International Water Management Institute

Tsunami Impacts on Shallow Groundwater and Associated Water Supply on the East Coast of Sri Lanka

A post-tsunami well recovery support initiative and an assessment of groundwater salinity in three areas of Batticaloa and Ampara Districts

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FUTURE HARVEST

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Executive Summary

The major tsunami of December 26, 2004 that hit many South Asian countries bordering the Bay of Bengal severely devastated the coastal regions of Sri Lanka. A key concern is the nature and extent of the tsunami impact on the water supply and, in more general, the water resources of these areas. In the coastal areas of Eastern Sri Lanka, the majority of the population, which is rural or semi-urban, is relying on groundwater for their domestic and agricultural activities, most predominantly through traditional private shallow open dug wells in the sandy aquifers. As the tsunami destroyed practically all wells within the reach of the flood waves, access to freshwater for these people was suddenly cut off and interim alternatives had to be sought urgently in the form of freshwater trucked in from unaffected areas.

Soon after the tsunami, massive efforts to clean the wells were initiated from a range of different actors in an attempt to rapidly return the water supply to normal conditions, or at least ameliorate the immediate impacts of the salinization of the wells. Based on indications that these efforts were un-coordinated, inadequate, inefficient and at the extreme harmful to the water quality and the well functioning, IWMI set in at various levels to try and guide and coordinate these efforts.

With the aim to assess and document the extent of the damages and the immediate and intermediate term impacts of the tsunami on groundwater and associated water supply, a field monitoring program was initiated in March 2005 (2.5 months after the tsunami) in three areas on the east coast (Kallady, Kaluthavalai, and Oluvil, in Batticaloa and Ampara District). A total of approximately 150 wells were selected within approx. 2 km distance from the coastline covering both affected and non-affected wells. Salinity, groundwater level, turbidity, and mosquito vector breeding were monitored on a regular basis, with from 20 to 40 days interval. In addition, salinity levels in sea and lagoon water were measured. Results indicate that 39% of the wells had been flooded by the tsunami, with the flooding being more severe in the two most northern sites (49% in both Kallady and Kaluthavalai), as compared to the last site (21% in Oluvil). This pattern could be explained by the way the waves had come in and had been received by the land complex.

Salinity levels in flooded wells decreased significantly from the estimated levels at the time of the tsunami (29,400 µS/cm) till the start of the monitoring (3200 µS/cm). This can be explained by the rainfall that occurred shortly after the tsunami and the rapid dissipation and mixing of intruding seawater with pre-tsunami fresh groundwater and potentially the well cleaning effects. As time passed, average salinity levels in flooded wells decreased only slowly, until the end of the study period (middle of July), when the average salinity was 2600 µS/cm. The slower decrease can be attributed to the unset of the dry season and the slower mixing and dissipation mechanisms as concentration gradients decreased. Non-flooded wells showed an opposite trend with salinity levels slightly increasing during the dry season (from 890 to 1090 µS/cm), a generally encountered phenomenon. Hence, seven months after the tsunami, flooded wells had higher average salinity level than background, non-flooded wells, indicating that the groundwater still had not recovered fully from the tsunami, and that at least one more rainy season was required to flush the system and restore the aquifers to pre-tsunami conditions.

Based on a drinking water salinity acceptance threshold derived from the actual use of the wells, it was found that a large fraction of the flooded wells (between 67 and 100% in the three sites), and even wells not flooded (between 17 and 50%) were not suitable for drinking at the end of the study period. This indicates that people in the areas had become accustomed to the alternative water sources supplied by various relief organizations, because background, non-flooded wells did not show increased salinity relative to pre-tsunami conditions and people generally were relying on the well supply for drinking water prior to the tsunami.

Guidelines for well cleaning and groundwater protection and general awareness raising and information sharing was a significant part of the project, and it is believed that the activities involved had an impact on the approach to well cleaning in the affected areas, by drawing attention to the potential problems involved, by linking various actors and by disseminating the knowledge and results generated in the project.

Organization of the Report

The introductory chapter is followed by Chapter 2 describing the potential impacts of the tsunami on groundwater, issues related to cleaning of wells in affected areas and a description of the geographical, demographic, and water use setting on the east coast as well as some key figures for the overall devastation caused in these areas. Chapter 3 describes the objectives of the present study, project implementation and the research methodology. The results of the well rehabilitation support and the monitoring program are given in Chapter 4 and finally, Chapter 5 synthesizes the findings and extracts the conclusions and recommendations for further work.

Abbreviations

ADB	Asian Development Bank
CDC	Centers for Disease Control and Prevention
CGIAR	Consultative Group on International Agricultural Research
DS	Divisional Secretary's Divisions
EUSL	Eastern University of Sri Lanka
GN	Grama Niladhari's Divisions (Grama Niladhari: administrative officer in charge of the smallest administrative divisions)
GPS	Geographical Positioning System
ICRC	International Committee of the Red Cross
IGRAC	International Groundwater Resources Assessment Centre
IWMI	International Water Management Institute
NGO	Non Governmental Organization
NGWA	National Groundwater Association
NWSDB	National Water Supply and Drainage Board
PHI	Public Health Inspector
TDS	Total Dissolved Solids
UNEP	United Nations' Environmental Programme
UNICEF	United Nations International Children's Emergency Found
WHO	World Health Organization
WRB	Water Resources Board

Chapter One

Background

The Asian tsunami of December 26, 2004 hit the Sri Lankan coasts with various impacts, but especially the eastern, northern and southern coasts were devastated (ADB, 2005; UNEP, 2005). The water supply for domestic purposes was affected through the breach of water distribution pipe lines and through the filling of wells with debris and saltwater. The flow of the seawater over the soil surface, stagnation of saline and possibly polluted water in local depressions and the disruption and loss of coastline also changed the properties and quality of soil and water resources in the coastal areas.

Shallow groundwater wells have traditionally provided the main domestic water source in the coastal areas. In urban areas, these sources have been supplemented with piped and tapped surface or groundwater (Panabokke and Perera, 2005). The disruption from the tsunami meant that an estimate of between 12,000 and 100,000 wells in the whole country was damaged, many left unfit for human consumption and even for bathing and washing purposes immediately after the tsunami (ADB et al., 2005; UNEP, 2005; Senaratne, 2005). The time frame and the prospect of rehabilitating this large number of wells to pre-tsunami conditions was not clear and posed major challenges for the authorities and other actors, like NGO's, in their continued efforts to remediate the situation on the ground.

A month after the tsunami, it was becoming clear that the manual cleaning of the wells by various pumping methods was not a straight-forward task, and that various problems encountered needed more specialized knowledge than possessed by the regular NGOs and other field-engaged personnel. Wells were reported to remain saline, even after repeated cleaning and emptying, wells collapsed during the cleaning process, and other sources of pollution potentially caused health hazards that previously did not present a significant problem. There was a need to support these cleaning efforts through the dissemination of knowledge on the functioning of the aquifers and the relation to salinity issues and especially the anticipated impacts of the tsunami and the measures most appropriate to ameliorate them.

At this point, no data existed on the extent of the salinization problems and there was an urgent need to initiate systematic monitoring and assessment of the immediate as well as longer term impacts that could lead to appropriate rehabilitation methods and the protection of the groundwater resources for future water supply.

Not withstanding the impacts of the tsunami on groundwater and the implemented relief measures, it was becoming clear that the groundwater use in the affected areas needed to be assessed within an integrated and longer term analysis of the complex of potential threats to groundwater-based water supply and groundwater use in general. There was a need for an integrated plan for water supply and use of water resources in affected areas as well as their joined hinterlands.

The present project was conceived as a first phase of a larger effort to support such an integrated approach. It was meant to support and guide the immediate efforts associated with the rehabilitation of tsunami-affected wells and to initiate a monitoring program, with emphasis on salinity, on the east coast in order to assess the short to intermediate impacts of the tsunami on the water supply from existing shallow groundwater wells in the area.

It was of high importance that the project was initiated soon after the tsunami, as field data collected shortly after the tsunami would be crucial for the assessment of the short term impacts. Also, well cleaning was progressing rather ad hoc, uncoordinated and unprofessionally with preliminary results showing that more harm than good could be done to the wells if improper methods were applied. Both arguments were giving high impetus for a rapid initiation of the project.

The understanding and experiences gained from the present study and the representative areas would be of relevance throughout most of the affected region on the east coast and hence serve as a general guide for future investigations and interventions.

Chapter 2

Possible effects of the tsunami on the coastal aquifers and ensuing issues related to domestic water supply

GENERAL OVERVIEW OF THE COASTAL GROUNDWATER AQUIFERS OF SRI LANKA

When looking at effects of the December 26, 2004 tsunami on groundwater and water supply in Sri Lanka, it is indispensable to look at the sandy coastal aquifers (Figure 1) because:

- The water supply in the coastal areas is heavily dependent on freshwater from these aquifers
- The majority of the flooded areas were underlain by these aquifers
- The aquifers are more prevalent on the east coast where the tsunami had a major impact

The sediments making up the coastal aquifers are mostly structureless sand, ranging from fine to moderately coarse. Technically, they are called regosols (Panabokke, 1996).

The aquifers stretch from 2 to 8 km inland. A characteristic feature of the east coast is the prevalence of coastal lagoons dotted along most of the coast line. The regosols comprise the land strips bordered by the lagoons and in many places reach beyond the lagoons into the hinterland.

The groundwater in these areas naturally presents a reliable and good quality source of freshwater for rural and urban populations. The freshwater exists and is sustained by virtue of the natural rainfall, which infiltrates and counteracts any intrusion from the saline seawater. The freshwater and saltwater are kept in a certain balance giving rise to an interface, or a mixing zone, between the two underneath the soil surface along the coast (Figure 2). The saltwater forms a wedge reaching underneath a body of freshwater, which in turn overlays the saltwater.

In case of an island, an isolated body of freshwater, a freshwater lens, forms underneath the island (Figure 3).

If the land area is confined by the sea on one side and a lagoon on the other, which is typical of the Sri Lankan east coast, a situation intermediary between Figure 2 and Figure 3 develops, because in most cases, the lagoon will contain brackish water (Figure 4).

Figure 1. Extent and location of the sandy coastal aquifers in Sri Lanka

The exact size and geometry of the freshwater lens will depend on the geological conditions, the water density (i.e. the salinity of the seawater and the brackish water in the lagoon, the annual recharge (i.e. the rainfall) and the pumping taking place from the freshwater aquifer.

The depth to an impervious layer is critical as it may limit the downward extension of the freshwater lens and hence the volume of freshwater available. In general, it can be said that the coastal aquifers, though potentially providing a good source of freshwater, also comprise relatively vulnerable systems because:

- They are very permeable allowing rapid infiltration of pollutants

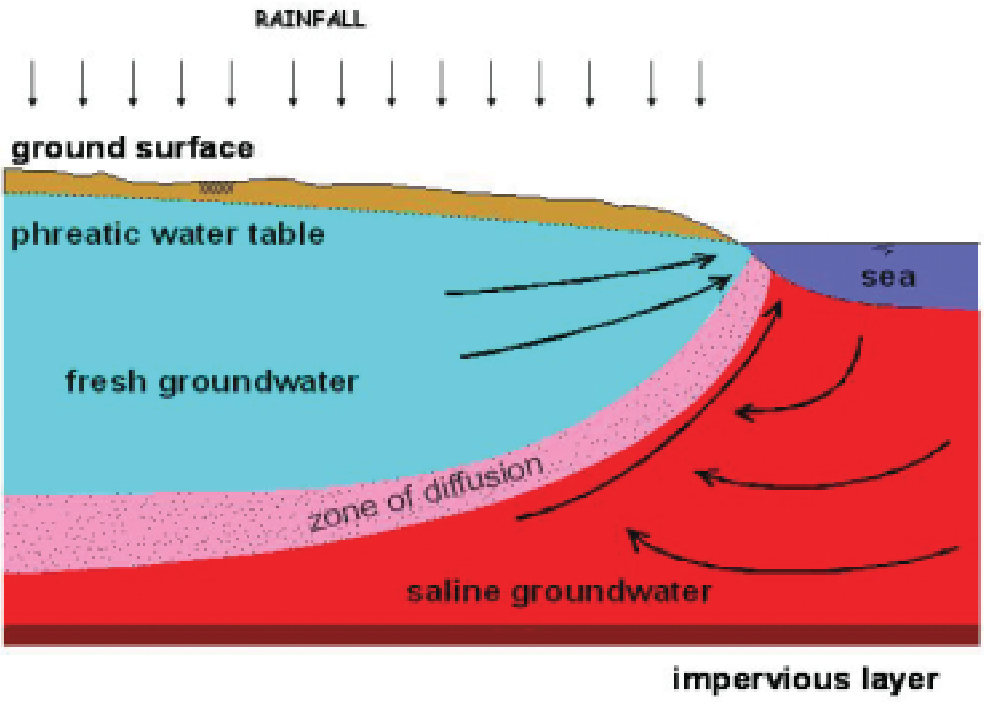


Figure 2. Conceptual sketch of how fresh and saltwater meet and mix in a coastal aquifer[a]

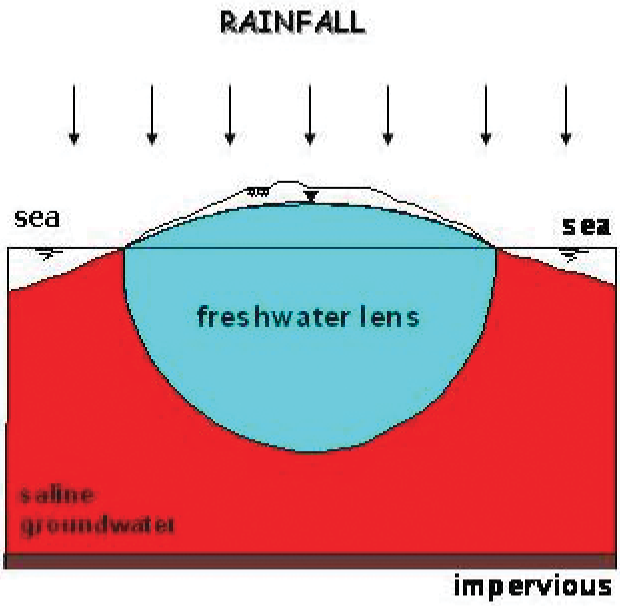


Figure 3. Conceptual sketch of a freshwater lens under an island[a]

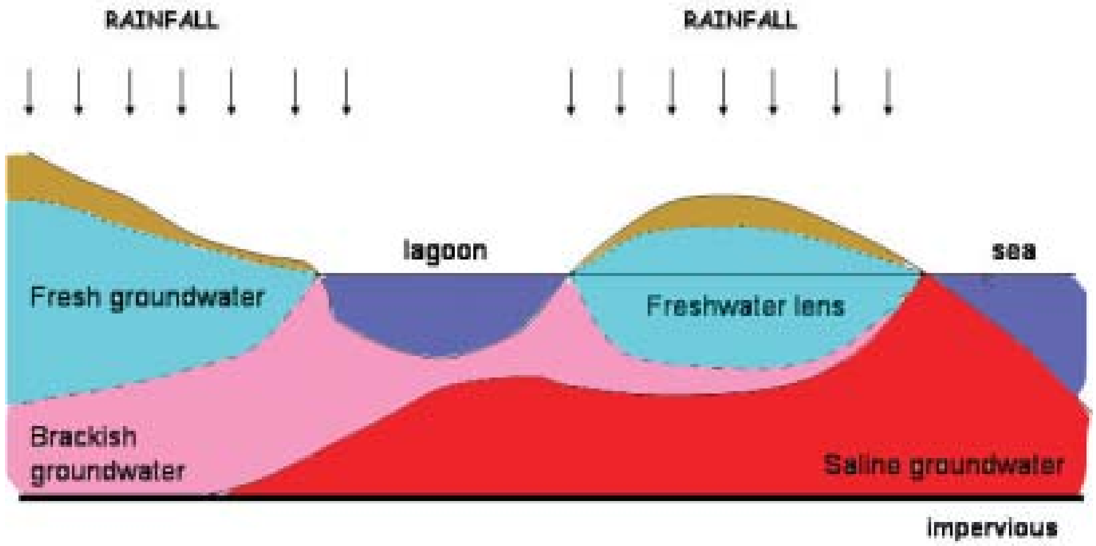


Figure 4. Conceptual sketch of fresh, brackish and saltwater under a strip of land bordered by a lagoon

- They are shallow and unconfined and with little retention capacity (i.e. in the form of organic matter), which also facilitates fast leaching of pollutants into the subsurface
- They are bounded by saline groundwater, and saltwater intrusion due to over-pumping is a real risk posing restrictions on amounts and means of pumping, even without the incidence of the tsunami

In general, there is growing pressure on the coastal aquifers from increased abstraction for domestic as well as other uses, including agriculture, and from increased load of contamination from various sources. The tsunami basically has aggravated this precarious situation and accentuated the need for protection and proper management of the coastal aquifers.

Finally, alternative groundwater resources from aquifers more inland are not as abundant, reliable and adequate in natural water quality as the coastal groundwater. Also, the transfer of treated surface water to the coastal areas, especially in the lagoon areas, are relatively costly and may conflict with traditional use of this water for other purpose, most notably irrigation, inland. Furthermore, since the population density is relatively higher along the coast, the demand for good quality drinking water here is higher, emphasizing the need for maintaining the coastal aquifers as a sustainable local source.

POSSIBLE IMMEDIATE EFFECTS ON COASTAL GROUNDWATER SYSTEMS

The tsunami affected the groundwater in various ways, the most direct and notable being the salinization from seawater. In addition, the groundwater may have been polluted from the leakage of various hazardous waste or chemicals (gasoline products, medicine, pesticides, etc.) that were spilled as a result of breakage of fuel tanks, storage containers, etc. Though these effects may be locally more critical and longer lasting and hence deserve special attention, the salinization was a widespread phenomenon that affected parts of the coastal aquifers along most of the east coast and will be the focus of this project.

The salinization could have occurred due to various mechanisms:

Infiltration from inundated land during the wave passage

Though the flooding during the tsunami was of a short duration it is expected that saltwater infiltration through the soil surface was significant, especially because the soils are very permeable and the flooded areas large (Figure 5). It is estimated that a stretch of land of between 50 m and more than 1 km from the coast was inundated[2]. The considerable variability was caused by a number of factors, including slope of the land (greater inundation distances in flatter areas), bathymetry (underwater topography), and orientation of the coastline. The infiltration of saltwater may have been partly restricted due to the phenomenon of air entrapment, i.e. the fact that air in the soil could not escape to allow water entry due to the massive inundation.

Salinization of groundwater by infiltrating water from accumulating water bodies

Infiltration of saline or brackish water continued in areas, which remained flooded after the tsunami (low-lying areas, eroded pockets, restricted drainage canals, etc.) (Figure 5). As opposed to the above, this mechanism prolonged, even after the retreat of the flood waves. Stagnation of water inland was further aggravated by the disruption and filling of natural or man-made drainage canals by the tsunami. However, the salinity from this source has decreased with time as rainwater following the tsunami has diluted the water bodies.

Salinization of groundwater by entry of water from flooded wells

Open shallow wells were totally filled with seawater during the passage of the flood waves. The excess water in the wells has entered and salinized the surrounding soil and groundwater.

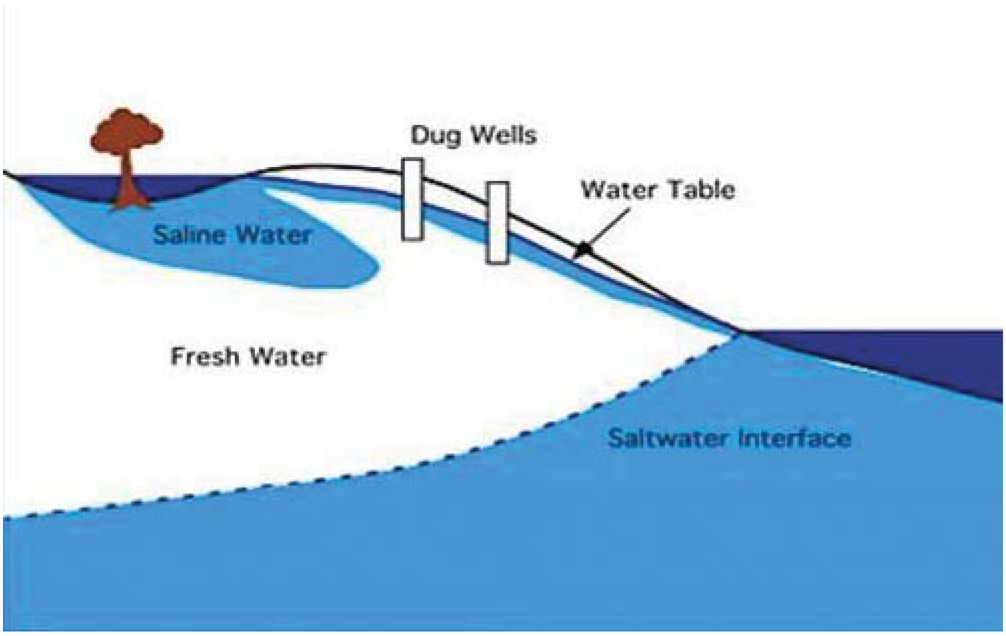


Figure 5. Influence of the tsunami on the coastal aquifer, showing infiltration of saltwater from land surface and water bodies[b]

[2]http://walrus.wr.usgs.gov/tsunami/srilanka05/index.html

Increased sea water intrusion by landward shift of the coast line

The destructive force of the tsunami removed coastal sediments resulting in a retreat of the coast line in some areas; the intrusion of sea water underground in the coastal aquifers is expected to shift landward over a similar distance, which may have affected nearby groundwater production wells.

Disturbance of the freshwater lens due to a pressure wave

The tsunami wave caused an underground pressure wave, which may have disturbed the freshwater/saltwater equilibrium. The pressure of the wave may have caused mixing of the fresh groundwater with saline water from below. This could result in a reduction of the volume of the freshwater lens.

Salinization from flooding of the lagoons and river mouths

The tsunami reached further inland in places where topography and man-made and natural barriers did not obstruct its advance. Lagoons, especially on the east coast, and river mouths may have funneled tsunami water, giving rise to large local variations in the flooding pattern. Where lagoons were flooded, the increased salinity, and possibly the hydraulic gradient, may have influenced the groundwater flow pattern and the configuration of fresh, brackish and saltwater in the subsurface (Figure 6).

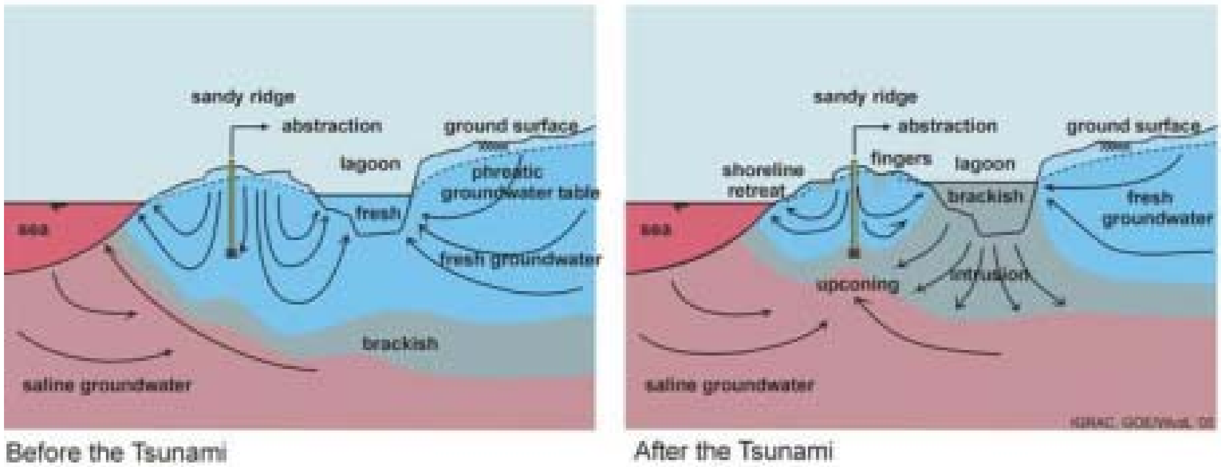


Figure 6. Influence of the tsunami on the coastal lagoons and associated groundwater (note: in this case the lagoon water was fresh prior to the tsunami)[a]

RECOVERY OR LONG TERM EFFECTS ON COASTAL GROUNDWATER SYSTEMS?

As time passes, the saltwater that has infiltrated, through the soil surface or from water bodies and wells, moves through the groundwater in a general downward and lateral direction towards the coast (or maybe towards a lagoon or inland water body). Eventually, and with a continued influx of rainwater, the saltwater will be suppressed, mixed, diluted and transported to the open water. These are natural processes that occur and allow that over the longer term, the aquifer can recover and return fresh.

The International Groundwater Assessment Centre (IGRAC) made some preliminary estimations of the time required to naturally rehabilitate the coastal aquifers[3]. Using a numerical simulation model and applying some simplifying assumptions of the land-groundwater system it was estimated that it would require a couple of years to obtain pre-tsunami salt concentrations in the aquifer, under conditions prevailing in the Maldives, which is an archipelago to the west of Sri Lanka, also impacted by the tsunami. Some of the uncertainties associated with this simulation are related to:

1. Insufficient knowledge of actual conditions. Some of the factors/parameters that have not been assessed based on actual conditions and measurements, and may significantly influence the results are:
    - The hydraulic conductivity of the aquifer, which determines the rate at which water moves through the sediments
    - The depth of the aquifers, i.e. if there is an impermeable layer restricting the freshwater lens
    - The influence of actual rainfall occurring in the affected areas
    - The amounts and patterns of pumping
2. Furthermore, some important processes/phenomena may not have been incorporated sufficiently:
    - The infiltration from stagnant water bodies has not been included
    - The possible disruption of the freshwater lens due to an underground pressure wave has not been included
    - The possible slow leaching of the saltwater in the aquifer due to low permeable zones, or so-called double-porosity characteristics

PUMPING AND CLEANING OF WELLS IN THE COASTAL AQUIFERS

Pumping wells

Most of the wells in the coastal areas are open, shallow wells, dug and cased with concrete casings, with diameter around 1-1.5 m and depth 3 to 6 m. The majority of wells are private and used for household use (drinking, bathing, and washing). Some wells also provide irrigation water for irrigated agriculture in the areas.

When extracting groundwater from the coastal aquifer from wells, some basic principles should be clear. Due to the proximity to the sea, there is a permanent risk of ingression of saltwater into the aquifer and into the wells. When pumping, the interface between the fresh and saltwater may be interrupted (Figure 7), resulting in so-called upconing of saltwater and possibly breakthrough of saltwater into the well.

The upconing depends on the drawdown in the well, i.e. the decrease in water level in the well from the static situation (being a function of the pumping rate and the hydraulic conductivity of the aquifer), and the depth of the well intake in relation to the bottom of the freshwater lens. The theory says that for each unit of drawdown, the upconing will be approximately 40 units. This means, that to avoid upconing, the distance between the bottom of the well and the saltwater interface should be more than 40 times the expected lowering of the water level in the well during pumping. As an example, a drawdown of 0.5 m will cause a local uplifting

[3]http://igrac.nitg.tno.nl/tsunami1.html

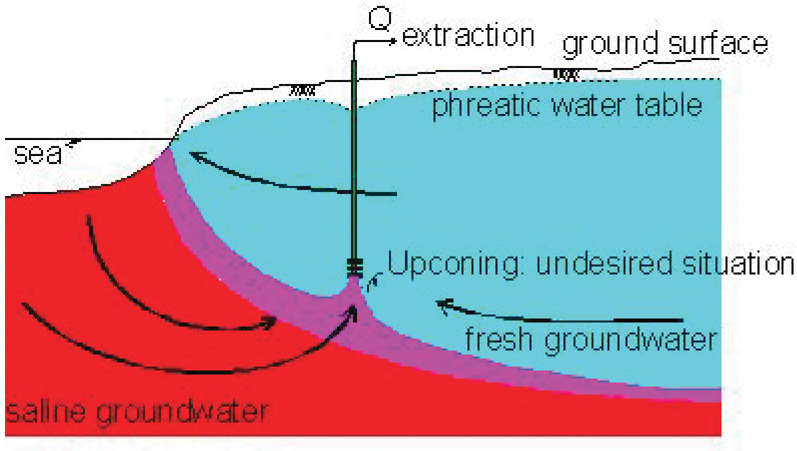


Figure 7. Upconing of saltwater into a well close to the coast[a]

of the interface by 20 m. It also explains why a well close to the coast stands a great risk of getting salinized if completely emptied. In general, the risk of saltwater intrusion in wells is increased when:

1. Pumping is intensive and prolonged, causing removal of a large part of the standing water in the well or constant lowering of the water table
2. Pumping is from wells close to the coast
3. Wells are deep
4. Pumping is performed in the dry season when the saltwater lens is smaller

Cleaning wells after the tsunami

A lot of effort went into cleaning wells after the tsunami, and much discussion and uncertainty regarding the best approach emerged. The rationale for cleaning wells was to revert the wells to their pre-tsunami condition and most methods involved pumping to remove the standing saltwater and any accumulated unwanted matter in the wells (sand, debris, waste, etc.) and possibly to purify the wells by in-situ chlorination.

Due to the perceived emergency of rehabilitating this large number of wells many different actors were involved (from NGOs, and WRB to volunteers and well owners), resulting in an overall quite un-coordinated, haphazard and non-professional approach. In addition, the outcome of the cleaning was not in general positive in the sense that many wells persisted to be saline after the cleaning procedures. It is likely that the excessive and repeated pumping and cleaning of the wells in many cases have deteriorated the salinity condition of the wells.

Various guidelines exist on the emergency cleaning and disinfection of wells, basically focusing on the bacteriological contamination following floods and other natural disasters (e.g. by WHO, NGWA, and CDC)[4]. However, no guidelines existed, at the time of the tsunami, on the approach to decontaminating tsunami, or saltwater, affected wells, let alone procedures relevant for the specific Sri Lankan conditions.

[4] http://www.who.int/water_sanitation_health/hygiene/envsan/technotes/en/
http://www.ngwa.org/pdf/welldisinfection.pdf
http://www.bt.cdc.gov/disasters/wellsdisinfect.asp

DENSITY EFFECTS OF SALTWATER INTRUSION INTO SOILS AND GROUNDWATER

When investigating tsunami impacts on salinity in coastal aquifers and giving recommendations to cleaning and rehabilitation of wells it is important to understand some fundamental physical and chemical characteristics, and differences, between saltwater and freshwater that govern how the saltwater entered into the previously freshwater systems.

Seawater, which is highly saline, is significantly heavier, or in technical terms denser, than freshwater. This means that freshwater, coming in from natural rainwater, tends to 'float' on top of the saltwater underneath the coastal areas (as in Figure 2, Figure 3, Figure 4). This is very fortunate because it ensures that fresh groundwater can easily be extracted from shallow depth for water supply etc. Also, because the difference between the two densities is high, the two waters do not mix, but rather create a stable system with a relatively sharp interface between them.

When the tsunami struck and saltwater entered from above, directly into wells and into the soil by infiltration, denser saltwater was floating on top of the less dense freshwater. This is basically an unstable situation that can be ameliorated either by slow mixing and diffusion, or by a more rapid process of overturning, whereby the saltwater sinks as separate 'blobs' or 'fingers' of water through the freshwater, without mixing with it, to reach the saltwater-freshwater interface below, again creating a stable situation (Wooding et al., 1997a, b). This process is likely to occur shortly after the tsunami when the density contrasts are large between incoming saltwater and resident freshwater. As time goes, and after this process has potentially occurred, the mixing of the freshwater and less concentrated and less dense saltwater, by diffusion, is likely to occur.

SALINITY MONITORING AND QUANTIFICATION

Water salinity is a measure of the amount or concentration of salts contained in an environmental water sample. Salts in water are dissolved and are present as charged species, called ions, deriving from the interaction of rainwater (containing little salt) with soil, geological materials and other elements in its passage from the interception with the land surface to its discharge to the sea. Hence, rainwater has very little salinity, whereas seawater has the highest salinity.

Salinity can be measured by the ability of the water to transmit a current through it. The higher the salinity, the higher is this ability. It is indicated by the electrical conductivity (EC) and is measured in micro Siemens per cm (µS/cm). It can also be measured by the total amount of dissolved solids (TDS), which gives a gravimetric measure of the mass of the ionic, dissolved species present in the water (e.g. in mg/l). Sometimes salinity is also measured as the content of chloride ions (mg Cl/l) as most of the salinity is attributed to sodium chloride. The unit used throughout this report for salinity is µS/cm. In this unit, seawater has a salinity of 50,000 to 55,000 µS/cm and rainwater a salinity of about 100 µS/cm. The water temperature affects the electric conductivity so that its value increases from 2 up to 3% per 1 degree Celsius. Usually, it is compensated for by the meters used to measure salinity.

To convert the EC of a water sample to TDS (in ppm, or mg/l), the EC (in µS/cm) must be multiplied by a factor between 0.46 and 0.9 (depending on the unique mixture of the dissolved materials). A widely accepted conversion factor is 0.67:

TDS (ppm) = EC (µS/cm) x 0.67

SALINITY LEVELS OF DRINKING WATER

WHO has established guidelines on drinking water quality, encompassing most of the parameters relevant in a health perspective (WHO, 2004). For salinity, there is no health-based guideline because salinity is a measure of various ionic species that together give rise to a salty taste of the water and because generally salinity is not of a health concern in the levels that people accept to drink.

High salt intake from drinking water and food may cause hypertension. However, it has not been confirmed that there is a firm relationship between high salinity in drinking water and the occurrence of hypertension. Hence, only indicative guidelines based on taste considerations are given (Table 1). Even these values should not be considered as strict upper limits to what is acceptable as what is acceptable to consumers depend very much on individual taste and habit.

Table 1. Taste threshold for individual ions in drinking water contributing chiefly to salinity (From WHO, 2004)

	Taste threshold, mg/l
Sodium (Na)	200
Chloride (Cl)	200-300
Calcium (Ca)	100-300
Magnesium (Mg)	<100

In general, a salinity level below 500 µS/cm in drinking water is considered good quality. For levels up to 1000 or 2000, the salty taste becomes increasingly objectionable to most people.

RESEARCH OBJECTIVES

The overall objective of the project was to support the efforts of re-establishing a functioning water supply in the affected areas and to ensure that viable long-term solutions are sought, focusing on groundwater. The specific objectives were:

1. to support the immediate relief efforts aimed at rehabilitating the decentralized water supply from groundwater. The major issues in the coastal areas were the cleaning and ensuring the long term functionality of the wells.
2. to establish a well monitoring program (for water quality) in representative affected areas on the east coast by the regular collection of data, with special emphasis on salinity, and some water supply and health relevant parameters pertaining to wells.
3. to assess the immediate and intermediate impacts of the tsunami on the wells in terms of salinity. The main focus here was to assess the time period required for the recovery of the wells within the first seven months after the tsunami, which corresponded with the dry season following the tsunami. This in turn would help strategise on alternative sources for domestic water.
4. to propose further studies and interventions required to secure the long-term quality and sustainable exploitation of the groundwater resources, to support the needs of the water supply in the east coast.

[a] Figure from IGRAC
[b] Figure from C. Harvey

Chapter 3

Research methodology

The project was carried out in two parts:

1. The support to the rehabilitation of wells on the east coast
2. The monitoring programme established at three sites on the east coast.

SUPPORT TO THE REHABILITATION OF WELLS ON THE EAST COAST

IWMI's efforts in this respect included:

- Preliminary visits to the east coast to inspect the damage on wells, discuss with operators on the ground regarding the cleaning of wells, observe and report their experiences, and to make preliminary measurements on salinity in wells in affected areas
- Liaise with NGOs and local authorities at district level to collect information on the actors involved and collect data on salinity from their monitoring activities
- Participate and contribute with technical knowledge in district and national level coordination meetings related to water supply and sanitation, and specifically in meetings related to well cleaning and salinity problems
- Contribute to a workshop on water quality and well rehabilitation[5]
- Develop and disseminate guidelines for the cleaning of wells and protection of groundwater in the wake of the tsunami
- Contribute to the streamlining and coordination of data collection from wells on the east coast

ESTABLISHMENT OF A MONITORING PROGRAMME

Despite the many efforts in cleaning wells and collecting data from these activities, it was felt that a systematic and consistent monitoring programme was needed to scientifically assess some of the immediate to intermediate impacts of the tsunami on the salinization of the wells and the associated aquifers. The advantages of such a program were:

- Data was collected by the same people, using the same equipment throughout the campaign

[5]'Water Quality and Well Rehabilitation Workshop', Trincomalee, May 2-3, 2005, organized by UNICEF for local PHIs and NGOs involved in water and sanitation.

- Data was collected on a recurrent basis and in the same wells and compiled into one database enabling the analysis of temporal and spatial trends more systematically

Finally, the field monitoring programme of this project was planned to be continued and extended through a second phase, enabling also longer term impacts to be assessed.

Field sites for monitoring program

Three sites on the east coast were selected for the monitoring programme after discussion with the stakeholders and authorities with knowledge of the local conditions: Kallady, Kaluthavalai and Oluvil, which belong to the districts of Batticaloa and Ampara. (Figure 8, Table 2). The sites were chosen to be representative of some of the general characteristics on the east coast with respect to physiography, demography, land and water use. Also, areas that were severely devastated by the tsunami were chosen, as these areas were expected to suffer most from salinization. Some tsunami damage and impact assessment data from the various districts on the east coast are given in Table 3. Finally, security considerations related to civil unrest, hindered the selection of some sites that would have been important from a scientific and humanitarian perspective (like Vakarai further north in Batticaloa District).

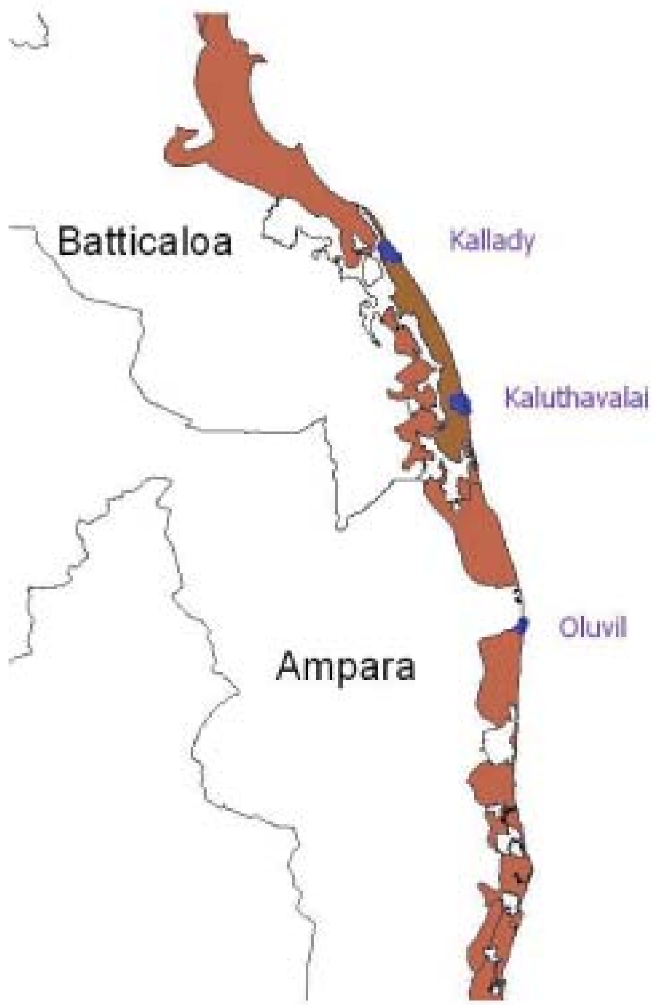


Figure 8. Monitoring sites on the east coast

Table 2. Main characteristics of monitoring sites

	Kallady	Kaluthavalai	Oluvil
District	Batticaloa	Batticaloa	Ampara
Size of study area	2.5 km^2	2.7 km^2	1.5 km^2
DS divisions covered	Manmunai North	Manmunai South and Eruvil Pattu	Addalachchenai
GN divisions covered	Nochichimunai Kallady Kallady Uppodai Kallady Veloor	Kaluthawalai 1-4	Oluvil1-7
Approx, no. of families	500	300	1000
Overall land use	Residential and open land	Vegetable cultivation	Paddy fields and residential
Soil type	Sandy regosol	Sandy regosol	Sandy regosol and alluvial soil of variable texture
Terrain	Flat, less than 7% Highest elevation: 14 m	Flat, less than 10% Highest elevation: 15 m	Flat, less than 4% Highest elevation: 12 m
Bordered by lagoon	Yes	Yes	No
Width of land strip at study area	1.5 – 2.0 km	2.7 -3.0 km	N.A.
No. of wells monitored	43	49	56

Table 3. Extent of tsunami damages in the northern and eastern Sri Lankan districts[a]

District	No. of death	No. of families affected	No. of displaced persons	No. of relief camps
Ampara	10,436	183,527	38,624	125
Batticaloa	2,497	203,807	57,219	100
Trincomalee	957	51,863	31,896	76
Vavuniya	0	641	111	5
Mullaitivu	3,000	24,557	5,373	19
Kilinochchi	560	40,129	10,568	12
Jaffna	2,640	48,729	13,652	43
Total NE Provinces	20,090	553,253	157,443	380

[a]Source: Consortium of Humanitarian Agencies in Sri Lanka (2005)

Monitoring program

The field monitoring program was initiated in March 2005 (2.5 months after the tsunami). A total of approximately 150 existing wells were selected within approx. 2 km distance from the coastline covering both affected and non-affected wells, approximately 50 wells at each site (Table 1). Because of the large density of existing wells not all wells were selected, and a pattern of four transects in each sites, with wells on lines perpendicular to the coast line was selected, with a distance between adjacent monitoring wells of 100-150 m (Figure 9*,* Figure 10*,* Figure 11). However, as the study progressed other wells were added to the monitoring program, to include the diversity of the types of wells that were encountered.

Salinity, groundwater level, turbidity, and temperature were monitored on a regular basis, at 20 to 40 day intervals (Table 4). Five field trips, each of 5 days duration, were required for the collection of information, with the last one occurring 6.7 months after the tsunami.

The monitoring period commenced at the tail end of the rainy season, and followed through the dry season. No significant rain fell in the areas during the period February to August, 2005.

Table 4. Field monitoring schedule

Monitoring trip no.	Dates	No. of months after the tsunami	Interval between trips, days
1	March 8 to 13	2.4	-
2	March 28 to April 2	3.1	20
3	May 3 to 9	4.3	37
4	June 10 to15	5.5	37
5	July 15 to 20	6.7	35

Figure 9. Sampling transects (red lines 1-4) at the Kallady site

Physico-chemical parameters

Groundwater levels in the wells were monitored by a measuring tape. Salinity, temperature, and turbidity were monitored by a 4.5 cm diameter stainless steel Troll 9000 monitoring probe from In-Situ Inc.[6] (Figure 12). Individual sensors registered the salinity (here reported as EC, specific electrical conductivity), turbidity, temperature, and the hydraulic pressure at the water level of the sampling point. The probe automatically compensated the EC measurements for temperature.

Because the probe was measuring the parameters in-situ, i.e. directly inside the well or whatever other water body, and because it was connected directly to a data logger (Figure 13), there was no need to extract samples and either measure them in the field with a portable monitoring probe or devise or to bring them to a laboratory for analysis. Also, the monitoring of salinity at different depths of a well could easily be achieved by sinking in the probe to the various levels and logging the results directly.

Figure 10. Sampling transects (red lines 1-4) at the Kaluthavalai site

Prior to the field trips, and to test the accuracy of the Troll probe, it was calibrated with a standard solution supplied with the instrument. Furthermore, it was tested using a standard addition principle with regular kitchen salt against the concurrent measurement with a handheld conductivity meter. The agreement between the two measurements was satisfactory and the EC was linearly correlated with salt content up to a level of 14.000 ìS/cm, with an intercept of (0,0) (Figure 14).

[6]www.in-situ.com

In addition to the variables mentioned above, the physical dimensions of the wells, the type of well (tube well or open dug well), the primary function of the wells (whether domestic, agricultural or production), the actual use of the wells (for drinking, bathing/washing, irrigation and whether in use at present), the water lifting system, the ownership of the wells (whether public or private), and whether the wells had been flooded by the tsunami was registered. At each monitoring visit, it was also recorded whether the wells were in actual use and whether any cleaning of the wells had occurred. The location of the wells and other measurement points were recorded with a GPS. Besides the wells, lagoon water, seawater, canal water and tank (small reservoir) water were monitored in a few locations.

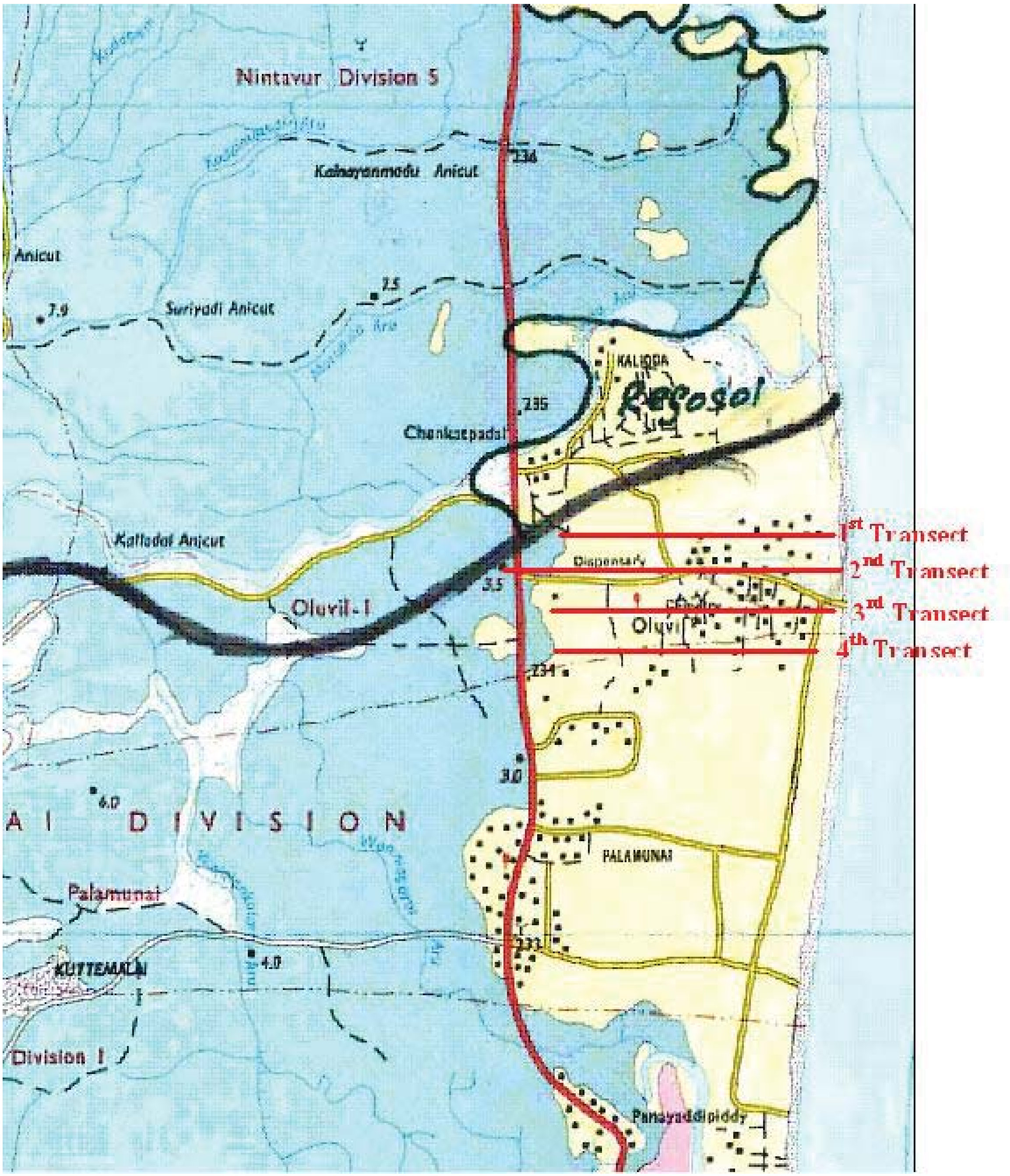


Figure 11. Sampling transects (red lines 1-4) at the Oluvil site

Figure 12. The Troll 9000 in-situ probe used in the monitoring program. Note that not all sensors applied in this study

Monitoring of wells and water bodies for mosquito vector breeding

When the Tsunami struck, concerns were raised over possible outbreaks of vector borne diseases, associated with increased breeding habitats, created by the flooding (resulting in ground water pools) and abandoning of wells due to high salinity. On the current status of malaria, technical updates have been provided by the World Health Organization (WHO, 2005a and 2005b). Prompted by these concerns, although not proposed in the original study, wells were monitored for mosquito vector breeding. An assessment on breeding of mosquito vectors was carried out, especially for those that were important in the transmission of diseases, and having the potential to colonise newly created surface water habitats, wells, paddy fields and other permanent surface water bodies.

As such, in this short study, an attempt was made to monitor the wells and selected surface water bodies for the presence of mosquito larvae and pupae, in order to assess the prevalence of at least the major genera of mosquitoes that are of importance from a disease perspective in the region. The mosquito larvae were sampled following standard methods (Amerasinghe & Ariyasena, 1990), but were not identified to the species level in all cases, due to lack of resources and time. Sampling was primarily centred on all types of wells (production wells, tube wells, agricultural wells and domestic wells), of which the domestic wells predominated. Other sampling habitats were temporary ground pools, sewage drains (lined and unlined), cemented and un-cemented ponds, a few rice fields and agricultural drainage canals, which accounted for around 10% of the total number of samples. The species level identification, which required more resources, funds and time, was not attempted during this study but envisaged to be undertaken during a second phase of the project. The selected genera identified using standard keys were the *Anopheles* (malaria), *Culex* (filariaisis and Japanese encephalitis) and *Aedes* (dengue) (Amerasinghe, 1992; Amerasinghe, 1996; Amerasinghe 1990).

Figure 13. The Troll 9000 monitoring probe and the associated data logger

Rainfall at the three monitoring sites

The rainfall pre- and post-tsunami was analyzed in order to understand the degree to which the pre- and post-tsunami rainfall conditions were particularly dry or wet compared to a 'normal' year. As rainfall is the primary agent for restoring the freshwater conditions in the aquifers the amount and timing of post-tsunami rainfall would give an indication of whether the salinity problems were representing a relatively bad or good situation and whether subsequent rains would be likely to remediate the situation relatively more or less than what was observed in this study.

Rainfall for each of the three sites was analyzed by using data from the rainfall station closest to the individual site. Rainfall data were obtained from the Department of Meteorology – Sri Lanka. Monthly data were used, and the stations and periods are given in Table 5. If the closest rainfall station had a relatively short time series of data, it was augmented by including data from another station a little further away. The maximum distance between a site and the corresponding station was 20 km and all stations were close to the coast (within 10 km) which was assumed to be the most representative. The two data series were merged by simple extension and averaging during periods with double coverage.

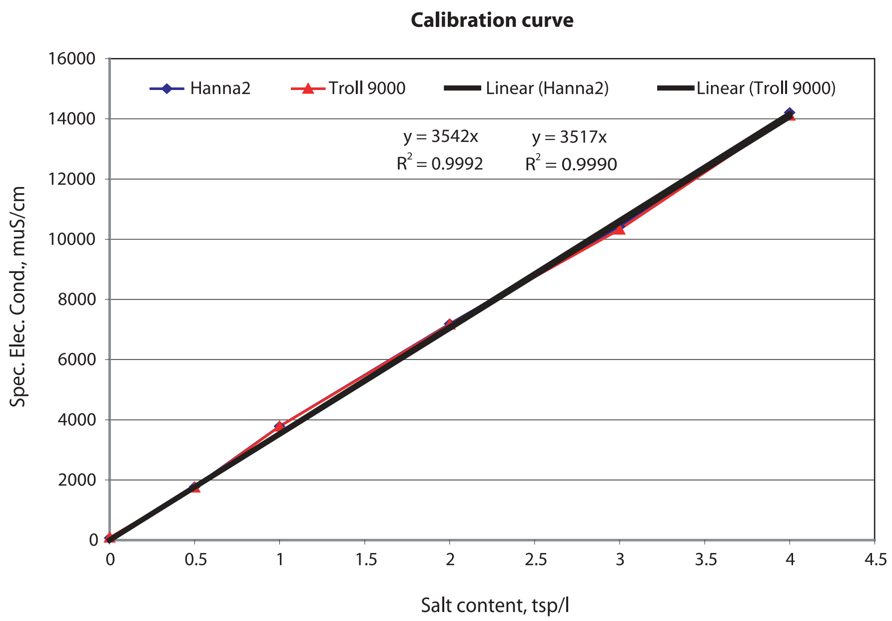


Figure 14. Calibration curve for the Troll 9000

Table 5. Rainfall data used

Site	Station	Coordinates		Period
		Longitude	Latitude	
Kallady	Batticaloa	81.699	7.7161	1869 - 2005
Kaluthavalai	Kalmunai and	81.83	7.42	1961 - 2004
	Navakiri Aru Tank	81.72	7.47	1989 - 2005
Oluvil	Akkaraipattu and	81.85	7.22	1993 - 2005
	Sagaman Tank	81.811	7.126	1872 - 2005

Chapter 4

Results and discussion

Figure 15. Initial well salinity monitoring in Maruthumunai, end of January, 2005

SUPPORT TO THE REHABILITATION OF WELLS ON THE EAST COAST

Problems encountered in the cleaning of wells

It was clear from the initial visits and personal communication with NGOs and local authorities that the well cleaning procedures were carried out in an uncoordinated and haphazard manner and with limited understanding of the physics of groundwater and wells and the possible negative consequences of the cleaning procedures.

However, providing clear, consistent and comprehensible guidance on the well cleaning was not a straightforward task for several reasons:

1. No formalized guidelines existed that were relevant for the situation encountered after a tsunami disaster. The existing emergency guidelines for well cleaning addressed basically the problems of wells being destructed and contaminated after flooding with dirty freshwater, and related more to the problems of microbiological contamination. All of these guidelines actually recommend the purging, or emptying, of the wells to remove contaminated water prior to chlorination and/or adviced to continue pumping until the well water become clear and free of saltwater.

2. As groundwater salinity varied quite substantially temporally as well as spatially, the same approach could not be expected to be generally applicable. The guidance required should apply to saltwater flooding and in addition take into account the processes generating the saltwater intrusion and spreading and their dependence on time and space under given conditions.

In general, cleaning of wells after the tsunami may or may not be fruitful, depending on the local and actual conditions of the wells and the surrounding aquifer and the knowledge and methods applied. In theory, removing the accumulated saltwater in the wells, as well as water accumulating in depressions on the ground, immediately after the tsunami and exporting this water to the sea would be the optimal solution and could alleviate the ensuing saltwater problems. This idea intuitively was behind the cleaning efforts initiated. However, the reality was different and the lack of apparent success of the cleaning was associated with the following explanations:

1. Most wells were not pumped immediately after the tsunami, leaving time for the saltwater in the wells to spread and dilute into the surrounding groundwater, yielding a smaller, or negative, effect of emptying wells later on.
2. Saltwater entered not only the drinking water wells but also the soil and groundwater from the albeit short-duration flooding by the tsunami waves. Hence, saltwater intrusion and contamination was much more widespread and of larger implications than just removing it from the wells themselves.
3. Water pumped out of the wells was not removed from the area; most often it was just left to infiltrate next to the well, basically recycling it to the groundwater.
4. Pumping occurred at a much too high intensity, giving rise to problems with the physical stability of the wells. Because most of the wells in the affected areas on the east coast were dug in sand, and only reinforced on the sides by concrete cylinders, they would cave in, incline, sink in or collapse if too much water and sand was removed suddenly.
5. Excessive pumping rates also increased the risk of ingress of contaminated water from other areas, e.g. from toilet pits, burial grounds or from accumulated salty surface water
6. Finally, excessive and repeated pumping could have resulted in saltwater upcoming from below, which is a general phenomena or risk in coastal-near regions and not strictly related to the tsunami (Figure 7).

After some point in time, pumping to clean wells should only be done to remove debris and sludge and not to decrease salinity. And pumping should be performed cautiously without creating large drawdowns. At this point, the lesser the aquifer was pumped, the faster the natural recovery of the aquifer from infiltrating rainwater would be.

IWMI's involvement

In an attempt to support in the rehabilitation and cleaning of the wells and the mitigation of saltwater problems, IWMI developed various sets of guidelines, appropriate for various times after the tsunami and applicable to the east coast sandy aquifers on which field experience had been collected. Appendix A gives the recommended approach in mid-February where it was still deemed appropriate to pump wells for cleaning, but applying cautious and slow pumping without total dewatering of the wells. Relatively shortly after the tsunami, wells still not used after the tsunami were found to be stratified with very high levels of salinity at the bottom and lower levels at the top, indicating that the primary recovery of the wells was occurring, due to the processes of mixing with rainfall, diffusion and the sinking of the more dense saltwater (see below). At this point in time it was recommended to only clean wells by pumping out a partial volume of the wells at the bottom, including sludge.

Later, in mid-May a new set of guiding principles for the cleaning of wells and rehabilitation of the aquifers were issued (Appendix B). In these guidelines, basically, pumping of wells for the amelioration of the salinity was not recommended. This set of guidelines were also reproduced in a series on Best Practices Guidelines from IUCN, in collaboration with IWMI, on the issues and approaches to problems related to water pollution after the tsunami (IUCN, 2005).

The guidelines were disseminated to relevant actors in the field as well as national and district level authorities, either through the internet (IUCN guidelines), email (Appendix A and B) or at meetings where the guidelines were supported by a presentation of the present project and preliminary results, the theory and processes behind salinization of wells and aquifers, potential impacts and recommendations for the cleaning, usage and protection of wells in the wake of the tsunami. Finally, at the end of the study, a final set of guidelines for well use and groundwater protection of the coastal areas were developed and disseminated to the NGOs and other stakeholder organizations. These guidelines were applicable for the period after 10 months after the tsunami when bowsering of water was still going on (Appendix C).

Meetings and presentations were given at local, national as well as international level:

- District level WATSAN coordination meeting, UNICEF premises, Batticaloa, Jan. 26, 2005
- ‘Water Quality and Well Rehabilitation Workshop’, Trincomalee, May 2-3, 2005, organized by UNICEF
- Sri Lanka Consultative Committee Meeting, IWMI, May 10, 2005.
- National level WATSAN coordination meeting , UNICEF, Colombo, May 20, 2005
- CARE Main Office, Colombo, June 14, 2005
- NSF Meeting, Colombo, June 30, 2005
- NSF Meeting, Kandy, Sep. 19, 2005
- Asia Pacific Network Workshop, Galadari Hotel, Oct. 5, 2005
- Stakeholder organization meeting, IWMI, Oct. 27, 2005
- 37th APACPH Conference & 2005 Asia Pacific Health Forum, Nov. 19-23, Grand Hotel, Taipei, Taiwan

The Trincomalee workshop resulted in a UNICEF publication with input from IWMI on the consequences of the tsunami on the coastal aquifers in eastern Sri Lanka, which included a set of guidelines for well rehabilitation relevant at that time (UNICEF, 2005). It was meant for the NGO’s and public health inspectors coping with the requirements of maintaining the water quality standards.

Reflecting the relevance and urgency of the problems of salinization of water resources, guidelines relevant for the eastern Sri Lankan conditions were also developed by NWSDB and UNICEF, and the French Red Cross/Veolia Water Force, pertaining to the situation in January. Basically, these guidelines were in agreement with the first IWMI guidelines, and were stressing the overriding principles of cautious pumping, removal of purged saltwater, and prior and subsequent monitoring and recording of salinity, and avoidance of impact from and to adjacent wells.

UNICEF in collaboration with the NWSDB took initiative to develop a protocol for well cleaning in Batticaloa District, encompassing a requirement to follow the guidelines, registration of partners before the unset of cleaning, the designation of specific geographical areas for various partners to work in, the requirement to use standard well cleaning monitoring charts and requirement to report to UNICEF/NWSDB on collected data and information. Though these efforts were not totally effective, it did give some overall control of the pumping activities in this district. IWMI was involved in the development of the standard well cleaning monitoring chart, headed by ICRC.

Finally, The UN Humanitarian Information Center took initiative to coordinate the collection, compiling and GIS database development of data from the well cleaning operations. Data was provided from the NGOs and local authorities involved in the cleaning, adhering to the protocol mentioned above. So far, no results or reports have been published as part of this work.

Initial data, indicating stratification of salinity in wells

End of January, 2005, IWMI made a reconnaissance trip to the east coast to assess the situation and the feasibility of initiating a study on the tsunami impacts on wells and groundwater. On this occasion, wells were monitored in the Kalmunai area (city of Maruthumunai), Ampara District. The aim was to asses the salinity relatively short after the tsunami as well as talk to people on the ground regarding their water supply situation.

Table 6 shows the salinity of the wells (not properly geo-referenced) that were located at increasing distance from the coast line (Photos in Figure 15 and Figure 16 were taken during the sampling). The wells were between 3 and 5 m deep and the groundwater level at this point was 1.5 to 2 m below ground level. The data shows that the wells were very saline, but the salinity was (with one exception) significantly higher at the bottom than at the top, up to a factor of almost 10. The salinity levels as well as the stratification decreased with distance from the coast. The explication for this could be that the wells close to the sea were abandoned and had not been in use since the tsunami whereas the wells more inland (last two) had been pumped causing a mixing of the well water. The two most distant wells belonged to houses that withstood the tsunami and hence their owners had tried to revive their water supply. It is however not clear whether these wells were in fact totally inundated by the waves.

Figure 16. Well sampling very close to the coast where the tsunami eroded large volumes of coastal sand

Evaluation of the effectiveness of the support to the rehabilitation of wells on the east coast

It may be asked, rightfully, if the guidelines and other support extended by IWMI and others to the well cleaning efforts did improve the approaches and methods for well cleaning and ultimately if the well cleaning efforts were effective, i.e. improved the well water quality, including the salinity, relative to a situation where the wells were not cleaned. Interesting as well is whether the cleaning procedures kept the aquifers intact, or impacted their properties somehow.

Table 6. Salinity levels in wells in Kalmunai, on January 26, 2005

Well no.[a]	Distance from the coast	Salinity at the top of the well	Salinity at the bottom of the well
	m	EC, µS/cm	EC, µS/cm
Well no. 1	70	5500	>19900[b]
Well no. 2	100	200	16400
Well no. 3	100	4400	17000
Well no. 4	150	3800	1100
Well no. 5	150	4400	18000
Well no. 6	200	2000	19000
Well no. 7	250	2100	>19900
Well no. 8	270	2000	2100
Well no. 9	270	1600	4400

[a]The numbering of these wells are outside the numbering system used in the monitoring program.

[b]Salinity was measured with a handheld salinity probe with a max. detection level of 19900 EC, µS/cm.

Answering these questions is difficult, because:

- There was no systematic testing of the various cleaning methods and comparison between them under otherwise equal conditions
- The cleaning of the wells were important not just because of the salinity problems but also because of inflow of debris and sediment and the microbiological pollution
- People living in the areas, in fact, requested their wells to be cleaned, sometimes more than once, because they believed that the tsunami water was dirty and a removal of this water was required for purification

Even in the monitoring program carried out as part of this study, it was difficult to register with great accuracy the time of the cleaning, the number of cleanings and the procedures applied for the individual wells. On top of that, each well was utilized and pumped for use differently, making comparisons between wells of the effect of the cleaning methods alone very difficult.

Having said this it is the impression of the research team that cleaning, at the time of the writing of this report, was no longer taking place indiscriminately and excessively, if nothing else due to the trial and error effect. People stopped repeating the cleaning when they observed that the salinity levels were not dropping.

MONITORING PROGRAM

Well characteristics

The characteristics of the wells monitored at the three sites are given in Table 7. About 40% of the wells were reported to be flooded, or inundated, by the tsunami waves. The majority of wells are open, dug, shallow, private domestic wells, with an average depth of 3.4 m and an average diameter of 1.4 m. The other categories of wells consisted of deeper, smaller diameter tube wells, with average depth of 5.7 m. They were mainly used for irrigation and public water supply. About one third of the wells had a mechanized pumping system whereas the rest relied on some simple, manual lifting techniques, like a bucket or a pulley. Since the wells were not selected totally randomly, the well statistics showed here, though indicative, may not reflect a true representative sample of wells.

Table 7. Characteristics of wells in the monitoring program

	Kallady	Kaluthavalai	Oluvil	TOTAL
No. of wells monitored	43	49	56	148
No. of monitored wells that were flooded	21 (49%)	24 (49%)	12 (21%)	57 (39%)
No. of domestic wells	40	33	53	126
No. of agro-wells	0	13	3	16
No. of public wells	6	2	7	15
No. of wells with mechanized pumps	16	19	13	48
No of tube wells	0	11	3	14
No of open dug wells[b]	43	38	53	134
Average depth of tube wells	-	5.9 m	4.7 m	5.7 m
Average depth of open dug wells	3.3 m	3.9 m	3.2 m	3.4 m
Average diameter of tube wells	-	0.2 m	0.2 m	0.2 m
Average diameter of open dug wells	1.7 m	1.3 m	1.1 m	1.4 m

[b]Wells in most cases are reinforced along the sides by concrete cylinders

Rainfall at the three monitoring sites

From the rainfall data it was found that approximately 75% of the 1000-1700 mm annual rainfall in the two districts falls in the months from October to February. This is the rainy season.

The rainfall prior to the tsunami was significantly higher than 'normal' and the rainfall after the tsunami was significantly less than 'normal' (Figure 17 to Figure 19). The 'normal' was estimated from the monthly averages of rainfall for the total length of the data series available for the rainfall stations. The rainfall in the months of January to and including September (or August in the case of Kallady) after the tsunami was only 83, 65 and 40 % of the normal rainfall in Kallady, Kaluthavalai and Oluvil, respectively. The rainfall in the months of August (or September in the case of Kallady) to and including November before the tsunami was 201, 161 and 170 % of the normal rainfall in Kallady, Kaluthavalai and Oluvil, respectively. In the month of December when the tsunami struck, a disproportionately higher amount of rainfall occurred after the tsunami: 37, 34, and 52 % in the three cases during the last 6 days representing only 20% of the time of that month.

This pattern, which is consistent between the sites shows that the areas were very wet before the tsunami. The soil was wet and the groundwater levels must have been high within the soil profile. This is considered a favorable condition as the unsaturated zone was small leaving little room for entry of saline water from the entering seawater.

Secondly, the heavy rains that followed just after the tsunami caused on one hand an increased influx of water aggravating the flooding situation and maybe spreading the saltwater more. On the other hand it may have helped to flush out and dilute the saltwater accumulated in ponds, wells, soils and groundwater.

Thirdly, the ensuing low rainfall after the tsunami meant that the aquifer systems were not replenished as much and the saltwater leaching was less than would be expected in a normal year. This is to be considered an unfortunate condition. On the other hand, it is very likely that the following dry season would give rise to more leaching and hence ameliorate the salinization problems relatively more than what was seen in this study. In general, it will, however, be the rainy season that really contributes to the flushing of the saltwater, and hence the dry season may be less relevant.

In conclusion, the rainfall pattern and amounts observed in the areas indicate that the impact of the tsunami in terms of salinity was relatively benign, representing rather a best case scenario.

Tsunami salinity impacts varied between sites

A clear difference was observed in the degree of salinization impaired on the three sites due to the tsunami. Figure 20 shows the salinity levels in the wells at the three sites during the first field trip. It is clear that Oluvil was not impacted as severely as the other two sites, reflected in the low average salinity here compared to the others. In addition, the spread of the EC was less in Oluvil because fewer wells were flooded in this area (21%) as compared to Kallady and Kaluthavalai (both 49%) (Table 7).

Based on the reports from the well owners and people in the areas, a flood line demarcating the distance to where the flood waves reached inland was determined. Basically, this was done by drawing the most probable line based on the distinction between flooded and non-flooded wells. In this definition, a well was considered flooded if seawater overtopped the well and entered directly into the orifice of the well.

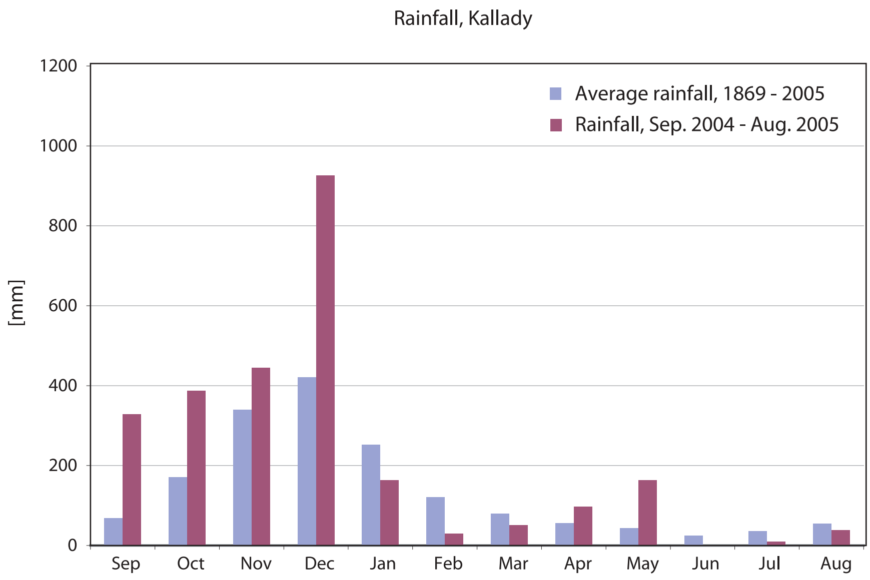


Figure 17. Rainfall in Kallady before and after the tsunami, compared to a 'normal' year

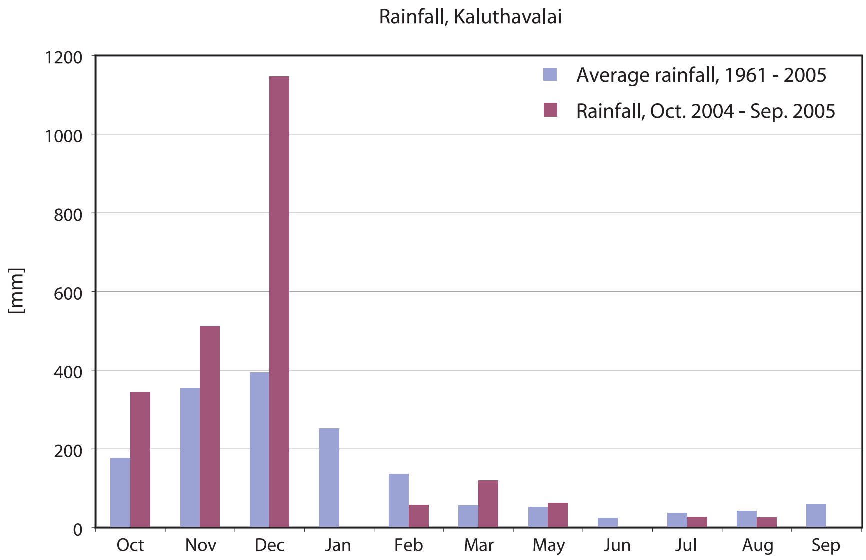


Figure 18. Rainfall in Kaluthavalai before and after the tsunami, compared to a 'normal' year

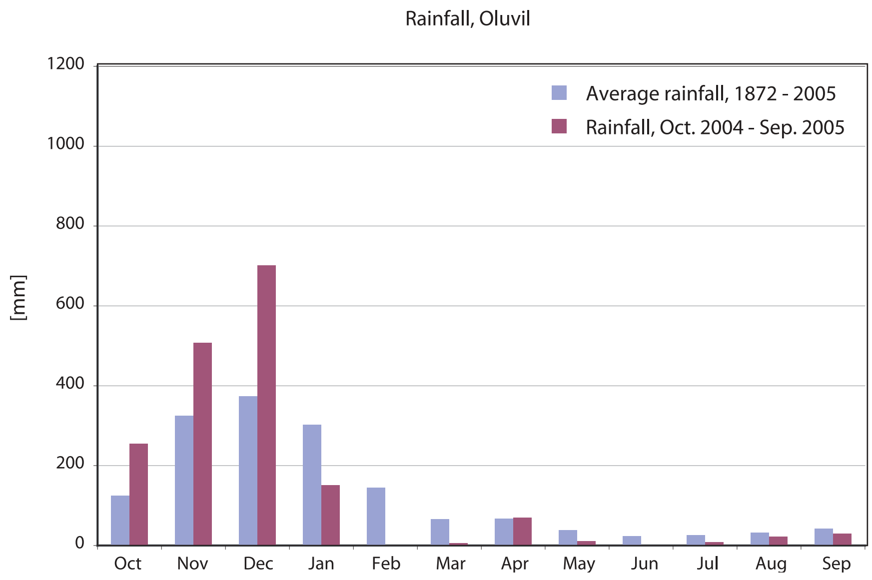


Figure 19. Rainfall in Oluvil before and after the tsunami, compared to a 'normal' year

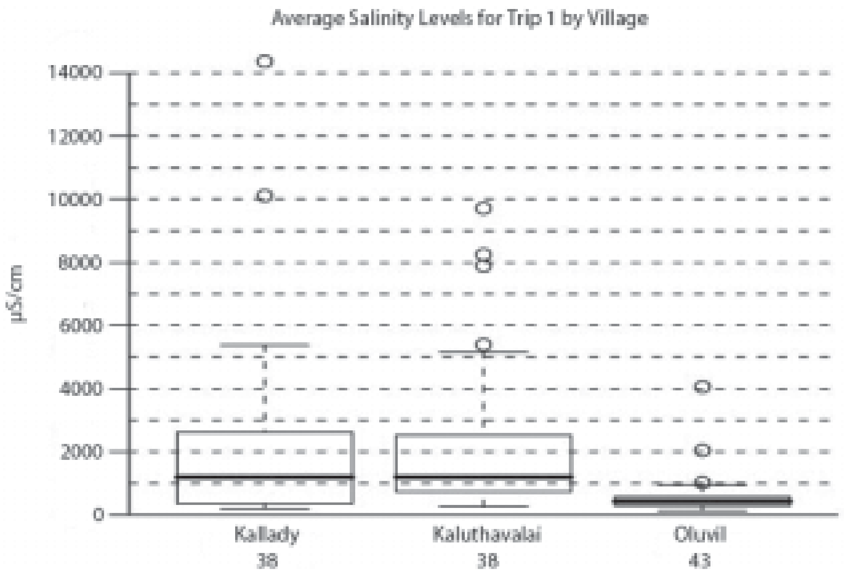


Figure 20. Average salinity levels for the three sites during field trip 1. Number of wells monitored in each site is given below village name

In agreement with the above observations, the Oluvil area was not flooded as much as the other two sites (Figure 24, Figure 25, Figure 26). The maximum observed inundation distance of flooded wells was approx. 1.4, 1.5 and 0.8 km in Kallady, Kaluthavalai and Oluvil, respectively. The variation between sites could be explained by the actual wave action at the time of the tsunami, influenced by factors such as the height and angle of the waves, the nature of the seashore, the topography and any protective and wave-breaking features at the sea bottom as well as the coast itself. When looking at the local topography and the flood line, there appears to be some correlation between the two (Figure 21, Figure 23), in the sense that lower lying areas were flooded more than more elevated areas. This trend however was not as clear in the Oluvil site (Figure 23), indicating that other factors played a larger role here. The large spatial variability in the impact of the tsunami waves and the inundation distance has been reported by other researchers (Liu et al., 2005; Anputhas et al., 2005).

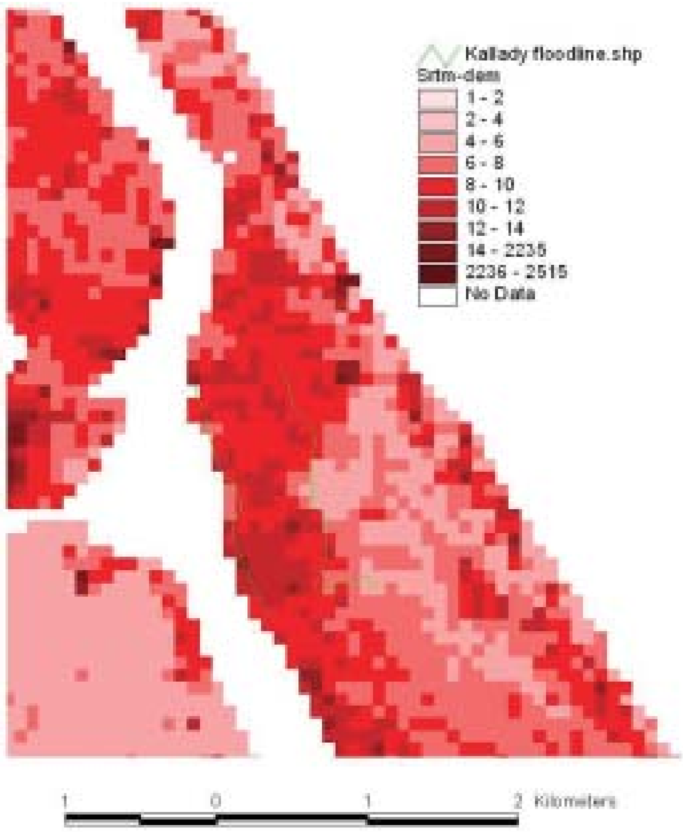


Figure 21. Topography map (SRTM-90m) with flood lines superimposed for the Kallady site

Salinity variation within sites

Inspecting Figure 24, Figure 25, and Figure 26, which show the salinity levels in the wells during the first field trips, there appears to be a general agreement between the wells that were reported as being flooded and a relatively higher level of salinity than non-flooded wells. In the Kallady area, there are about 6 wells in the northern part that appeared quite saline despite the fact that their owners reported them as being not flooded. After renewed interrogation, it was reported that only gradually after the tsunami did these wells become saline. Some reported that seawater entered into holes along the perimeter of the wells but did not overtop the wells. Hence, these cases could be considered border cases where saltwater did not enter directly by inundation of the whole well but rather seawater seeped in by other relatively fast pathways either through the soil itself or because of the well structure itself, or a combination. In the further analysis, these wells have been considered as non-flooded wells.

Conversely, there are also wells that were reported as flooded, but did not appear to be very saline at the time of the first sampling. Whether these wells were indeed flooded and recovered relatively faster than the other wells or whether these wells were in fact not totally inundated by the waves is not clear. These wells have in the analysis been categorized as flooded.

From the above discussion it can be said that the defining of wells as flooded and not-flooded was not a straight forward task, and by sticking to the way that people reported the wells, in some cases contrary to expectations, lead to a higher variability in salinity levels for the two groups than if the wells were categorized according to a criterion based on actual salinity levels observed.

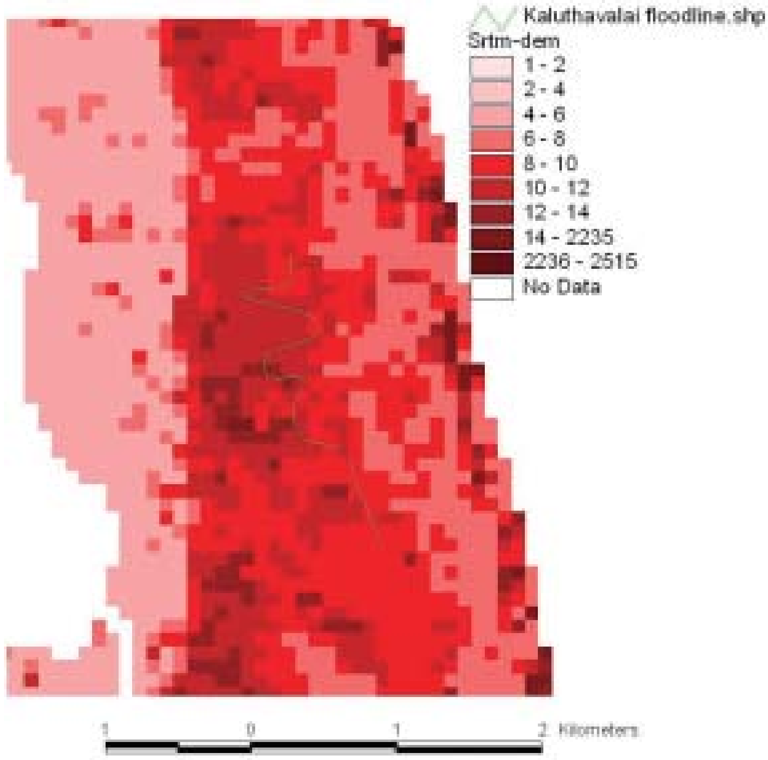


Figure 22. Topography map (SRTM-90m) with flood line superimposed for the Kaluthavalai site

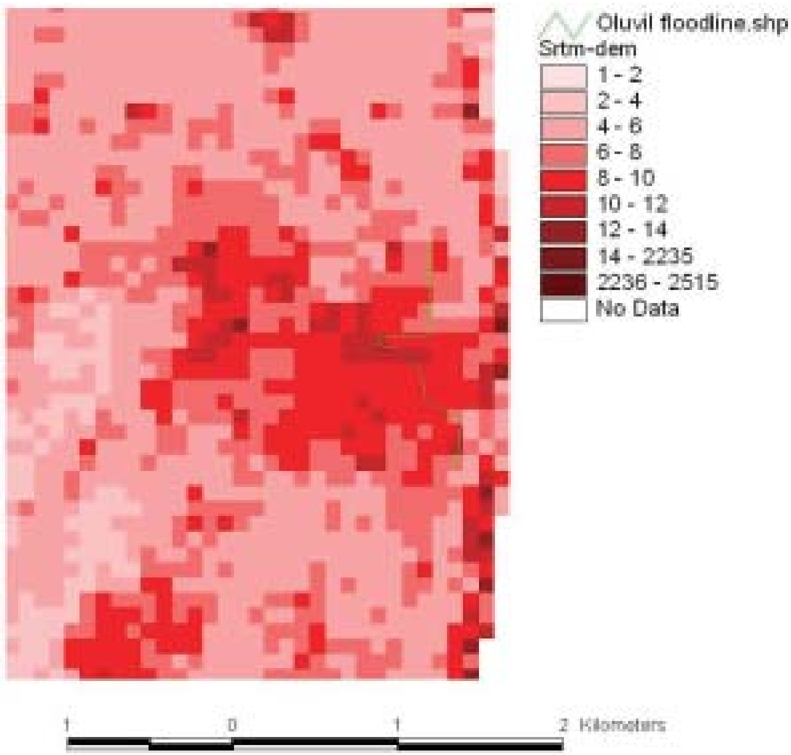


Figure 23. Topography map (SRTM-90m) with flood line superimposed for the Oluvil site

In the Kallady area, the salinity in the lagoon was also monitored, which indicated a decrease in salinity with the distance from the outlet of the lagoon (to the north of Figure 24). Also in Kallady, two flood lines are indicated because the tsunami generated a flood wave into the lagoon itself, which in turn created flooding inland from the lagoon side. In agreement with this, one of the monitoring wells, the one closet to the lagoon, was flooded, too and indicated a relatively higher salinity. The salinity levels in the lagoon were less than, but comparable to the levels of the seawater, again indicating the impact of the tsunami. However, since no data was available on the pre-tsunami salinity of the lagoon, this cannot be stated with great certainty.

The single highest measurement of well salinity during the whole monitoring period was recorded in well 2 in Kallady during field trip 1, with an EC of 14,360 µS/cm.

Salinity of wells generally decreased with distance from the coast, this trend being more pronounced for the flooded wells (Figure 27). However, because of the great variability, many wells very close to the coast, whether flooded or not flooded, exhibited low salinity levels, i.e. below 1000 µS/cm.

The quite high variability of salinity of the wells within the flooded areas (Figure 24, Figure 25, Figure 26) can be explained by various factors:

- Local differences in the flooding pattern. This is related to how much water was standing on the surface during the inundation and the duration of the flooding over the sites
- Soil and aquifer conditions and micro topography. This influences the amount of tsunami water that infiltrated during and after the tsunami

- Well characteristics. Some wells were closed, like the tube wells, impeding a direct influx of the tsunami wave into the wells
- Post-tsunami pumping and cleaning impacts. Individual wells were operated and treated differently after the tsunami, which could influence the local salinity levels

Salinity level important for the actual use of the well water

That the salinity level to a large degree governs the actual use of the well water is not surprising. Figure 28 illustrates this point and shows that the requirement for low salinity is decreasing in the order: Drinking > Irrigation > Bathing/ Washing. Basically, the well water is only used for drinking, if the salinity is below some acceptance level, which was found to be quite constant throughout the monitoring period at about 1000 µS/cm.

In conclusion, if the water tastes too salty and/or the salinity is expected to interfere with its use, such as e.g. irrigation, such use is generally discontinued by the well users.

Figure 29 shows the average salinity for the wells according to water extraction mechanism of the wells. It shows clearly that wells without a water extraction mechanism had the highest salinity. The most likely reason for this is that the wells without a water extraction mechanism were abandoned because of too high perceived salinity.

Salinity changes after the tsunami

Salinity changes with time and between sites

The salinity in the flooded wells decreased significantly from an estimated average salinity at the time of the flooding (Figure 30). The initial well salinity just after the tsunami was important to know as it would give a measure of the maximum level which would be expected to occur immediately after the tsunami. There were no measurements done and hence it was estimated by assuming that a well with average dimensions of the flooded wells and with a groundwater level equal to 1.3 m below the ground and with a pre-tsunami salinity of 770 µS/cm was totally filled and mixed with seawater with an EC of 53,100 µS/cm. This yielded a salinity of 29,400 µS/cm, which was not unrealistic compared to the levels registered in affected wells one month after the tsunami in the Kalmunai area (Table 6).

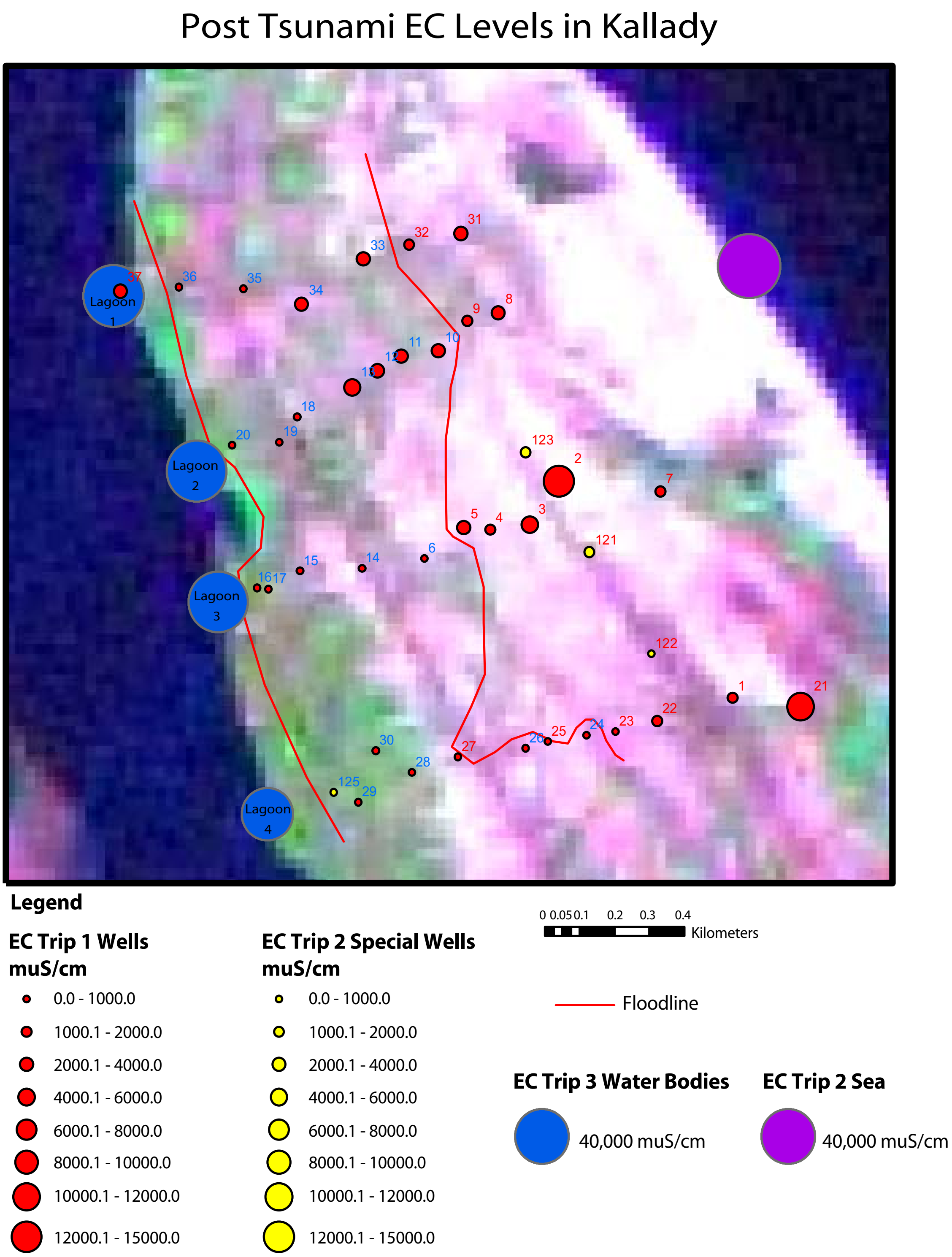


Figure 24. Salinity levels at the Kallady area, during the beginning of the monitoring period. The flood line is indicated. Note the two lines because water also inundated land from the lagoon side

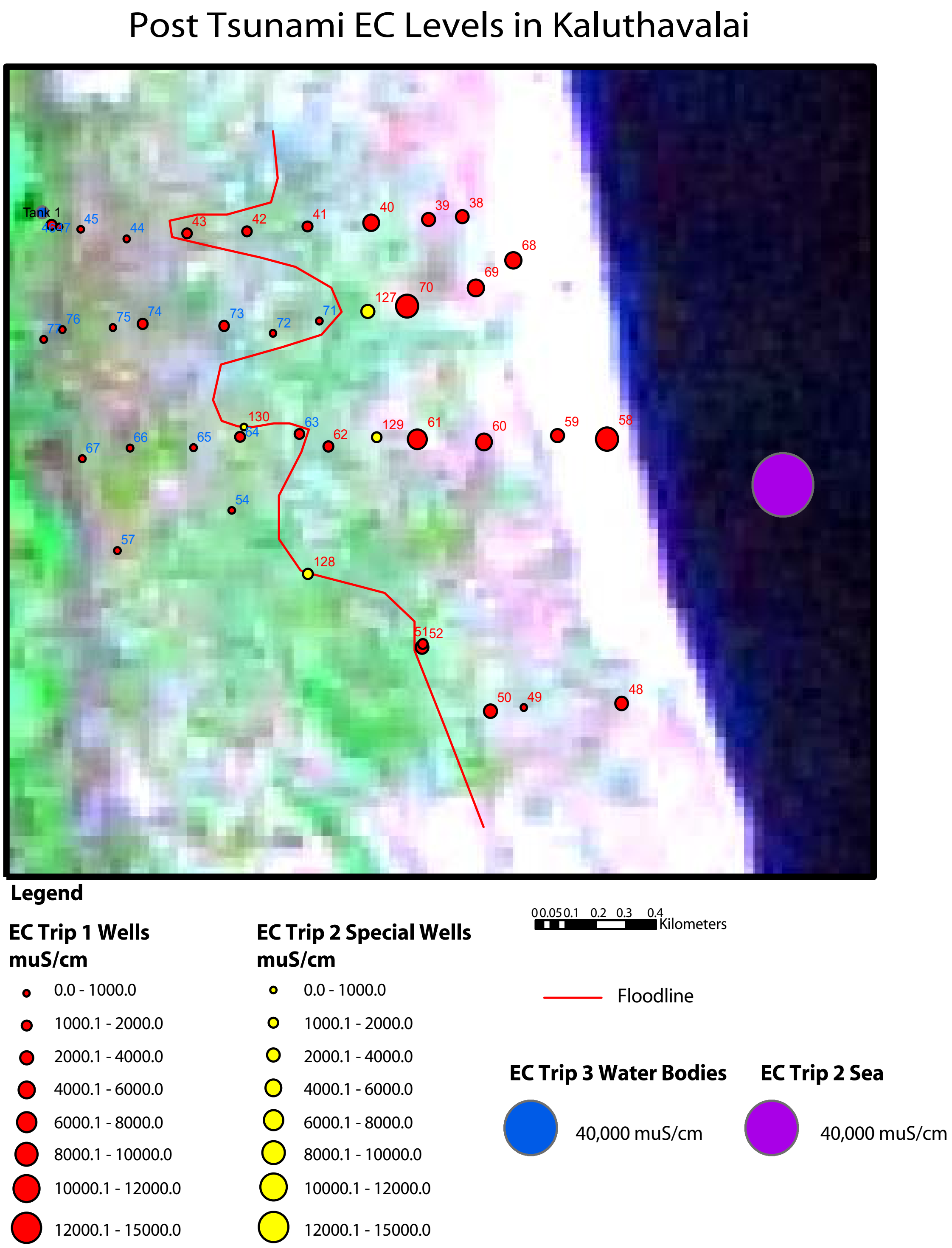


Figure 25. Salinity levels at the Kaluthavalai area, during the beginning of the monitoring period. The flood line is indicated

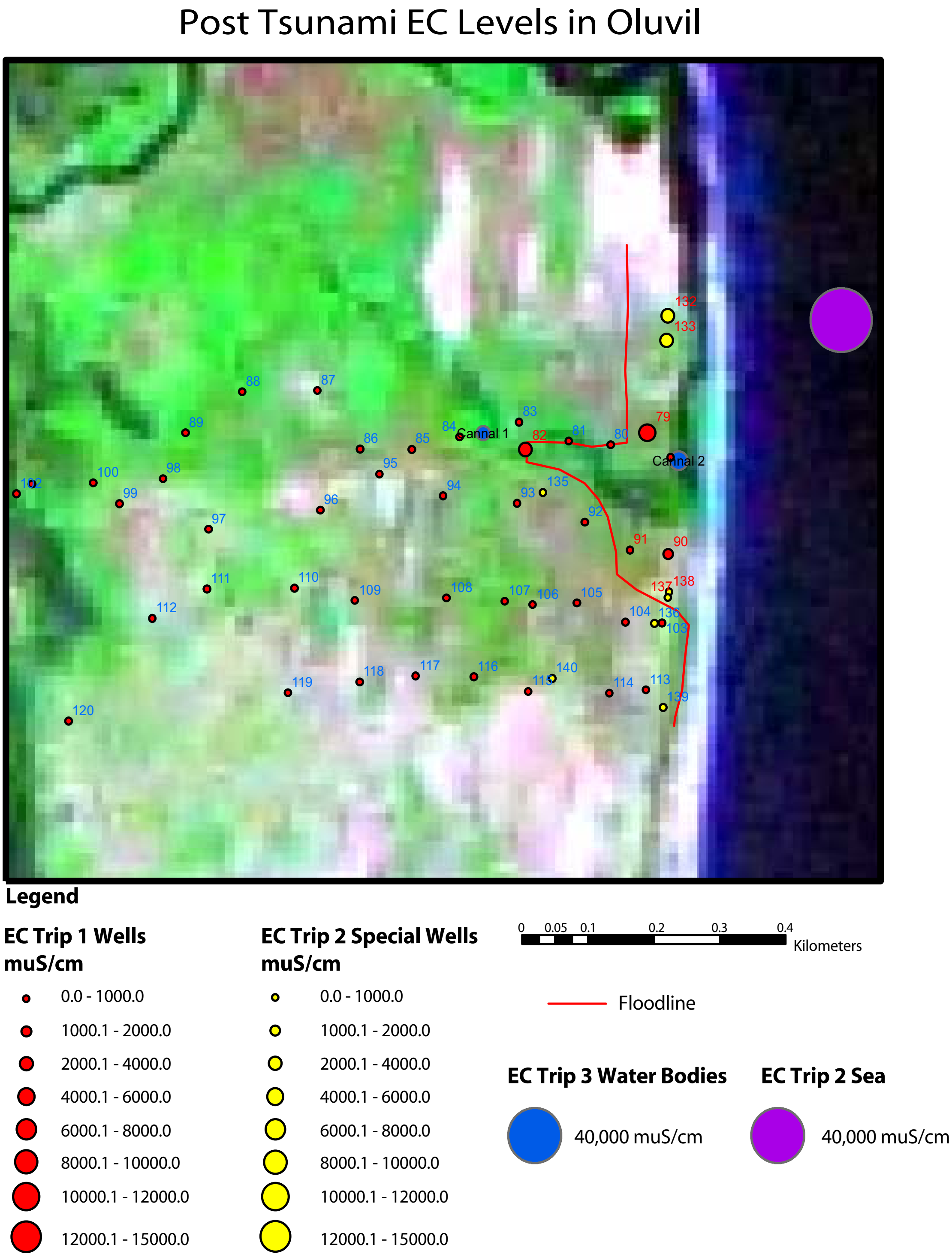


Figure 26. Salinity levels at the Oluvil area, during the beginning of the monitoring period. The flood line is indicated

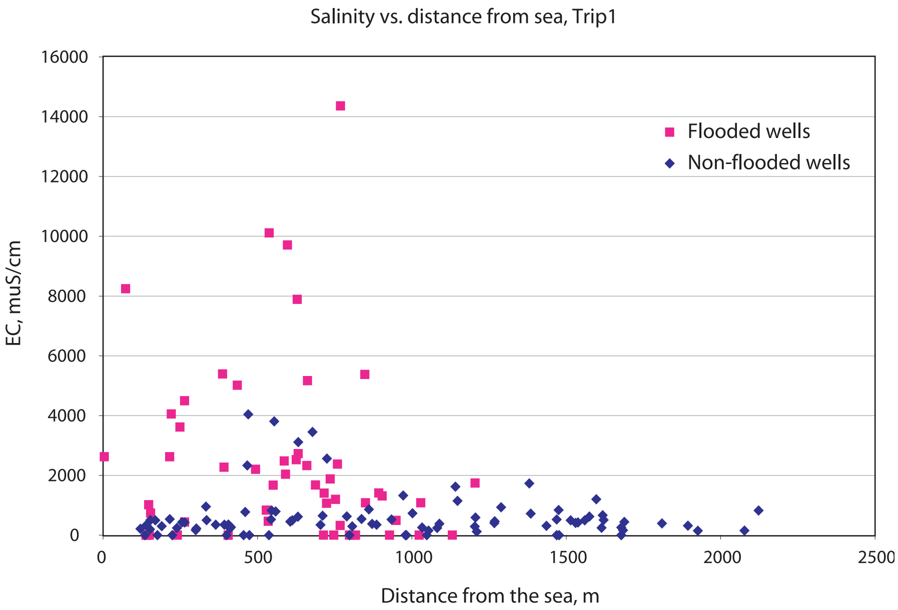


Figure 27. Salinity levels of flooded and non-flooded wells as a function of distance from the coast line during trip 1

According to this analysis, the flooded wells appear to have improved rapidly initially, during the first 2.5 months after the tsunami, whereas the recovery was much less pronounced during the following actual monitoring period. This could be explained by the factors:

- Due to the increased hydraulic head in the wells during and just after the inundation, much of the infiltrated water quickly infiltrated into the groundwater and possibly also out from the sides of the wells above ground leaving water left less saline
- Due to the large initial concentration and density gradients between the incoming seawater and the resident freshwater, mixing and sinking of the denser saltwater occurred quickly
- Just after the tsunami, heavy rain occurred on the east coast (Figure 17 to Figure 19), which diluted the well water and possibly the groundwater though this is difficult to say because saltwater in the soil profile may have actually increased the groundwater salinity initially as a pulse of saltwater moved down with the infiltrating rainwater

All the above factors tend to dissipate the saltwater and even out the initial concentration differences. As time went on, these dissipation mechanisms were less effective which explains the slower decrease as time passed. Also, there was little rain after January on the east coast (Figure 17 to Figure 19) leaving out this mechanism for subsequent recovery. From trip 1 to trip 5, the average salinity in flooded wells decreased only from 3240 to 2600 µS/cm.

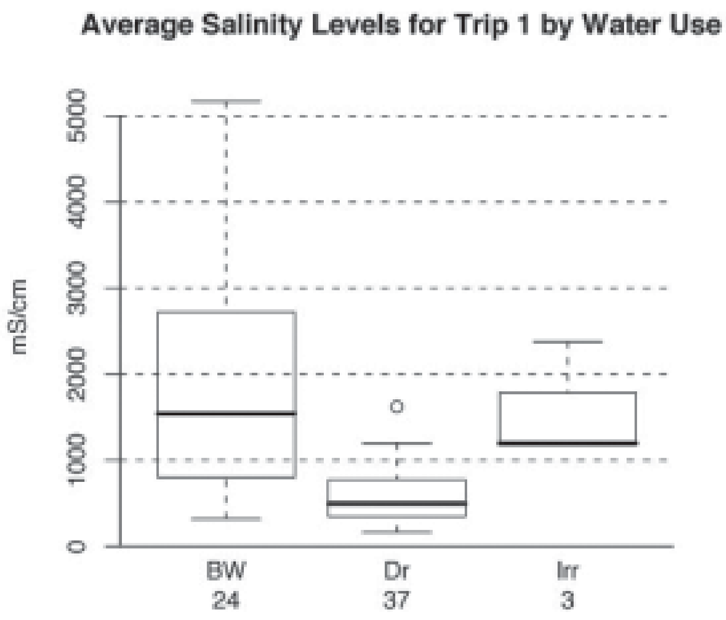


Figure 28. Average salinity levels for well water used for different purposes (BW: Bathing/Washing, Dr: Drinking, Irr: Irrigation)

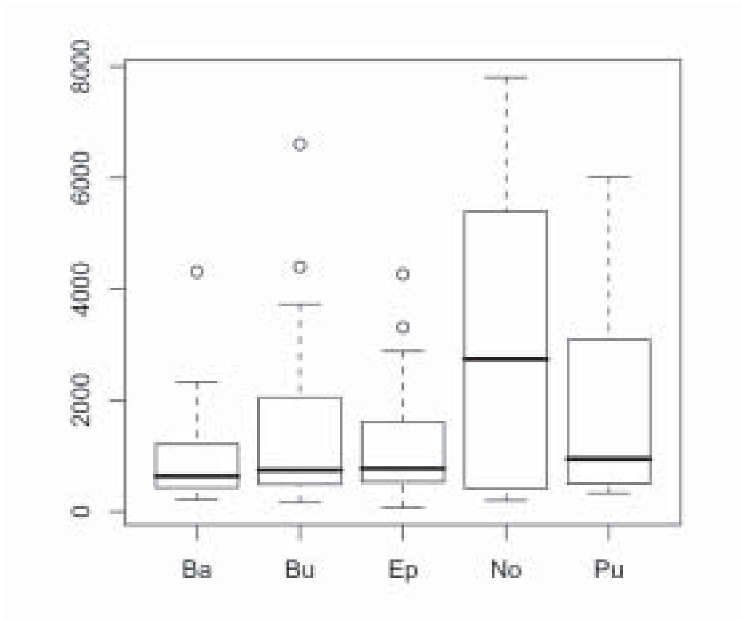


Figure 29. Average salinity for the various water extraction mechanisms on the wells (Ba: Balance, Bu: bucket, Ep: Electrical pump, No: No mechanism, Pu: Pulley)

The flooded wells remained more saline than the background, non-flooded wells throughout the monitoring period (Figure 30). This means that after seven months after the tsunami, towards the end of the dry season, the wells still had not totally recovered to pre-tsunami conditions and that at least one more rainy reason would be required to leach out the residual excess salinity, if possible. At this point in time, the flooded wells had an average salinity of 2600 µS/cm, compared to the non-flooded wells of 1084 µS/cm. Though flooded wells generally were closer to the coast than non-flooded wells and these wells potentially exhibit somewhat higher salinity, it is hypothesized that the flooded wells in general had not recovered to pre-tsunami-levels.

In contrast to the flooded wells, for the non-flooded wells, which serve as wells with background concentrations, there was a slight increase in average salinity over the monitoring period, from 890 to 1080 µS/cm (Figure 30). This can be explained by various reasons:

- Incremental and accumulated evaporation of water from the open wells as well as directly from the groundwater table during the monitoring period that coincided with the dry period. This would leave the water in the wells increasingly saline
- Progressive influx of saline water from the affected areas. This effect is expected to be greater in the areas with a lagoon (here in Kallady and Kaluthavalai) compared to areas without a lagoon, because there will be a groundwater divide somewhere in the middle of the strip of land and a flux of groundwater towards the lagoon as well as towards the sea on the two sides of this divide. If the saltwater had reached beyond the divide, it could have major flow direction towards the lagoon giving rise to contamination of previously unaffected wells. If no lagoon is present inland (as in the Oluvil case) the groundwater flow direction will be unilaterally towards the sea and hence the affected areas are downstream of, and will not impact the unaffected areas (compare Figure 2 and Figure 3)
- Excessive pumping of unaffected wells could reverse the local groundwater flow from being towards the sea to be towards a well in the non-inundated area. This could also attract saline groundwater into otherwise unaffected wells

From Figure 31, showing the change in salinity for flooded and non-flooded wells, split into the three sites, there appear to be no distinct difference between the increase in salinity for the non-flooded wells between the three sites. This indicates that up to this point in time, there is no significant influx of tsunami-related saltwater into unaffected areas in the lagoon settings, and the increase in salinity observed is more likely related to the generally observed increase in salinity due to evaporation processes. This is confirmed by the comparison with pre-tsunami observations of salinity levels in the Kaluthavalai area, which gave very similar values and increases over the same period of the year (Jeyakumar et al., 2002; Vaheesar et al., 2000). In conclusion, the non-flooded wells did not appear to be impacted by post-tsunami spreading of saline groundwater from affected to non-affected areas. This also implies that the non-affected wells could be used, with caution, to augment or substitute the local water supply impaired in the affected areas.

The average salinity levels for non-flooded wells for the lagoon sites (Kallady and Kaluthavalai) were consistently higher than for the Oluvil site. This could be due to generally higher salinity levels in these areas that are not flushed by groundwater from the hinterlands or infiltrating surface water from the paddy fields, like the Oluvil site. The ambiguity in the characterization of wells as flooded or non-flooded could also mask the picture. As stated previously, the wells in the Kallady site that were classified as non-flooded, but in fact had rather high salinity (Figure 24), increased the average salinity levels for this site, explaining why this site had the highest average salinity throughout the study compared to the other sites.

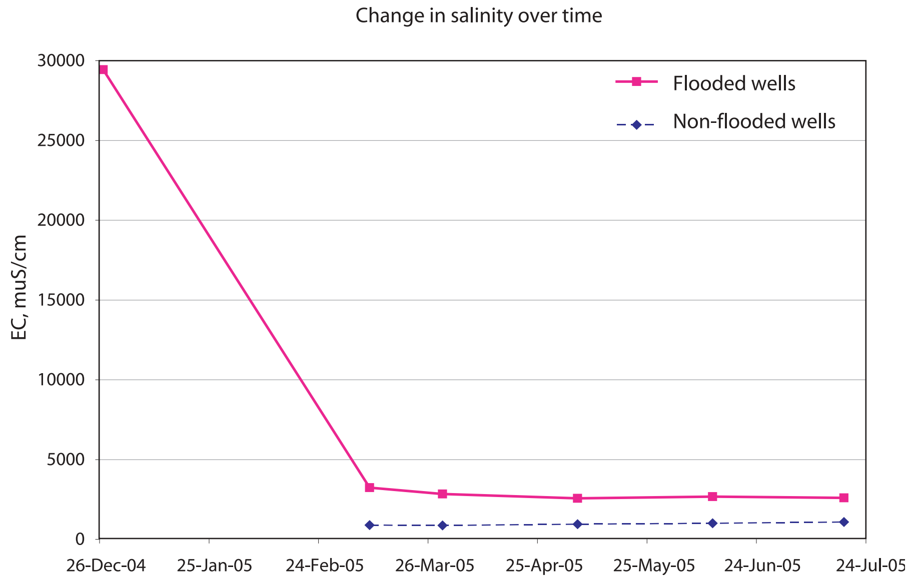


Figure 30. Average well salinity with time after the tsunami for flooded and non-flooded wells

Impact of tsunami on suitability of wells for drinking

In order to express the tsunami impacts on the drinking water supply from the increased salinity during the monitoring period, as seen from Figure 30, the number of wells with a salinity level above the drinking water acceptance level (here set at 1000 µS/cm, see above) was derived. Figure 32 shows the trend in the percentage of wells that exceeded the acceptance level and it is clear that a large fraction of the flooded wells, according to this criterion, were not suitable for providing drinking water for the period investigated. The figures vary from 60% in the start of the period for the least affected area in Oluvil to 100 % at the end for the most affected area, Kaluthavalai.

It is interesting to note that the average salinity levels of flooded wells decreased slightly over the monitoring period (Figure 31), whereas the percentage of flooded wells unsuitable for drinking actually increased slightly over the same period (Figure 32). This is possible because the variability in salinity initially was very large with a smaller number of wells having very high salinity and hence implying a high average salinity. As time went on, these wells decreased significantly in salinity, lowering the overall average, while wells with lower initial salinity actually increased beyond the 1000 µS/cm level, increasing the number of wells above this threshold.

For the non-flooded wells, also quite a large proportion of the wells became unsuitable for drinking purposes, again according to the criterion set up. At the end of the monitoring period, the percentage was 17% for the least affected area (Oluvil) and 50% for the most affected area (Kaluthavalai). These high percentages are somewhat surprising as these wells were not affected by the tsunami and hence represent the conditions without any tsunami influence. This means that prior to the tsunami, people living in the areas were faced with a local water supply with in many cases higher salinity than 1000 µS/cm and supposedly these levels were acceptable because of the lack of alternative water supply sources (except maybe bottled water, which may be used if affordable to the people).

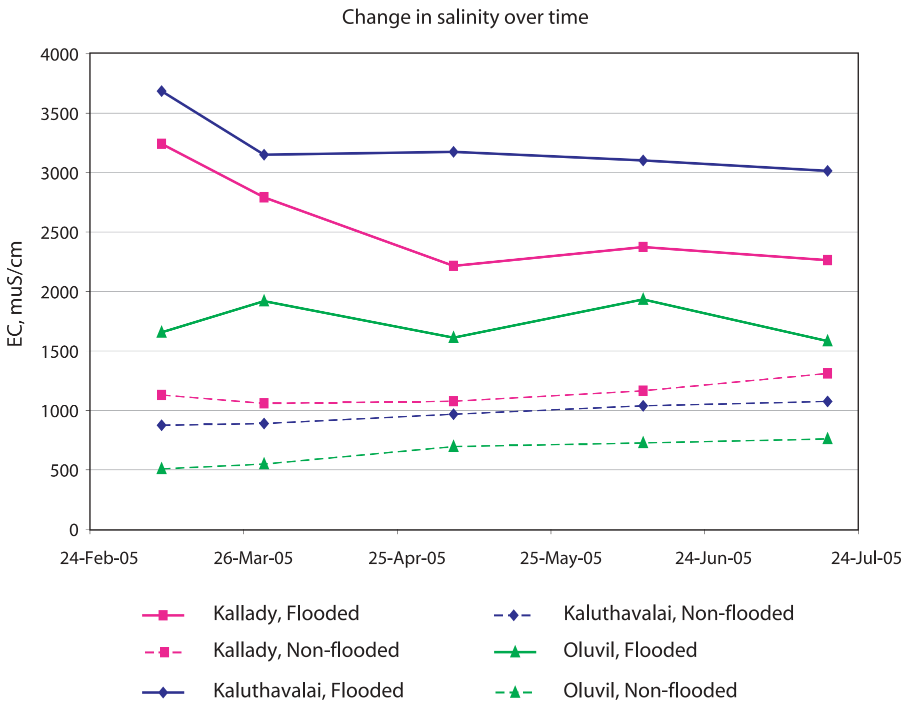


Figure 31. Average well salinity with time after the tsunami of flooded and non-flooded wells and split into the three areas

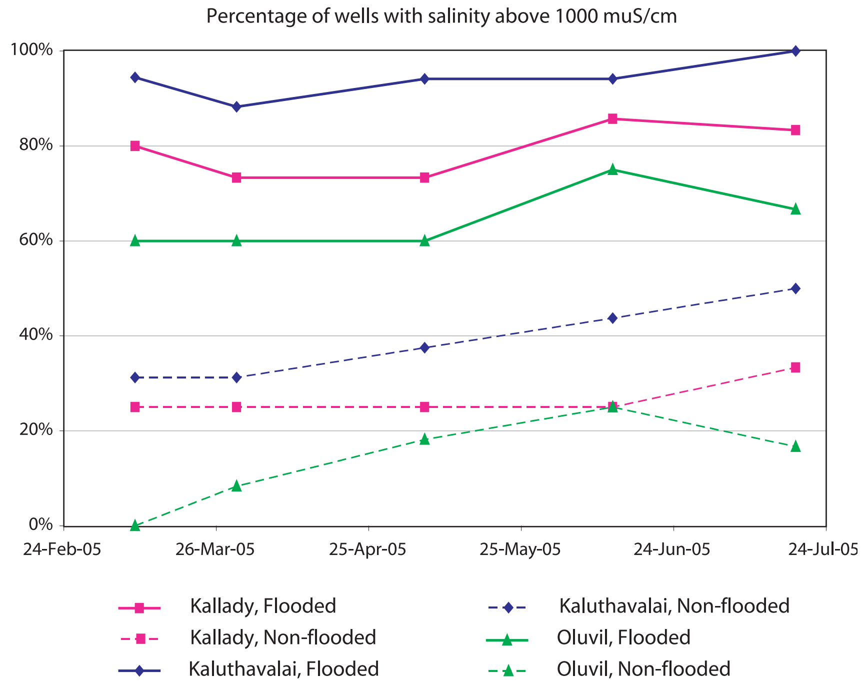


Figure 32. Percentage of wells with salinity above the drinking water thresholds a function of time after the tsunami

Change in Salinity Levels in Kallady

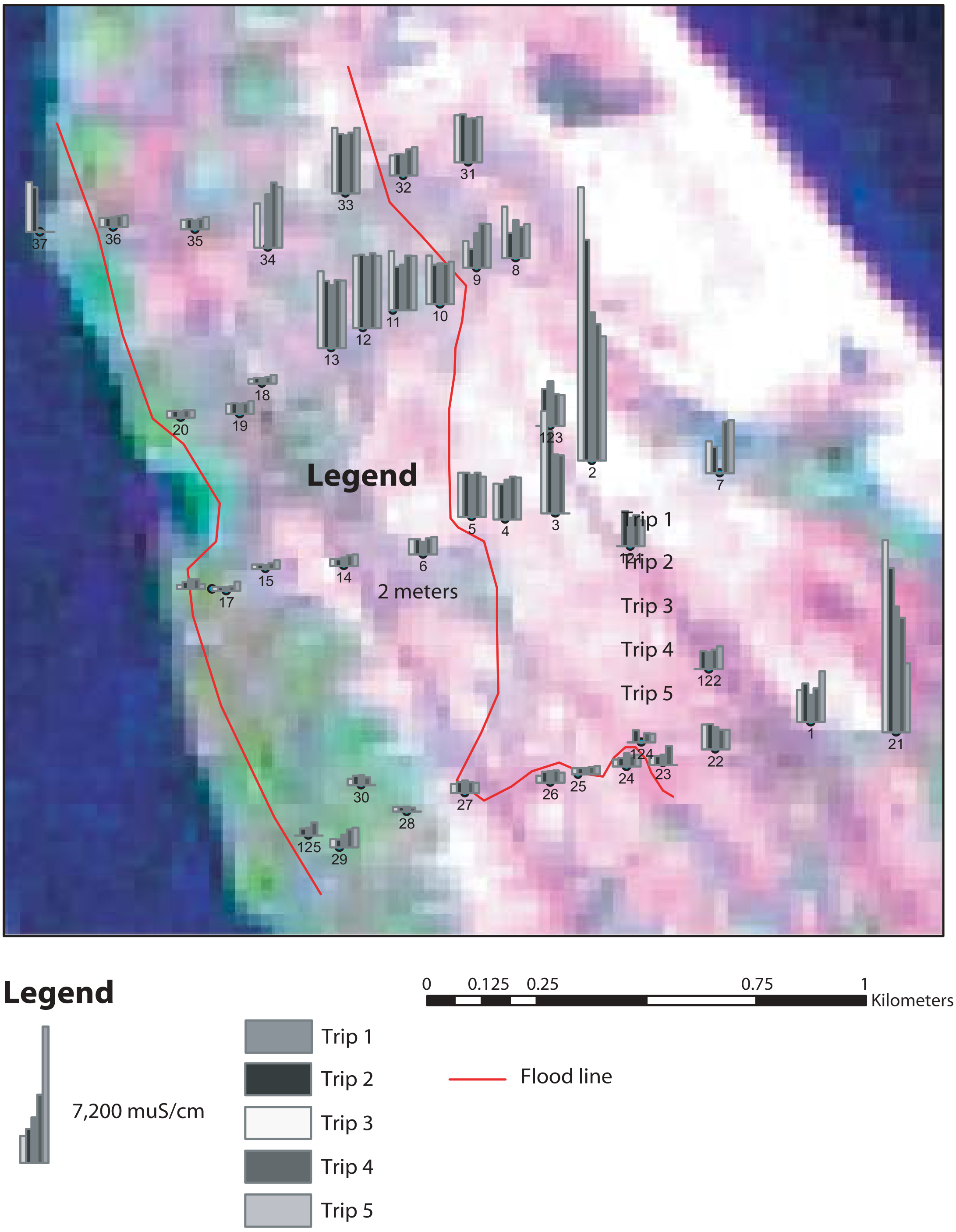


Figure 33. Salinity changes in individual wells in the Kallady site over the study period

Change in Salinity Levels in Kaluthavalai

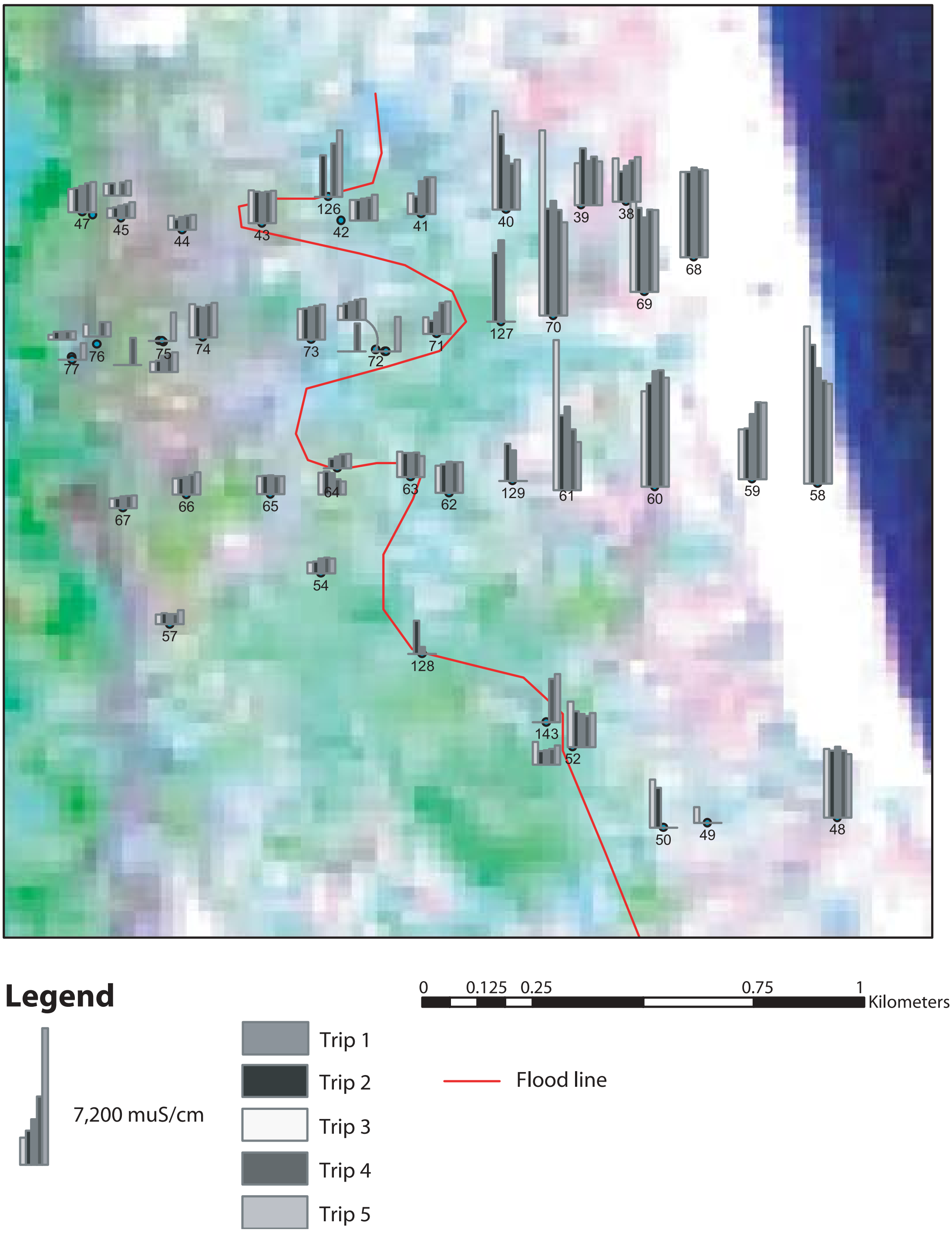


Figure 34. Salinity changes in individual wells in the Kaluthavalai site over the study period

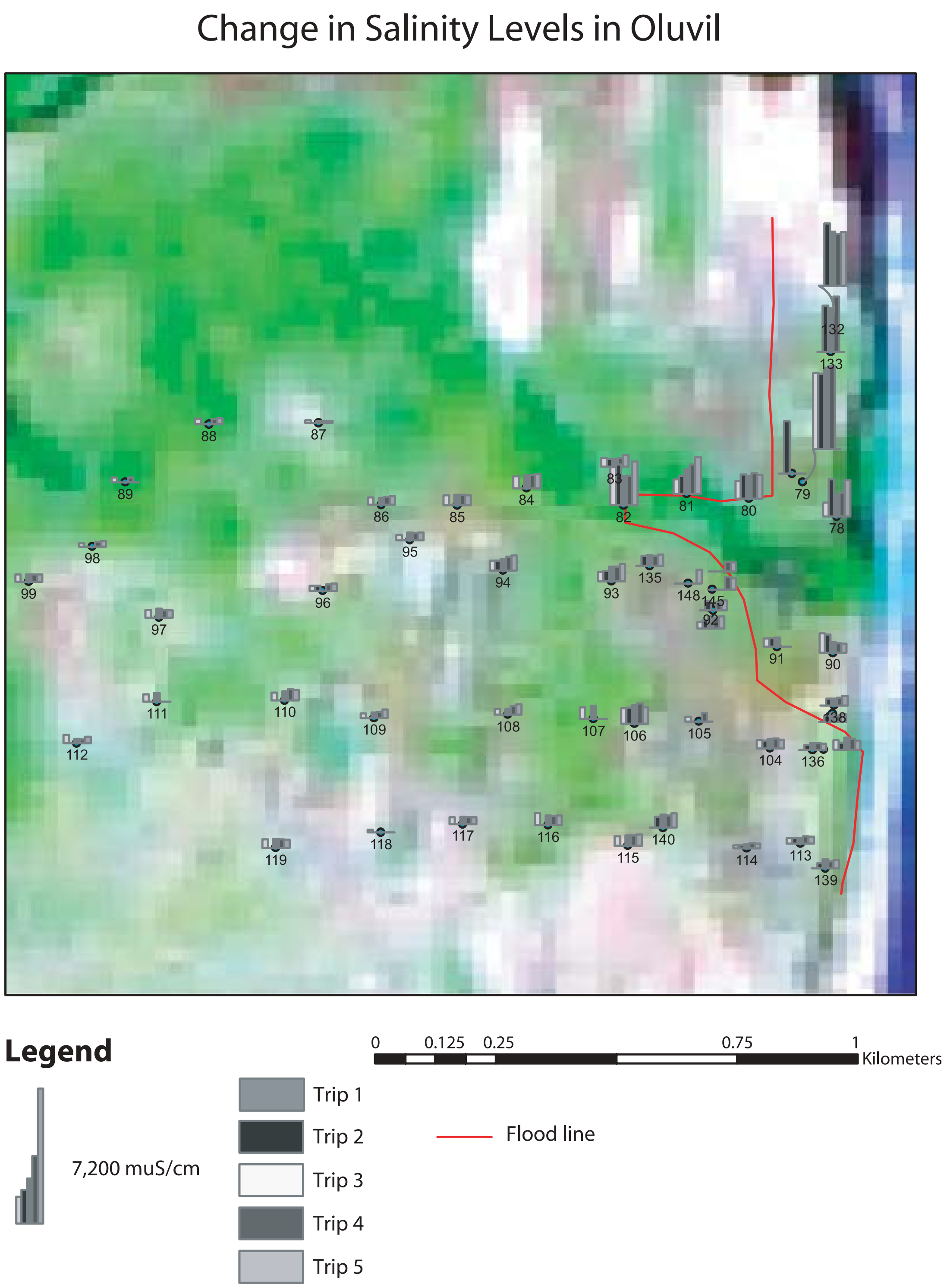


Figure 35. Salinity changes in individual wells in the Oluvil site over the study period

The results indicate that people in the areas are not as willing to consume high salinity water as prior to the tsunami. This could be explained by the fact that water has been supplied for emergency relief to the communities as an alternative to their well supply. If this water in general has been much better than what they have been previously accustomed to (no data obtained to support this, however) the implication is that people do no longer want to use their well water for extended times of the year, if they can avoid it. Basically, their requirements in terms of water quality have increased. This may in itself create problems in the longer term for any rehabilitation efforts and should be taken into account in the longer term planning for water supply. The question becomes whether stricter demands on water quality can be accommodated in these areas on a sustainable basis.

Temporal salinity changes within sites

The general pattern of improving groundwater quality, in terms of salinity, in flooded wells as seen in Figure 30 and Figure 31, masks a lot of spatial variability. In Figure 33, Figure 34, and Figure 35, the changes in salinity over the monitoring period in individual wells in the three sites are shown. It is seen that:

- A decrease in salinity was observed in the majority of wells located in flooded areas
- A rapid decrease in salinity was observed in wells in flooded areas with highest salinity
- A marginal increase in salinity was observed in wells located in non-flooded areas
- In some instances, two adjacent flooded wells showed opposite trends, i.e. one well was improving and the other was deteriorating in terms of salinization (e.g. wells 3 and 4 in Kallady, wells 40 and 41 in Kaluthavalai, and 79 and 80 in Oluvil). It is a result of the levelling out of the salinity differences between the wells as they appeared early in the period, with the initially highly saline well improving while the initially less saline well increasing in salinity

Salinity levels with depth

The salinity was practically uniform with depth in all the wells during the monitoring period. Figure 36 demonstrates this for field trip 1, but results were consistent for all the trips. This is in contrast to the observations done shortly after the tsunami when there was a significant stratification in salinity, with water significantly more saline at the bottom of the wells (see Table 6). There could be three major reasons for this. Firstly, between the initial sampling and the start of the monitoring period, the wells could have had time to equilibrate and even out the vertical concentration gradients, also by vertical overturning due to the density instability phenomenon. Secondly, heavy rainfall occurred just after the tsunami, partly explaining that freshwater was at the top of the wells. Thirdly, most likely all the wells at the time of the first field trip would have been pumped, either due to use or due to cleaning, or both. The pumping of the wells would tend to smooth out the differences in salinity with depth due to mechanical disturbance and mixing of the water column. It appears that the continuous usage of the wells was not required to maintain a uniform salinity profiles in the wells because all the wells showed the same smooth picture throughout the monitoring period irrespective of whether they were used or not. This supports the explanation of the rapid overturning and sinking of the denser, highly saline water overlying freshwater.

Constituting the only exception to the first statement in the section above, one of the wells in the monitoring program exhibited a significant increase in salinity with depth during the monitoring period, namely well 51 in Kaluthavalai, which was located 0.8 km from the coast and also was the deepest of all the monitored wells, 10.1 m (Figure 37). At approximately 8.5 m depth, the salinity increased abruptly from a steady background level of 800 µS/cm to max. 5000 µS/cm at the bottom.

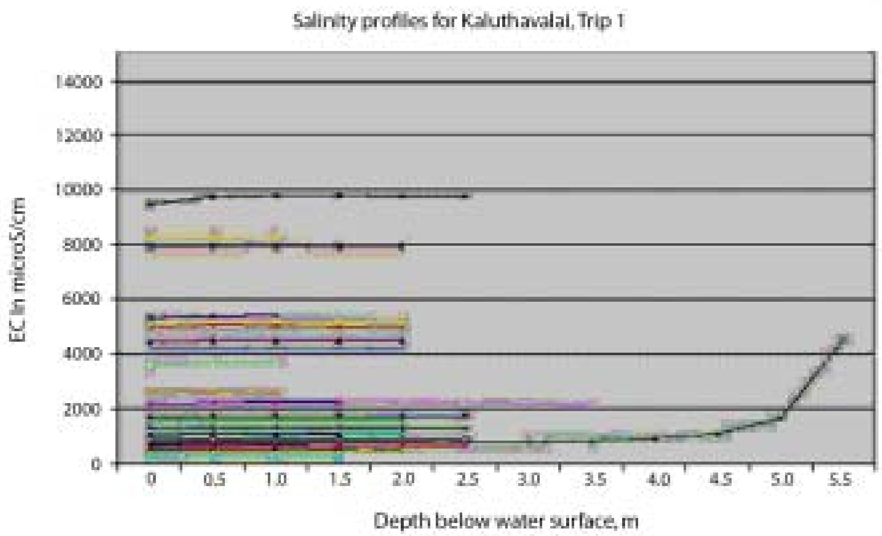


Figure 36. Salinity profiles in wells in Kaluthavalai, trip 1

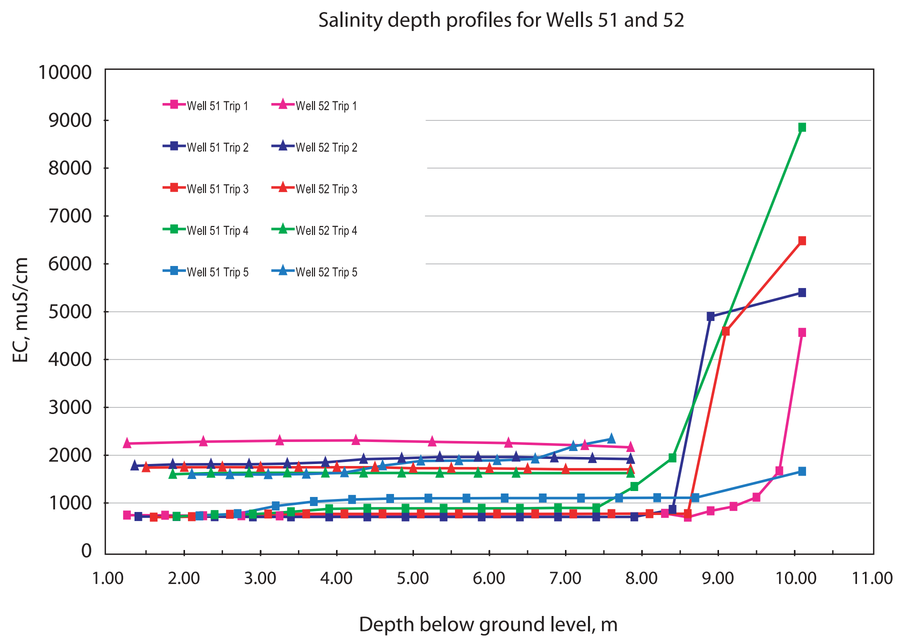


Figure 37. Salinity profiles of two wells located 50 m apart, in Kaluthavalai. Values are given for the five field trips

In Figure 37, well 52, which is only 50 m away from well 51, is shown as well. It is seen that this well is distinctively and consistently more saline than well 51. However, there is no significant salinity increase at the bottom of this well, which could be explained by the fact that this well was not as deep as well 51 and the bottom of well 52 did not reach into the highly saline zone of well 51. There were no indications that well 51 was pumped more heavily than well 52 (data not shown), which could have explained a higher salinity due to salinity intrusion from below (Figure 7). The interpretation of the results is that well 51 reaches the underlying interface between fresh and saltwater (Figure 2). Whether this is an intermittent layer of saltwater that is due to the infiltration of saltwater from the tsunami or whether this is a more permanent transition to the saline water below cannot be inferred from the present results.

Groundwater levels with time and space

The groundwater level dropped progressively during the study period, from an average level of 1.33 m to 1.99 m below the ground surface (Figure 38). The groundwater level was in general somewhat lower in the non-flooded wells compared to the flooded wells. This can be explained by the fact that the flooded wells were closer to the coast, and hence had a water table close to the land surface (Figure 39).

The decrease in the groundwater table was comparable for the two categories of wells. The non-flooded wells had a slightly higher decrease in groundwater level over the period (0.78 m) compared to the flooded wells (0.73 m). Again this is expected, as wells closer to the beach do not fluctuate as much seasonally as wells more inland. These averages cover a lot of variability, e.g. potential drawdowns in individual wells due to pumping. However, the results also show that the pumping in general does not influence the overall groundwater flow pattern in the aquifer as a whole.

Most of the individual wells showed a consistent decrease in groundwater level, however, a few wells did show a more irregular pattern, with intermittent excessive decreases, indicating temporary intensive abstraction, e.g. well 121 in Kallady (Figure 40), well 72 in Kaluthavalai (Figure 41), and well 139 in Oluvil (Figure 42). The absolute levels of the wells were not monitored as part of this study. Hence, it was not possible to develop an exact picture of the piezometric surface at the various sampling times, and from that derive the groundwater flow patterns.

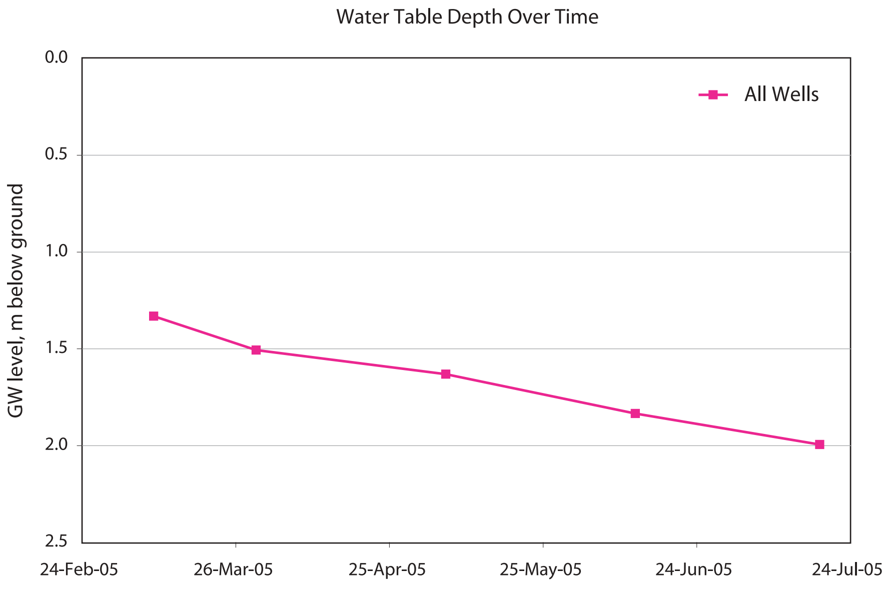


Figure 38. Drop in groundwater level during the study period for all wells

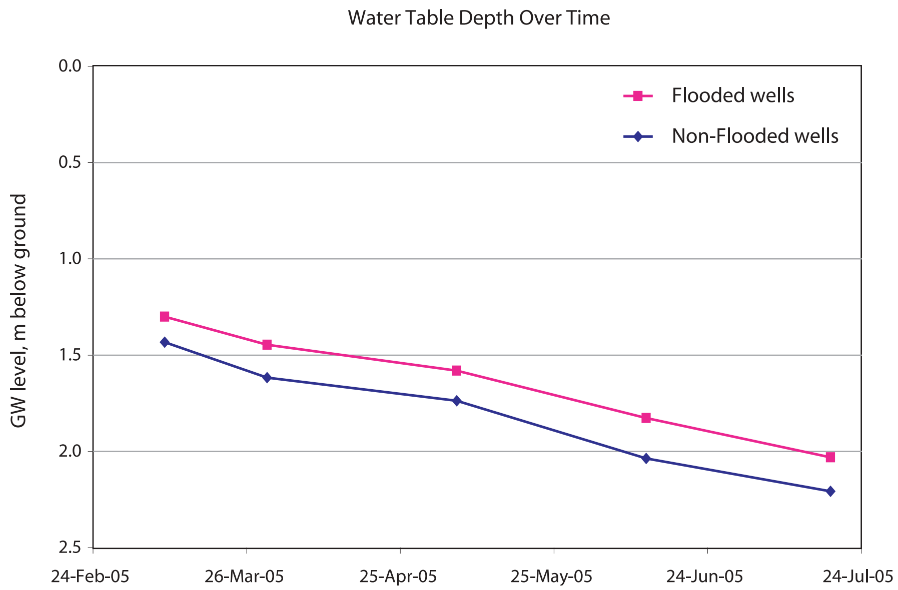


Figure 39. Drop in groundwater level during the study period for flooded and non-flooded wells

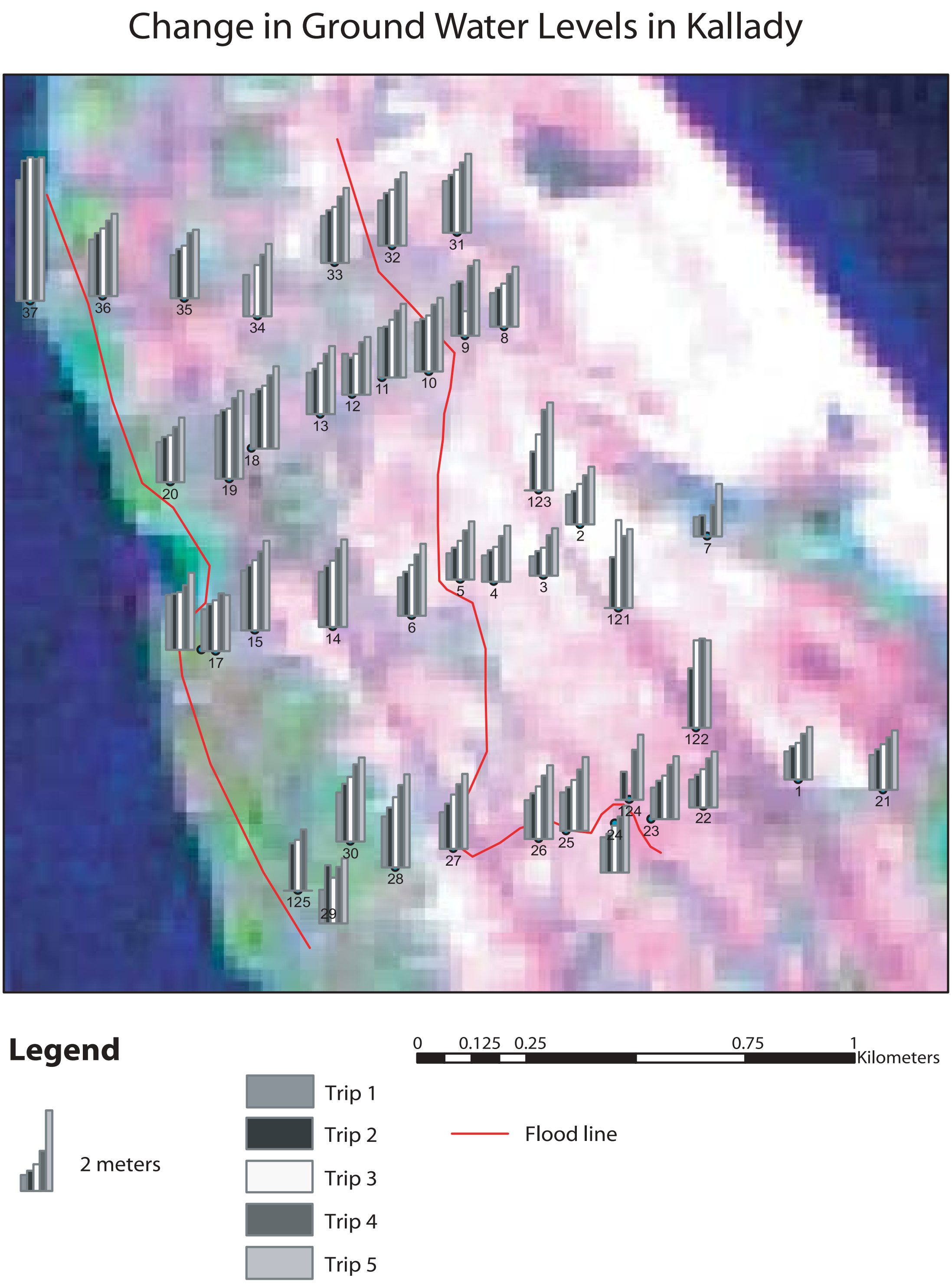


Figure 40. Groundwater levels in individual wells in the Kallady site throughout the study period. Note that an increase in the size of the bars indicates a drop in the groundwater table

Change in Ground Water Levels in Kaluthavalai

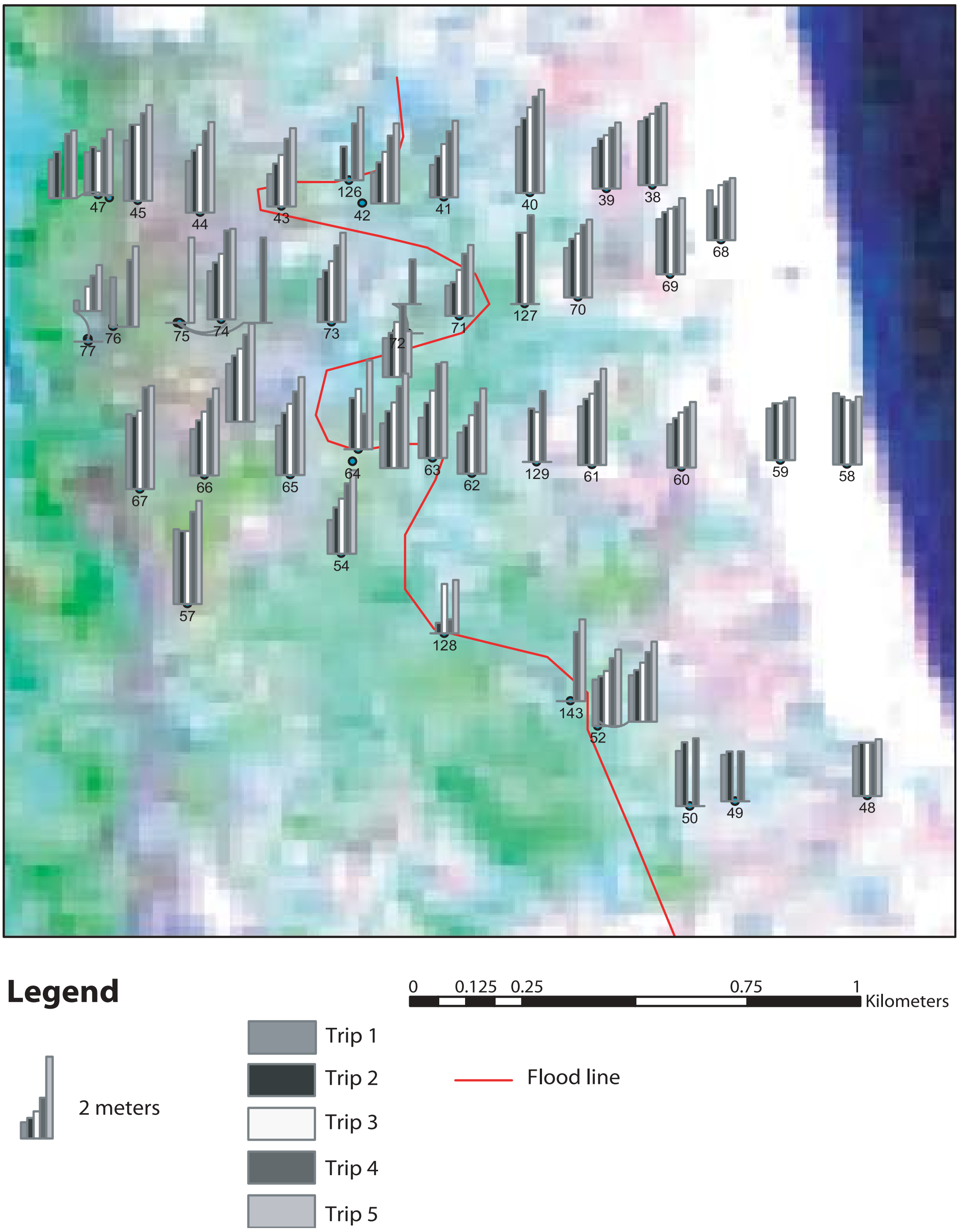


Figure 41. Groundwater levels in individual wells in the Kaluthavalai site throughout the study period. Note that an increase in the size of the bars indicates a drop in the groundwater table

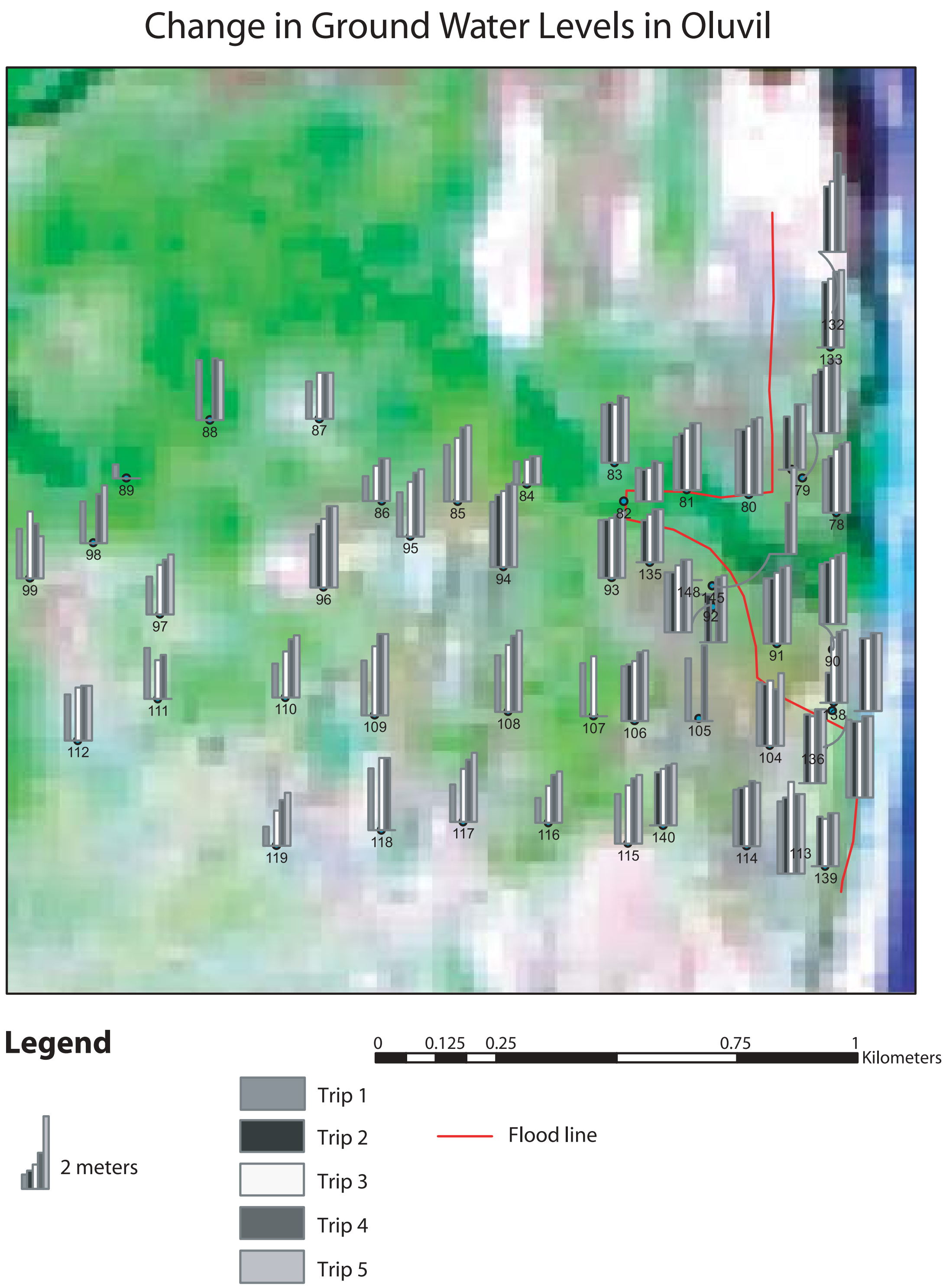


Figure 42. Groundwater levels in individual wells in the Oluvil site throughout the study period. Note that an increase in the size of the bars indicates a drop in the groundwater table

Monitoring of wells for breeding of mosquito vectors

Immature mosquitoes (larvae and pupae) belonging to the three genera (*Culex*, *Anopheles* and *Aedes*) were prevalent at varying degrees in all three sites, and in all types of habitats (Figure 43 and 44). Between 28 and 32% of all samples, and between 23 and 27% of all wells were positive for mosquito larvae and pupae three months after the tsunami, which declined gradually through the dry season. However, an increase in prevalence was observed during July/August, especially in two sites, probably associated with intermittent rains between trips.

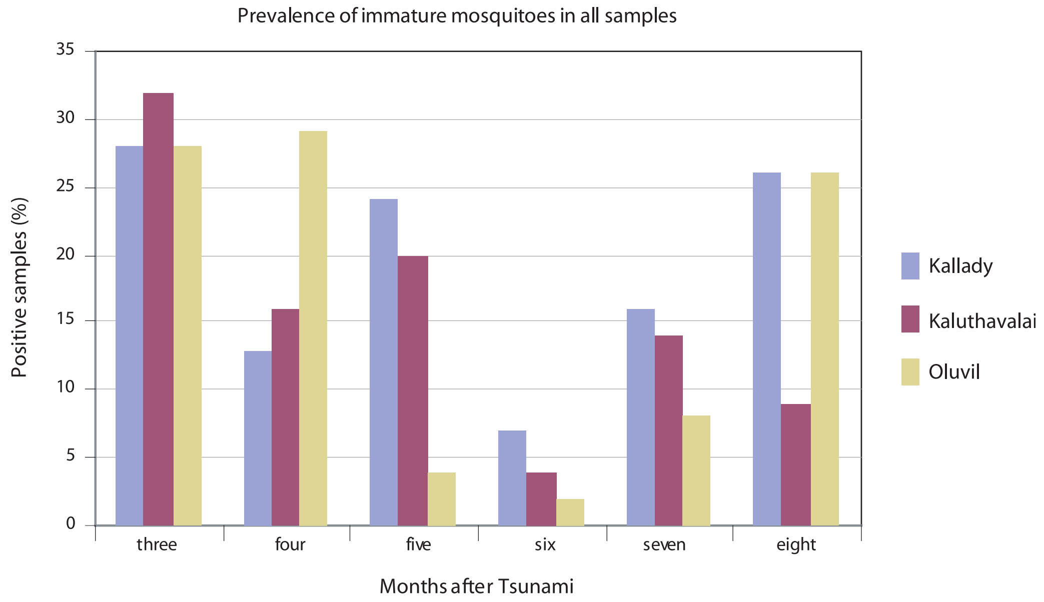


Figure 43. Prevalence of mosquito larvae and pupae in all the samples (wells, drains, rice fields, lagoons etc.)

All types of wells were potential habitats for mosquito breeding, including agro-wells and a production well that had its cover destroyed after the tsunami (Figure 44). Mosquito larvae and pupae were prevalent in domestic wells having salinity levels up to 5500 µS/cm (salinity levels increased up to 14,632 µS/cm), groundwater levels at a range of 0.8 to 1.8 m, and a turbidity range of 0.5 to 63.84 ntu, during the first trip (Figure 45).

In terms of densities, the *Culex* spp. were the most abundant, often when water was foul and contaminated with debris. Although not shown in these figures, the totals collected for the genus *Culex* varied from 100-1000 per six dips, in comparison with *Anopheles* spp. and *Aedes* spp., where the numbers were relatively few (10-20 per six dips). Of these, the carrier of lymphatic filariasis, *Culex quinquefasciatus* was the most abundant. In comparison, *Culex fuscocephala* (carrier of Japanese encephalitis) were recorded only at low densities. Although the genus specific figures (Figure 46, 47 and 48) do not show the eighth sampling point (genus separation could not been done due to unavoidable circumstances) the prevalence had increased with the intermittent showers experienced in between field trips. The impending monsoon period for the area (November - January) can be expected to generate an increase in larval densities together with new habitats that might be created with excessive rains. *Aedes* spp. was the least prevalent of all mosquito species and in terms of transmission of dengue, the wells are an unlikely breeding habitat for this container breeding species (*Aedes aegypti*).

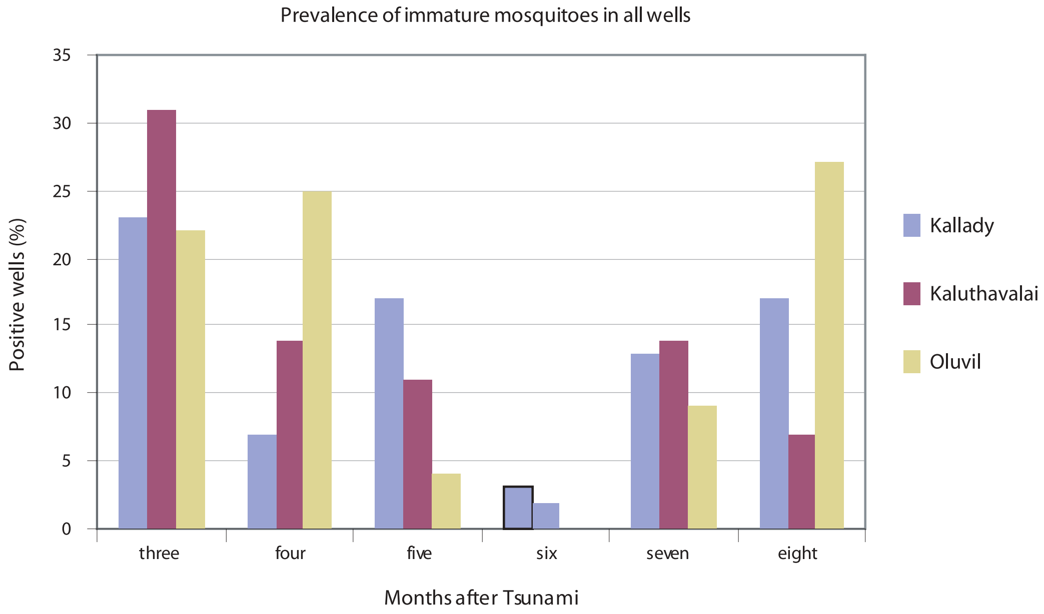


Figure 44. Prevalence of mosquito larvae and pupae in all wells (domestic wells; n =130, production wells; n=3, and agro-wells; n=3.)

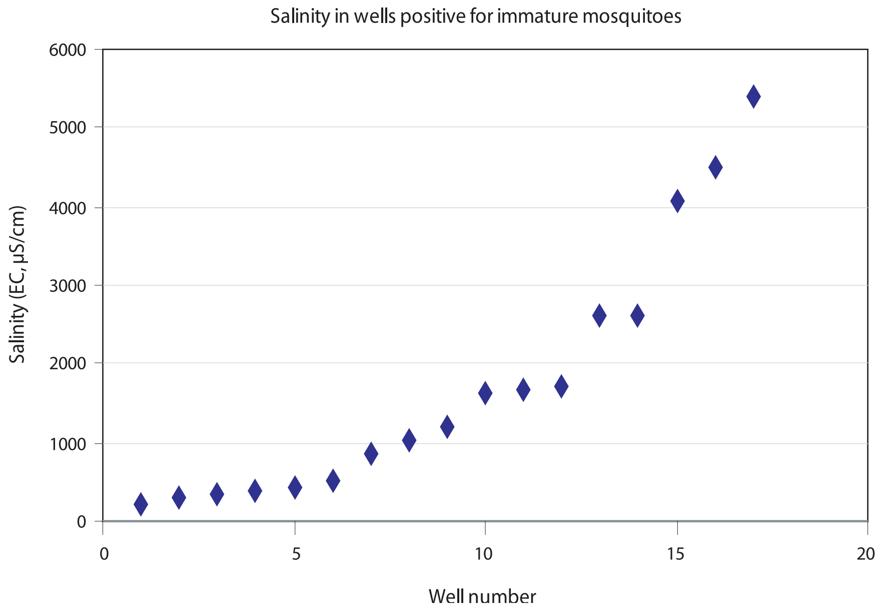


Figure 45. Salinity levels in wells that were positive for mosquitoes during the first trip (three months after the tsunami)

Studies on pre-tsunami transmission dynamics of vector borne diseases for the North Eastern Province are meagre. A previous preliminary study on human biting mosquitoes carried out in the Batticaloa district (Vanthrumoolai and Batticaloa town) highlighted the potential for vector borne diseases especially for malaria, dengue and Japanese encephalitis, owing to the presence of the specific vectors in some selected sites (Kirupairajah 1994). Since then, both Batticaloa and Ampara Districts have been identified as regions of high transmission for malaria and dengue in the recent past, from patient registrations at hospitals (Jeyakumar, personal communication).

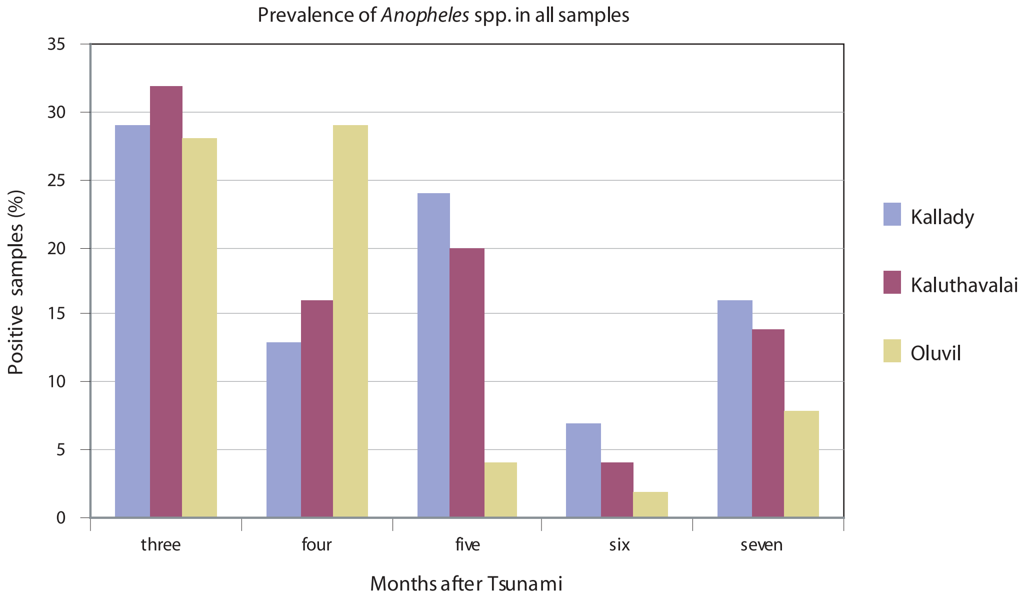


Figure 46. Prevalence of *Anopheles* spp. in all samples

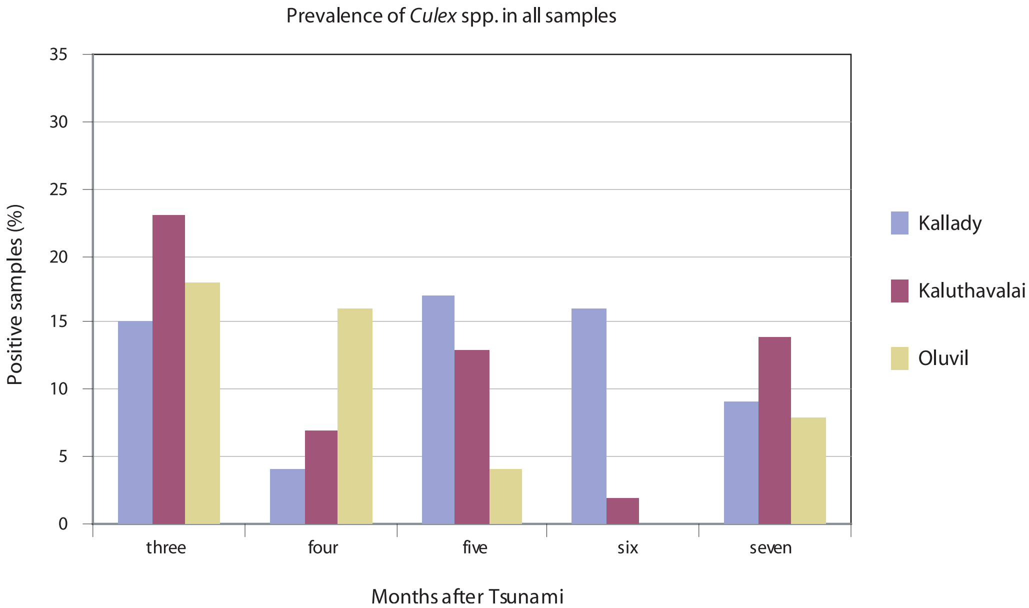


Figure 47. Prevalence of *Culex* spp. in all samples

A post-Tsunami, appraisal has been made on the possible consequences of inundation with sea water, with regard to malaria in the east and southern coasts of Sri Lanka (Briet et al., 2005). It discusses the unlikely chance of an epidemic in connection with the tsunami-created surface water bodies, especially in relation to the saltwater breeding *Anopheles* (Abhayawardana et al., 1996). However, environmental disturbances leading to an increase in the vector mosquitoes, namely *An. sundaicus* and *An. subpictus* were noted in the Andaman and Nicobar islands of India. In these islands, the paddy fields and fallow land that were freshwater habitats, turned saline with flooding, which enabled the brackish water species

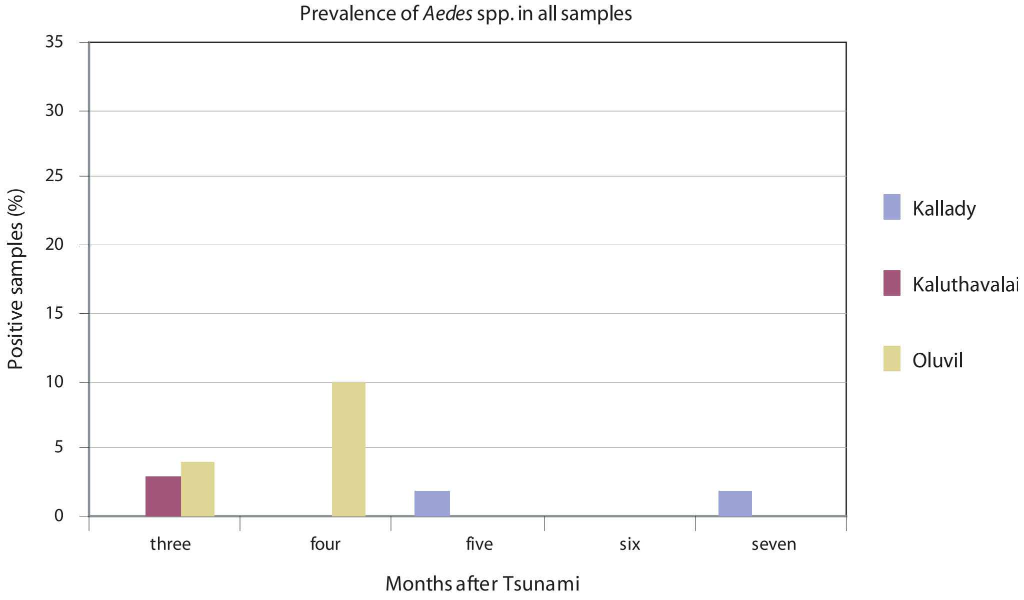


Figure 48. Prevalence of *Aedes* spp. in all samples

to thrive. Consequently, the malaria incidence rose indicating a risk of a malaria outbreak in the islands (Krishnamoorthy et al., 2005). The present study showed that the species important in the transmission of malaria, namely, *An. culicifacies*, *An. subpictus*, *An. vagus* and *An varuna* were present, in all types of habitats, but in such small numbers that there is no immediate threat of epidemics, in the sites that were studied. However, close monitoring should be continued, for increases in larval densities and new human cases from the hospitals so that early action can be taken towards the reducing the spread of disease. The overall vector borne disease indices for 2005, in the Batticaloa District were reported as follows: Malaria = 873 cases, Japanese encephalitis = 21 cases, Dengue = 12 cases and no reported cases for filariasis. The current malaria situation being low is also a positive factor, as we can expect low levels of circulating parasites among the reservoir hosts. Thus, keeping mosquito densities at low levels can help keep disease transmission under control.

This study shows that the major vector of malaria as well as the subsidiary vectors breed in all types of wells that are open and, sunlit, but not in the production wells and tube wells that are closed. While climatic factors affect the breeding potential of mosquitoes, the unusual cleaning of wells and chlorination could have contributed to the lowering of larval densities. However, despite the heavy cleaning and chlorination, re-colonization had taken place and it appeared that a salinity level of up to 5500 µS/cm was tolerated by a majority of the species collected during this study. This requires further systematic investigation.

With inadequate information on the pre-tsunami status on vector breeding, it is difficult to assess a post-tsunami impact on mosquito larval breeding. In general, these habitats could become potentially dangerous, in the event there is a rise in the circulating parasite populations and such a risk cannot be overlooked. This is said in light of unusual movement and congregation of people in welfare camps after the tsunami. Although wells are not the primary breeding habitats for the species encountered here, the close proximity of wells to dwellings warrant appropriate advice. Therefore, it is recommended that the domestic wells be covered, and also surveillance program be established to monitor outbreaks early, for quick remedial action.

Chapter 5

Conclusions and recommendations

At the time of the finalization of this report (Oct., 2005), the following conclusions and recommendations emerged.

Conclusions with respect to well cleaning

- Well cleaning just after the tsunami was recommended from a contamination point of view[7], to avoid outbreaks of infectious diseases from pathogenic microorganisms, to remove debris and basically making the wells fit for post-tsunami purposes, albeit not drinking in many cases, because the salinity often remained high, even after repeated cleaning
- Later (after three to four months), the cleaning of wells for removal of salinity was not recommended because the effect was minimal and there was a risk of deteriorating rather than improving the salinity due to ingress of higher saline water from the surrounding and underlying aquifer
- Guidelines for well cleaning and groundwater protection were developed as part of the project. Realizing that the conditions and impacts of cleaning changed over time, a set of three guidelines were developed (Appendix A to C)
- The awareness of the problems and implications of groundwater pumping for well cleaning among local authorities and NGOs had increased since the tsunami due to their personal experiences as well as the due to the efforts of this project
- At the time of writing, pumping for cleaning had stopped or was performed more cautiously than earlier
- Initiatives for collecting/compiling and processing data from various sources on the groundwater quality after the tsunami was emerging, albeit slow and still not very coordinated

Conclusions with respect to the well monitoring program for salinity and mosquito vector breeding

- Wells were affected up to 1.5 km inland
- 39% of the monitored wells within 2km from the coast were flooded by the tsunami
- The three study sites were impacted to various extent, in terms of number of flooded wells and the distance to which the waves reached inland (Kaluthavalai $\gtrsim$ Kallady $\gg$ Oluvil)

[7]Based on theoretical considerations and qualitative, rather than strict quantitative findings in the field.

- The topography could explain some of the variability of impact between sites. However, other factors such as bathymetry, number of waves, wave height and angle and wave braking features on the coast were probably equally important
- Well water salinity varied significantly within the flooded areas due to different flooding patterns, soil and well characteristics and possibly post-tsunami pumping and cleaning impacts
- The rainfall pattern and amounts observed in the areas pre- and post-tsunami indicated that the impact of the tsunami in terms of salinity was relatively benign, representing rather a best case scenario
- Average well water salinity in flooded wells remained higher than salinity of non-flooded wells throughout the monitoring period indicating that the wells had not recovered and that the salinity impacts persisted after seven months after the tsunami
- The average well water salinity of flooded wells decreased rapidly within the first few months after the tsunami, but excess residual salinity persisted throughout the dry season ensuing the tsunami
- The average salinity of non-flooded wells increased slightly throughout the monitoring period. The rate of increase and the levels observed were comparable to pre-tsunami observations, indicating that the shallow aquifers in the non-flooded areas were not affected by the tsunami and that the increase observed was a normal process due to the drying out of the areas. This implies that wells in non-flooded areas could be used, with caution, to augment or substitute local water supply in flooded areas
- The majority of wells in the flooded areas were unfit for drinking seven months after the tsunami. The estimation was based on a drinking water acceptability criterion based on the actual use of the well water after the tsunami. This criterion may however be stricter than under normal, pre-tsunami times, because people were getting accustomed to better drinking water from the relief supply
- Highly saline water was consistently encountered at approx. 10 m depth below the ground, at a distance of 0.8 km from the coast. Whether this was tsunami water still sinking into the aquifer or pre-tsunami saltwater at the bottom of the freshwater lens could not be inferred in the study
- From the above conclusions it can be understood that the well cleaning efforts alone, taking place as part of the relief work, did not recover the flooded wells
- Recovery of the flooded wells and restoring freshwater conditions in the affected shallow aquifer required at least one more monsoon season. Recovery from rainfall recharge and potentially additional recharge from natural or constructed ponds are the primary means of flushing and restoring the aquifers
- A high percentage of wells (22-32%) were positive for disease transmitting vector mosquitoes. These mosquitoes were able to tolerate high levels of salinity (5500 µS/cm)

It was not possible to detect whether the cleaning initiatives were in fact predominantly ameliorating or aggravating the salinity in the wells. Also, it is not clear whether the present pumping patterns are threatening the groundwater salinity.

Recommendations

- Follow the guidelines given in Appendix C, which apply to the time and conditions at the east coast at the time of the publication of this report
- Continue the monitoring program. Extend the parameters to address some of the most critical and relevant contamination problems, like nitrate and certain pesticides, and microbiological contamination
- Extend the monitoring program to sites with different geological conditions and compile and compare other past and ongoing studies on groundwater salinity issues
- Extent the study with more in depth analysis of the salinization processes, e.g. the infiltration of saltwater into soils and shallow fresh groundwater, and the recovery of the aquifer due to rainfall
- Implement detailed studies and modelling to understand processes and to recommend the optimal or maximum usage of the groundwater in the coastal areas, taking into account the present and future stress, in term of abstraction demand and pollution load
- Expand the analysis on the water supply situation and how people cope with the salinity problems
- Support NGOs, local authorities, and other actors with scientifically based studies and training, in their effort to develop, use and protect the groundwater resources for continued relief measures and more long term planning
- Develop a set of internationally accepted and endorsed guidelines that apply to the rehabilitation of well water supply conditions after flooding by saltwater, e.g. a tsunami
- Continue/reinforce awareness raising among local stakeholders on groundwater issues and how best to use and protect groundwater
- Cover wells to prevent mosquito vector breeding, especially those that are in close proximity to dwelling places
- Establish a surveillance program for disease outbreaks, so that early action can be taken to minimize the spread of diseases

The tsunami has accentuated the importance of the coastal aquifers in a water supply context, and at the same time their vulnerability to contamination and over-exploitation. However, the thrust and premise of any continued efforts to rehabilitate the water supply and aquifer systems must be one of protecting and optimizing the use of these resources rather than one of negligence, in which the groundwater is sacrificed in the belief that alternative and more promising water resources can be developed. This may prove to be a false hope.

References

Abhayawardana T.A, Wijesuriya S.R, Dilrukshi R.K: 1996. *Anopheles* subpictus complex: distribution of sibling species in Sri Lanka. Indian Journal of Malariology. 33:53-60.

ADB, Japan Bank for International Cooperation and WB, 2005. Sri Lanka – 2005 Post-Tsunami Recovery Program. Preliminary Damage and Needs Assessment. Colombo, Sri Lanka. Jan. 10-28, 2005. *http://www.adb.org/Tsunami/sri-lanka-assessment.asp*

Amerasinghe, F.P. and Ariyasena T.G., 1990. Larval survey of surface water-breeding mosquitoes during irrigation development in the Mahaweli project, Sri Lanka. Journal of Medical Entomology. 27 (5): 789-802

Amerasinghe, F.P., 1990. A guide to the identification of Anopheline mosquitoes (Diptera: Culicidae) of Sri Lanka. I. Adult females. Ceylon Journal of Science (Biological Sciences) Vol. 21, No. 1

Amerasinghe, F.P., 1992. A guide to the identification of Anopheline mosquitoes (Diptera: Culicidae) of Sri Lanka. I. Larvae. Ceylon Journal of Science (Biological Sciences) Vol. 22, No. 1

Amerasinghe, F.P., 1996. Keys to the identification of the immature stages of genus *Culex* (Diptera: Culicidae) Sri Lanka. Journal of the National Science Council. Sri Lanka 24 (1):37-50

Anputhas, M., Ariyaratne, R., Gamage, N., Jayakody, P., Jinapala, K., Somaratne, P.G., Weligamage, P., Weragala, N., and Wijerathna, D., 2005. Bringing Hambantota back to normal: A post-tsunami livelihoods needs assessment of Hambantota District in Southern Sri Lanka. Colombo, Sri Lanka: IWMI. 59p.

Briët O.J.T., Galappaththi G.N.L., Konradsen F., Amerasinghe P.H., Amerasinghe F.P., 2005. Maps of the Sri Lanka malaria situation preceding the tsunami and key aspects to be considered in the emergency phase and beyond. Malaria Journal, 4:8

Liu, P.L.F., Lynett, P., Fernando, H., Jaffe, B.E., Fritz, H., Higman, B., Morton, R., Goff, J., Synolakis, C., 2005. Observations by the International Tsunami Survey Team in Sri Lanka. Science, 308, 10 JUNE 2005.

IUCN and IWMI, 2005. Series on Best Practice Guidelines (Sri Lanka).After the Tsunami: Water Pollution. Information Paper No. 11, *http://www.iucn.org/places/srilanka/images/information%20paper%2011%20water%20pollution%20paper1.pdf*

Jeyakumar, P., Premanantharajah, P. and Mahendran, S., 2002. Water quality of agro-wells in the coastal area of the Batticaloa district. Proceedings from Symposium on the Use of Groundwater for Agriculture in Sri Lanka, 30 September, 2002, Peradeniya, Sri Lanka..

Kirupairajah, S., 1994. A preliminary study of night human biting mosquitoes at two locations in the Batticaloa distirct. Research report submitted for the special degree course in Zoology at the Eastern university, Sri Lanka 48pp

Krishnamoorthy, K., Jambulingam P., Natarajan R., Shriram A. N., Das P. K. and Sehgal, S. C., 2005. Altered environment and risk of malaria outbreak in South Andaman, Andaman & Nicobar Islands, India affected by tsunami disaster. Malaria Journal 2005; 4: 32.

Panabokke, C.R., 1996. Soils and Agro-Ecological Environments of Sri Lanka. Natural Resources Series – No. 2. Natural Resources, Energy and Science Authority of Sri Lanka.

Panabokke, C.R. and Perera, A.P.G.R.L., 2005. Groundwater Resources of Sri Lanka. Paper presented at the NSF Workshop: 'Impact of Tsunami on Groundwater, Soils and Vegetation in Coastal Regions of Sri Lanka' in Kandy, Sep. 19, 2005.

Senaratne, A., 2005. Personal communication.

Sri Lanka Department of Census and Statistics. 2005a. List of GN divisions Affected by tsunami. *http://www.statistics.gov.lk*

UNEP, 2005. After the Tsunami - Rapid Environmental Assessment. *http://www.unep.org/tsunami/tsunami_rpt.asp*

UNICEF, 2005. Consequences of the tsunami on the coastal aquifer in Eastern Sri Lanka – Guidelines on wells rehabilitation. Trincomalee, May, 2005.

Vaheesar, K., Mahendran, T., and Priyantha, N., 2000. Analytical studies on irrigation water at Kaluthavalai in the Batticaloa district, Journal of Science, Faculty of Science, Eastern University of Sri Lanka, Vol 1 (1), 10-15.

WHO, 2004. Guidelines for Drinking-water Quality – Third Edition World Health Organization, Geneva. *http://www.who.int/water_sanitation_health/dwq/gdwq3/en/*

WHO. Technical Note 2005a: Malaria risk and malaria control in Asian countries affected by the tsunami disaster. *http://mosquito.who.int/docs/Asia_tsunami_malaria_risk-v1-5Jan.pdf*

WHO, 2005b. World Health Organization Weekly Tsunami Situation Report. 2005. *http://www.who.int/hac/crises/international/asia_tsunami/sitrep/30/en/*

Wooding, R.A., Tyler, S.W., White, I., and Anderson, P.A. (1997a). Convection in groundwater below an evaporating salt lake: 1. Onset of instability. Water Resources Research, 33, 6, 11199219-1228.

Wooding, R.A., Tyler, S.W., White, I., and Anderson, P.A. (1997b). Convection in groundwater below an evaporating salt lake: 2. Evolution of fingers or plumes. Water Resources Research, 33, 6, 1219-1228.

Appendix A

Information note, disseminated mid-February, 2005, on the actual status of wells, the impact of pumping/ cleaning of wells and the best approach to cleaning of wells at that point in time.

INFORMATION ON WELL CLEANING

Relevant for the east coast of Sri Lanka, one to two months after the tsunami

After the tsunami, the majority of shallow, private wells (approx. 12.000) in the rural and semi-urban areas on the East coast of Sri Lanka have been filled with saltwater. To rehabilitate these wells and return them to a condition that is suitable for reuse for the households, cleaning has been done by NGOs, volunteer groups and the owners themselves. However, there is a general frustration and uncertainty as to the best way to go about the cleaning, to ensure that the well water is fit for use, and the well and aquifer around it is not hampered in the process.

Some report that the wells remain salty, even after repeated pumping out of the wells, other report of problems with disruption and collapse of the wells.

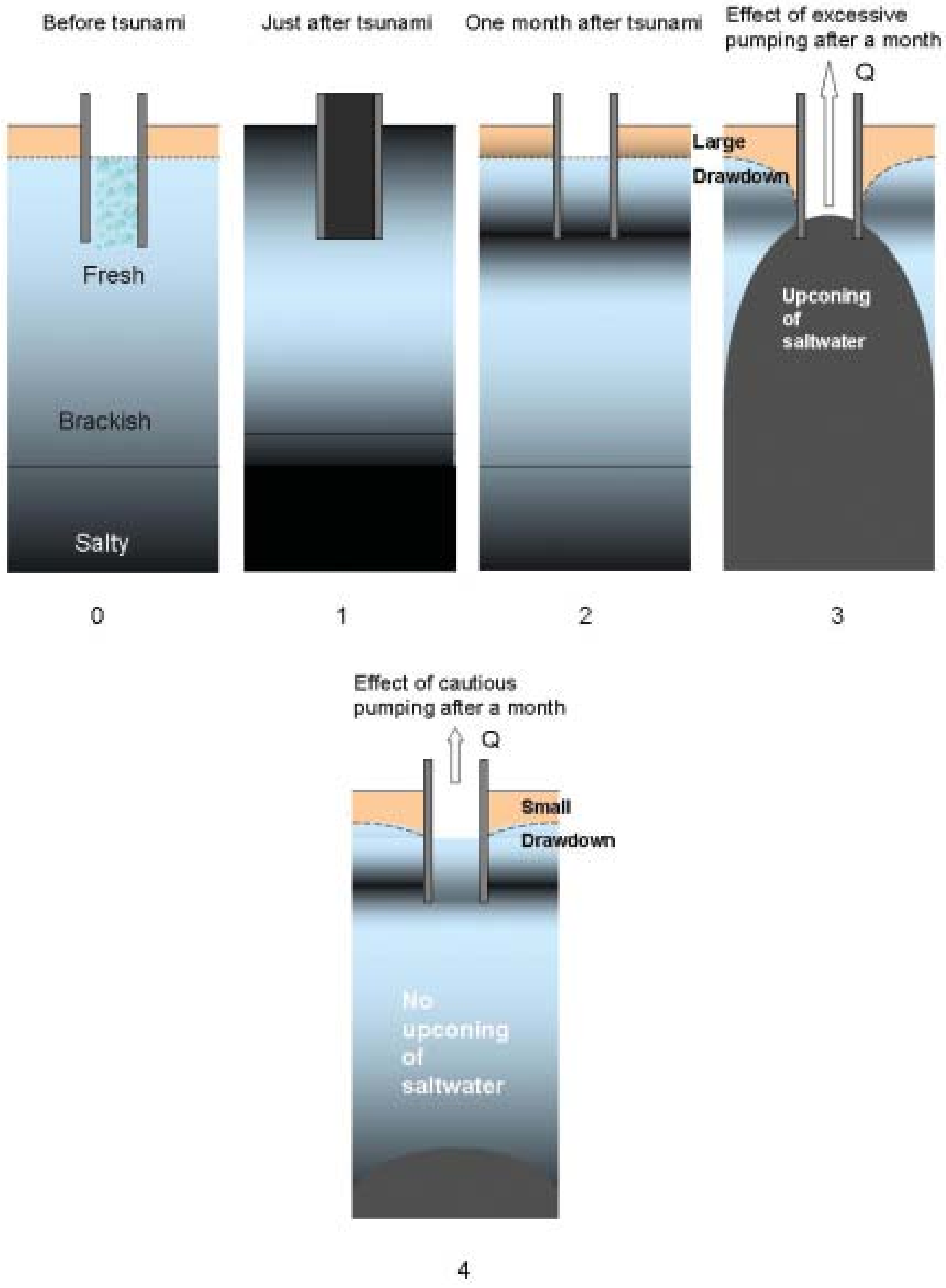
It can be said that if a well has previously been fresh, it is likely, in most cases that it will turn fresh again, by the natural flushing from rainfall. It may take time (up to a couple of years), but generally salinization is a reversible process. Having said this, there may be situations, where the aquifer has been more permanently damaged due to the tsunami, e.g. where the coast line has receded. In these cases, the wells very close to the sea will have to be abandoned.

Even though the wells will turn fresh naturally, the rationale for cleaning them by pumping is that by removing the saltwater standing in them (Situation 1 in Figure), they will become fresh faster. Also debris, sediment and organic matter that have accumulated in the wells due to the tsunami will have to be taken out and preferably the wells disinfected before reuse.

When the wells do not turn fresh after pumping it is because the groundwater in the aquifer adjacent to the well is salty, and it is replacing the pumped out water. If the drawdown due to the well pumping, i.e. the decrease in the water level in the well, is high (as it is when the well is emptied totally during the rainy season, where the water table is high) saltwater is likely to enter the well from below as well (Situation 3 in Figure). If only small amounts of water are pumped out, giving rise to a small drawdown, the water that re-enters the well will be coming from the top of the aquifer. Before the tsunami, the interface between the fresh and saltwater will be at a depth between 0 and 50 m, lowest close to the sea (Situation 0 in Figure). So the problem of ingress from saltwater from below will be largest close to the sea. There may also be cases, where saltwater keep entering the well even further from the coast. This can be the case, if saltwater has been accumulating in depressions on the surface forming ponds or lakes. In this case, the groundwater infiltrating in that area will be more saline and may enter the wells.

Now, more than a month after the tsunami, the wells that have not been pumped are less salty due to the rainfall that has occurred. The same can be said about the soil and the upper groundwater around the wells. In fact, measurements on some wells in Batticaloa indicate that the water in the wells are highly stratified, with brackish water on the top and salty water on the bottom (Situation 2 in Figure). The rainfall, plus the fact that saltwater sinks due to its higher density compared to freshwater explains this. This means that at this time it does not make sense to empty out all the well water in an attempt to clean them as the water that replaces the well water might be more salty. For wells that have not been cleaned, a modified cleaning method is to just pump moderately (say total volume equal to 0.5 to 1 m^3 or a depth of 30 cm in a 1.5 m diameter well, with a submersible pump at the bottom, to get out the salty water there as well as sludge accumulated, and then water naturally will be replenished by more freshwater from the shallow groundwater. Then the well should be left for further natural flushing and cleaning from rainfall. Chlorination may be performed according to suitable standards.

This method should ensure that the well itself it not physically disrupted. Also, if the wells being cleaned are very close to latrines, this method should minimize bacteriological cross-contamination.



Appendix B

Information note, disseminated mid-May, 2005, on the best approach to cleaning of wells at that point in time

1. Pumping should not be done to decrease salinity of the wells. If pumping is needed to remove sludge and debris, only slow pumping (preferably with a sludge pump at the bottom) can be done. The drawdown in the well must not exceed 0.5 m for more than 15 min's. The well must not be emptied if more than 0.5 m of standing water is present.
2. If pumping/cleaning was performed previously on the well and the salinity increased, the well should not be cleaned again.
3. Cleaning should only be done by qualified and trained personnel with reporting to the local authorities (NWSDB)
4. Cleaning should be done with accompanying monitoring of salinity, before and after, at the bottom and top of the well, respectively.
5. Repeated chlorination of wells, with accompanying emptying of wells, is not recommended. The (smaller) portion of extracted water that is used for drinking should be purified separately by other means, e.g. by chlorine tablets, boiling, or by the SODIS (Solar Disinfection) method.
6. Wells that are salty or becoming salty should be pumped less or abandoned temporarily, and freshwater should be sought from neighbor wells that are not salty.
7. Abandoned wells should be covered to reduce risk of mosquito breeding, and to indicate that the well is not in use.
8. Deep wells (more than 5 m deep) and wells pumped with motorized pumps should be regularly monitored for salinity as they stand a greater risk of salinization
9. Wells should not be deepened in the coastal aquifers in an attempt to avoid saltwater.
10. New deep wells should not be drilled in the coastal aquifers in an attempt to get freshwater.
11. Stagnant water bodies should be cleaned for debris. In case of suspicion of pollution of the water body (e.g. by visible oil film on the surface), it should be drained to the ocean. Cases should be reported to the authorities who should take action in the clean-up.
12. In other cases, stagnant water bodies should not be drained in an attempt to remove saline water. Rather the deliberate accumulation of rainwater in depressions should be performed in order to increase the flushing and cleaning of the groundwater.

Appendix C

Guidelines for use of wells and groundwater protection in the tsunami-affected coastal areas, relevant after ten months after the tsunami

Preamble

When the tsunami struck Sri Lanka, wells and groundwater were impacted severely. Wells up to 1.5 km inland were flooded and groundwater was salinized by seawater infiltrating through soil and trapped water pools. Ten months after the tsunami, the salinity in the affected areas is still above background levels[9]. Therefore enforced precautions are needed for the use, rehabilitation and protection of wells and groundwater. The following guidelines are applicable to the situation prevailing at and after the first dry season after the tsunami, primarily on the East coat of Sri Lanka

The recommendations are based on a study by IWMI[1], field level experience and internationally accepted guidelines. It is important to carefully follow the guidelines and seek professional assistance if in doubt.

Guidelines

1. Do not pump/clean wells to decrease salinity. In fact, over-pumping can increase salinity.
2. Do not repeatedly empty wells. Empty wells only at the end of the dry season, e.g. to remove sludge and debris and to chlorinate when little water (< 1m) is in the well. This applies to both tsunami-affected and non-affected wells.
3. Do not repeatedly chlorinate wells. A single shock-chlorination strictly following standard procedures[9] and minimizing pumping[10] can be done.
4. Drinking water should be purified separately (e.g. by chlorine tablets, by boiling, or by the SODIS (Solar Disinfection) method[11].
5. Wells that are salty or becoming salty should be pumped less or abandoned temporarily, and freshwater should be sought from neighboring wells that are not salty.
6. Abandoned wells should be covered to reduce the risk of mosquito breeding. Even some wells that are being used are mosquito positive. Cover all domestic and agro-wells to prevent mosquito breeding.
7. Large scale abstraction (like for bowsers and agro-wells) from single wells should be avoided. Apportion abstraction to more, inter-changeable wells.
8. Deep wells (> 5 m) and wells pumped intensively with motorized pumps (agro and bowser) should be regularly monitored for salinity, at the top and bottom of the well.

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[8]See IWMI report: ‘Tsunami Impacts on Shallow Groundwater and Associated Water Supply on the East Coast of Sri Lanka’, Oct., 2005.

[9]http://www.who.int/water_sanitation_health/hygiene/envsan/technotes/en/

[10]Strike a balance between pumping intensively and quickly to remove only water standing in the well, and not disrupting or destroying the well structure from cave-in due to high pressure force from surrounding sediments and water entering the well.

[11]http://www.sodis.ch/

9. Preferably, pump from shallow wells (< 5m). Avoid pumping close[12] to the coast and lagoons with salty/ brackish water, tsunami-flooded areas, other intensively pumped wells and other sources of pollution, like dumpsites, cemeteries and petrol stations.
10. Wells should not be deepened in the coastal aquifers(groundwater systems) in an attempt to avoid saltwater. This will result in more saltwater intrusion.
11. New deep wells (> 10 m) should not be drilled in the coastal aquifers in an attempt to get fresh water.
12. Stagnant water bodies that are not polluted and do not cause health concerns from e.g. vector borne diseases can be left to replenish and flush the aquifer.
13. Depending on the soil conditions, the deliberate collection and infiltration of rainwater and excess run-off should be encouraged, provided that health risks from e.g. vector borne diseases are taken into account.
14. Keep a record of well treatment activities for future reference.

[12] within 200 m for low abstraction wells, and 500 m for high abstraction wells

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