

EFFECT OF THE INDIAN OCEAN TSUNAMI ON GROUNDWATER QUALITY IN COASTAL AQUIFERS IN EASTERN SRI LANKA

METHTHIKA VITHANAGE^{1,2},
KAREN G. VILLHOLTH³,
KUSHANI MAHATANTILA⁴,
PETER ENGESGAARD¹ AND
KARSTEN H. JENSEN¹

¹*Department of Geography and Geology, University of Copenhagen, Denmark,*

²*International Water Management Institute, Battaramulla, Sri Lanka,*

³*Geological Survey of Denmark and Greenland, Copenhagen, Denmark*

⁴*Department of Material Science, Interdisciplinary Faculty of Science and Engineering, Shimane University, Matsue, Japan,*

meththikavithanage@gmail.com
Tele: +94 112 833 101

ABSTRACT

Changes in water quality of a sand aquifer on the east coast of Sri Lanka due to the December 26, 2004 tsunami and subsequent disturbance due to well pumping and flushing by precipitation were investigated. Two closely spaced tsunami affected transects, spanning the ocean and an interior lagoon across a 2 km wide land strip were monitored from October, 2005 to September, 2006. Water samples were collected from 15 dug wells and 20 piezometers, from the disturbed and undisturbed sites respectively to evaluate the temporal and spatial trends in water quality.

The EC values observed from the undisturbed area showed a significant decrease (3000 to 1200 $\mu\text{S}/\text{cm}$) with the rain from November 2005 to March 2006, while the values in the disturbed area appeared to have stabilized without further decline through the same period. The concentration range of EC, Ca, K, Na, alkalinity, total hardness and sulphate were higher in the disturbed site than in the undisturbed site. PHREEQC modeling showed that the mixed sea water fraction is higher in the disturbed site than in the undisturbed site, and this is likely due to the movement of the disturbed plume by water extraction through pumping and extensive well cleaning after the tsunami, causing forced diffusion and dispersion. No arsenic contamination was observed as all observed arsenic concentrations were below 10 $\mu\text{g}/\text{L}$. For the sites investigated, there are clear indications of only a slow recovery of the aquifer with time in response to the onset of the monsoon.

Key words: Tsunami, water quality, groundwater, coastal aquifers, geochemical modelling, Sri Lanka

INTRODUCTION

On December 26th 2004, tsunami waves devastated the coastal region of Sri Lanka. Coastal belt of Sri Lanka comprises of shallow coastal sandy aquifers, which provides reliable water resources throughout the year. The severely affected east coast of Sri Lanka consists of regosols overlying directly unconfined sandy aquifers ranging from fine to moderately coarse structure-less sands (Panabokke and Perera, 2004). These shallow groundwater aquifers are very susceptible to contamination. When a dense fluid is situated above the less dense fluid it comprises of an unstable density configuration and is referred to as an unstable-interface problem. Previous studies (Schincariol and Schwartz, 1990; Koch and Zhang, 1992; Oostrom et al., 1992; Simmons et al., 2001) have revealed that when density differences are significant, solute transport is a result not only of forced (hydraulically driven) advection and dispersion or diffusion, but also of free convection (buoyancy driven) resulting in gravitational instabilities. Therefore they have the potential to contaminate larger regions of an aquifer and can mix naturally with the ambient water to a larger degree due to mixed convection (Oostrom et al., 1992). The anthropogenic processes that aggravate mixing (such as water abstraction) could result longer aquifer cleansing time compared to the contamination by natural mixing.

People use shallow open dug wells for their domestic water supply as the surrounding sandy aquifer. However, as a result of the tsunami the coastal belt was completely flooded and the shallow groundwater aquifer was contaminated by saltwater. Open dug wells in the affected areas up to 1.5 km inland were filled with seawater (Villholth et al., 2006a, 2006b). It has been estimated that more than 50,000 water supply wells were affected in Sri Lanka by the tsunami (UNEP, 2005). The diffuse contamination of ground water and the point source contamination of wells along the affected coastal zone were aggravated by the influx of wastes from septic materials, pit latrines, chemical spills, dead bodies and surface debris. The waste and debris directly contaminated the wells or accumulated in the surface depressions and infiltrated into to the aquifer for several days following the event. This study investigates the change in water quality of the highly vulnerable local sand aquifers due to tsunami and its “natural cleaning” response by precipitation over time and the effect of well cleaning and pumping water for domestic uses.

Study area

Location

The present study was carried out in a tsunami affected village located in the Batticaloa District of eastern Sri Lanka (Fig. 1). The east coast is prevalent with elongated, north-south oriented coastal lagoons with land stretches bordered by saline ocean water and brackish lagoon water on both sides. Hydrogeologically, these land stretches act as oceanic islands and local, productive aquifers which are created as freshwater lenses floating on the underlying denser saline water (Underwood et al., 1992). The study area extends as an east west oriented narrow strip of land about two kilometers wide. The ground surface is almost flat and the elevation in the middle part between the sea and the lagoon is about 3 to 4 meters above mean sea level (msl). Freshwater at the site originates entirely from local excess precipitation and the available quantity is thus limited.

Exploitation of the freshwater poses a risk of contamination by sea water due to over extraction and hence the fresh water lens needs to be used in a sustainable manner as there are limited reliable freshwater sources inland to supplement water for the coastal zone.

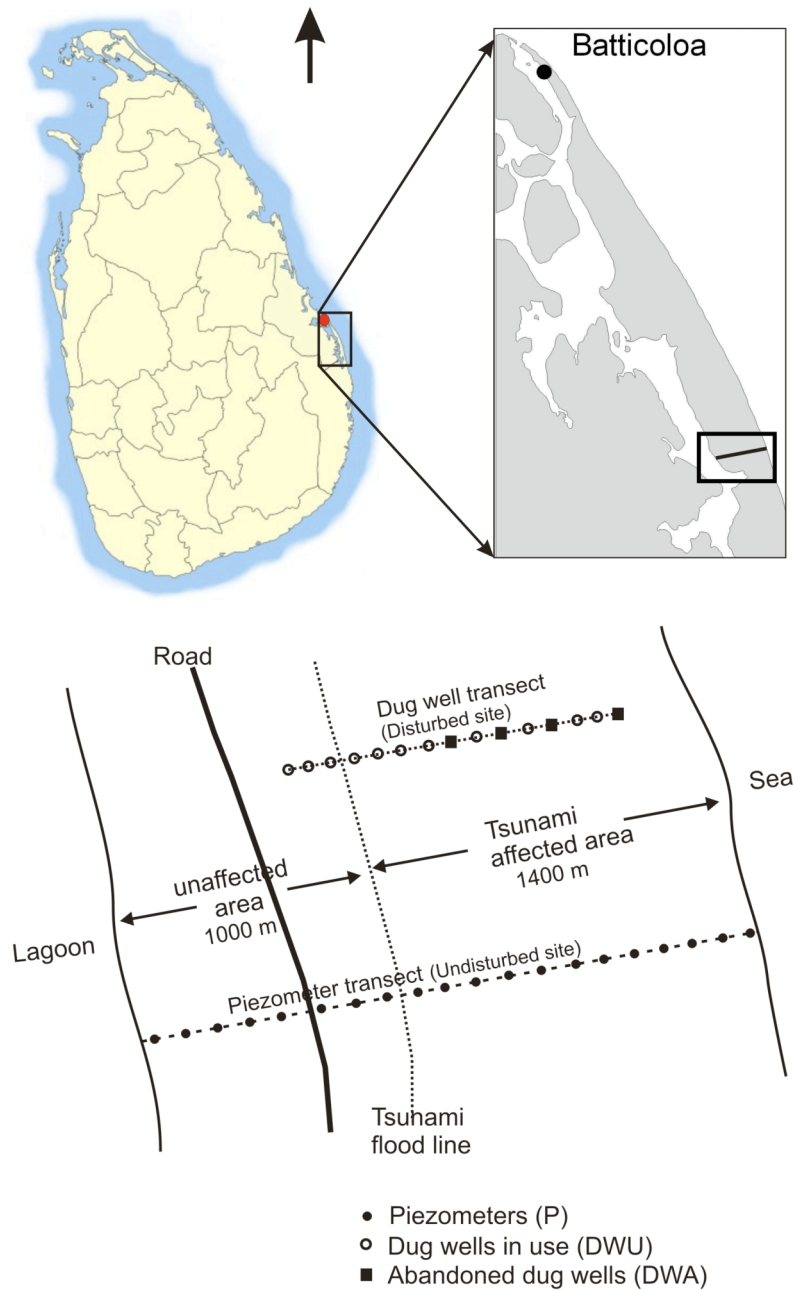


Fig. 1. Location map of the study area. Piezometer transect (undisturbed site) is in 2 km demarcated by the sea ($7^{\circ} 36' 24''$ N and $81^{\circ} 47' 01''$) in the east and Lagoon ($7^{\circ} 35' 59''$ N and $81^{\circ} 45' 50''$) in the west. The village considered as the disturbed site.

Science of Tsunami Hazards, Vol. 28, No. 3, page 220 (2009)

Two transects are located in the Kirankulum village of the Batticaloa District. The two sites have similar characteristics with the major difference being that one of them is only exposed to natural rainfall conditions and no pumping activities present (hereafter referred to as the undisturbed site) while the other site is subject to well pumping (referred to as the disturbed site). The undisturbed site consists of thorny shrubs and cashew plantation, while the adjacent village, which consists of a cluster of small one-story houses and relatively little paved areas with numerous dug wells for water supply, is considered as the disturbed site.

Twenty piezometers were installed along a transect perpendicular to the coast and across the entire land strip in the undisturbed site. Fifteen existing open dug wells from the village along a second transect, covering a smaller section of the land strip, were selected for the detailed study (Fig. 1). The two transects are 0.5 km apart. The disturbed site consists of a total of 57 dug wells within an area of 0.25 km² used by 113 families. Fifty wells in this area were affected by the tsunami. Most of these wells are used for household purposes. In both sites, the tsunami run-up was around 1 km from the coast line. In the village transect, only two dug wells were in the tsunami non-affected area, while the undisturbed transect consists of 12 piezometers in the affected area and 8 piezometers in the non-affected area.

Climate

The study area belongs to the dry zone of Sri Lanka with an annual rainfall of 1200 to 1900 mm. Eighty percent of the annual rainfall falls intensively during the north-east monsoon period from November to February and during the inter monsoon period from March to April (Panabokke et al., 2002). As the ambient temperature is high year round (30 – 35 °C) evaporation is estimated to be high, around 30 – 50 % of the precipitation (Panabokke, 2001).

Geology and hydrogeology of the study area

In Sri Lanka, Miocene limestone are found along the northern and North West coast and throughout the Jaffna Peninsula, while on the southeast, south and southwest coast, rocky headlands are prevalent. The geology around the study area is dominated by Quaternary unconsolidated beach deposits on the top of Precambrian metamorphic rocks Cooray (1985).

The two areas are assumed and expected to be similar in the lithological settings. The lithology of a field site about 15 km north of the study area was reported by Wickremaratne (2004), first, a medium to coarse sand layer of approximately 9 m depth with a small fraction of clay and shell fragments is found.

A clay and silty clay layer of about 5-10 m in thickness is found below the sand layer, which is then followed by a thin coarse sand layer of about 2 m in thickness. The thickness of the sandy formations increases towards sea whereas the thickness of the clayey layers increases towards the lagoon. It was reported that the bed rock is found around 15-25 m deep which is corroborated by transient electromagnetic soundings carried out by Hoareau et al., (2006) in the particular study area.

Pre-tsunami hydrogeochemistry

Few studies have been carried out to investigate the pre-tsunami water quality in the shallow ground water aquifers in eastern Sri Lanka (Mahendran et al., 2000; Vaheesar, 2002; Panabokke et al., 2002; Jeyakumar et al., 2002; Sugirtharan et al., 2004; Wickramaratne, 2004). Some of the recorded EC levels were relatively high in the pre-tsunami studies. According to Panabokke et al., (2002) only in two agro wells out of 25 from the Trincomalee District (located north of the study area) had low EC values (<500 $\mu\text{S}/\text{cm}$) and most were above 1000 $\mu\text{S}/\text{cm}$ while some were as high as 2500 $\mu\text{S}/\text{cm}$). However, as agro wells have become larger in size and pumped more heavily to supply water for irrigation, they may not be considered as representative of the domestic wells. As a consequence, agro wells have shown consistently higher salinity levels than domestic dug wells (Vaheesar et al., 2000; Jeyakumar et al., 2002). In the study by Wickramaratne (2004), EC levels below 700 $\mu\text{S}/\text{cm}$ were reported for shallow tube wells. Calcium and magnesium concentrations of well water have been recorded between 250 – 1450 mg/L and 30 – 250 mg/L respectively (Mahendran et al., 2000). Nitrate concentration in most areas in the Batticaloa District are above the WHO standard limit (45 mg/L).

Post tsunami water quality

The shallow groundwater aquifers were affected in several ways by the tsunami: direct infiltration from tsunami inundation, infiltration from pooled sea water left behind, permeation from flooded wells, and salinization from flooding of lagoons and river mouths (Villholth et al., 2006a). A few studies have documented the impact on the water quality in wells mainly in terms of electrical conductivity (EC), total dissolved solids (TDS) and salinity (Villholth et al., 2006a; Illangasekare et al., 2006). Water quality measurements carried out by Villholth et al., (2006b) have documented a significant difference between the tsunami affected and non-affected well water. Interestingly, Pilapitiya et al., (2005), have reported on elevated arsenic contamination due to tsunami in Sri Lanka

MATERIALS AND METHODS

Twenty piezometers were installed along a 2 km transect with 500 m mutual distance in the undisturbed site. All these piezometers were installed just prior to the onset of the north east monsoon when the water table was the lowest. The depth of piezometers varied along the transect according to the level of the water table and they were installed 1.5 m below the water table to avoid the possibility of being dry. The piezometers were made of standard pvc tubes with an inner diameter of 3.7 cm and equipped with a 15 cm slotted screen at the bottom and with an end cap, which was covered by a 1 mm mesh to protect the piezometer from siltation. They were installed in 8.7 cm diameter boreholes constructed by slug boring method at the proper level and securely sealed. Fifteen existing open dug wells along a transect were selected from the village (disturbed site) for detailed monitoring of water quality (Fig. 1). The wells had an average diameter of 1.3 m and an average depth of 3.2 m. Rainfall at the site was recorded daily at 08:00 using a standard rain gauge provided by the Meteorological Department of Sri Lanka.

Chemical Analysis

EC was measured in the field in both dug wells and piezometers using a Hanna hand held EC meter, during the months of October, 2005, January, March, June and October, 2006. All 57 wells in the village were monitored for EC, however, results given in this paper for the dug wells are all from the 15 wells along the transect.

In January, March and October 2006, duplicate well water samples were collected for chemical analysis. One sample of water was acidified to measure the metal ions and the other was frozen. Nitrates, phosphates and sulphates were measured using a HACH 2400 UV-VIS Spectrophotometer and the inorganic ions, Ca, Mg, Na, K, Fe and Mn were measured using an Atomic Absorption Spectrophotometer (Perking Elmer, 2300).

In-situ arsenic analysis was carried out using the Arsenic measuring field kit (VISUAL ARSENIC DETECTION KIT WAG-WE 10600). In this case only water in open dug wells, which may have been filled with oceanic sediments by the tsunami were analyzed.

Geochemical Modeling

The water quality data sets obtained from all the sites were analyzed using the geochemical model, PHREEQC (Parkhurst and Appelo, 1999), The PHREEQC code simulates chemical reactions and transport processes in water using observed field data. The model has an inverse modeling capability, which attempts to find sets of mineral and gas mole transfers that account for differences in composition between waters while accounting for specified uncertainties (Parkhurst and Appelo, 1999).

Our intention was to use inverse modeling to back calculate and reproduce the data obtained from the water quality analysis, and determine the composition of the water samples. In inverse modeling, one aqueous solution is assumed to be mixed with the other aqueous solutions to react with mineral and gas phases to produce the observed composition of the tertiary solution and all the mixing fractions and mole transfers of the phases are calculated (Parkhurst and Appelo, 1999). Assumed here are three water analyses, sea water (from the PHREEQC data base), fresh water (from none affected dug wells) and water in the affected area (water quality observations) subject to mixing and ending with a certain water composition along the flow path.

The numerical method of inverse modeling of PHREEQC is based on the mole balance equations, which are included for (a) each element, (b) alkalinity, (c) electrons, (d) water and (e) each isotope. Furthermore, it includes inequalities to constrain the uncertainty (Parkhurst and Appelo, 1999).

The uncertainty represents potential analytical error and spatial or temporal variability in concentration of each component in each aqueous solution and in mineral compositions. Uncertainty in the aqueous species in the models was set in between 0.1-0.2 to make the model converge with reasonable results. To consider uncertainties in mineral compositions, three mineral phases (calcite, dolomite and anhydrite) and one gas phase (CO₂) were added to the models.

RESULTS AND DISCUSSION

Precipitation

The precipitation data recorded at the field site is show (Vithanage et al., 2009) that the rainfall due to the onset of the north-east monsoon period in October with the highest rainfall in November. Nearly 90% of total annual rainfall precipitates during the north-east monsoon period from November to February.

Electrical Conductivity (EC)

The tsunami impact on chemical groundwater characteristics was significantly manifested in the salinity levels. Because there were very few records of pre-tsunami EC levels and chemical parameters of shallow ground water (Mahendran et al., 2000; Vaheesar, 2002; Wickaramaratne, 2004) the data from the present study of the areas not flooded by the tsunami, basically the 8 and 2 most inland wells for the undisturbed and disturbed site, respectively (Fig. 2), were considered representative of the original water quality of the local aquifer system. The original EC levels of the Kirankulum study area, except for the well closest to the lagoon, which could have been affected by the tsunami by the seawater flooding directly into the lagoon mouths (Villholth et al., 2006b), were relatively lower than the data from previous reports, generally $< 300 \mu\text{S}/\text{cm}$.

It is noted that the EC levels showed more spatial variability across the transect in the disturbed site than in the undisturbed site (Fig. 2).

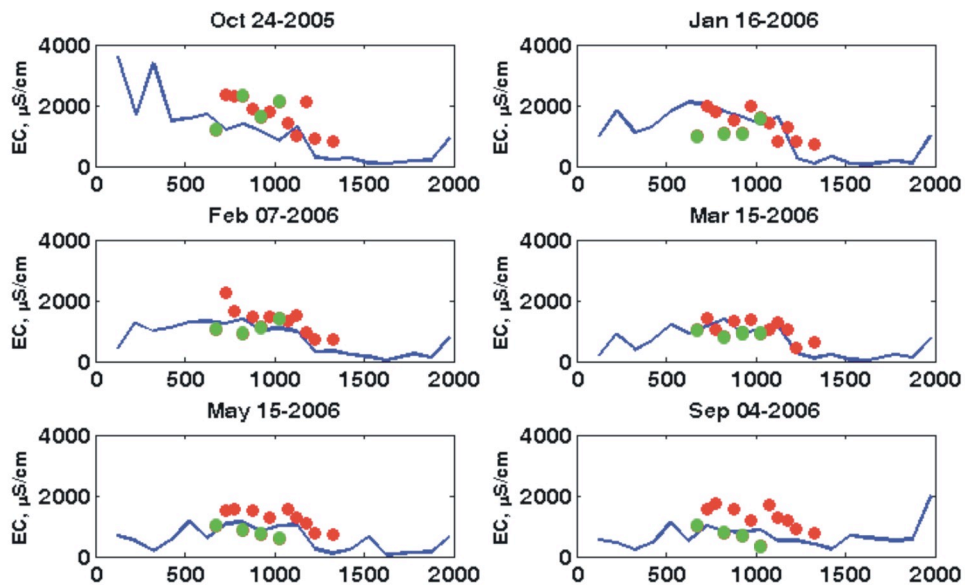


Fig. 2. Change in EC levels both in undisturbed (solid line) and disturbed sites (circles) in October, 2005, January, February, March, May and September, 2006. Red circles represent dug wells that are pumped for cleaning purposes and green circles represent abandoned dug wells.

This could indicate that different patterns of use of individual wells after the tsunami had meant a different degree of residual tsunami imprint. This pattern of larger small-scale variability within the disturbed transect than the undisturbed one was also evident in most of the other chemical variables, supporting the hypothesis that the degree of reminiscence of the tsunami impact locally is a function of the aquifer disturbance in terms of well pumping and cleaning going on in the wells since the tsunami. Intensive and frequent well cleaning through emptying of wells and chlorination had been carried out since shortly after the tsunami. Furthermore, the most prevalent cleaning procedure was simple and entailed discharging the well water next to the well and hence basically recycling the contaminated water into the system and increasing the overall mixing and retarding the downward and lateral movement of the tsunami pulse. Hence, well cleaning, abstraction of water and degradation of debris may have delayed the natural recession of the tsunami effect at the disturbed site. In the undisturbed site, natural flow process had taken place, encompassing rapid sinking of the denser saltwater immediately after the tsunami (Illangasekare et al., 2006) and hence, the tsunami effect, after about one and half years, was less and more uniform across the transect compared to the disturbed site. Further supporting this hypothesis is the fact that well no. 1, 4, and 11 in the disturbed site were abandoned since the tsunami and these wells showed lower values of the chemical parameters.

Water Quality Analysis

The values obtained from the water quality analysis were normalized according to the sea water and plotted against time. The results of water quality analysis in January, 2006 showed that Ca concentrations in dug wells are slightly higher than in the piezometers (Fig. 3).

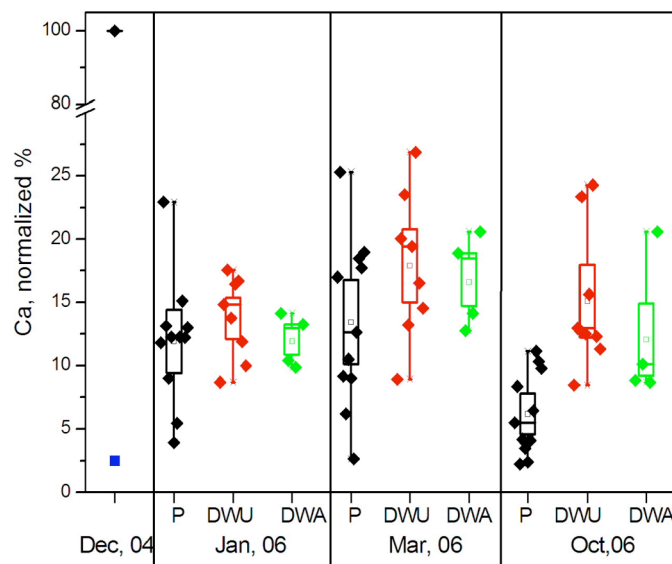


Fig. 3. Normalized calcium concentrations in the undisturbed site (P), dug wells in use (DWU) and abandoned dug wells (DWA) for January, March and October, 2006

Sodium concentrations for undisturbed site were almost same (>100 mg/L) as for the disturbed site in January. In March the concentrations decreased for both sites, most notably for the undisturbed site (Fig. 4). The original Na concentration in the aquifer was below 10 mg/L, and still most of the dug wells had much higher Na concentrations in March, 2006 (several above 100 mg/L) which is a clear imprint of the tsunami.

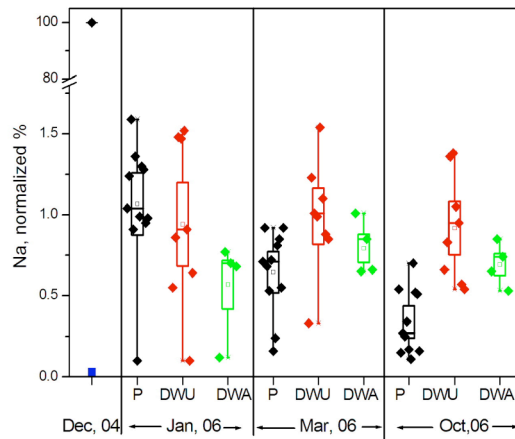


Fig. 4. Normalized sodium concentrations in the undisturbed site (P), dug wells in use (DWU) and abandoned dug wells (DWA) for January, March and October, 2006

The behavior of potassium concentrations was similar to Na (Fig. 5). The original K levels were less than 4 mg/L, and as shown by the figure many of the dug wells were higher in concentrations. Similar to sodium the concentrations are generally higher than for the piezometer measurements except for the two piezometers adjacent to the sea and lagoon respectively.

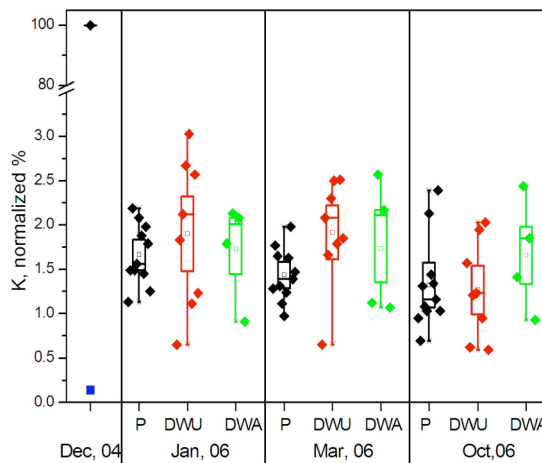


Fig. 5. Normalized potassium concentrations in the undisturbed site (P), dug wells in use (DWU) and abandoned dug wells (DWA) for January, March and October, 2006

The measured concentrations for alkalinity corroborate the findings for the other chemical parameters that the concentration levels for the disturbed site are marginally higher than for the undisturbed site (Fig. 6). Manganese also shown a similar behavior, and conversely, iron concentrations were high in undisturbed environment. Manganese from the sea sediments, which has deposited in the dug wells may have played a major role here causing the difference in between affected and non-affected area of the village transect. Though Pilapitiya et al., (2005) has measured elevated arsenic contaminations in groundwater due to tsunami there were no sign of arsenic in the water samples tested onsite. All the samples showed concentrations below 10 µg/L (WHO recommended guidelines).

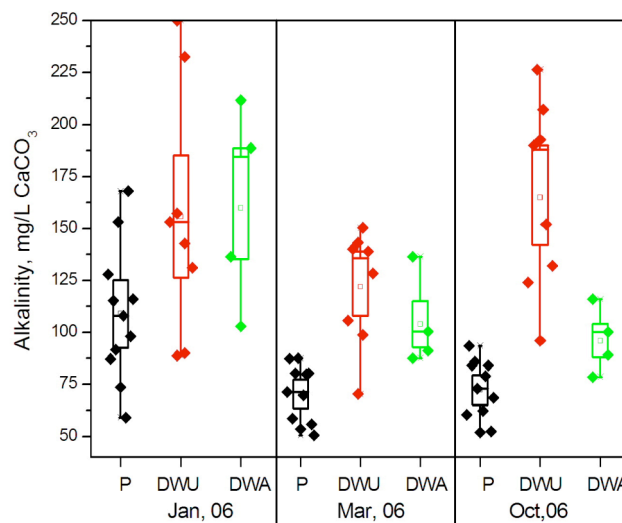


Fig. 6. Alkalinity concentrations in the undisturbed site (P), dug wells in use (DWU) and abandoned dug wells (DWA) for January, March and October, 2006

Hydrogeochemical Modeling of data

PHREEQC was used to model the chemical datasets from both undisturbed and disturbed sites to validate the analytical work and obtain the mixed sea water and fresh water fractions. Different mineral and gas phases were added according to the inequalities obtained in the output. Some samples showed that they are strongly undersaturated with solid sulphates and iron, and saturated with respect to calcite and dolomite. Therefore, possible precipitation of calcite or dolomite and dissolution of anhydrite were set as model constraints. For those solutions, it was necessary to add redox phases such as goethite or pyrite. A possible sink for CH₂O and a CO₂ source were set for equilibrate the reactions with organic matter. Since the upper most layer of the aquifer is geologically characterized as coarse to fine sand and no clay minerals are present, cation exchange was not considered. Sea water composition was obtained from the PHREEQC data base. The observed values of pH, alkalinity, C, Cl, Mg, Na, S and Ca were used as input to include mole balance equations for elements not contained in any of the phases.

Science of Tsunami Hazards, Vol. 28, No. 3, page 227 (2009)

Most solutions had 1-3 possible simulated models. Dissolution of anhydrite was encountered in all models, while most of the models were characterized by small amount of precipitating carbonates as calcite and dolomite. PHREEQC was able to simulate the observed chemical data well as shown by the scatter plots of simulated versus observed results for various parameters collected during the month of October 2006 (Fig. 7 and Fig. 8). The correlation coefficients of each parameter was very high (0.82 – 1.0) indicating an excellent fit by the model.

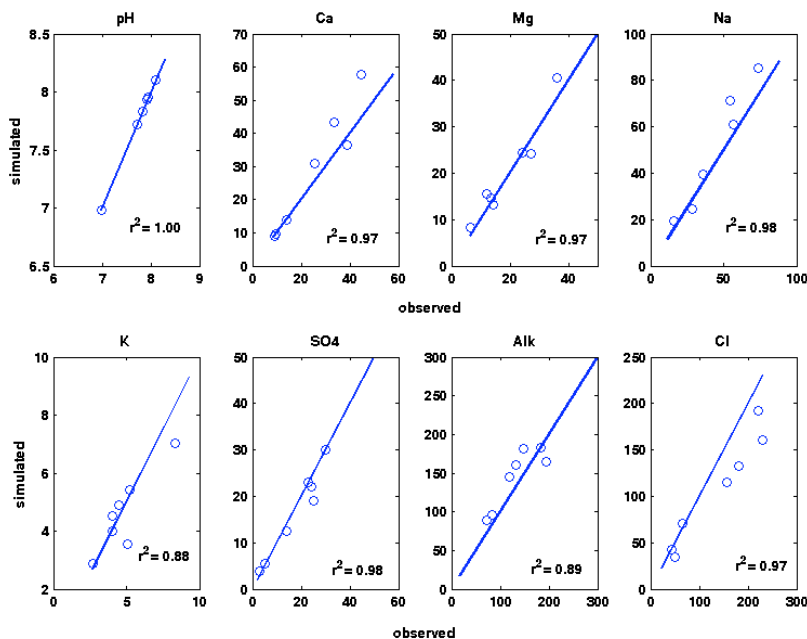


Fig. 7. Fitted results for the October, 2006 in the undisturbed site with correlation coefficients obtained from hydrogeochemical modeling using PHREEQC.

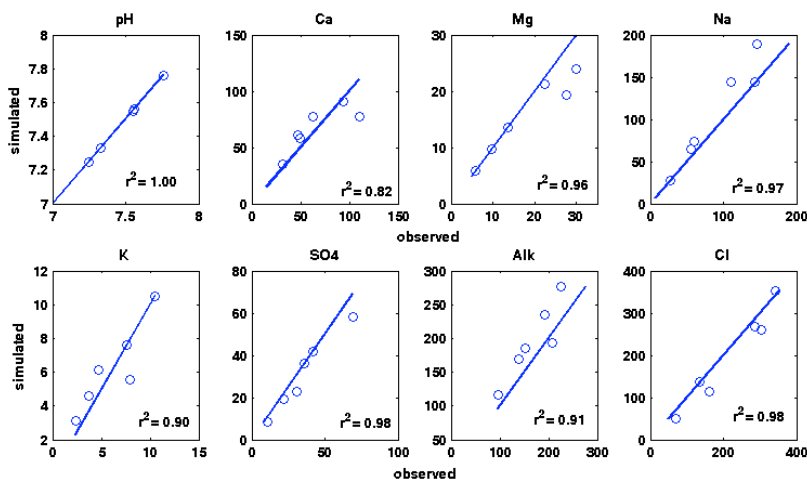


Fig. 8. Fitted results for the October, 2006 in the disturbed site with correlation coefficients obtained from hydrogeochemical modeling using PHREEQC.

Mixing of solution fractions

Mixing of solution fractions (sea water and fresh water) were obtained from the PHREEQC simulations. All the solution fractions from the month October, 2006 are plotted as a box and whisker plot (Fig. 9). The box plot of the undisturbed site has a median of 5.5×10^{-3} of sea water fraction and the range of data lies below 1×10^{-2} . The sea water fraction, is more uniform over the undisturbed site. However, the median value of the sea water fraction of the disturbed site with dug wells is 9×10^{-3} , which is about twice as that for the undisturbed site. Furthermore, the variance of data in the disturbed site is greater than the undisturbed site. Hence, it can be postulated that the mixing is higher in the disturbed site compared to the undisturbed site. The higher fraction of mixing can be due to the difference of usage of these dug wells, in terms of pumping, and the well cleaning in the area. As the sea water is denser than fresh water, the salt water will move downward into an undisturbed aquifer with lesser diffusion and dispersion. This phenomenon may be the cause of lesser variance observed for the undisturbed site. Conversely, the wells in the disturbed site were subjected to frequent cleaning and thereafter water extraction by pumping activities which may have disturbed the natural downward movement of dense salt water plume accelerating the contamination of wells with a possible permanent damage to the aquifer. This was also evident from the water quality analyses.

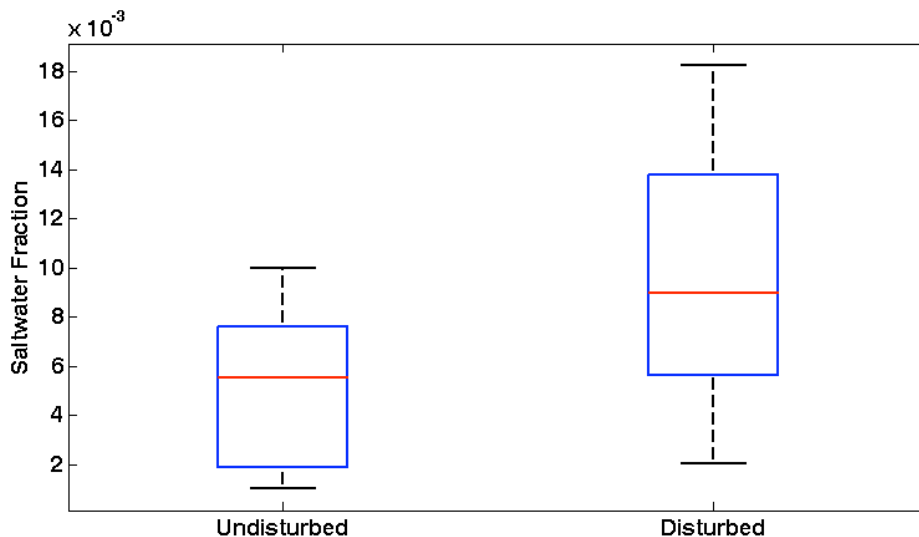


Fig. 9. Salt water fractions obtained by PHREEQC simulations for both disturbed and undisturbed sites data.

CONCLUSION

Observed values of electrical conductivity, alkalinity, total hardness and concentrations of calcium, sodium, potassium, manganese, and sulphate in the disturbed site were slightly higher than that in the undisturbed site during the months of January, March, and October 2006. Furthermore, water quality parameter values in dug wells were generally higher than in abandoned wells within

the disturbed site. This was also evident from the geochemical inverse modelling with PHREEQC. The geochemical modelling showed excellent fits of observed data and it showed that the mixing fraction of sea water fraction in the disturbed site was twice as high compared to the undisturbed area. These findings support the hypothesis that well cleaning and abstraction of water for general purposes disturb the natural downward movement and the recession of the tsunami impacts and therefore, the imprint of the tsunami may have been prolonged in the disturbed site compared to the undisturbed site. Even after a more than one and half years since the tsunami tragedy, the detrimental effect of it on water quality still appear to persists in both sites and the aquifer has not recovered to its original status.

Acknowledgements

Authors acknowledge Dr. David Parkhurst, Dr. Jayantha Obeysekera and Dr. Rohana Chandrajith for their valuable assistance. *Action contre la Faim* (AcF), for the travel arrangements and assistance given. Lawrence in Tharmapuram village, Predeeban and Amalraj at the Eastern University are also acknowledged for their support given throughout the study.

REFERENCES

- Cooray P.G. (1985). *Geology of Sri Lanka*. National Museum of Sri Lanka.
- Hoareau J. Guérin R. Vouillamoz J. M. & Vithanage M. (2006). The use of Transient Electro-Magnetism to localize saline water intrusion in Sri Lanka. 32nd WEDC International Conference. Sustainable Development of Water Resources, Water Supply and Environmental Sanitation. Colombo, Sri Lanka, Nov. 13-17, 2006
- Illangasekare T., Tyler S.W., Clement T.P., Villholth K.G., Perera A.P.G.R.L., Obeysekera J., Gunatilaka A., Panabokke C.R., Hyndman D.W., Cunningham K.J., Kaluarachchi J.J., Yeh W.W-G., Van Genuchten M.R. & Jensen K.H. (2006). Impacts of the 2004 Tsunami on Groundwater Resources in Sri Lanka. *Water Resources Research*, 42, W05201.
- Jeyakumar P., Premanatharajah P. & Mahendran S. (2002). Water quality of agro-wells in the coastal area of the Batticaloa District. *Symposium proceedings on the Use of Groundwater for Agriculture in Sri Lanka*, 99-107
- Koch, M. & Zhang G. (1992). Numerical simulation of the effects of variable density in a contaminant plume, *Groundwater* 30(5): 731–742.
- Mahendran S., Jeyakumar P., Premanatharajah P. & Thiruchelvam T. (2000). Study on groundwater quality of some selected wells during dry season in the municipal council area of Batticaloa. *Proceedings of first annual research sessions-* Eastern University of Sri Lanka. 53-61
- Oostrom M., Hayworth J. S., Dane J. H. & Güven O. (1992). Behavior of dense aqueous phase leachate plumes in homogeneous porous media, *Water Resources. Research* 28(8): 2123– 2134.
- Panabokke C.R. & Perera A.P.G.R.L. (2004). *Groundwater resources of Sri Lanka*. World water Assessment Program, Sri Lanka.

- Panabokke C.R. (2001). Groundwater studies of the coastal sand aquifers of Sri Lanka, Consultancy Report, International Water Management Institute, Sri Lanka
- Panabokke C.R., Pathirana S.R.K. & Wijekoon D. (2002). Water quality of agro-wells in the coastal sand aquifer in Trincomalee District. *Symposium proceedings on the Use of Groundwater for Agriculture in Sri Lanka*, 85-98
- Parkhurst D.L. & Appelo C.A.J. (1999). User's guide to PHREEQC (version 2) – A computer program for speciation, batch reaction, one dimensional transport and inverse geochemical calculations. *USGS Water Resources Investigation Report*. 99-4259. Denver.
- Pilapitiya S., Vidanaarachchi C. and Yuen S. (2006). Effect of tsunami on waste management in Sri Lanka. *Waste Management*. 26, 107-109
- Schincariol R.A. & Schwartz F. W. (1990). An experimental investigation of variable density flow and mixing in homogeneous and heterogeneous media, *Water Resources. Research* 26(10): 2317– 2329.
- Simmons C.T., Fenstemaker T. R. & Sharp Jr. J. M. (2001). Variable-density groundwater flow and solute transport in heterogeneous porous media: approaches and challenges. *Journal of Contaminant Hydrology* 52(1-4): 245- 275.
- Sugirtharan M., Sutharsan S. & Thiruchelvam T. (2004). Quality assessment of well water at Thuraneelawanai area of Batticaloa District. *Annual Research Sessions-* Eastern University of Sri Lanka
- Underwood M.R., Peterson F.L. & Voss, C.I. (1992). Groundwater lens dynamics of atoll islands, *Water Resources Research*, 28(11): 2889-2902
- UNEP (2005). After the Tsunami: Rapid Environmental Assessment (available at http://www.unep.org/tsunami/reports/TSUNAMI_report_complete.pdf)
- Vaheesar K., Mahendran T. & Priyantha N. (2000). Analytical studies on irrigation water at Kaluthaweli in the Batticaloa District. *Journal of Science*-Eastern University of Sri Lanka. 1(1), 10-15
- Villholth K.G., Amerasinghe P.H. & Jeyakumar P. (2006a). Tsunami Impacts on Shallow Groundwater and Associated Water Supply on the East Coast of Sri Lanka, International Ground Water Conference, Feb., India
- Villholth K.G., Manamperi A.S.P. & Buergi N. (2006b). Chemical Characteristics of Tsunami-Affected Groundwater and Lagoon on the East Coast of Sri Lanka. Paper submitted to the 32nd WEDC International Conference. Sustainable Development of Water Resources, Water Supply and Environmental Sanitation. Colombo, Sri Lanka, Nov. 13-17, 2006
- Vithanage M., Engesgaard P., Villholth, K. & Jensen, K. (2009). Effect of December 2004 tsunami on groundwater in a coastal aquifer on the East coast of Sri Lanka: Field observations and numerical modeling (Under review, *Journal of Contaminant Hydrology*).
- Wicremaratne H.U. (2004). Use of groundwater for coastal water supply schemes, minimizing the salinity problem; A case study at Kattankudy in Batticaloa District, Sri Lanka. MSc Thesis. Post Graduate Institute of Science, University of Peradeniya, Peradeniya, Sri Lanka.