Effect of well cleaning and pumping on groundwater quality of a tsunami-affected coastal aquifer in eastern Sri Lanka

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[1] Changes in water quality of a sand aquifer on the east coast of Sri Lanka due to the 26 December 2004 tsunami and subsequent remediation attempt by pumping were investigated. Two transects, disturbed (where pumping of groundwater took place) and undisturbed (where no pumping occurred), were monitored. In the undisturbed area, the average electrical conductivity (EC) in the wells affected by the tsunami showed a decrease from 3000 to 1200 μS/cm after the first full rainy season following the disaster; however, in the disturbed area the average EC stabilized around 1500 μS/cm. The observations were further analyzed by calculating hydrogeochemical mixing ratios, which showed that the seawater fraction was higher in the disturbed site than in the undisturbed site. The disturbance caused by physical cleaning by extensive pumping and subsequent disposal of the pumped water adjacent to the wells likely led to retention of salinity in the aquifer.

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1. Introduction

[2] On 26 December 2004, the earthquake off the southern coast of Sumatra in the Indian Ocean generated tsunami waves, resulting in devastation of the coastal regions of Sri Lanka. The majority of the population living in the coastal areas of Sri Lanka use shallow dug wells for their domestic water supply because the underlying sandy aquifers provide relatively reliable freshwater resources throughout the year. However, as a result of the tsunami waves, the coastal belt in most parts of the country was completely flooded, and the shallow groundwater aquifers were contaminated by salt water. Almost all the open dug wells in the affected areas, up to 1.5 km inland, were filled with seawater [*Illangasekare et al.*, 2006]. It was estimated that more than 50,000 water supply wells were affected by the tsunami in Sri Lanka [*U.N. Environment Programme*, 2005].

[3] The groundwater contamination by an event like a tsunami is considered to be an unstable variable density flow and solute transport problem on the basis of the location of the dense fluid. Both hydraulically driven forced convection and buoyancy-driven free convection are present in these systems, leading to contamination of larger regions of an aquifer due to mixed convection [*Oostrom et al.*, 1992].

[4] Rainwater is the only significant agent to flush and remove the salinity from the aquifers affected by the tsunami in the eastern coastal aquifers in Sri Lanka since there is no other means of freshwater recharge. The rainfall recharge considered to be high during the intense rainy season, when flooding often takes place since the groundwater table is shallow (0.5–3 m below the surface) [*Wickramaratne*, 2004]. The background dug well water quality in the eastern coastal belt showed very low concentrations of ions and drinking quality water [*Wickramaratne*, 2004], which indicates the rainwater chemistry since rainfall recharge is the only source of groundwater in the particular coastal belt. The shallow groundwater aquifers were affected by the tsunami in several ways [*Illangasekare et al.*, 2006]. In most affected areas, the open dug wells were instantly filled with the seawater, and large volumes of salt water were infiltrated into the freshwater lens through these dug wells. In addition, the seawater accumulated in the low-lying areas, resulting in long-term direct infiltration of saline water into the aquifers as well as the direct infiltration at the time of tsunami flooding. It was thought that the rainfall recharge might dilute the salt concentrations and might also push the dense saltwater plume down to the aquifer. In an attempt to speed up the process of rehabilitating the remaining contaminated water in wells, large-scale and intensive campaigns went into cleaning and rehabilitating wells through pumping out saline water (physical cleansing) and chlorination (chemical treatment) to diminish the risk of outbreaks of water-borne diseases [*Villholth et al.*, 2005]. However, it was unclear whether these attempts improved the well water quality, especially in terms of salinity. The hypotheses brought forward for this investigation are that (1) the rainy season would reduce the imprint of the tsunami because of fresh recharge diluting and pushing the salt plume downward and (2) pumping and cleaning of wells had a negative impact on the natural rainwater and cleaning of the aquifers because of mixing recirculation of saline

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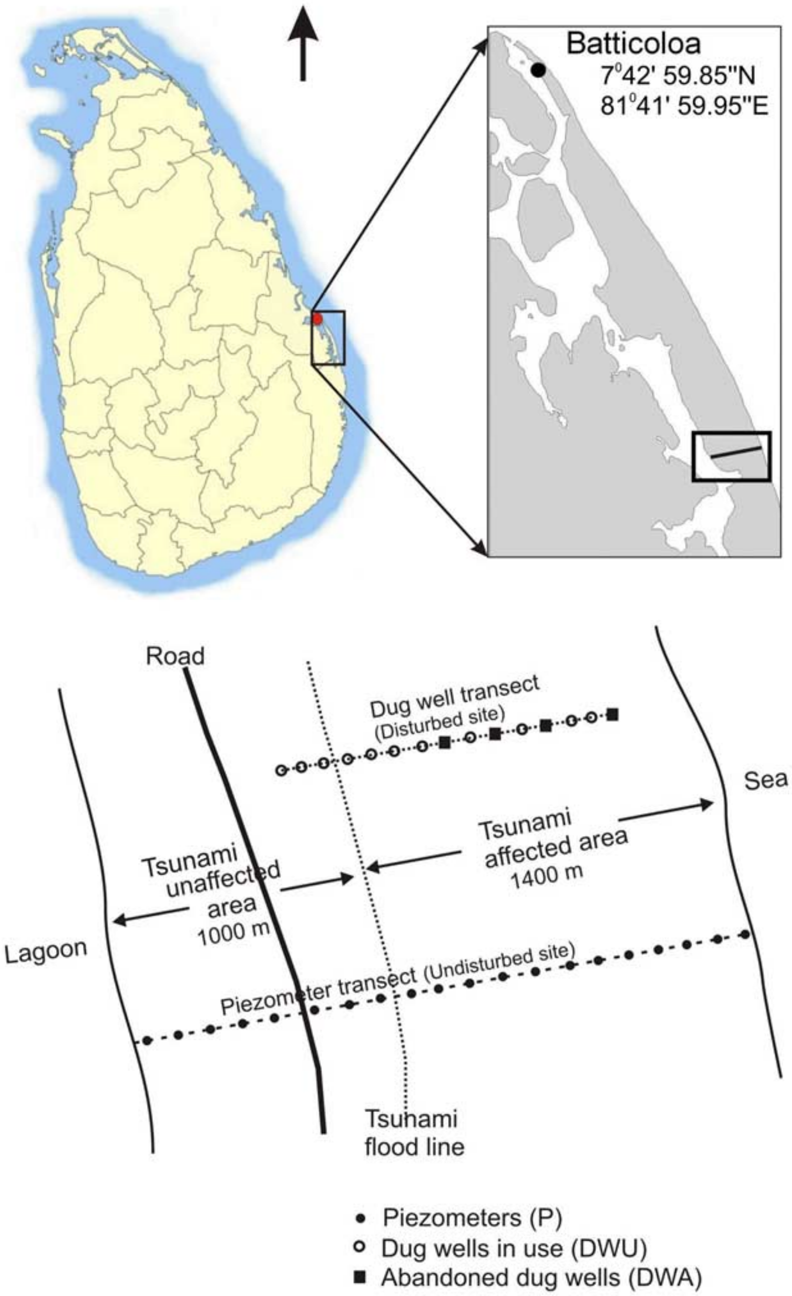

Figure 1. Sketch map of the two transects of wells used for water quality monitoring. The piezometer transect (undisturbed site) demarcated by the sea in the east and a lagoon in the west and the village area is considered as the disturbed site.

water between the wells and the land surface. The idea behind this assessment was to determine the percentage of seawater still present in the different aquifer conditions and its evolution since the tsunami.

2. Study Area

[5] The present study was carried out in and just outside a tsunami-affected village, Kirankulam, located in the Batticaloa district of eastern Sri Lanka (Figure 1). The east coast is dominated by elongated, north-south oriented coastal lagoons with land areas bordered by saline ocean water to the east and brackish lagoon water to the west. The land use comprises built-up areas with individual houses and areas with home gardens and extensively cultivated and abandoned land with natural vegetation.

[6] Two transects were selected on a 2 km wide land strip between the sea and the lagoon, located in the Kirankulam village of the Batticaloa district (Figure 1). We assumed that the two transects have similar hydrogeological characteristics because they are only 500 m apart. Lithostratigraphy

was identified from sand samples collected from boreholes at the undisturbed site and was found be similar to a location (Kattankudy) 15 km north of the undisturbed site [*Wickramaratne*, 2004]. Alternative layers of medium sand and find sand with silt were found in both sites, although the depths of layers showed a difference. The bedrock is found at 15–25 m depth at the site investigated by *Wickramaratne* [2004]. Both transects were exposed to natural rainfall conditions, with the major difference being that no groundwater pumping took place at one of the sites (referred to as the undisturbed site), and posttsunami well pumping occurred at the other site (referred to as the disturbed site). The undisturbed site consists of 20 piezometers and no dug wells.

[7] The disturbed site is a semiurban area covered by a cluster of small one-story houses with relatively few paved areas and numerous dug wells for water supply. This site contains 57 dug wells within an area of 0.25 km^2 used by 113 families. Fifty wells at the disturbed site were affected by the tsunami, and the tsunami inundation distance (affected area) is demarcated in Figure 1. These wells are used in many of the coastal areas as individual or community wells for getting potable water. They are designed to tap the shallow fresh groundwater in the coastal aquifers. Sri Lankan coastal villages are densely populated, and the well density is approximately 90–125 km^2 [*Illangasekare et al.*, 2006]. These wells are built by concrete cylinders in open excavations which have open ends; the water rises from the bottom of the cylinder with no sealing of the outside annular space and no openings inside the well. Small domestic water pumps and/or buckets are used for water withdrawal. Some of these affected dug wells were cleaned after the tsunami, and others were abandoned. Most of these wells were used for household purposes. Only 15 wells were selected along a transect from the 57 wells in the village area. The average pumping rate of an active dug well is approximately 0.05 m^3/d. Only a few wells are used for agricultural pumping, and their extraction rate is approximately 0.1 m^3/d. However, pumping could vary for several reasons such as the family size and the season of the year. Given the presence of sandy soils and the small pumpage in the domestic wells, the drawdown is small, and the cone of depression does not influence the neighboring wells. After the tsunami, various organizations attempted to clean the domestic wells by frequent intensive pumping (physical cleansing), which often increased the pumping rate to approximately 50 times higher than the average intermittent daily pumping. Intensive and repeated well cleaning by chlorination (cleaning by chemical treatment) was carried out since shortly after the tsunami. The cleansing of these wells occurred approximately once a week. The most prevalent cleaning procedure was physical cleaning, which simply entailed discharging the purged well water next to the well. The total pumping at once is approximately about one well volume ($\sim$5 m^3); however, no ponding on the ground was observed, indicating a high infiltration rate leading to aggravated mixing. This process could have recycled the contaminated water and increased the overall mixing, thereby retarding the downward and lateral movement of the tsunami pulse.

[8] The initial condition of the two sites at the time of the tsunami was different. At the disturbed site, the infiltration of salt water took place both by direct infiltration at the ground surface and by infiltration of water that filled the dug wells. The undisturbed site had only direct infiltration. Therefore, it is possible that the disturbed site had higher contamination of salt water than the undisturbed site at the initial stage. If the difference of initial saltwater infiltration caused any dissimilarity between the two sites in water quality, then the behavior of the chemical species in abandoned wells and dug wells in use should be similar because the initial conditions in both abandoned and dug wells in use were the same.

[9] The study site is located in the dry zone of Sri Lanka, which receives an average annual rainfall of 1200–1900 mm. However, this rain falls in only a few months of the year from late October to the end of February, when the rainfall is intense, and often floods inland where, normally, the highest rainfall is recorded in November and December. The first full rainy season after the tsunami is considered to be the northeast monsoon rain which occurred between October 2005 and February 2006. The tsunami took place in the middle of the rainy season in 2004–2005. The rainfall in the year 2004–2005 was less compared to average annual rainfall, and therefore, the year 2005 can be considered as a dry year (1379 mm/a in 2005 where the average rainfall is 1600 mm/a). The monitoring started in October 2005 just before the first heavy monsoon rain after the tsunami event.

3. Materials and Methods

3.1. Piezometers

[10] Twenty piezometers were installed at the undisturbed site in October 2005 along the 2.4 km transect (Figure 1), termed ‘‘undisturbed transect’’. All these piezometers were installed prior to the onset of the northeast monsoon when the water table was at the annual lowest. The average depth of the piezometers was 3.5 m, and depths ranged from 1.8 to 4.5 m below ground surface, depending on the level of the groundwater table during installation. The depths of piezometers were similar to the depths of local dug wells, and the screens were installed 1.5 m below the water table at the time of installation so that the screen would not go dry. The piezometers were made of standard PVC tubes with an inner diameter of 3.7 cm and were equipped with a 15 cm slotted screen and an end cap at the bottom. The screen was covered by a 1 mm mesh to protect the piezometer from siltation. There were no piezometers installed in the disturbed site, and the term ‘‘piezometer’’ in the text hereafter will always refer to the undisturbed site.

3.2. Dug Wells

[11] Fifteen existing open dug wells from the village (at the disturbed site) were selected along a transect (termed ‘‘disturbed transect’’) parallel to the undisturbed transect for the detailed sampling of water quality (Figure 1). Of these, four wells were wells that had been abandoned. Twelve dug wells and piezometers at each site were located within the affected area of the tsunami. The wells selected at the disturbed site had an average diameter of 1.3 m and an average depth of 3.2 m. The word ‘‘wells’’ (dug wells in use or abandoned wells) will refer to the disturbed site in the text.

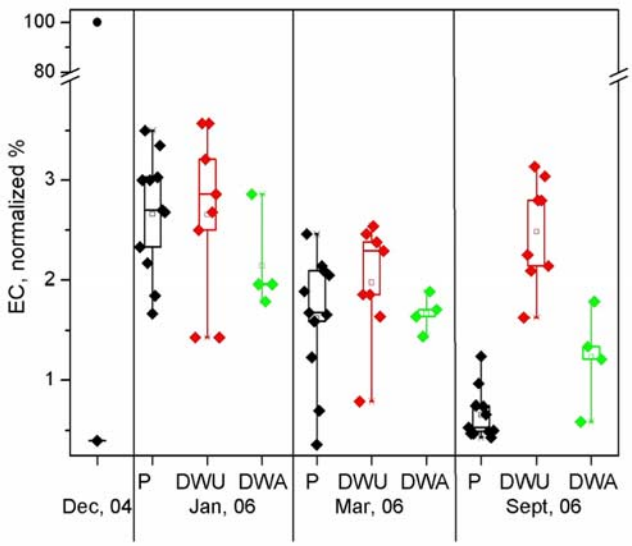

Figure 2. Box and whisker plot of normalized EC data in the affected wells of the undisturbed site for March, May, and September 2006. Affected wells of the undisturbed site, dug wells in use, and abandoned wells in the disturbed site are denoted as P, DWU, and DWA, respectively. The lower point corresponding to December 2004 shows the normalized value of fresh water, while the upper point corresponds to the value for seawater.

3.3. Chemical Analysis

[12] Electrical conductivity (EC) was measured in the field both in dug wells and in piezometers by dipping a Hanna handheld EC meter into an extracted water sample. Three well volumes were pumped out from the piezometers before extracting a small water sample. However, dug wells were not purged prior to sampling because of their large volume, and equilibrium with the surrounding aquifer water quality had to be assumed. One round of measurements was taken during each of the months of October 2005 and January, March, May, June, September, and October 2006 for EC. Only 15 wells at the village were monitored for EC; however, results given in this paper for the dug wells are only from the 12 affected wells along the disturbed transect. These wells were sampled for water quality analysis. Since chemical analysis was limited because of lack of resources, only 15 wells (out of 57) and 20 piezometers were subjected to monitoring of EC.

[13] It was not possible to measure chloride in the solution because of lack of access to chloride analysis. Therefore, we could not use it as the tracer to quantify the mixing or refreshing. However, we found that it was possible to use EC as ‘‘conservative tracers’’ in this particular study on the basis of a few assumptions. Mixing fractions of EC were calculated for all affected wells assuming that mixing and dilution between fresh groundwater and seawater are the dominant processes in the aquifer. Our justification for considering EC as a conservative tracer for this study is that chemical analysis results show that measured ions behave in a similar manner as EC, which is mainly sensitive to the chloride concentration of the solution, especially when considering seawater contamination.

4. Results and Discussion

4.1. Electrical Conductivity

[14] The pattern of EC showed a decrease in concentration with time, which was most pronounced at the undisturbed site (factor of ~5 from January to September 2006), while the concentrations at the disturbed site, even after one and a half years, were elevated compared to those at the undisturbed site (Figure 3). The EC values at the disturbed site were in the range of 250–1500 μS/cm. The EC values of the dug wells in use were higher and have a range of about 1000–1500 μS/cm, while the abandoned dug wells were much lower, with values in the range of 750–1000 μS/cm. The temporal behavior of the EC in the abandoned wells and the piezometers was similar.

[15] The piezometers and wells at the sites eventually will return to the same pretsunami water quality conditions, and the same pretsunami water quality characteristics then will appear to all locations on the basis of the observations made during monitoring. Figure 2 shows the normalized percentages of EC to seawater. However, the fact that the abandoned dug wells at the disturbed site showed behavior similar to the piezometers at the undisturbed site (Figure 2) and yet different from the dug wells in use suggests that the pumping of the dug wells after the tsunami had an effect on water quality recovery in those wells. This observation supports the hypothesis that the tsunami imprint seen in the wells that are in use could be due to the extensive physical cleaning activities taking place after the flooding event. However, chemical treatment, chlorination, was beneficial for microbe control in the dug wells.

[16] As observed by *Andersen et al.* [2005], the saltwater migration after a storm flooding event is normally fast. Intensive physical well cleaning and disposal of water in the vicinity of wells may have enhanced mixing, disturbing and delaying the natural recession of the tsunami effect at the disturbed site. At the undisturbed site, natural flow processes, rainfall recharge, took place, encompassing rapid sinking of the denser concentrated salt water immediately after the tsunami [*Illangasekare et al.*, 2006], and hence, the tsunami effect, after about one and half years, was lower and became more uniform across the undisturbed transect compared to the disturbed transect.

4.2. Mixing of Solution Fractions

[17] Mixing fractions of EC were calculated for all affected wells and piezometers assuming that mixing and dilution between the two end-member solutions, fresh groundwater and seawater, was the dominant processes in the aquifer. Further, a linear relationship was assumed between seawater (EC 56 mS/cm) and fresh water (EC 0.3 mS/cm). Hereby, the percentage of seawater still present in the aquifer and its evolution since the tsunami were computed by normalizing the prevailing concentrations of EC to the seawater concentrations. Figures 2 and 3 show the normalized percentage of EC levels during 26 December 2004, which is 100% (Figure 2), and the concentrations in fresh water, which is 0.5%, and mixing fraction of seawater to freshwater (Figure 3).

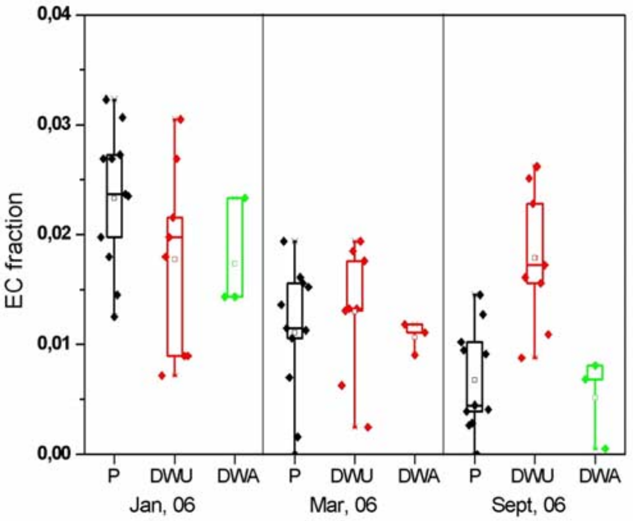

Figure 3. Box and whisker plot of calculated mixing fractions of seawater and freshwater based on EC for the individual affected wells from the months of January, March, and September 2006. Affected wells of the undisturbed site, dug wells in use, and abandoned wells in the disturbed site are denoted as P, DWU, and DWA, respectively.

[18] All the calculated mixing fractions based on EC content for the individual affected wells from the months of January 2006, March 2006, and September 2006 were plotted as a box and whisker plot (Figure 3). In Figure 3, an estimate of mixing fraction (seawater relative to fresh water) is used by assuming a linear relationship of the fraction with EC. Since the EC in fresh water is very low compared to seawater, the values showed a similarity to the normalized concentrations in Figure 2. However, in Figure 3 it is clearly seen that the seawater fraction in the disturbed wells is much higher than that of piezometers and abandoned wells. The box plot of the results from the undisturbed site from September 2006 has a median mixing fraction of 2.4×10^{-2}, which showed a decrease from 1.4×10^{-2} in January 2006. The range in mixing fraction is more uniform over the undisturbed site as compared to the disturbed site. The median value of the mixing fraction of the disturbed site with dug wells in use is 1.75×10^{-2} in September 2006, which is about 3 times that of the undisturbed site. Furthermore, the variance in the data at the disturbed site is greater than in the data from the undisturbed site, suggesting that mixing is higher at the disturbed site compared to the undisturbed site. The higher mixing fraction indicates a higher persistence of the tsunami impact and can be due to the higher usage of these dug wells, in terms of pumping, and the well cleaning in the area. At the undisturbed site, the saltwater plume movement in the subsurface will be affected by less mixing than at the disturbed site, which thus indicates a smaller variance across the transect.

5. Conclusion

[19] The rain falling during the first full rainy season after the tsunami significantly improved water quality in the undisturbed area, while improvement was less and slower in the dug wells at the disturbed site. Measured values of electrical conductivity at the disturbed site were slightly higher and maintained higher spatial variability than at the undisturbed site during the period of October 2005 to October 2006. EC observations support the hypothesis that the well cleaning, with discharge and reinfiltration of the pumped water near the wells, and abstraction of water for general purposes disturbed the natural downward movement of salt water and the recession of the tsunami impacts. As a result, the imprint of the tsunami was prolonged in the disturbed site compared to the undisturbed site. The results show that the intensive pumping methods used for well cleaning did not have the intended effect of speeding up the fresh water restoration and might instead have prolonged the salt water problem while the chlorination was beneficial for controlling the growth of microbes for water-borne diseases. These findings may have more general applicability, for example, to saltwater flooding caused by typhoons and hurricanes. Hence, rehabilitating well water quality after such events in similar settings is probably most appropriately addressed by not introducing disturbances in terms of pumping and recycling of water.

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