open dug wells had the most rapid impact on the aquifer and water supplies.

[20] The sudden surcharge of seawater into the open dug wells is analogous to an aquifer slug test, albeit with a slightly denser, but miscible fluid. The height of the surcharge was highly variable and depended on the initial depth to the water table and other factors; but given that flood levels were as high as the tops of coconut palm trees in many places, it is probable that most inundated wells were completely filled with seawater. Because of the density contrast and high permeability, it is likely that the excess head of seawater in the open dug wells dissipated through the aquifer rather quickly.

[21] The surcharge of hydraulic head from infiltration to the water table could have led initially to a forced convection regime. The saltwater infiltration would also have resulted in a density driven unstable situation in the aquifer in which seawater (density $\sim$1025 kg m^{-3}) overlies fresh water (density $\sim$1000 kg m^{-3}) suggesting a free convection system. The relative importance of forced and free convection can be assessed through a convective ratio, M, as defined by *Bear* [1972] and *Wood et al.* [2004]. When $M \ll 1$, forced convection dominates over free convection, while for $M \gg 1$, free convection is the dominant process. For a simple layered system, the convective ratio can be related to the head surcharge, Δh, the vertical length scale over which the excess head is to be dissipated, ΔL and the density excess, $\Delta\rho$, as

$$M = \frac{\Delta\rho/\rho}{\Delta h/\Delta L}. \tag{1}$$

The convective ratio parameters related to excess head would have varied considerably depending upon the flood height, vadose zone thickness and aquifer thickness, but a first-order approximation can be made at the time of inundation. Assuming a seawater surcharge equivalent to a typical coastal vadose zone ($\sim$2 m) on fresh water (ρ_{sea} = 1025 kg m^{-3}, $\Delta\rho$ = 25 kg m^{-3}) and an aquifer thickness of 10 m, the convective ratio from (1) immediately after the tsunami would have been $\sim$0.1, indicating that forced convection was likely the dominant mixing mechanism and that seawater initially migrated into the aquifer because of the fluid head gradients. As the surcharged head dissipated, that is, Δh decreasing, the convective ratio would increase and free convection of seawater in the aquifer could then dominate the mixing process.

[22] The Rayleigh criterion provides a preliminary assessment of the likelihood that this layer of seawater will remain superimposed on the freshwater lens where it would gradually mix by diffusion, or if it will undergo free convection. The onset of free convection depends on the critical Rayleigh number, which is dependent on fluid, media and solute properties as well as boundary and initial conditions. *Lapwood* [1948] theoretically showed using linear stability analysis that under the conditions of a linear density contrast due to temperature differences, convection will begin when the critical Rayleigh number, Ra_c exceeds $4\pi^2$ ($\sim$40), or

$$Ra_c = \frac{k\Delta\rho g H}{D\mu} > 4\pi^2, \tag{2}$$

where k is the intrinsic permeability, $\Delta\rho$ is the difference in densities of fresh water and seawater, g is the acceleration due to gravity, D is the effective diffusion coefficient of the solute (accounting for porosity and tortuosity) and μ is the fluid dynamic viscosity. In soils, the onset of convection can occur at Rayleigh numbers smaller than theoretical values obtained using linear stability methods [*Simmons et al.*, 2001] and as a result, we used the critical Rayleigh number here only as a qualitative criterion to evaluate if mixing of seawater and fresh water is probable.

[23] The length scale over which the density varies is unknown, but we assigned this length to be characteristic of the vadose zone thickness of a typical coastal sand aquifer ($\sim$2 m). Assuming a coastal sand aquifer permeability of 10^{-11} m^2 (or 10^{-4} m s^{-1}), fluid density contrast of 25 kg m^{-3}, an effective diffusion coefficient of 10^{-9} m^2 s^{-1}, and a viscosity of 10^{-3} kg ms^{-1}, the calculated Rayleigh number is approximately 5,000 which greatly exceeds the critical value of $\sim$40. *Simmons et al.* [2002] used sand tank experiments to show that mixing would take the form of fingers in the saturated zone, but would likely be a stable wetting front through the unsaturated zone.

[24] Our preliminary stability analysis suggests that infiltrated seawater would have been driven into the aquifer by the excess fluid head, and then quickly mixed and fingered through the shallow freshwater lens as free convection began to dominate. The mixing would lead to elevated salinity levels throughout the freshwater zone as a result of mixing; however, much of the salinity would be transferred to the top of the seawater wedge.

5. Physical Modeling of Post-tsunami Mixing

[25] Preliminary physical experiments were conducted to further investigate mixing of infiltrated seawater in an unconfined aquifer and also to gain a qualitative under-

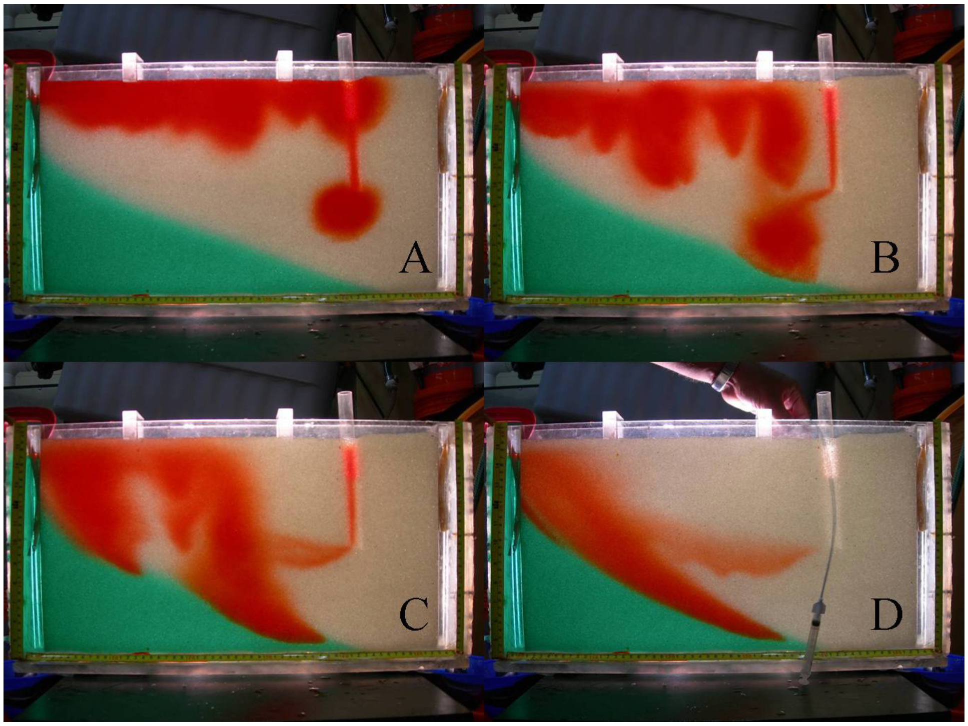

Figure 3. Physical model of tsunami injection and infiltration into a shallow coastal sandy aquifer at (a) 2, (b) 5, (c) 11, and (d) 19 min. The pre-tsunami seawater wedge is dyed green, and the pre-tsunami fresh water flowing from right to left is light brown. Infiltrated tsunami water, dyed red, is injected across the top of the aquifer. Tsunami water is also immediately injected into the aquifer through the open borehole. Dense seawater quickly develops into plumes that reach the preexisting seawater wedge.

standing of the fate of flooded open dug wells in this unique scenario resulting from a tsunami. Experiments were conducted in a rectangular flat tank constructed from Plexiglas™. The dimensions of the tank were 53 cm by 30 cm by 2.7 cm. The tank was filled with homogeneous glass beads to simulate a coastal aquifer system with an intrinsic permeability of 1.4×10^{-9} m^2, measured using a constant head permeameter. The permeability is approximately two orders of magnitude greater than those typically observed in clean beach sands, but this allowed us to complete a rapid visualization experiment. The flow tank was divided into three sections: a main flow cell filled with sand, and inflow and outflow reservoirs at both ends. The sand was fully saturated, thus there was no vadose zone present in the experiments. The reservoirs were separated from the main cell using a fine mesh screen. A 2-cm diameter impermeable glass tube, open at both ends, was inserted into the model to represent an open dug well. Seawater was prepared in 170 L drums by dissolving NaCl in deionized water. The average density of saltwater used in the experiment was 1025 kg m^{-3}. To avoid any variation in density or chemical composition, the same batch of water was used in a particular set of experiments to supply both seawater and tsunami water. A small amount of food coloring was used to differentiate sea, fresh and tsunami waters and to visualize their mixing patterns.

[26] The initial condition, representing the pre-tsunami scenario was simulated by setting up a regional hydraulic gradient across the length of the model that would force uncolored groundwater (identified here as "fresh water") to flow from right to left (see Figure 3a). The green-colored saltwater (identified as "seawater") was allowed to intrude the aquifer from the left to form a steady seawater wedge. The inundation caused by the tsunami wave was simulated by evenly discharging a fixed amount of red-colored saltwater (identified as "tsunami" water) at the top surface of the model and also directly into the open well. Tsunami waters invaded the unconfined aquifer model by infiltration (identified as "infiltrated tsunami water") from the top of the water table boundary. Tsunami water also entered the saturated region by injection from the open well. Fresh water continued to enter the model from the constant head boundary on the right.

[27] Figure 3 illustrates the transport patterns at 2, 5, 11 and 19 min 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 finger and contaminated the deeper aquifer (see Figure 3b). The infiltrated tsunami water eventually merged with seawater from the flooded well. An important observation from the experiments is that tsunami waters (both from surface infiltration and the flooded well) always remained above the regional seawater interface. This is expected as the density of both tsunami water sources decreased because of dilution as they migrated through the aquifer and mixed with fresh water. Hence the net density of tsunami water had decreased below that of seawater before reaching the seawater wedge. Therefore tsunami waters (both via infiltration and flooded wells) would likely not penetrate the regional seawater wedge, which has seawater density. Instead, tsunami water remained floating above the wedge and was eventually

advected by the regional freshwater flow along the wedge. This process would have occurred under natural aquifer conditions and perhaps is a factor in the slow recovery to pre-tsunami salinity levels observed in many wells.

[28] Another major observation was that water in the open well remained contaminated for a relatively long period. As shown in Figures 3a–3b, the bulk of the tsunami water injected into the well moved downward as a blob within about 5 min. 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 min, a clinical syringe was used to extract three storage volumes directly from the open well and this process removed the remnant saltwater from the well.

[29] These simulation results provided a conceptual framework for understanding the seawater transport processes from both surface infiltration and from direct injection into the wells. Although permeability and scales of the experimental tank are different from those in the field, it is possible to scale the results to approximate the transport times expected in the field. The velocity of the downward moving seawater plumes can be approximately scaled using the relationship developed by *Wooding et al.* [1997, equation (6)] that provides the travel distance/time relationship of a single dense plume to the Nusselt and Rayleigh numbers. Here we scale Wooding's equation (6) by the ratio of laboratory to field permeability values while keeping the numerically determined constant of proportionality of 0.615. The permeability of the tank material is approximately two orders of magnitude greater than that of typical beach sands of Sri Lanka, whereas the density contrast is similar to that found in the field. Figures 3a–3c show the dense fingers descended at a rate of about 2 cm min^{-1} before they reached the seawater interface. Scaling this velocity by the typical field permeability for coastal sand aquifers (about 10^{-11} m^2) and assuming a maximum fresh water lens thickness of 10 m, the scaled travel time through the fresh water lens is on the order of 10 days. It is important to note that at field scales, the plume may be substantially influenced by heterogeneity, but this simple analysis suggests that seawater could easily have traveled through a typical fresh water lens in timescales of only days to weeks. Although the experiments did not simulate the vadose zone, the time required for seawater to pass through the 1 to 3 m thick vadose zone would be on the order of hours for a permeability of 10^{-11} m^2 (or 10 m d^{-1}), which would not add significantly to the time of mixing. This preliminary analysis indicates that the seawater that entered the aquifer through infiltration probably reached the bottom of the freshwater lens rather quickly after the tsunami event.

[30] These simulation results also demonstrate the mixing processes that would have occurred in flooded open dug wells. Although the analyses presented here are simple and qualitative, but they provide insight into the basic processes that may have occurred during this unusual event. The behavior of the system under much more complex field conditions will require further study than presented in this work and will require more sophisticated physical modeling, field studies, and mathematical modeling. Areas needing further study include estimating: the amount of seawater infiltration at various locations, aquifer heterogeneity, well construction affects, and the effects of residual salinity in the unsaturated zone. The laboratory-scale model results, however, provide a preliminary understanding of the mechanisms of contamination and the probable timescales of aquifer contamination and corresponding remediation.

6. Discussion and Long-Term Outlook

[31] The short-term impacts of tsunami flood waves on coastal groundwater resources and supplies in much of Sri Lanka were severe. Thousands of open dug wells, a critical water supply source for coastal communities, were made unusable. Although salinity in some wells declined rapidly within a few months after the tsunami, some wells in these locations remain unfit for drinking because of residual salinity.

[32] The preliminary analysis and observations of this study support the conclusion that the 2004 tsunami produced a surcharged head and an unstable density contrast in the shallow coastal sandy aquifers leading to vertical mixing of salinity within the freshwater lenses. Since March 2005, salinity levels have only declined slowly, if at all, in many of the wells that continued to be pumped. In some wells, there is evidence that overpumping occurred, causing seawater to be drawn up from the interface and further contaminating the wells.

[33] Many of the coastal areas that were most affected by inundation did not receive substantial rainfall for almost a year, thus aquifer recharge had been very limited. Sri Lanka has received substantial monsoon rains during December of 2005, yet it remains to be seen how many monsoon seasons will be needed for aquifers to recover. The magnitude of the salinity reduction each year will depend on the rate of recharge, the accumulation of salinity in the vadose zone, the permeability of the aquifers, and the pumping intensity. If we assume an aquifer porosity, n, of 30%, complete mixing of the upper 2 m of a freshwater lens, an initial residual salinity, S_{pre}, of the freshwater lens of 2,600 μS cm^{-1} before the rainy season [*Villholth et al.*, 2005], and a recharge of 0.5 m yr^{-1} (or 500 mm yr^{-1}), the resulting salinity, S_{post}, of the 2 m lens after the monsoon recharge is

$$S_{post} = S_{pre} \frac{Ln}{(Ln + R)} = 1420 \ \mu\text{S cm}^{-1}, \qquad (3)$$

where L is the initial freshwater lens thickness and R is the recharge depth. This simple mixing approach ignores residual salinity in the vadose zone and is provided only as a hypothetical example; however, it may indicate that aquifers will recover to pretsunami levels (<1000 μS cm^{-1}) after a few rainy seasons. While this is a positive outlook, other factors must be considered by the Sri Lankan government and water authorities for long-term use of these aquifers for potable water. As seen in Figure 1, the density of pre-tsunami housing on many coastal aquifers was high and there exists no central wastewater collection in most areas. The combination of highly permeable sand, a shallow vadose zone, and dense developments makes these areas susceptible to groundwater contamination by nitrates and pathogenic organisms. Prior to the tsunami, coastal residents seemed well aware of this risk, and chlorination of open dug wells was a common practice.

[34] The long-term sustainability of the coastal aquifers for private drinking water will continue to be a major concern. Planning efforts are currently underway to construct piped water systems in many coastal villages rather than rebuilding the reliance upon individual, open dug wells. Centralized sewage collection may also expand, but it is unlikely to be practical across the whole country. Legislation to require minimum setbacks from the sea for housing and buffer zones near the coast have been proposed to reduce the hazards of inundation; but the challenges of finding appropriate land for resettlement for the thousands of people who rely on coastal proximity for their livelihood are enormous. Sri Lanka has no formal permitting system for the private use of groundwater; hence limiting the use of coastal aquifers will be difficult. Long-term sustainability of coastal aquifers is also impacted by the deterioration of beaches due to lack of sand replenishment due to mining in both coastal areas and in the upland rivers as well as coastal erosion. The 2004 tsunami has highlighted the vulnerability of these aquifers to contamination and the need for conjunctive use of surface water and groundwater for sustainable water resources. New modeling tools available for integrated management of surface and groundwater systems, geophysical technologies for characterization and GIS tools for data analysis and interpretation should be valuable in this task. Introduction of these tools need to be coordinated with capacity building for training of scientists and engineers who should be versatile in the application of these tools.

[35] As coastal populations continue to grow, devastating floods from sources other than tsunamis such as flood waves/storm surges, cyclones hurricanes/typhoons, and rising sea level will continue to impact coastal areas. While we, the hydrology community, cannot prevent such large-scale natural disasters, we can certainly participate in the development of emergency planning procedures that can considerably reduce the unnecessary human suffering. We should first take the necessary efforts to carefully document and study the hydrologic problems associated with these disasters. These results can and must be used to develop internationally recognized emergency guidelines for treating contaminated water supply sources (such as wells), and long-term planning tools for managing groundwater in coastal areas affected by seawater inundation.

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