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Study on the hydrogeochemical characteristics in groundwater, post- and pre-tsunami scenario, from Portnova to Pumpuhar, southeast coast of India

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Abstract Natural hazards cause great damage to humankind and the surrounding ecosystem. They can cast certain indelible changes on the natural system. One such tsunami event occurred on 26 December 2004 and caused serious damage to the environment, including deterioration of groundwater quality. This study addresses the groundwater quality variation before and after the tsunami from Pumpuhar to Portnova in Tamil Nadu coast using geochemical methods. As a part of a separate Ph.D. study on the salinity of groundwater from Pondicherry to Velankanni, water quality of this region was studied with the collection of samples during November 2004, which indicated that shallow aquifers were not contaminated by sea water in certain locations. These locations were targeted for post-tsunami sample collection during the months of January, March and August 2005 from shallow aquifers. Significant physical mixing (confirmed with mixing models) within the aquifer occurred during January 2005, followed by precipitation of salts in March and complete leaching and dissolution of these salts in the post-monsoon season of August. As a result, maximum impact of tsunami water was observed in August after the onset of monsoon. Tsunami water inundated inland water bodies and topographic lows where it remained stagnant, especially in the near-shore regions. Maximum tsunami inundation occurred along the fluvial distributary channels, and it was accelerated by topography to a certain extent where the southern part of the study area has a gentler bathymetry than the north.

Keywords Groundwater · Hydrogeochemistry · Tsunami · Salt leachate · Mixing

Introduction

The historic event of the tsunami on December 26th, 2004, caused havoc, disturbing the natural environment and causing heavy losses in human lives and property. Causalities of this event in tsunami-affected Indian states show Tamilnadu as one among the worst affected in the south

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eastern part of the Indian subcontinent (Pal 2005). It is appealing to study their remains and examine the extent of damage, or changes incurred to the natural system off the coast caused by the deep water brought by the tsunami. There are few regions where tsunami run-up water have washed the surface and returned back to the sea, but there are many places where water has easily entered inland through distributary channels of rivers and along river mouths, where water got locked up and slowly infiltrated till shallow aquifers. One such area is from Portnova to Pumpuhar, located in the southeast coast of India. The study area is geomorphologically a coastal plain chiefly of recent alluvium. The estuary of the Vellar and Coleroon rivers forms a lagoonal environment hosting the mangroves of Pichavaram. Considerable extraction of groundwater for agriculture purposes and aquaculture ponds is also taking place along this coastal tract. In this scenario, this study was attempted to understand the impact of the tsunami on the costal groundwater quality, especially on the shallow aquifers in the district were millions of people were using this groundwater for their domestic and drinking water supply before the tsunami.

Palanivelu et al. (2006) has studied the ground water quality assessment in the tsunami-affected coastal areas of Chennai, located 250 km north of the study area. They have studied the TDS values and observed that at few locations away from the sea showed an increase of TDS from May to September 2005. Villholth et al. (2005) reported the tsunami impacts on shallow groundwater and associated water supply on the east coast of Sri Lanka. They have inferred that the 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 their monitoring (3,200 μS/cm). 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. The World Health Organization (2005) report after the tsunami observed that destruction brought by the tsunami (mainly in India) on piped-in water supplies and groundwater pumps, the saline water intrusion of shallow wells and surface sources, rendered much of the pre-tsunami supplies throughout the affected area completely unusable.

Muralideran et al. (2005) has studied the imprint of the 26 December 2004 Sumatra earthquake in aquifers of Hyderabad granite pluton. They explained that the earthquake had induced hydrological changes caused by changes in hydrostatic pressure due to earthquake-induced changes in crustal volumetric strain. The study indicates that a rise in water level during the earthquake period was observed by them and by the nearby observatory wells along the coast in Andhra Pradesh, India.

Kanakasabai and Rajendran (2005) reported the trend of micrometeorological parameters during the tsunami in the east coast of India. They measured the micrometeorological parameters continuously at Portonova on the east coast of India. The parameters like wind speed, wind direction, temperature and solar radiation were recorded during the time of the tsunami.

Geophysical techniques were used to find out the impact post-tsunami in the shallow groundwaters and the contamination in the perched aquifer (Chidambaram et al. 2008). The impact of the tsunamigenic sediment on the Pichavaram mangrove region was studied in detail before and after the event, by collecting core samples. It was noted that high concentrations of Cd, Cu, Cr, Pb and Ni were observed in tsunamigenic sediments. There were little variations with respect of Fe, Zn and Mn concentrations (Ranjan et al. 2008). Similar studies were carried out by Szczucinski et al. (2005) and Scheffers and Kelletat (2003). Observations of tsunami in the Kerala coast of India were made by Narayana et al. (2005).

All these studies focused on the importance of ground water quality and its role in drinking water supply to tsunami-affected regions in Asia. Our study is also aimed in this direction to get insight into the ground water quality deterioration and the processes responsible for the hydro chemical changes immediately after the tsunami. The study also focuses on its evolution over a period of time which will reflect the present situation of ground water quality in these affected regions and help in guiding various utility purposes.

Study area

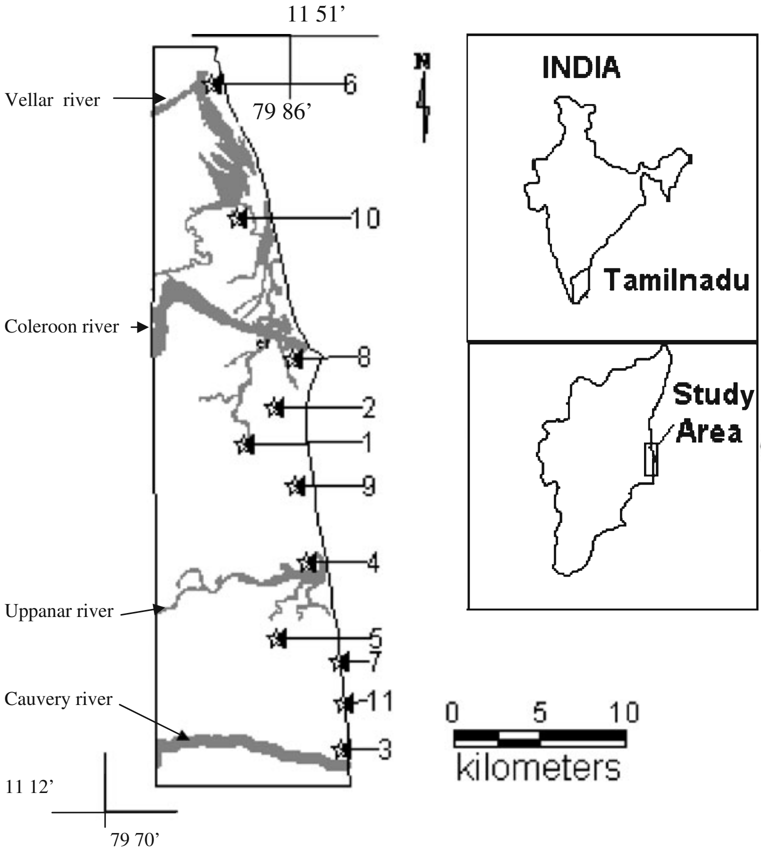
The study area extends from Parangipettai (Portnova) to the Pumpuhar area between 79° 46′E and 79° 51′ E longitudes and 11°07′ N and 11° 30′ N latitudes (Fig. 1). It occurs within the survey of India toposheets no. 58 M/15 & 16. The Vellar and Coleroon are the major rivers flowing into the study area; they form an estuary with a marshy mangrove environment at Pichavaram.

Geological succession

Era	Age formations	Lithology
Quaternary	Recent	Soils, alluvium
	Sub-recent	Laterite and coastal sands, clays, kankar and laterite

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). The groundwater of this region is found in both unconfined and confined aquifers (Fig. 2). In the major part of the study area, depth to water table ranges from 5 to 20 m below ground level (mbgl) during pre-monsoon, whereas during post-monsoon it ranges between 2 and 10 mbgl. In the south-eastern part of the study area along Coleroon alluvial belt, the shallow water table less than 2 mbgl is observed. The Vellar alluvium and coastal alluvial formations in the east signify the extent of water logging conditions during the postmonsoon period. The water level observations for certain locations in the study area during the tsunami indicate considerable increase of water level in certain locations accompanied by falls in a few regions. Aquifer parameters, like specific capacity, transmissivity

Fig. 1 Study area with the groundwater sampling locations



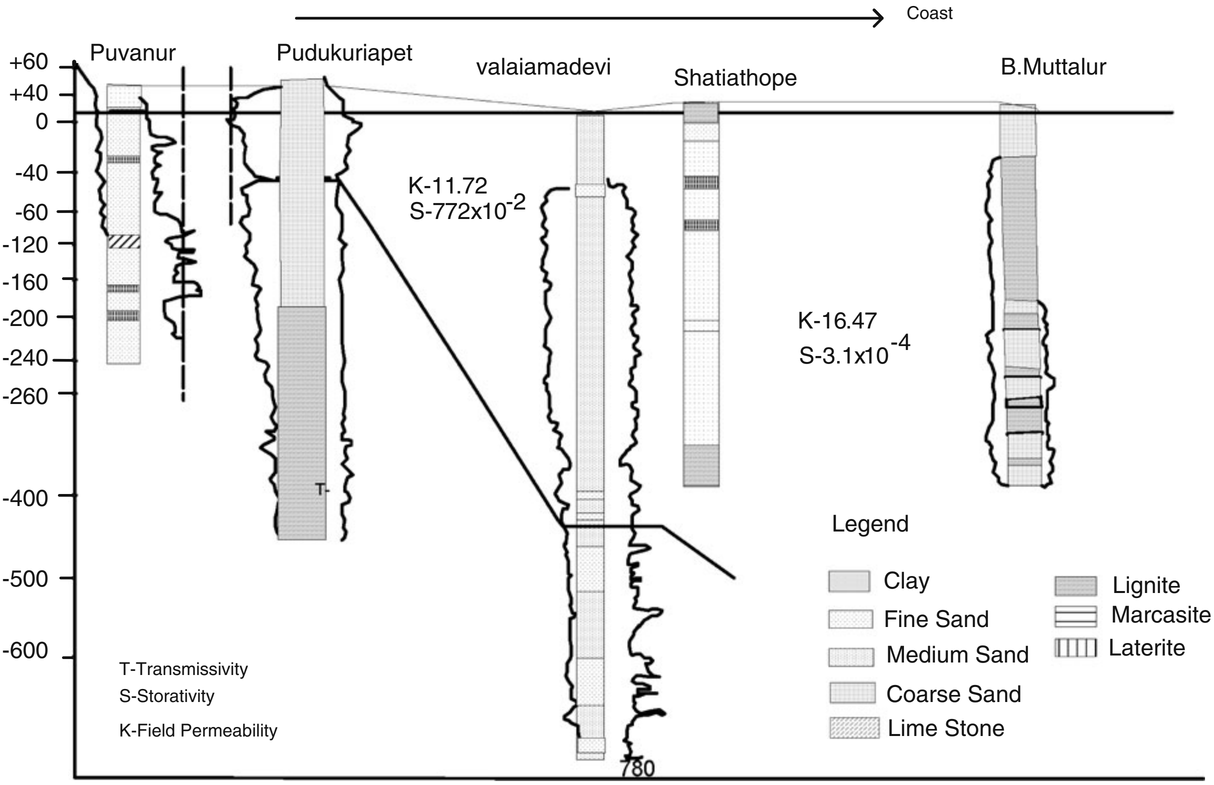


Fig. 2 Hydrogeological cross section from inland to coast derived from lithologs

and hydraulic conductivity of the region, were analysed. The transmissivity ranges from 295 to 838 m^2/day (CGWB 1997). Hydraulic conductivity estimated by storativity (S) is 1.77*10–3 m^2/day approximately. The movement of water from one region to another is governed by (K), which ranges from 13.6 to 23.6 m/day.

Methodology

In total, 11 samples were collected (Fig. 1) in the months of November 2004, January 2005, March 2005 and August 2005. The samples were collected from shallow aquifers through tube wells of depth 20 mbgl. Samples collected in the month of November 2004 (suffix 'pr' collected for Ph.D. work on sources of salinity in coastal aquifers in Annamalai University), January 2005 (J), March 2005 (suffix 'M') and August 2005 (suffix 'A'). Around 40 samples collected during November 2004 from Pondicherry to Velankanni showed that 11 locations in shallow groundwater were uncontaminated by seawater intrusion along the coast and, hence, are identified/selected for post-tsunami impact studies (these 11 sampling locations were selected for targeting the changes after tsunami). The samples were collected mainly from shallow aquifers (40–100-ft 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 from about 0.2 to a maximum of 3 km from the coast and also were not earlier affected by salt water intrusion. The chemical parameters analysed for all these samples are electrical conductivity (EC), pH, TDS, Na, K, Ca, Mg, HCO_3, Cl and SO_4. These parameters are used for the hydrogeochemical interpretations. The samples collected are analysed for major cations like Ca and Mg by titrimetry and

Table 1 Run up and inundation during tsunami in the study area

S.No	Location	Dissidence from coast in KM	Inundation distance (km)	Run up (m)
1	Thirumulaivasal	0.32	102	27
2	Melmokkarai	0.52	0.75	22
3	Poombukar	0.2	0.32	3
4	Vazhuthalakudi	2.80	3.24	29
5	Palayar	0.64	0.78	26
6	T.kulam	1.66	2.97	1.16
7	Kulayar	1.96	2.67	198
8	T.S Pettai	1.97	3.1	21
9	Portnova	1.12	168	20
10	Kottayamedu	0.32	0.72	3
11	Nayakarpalayam	0.8	156	27

Na and K by flame photometer (CL 378). They are also analysed for anions like Cl and HCO_3 by tirimetry and SO_4 by spectrophotometer (SL 171 minispec). EC and pH were determined in the field using electrodes. The analyses were done by adopting standard procedures (APHA 1998). The results of the analysis were checked by the cation anion balance, which was within ±8%. A computer programme WATCLAST in C++ was used for calculation and graphical representations (Chidambaram et al. 2003). An experiment conducted with sea water evaporation and seawater infiltrate (Xue et al. 2000) was used for delineating the sea water impact on fresh groundwater. The saline soils formed by the evaporation of stagnant sea water by forming white crust were observed in an area north of the study area, due to poor drainage and high evaporation. Hence, lechate from those soils with these salt precipitates was also studied as lechate. The 100 g of sediment with salt deposits on the surface were taken and added to 250 ml of distilled water, and it was stirred (mechanically) for 24 h. Later, this was filtered and the filtrate was taken and analysed as lechate. These results were compared to the standard and measured seawater chemistry from Palayar region in the study area.

Results and discussion

Groundwater is generally alkaline in nature with pH ranging from 7 to 8.8, with an average of 7.58, pre-tsunami and from 7.1 to 8.1, with an average of 7.44, post-tsunami. EC ranges from 261 to 2,897 μS/cm, with an average of 1,284 μS/cm, pre-tsunami and from 294.83 to 6,743 μS/cm, with an average of 2,127 μS/cm, post-tsunami (Table 2).

Anions

Chloride concentration in samples varies between 26.7 and 744 mg/l, with an average of 242 mg/l, pre-tsunami and from 177.25 to 3,217 mg/l, with an average of 1,146 mg/l, post-tsunami, indicating the long residence time of the tsunami water in the shallow aquifers. Bicarbonate concentration in analysed samples varies between 44.18 and 549 mg/l, with average of 237 mg/l, pre-tsunami and from 24.39 to 1,043 mg/l, with an average of 378 mg/l, post-tsunami. Sulphate ranges from 16.9 to 110.24 mg/l, with an average of 51.66 mg/l, pre-tsunami and from 38.13 to 507.5 mg/l, with an average of 164 mg/l, post tsunami.

Cations

With Na being the dominant cation, it ranges from 11.34 to 280.19 mg/l, with an average of 83.78 mg/l, pre-tsunami, and it ranges from 69.7 to 1,837 mg/l, with an average of 495 mg/l, post-tsunami; this shows there was an increase in Na concentration after the tsunami. The coastal groundwater of this region shows higher concentrations of Na followed by Ca (Chidambaram et al. 2005). Ca ranges from 28.99 to 340 mg/l, with an average of 104.81 mg/l, pre-tsunami and from 40.75 to 311.99 mg/l, with an average of 134.39 mg/l, post-tsunami. Magnesium concentration ranged from 7.98 to 72.16 mg/l, with an average of 29.41 mg/l,

Table 2 Chemical composition of groundwater in the study area for different periods

S.No		Location	pH	EC	Ca	Mg	Na	K	Cl	Hco_3	So_4	TDS
pr1	November, 2004	Kottaiyamedu	7.4	1,610	340.68	30.54	72.43	72.13	744.42	134.2	64	1,127
pr2		T.kulam	7.2	723	180.36	23.28	43.45	11.2	177.24	427.09	27.86	506.1
pr3		Poombukar	7.4	1,890	69.36	37.29	171.35	9.78	177.24	494.1	57.89	1,323
pr4		Thirumullaivasal	8.8	953	56.39	72.16	83.14	36.66	319.05	195.2	44.89	667.1
pr5		Valuthalaikudi	7.8	1,920	140.28	29	44.18	34.4	354.48	122.03	72.45	1,344
pr6		Parangipettai	7.6	1,660	61	30.54	95.45	42.13	136.83	305.06	64	1,162
pr7		Melmokkarai	7.8	261	28.99	9.45	20.78	1.61	31.71	122.03	16.9	182.7
pr8		Palayar	7	1,490	82.62	7.98	62.61	42.92	177.24	44.18	110.24	1,043
pr9		Kulayar	7.2	340	29.83	11.86	11.34	6.73	26.7	47.89	63.98	238
pr10		T.S.pettai	7.5	380	42.02	9.01	36.7	4.23	59.59	176.94	19.12	266
pr11		Nayakarpalayam	7.7	2,897	121.4	62.36	280.19	48.56	438	549.12	26.94	2,027.9
j1	January, 2005	Kottaiyamedu	7.02	1,080	165	19	35	11	367.25	129.35	12	739.12
j2		T.kulam	7.29	1,100	227.66	14	85.9	31	382.64	359.9	41	1,122.09
j3		Poombukar	7.76	2,130	38	19	210	15	260.9	231.8	94	868.7
j4		Thirumullaivasal	7.6	2,430	80	93	110	41	136.83	693.11	64	12,210
j5		Valuthalaikudi	7.79	1,890	63	42	78	44	181.5	311.1	98	815.6
j6		Parangipettai	7.89	1,750	57	44	192	51	186.2	438.24	102	1,088.44
j7		Melmokkarai	7.51	204	47.29	1.7	21.79	2.04	30.13	143.99	7.82	254.73
j8		Palayar	7.16	1,854	104.72	10.61	142.6	54.4	189.54	268	125.8	895.87
j9		Kulayar	8.06	194.27	34	8.98	10.2	6.8	30.13	51.85	78.2	220.16
j10		T.S.pettai	6.95	393.43	67.33	11.42	44.2	6.8	33.92	278.22	21.76	463.65
j11		Nayakarpalayam	7.75	3,060	2.72	76.5	377.4	54.4	538.9	424.65	15.64	1,490.21

m1	March, 2005	Kottaiyamedu	7.62	924.77	98.85	90.81	261.15	127.28	933.17	82.98	110.15	200.06
m2		T.kulam	7.18	740.94	58.82	52.94	261.15	77.54	538.37	319.1	75.4	174.79
m3		Poombukar	7.45	1,871.87	107.56	116.45	390.8	225.03	1,063.45	427.09	116.48	430.2
m4		Thirumullaivasal	7.21	942.88	100.49	144.21	390.8	234.75	1,063.45	610.13	87.95	226.53
m5		Valuthalaikudi	7.6	2,010	184.34	163.1	275.86	426.23	1,240.69	427.09	296.18	1,407
m6		Parangipettai	7.11	1,567.24	79.93	72.64	206.9	95.84	531.73	305.06	87.21	430.2
m7		Melmokkarai	7.32	548.87	40.75	34.69	252.87	56.54	431.31	294.38	38.13	134.06
m8		Palayar	7.25	2,012.95	133.56	123.5	436.78	174.26	1,238.64	366.08	179.21	610.72
m9		Kulayar	7.18	294.83	90.02	189.85	390.8	178.66	1,417.94	183.04	103.2	82.56
m10		T.S.pettai	7.2	1,303.72	53.35	52.51	396.78	94.7	890.39	143.99	59.9	312.24
m11		Nayakarpalayam	7.45	3,718.63	135.04	146.42	574.71	358.28	1,772.42	75.05	206.46	790.45
A1	August, 2005	Kottaiyamedu	7.1	3,215.53	311.99	16.8	388.3	103.6	1,102.79	213.5	170	2,250.87
A2		T.kulam	7.1	2,182.5	88	67.2	364.2	4	593.79	298.9	147.5	1,527.75
A3		Poombukar	7.6	1,766.57	190	45	353.6	22	576.2	542.9	100.5	1,236.6
A4		Thirumullaivasal	7.5	2,133.12	220	216	1,837	36	3,217.09	988.2	507.5	1,493.19
A5		Valuthalaikudi	7.9	6,743.84	231.99	144	1,246	134.3	2,384.01	536.8	270	4,720.69
A6		Parangipettai	7.1	3,383.57	140	76.8	518.7	29.7	1,195.25	193	127.5	2,368.5
A7		Melmokkarai	7.7	1,532.12	60	36	69.7	29	177.25	30.5	162.5	1,072.49
A8		Palayar	7.7	4,576.16	80	93.6	34.2	192.3	797.63	24.4	287.5	3,203.31
A9		Kulayar	7.5	555.93	180	156	800.9	119.9	1,347.1	890.6	125	389.15
A10		T.S.pettai	7.9	,599.04	140	84	898.2	59.4	1,683.88	335.5	220	1,119.33
A11		Nayakarpalayam	8.1	3,182.71	231.99	304.8	250	230.7	1,025.4	1,043.1	150	2,227.9
r1		Palayar sea water	7.5	15,200.97	1,028	151.2	5,765	191.8	10,230.5	195.2	215	10,640.68
r2		Salt leachate	7.4	21,571.43	72	878	7,720	141.8	13,626	152.5	185	15,100
r3		Standard sea water	8.2	50,207.14	411	1,290	10,800	392	19,400	142	2,710	35,145

All values in mg/l except electrical conductivity (EC) in µS/cm and pH pre-tsunami and from 16.8 to 304.8 mg/l, with an average of 110.33 mg/l, post-tsunami. The is a notable increase in the average of Mg rather than Ca, during the post-tsunami period. Potassium ranges from 1.61 to 48.56 mg/l, with an average of 25.49 mg/l, pre-tsunami and from 4 to 426 mg/l, with an average of 136 mg/l, post-tsunami.

Discussion

The pH in these groundwaters has slightly decreased after the tsunami, whereas EC shoots up considerably, reflecting the impact of tsunami waters which exist even 3–8 months after the tsunami. Cl average value is 1,146 mg/l post-tsunami, which has increased several folds later, indicating the long residence time of the tsunami water in the shallow aquifers. Bicarbonate with an average of 378 mg/l in post-tsunami reflects the leaching of sea water. Sulphate is generally derived from oxidative weathering of sulphide-bearing minerals (Prasanna et al. 2007) like Marcasite (which is abundant in these regions), but the sudden shoot of these ions to above 500 mg/l is a clear indication of the role played by tsunami waters. Dominance of anions in the study area is as follows: Cl > HCO_3 > SO_4 both pre-tsunami and post-tsunami. Though the order of dominance is maintained, the value of Cl shows a higher value post-tsunami. The order of abundance of cations is as follows: Ca > Na > Mg > K pre-tsunami and Na > K > Ca > Mg post-tsunami. Na dominates the cations during the post-tsunami period. Among the major ions, the many-fold increase of Na and Cl is indicative of the long residence time spent by tsunami waters in these aquifers.

The Piper (1944) trilinear diagram shows (Fig. 3) that there are two groupings; one is near the weathering zone and another is in the evaporation-dominant zone. Later in the subsequent periods, there has been an increase in Cl and Na in the system, which has eventually helped in the migration of these groups towards the sea water composition. It is also observed that there is a subsequent decrease of relative HCO_3 concentration in the system. The arrows in the diagram indicate the migration of samples from the pre-tsunami period to the sea water composition in August 2005. These observations indicate the long-term impact of tsunami waters on the aquifers' water quality.

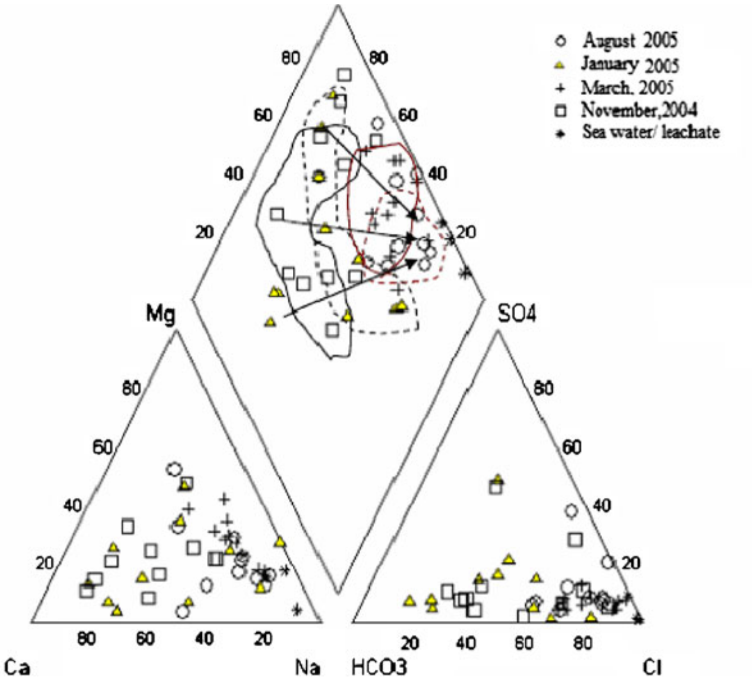


Fig. 3 Piper plot showing the migration of chemical composition of samples towards sea water composition (sampled for a period from November 2004 to August 2005)

Ternary diagram

The ternary diagram with Ca, Cl and HCO_3 at the vertex of the triangle with equivalent part per million (epm) values indicates that the samples of the pre-tsunami period and of January fall in the central part zone II, with HCO_3 dominance, whereas in March and August, samples fall in zone I, which indicates dominance of Cl (Fig. 4). This is similar to the Spensers triangle of three components to represent the pathway or the evolution of water composition (Jones and Bodine 1987; Spencer et al. 1990). The migration of this composition is also witnessed in the Pipers plot. The ternary diagram with epm values of Ca, Mg and HCO_3 indicates that they fall in zone II with dominance of HCO_3 during the pre-tsunami period, but during March and August, there is an increase of Mg content relative to Ca and HCO_3, but they still have higher concentrations of HCO_3 (Muller et al. 1972) observed in August than in March. This indicates the predominance of evaporation during March when compared to August, whereas dilution is significant after monsoon. This is also supported by the other observations as discussed below.

The total ionic strength (IS) of the samples is less during pre-tsunami and January. Later, they have increased in March and subsequently in August (Fig. 5). The EC of the samples also varies from low to very high values. In general, the IS of the samples is below 0.06. Higher IS is noted in March and in August. The higher ranges of EC were noted in January and in August, but August sample show higher EC and IS as well. The increase of IS is mainly due to the longer residence time of the saline water in the aquifer (Chidambaram et al. 2005) or recharge of the evaporated saline water.

Saturation index

The saturation index (SI) of carbonate minerals (McMahon and Chapelle 1991) in the samples for different periods indicates that they are saturated to near-saturated with calcite (C) and aragonite (A) (Fig. 6). They are under-saturated to near-saturated with magnesite (M). Dolomite (D) shows under-saturation in the pre-tsunami samples, but it shows super saturation during August. This may be due to the increase of Mg concentration in the subsequent periods. It can be related that Ca is weakly correlated with other ions in January, which may be due to the removal of Ca from the system by precipitation of calcium carbonate salts. The SI_D is still higher in August

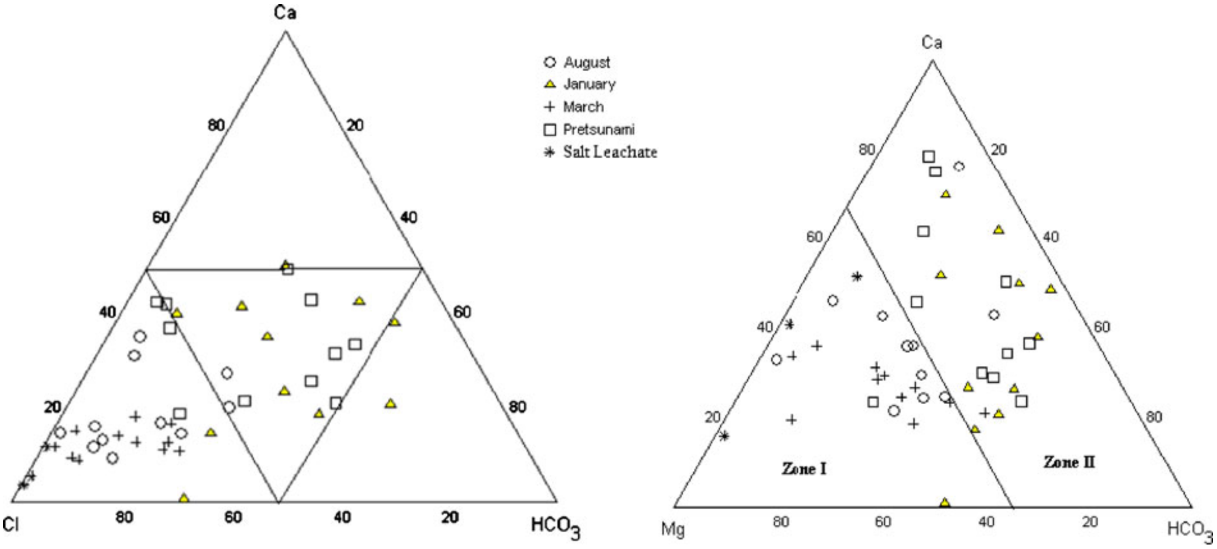


Fig. 4 Spencer diagram for Ca–Cl–HCO_3 and Ca–Mg–HCO_3, indicating the clustering of samples collected in different periods

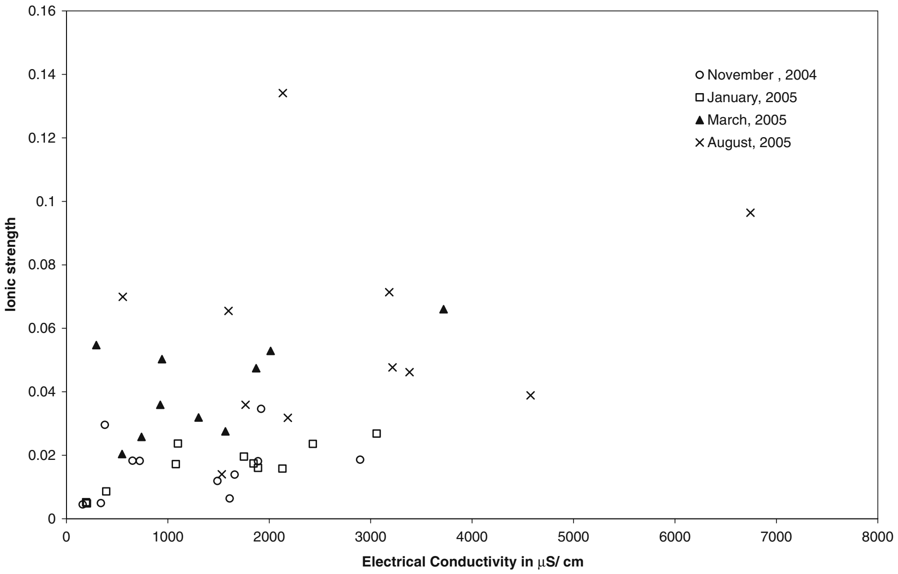


Fig. 5 The relationship of ionic strength with electrical conductivity in samples collected in different periods

than in March because of the dissolution of the salts that precipitates after March, thereby adding magnesium into the system.

Since the study covers periods like monsoon, post-monsoon and summer, there are variations in temperatures. This study will throw more light on the relation of the SI with temperature and various other mechanisms operating in the underground environment that control the SI of carbonate minerals. It is generally known that there is a significant change in SI of minerals with temperature (Garrels and Christ 1965). The variation of SI of the Palayar region sea water at different temperatures was discussed. Carbonate minerals show positive SI in the following order: $SI_D > SI_C > SI_A$ (SI_D, dolomite; SI_C, calcite and SI_A, aragonite), though with increase of temperature the trend becomes positive, there is a parallelism between SI_C and SI_A. Hence, it can be inferred that the temperature variation effects on

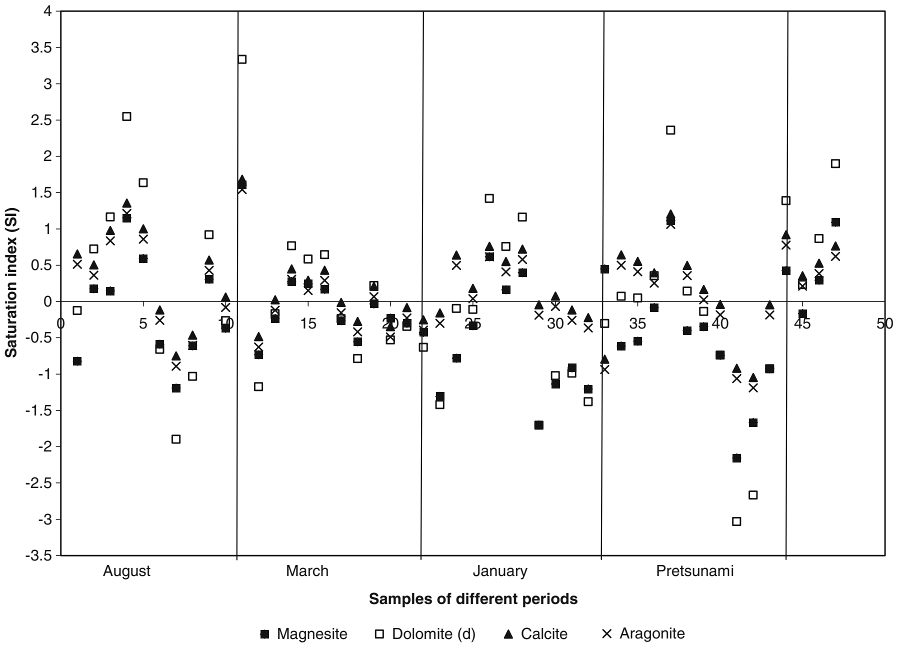


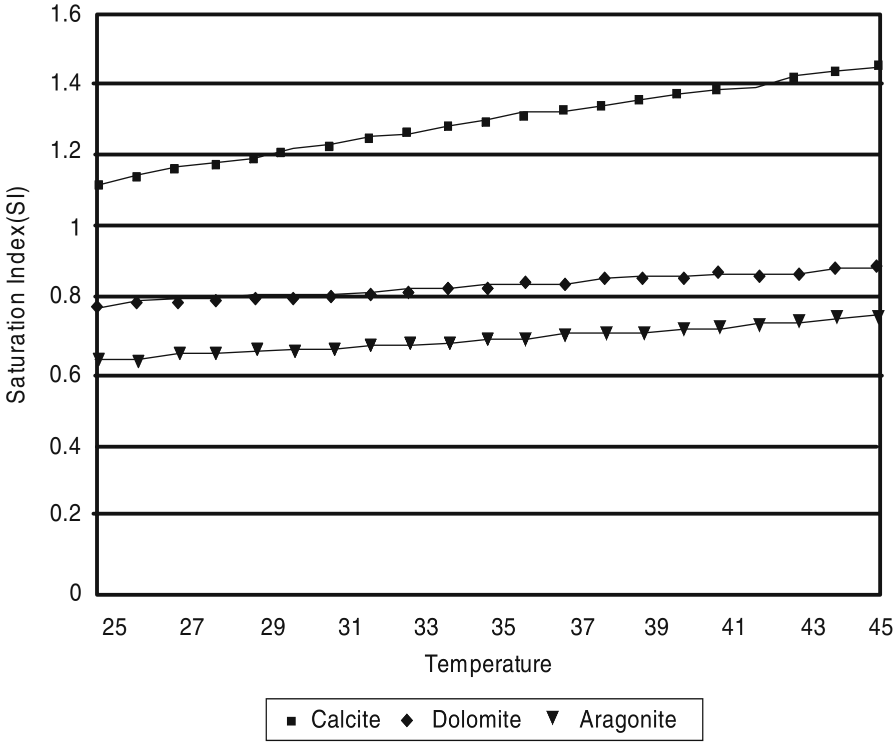
Fig. 6 Variation of saturation indices for different carbonate minerals in groundwater samples collected from November 2004 to August 2005

SI_C and SI_A are similar but the trend with SI_D varies (Fig. 7), and the increase of temperature thus increases the SI. It is further noticed that the higher temperatures noted in March lessen the SI of carbonate minerals. This may be due to the impact of infiltered rain water or due to the removal of ions by precipitation of salts. Since no showers of rainfall were recorded during the months of February or March, along with higher EC and IS than the pre-tsunami waters, it rules out the possibility of dilution by rain water. Lechate composition chiefly reflects the evaporate concentration of the sea water entrapped in the land. The SI of lechates matches with the groundwater saturations in August. Thus, it indicates that the changes in groundwater chemistry during August have not attained similar compositions with increase in temperatures but due to precipitation and dissolution.

Statistics

The correlation between the chief cation and anion was carried out. They indicate, during the pre-tsunami condition, that good correlation exists between Na and HCO_3: Ca and Cl. Mg has also had good correlation with all ions. Ca and SO_4 do not have correlation with any other ions. In January, Na develops positive correlation with Cl, Mg and K. Good positive correlation exists between Mg and HCO_3. Ca and SO_4 did not correlate with other ions present in the system. During March, good correlation exists between major cations Ca and Mg. Cl shows good correlation with Na; SO_4 with K, Ca, Mg and Cl. The samples in August reveal that HCO_3 has good correlation with Na, Mg, Ca and Cl: good correlation also exists between Na, SO_4 and Cl. All the ions are represented well in the correlation matrix (Fig. 8). The matrix records show that there is no relationship between Na and Cl during the pre-tsunami period, but it developed a poor positive correlation during January. After that, they show excellent correlation between Cl and Na in March and August. It is further noted that the association of HCO_3 with Na decreased from November 2004 to August 2005. The enrichment of HCO_3 in August compared to March indicates that dissolution

Fig. 7 Variation of saturation index (SI) of carbonates in Palayar sea water at different temperature (OC)



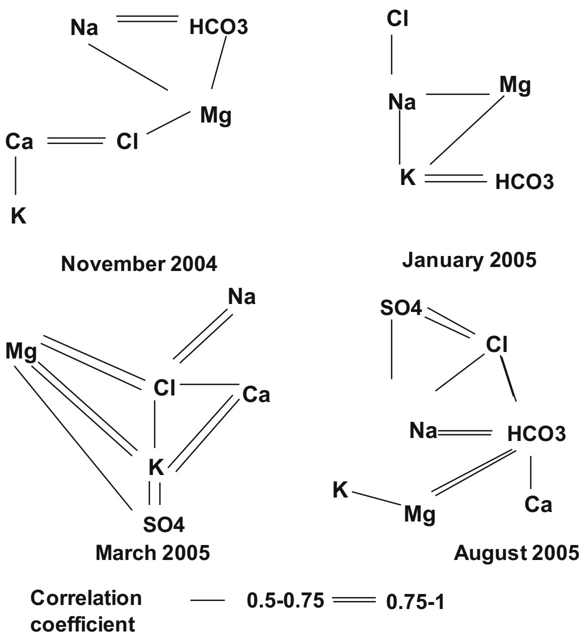


Fig. 8 Correlation of different ions in groundwater samples collected in different study periods

Table 3 Factor analysis of major cations and anions during Pre and Post tsunami conditions

	Factor 1	Factor 2	Factor 3
November, 2004			
Ca	−0.2	0.98	0.03
Cl	0.32	0.90	0.23
HCO_3	0.83	0.02	−0.38
K	0.45	0.43	0.72
Mg	0.84	0.21	0.09
Na	0.94	0.09	0.06
SO_4	−0.23	0.04	0.91
January, 2005			
Ca	−0.10	−0.07	0.99
Cl	0.67	−0.53	0.30
HCO_3	0.81	0.21	0.05
K	0.87	0.37	0.09
Mg	0.85	0.00	−0.22
Na	0.82	−0.09	−0.31
SO_4	0.16	0.89	−0.03
March, 2005			
Ca	0.96	−0.07	
Cl	0.80	0.59	
HCO_3	0.27	−0.78	
K	0.96	0.04	
Mg	0.86	0.18	
Na	0.47	0.72	
SO_4	0.91	−0.02	
August, 2005			
Ca	0.28	0.58	
Cl	0.93	0.30	
HCO_3	0.39	0.78	
K	−0.25	0.79	
Mg	0.29	0.86	
Na	0.97	0.16	
SO_4	0.86	0.07	

of the precipitated salts was prominent only during August, i.e. after the onset of monsoon. The rains during June and July have increased the migration of ions either by weathering or leaching of salts precipitated in summer (Srinivasamoorthy et al. 2007). In total, it is believed that K–Mg–Na–Cl represents the dominant ionic group during the period of study.

PCA was done by using Varimax rotation (Table 3). Factor analysis indicate that three prominent factors were extracted for pre-tsunami and January (post-tsunami) and two for August and March. The first component of factor loading 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 sea water and fresh water. But during March, the first factor representation was slightly changed to Cl, Ca, K, Mg, and Na, indicating the existence of 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 from the surface due to precipitation (Chidambaram et al. 2008). Hence, there is an enrichment of Cl and Na. In August, the first factor is represented by Cl, Na and SO_4, where the impact of saline water is noted along with the association of Ca, HCO_3, Mg and K as a second factor. This is due to the leaching and dissolution of salt precipitated during March. Later, the rains during June and July have considerably increased leaching and added the ions into the system.

Comparison

The comparison is calculated by the similarity coefficient between the samples (including pre- and post-tsunami) with the sea water of the study area. This is done by means of a linear regression logarithm. Similar samples that have correlation coefficients close to the correlation coefficient table ratios were taken into account rather than the absolute values. Therefore, samples being diluted by precipitation may still have a correlation coefficient with respect to its original composition even though the quality of dissolved minerals is very different. The difference in absolute concentration is expressed by the Euclidean distance.

$$\mathrm{Dij} = \frac{\sum n\,k - 1\,\left(\mathrm{Xik} - \mathrm{Xjk}\right)}{n},$$

where Xik denotes the K^{th} variable measured on samples i and Xjk is the K^{th} variable measured on sample j, in all 'n' variables are measured on each sample and Dij is the distance between sample i and sample j.

This is obtained by comparison of seven parameters, Ca, Mg, Na, K, Cl, HCO_3 and SO_4 where samples with correlation coefficient values greater the 0.75 are displayed (Fig. 9). The comparison is done with all the samples, first with that of seawater then with the salt-leached water. Higher correlation was found in the samples of March and August (A10, A5, A7, M10, A4 and A8). The samples show better correlation to salt leacheates than that of the seawater. Hence, it is clear that samples from August have better comparison to the leachate and seawater than with other periods. Thus, it is evident that the mechanism that has altered the groundwater is not the direct infiltration but due to precipitation and dissolution of the salts entrapped from sea water.

Percent of mixing

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 by earlier comparison and their corresponding pre-tsunami compositions were selected to identify the mixing proportion. This was done by using the following formula:

$$\text{Mixing percentage} = \frac{(\mathrm{Cl} + \mathrm{Na} + \mathrm{SO_4})\ \text{concentration in post-tsunami} - (\mathrm{Cl} + \mathrm{Na} + \mathrm{SO_4})\ \text{pre-tsunami concentration} * 100}{(\mathrm{Cl} + \mathrm{Na} + \mathrm{SO_4})\ \text{concentration in sea water of the study area}}$$

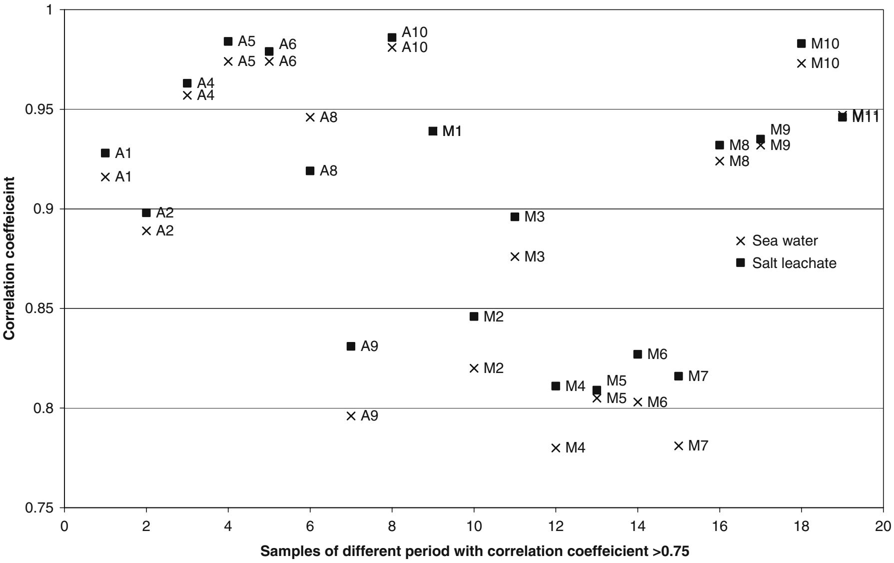


Fig. 9 Diagram showing the relationship of correlation coefficients for groundwater samples to seawater of the study area and the salt leachate

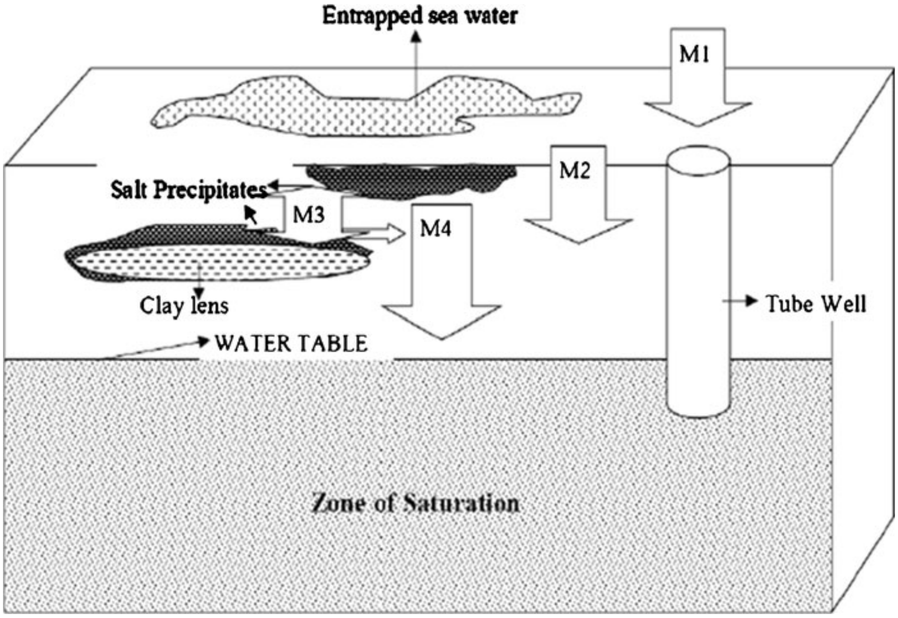
Table 4 Percent of sea water mixing identified in the August samples

S.No	Location	Percentage of mixing
1	Kottaiyamedu	4
2	T. Kulam	4
4	Thirumulaivasal	34
5	Valuthalakudi	22
6	Parangipetai	11
8	Palayar	7
10	T S Pettai	18

The results were also confirmed using Aquachem software. So, the pre-tsunami water chemistry of the region is taken for the respective August location and the amount of mixing is calculated.

The percentage of sea water mixed with the groundwater after the tsunami event is obtained by the above said equation. The results of the mixing percentage of the sea water with groundwater in the sample (Table 4) 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 is favoured by the distributary's channels and river mouth. From this study, we have inferred that these processes (Fig. 10) 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 result 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), enhancing 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.

Fig. 10 A schematic representation of the possible factors for the hydrogeochemical change, after the tsunami



Conclusion

It is inferred that the sea water has also entered inland along the river mouth and drainage canal during the event. Most of the water has drained back to the sea, and the rest was stagnated inland. This study suggests that, after the tsunami, saline water had entered the subsurface groundwater, forming a mixture of fresh and saline water during the month of January. Later, during March, there had been depletion in the water table along with the increase in temperature, resulting in evaporation and precipitation of salts in the pore space and on the surface. The changes in the composition during these months are well established by the variation in the IS and by the Spencers plot. A clear shift in hydrogeochemical facies of the groundwater is also noted with respect to different periods of observation. The subsequent rains during June/July have leached the precipitated salt solution from the surface and the pore spaces, which has increased the complexity of the chemical relationship in August. The rise in the water level has dissolved the precipitated salt in the pore space. The statistical analysis of the data and the SI of the carbonate minerals in the groundwater also confirm the above observations. Higher percentage of seawater is noted in the groundwaters of the southern part of the study area in samples A4 and A5. Both shallow unconfined aquifers and perched aquifers got altered due to inundation, stagnation, precipitation and subsequent leaching, which resulted in water quality deterioration.

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