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Lucy Lytton
MSc, CGeol, FGS, CSci
is senior hydrogeologist at
Veolia Water

Deep impact: why post-tsunami wells need a measured approach

Following the Asian tsunami of 26 December 2004, the vital domestic fresh-water wells in the coastal zone were either scoured out of the ground entirely or filled with salt water, mud, debris and bodies. Emergency teams naturally exerted huge efforts in trying to restore intact wells, first clearing and then pumping them out. However, it soon became apparent little could be done to rehabilitate the wells in the short term due to the massive intrusion of saline groundwater as well as the fundamentally unsatisfactory nature of local water supply and drainage arrangements. Based on a study carried out on 64 wells in the Ampara district a month after the event, this paper identifies the long-standing issues that need to be solved before a reliable water supply can be established in the coastal zone.

Fig. 1. NASA satellite image of tsunami waves inundating the coast of Sri Lanka on 26 December 2004 about an hour after the first wave hit (Copyright DigitalGlobe)

The shockwave caused by the sub-marine earthquake off the west coast of Sumatra on 26 December 2004 generated a tidal wave that inundated the coastal margin of the countries bordering the Bay of Bengal (Fig. 1).

On the east coast of Sri Lanka, the majority of the population obtain their domestic water supply via numerous private and public hand-dug wells sunk into the sandy coastal sediments. Most of these wells were inundated by the tidal wave.

Immediately after the sea had retreated, both local and international teams of volunteers started to clean up the wells by removing debris and corpses and pumping out the mud. Following this, efforts were made to pump out the salt water but, a month later, doubts were growing as to the effectiveness of pumping since the salinity of most wells was not reducing.

This paper describes efforts to develop rapid rehabilitation methods for wells affected by saline inundation in the Ampara district (Fig. 2) and thereby to restore drinking water to the affected population.

Hydrologeological setting

The populated coastal margin of the Ampara district rests on an unconfined, highly permeable, sandy aquifer, which forms the barrier between the beach and the hinterland. Granitic rocks of the Precambrian metamorphic basement (the Vijayan complex) outcrop in the hinterland[1] and underlie the coastal sediments at depth.

The classic relationship at equilibrium of the interface between marine salt water and the overlying fresh water in a sedimentary coastal aquifer is known as the Ghyben–Herzberg relation,[2] shown schematically in Fig. 3, where the fresh water rests on top of the denser brine, forming a sloping interface that inclines downward towards the inland.

The large difference in salinity between the two waters means that the interface is relatively sharp, with only a narrow mixing zone between them. Although the interface moves daily in response to pressure changes caused by tidal fluctuation, the normal annual tidal range in Sri Lanka is relatively small, at around 0·7 m.[3]

In such an environment, the salinity of well water is sensitive to up-coning, where saline water is drawn into the overlying freshwater lens in response to over-vigorous pumping, thereby contaminating supplies.

The impact of the tidal wave on such a fragile equilibrium should therefore be considered in terms of the influx of salt water from above, through surface inundation of the permeable sediments including maintenance of a pressure head of salt water, and from within the aquifer by injection from flooded wells.

As soon as the tsunami wave subsided the equilibrium relationship between the fresh water and salt water, as described above, would have started to re-establish itself, aided by the monsoon rains that were occurring at the time. The vulnerability of the coastal aquifer to pumping after such an event is enhanced because of the potential for re-mixing fresh and saline water (Fig. 4).

A prominent geomorphological feature

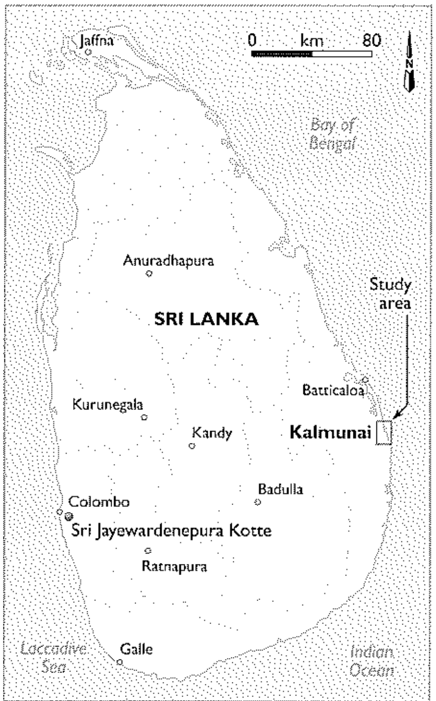

Fig. 2. Map of Sri Lanka showing study area centred on Kalmunai in Ampara district (basemap courtesy of the UN Cartographic Section)

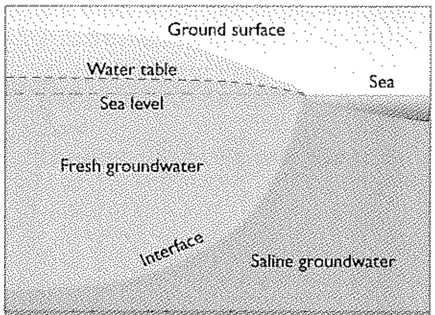

Fig. 3. Schematic of classic freshwater/saline relation in coastal sedimentary aquifer (courtesy UK Groundwater Forum)

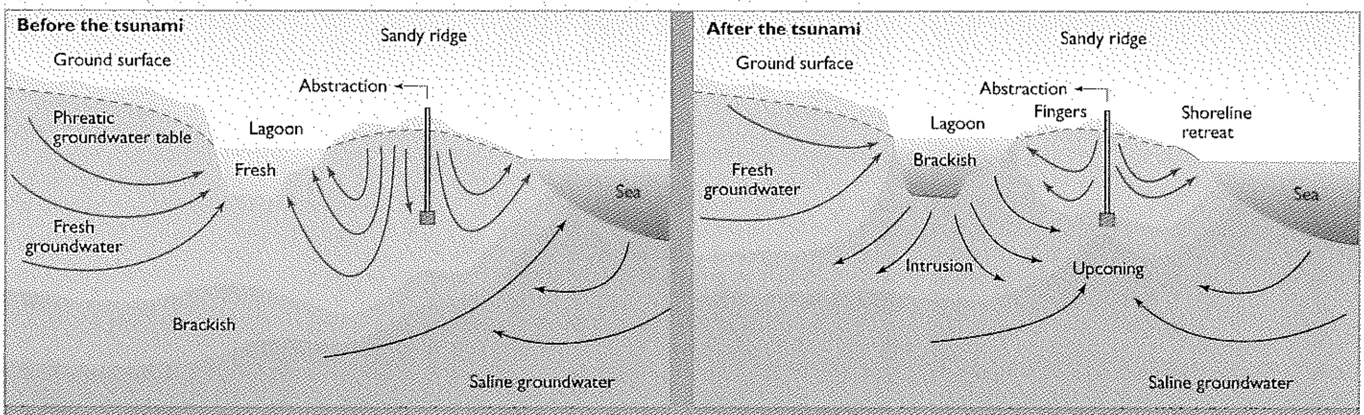

Fig. 4. Illustration of the likely situation of the salt and fresh water in the Ampara coastal aquifer (a) before and (b) after the tsunami (courtesy IGRAC)

Wells nearer the coast had been inundated by the overtopping wave that deposited varying amounts of debris in them

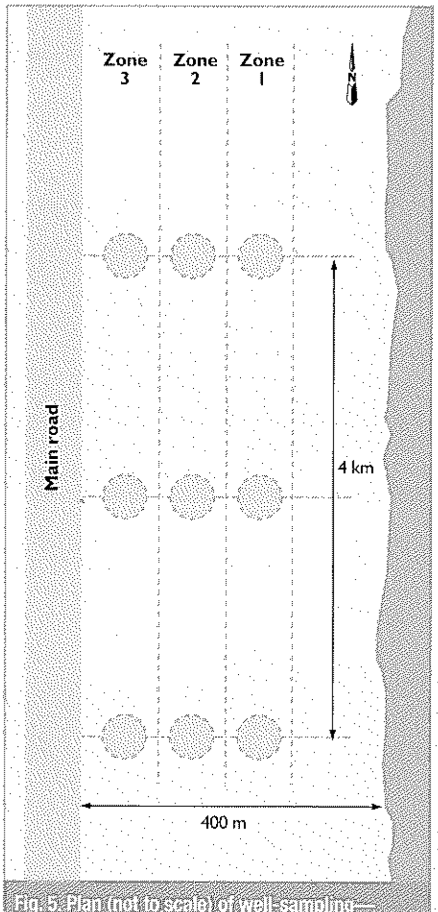

Fig. 5. Plan (not to scale) of well-sampling—oval shapes indicate cluster locations for well sampling

of the Ampara district is the presence of lakes and lagoons extending parallel to the coast several hundred metres landward of the sandy coastal barrier margin. These may play a significant role in recharging and maintaining water levels in the coastal aquifer.

Evaluation study

Prior to attempting the development of suitable well-rehabilitation methods for the district, a study was conducted to establish local factors that might influence the approach. The initial assumption was that saline contamination of the wells was by individual inundation and that removal of the contaminated water from the wells would serve to restore the water quality to pre-tsunami conditions.

Study area

For five days in late January 2005, wells within a 4 km by 400 m strip between the main road and the coast, in the town of Kalmunai, were studied to evaluate both the impact of the tsunami and suitable rehabilitation techniques. The study area was divided into three zones parallel to the coast, each around 130 m wide, to determine physical and chemical changes with distance from the shore. Three transects across these zones (Fig. 5), spaced approximately 2 km apart, were used to select clusters of wells for evaluation.

Before the tsunami, the study area contained a moderately dense urban grid running parallel to the coast. The original single-storey dwellings each had a small garden plot and generally at least one well. Many of the dwellings were destroyed, particularly in the zone closest to the coast.

Each dwelling had its own domestic toilet pit that was sunk to a depth of up to 3 m and all washing facilities also drained nearby. The separation of the wells, or of the wells and toilet pits, was rarely more than 10 m. The vegetation consisted of some tall trees, including coconut palms, but little ground cover over the sandy soil.

Evidence of the tsunami impact

The waves generated by the tsunami inundated the coastal zone of the Ampara district to depths of up to 5 m and hundreds of metres inland of the coast. It reduced most buildings to rubble and left few walls standing (Fig. 6). Detritus was lodged in the branches of trees and filled wells. Piles of rubble lined the roads that had been cleared after the tsunami subsided to allow access. Mass burial pits were constructed in the destroyed area within days of the event.

In the area closest to the coast, some of the wells appeared unharmed, others leant

Fig. 6. The tsunami reduced most coastal buildings to rubble and left few walls standing (courtesy Jocelyn Duval)

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to one side and others still were entirely exhumed (Fig. 7) and lay on the surface. Of the surviving wells, those further from the ocean were protected from inundation by their upstand. Wells wells nearer the coast had been inundated by the overtopping wave that deposited varying amounts of debris in them (Fig. 8). Evidence of the narrow separation between toilet pits and wells is shown in Fig. 9.

Measured parameters

Using a dip meter and hand-held field instruments for measuring temperature, electrical conductivity (EC, as a proxy for salinity), turbidity and pH, the structural condition of each studied well was evaluated together with the water level and water quality parameters. A subsection of wells was sampled to assess the extent of bacterial contamination.

Then, using a submersible pump and several hundred metres of discharge pipeline laid towards the ocean, variable-rate pumping tests (up to 30 m^3/h) were conducted on some wells. Meanwhile the physical and chemical response of each pumping well and the surrounding wells was monitored to assess the impact of clearance pumping.

Study results

A total of 64 wells was studied over the five-day period. Most of these were in reasonable structural condition. Typically, they were constructed by hand, were 1–1·5 m in diameter and up to 4 m deep, and had a brick or concrete lining that generally resulted in restricting significant ingress of aquifer water to the base of the well. Most wells had a concrete upstand of up to 1 m, guarding against overtopping but generally without a protective concrete apron around the base.

The water level in the wells was at, or

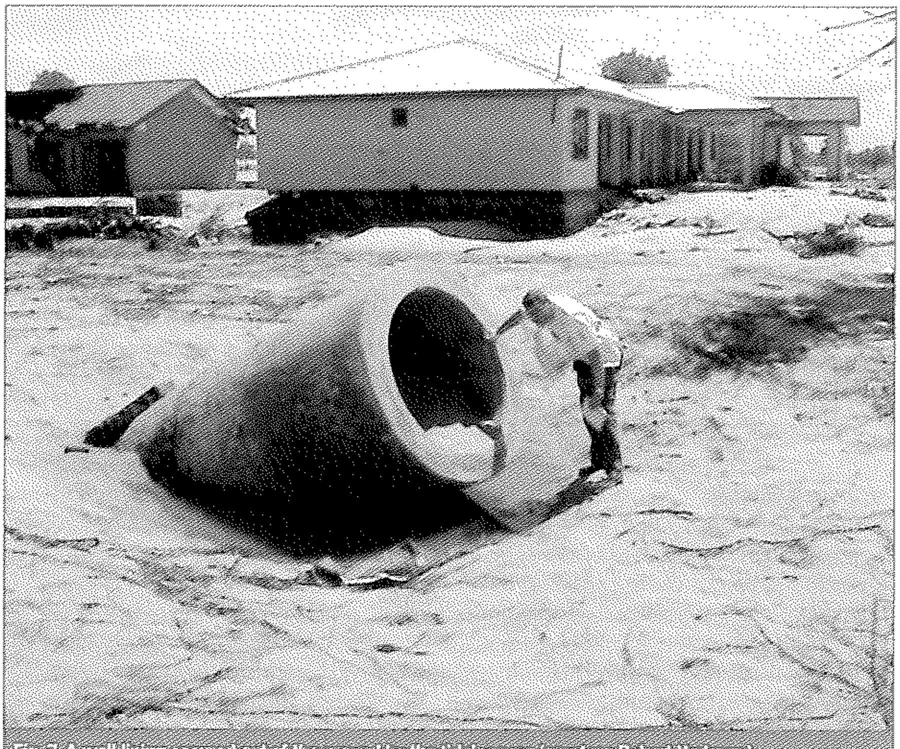

Fig. 7. A well lining scoured out of the ground by the tidal waves (courtesy Robert Hodgson)

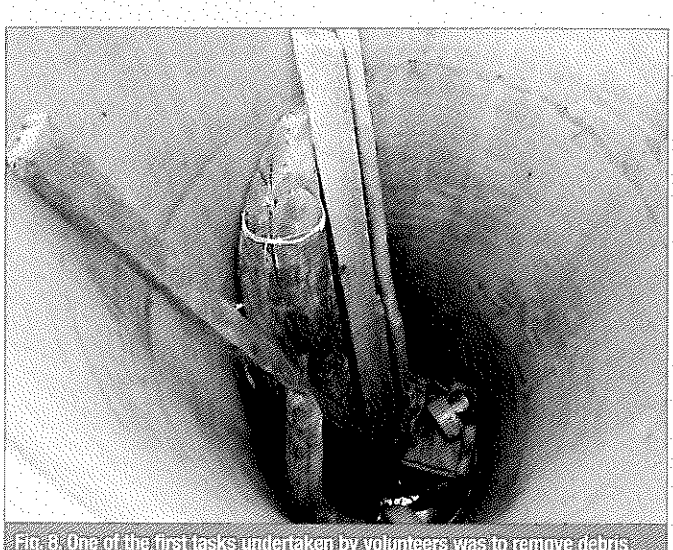

Fig. 8. One of the first tasks undertaken by volunteers was to remove debris and corpses from wells and start pumping out mud (courtesy Jocelyn Duval)

Fig. 9. Toilet pits (foreground) are typically just a few metres from wells, adding further to aquifer contamination (courtesy Jocelyn Duval)

Table 1. Summary of water quality analyses from well study in Kalmunai—the salinity (indicated by electrical conductivity) of most wells was far in excess of that suitable for potable use, even in wells in the zone furthest from the coast (III) that had not been inundated

Parameter		Zone I	Zone II	Zone III
pH	Maximum	7·1	7·5	7·1
	Mean	6·6	6·9	6·7
	Minimum	6·0	6·5	6·7
Turbidity: NTU	Maximum	8·49	7·54	6·05
	Mean	3·80	3·08	3·00
	Minimum	1·25	1·20	0·68
Electrical conductivity: µS/cm	Maximum	16 710	9200	7500
	Mean	5209	3861	2408
	Minimum	1430	642	355

near, ground level during the study. Some of the wells were surrounded by standing water (Fig. 10), which varied from fresh water (dominated by monsoon rains) to saline water (dominated by the tsunami wave). Samples were collected by bucket from near the surface of the water column in each well. There was heavy rainfall during the study that was predicted to continue for a few more weeks until the end of the monsoon season.

As envisaged, the salinity measured in the wells decreased with distance from the coast (see Table 1), as did the turbidity. In fresh water, the salinity, or total dissolved solids (TDS), can be approximated by the equation

$$EC\ (\mu S/cm) = a \times TDS\ (mg/l)$$

where a is in the range 1·2 to 1·8, tending towards the higher value for chloride-rich waters.[4] Although there is no health-based value for TDS, taste considerations render increasingly unpalatable those waters containing in excess of about 1000 mg/l.[5] Using the higher constant in the equation, this approximates to an upper EC value of around 1800 µS/cm.

Although there were isolated wells apparently containing fresh water (as indicated by the minimum EC values for each zone shown in Table 1), the salinity from most wells in all of the zones was far in excess of that suitable for potable use, even in wells that had not been inundated. pH values showed little variation between the zones and the bacteriological tests showed all samples to be highly contaminated, each sample having colonies too numerous to count.

Monitoring during the pumping tests showed no reduction in salinity, despite measures to avoid up-coning of saline water. With the water table at ground level, a highly permeable aquifer and no surface drainage, the chief problem in this activity was avoiding re-circulation of the saline discharge from the wells. There was also evidence of well subsidence when pumping at higher rates.

The pumping tests were terminated after only five wells when it became clear that pumping was at best making no difference and at worst leading to a deterioration of the water quality and/or of the well structure.

The results of the study indicated that the contamination of the aquifer was widespread and, therefore, pumping to remove saltwater was futile

Fig. 10. Groundwater levels were typically at ground level during the study, with many wells surrounded by standing saline or fresh water (courtesy Jocelyn Duval)

Observation of local well-cleaning

A large number of organisations were involved in well-cleaning in the Ampara district with little co-ordination. Observation and discussion with well-cleaning teams quickly revealed a number of problems. Contaminated well water was frequently being discharged to the ground immediately adjacent to the wells (see Fig. 11) which, given the permeability of the ground, would lead to rapid recirculation of saline water back into the aquifer.

Few teams were recording measurements (such as of EC or water level) that would allow evaluation of the efficacy of their intervention. Motorised pumps were introduced to wells that had previously been exploited by more modest means, thereby risking both up-coning from the underlying saline wedge and the drawing of contaminants into the wells from other sources, particularly toilet pits and burial pits. Many teams appeared to be unaware of potential water-quality issues related to pumping.

Study conclusions

The presence of fresh water in a few of the wells following inundation by the tsunami was interpreted as being due either to the recent influx of monsoon rains into the well and the local aquifer, or to isolated pockets of fresh water preserved within the aquifer. In either case they were considered to be of limited extent.

The proximity of the wells to both toilet and burial pits and the fact that all drainage water is returned to the ground locally means the water cycle is very short, both spatially and temporally, with all waste water returning rapidly to the aquifer from which it is abstracted and little residence time to attenuate any contaminants. The only losses from this cycle would be evaporative and the gains from monsoon rains.

The study concluded that, due to gross contamination of the aquifer, there was no feasible means of recovering the wells in the area in the short term and recommended to

- provide alternative supplies of drinking water to residents and refugees in the affected zone
- abandon the wells for potable use until the end of the dry season then, if necessary, clean them out prior to the next monsoon rains
- plan for residual salinity in the coastal wells, particularly towards the end of the dry seasons, in the ensuing few years
- separate permanently the water supply environment from that of the toilet pits.

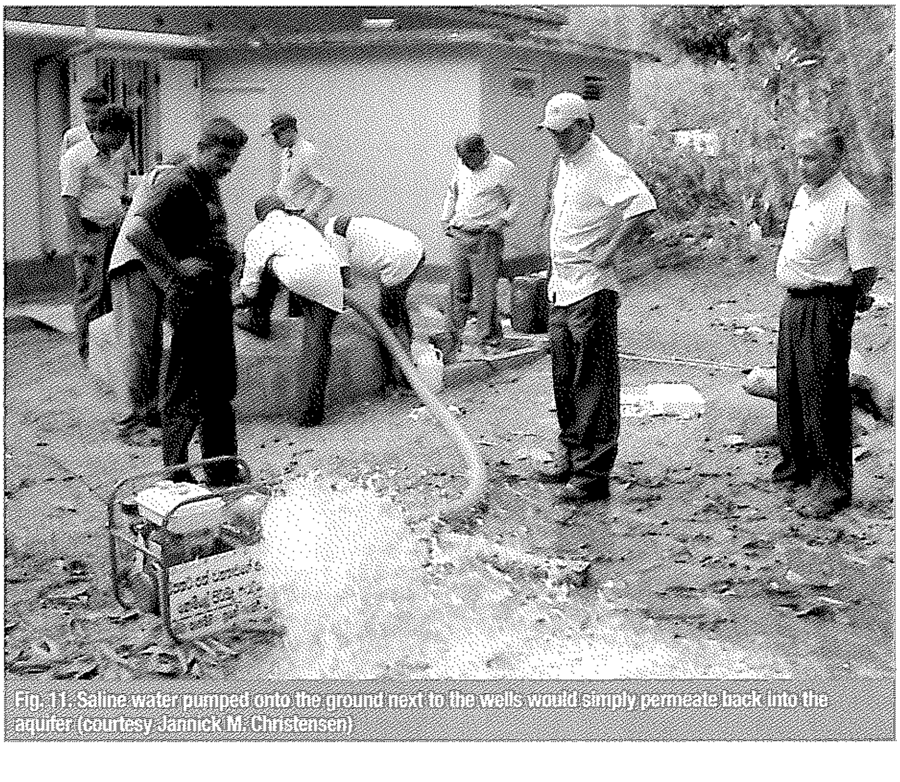

Fig. 11. Saline water pumped onto the ground next to the wells would simply permeate back into the aquifer (courtesy Jannick M. Christensen)

Research activities

While the emergency work was being conducted, joint international and Sri Lankan research teams were commencing essential, more-detailed and longer-term research studies on the east coast than were possible during the rapid evaluation described above. These have produced several papers covering post-tsunami well rehabilitation and tsunami impacts on groundwater.

In 2005, Villhoth *et al.*[6] described the development of the salinity profile measured in wells during the months following the tsunami and proposed well-cleaning approaches for tsunami-impacted wells based on these measurements. In 2006, Villhoth *et al.*[7] tracked the changes in salinity and other water quality parameters in wells and lagoons before and after the first rains several months after the tsunami.

Also in 2006, Illangasekare *et al.*[8] presented the results of physical modelling (tank experiments) that demonstrate the development of the salinity profile in a sandy aquifer following a tsunami wave in a physical setting such as that seen in the Ampara district.

Discussion

Post-tsunami experience in the Ampara district demonstrates the importance of understanding the relevant physical and unique characteristics of coastal aquifers and of taking essential measurements, even while attempting to address urgent issues in the immediate aftermath of a disaster such as the Asian tsunami. A discussion of appropriate post-tsunami well-cleaning methods is presented by Villhoth *et al.*[6]

The results of the study indicated that the contamination of the aquifer was widespread and, therefore, pumping to remove saltwater was futile. Although the monsoon rains would have been recharging the aquifer since the inundation by the tidal wave, and freshwater lenses may have started to form in the aquifer at shallow depths, this would have been of very limited extent. Pumping in this environment leads to three potential problems

1. the action of pumping a well will remove any residual or newly-formed lenses of freshwater
2. pumping causes mixing of the water in the aquifer around the well, thus contaminating any freshwater lens that may be present
3. the act of discharging polluted well water on top of the aquifer causes another saline inundation event, similar to that of the tsunami itself, and prevents the fresh–saline equilibrium from re-establishing itself.

Wells are traditionally sunk by hand in the region, commonly towards the end of the dry season when the water table is at its lowest and the maximum possible depth can be achieved with the minimum amount of de-watering. It is therefore reasonable to assume the depth of the wells indicates the position of the water table at the end of the dry season. This implies that, despite the closed nature of the water cycle, the aquifer naturally drains itself by the end of the dry season. Thus it can be assumed the saline water would also drain out of the aquifer, although some salt is likely to adhere to the sediment.

During the following monsoon season, the aquifer would be replenished with fresh water leading to groundwater more saline than usual due to the residual salt trapped in the sediments. Successive seasons will lead to a gradual return of the aquifer to its pre-tsunami quality. The progression of the salinity in the wells of the Ampara district in the months following the tsunami is documented by Villhoth *et al.*[7] and the physical processes involved are discussed by Illangasekare *et al.*[8]

Reports that well-desalination efforts had been successful in other regions point to differences in the geomorphological, geological and hydrological parameters found at each site.

Conclusion

The work conducted in the Ampara district revealed two categories of contributing problems: those pre-existing and those that arose from the tsunami.

Pre-existing problems included

- seasonally high water table and consequent lack of drainage
- discharge from toilet pits and washing facilities into the highly permeable water-supply aquifer.

The tsunami-related problems were

- gross and widespread contamination of the aquifer by rapid percolation of saline water through the top of the highly permeable sediments as well as injection via many of the wells
- contamination of the aquifer by burial pits
- no suitable means of discharging contaminated well-water
- inappropriate well-clearance pumping potentially leading to further water-quality problems.

Whereas removal of debris and mud from the inundated wells was essential in the immediate aftermath of the inundation by the tidal wave, a proper evaluation and measurement of local conditions in the days and weeks following the tsunami would have demonstrated whether clearance pumping would be effective.

The use of a down-hole conductivity probe in wells prior to pumping would have greatly facilitated an understanding of salinity profiling within the wells and guided the decision as to the manner and advisability of pumping. It is important to recognise that, in some circumstances, the best course of action is to do nothing.

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