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Application of Hydro-Geochemical and Geo-Electrical Techniques to Identify the Impact of Tsunami in the Coastal Groundwater

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1. Introduction

In general, the Coastal zones are dynamically active because of multivariate tectonic, fluvial marine and Aeolian geomorphic process which may vary in their dynamism with space of time. The tectonically active coasts show a greater influence on the land ocean interactive process. Tsunamis are ocean waves produced by earthquakes or underwater landslides. The word is from Japanese and means "harbor wave," because of the devastating effects these waves have had on low-lying Japanese coastal communities. On 26th December 2004, Indian subcontinent experienced the most devastating tsunami in its recorded history. The phenomenon was triggered by a submarine earthquake located at 3.4° N, 95.7° E off the coast of Sumatra (Indonesia) with an intensity of 9RSU. Tsunamis are most often generated by earthquake-induced movement of the ocean floor. Such massive earthquakes only occur in subduction zones where two of the rigid tectonic plates that comprise the earth's surface are converging, and one plate, usually composed of heavier oceanic material, dives beneath another, usually composed of lighter continental material. Aftershocks appear to be active over a 1300 Km section of the zone stretching from the Andaman Islands in the north to the earthquake epicentre below the northern tip of Sumatra, the seismic waveform data appears to indicate that only a 450 Km length of the subduction zone off northern Sumatra ruptured (Cumins & Leonard 2005). September 2004 AusGeo News article surmised, the greatest tsunami threat in the Indian Ocean appears to be posed by great subduction zone earthquakes of Sumatra.

Studies of the Indian ocean tsunami has been carried out by several workers (Table 1), it reveals that the signature of tsunami has been clearly demarcated in the sediments and only a few studies were carried out in the groundwater. Still the impact of tsunami in the groundwater by both geochemical and geophysical methods has been carried out by very few researchers. This chapter concentrates mainly on the application of the geophysical (Chidambaram et al 2008) and geochemical nature (Chidambaram et al 2010) of the ground water to characterize the tsunami signatures and to bring out the process/mechanism after the event.

2. Study area

The study area extents from Parangipettai to Pumpuhar and lies in between 79° 46'E to 79° 51' E longitudes and 11°07' N to 11° 30' N latitudes (Fig 1). It occurs within the survey of India toposheets of 58 M/15 & 16. The Vellar and Coleroon are the major rivers flowing in the study area they form a an Estuary with marshy mangrove environment at Pichavaram.

3. Geological succession

The maximum temperature ranges between 27.9°C and 36.9°C, with mean ranging from 20.8°C to 27.1°C. The long-term analysis of the rainfall data from January to May indicates that average rainfall is in the order of 1,162.35 mm/year with a maximum contribution from the NE monsoon (53.01% of the total rainfall).

Era	Age	Formations	Lithology
Quaternary	Recent to Sub-Recent	Alluvium& Laterite	Soils, alluvium and coastal sands, Clays, kankar and Laterite
------------------------- UNCONFORMITY -------------------------------			
TERTIARY	Mio-Pliocene	Cuddalore Sandstones	Argillaceous and pebble bearing grits, Clays (variegated) with lignite seams and pebble beds.
------------------------- UNCONFORMITY -------------------------------			

4. Hydrogeology

Aquifers in the study area are confined to unconfined. Water table in majority of the study area ranges from 5 – 20 mbgl (meter below ground level) during premonsoon. Whereas, depth to water table during post monsoon period it ranged between 2 and 10 mbgl. In Coleroon alluvial belt the shallow water table conditions exist less than 2 mbgl. The areal extent of this region has been further extended occupying major part of Vellar and coastal alluvial formations in east indicating extent of water logging conditions during post monsoon period. Water level observations for certain locations in the study area (Fig 2) during the period of tsunami indicate that there is considerable increase of water level in certain location accompanied by fall in few regions. Yield of bore wells tapping permeable granular zones, older sediments of study area ranges from 1176 and 29481 for drawdown ranging from 2.15 to 9.6m.Transmissivity is also higher and it ranges from 295 – 838m^2/day. Movement of water from one region to other is also governed by hydraulic conductivity (k) ranges from 13.6 to 23.6m/d.

5. Methodology

Around 40 samples collected during November 2004 from Pondicherry to Velankanni it showed that nearly eleven locations in shallow groundwater were uncontaminated by seawater intrusion along the coast and then eleven samples were identified/selected for post tsunami impact studies (In total eleven sampling locations were selected for targeting the changes after tsunami). Eleven ground water samples were collected (Fig 3a,b), during each period of sampling in the month of November 2004, January 2005, March, 2005 and August, 2005. The samples were collected from shallow aquifers through tube wells depths of 20mbgl . Samples collected in month of November 2004 (Prefix 'pr'), Jan 2005 (Prefix 'J'), March, 2005 (Prefix 'M') and August, 2005 (Prefix 'A').The samples were collected mainly from shallow aquifers (40-100 feet depth). The inundated region ranges from 0.5 to 1 Km from the coast (Table 1). These wells were selected in such a way that they are in the tsunami inundated region ranging at least about 0.2 to a maximum of 3Km from the coast and also were not earlier affected by salt water intrusion. The chemical parameters like EC (Electrical conductivity), pH, TDS, Na, K, Ca, Mg, HCO_3, Cl and SO_4. These parameters were used for the hydro geochemical interpretations. The collected samples were analyzed for major cations like, Ca and Mg by Titrimetry, Na and K by Flame photometer (CL 378); anions, Cl and HCO_3 by Tirimetry, SO_4 by Spectrophotometer (SL 171 minispec). EC and pH were measured in the field using electrode. All the analyses were carried out by adopting standard procedures (APHA, 1998). The results of the analysis were checked by the cation anion balance which was within ±8%. Heavy metal analysis were carried out by using ICPMS at NGRI, Hyderabad.

The soundings were performed by the DDR III Resistivity meter by adopting Schlumberger electrode array with maximum spacing (AB/2) in the range of 2 – 90m. Pre-tsunami resistivity was done up to 50m depth during August, 2004 and post-tsunami survey was done in 2005 at different locations (Fig 4). Interpretation of resistivity curves was done by curve matching technique using standard graphs (Rijkswaterstaat, 1969) and master curves (Ornella & Mooney, 1966) for determining thickness and resistivity of corresponding layers. Impact of saline water due to Tsunami is expected to be in shallow waters and hence the geoelectrical variations of shallow ground waters were only considered.

6. Geochemistry

Dominance of anions in the study area are in the following order; $Cl>HCO_3>SO_4$ in both pre-tsunami and post-tsunami. Though the order of preference is maintained the value of Cl has increased in Post tsunami. The order of dominance of cations in the study area is Ca>Na>Mg>K in pre-tsunami and Na>K>Ca>Mg in post-tsunami (Table 2). The figure 4 shows that there is a considerable increase in the EC, Ca, Mg, Na along with Cl and HCO_3. Increase of EC, Na and Cl are more prominent during the period of the study than other ions.

7. Heavy metals

Heavy metals like Fe, Al and Mn were analysed for these samples during post tsunami . Iron ranges from 0.12 mgl^{-1} to 0.72 mgl^{-1} with an average of 0.37 mgl^{-1} in the month of March and from 0.03 mgl^{-1} to 0.58 mgl^{-1} with an average of 0.39 mgl^{-1} in the month of August. Manganese ranges from 0.05 to 1.52 with an average of 0.52 in the month of March and from 0.009 mgl^{-1} to 1.86 mgl^{-1} with an average of 0.42 mgl^{-1} in the month of August. Aluminium ranges from 0.03 to 0.08 mgl^{-1} with an average of 0.055 mgl^{-1} in the month of March and from 0.04 mgl^{-1} to 0.08 mgl^{-1} with an average of 0.056 mgl^{-1} in the month of August. It is evident that there is no significant variation in the heavy metals subsequent to tsunami (Table 3).

8. pCO_2 and ionic strength

Partial pressure of CO_2 (pCO2) in rivers are commonly out of equilibrium with atmosphere. Two possible explanations for this apparent paradox are: (1) River waters (particularly perennial rivers) contain a significant fraction of high CO_2 groundwater and (2) the rate of re-equilibrium with the atmosphere (by releasing the excess CO_2) is relatively slow (Stumm & Morgan, 1996; Holland,1978). The Log pCO_2 (Raymahashay, 1986) for each samples are determined to study its relation to recharge (Prasanna et al,2009, Chidambaram et al,2008). Log PCO2 value, during ranges from -0.83 to -3.62 (Fig 5). The ionic strength does not show any linearity with log pCO_2 values during January and Pre-tsunami. This may be due to higher pH or lesser neutralizing ions like Ca^{2+} (Raymahashay, 1986). The samples collected during the January and pre-tsunami show lesser values of pCO2, the higher values are noted in the month of August and March. The average values of pCO2 shows the order of dominance March> August> January> Pre-tsunami. This reveals that recharge is predominant during the pre-tsunami and the January months. The Atmospheric interaction becomes lesser during March and August with more matrix interaction. The South west monsoon showers during the month of August has decreased the pCO_2values than that of March.

Ionic strength (IS) is a measure of total concentration of ions which emphasizes increased contribution of species with charges greater than one to solution non-ideality (Domenico & Schwartz, 1990).

$$\mathbf{I = 0.5 \sum mz^2(1)} \qquad (1)$$

Where m is the concentration of a given ion in moles per liter and z is the charge on that ion. The terms in the summation include one for each ionic species present. A monograph, which simplifies calculation of ionic strength from analytical data in milligrams per liter, has been published by Hem (1961).

The approximate value of Ionic Strength can also be computed from the specific conductance of the solution if this has been measured (Lind, 1970). However, calculation should not be made unless one should have some knowledge of what the principal dissolved species present in the solution. If the composition is unknown for water with a specific conductance of 1,000 µ mhos, calculated value of IS ranges from 0.0032 to 0.134. The distribution of the ionic strength in the samples varies from lower to higher ranges. There is no significant demarcation of the IS with sampling interval except during August and March . Higher ionic strength is noted during the month of August, March, followed by

January and then Pre-tsunami. The increase of ionic strength shows linearity during the month of March and August

9. Intensity of Tsunami

There are two different tsunami intensity scales proposed by Soloviev (1970) and Ambraseys (1962). Soloviev pointed out that Imamura-Iida's scale is more like an earthquake intensity scale rather than a magnitude. He also distinguished the maximum tsunami height **h** and the mean tsunami height **h**. He then defined tsunami intensity **I** as $\mathbf{I = log_2(h)}$. Sieberg tsunami intensity scale – a descriptive tsunami intensity scale which was later modified into Sieberg-Ambraseys tsunami intensity scale (Ambraseys,1962); which describes tsunami from light tsunamis (Level 1) to disastrous tsunami (level 6) based on physical distraction caused by tsunami. Based on the calculation made with the average wave height (Table 4) in different states along the east coast of India, viz., Andhra Pradesh, Kerala, Puducherry and Tamilnadu, it is evident that the Tamilnadu and the Puducherry are the regions with higher Tsunami intensity.

10. Spatial distribution

Cl/HCO_3 ratio is generally used to identify the extent of salt water intrusion in the aquifers. An attempt has been made (Fig 6.1) to find out the relation of EC with the ratio, this indicates that EC increases in the month of March and August, it is also observed that certain amount of linearity is noted between EC and the Cl/HCO_3 ratio during all the periods of study. But higher ratios were noted only during the month of March and August 2005. The Spatial distribution of this ratio (Fig 6.2 a, b and c) during different periods of study indicates that area covered by higher ratios of these ions was noted along the river mouth and in few pockets where the water got stagnated during the event. There is a considerable increase noted in the distribution of this ratio in the month of August 2005. The average composition of the groundwaters of this region is shown by the figure 4. It indicates that the Na concentration is higher in cation and Cl in anion. Hence, the variation of these ions determines the overall water chemistry of the region.

11. Factor analysis

The statistical analysis of the data helps us to decipher the major chemical process responsible for the water chemistry of the region. The factor analysis was carried out by using Varimax rotation. Factor analysis carried out by Chidambaram et al (2010) for the study area indicate that three prominent factors were extracted for pre-tsunami and January and two factor for the month of August and March. The first component of factor loading (Figure 7a) in Pre-tsunami was represented by HCO_3, Mg, and Na indicating the process of weathering. The first component of January was represented by Cl, HCO_3, K, Mg, and Na indicating the mixing effect of seawater and fresh water. But during the month of March the first factor was represented by Cl, Ca, K, Mg, and Na indicating the evaporation mechanism, the second factor was represented by Cl and Na with negative representation of Ca,HCO_3,Mg, and SO_4 which indicates that there is a removal of these ions from the system by the precipitation of salts in pore spaces and on the surface due to precipitation. Hence there is an enrichment of Cl and Na. In August its represented by Cl, Na, and SO_4 where the

impact of saline water is clearly noted as the first factor and there is an association of Ca, HCO_3, Mg and K as second factor (Fig 7b). This is due to the leaching and dissolution of salt precipitation during the month of March. The rain during June and July has considerably leached and added these ions into the system. The representation of HCO_3 is noted during August and not in March indicate that dissolution of the precipitated salts were prominent only during the month of August after the onset of monsoon. The rains during June and July, has increased the migration of ions either by weathering or leaching of salts precipitated in summer.
The chemical compositions of different samples of the study area for different seasons are compared with the chemical composition of the sea water in the study area and the leached waters from the salt precipitate (Xue et al. 2000). The samples of August identified to have good correlation with seawater composition and that of salt precipitate. Their corresponding pre-tsunami compositions were used to obtain the mixing proportion (Chidambaram et al 2010). So the pre-tsunami water chemistry of the region is taken for the representative locations and the amount of mixing has been calculated.

Pre tsunami sample + X % Seawater → Post tsunami

The X % is determined by the mixing calculation

The percentage of sea water mixed with the groundwater after the tsunami event was obtained by the above said equation in the previous study. The results of the mixing percentage of the sea water with groundwater (Fig 8) shows the following order, A4 > A5 > A10 > A6 > A8 > A1 = A2. The higher rate of mixing is noted in the regions with more distribution channels of rivers where the water has entered and stagnated, precipitated and leached into the system. It is also noted that the bathymetry is gentle in the southern part of the area, where the tsunami water might have entered a long distance inland, where the inundation was favoured by the distributary's channels and river mouth. Chidambaram et al (2010) inferred that these processes (Fig. 9) might have been controlling the hydro-geochemical changes of ground water after the tsunami. After the tsunami, seawater entered the water table through the open wells or tube wells (M1), and the entrapped water (M2) got infiltered into the water table of the coastal alluvium during January 2005. Later high temperature in the summer months might have resulted in the formation of salt precipitates (M3) (due to evaporation of infiltered/stagnated water by impermeable clay layers) near the surface or in pore spaces and subsequent dilution in the end of March 2005 by sparse rain. After precipitation and dissolution, salt leached out from surface to the shallow groundwater zones (M4), enhances the EC and TDS of the groundwater of August 2005. Thus, the impact of direct infiltration or direct mixing of tsunami waters (M1) has a relatively lower effect than the subsequent precipitation and dissolution of salts formed by the entrapped sea water, which happened after the tsunami event.

12. Geophysical study

The geophysical survey conducted in 20 specific location in the study area (Table 5.1 and 5.2) which indicates that three to four layers were identified with resistivity for 1st layer raging from 0.012Ωm to 42Ωm, 2nd layer 0.05 Ωm to 120 Ωm and 3rd layer 0.02 Ωm to 360 Ωm. Thickness of the formation of 1st layer rays from 1 to 17, 2nd layer 2.5 to 85 and 3rd layer 7 to α. VES all four types of curves were found in the study area (Chidambaram et al 2008).

13. Curve types

There are different curve types inferred during the geophysical interpretations. The general trend of the saltwater intruded coastal aquifer is expected to be Q or K where in the resistivity values keep on decreasing with depth or decreases in the shallow and deeper aquifer respectively indicating higher conductivity. Hence, when the deeper aquifers are contaminated with saltwater they show lesser resistivity values. When the shallow aquifer are affected by the presence of saltwater they tend to give an A or K type curve, Where the first layer has low resistivity values than the under laying layers. In the study area nearly 40% of the locations have A type 15% have K type curve indicating the possibility of the recharge of tsunami waters in the shallow aquifers. All these locations with A & K type curve (Chidambaram et al 2008) are reported to have more causalities in the Tsunami event and sea water has also invaded inland through several inlets backwater, river mouths, distributaries channel etc., the entered water has left the signature into these aquifer by infiltrating into the system.

14. Formation resistivity & factor

It was found that the aquifers of shallow depths were more affected during the event of tsunami and hence the values of the 3m, 5m, 10m and 15m are, taken for discussion. Study on resistivity of the formation for the shallow depth of 3m indicate pre-tsunami samples range from moderate to saline, with almost 50% of locations showing salinity (Table 6). After the event almost all locations show salinity reflexes from resistivity values. Formation factor is obtained by ratio between formation resistivity and water specific conductance (Van Overmeeren, 1987). It is suggested that a value of 4 is for fresh water aquifer, almost all samples in post event falls in saline nature and 6 samples of pre-tsunami falls in this category. EC for rest of the samples in the Pre tsunami was not available.

15. Spatial distribution of apparent resistivity

The apparent resistivity values for specific depth have been distributed spatially trended to develop an isoresistivity map and to get and overall perspective view of the study area, three specific depth were selected for 3m,5m and 10m isoresistivity map were prepared using GIS. The 3m (Fig. 10a) isoresistivity map indicates that more region in the central part of the study area are affected with high conductivity which is interpreted with low resistivity values. The 5m (Fig.10b) isoresistivity map indicates that certain regions in the central part of the study area are affected. The 10m (Fig. 10c) isoresisitivty contour also helps us to identify only certain location along the coast show low resistivity values. The study of the resistivity values of different depths establishes that the shallow aquifers are more saline than the deeper ones.

In general due to the presence of higher intensity of tributary channels, and allows the rivers mouths (Vellar, Patinatharu etc,.) reveals the association of highly affected region, but the region with mangroves were not much affected. More over the bathymetry study in this region shows that the shelf is gentle in the southern region than in the north, which helps the giant wave to easily progress through inland.

16. Geoelectrical section

Location and thickness of fresh water lens obtained by GECS was used to delineate fresh water zones of island and thematic contour map was prepared, depicting the variation of thickness of fresh water A similar study for delineating the fresh water lenses in an Atoll (Ajay kumar, 1966) has also been carried out by researchers. The geoelectical cross section (GECS) for pre and the post Tsunami by Chidambaram et al (2008) (Fig 11.A and 11B) indicates that the lower resistivity values are noted in the north of Perunthottam. It is also suspected with a fresh water lens at a depth of 5-8m , with resistivity ranging from 100-60 ohm meter, below Kulaiyar and it extends to south of Palayar. During the Post tsunami it is noted that the southern part of the study area has been more contaminated by saline water, from Pumpuhar to Kulaiyar. It is also interesting to note that the lens has moved further north due to the compression by dense saline water from Thirumullaivasal towards north. The lesser value of this lens may also indicate that the saline water has also contaminated this perched aquifer.

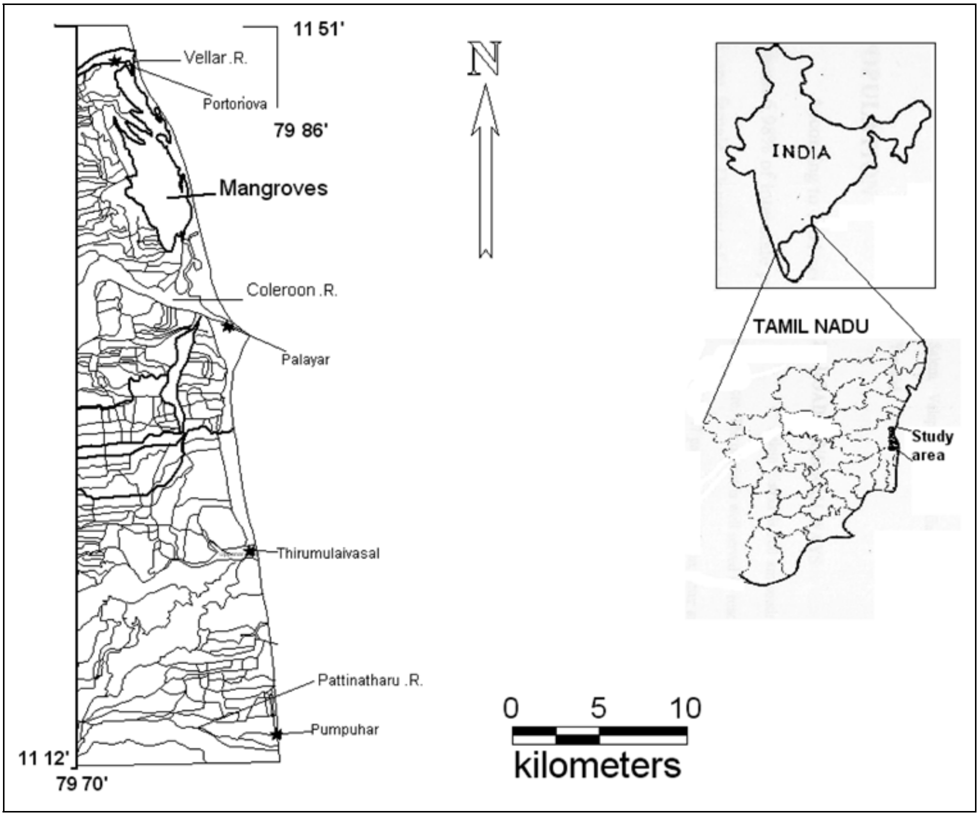

Fig. 1. Location of the study area

17. Conclusion

As the study area falls in the coastal region the water chemistry in generally expected to be saline. Hence, eleven sampling location not contaminated by Sea water intrusion were selected and the impact was noted in the shallow unconfined aquifers that too in the region where the water got stagnated and near the mouth of the river. The impact of beginning of South west Monsoon is also noted in the month of June, July and August. Few region with dilution of water chemistry is also noted after the monsoon. The gentle nature of the bathymetry has helped the tsunami wave to propagate to a greater distance inland through the river mouth and the distributary channels. The study area basically has regions with backwater recharge, impact of aquaculture, salt pans, sea water intrusion and paleo connate waters. A detailed study has to be done by using the isotope data and by biomarker approach to identify the aquifer vulnerability regions. This will help us to take necessary preventive measures in case of future calamities.

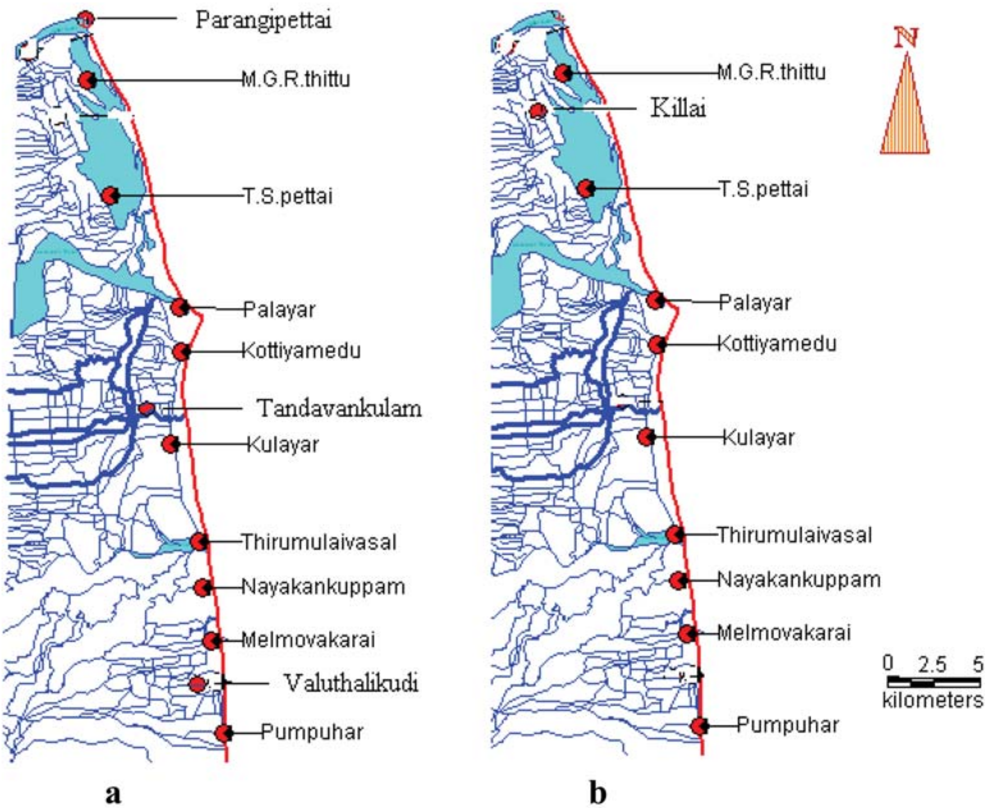

Fig. 2. Sampling location of the study area a) water sample location b) resistivity sample location

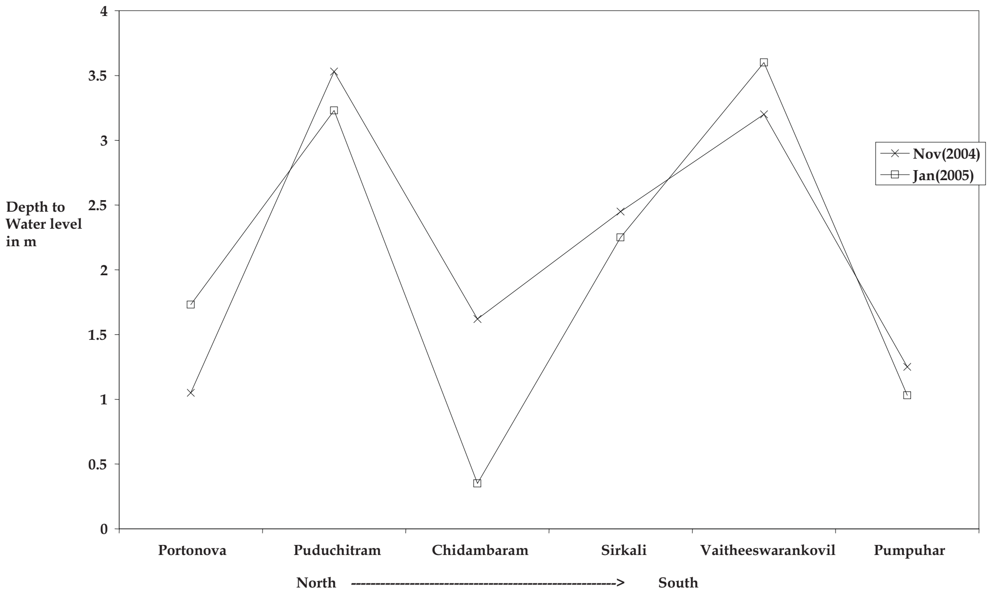

Fig. 3. Waterlevels of the study area for Pre and Post Tsunami

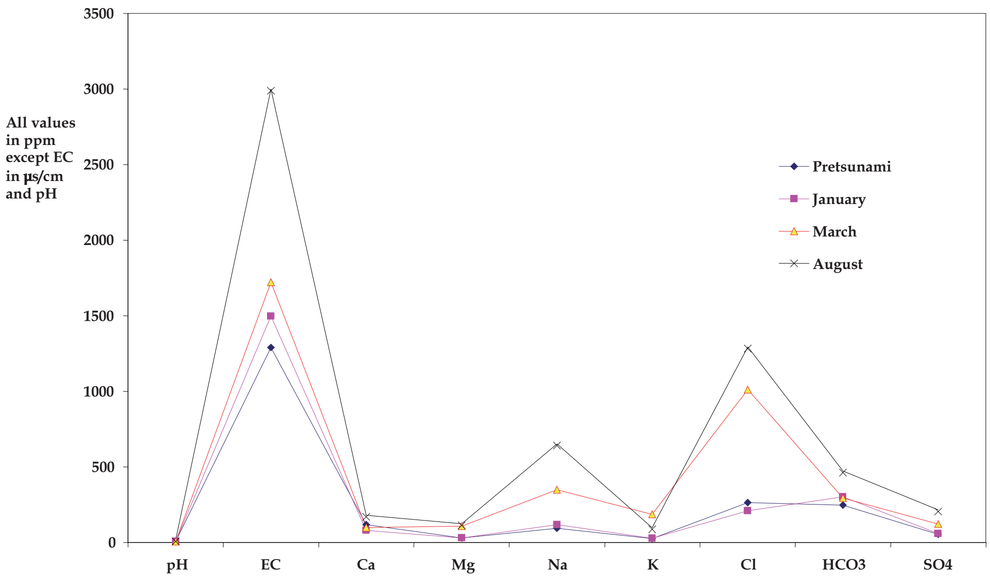

Fig. 4. Short term variation of chemical parameters after tsunami

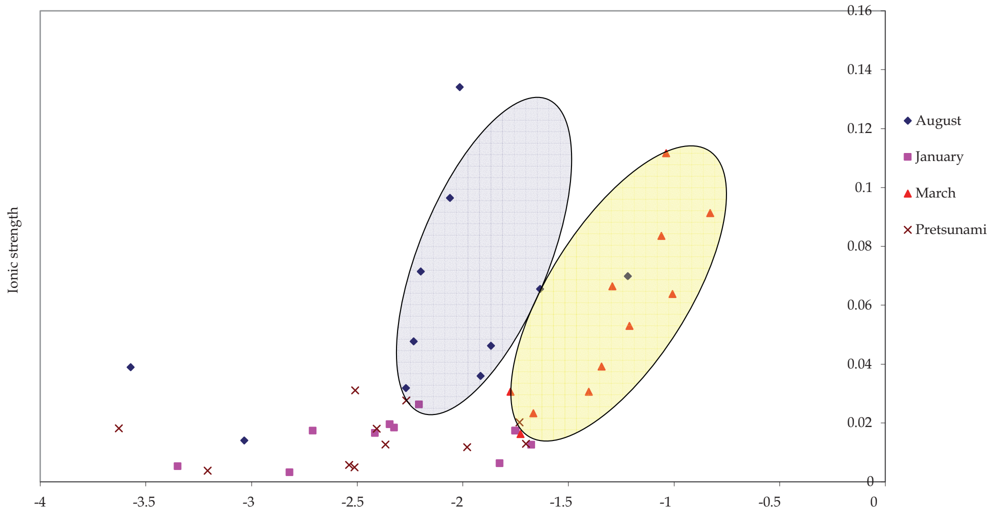

Fig. 5. Ionic strength Vs Log pCO

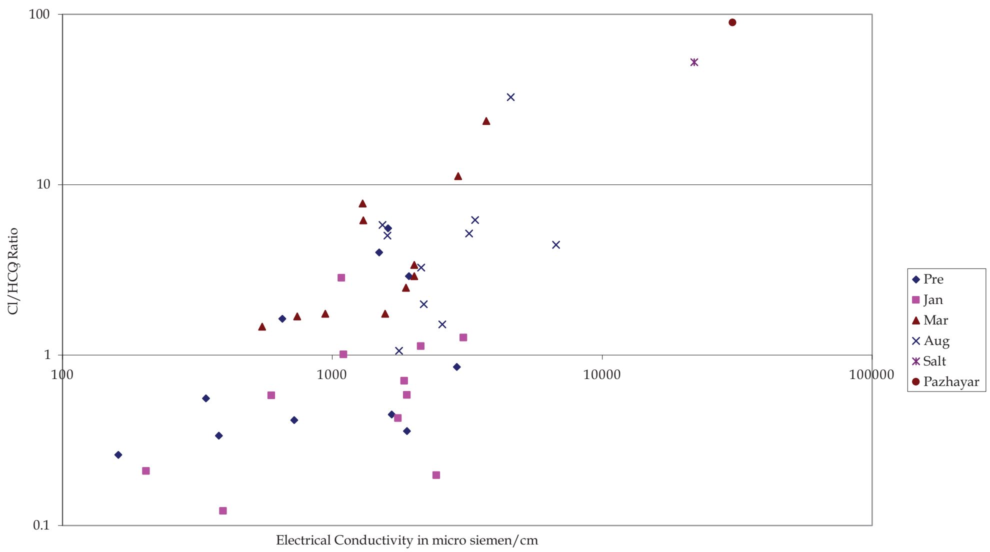

Fig. 6.1. Realtionship of the conductivity to Chloride bicarbonate ratio

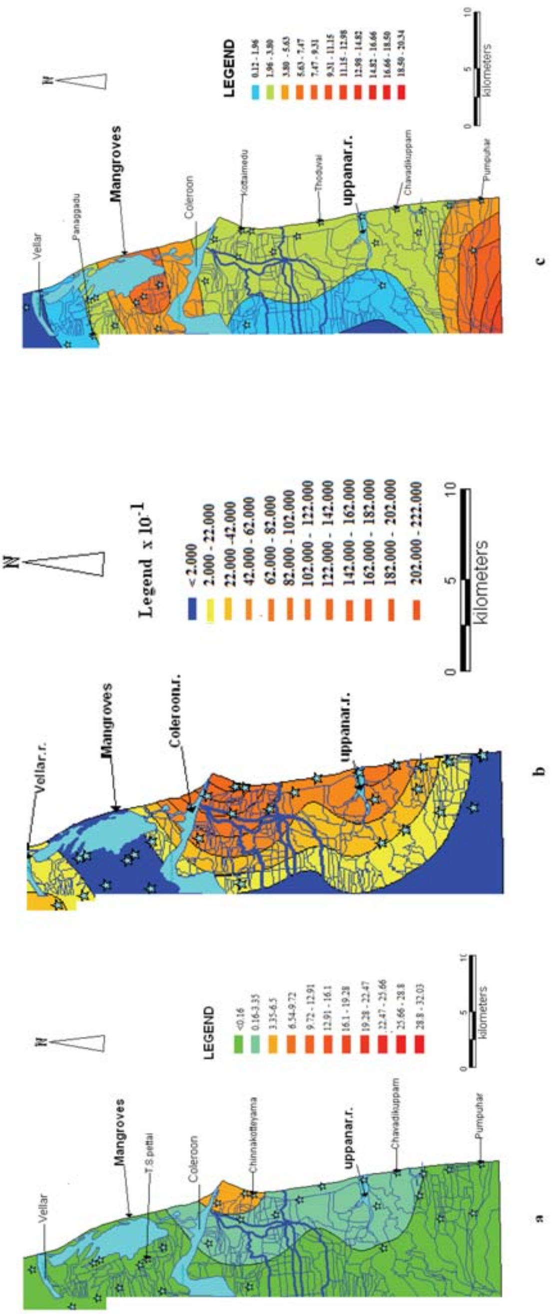

Fig. 6.2. Spatial distribution of Cl/HCO_3 ratio during a) January b) March and c)August, 2005

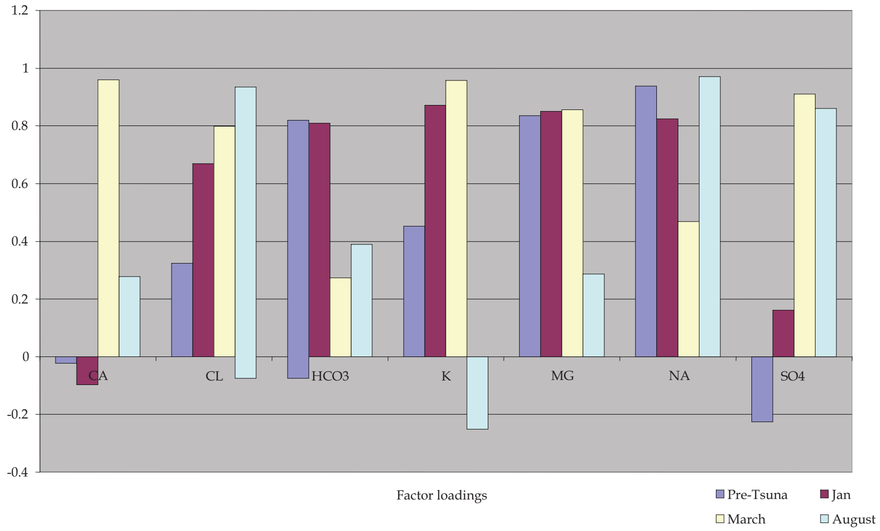

Fig. 7a. Represetation of First factor

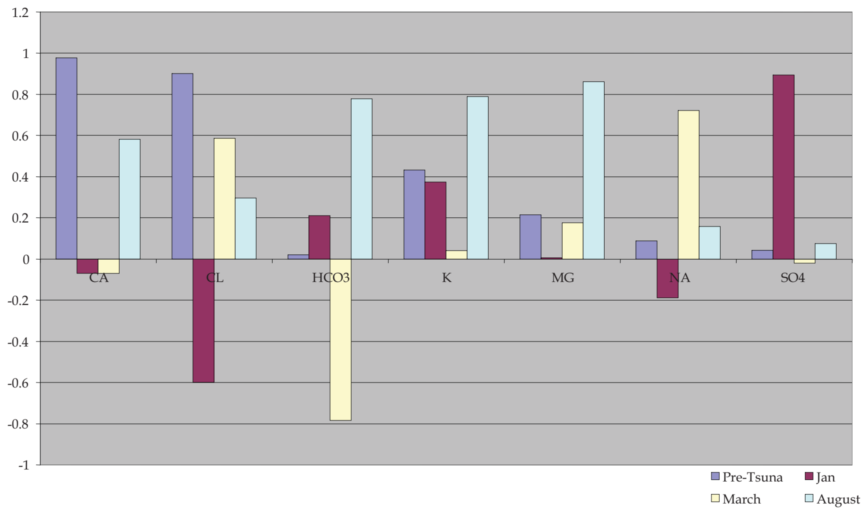

Fig. 7b. Representation of Second factor

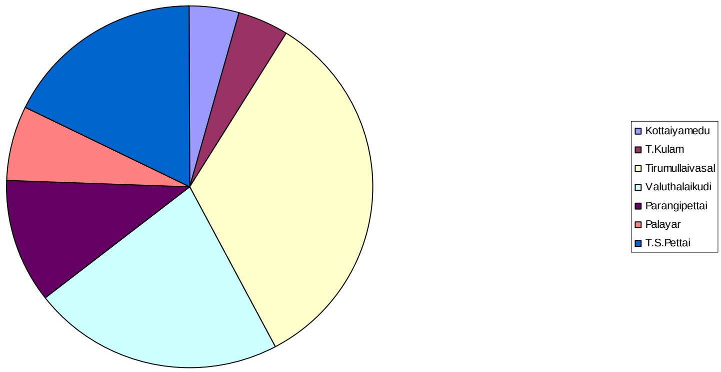

Fig. 8. Mixing proportion of sea

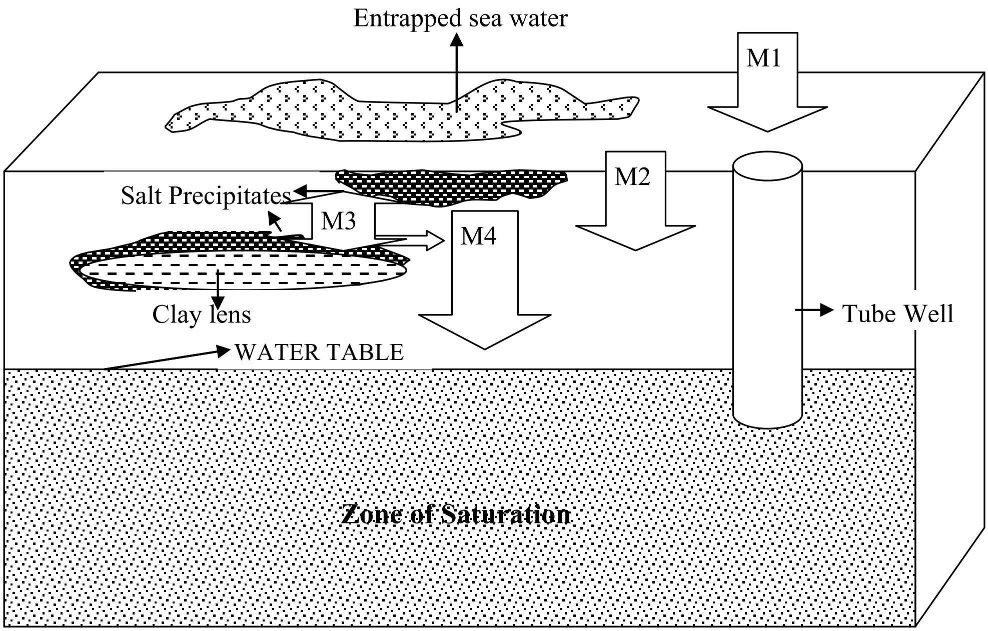

Fig 9. A Schematic representation of the possible factors for the hydrogeochemical change, after the Tsunami (Chidambararam et al 2010).

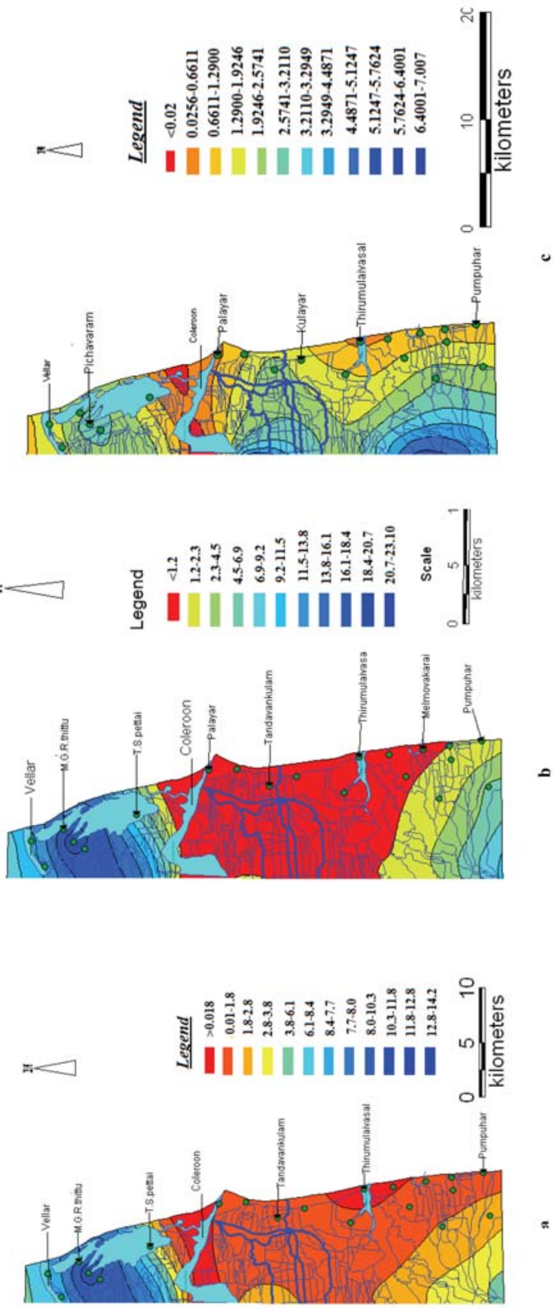

Fig. 10. Spatial distribution of apparent resistivity during a) 3m b) 5m and c)10m after Tsunami

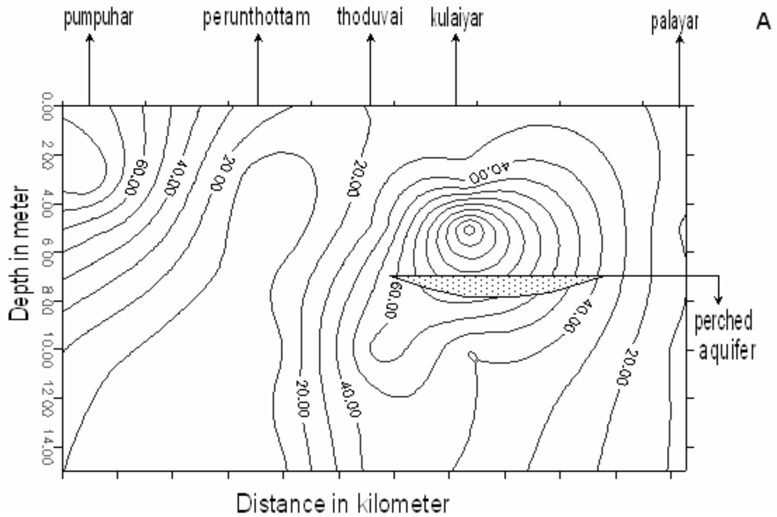

Fig. 11a. Nature of Perched aquifer during Pre-Tsunami (Chidambaram et al,2008)

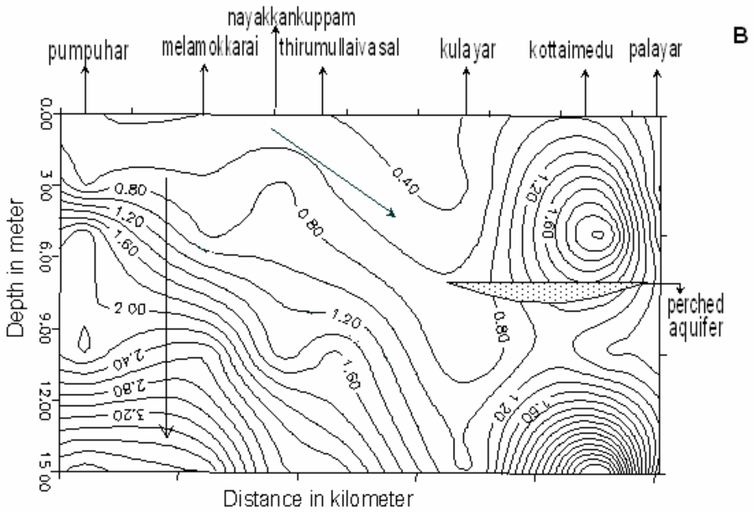

Fig. 11b. Nature of Perched aquifer during Post-Tsunami (Chidambaram et al,2008)

S. No	Authors Year	Area	Remark
1	Rai et al (2002)	Kanpur	Earthquake future
2	Scheffers and Kelletat (2003)	World wide	Tsunamigenic Sediments
3	Jain et al (2004)	General note on civil Engineering structures	Effects of M 9 Sumatra earthquake and tsunami
4	Cisternas et al (2005)	Chile	Predecessors of the giant 1960 Chile earthquake
5	Villholth et al. (2005)	Sri lanka	EC level variation
6	Kawata (2005)	Srilanka	FieldSurveyaroundGalle,SriLanka
7	Pal (2005)	India	Life loss due to tsunami
8	World Health Organization (2005)	India	Piped in water supplies and groundwater pump
9	Muraluideran et al. (2005)	Hyderabad	Earthquake had induced hydrological changes
10	Kanakasabai and Rajendran (2005)	Portonova India	Micrometeorological parameters
11	Sato(2005)	Srilanka	field investigations carried out along the west and south coasts ofSriLanka
12	Szczucinski et al. (2005)	Thailand	Tsunamigenic Sediments
13	Narasimha et al.(2005)	Nagapattinam,Tamilnadu	Six months after the tsunami.
14	Narayana et al. (2005)	Kerala coast, India	Tsunamigenic Sediments
15	Cummins and Leonard (2005)	General note	Boxing Day 2004 Tsunami
16	Altaff (2005)	Chennai, India	Impact of tsunami
17	Thangadurai (2005)	Ennore,Chennai,India	Tsunamigenic Sediments
18	Chadha et al.(2005)	East coast of India	Study on the Impact on the east coast of India
19	Nagendra et al(2005)	Nagapattinam coast	Tsunamigenic Sediments
20	Liu et al.(2005)	Srilanka	Observations by the international tsunami survey team in Sri Lanka.
21	Willams e al(2005)	Washington	Multiple sources for late-Holocene tsunamis at Discovery Bay, Washington State
22	Arya et al. (2006)	India	Some aspects of tsunami impact and recovery in India
23	Hawkes et al (2006)	Malaysia-Thailand	Sediments deposited by the 2004 Indian Ocean tsunami along the Malaysia–Thailand Peninsula
24	Nanayama and shigeno (2006)	Southwest Hokkaido.	Inflow and outflow facies from the 1993 tsunami in southwest Hokkaido
25	Goff (2006)	Srilanka	field survey after the 2004 Indian Ocean tsunami

S. No	Authors Year	Area	Remark
26	Kench et al. (2006)	Maldives	Geological effects of tsunami on mid-ocean atoll islands: the Maldives before and after the Sumatran tsunami.
27	Palanivelu et al. (2006)	Chennai India	TDS variation
28	Illangasekare et al.(2006)	Srilanka	Impacts of the 2004 tsunami on groundwater resources in SriLanka
29	Alpa Sheth et al (2006)	Indian Ocean	Tsunami on the Indian Mainland Earthquake Spectra
30	Richmond, et al (2006)	Indonesia, Sri Lanka, and The Maldives	Geologic Impacts Of The 2004 Indian Ocean Tsunami
31	Rasheed et al (2006)	South Kerala Coast and West Coast India	Tsunami Impacts On Morphology Of Beaches
32	Pilapitiya et al(2006)	Srilanka	Effect of tsunami on waste management in Sri Lanka.
33	Singarasubramanian et al (2006)	Tamilnadu coast, India	Tsunamigenic Sediments
34	Mastronuzzi et al (2006)	impacts on coastal environment	Risk assessment of catastrophic waves
35	Weiss (2006)	Indonesia	Numerical modelling of generation, propagation and run-up of tsunamis caused by oceanic impacts: model strategy and technical solutions
36	Chidambaram et al (2006)	Portnovo to Poompuhar,Tamilnadu, India	Impact of Post Tsunami in groundwater (water chemistry)
37	Rengalakshimi (2007)	Nagappattinam District	Reclamation and status of tsunami damaged soil in Nagappattinam District
38	Jaffe and Gelfembuner (2007)	Phuket, Thailand	A simple model for calculating tsunami flow speed from tsunami deposits.
39	Stein et al (2007)	Indian Ocean	Implication for regional tectonic and subduction zones
40	Chandrasekharan et al (2008)	Nagapattinam district, Tamilnadu	Variability of soil–water quality due to Tsunami-2004 in the coastal belt
41	Ranjan et al. (2008)	Thailand	Tsunamigenic Sediments
42	Martin et al (2008)	Poompuhar,Tamilnadu	Impact of Tsunami
43	Chidambaram et al. (2008)	Portnovo to Poompuhar,Tamilnadu, India	Impact of Pre and Post Tsunami in groundwater (Geoelectrical techniques)
44	Pierre leclerc et al. (2008)	Ampara district in Eastern Sri Lanka:	Tsunami impact on shallow groundwater, Conductivity measurements and qualitative interpretation
45	Sangeeta sonatz et al (2008)	India	Green reconstruction of the tsunami-affected areas in India using the integrated coastal zone management concept
46	Ravisanker and Pongathai(2008)	Sirkazhi taluk, Nagapattinam district, Tamilnadu	A study on groundwater quality

S. No	Authors Year	Area	Remark
47	Srinivasalu(2008)	South east coast of India	Tsunamigenic Sediments
48	Singh (2008)	Neill Island (SouthAndaman)	Impact of the earthquake and tsunami on the groundwater regime
49	Takashi et al.(2009)	Nagapattinam district	Impact of the tsunami on soil, groundwater and vegetation
50	Vithanage et al.(2009)	Eastern sri lanka	Effect of the Indian ocean tsunami on groundwater quality in coastal aquifers
51	Singarasubramanian et al (2009)	Tamilnadu coast, India	Geomorphology and Sedimentological
52	Rajesh et al (2009)	Pichavaram, Tamilnadu coast, India	Study on the sediments Mangrove environment after Tsunami
53	Pignatelli(2009)	Southern Apulia coastline,Italy	Evaluation of tsunami flooding using geomorphologic evidence
54	Wijetunge (2009)	East-Coast of Srilanka	Field measurements and numerical simulations of the 2004 tsunami impact on the east coast of Sri Lanka
55	Chidambaram et al (2010)	Portnovo to Poompuhar,Tamilnadu, India	Impact of Pre and Post Tsunami in groundwater (water chemistry)

Table 1. List of references for the related to Tsunami

	Pre Tsunami			**January**		
	Maximum	Minimum	Average	Maximum	Minimum	Average
pH	8.8	7	7.630769	8.06	6.95	7.522727
EC	2897	161	1290.923	3060	204	1497.948
Ca	340.68	28.99	117.1231	227.66	2.72	80.65909
Mg	72.16	7.98	31.04692	93	1.7	30.92818
Na	280.19	11.34	93.31923	377.4	10.2	118.8418
K	48.56	1.61	25.42462	54.4	2.04	29.22182
Cl	744.42	26.7	264.8938	538.9	30.13	210.7218
HCO_3	549.12	44.18	247.0108	693.11	51.85	302.5645
SO_4	110.24	16.9	53.49308	125.8	7.82	59.83818
	March			**August**		
	Maximum	Minimum	Average	Maximum	Minimum	Average
pH	7.62	7.11	7.324545	8.1	7.1	7.563636
EC	3718.63	548.87	1721.518	6743.839	1532.123	2988.282
Ca	184.34	40.75	98.42818	311.99	60	170.3609
Mg	189.85	34.69	107.92	304.8	16.8	112.7455
Na	574.71	206.9	348.9636	1837	69.7	641.8909
K	426.23	56.54	186.2827	230.7	4	87.35455
Cl	1772.42	431.31	1011.051	3217.09	177.25	1281.854
HCO_3	610.13	75.05	293.9991	1043.1	24.4	463.4
SO_4	296.18	38.13	123.6609	507.5	100.5	206.1818

Table 2. Maximum, Minimum and Average of the ion concentration all values in mg/l except EC in ms/cm and pH

S.No	Location	Fe	Mn	Al
M1	Thirumullaivasal	0.7231	1.2036	0.0623
M2	Melmokkarai	0.2931	0.0532	0.0625
M3	Pumbuhar	0.3214	0.6231	0.0321
M4	Vazhuthalaikudi	0.3897	0.7963	0.0432
M5	Palayar	0.456	1.521	0.0487
M6	Tandavankulam	0.6543	0.2356	0.0895
M7	Kulayar	0.3	0.0658	0.0823
M8	T.S.Pettai	0.3012	0.2589	0.0412
M9	Portonovo	0.4	0.1258	0.0564
M10	Kottaiyamedu	0.2136	0.4836	0.0512
M11	Nayakarpalayam	0.1256	0.456	0.0426
A1	Thirumullaivasal	0.5283	0.1065	0.0721
A2	Melmokkarai	0.3698	0.0658	0.0521
A3	Pumbuhar	0.036	0.0092	0.042
A4	Vazhuthalaikudi	0.3789	0.8357	0.0456
A5	Palayar	0.523	1.867	0.059
A6	Tandavankulam	0.5894	0.1236	0.0658
A7	Kulayar	0.302	0.0595	0.0835
A8	T.S.Pettai	0.2896	0.2136	0.0587
A9	Portonovo	0.4557	0.186	0.0428
A10	Kottaiyamedu	0.5012	0.2365	0.0563
A11	Nayakarpalayam	0.527	0.1319	0.05
R1	Palayar Sea water	0.034	0.06	0.003

Table 3. Heavy metals for post-tsunami

State	Incursion of water into the land	Average height of waves	Average intensity of Tsunami
Andhra Pradesh	500m to 2Km	2m to 5m	1 to 2.32
Kerala	1Km to 2Km	3m to 5m	1.64 to 2.32
Pondicherry	300m to 3Km	8m to 10m	3 to 3.32
Tamil Nadu	1Km to 1.5Km	7m to 10m	2.80 to 3.32

Table 4. Intensity of Tsunami along the eastern coastal states of India

S. No	Location	I Layer		II Layer		III Layer		Curve type
		Resistivity (Ωm)	Thickness (m)	Resistivity (Ωm)	Thickness (m)	Resistivity (Ωm)	Thickness (m)	
1	Kuliyar	1.24	2	1.25	5	1.28		A
2	M.G.R Thittu	16	2	240	30	96		K
3	Kavarapattu	8	2	10.5	1	2.23	∞	K
4	Perunthotum	2.2	1	1.8	5	1.44	∞	K
5	Palayar	1.6	1	0.5	7	2.25		H
6	Killar	2.52	2	1.43	5	23		H
7	Kulaiyar	28	2	1.33	4	27		H
8	T.S pettai	5.82	1	2.84	2	3.56		H
9	Thoduvai	180	3	36	5	35	9	Q
10	Pumpuhar	75	2	37.5	8	2.625	3	Q

Table 5.1. Resistivity survey values – Pre-tsunami (Chidambaram et al 2008)

S. No	Location	1st Layer		2nd Layer		3rd Layer		Curve type
		Thickness (m)	Resitivity (Ωm)	Thickness (m)	Resitivity (Ωm)	Thickness (m)	Resitivity (Ωm)	
1	Kulaiyar	5	0.8	25	1.8	∞	50	A
2	Thirumullaivasal	2	1.34	4	2.1	∞	23	A
3	Killai	5	3	35	120	∞	360	A
4	T.S.Pettai	10	1.15	18	5.2	∞	12.8	A
5	Melmuvakkarai	1	2.4	2.5	9.6	∞	48	A
6	Puthukkuppam	2	1.2	26	2.4	∞	48	A
7	Portonova	1	4.6	2.5	12.3	9.8	25.3	A
8	Thandavankulam	1	2.2	8	6.6	11.2	14.2	A
9	M.G.R Thittu	5	1.9	9.5	5	∞	2.3	K
10	Poombugar	1	2.78	6	4.89	∞	2.86	K
11	Kottayamedu	5	2.6	55	6.5	∞	3.75	K
12	Nayakkan Kuppam	1	3.35	8	1.7	22	6.1	H
13	Palaiyar	5	7.5	35	5	∞	15	H
14	Manampadi	5	1.4	5.5	1.2	∞	0.8	Q
15	Kilperumpalam	1	20.4	3	10.2	8	1.53	Q
16	Perunthotam	1	1.8	16	1.4	∞	0.244	Q
17	Thiruvenkadu	1	3.2	3	2.25	33	1.1	Q
18	Neithalvasal	1	42	16	2.52	∞	0.23	Q
19	Vazhuthalaikudi	1	10.1	3	6.2	7	2.57	Q
20	Pitchavaram	1	20.4	4	10.4	7	5.1	Q

Table 5.2. Resistivity survey values – Post-tsunami (Chidambaram et al 2008)

Category	Formation Resistivity			Formation Factor		
		Pre(10)	Post(20)		Pre(10)	Post(20)
Fresh	>300	0	0	>0.50	0	0
Slightly Fresh	150 – 300	0	0	0.25 – 0.50	0	0
Moderate	50 – 150	3	2	0.10 – 0.25	0	0
Slightly Saline	25 – 50	2	0	0.05 – 0.10	0	0
Saline	< 25	5	18	<0.05	6	20

Table 6. Variation in Formation Resistivity and formation factor, before and after tsunami

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