

Groundwater quality in and around Tuticorin town, Southeast coast of India

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ABSTRACT

Rapid urbanization coupled with growth in agriculture and industries has led to deterioration of groundwater quality. The problem is severe in the coastal tracts due to salinity ingress since the last few decades. The present paper deals with a systematic hydrogeochemical study carried out in and around Tuticorin town covering an area of about 120 km² to assess groundwater quality. A total of 29 groundwater samples were collected and analyzed. Analysis of major ions has shown the anomalous values for total dissolved solids (TDS), sodium (Na⁺), magnesium (Mg²⁺), chloride (Cl⁻), and sulphate (SO₄²⁻) resulting in degradation of groundwater quality. Only 21% of samples are potable based on the TDS values. The order of major cations and anions obtained are Na⁺ > Mg²⁺ > Ca²⁺ > K⁺ and Cl⁻ > SO₄²⁻ > HCO₃⁻ > NO₃⁻ > F⁻, respectively. The results of these parameters were interpreted with the help of Piper, Wilcox and Gibbs diagrams apart from correlation matrix analysis. Cross plot of HCO₃⁻/Cl⁻ (molar ratios) versus TDS indicated that about 72% of the analyzed samples are brackish and saline in nature. Out of them, about 42% samples are NaCl-type. On the basis of interpretation of US Salinity diagram, it is found that majority of the samples have very high salinity hazard and sodium hazard, and represent evaporation dominance.

Key words: Hydrochemistry, Drinking and Irrigation, Groundwater salinity, Coastal aquifer, Tuticorin town, Tamil Nadu and India.

INTRODUCTION

Groundwater in a coastal tract is relatively vulnerable to contamination by sea water (Todd, 1980). It is of paramount importance to assess the suitability of groundwater for drinking, domestic and irrigation purposes. Saline water intrusion in coastal aquifers is a common global problem (Saxena et al., 2003; Batayneh, 2006; Singh et al., 2009; Mondal et al., 2010a; Antony Ravindran et al., 2015). This phenomenon can be attributed to a variety of factors like gentle coastal hydraulic gradients, tidal and estuarine environments, sea level rise, excessive groundwater withdrawal and local hydrogeological conditions (Rajmohan et al., 2000, Saxena et al., 2004, Sherif and Kacimov, 2007; Mondal et al., 2008; Kim et al., 2009). However, natural hazards like tidal waves and tsunami engulfing the coastal regions also result in the percolation of seawater into shallow and unconfined aquifers (Villholth et al., 2006). One of the most common methods for assessing the extent of saline water ingress in coastal aquifers is through periodic analysis of groundwater chemistry (Sukhija et al., 1996; Saxena et al., 2003; Sarwade et al., 2007; Kim et al., 2009). In case of seawater intrusion, groundwater generally exhibits high concentrations not only in total dissolved solids and major ions (Richter and Kreitler, 1993) but also enrichment of selective trace elements (Saxena et al., 2004; Mondal et al., 2010b).

Tuticorin town, a part of the southeastern coast of Tamil Nadu, is chosen as the study area which is affected by seawater ingress as well as in-situ salinity in the geological past. The objective of this paper is to characterize groundwater quality of shallow coastal aquifers by identifying hydrogeochemical facies. This will help in providing a better understanding of possible changes in groundwater quality with the rapidly developing coastal belt in and around Tuticorin town. In order to understand the pollution, it is essential to have knowledge of the natural baseline quality so that the imposed environmental change can be measured with an acceptable degree of confidence (Edmunds et al., 2003).

The Study Area

The study area, Sterlite Industries India Ltd. (SIIL) watershed, covering an area of about 112 km² lies between 78.04 to 78.17°E longitudes and 8.77 to 8.85°N latitudes. It is situated in the eastern part of Tuticorin district along the eastern coastal belt of Tamil Nadu, India. (Figure 1). The topographic elevation varies from 26.22 m above mean sea level (amsl) in the east near Tuticorin town to the sea level near sea. The study area receives a good amount of rainfall (average 568 mm) during the northeast monsoon season between October and December of each year. The long-term average annual rainfall at Tuticorin

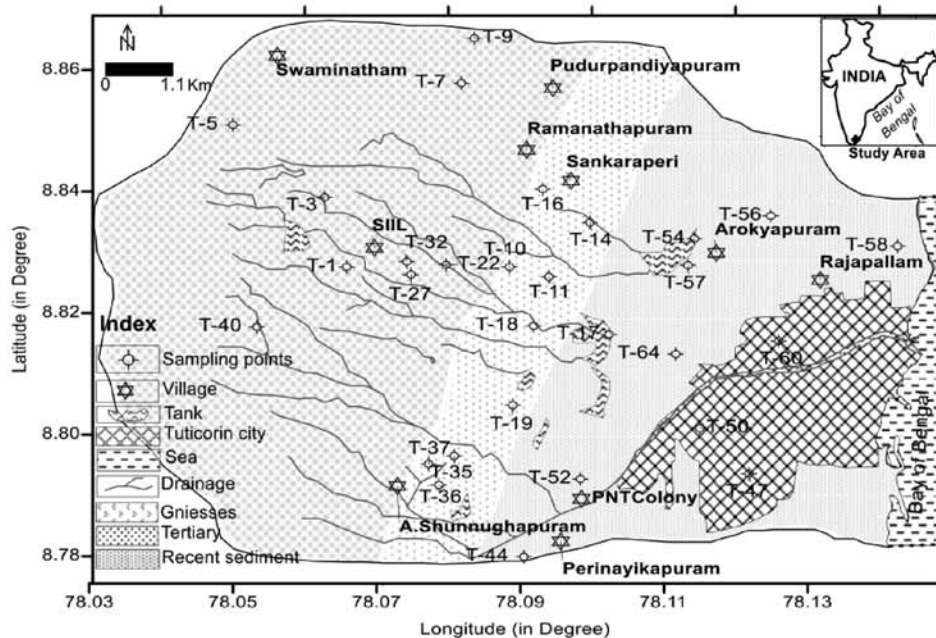


Figure 1. Location of the study area along with monitoring wells.

town is about 568 mm (IMD data) (Singh et al., 2006; Rangarajan et al., 2009).

Geomorphologically, the study area consists of flood plains, deltaic plain and natural levees. The slope of the topography is gentle in the western and central parts, but nearly flat in the eastern part of the watershed. Geologically, the area is underlain by rocks of Archaean age and recent alluvium. The Archaean rocks are mainly foliated crystalline igneous and metamorphic rocks trending in NW–SE direction (Balasubramanian et al., 1993). The quartzite ridges in the western part are weathered, jointed and fractured. Sub-recent alluvium sands characterize the coastal areas along with coarse and calcareous grits, sandstones, shales and limestones. The watershed area is covered with black soil in the western part (in and around the SIIL Plant), red soil (sandy loam to sandy soil) in the central part and alluvial sandy soil in the eastern part. The maximum soil thickness is about 3.0 m. The sandy soil derived from sandstones has low soil moisture content. The alluvial soil is windblown, derived mainly from sands and shales including the beach sand and coastal dunes, which has low soil moisture content.

Systematic hydrogeological survey was also carried out during the year 2007 covering a number of hand pumps, dug wells and boreholes tapping shallow unconfined alluvial and fractured aquifer systems. The depth of dug wells ranges from 7 to 12 m, while the borehole depth varies from a few metres to a maximum of 70 m (bgl) (Singh et al., 2006). The sandy zone constitutes the main aquifer system in the alluvium areas while the fractured rocks too are water yielders (Mondal et al., 2009). The depth to

groundwater level during the pre-monsoon season varies from 1.8 to 14.4 m bgl whereas in the post-monsoon season, it varies from 0.9 to 12.9 m bgl (Rangarajan et al., 2009).

MATERIALS AND METHODS

The analysis of water samples was carried out following Brown et al. (1983) and APHA (1985) methodologies. pH, TDS and EC were measured in in-situ condition by using portable EC and pH meters. Sodium (Na^+) and potassium (K^+) were determined by atomic absorption spectrophotometer (AAS). Total hardness (TH) as CaCO_3 , calcium (Ca^{2+}), hydrogen carbonate (HCO_3^-), and chloride (Cl^-) were analyzed by volumetric methods. Magnesium (Mg^{2+}) was calculated from TH and Ca^{2+} contents. Sulfate (SO_4^{2-}) was estimated adopting the spectrophotometric technique, whereas nitrate (NO_3^-) was determined by ion chromatography and fluoride (F^-) by fluoride meter. All concentrations were expressed in milligrams per litre (mg/l), except pH and EC.

RESULTS AND DISCUSSION

General groundwater chemistry

The results of chemical analysis (carried out at CSIR-NGRI) are summarized in Table 1. The pH in the groundwater samples varies from 7.10–8.67. Comparison of hydrogeochemical data with drinking water standards of WHO (1993) shows that about 82.8% ($N = 24$), 75.9%

Table 1. Results of hydrogeochemical parameters collected in and around Tuticorin town, Southern India.

Sl. No.	Well code	Village Name	Longitude	Latitude	pH	EC	TDS	TH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	NO ₃ ⁻	F ⁻
1	T-1	Terku Virapadiyapuram	78.066	8.828	7.60	3850	2464	280	64	29	288	10	103	385	268	8	0.88
2	T-3	Kumargiri	78.063	8.839	7.70	3370	2157	1032	275	83	271	8	220	914	293	25	0.43
3	T-5	Swaminatham (S)	78.050	8.851	7.42	6000	3840	1800	400	192	478	16	1029	1142	180	40	1.30
4	T-7	Nayinapuram	78.082	8.858	7.80	500	320	96	16	13	76	2	14	5	293	1	0.91
5	T-9	Pudur Pandiyapuram	78.084	8.865	7.70	400	256	112	22	13	52	2	21	17	220	1	1.12
6	T-10	Pandarampatti	78.088	8.828	7.80	7900	5056	1600	256	230	1260	151	1136	2439	415	54	2.59
7	T-11	Pandarampatti (W)	78.094	8.826	7.40	2230	1427	736	170	75	134	6	355	384	146	15	0.50
8	T-14	Sankarapereri (E)	78.100	8.835	7.10	6300	4032	4880	816	681	28	140	4082	1089	265	27	0.79
9	T-16	Ramanathampuram	78.093	8.840	7.37	1846	1181	4320	832	538	267	16	2840	476	488	26	0.25
10	T-17	Silverpuram	78.102	8.816	7.32	10380	6643	1080	192	144	5.6	41	1065	492	244	20	7.23
11	T-18	Milavittam	78.092	8.818	7.39	4600	2944	1600	368	163	557	30	1526	397	317	25	0.99
12	T-19	Madathur (N)	78.089	8.805	7.44	2200	1408	800	128	115	175	11	532	222	244	13	0.65
13	T-22	SIIL-II (N, PZ-11)	78.080	8.828	7.76	12290	7866	2360	464	288	1317	126	1171	2856	854	63	0.60
14	T-27	SIIL-VII (W, PZ-2)	78.075	8.826	7.68	5300	3392	1800	608	67	166	5	390	1346	220	35	6.76
15	T-32	SIIL-XI (N)	78.074	8.828	7.46	7300	4672	2480	448	326	1575	140	923	4226	415	45	5.33
16	T-35	Ayynaduppu	78.081	8.797	8.10	5230	3347	1840	368	221	382	21	568	1577	293	15	0.68
17	T-36	Shunmughapura	78.079	8.792	7.87	3100	1984	1880	304	269	103	3	568	1016	268	30	0.92
18	T-37	Kailashpuram	78.077	8.795	8.08	200	128	88	22	8	6	ND	7	10	98	ND	0.32
19	T-40	Vadakka Silukkanpatti (E)	78.053	8.818	8.57	3300	2112	80	10	13	131	2	28	101	268	3	0.67
20	T-44	Periyanayakapuram	78.090	8.780	8.12	4800	3072	880	128	134	808	45	1420	432	293	14	1.67
21	T-47	Levinipuram	78.122	8.794	7.77	4500	2880	800	128	115	839	24	923	517	634	15	0.44
22	T-50	Seetapuram Nagar	78.115	8.801	8.10	1700	1088	560	144	48	355	17	355	440	464	16	0.74
23	T-52	PNT Colony (S)	78.098	8.793	7.32	900	576	240	67	17	23	0.78	21	77	220	2	0.21
24	T-54	Mappali Urani	78.114	8.832	7.33	12600	8064	920	192	106	1960	103	1775	480	244	14	0.38
25	T-56	Davishpuram	78.125	8.836	7.46	9100	5824	2200	320	336	1475	76	3209	733	244	20	0.78
26	T-57	Arokayipuram	78.113	8.828	7.62	7200	4608	1120	192	154	977	61	1775	484	366	18	0.92
27	T-58	Rajapallam	78.143	8.831	8.00	2100	1344	72	13	9	247	10	128	72	439	5	2.63
28	T-60	SBI Colony (St. Ann's School)	78.126	8.815	7.72	2800	1792	448	90	54	373	16	248	240	464	2	0.94
29	T-64	Chinakannupur	78.112	8.813	7.34	17597	11262	3760	688	490	2443	179	5786	826	317	32	1.22

pH: $-\log_{10}H^+$ at 25°C; EC in $\mu S/cm$, All Ions in mg/l; TH total hardness as CaCO₃; the samples were collected on April 2007, ND: Not detected.

(N = 22), 75.9% (N = 22), and 65.5% (N = 19) of the samples exceeded the upper limit for total dissolved solids (TDS=500 mg/l), magnesium (Mg²⁺=30 mg/l), chloride (Cl⁻ =200 mg/l) and sodium (Na⁺ = 200 mg/l), respectively. This indicates significant water quality deterioration in the study area.

To ascertain the suitability of groundwater for various purposes, it is essential to classify the groundwater based on their TDS values (Freeze and Cherry, 1979). The classification of groundwater based on the TDS shown that about 21% are fresh, 3% are saline and rest of the samples are moderately fresh (76%). It also indicates that only 17% of the samples falling below 500 mg/l of TDS which can be used for drinking purpose without any risk (Table 2).

The contour map of TDS (Figure 2) clearly shows that a higher value of TDS > 3000 mg/l was observed in the middle part covering more than 50% of the area, in particular, at the wells T-10, 19, 18, 14, 16, 56, 57, 54, 64, 47, and SIIL premises. Similarly, wells T-35 and 44 in the southern part and well T-5 in the north western part were also affected with higher TDS values (>3000 mg/l). This may indicate the possibility of a high rate of sea water intrusion in the middle, southern and north-western parts of the study area, where a high rate of withdrawal of groundwater was also observed (Mondal et al., 2009). It is noticed that the central and eastern parts are comparatively more populated, have larger industries and also have a large concentration of number of dug, tube, and bore wells (Singh

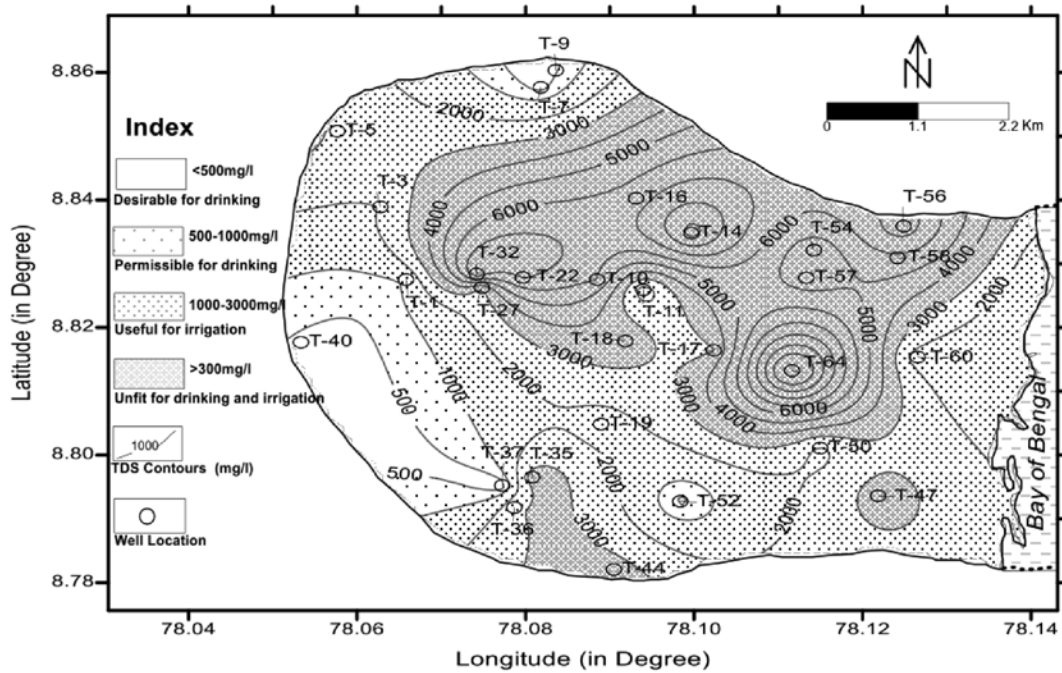


Figure 2. TDS contour map of the study area.

Table 2. Classification of the groundwater samples in the study area (Freeze and Cherry, 1979).

Total dissolved solids (TDS)	Water type	Samples	No. of samples	% of samples
<1,000	Fresh	T-7, 9, 37, 40, 52 and 58	6	21
1,000-10,000	Brackish	T-1, 3, 5, 10, 11, 14, 16, 17, 18, 19, 22, 27, 32, 35, 36, 44, 47, 50, 54, 56, 57 and 60	22	76
10,000-1, 00, 000	Saline	T-64	1	3
>1, 00, 000	Brine	Nil	Nil	Nil
Total			29	100

et al., 2006). The TDS in groundwater was observed as low as 126 mg/l in the village of Kailashpuram well (no. T-37), which indicates the availability of fresh groundwater because of its proximity to tanks and recharge area.

Cation chemistry

The concentration of Ca^{2+} in groundwater was found to be in the range of 10 to 832 mg/l, in the study area. Similarly, the concentrations of Mg^{2+} in 75% samples were found to be above the permissible limit of 50 mg/l (WHO, 1993). Sodium (Na^+) is one of the important naturally occurring cation and its concentration in fresh waters is generally lower than that of Ca^{2+} and Mg^{2+} . The average concentration of Na^+ comparatively is higher than that of Ca^{2+} and Mg^{2+} corroborating with earlier results

(Balasubramanian et al., 1993). The values of Na^+ range between 6 and 2443 mg/l with average of 578 mg/l. It is observed that 65% of samples were above the permissible limit. The geological influence on the concentration of the cations is quite apparent as the study area is underlain by mainly granite gneisses. The concentration of potassium shows very low in the study area. Only 24% of samples are above permissible limit with an average of 45 mg/l in the groundwater samples. The total hardness (TH) varies from 72 to 4880 mg/l. The maximum allowable limit of TH for drinking purpose is 500 mg/l and the most desirable limit is 100 mg/l as per the WHO International standard. But the most desirable limit is 80–100 mg/l (Freeze and Cherry, 1979). Groundwater exceeding the limit of 300 mg/l (Table 3) is considered to be very hard (Sawyer and McMcarty, 1967).

Table 3. Groundwater classification based on total hardness (Sawyer and McMcarty, 1967).

Total Hardness as CaCO ₃ (in mg/l)	Type of water	Sample numbers	Number of samples	Percentage of samples
<75	Soft	T-58	1	3
75-150	Moderately high	T-7,9,37 and 52	4	14
150-300	Hard	T-1 and 52	2	7
>300	Very hard	T-3, 5,10, 14, 17, 18, 19, 22, 27, 32, 35, 36, 44, 47, 50, 54, 56, 57, 58, 60 and 64	22	76
Total			29	100

Table 4. Hydrogeochemical facies for the groundwater samples.

Facies	Sample numbers	No. of samples	% of samples
NaCl	T-1, 10, 22, 32, 44, 47, 50, 54, 56, 57, 60 and 64	12	42
CaCl ₂	T-5, 11, 14, 16, 17, 27, 35 and 36	8	28
Mixed Ca-Ma-Cl ₂	T-3, 18 and 19	3	10
Mixed Ca-Na-HCO ₃	T-9, 40 and 58	3	10
Ca-HCO ₃	T-37 and 52	2	7
Na-HCO ₃	T-7	1	3
Total		29	100

Anion chemistry

The chloride (Cl⁻) content of samples varies between 7 to 5786 mg/l (an average: 1111 mg/l). Of the total samples, 22% of samples are exceeding the permissible limit. Similarly, 80% of the dug well samples show bicarbonate (HCO₃⁻) above the permissible limit with a wide variation in concentration between 98 and 854 mg/l with an average concentration of 327 mg/l. Sulphate concentration ranges from 5 to 4224 mg/l with about 79% of samples above the permissible limits. Only 10% of samples reveal nitrate concentration above permissible limit. Though the nitrate in the samples was ranging from 1 to 63 mg/l; the average shows slightly higher value (21 mg/l) as observed at the well no. T-22 (63 mg/l) and well T-10 (54 mg/l). Being loosely bound to soils, nitrate is expected to be more in runoff.

Fluoride values in the study area varies from 0.21 to 7.23 mg/l against the permissible limit of 1.50 mg/l (WHO, 1993) which can be attributed not only to mere presence of fluoride bearing minerals in rocks but also to the degree of weathering and leachable fluoride in the study area. The distribution of fluoride is quite sporadic and marked differences in concentrations are observed within very short distances with values less than 1.5mg/l in 24 samples and higher in only 5 samples. In the present case, the study area is underlain by crystalline formations such as charnockite and granitic gneiss which comprise quartz, feldspars (potash feldspars and albite), hornblende, biotite, etc. The acid charnockite of this area has quartz,

k-feldspars, hypersthene, and biotite minerals of coarse-grained nature, which are potential sources of fluoride.

Hydro-geochemical facies

Chemical data of the groundwater samples are plotted on a Piper trilinear diagram (Piper, 1953). It provides a convenient way to classify and compare water types. The concentrations of major anions and cations were plotted in two trilinear diagrams and diamond shaped field of Piper diagram. On the basis of chemical analysis of water, it is divided into mainly six facies (Figure 3). The hydrogeochemical facies of water are summarized in Table 4. It is observed that Na-Cl type of water dominates the study area. The percentage of samples falling under the Na-Cl, Ca-Cl₂, mixed Ca-Na-HCO₃ and Ca-Mg-Cl₂, Ca-HCO₃ and Na-HCO₃ types are 42%, 28%, 10%, 10%, 7% and 3 %, respectively.

Correlation analysis and cross plots

The correlation matrix indicates the degree of linear relationship between the independent and dependent variables (Nair et al., 2005). The EC strongly correlates with Na⁺ (0.82), K⁺ (0.81), TDS (0.77) and Cl⁻ (0.69). Chloride (Cl⁻) shows high correlation with TDS (0.89), Mg²⁺ (0.84), Ca²⁺ (0.72), K⁺ (0.71) and Na⁺ (0.60). The results of correlation matrix show that the dissolved ions in the groundwater are responsible for EC. Likewise, NO₃⁻ ions

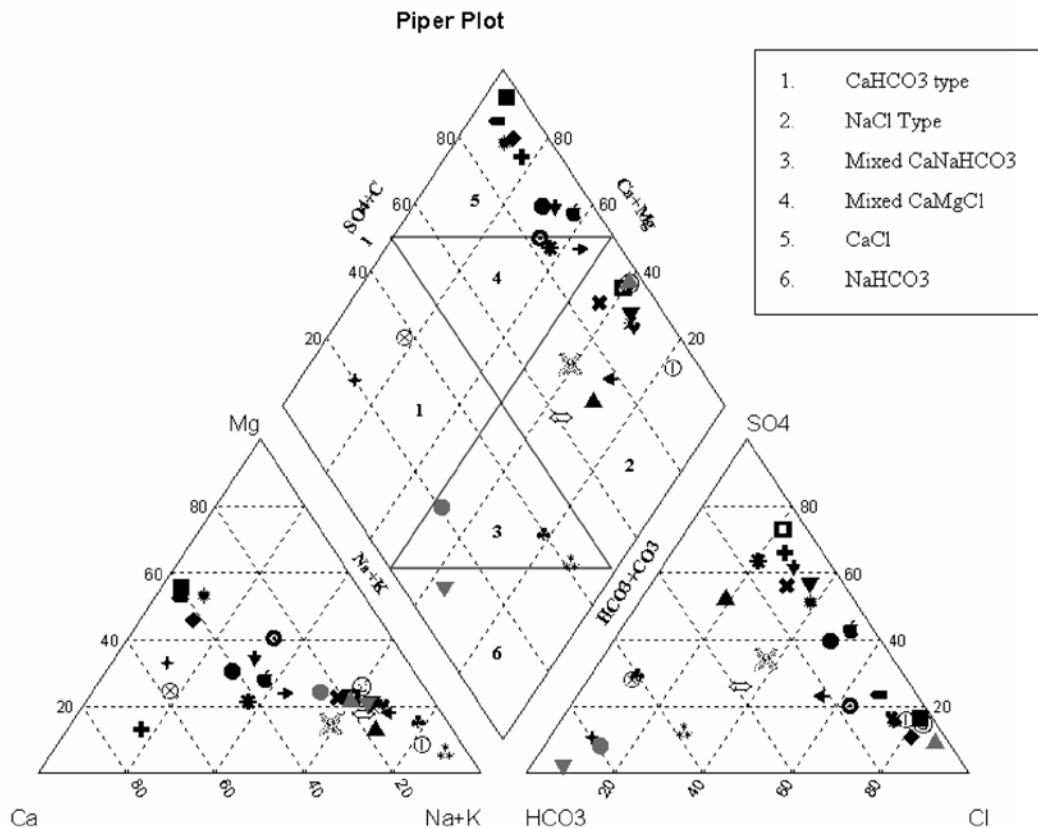


Figure 3. Piper diagram depicting hydrogeochemical facies of groundwater.

showed moderate to high correlation with SO_4^{2-} (0.82), TDS (0.65), Ca^{2+} (0.63) and K^+ (0.63) during the study period. A significant correlation has been noticed between K^+ with EC and TDS. The major exchangeable ions Na^+ and Ca^{2+} ; Na^+ and Mg^{2+} correlate positively as observed in the study area. It can therefore be postulated that the concurrent increase/decrease in the composition of ions in these waters is predominantly due to dissolution/precipitation reaction and concentration effects.

Sodium and chloride are the dominant ions of seawater/saline water, while calcium and bicarbonate are generally the major ions of fresh water (Hem, 1989). Thus, High levels of Na^+ and Cl^- ions in coastal groundwater may indicate a significant effect of seawater mixing and occurrence of saline water (Mondal et al., 2008); while considerable amounts of HCO_3^- and Ca^{2+} mainly reflect the contribution from the water-rock interaction. A plot of $\text{HCO}_3^-/\text{Cl}^-$ versus TDS (Figure 4) showed that the values of $\text{HCO}_3^-/\text{Cl}^-$ (molar ratios) were <1.0 in the high TDS concentration ($>1,000$ mg/l) range of 72% analyzed samples, while its slope was steep negative in the low TDS concentration range (<1000 mg/l). This result may indicate that groundwater with high TDS concentration is enriched with chloride due to seawater intrusion/saline

water occurrence, and that groundwater with low TDS concentration is not or less affected by seawater/saline water.

Drinking water quality

The chemical parameters of groundwater samples are compared with the standard values of the World Health Organization (WHO, 1993) for drinking and public health standards. Based on the permissible limits of all aspects i.e., TDS (500 mg/l), TH (200 mg/l), Ca^{2+} (75 mg/l), Mg^{2+} (30 mg/l), Na^+ (200 mg/l), K^+ (100 mg/l), Cl^- (200 mg/l), SO_4^{2-} (200 mg/l), HCO_3^- (200 mg/l), NO_3^- (45 mg/l) and F (1.50 mg/l) in groundwater, the well no. 37 (village: Kailashpuram) is the only suitable one for drinking purpose.

Irrigation water quality

Chemical data of groundwater sample in the area had been studied with respect to sodium hazards and are plotted in Wilcox diagram (Richards, 1954) as shown figure 5. In this diagram, Sodium Adsorption Ratio (SAR) vis-à-vis EC classifies the water according to sodium hazard (C1, C2, C3 and C4) and salinity hazard (S1, S2, S3 and S4) expressed as low, medium, high and very high, respectively (Piper,

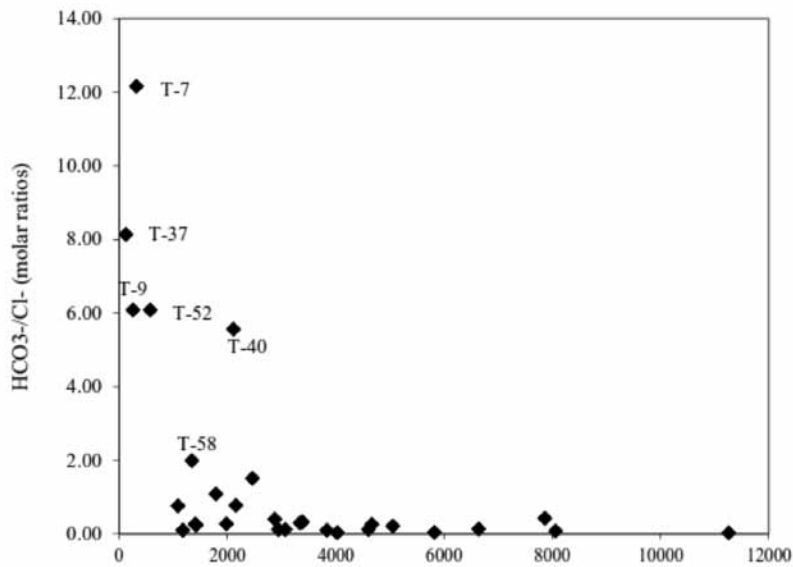


Figure 4. Cross plots of molar ratios of HCO₃⁻/Cl⁻ with TDS.

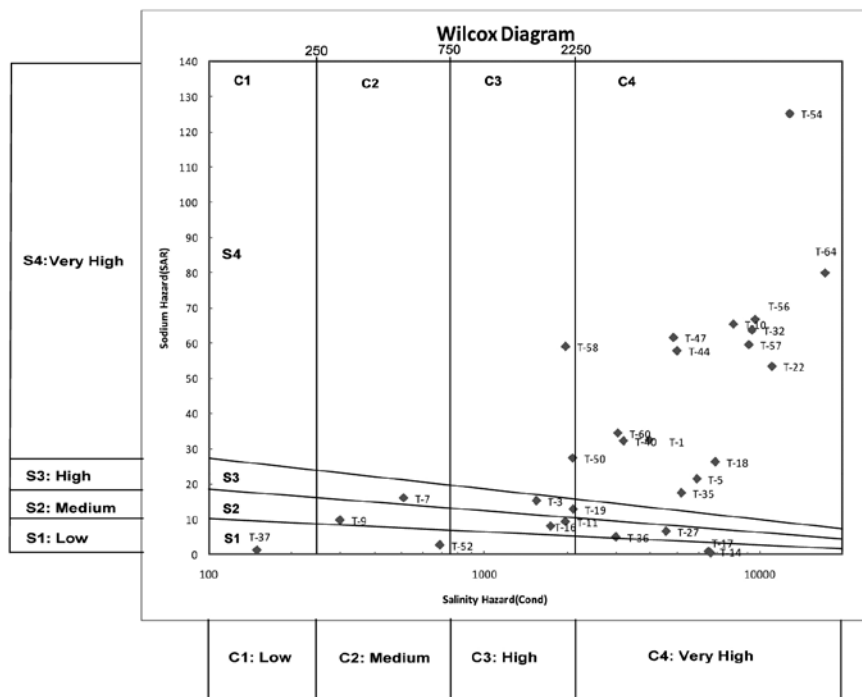


Figure 5. Wilcox diagram of the groundwater samples in the study area.

1953). Water from well nos. T-10 and T-11 are showing medium salinity and low sodium hazard and can be used for drinking purpose. The well nos. T-16, T-19 and T-52 are showing high salinity and low sodium hazard and this kind of water cannot be used for drinking purpose. The most important finding is from well nos. T-1, 3, 18, 36, 40 and T-60 which show very high salinity and medium sodium hazard and such type of waters cannot be used for

drinking purpose. The study reveals very high salinity and low sodium hazard at well nos. T-14, 17 and very high salinity and high sodium hazard at well T-35, medium salinity and sodium hazard at well T-9 and 27, medium salinity and high sodium hazard at well T-7. Wells T-50 and 58 are not suitable for irrigation purpose due to high salinity and very high sodium hazard. The sample no. T-37 is found only with low salinity and low sodium

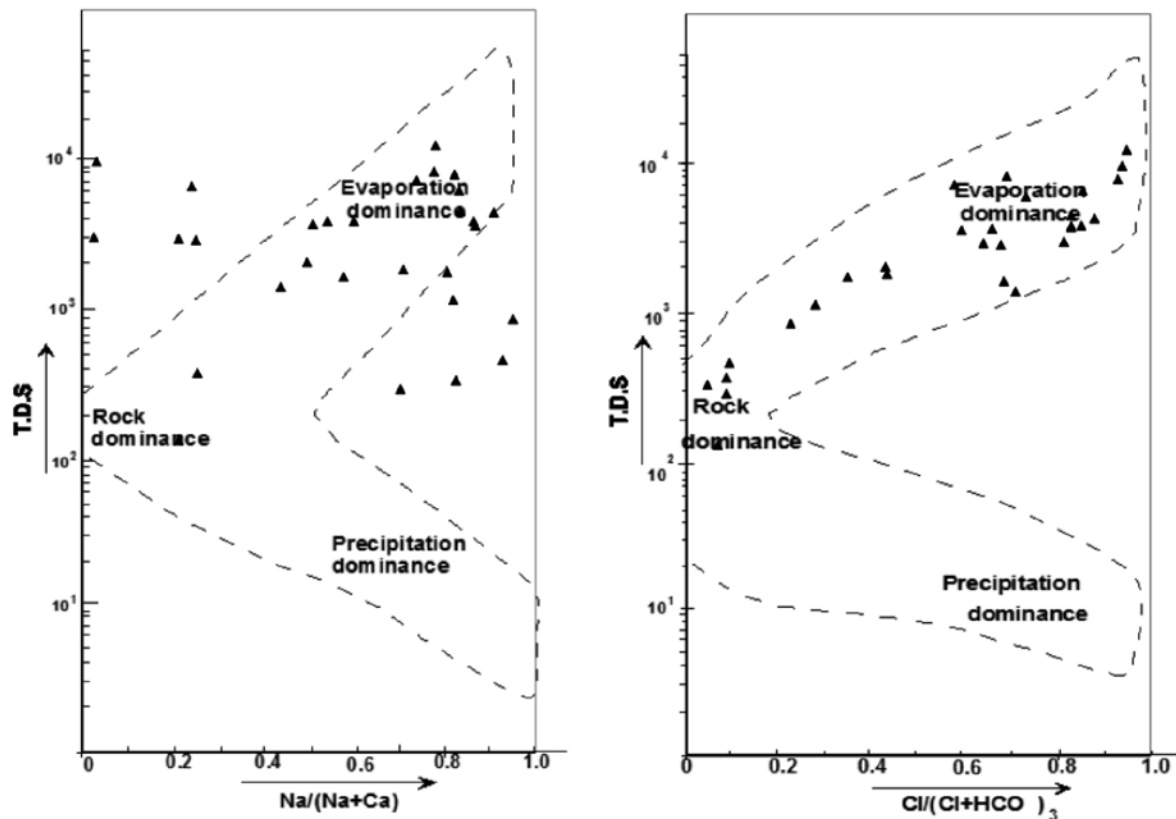


Figure 6. Gibbs diagram showing the rates of evaporation and rock dominance samples.

hazard, and this water can be used for both drinking and irrigation purposes. Water from well nos. T-5, 22, 32, 44, 47, 54, 56, 57 and T-64 are very high in both the classes and hence unsuitable for domestic as well as irrigation purpose. The study area nearby the coastal region covered by the well numbers T-44, 47, 54, 56, 57, 60, 64 (recent to sub-recent sediments) shows very high salinity due to sea water intrusion.

Mechanism controlling groundwater chemistry

Lastly, to know the groundwater chemistry and relationship of the chemical components of groundwater from their respective aquifers such as chemistry of the rock types, chemistry of precipitated water and rate of evaporation, Gibbs (1970) has suggested a diagram in which ratios of dominant anions and cations are plotted against the values of total dissolved solids (TDS), representing the ratio-I for cations $[(Na^+)/[Na^+ + Ca^{2+}]]$ and ratio-II for anions $[Cl/ (Cl + HCO_3^-)]$ as a function of TDS to assess the functional sources of dissolved chemical constituents, such as precipitation-dominance, rock-dominance and evaporation dominance. The chemical data of groundwater samples were plotted on the Gibbs diagram (Figure 6). It is found that about 38% of samples suggest chemical

weathering of rock-forming minerals and is influencing the groundwater quality by means of dissolution of rocks through which water is circulating. But 62% of samples represent evaporation dominance and most of the samples falling in the evaporation dominance are collected from dug wells in the close proximity to the sea. Evaporation makes salinity increase by increasing Na^+ and Cl^- with relation to the increase of TDS. In addition, anthropogenic activities (agricultural fertilizers) and irrigation return flows also influence the evaporation by the increasing Na^+ and Cl^- , and thus TDS.

CONCLUSIONS

In order to assess the groundwater quality in Tuticorin area of Tamil Nadu, groundwater samples had been collected and analyzed. The pH values of groundwater, in general, are slightly basic in nature (average = 7.67). The TDS values of nearly 79% of the samples exceed the upper limit of drinking water as per WHO standards. About 83% of samples are hard and very hard types with majority cations showing values above permissible limits for drinking water. The order of abundance of cations is $Na^+ > Mg^{2+} > Ca^{2+} > K^+$. Among major anions, Cl^- and SO_4^{2-} are generally dominant representing of 90% and 80%, respectively. The

order of anionic abundance is in the order of $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^- > \text{NO}_3^- > \text{F}^-$. The irrigation water quality studies show that about 90% samples fall beyond permissible limits, hence are not suitable for agricultural purpose. Based on the relative dominance of major cations and anions, different hydrogeochemical facies have been identified and majority of the samples are represented by Na-Cl and Ca-Cl₂-types of water. Quality of groundwater in the open well samples are mainly by evaporation while remaining samples are dominated by chemical weathering of rock forming minerals. The spatial variation of groundwater parameters shows increasing values of chemical parameters towards the sea in the study area.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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