

Assessing groundwater quality in lower part of Nagapattinam district, Southern India: using hydrogeochemistry and GIS interpolation techniques

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Abstract The aim of this present study was to evaluate groundwater quality in the lower part of Nagapattinam district, Tamil Nadu, Southern India. A detailed geochemical study of groundwater region is described, and the origin of the chemical composition of groundwater has been qualitatively evaluated, using observations over a period of two seasons premonsoon (June) and monsoon (November) in the year of 2010. To attempt this goal, samples were analysed for various physico-chemical parameters such as temperature, pH, salinity, Na^+ , Ca^{2+} , K^+ , Mg^{2+} , Cl^- , HCO_3^- and SO_4^{2-} . The abundance of major cations concentration in groundwater is as $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$, while that of anions is $\text{Cl} > \text{SO}_4 > \text{HCO}_3$. The Piper trilinear diagram indicates Ca– Cl_2 facies, and according to USSL diagram, most of the sample exhibits high salinity hazard (C3S1) type in both seasons. It indicates that high salinity (C3) and low sodium (S1) are moderately suitable for irrigation purposes. Gibbs boomerang exhibits most of the samples mainly controlled by evaporation and weathering process sector in both seasons. Irrigation status of the groundwater samples indicates that it was moderately suitable for agricultural purpose. ArcGIS 9.3 software was used for the generation of various thematic maps and the final groundwater quality map. An interpolation technique inverse distance weighting was

used to obtain the spatial distribution of groundwater quality parameters. The final map classified the ground quality in the study area. The results of this research show that the development of the management strategies for the aquifer system is vitally necessary.

Keywords GIS · Interpolation · Groundwater quality · IDW · Nagapattinam · Hydrogeochemistry

Introduction

Groundwater quality is mainly affected by the geological formations that the water passes through its course and by anthropogenic activities (Kelepertsis 2000; Siegel 2002; Stamatis 2010; Sullivan et al. 2005). In some cases, natural water may contain elevated concentrations of several potentially toxic elements or microbiological contaminants that may lead to adverse effects on human health (De Figueiredo et al. 2007; Kelepertsis et al. 2006; USEPA 2001, 2006; WHO 2004; Yang et al. 2002). Because of the long coastline of the India and the overexploitation of groundwater, saline water intrusion has also become an important problem (Daskalaki and Voudouris 2008; Mimikou 2005; Sofios et al. 2008; Voudouris et al. 2004).

The proximity of coastal aquifer to the sea, the presence of brines and saline soils in the region, the agriculture activities and the hydraulic properties of the aquifer are also important factors which can become the sources of salinity of this aquifer. The chemical composition of groundwater is controlled by many factors that include composition of precipitation, geological structure and mineralogy of the watershed sand aquifers, and geochemical processes within the aquifer. The interaction of all factors leads to various water facies (Murray 1996;

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Rosen and Jones 1998). In this article, different maps and graphical representations are used to classify and interpret the geochemical data in terms of interpolation map of chemical parameters, Piper diagram and geochemical modelling. An appropriate assessment for the suitability of groundwater requires the concentrations of some important parameters like pH, electrical conductivity (EC), TDS, Ca^{2+} , Mg^{2+} , K^+ , Na^+ , Cl^- , HCO_3^- and SO_4^{2-} compared with the guideline values set for potable water (WHO 1996). Poor quality of water adversely affects the human health and plant growth (WHO 2004; Nag and Ghosh 2013). The importance of water quality in human health has recently attracted a great deal of interest. In developing countries like India, around 80 % of all diseases are directly related to poor drinking water quality and unhygienic conditions (Olajire and Imeokparia 2001; Prasad 1998; David et al. 2011; Limbachiya 2011; Kaveh Pazand and Ardeshtir Hezarkhani 2013, Khadri et al. 2013). In general, the assessment of water quality criteria is based on the consideration of physicochemical properties of the soil and the impact on crop yield. Numerous publications have reported that urban development and agricultural activities directly or indirectly affect the groundwater quality (Giridharan et al. 2008; Mohsen 2007; Kumar et al. 2006; Tatawat and Singh Chandel 2008; Fantong et al. 2009; Ramkumar et al. 2011; Kim et al. 2012).

In the recent years, due to heavy pumping of groundwater especially in summer seasons, the reversal of groundwater flow results in sea water intrusion in the inlands along the coastal belt and consequently making the bore well as well as the open well water unfit for crop production and drinking. The hydrogeochemical study with GIS reveals the zones where the quality of water is suitable for drinking, agricultural and industrial purposes. In any area around the world, groundwater quality and risk assessment maps are important as precautionary indicators of potential risk environmental health problems. GIS has been widely used in risk mapping (Daniela 1997; Bartels and Beurden 1998; Hong and Chon 1999; Anbazhagan and Nair 2005; Singh and Lawrence 2007; Singh et al. 2007; Rahman 2008; Mimi and Assi 2009; Khalifa and Arnous 2010; Arnous et al. 2011; Ghodeif et al. 2011; Babiker et al. 2007; Machiwal et al. 2011). The use of maps is common practice in earth-related sciences in order to evaluate the evolution of physical phenomena and predict natural variables as well as assess the risk regarding surface and groundwater contamination in waste disposal industrial and other sites (Xenixd et al. 2003; Gnanachandrasamy et al. 2012).

The principal benefit of geographical information system (GIS) to modelling environmental issues is their ability to deal with large volumes of diverse, spatially oriented

data that geographically anchor processes occurring a cross-space and time. GIS is an effective tool for storing large volumes of data that can be correlated spatially and retrieved for the spatial analysis and integration to produce the desirable output. GIS has been used by scientists of various disciplines for spatial queries, analysis and integration for the last three decades (Burrough and Donnell, 1998; Anbazhagan and Nair 2005). A number studies were conducted to determine potential sites for groundwater exploration in diverse geological set-ups using remote sensing and GIS techniques (Krishnamorthy and Srinivas 1995; Nas and Berkay 2010). Ahn and Chon (1999) investigated groundwater contamination and spatial relationships among groundwater quality, topography, geology, land use and pollution sources using GIS in Seoul, Korea. Interpolation is an estimation of Z values of a surface at an unstapled point based on the known Z values of surrounding points. There are two main interpolation techniques: deterministic and geostatistics. Deterministic interpolation techniques create a surface from measured points, based on their extent of similarity [e.g. inverse distance weighted (IDW)] or the degree of smoothing (e.g. radial basis functions). Geostatistical interpolation techniques (e.g. kriging) utilize the statistical properties of the measured points (ESRI 2001). The aim of this investigation was to provide the groundwater quality and to determine the spatial interpolation of the major physical and chemical parameters of the groundwater samples in the study area. The character of groundwater in different aquifers over space and time proved to be an important technique in solving different geochemical problems (Cheboterev 1955; Hem 1959; Back et al. 1965; Gibbs 1970; Srinivasamoorthy et al. 2005). In addition, there is a significant increase in water demand for industrial and urban uses (Sofios et al. 2008). Since the supply of safe drinking water is considered a top priority issue in coastal areas of Tamil Nadu as well as in any civilized society, the present work aims to identify the spatial and temporal variability of groundwater quality and the main hydrogeochemical processes controlling the evolution of groundwater chemistry in the study area.

Study area

Nagapattinam is a coastal district and covering a total area of 2,715.83 km². Out of the total area, around 1,261.49 km² are classified as wetland, 618.80 km² as dry land and the remaining 835.48 km² as government land. (Thamizoli et al. 2006). It is located in the longitude between 79°35'E to 79°50'E and latitude between 10° 35'N to 11°25'N with the MSL 9 m up (Fig. 1). It is situated in the Cuddalore district north, Thanjavur district west,

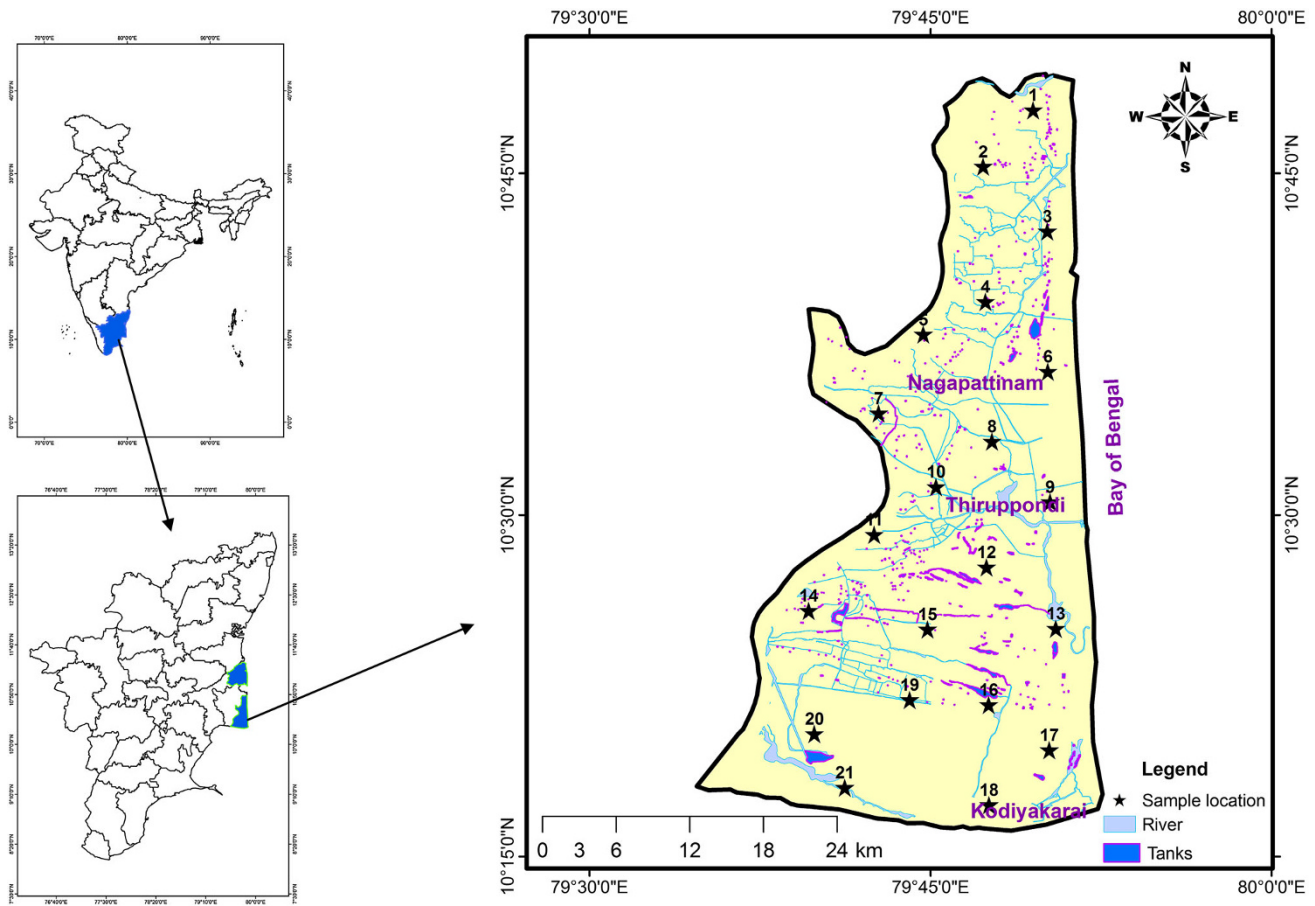


Fig. 1 Study area map

southern and western sides totally covered by Bay of Bengal. The physiographic terrain is a plain topography with gentle gradient towards the coast. Major River is Coleroon, recent formations with alluvium. Type of aquifer is fairly thick discontinuous confined fresh groundwater overlaid by saline water towards the coast with the water level ranged from 1 m to 8 m. The soil is predominantly sandy in texture and clayey in certain pockets, with slight salinity/alkalinity. The soil in the region belongs to Valudalakudi series; dark brown to brown, deep, sandy and possessing characteristics of mild-to-moderate alkalinity levels. The area lying between Nagapattinam and Vedaranyam is dominated by sand dunes, and cultivated soils are mostly sandy in texture. Regarding the water table, fresh water is overlying saline groundwater. The cultivation depends primarily on rainfall, supplemented by underground water.

The district receives rainfall under the influence of both south-west and north-east monsoon. A good part of the rainfall occurs as very intensive storms resulting mainly from cyclones generated in the Bay of Bengal especially during north-east monsoon. The area receives an average of 1,372 mm of rainfall annually; nearly 76 % occur during

the north-east monsoon, followed by 17.3 % during the south-west monsoon. The rainfall pattern in the district shows interesting features. Annual rainfall, which is 1,500 mm at Vedaranyam, the south-east corner of the district, rapidly decreases to about 1,100 mm towards west of the district. The district enjoys humid and tropical climate with hot summers, significant to mild winters and moderate to heavy rainfall. The temperatures vary from 40.6 to 19.3° C with sharp fall in night temperatures during monsoon period. The relative humidity ranges from 70 to 77 %, and it is high during the period of October to November.

Materials and methods

Groundwater sampling and measurement premonsoon and monsoon samples were collected from 21 locations (Fig. 1). The GARMIN GPS was used to locate the exact coordinates of the sample collection to continuous monitoring purposes. Groundwater samples were collected from 21 hand pumps during premonsoon (June) and monsoon (November) in the year of 2010. Methods of collection and

analysis of water samples followed are essentially the same as given by (APHA 1998). Samples were collected in one-litre capacity polyethylene bottles. Prior to the collection, bottles were thoroughly washed with diluted HNO₃ acid and then with distilled water in the laboratory before filling bottles with samples. Each bottle was rinsed to avoid any possible contamination in the bottling, and every other precautionary measure was taken. Calcium (Ca²⁺) and magnesium (Mg²⁺) were determined titrimetrically using standard EDTA. Chloride (Cl⁻) by standard AgNO₃ titration and bicarbonate (HCO₃⁻) concentration were determined by acid titration of 0.02 N H₂SO₄. Sodium (Na⁺) and potassium (K⁺) were determined by flame photometry (ELCO CL361). Sulphate (

SO₄²⁻

) was determined by spectrophotometer. Electrical conductivity (EC), pH and TDS measurements were performed in situ with portable meter. The analytical precision for ions was determined by the ionic balances calculated as $100 \times (\text{cations} - \text{anions}) / (\text{cations} + \text{anions})$, which is generally within $\pm 10\%$. The equipment and instruments were tested and calibrated with calibration blanks and series of calibration standards as per specifications outlined in standard methods of water (APHA et al. 1998). A computer program WATCLAST in C++ was used for calculation and graphical representation of Gibbs and USSS diagrams (Chidambaram et al. 2003). Total hardness (TH) was calculated by the following equation (Raghunath, 1987) $\text{TH} = (\text{Ca} + \text{Mg}) \times 50$ where TH is expressed in meq/L, and the concentrations of the constituents are expressed in meq/L.

The sodium adsorption ratio (SAR)

The sodium adsorption ratio (SAR) was calculated by the following equation given by Richards (1954) as:

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}}$$

Accordingly, if the several dissolved constituents are measured in terms of percentage of reacting values, then this is, according to their “equivalents per million”, expressed as a percentage of the sum of the equivalent for the entire constituent. The concentrations of any constituent in equivalents per million (milligram equivalent per kilogram) are computed by multiplying its concentrations in parts per million by the reciprocal of the combining weight. The subtotals of the cations and anions are necessarily each 50% of the whole. Rockwork (ver 15) was used to correlate the mixing proportion identified by the Piper diagram along with the original sample.

Geographical information system and mapping

In the present study, the base map was prepared using Survey of India Toposheet nos. 58N/13, 14, and 15 on 1:50,000 scale. The analytical results were entered as an attribute of the groundwater sample location in Arc GIS software. The ability of GIS to integrate spatial data from different sources with different formats, structures, projections or levels of resolution is a powerful aid in spatial analysis. GIS is not only a digital store of spatial objects (points, lines and areas), but is also capable of spatial analysis based on the interactions between these objects, including the relationships between objects defined by their location and geometry. In addition, the features of GIS include the support for the transfer of data to and from analytical packages. Analytical data can be used for the classification of water for utilitarian purposes, solving problems of saline water intrusion or ascertaining various factors on which the chemical characteristics of water depend. Geographical information system (GIS) software utilities are used to spatially represent data sets for the purpose of generating maps and making spatial comparisons of data. Arc GIS spatial analyst was the primary tool used to produce maps that aided analysis. The maps spatially integrated and the analytical results of hydrological parameters show the study area water quality. The spatial analysis of various physico-chemical parameters was carried out using the ArcGIS 9.3 software. In order to interpolate the data spatially and to estimate values between measurements, an IDW algorithm was used. The IDW technique calculates a value for each grid node by examining surrounding data points that lie within a user-defined search radius (Burrough and Mc Donnell 1998; Sarath prasanth et al. 2012). All of the data points are used in the interpolation process, and the node value is calculated by averaging the weighted sum of all the points (Table 1).

Results and discussions

Hydrogeochemistry

Electrical conductivity is a parameter related to total dissolved solid (TDS). The importance of TDS and EC lies in their effect on the corrosivity of a water sample and their effect on the solubility of slightly soluble compounds such as CaCO₃ (Nas 2010). According to Langenegger (1990), the importance of electrical conductivity is an indirect measure of salinity in many areas, which generally affects the taste and thus has a significance on the user acceptance of the water as potable. Majority of the sample exceeds the permissible limit in

Table 1 Water quality parameters—all values in mg/l except EC its $\mu\text{S}/\text{Cm}$

Parameters	Premonsoon			Monsoon			Drinking water standards	
	Min	Max	Avge	Min	Max	Avge	WHO 2008 mg/l	BIS mg/l
pH	7.5	8.2	7.8	7.4	7.8	7.6	6.5–8.5	6.5–8.5
EC	1,944.7	2,909.4	2,383.9	1,942.3	2,880.2	2,410.1	1,400	–
TDS	1,244.6	1,862.0	1,525.7	1,243.1	1,843.3	1,542.5	500	500–2,000
TH	963.6	1,778.6	1,229.3	1,029.9	2,056.1	1,359.9	–	300–600
Ca	115.0	312.0	205.4	124.0	355.4	227.4	75	75–200
Mg	95.2	305.4	180.1	108.0	310.0	190.1	50	–
Na	109.3	362.4	239.1	115.8	375.1	246.8	200	200–400
K	18.6	68.4	33.6	20.8	107.4	41.5	–	–
HCO ₃	101.3	315.9	207.7	107.5	324.9	219.6	300	–
Cl	312.8	591.4	448.8	255.6	576.3	398.5	500	250
SO ₄	107.4	378.2	214.7	112.3	398.6	226.6	400	200–400

Table 2 Water quality classification of based on electrical conductivity (EC) (Langenegger 1990)

Range $\mu\text{S}/\text{cm}$	Quality	Representing samples	
		Premonsoon (samples)	Monsoon (samples)
0–333	Excellent	–	–
333–500	Good	–	–
500–1,100	Permissible	–	–
1,100–1,500	Brackish	9	11
1,500–10,000	Saline	12	10

the premonsoon season as well as monsoon season sample. The classification is shown in Table 2 In the premonsoon period, maximum values of electrical conductivity values were observed in 2964.7 $\mu\text{S}/\text{cm}$ in sample no 20 and minimum electrical conductivity were observed in sample no 9 with values of 1,944.7 $\mu\text{S}/\text{cm}$ where as the monsoon season, the maximum values are 2,880.2 $\mu\text{S}/\text{cm}$ (sample no 4) and minimum values observed in sample no 9 with the values of 1,942.3 $\mu\text{S}/\text{cm}$. The spatial distribution map of the electrical conductivity in the study area is shown in Fig. 2b.

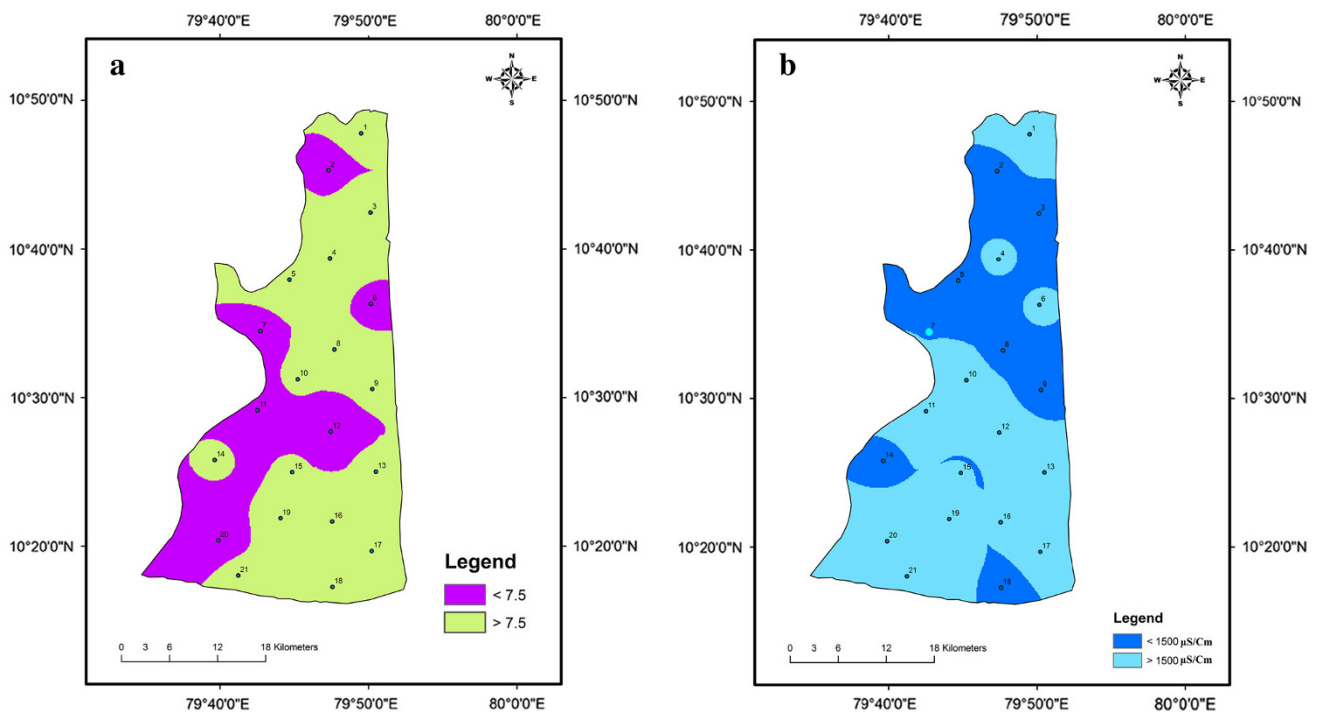


Fig. 2 a Spatial distribution map of pH b spatial distribution map of EC

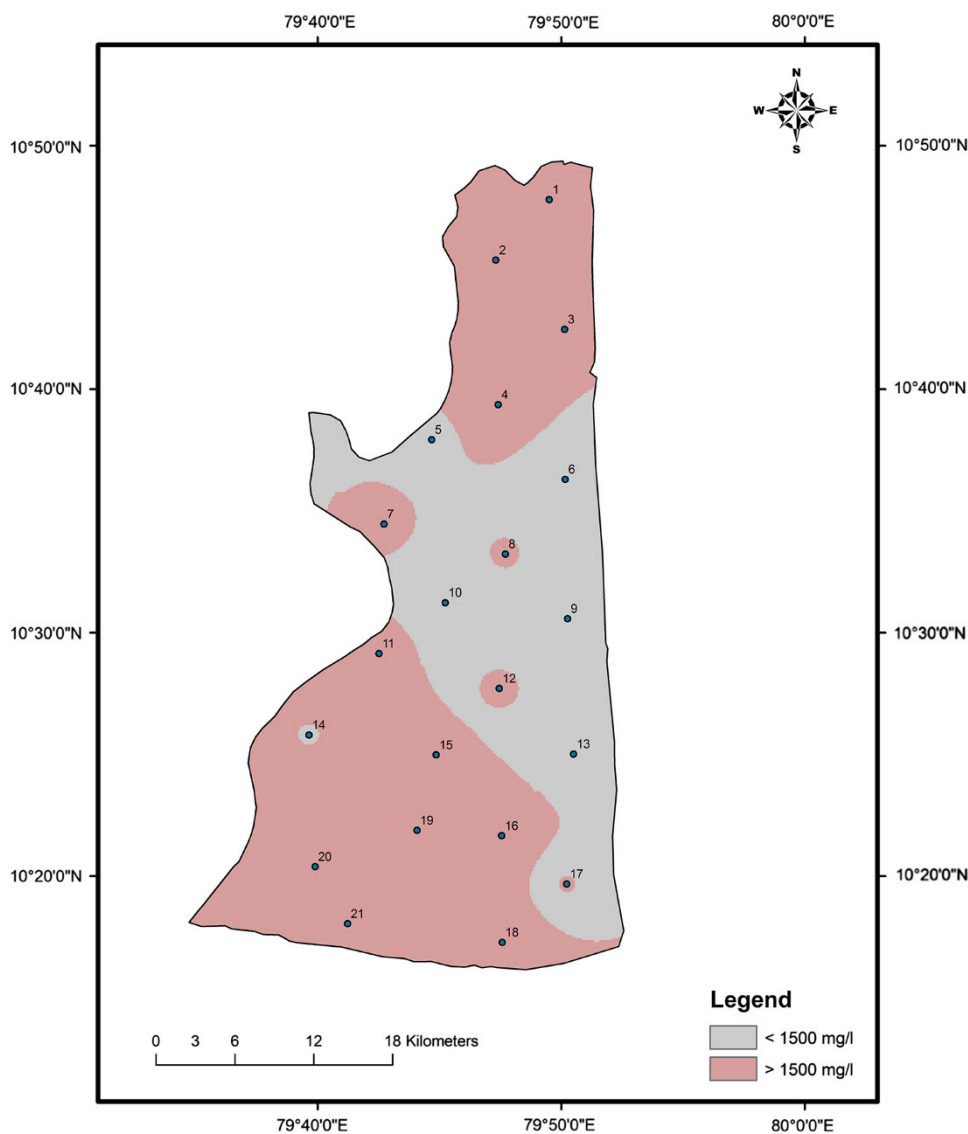
Total dissolved solid is an important parameter in drinking water and other water quality standards. (Caroll 1962) proposed four classes of water based on TDS values (Table 3). Total dissolved solid denotes the various types of minerals present in water in dissolved form. In natural waters, dissolved solids are composed of mainly carbonates, bicarbonates, chlorides, sulphate, phosphate, silica, calcium, magnesium, sodium and potassium. In the study

Table 3 Water quality classification based on TDS (Caroll 1962)

TDS in mg/l	Water quality	Premonsoon	Monsoon
0–1,000	Freshwater	5	3
1,000–10,000	Brackish water	16	18
10,000–100,000	Salty water	–	–
>100,000	Brine water	–	–

area, majority of the TDS in the study area falls above the 1,000 mg/l and also classified as brackish water. Based on the (WHO 2004) standards in some locations of the monsoon, values fall within the permissible limit. In the study area, TDS values ranged from 1,243.1 to 1,862.0 mg/l. The maximum values 1,862.0 mg/l are observed in location 19 during the premonsoon season, whereas in the monsoon season, the values ranged from 1,243.1 to 1,843.1 mg/l with an average of 1,542.5 mg/l. During the study period, the minimum value (1,243.1 mg/l) was observed in sample no 9. In the coastal tract, the reason for increased level of total dissolved solid is not only saline water intrusion into the coastal aquifers, sometime deep water condition dissolution of rock in ion particle mixed with freshwater, increasing the total dissolved solid in groundwater (Freeze and Cherry 1979). Fig. 3 shows a spatial distribution map of total dissolved solid. In spatial distribution maps,

Fig. 3 Spatial distribution map of TDS



majority of the location is above the desirable limit. The reasons for increasing total dissolved solid in these areas are very close to the Bay of Bengal.

Hydrogeochemical facies

Hydrogeochemical facies interpretation is a useful tool for determining the flow pattern and origin of chemical histories of groundwater, and it is used to express similarity and dissimilarity in the chemistry of groundwater samples based on the dominant cations and anions (Piper 1953). This diagram is an effective tool in suggesting analysis data with respect to sources of the dissolved constituents in groundwater and modifications in the character of water as it passes through an area and related geochemical problems. The Piper diagram in Fig. 4 consists of three distinct fields, two triangular fields and a diamond-shaped field. The percentage equivalents per mole (epm) values are used for the plot (Todd 1980). The overall characteristic of the water is represented in the diamond-shaped field by projecting the position of the plots in the triangular fields. Different types of groundwater can be distinguished by their plotting position, occupying certain sub-areas of the diamond-shaped field. Piper trilinear plots were made for the sample collected during premonsoon and monsoon seasons. The Piper trilinear diagram is one way of comparing quality of water. Rockworks software is used for the plotting of Piper trilinear diagrams. The analytical values obtained from the groundwater samples are plotted on Piper trilinear diagram to understand the hydrochemical regime of the study area, which clearly explains the variations of cation and anion concentration in the study area.

The geochemical evolution can be described from the Piper plot, which has been divided into six sub-categories viz. (1) Ca–HCO₃ type, (2) Na–Cl type, (3) mixed Ca–Na–HCO₃ type, (4) mixed Ca–Mg–Cl type, (5) Ca–Cl type and (6) Na–HCO₃ type. In the premonsoon and monsoon season, majority of the samples fall in Ca–Na–Mg facies followed by Cl–SO₄ facies. The Piper trilinear diagram both premonsoon and monsoon season representation shows most groundwater samples fall in Ca–Cl₂ water type. This type of result was observed Galivindo et al. (2007). High sodium waters can be explained by the combination of dilution factors, ion exchange and sulphate reduction (Krothe and Oliver 1982). This supports the premise that shallow groundwater is evolved or derived from adjacent waters in deeper aquifers. Just as water, moving along the flow path in deeper groundwater, evolves into the adjacent facies through groundwater–rock interactions and mixing with waters derived from recharge in different geologic settings, it does the same during upward migration. Some of the samples appear more transitional and plot with more similarity to physically adjacent deeper geochemical facies.

Mechanism controlling the groundwater geochemistry

The Gibbs diagram can evaluate the hydrochemistry of groundwater in the study area. Mechanism controlling groundwater geochemistry a reaction between groundwater and aquifer minerals has a significant role in water quality which is useful to understand the genesis of water (Gibbs 1970; Subramani et al. 2009; Vasanthavigar et al. 2012). Majority of the samples irrespective of the formation falls in

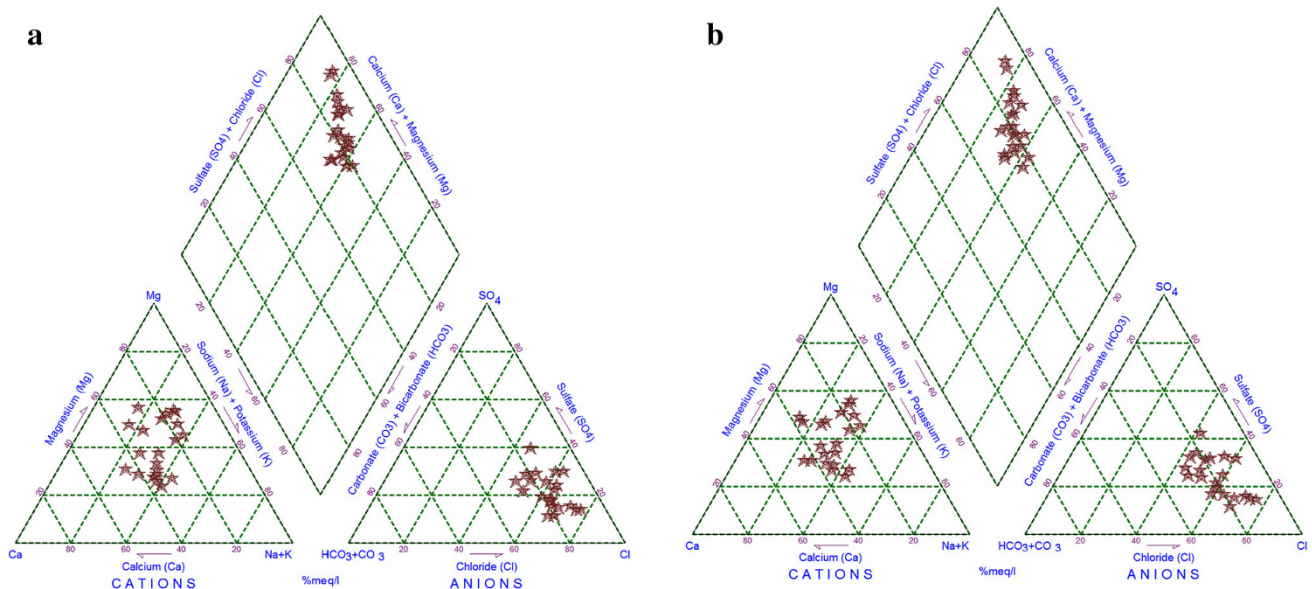


Fig. 4 a Premonsoon groundwater samples plotted in piper trilinear diagrams, b monsoon groundwater samples plotted in Piper trilinear diagrams

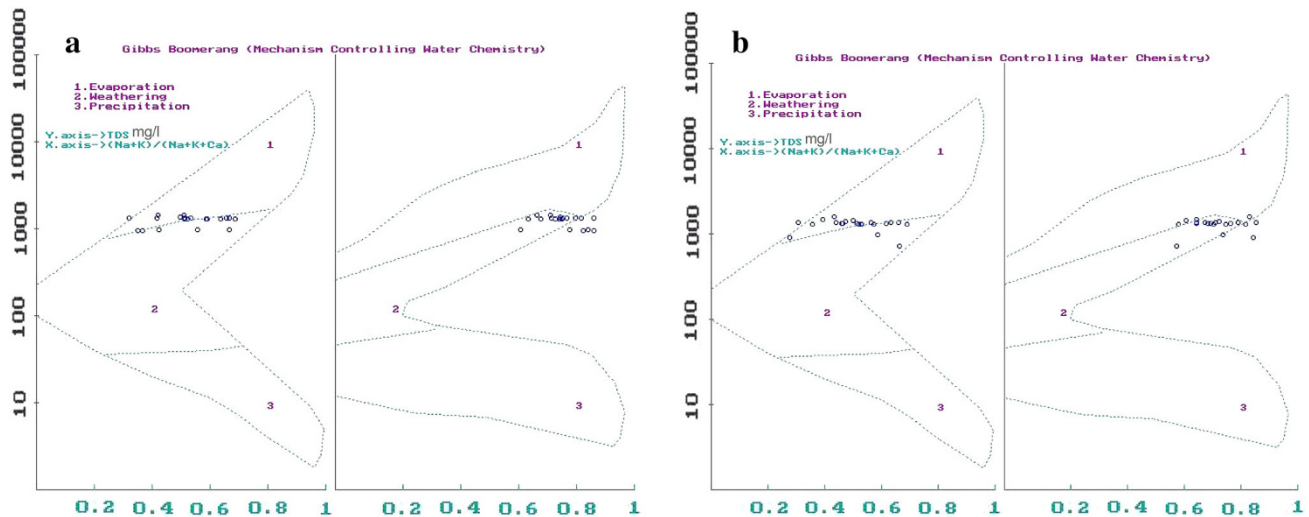


Fig. 5 Mechanism controlling groundwater geochemistry (a) premonsoon and (b) monsoon seasons

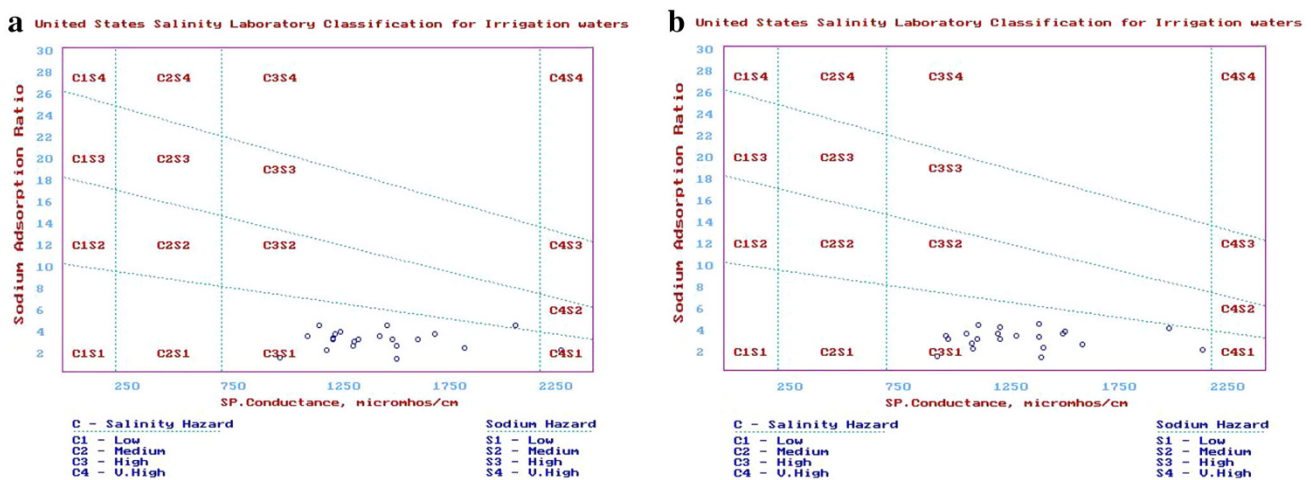


Fig. 6 USSSL-based classification of water (a) premonsoon (b) monsoon

the rock weathering region. The samples falling in rock weathering zone may be due to the chemical weathering with the dissolution with rock forming minerals. The samples falling outside the plot preview may be due to the process of anthropogenic activities (Chidambaram et al. 2008; Srinivasamoorthy et al. 2008). The chemical data of premonsoon and monsoon ground samples of the study area were plotted in Gibbs diagram (Fig. 5a, b). It is represented by plotting the ratios of (1) $\text{Na}^+ + \text{K}^+ / \text{Na}^+ + \text{K}^+ + \text{Ca}^{2+}$ and (2) $(\text{Cl}^- / \text{HCO}_3^- + \text{Cl}^-)$ against TDS. The total enveloping curve for the chemistry of the water of the globe after Gibbs had demarcated by the continuous line. The region of lowed TDS represents precipitation as the main factor for their chemistry and that of extreme concentration of TDS for the evaporation dominance. Weathering dominant (rock dominance) zone represents the intermediate region. From the Fig. 5a, b, it is indicated that the almost all

the samples were in the border of evaporation dominance to weathering dominant zone. Hence, the weathering was one of the significant factors for the chemistry of the study area. It indicates the interaction between rock chemistry and the percolating water into the subsurface. The dominance of NaCl also indicates the partial influence of sea water into groundwater. Based on Gibbs' ratio, water samples from premonsoon and monsoon seasons fall in the rock dominance sector. The diagram suggests that chemical weathering of the rock forming minerals is the main processes which contribute the ions to the groundwater.

Sodium adsorption ratio (SAR)

Irrigation water is classified based upon the sodium adsorption ration (SAR) and electrical conductivity (EC). The SAR indicates the relative proportion of sodium to

calcium + magnesium. In general, the classification of positively charged ions, especially of sodium, is more important than others. High concentrations of sodium, both in absolute and in relative terms, make water unsuitable for irrigation. If water is used for irrigation is high in sodium and low in calcium, the cations exchange complex may become saturated with sodium. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected. Salinity of groundwater and SAR determine its utility for agricultural purposes, and salinity originates in groundwater due to weathering of rocks and leaching from topsoil, anthropogenic sources along with minor influence on climate (Tijani 1994). Based on SAR classification by Richards (1954) shows the USSL diagram for premonsoon and monsoon season groundwater samples fall in C3S1 category with high salinity (C3) and low sodium (S1) hazard. In this study, most of the samples were in the high salinity and low sodium hazard, but one sample during premonsoon season was in the C4S1 type. It indicates very high salinity (C4) and low sodium hazard (S1). The sample was falling in the high salinity and low sodium hard can be used for irrigation with proper drainage. So the groundwater during the monsoon was permissible for irrigation than that of premonsoon season. In place of rigid limits of salinity for irrigation, water quality is commonly expressed by classes of relative suitability. High salinity water C3 cannot be used on soils which restricted drainage. The study reveals that most of the samples are poor category for irrigation and some of the samples moderately suitable for irrigation purposes. Such areas need special attention as far as irrigation is concerned. Since the diagram for maximum conductivity is 2,909 $\mu\text{S}/\text{cm}$, Fig. 6 shows the USSL classification water quality depends on the salinity and alkalinity.

Spatial interpolation of groundwater

Applications of GIS are varied and support natural resources management, disaster management, planning and development, environmental management, land and water management, ocean and marine research, climate change and many other areas where people and society are involved. Groundwater quality gives a clear picture about the usability of the water for different purposes. There are specific standards for quality of water for various uses. Drinking water should satisfy many quality criteria as it is the most sensitive among different purposes.

Groundwater quality has been classified on the basis of physical and chemical parameters and to compare with World Health Organization (WHO 2004) and Bureau of Indian Standards (BIS). It has been found that majority of the samples show chloride (Cl^-), values above desirable limits. The values were plotted in the respective sample

locations, and contours were generated using the method of IDW interpolation techniques. The process estimates point values between sampled locations in a grid using an inverse distance weighing of nearby sample points and allowing for variance of each sample (Isaaks and Srivastava 1989). Water quality maps were generated for chloride in the study area showing areas falling under undesirable limits, and in some areas, TDS values fall under desirable limits according to World Health Organization (WHO) 2004. Using chemistry as a tool to evaluate risk for sea water

Table 4 Categorization and rank assigned for thematic layers

S.No	Thematic layers	Season	Category	Rank	Total number of polygons
1	EC	Premonsoon	<1,000	2	6
			>1,000	1	
		Monsoon	<1,000	2	7
			>1,000	1	
2	TDS	Premonsoon	<1,000	2	9
			>1,000	1	
		Monsoon	<1,000	2	5
			>1,000	1	
3	Calcium	Premonsoon	<200	2	5
			>200	1	
		Monsoon	<200	2	6
			>200	1	
4	Magnesium	Premonsoon	<150	2	3
			>150	1	
		Monsoon	<150	2	6
			>150	1	
5	Sodium	Premonsoon	<200	2	4
			>200	1	
		Monsoon	<200	2	4
			>200	1	
6	Chloride	Premonsoon	<500	2	3
			>500	1	
		Monsoon	<500	2	4
			>500	1	
7	Sulphate	Premonsoon	<250	2	2
			>250	1	
		Monsoon	<250	2	2
			>250	1	

Table 5 Weights assigned for different groundwater quality map

S.NO	Parameter	Weight
1	EC, TDS, calcium, magnesium, sodium, chloride, sulphate good in premonsoon and monsoon season	50 (D)
2	EC, TDS, calcium, magnesium, sodium, chloride, sulphate bad in premonsoon and monsoon season	30 (UD)

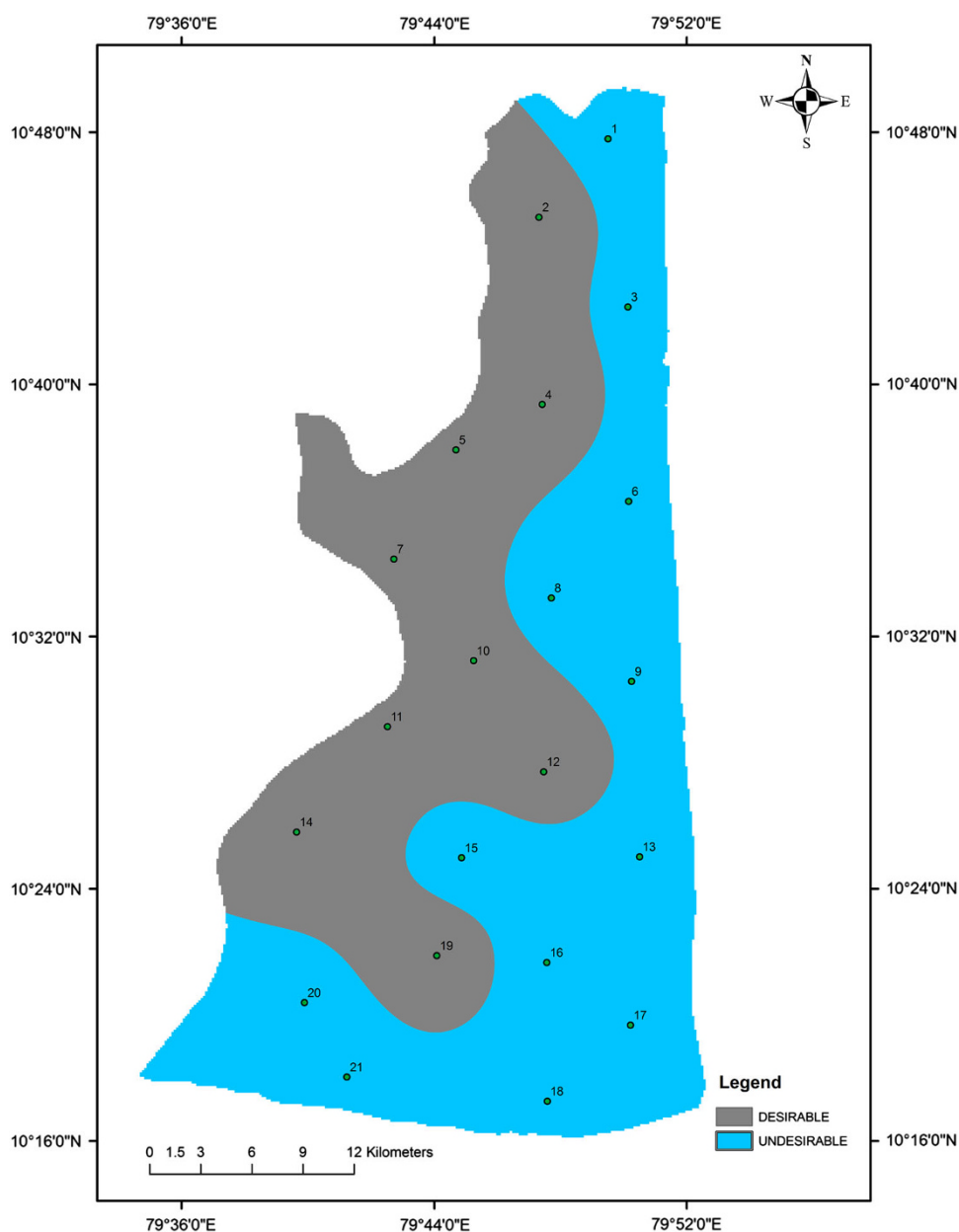
D desirable, UD undesirable

intrusion may show intrusion is occurring (excluding the problems with false positives discussed previously), but it cannot evaluate whether intrusion is likely to occur in the future. In essence, chemistry is not a predictive tool; it cannot predict that intrusion will occur in the future. Instead, chemistry is a reactive tool, capable only of reacting to intrusion once it begins to occur, and in some cases too late to prevent significant degradation of groundwater quality. The plan for the over-exploitation of coastal groundwater resources is based on the examination of the present and the future balance between the water supply and the water needs. The development perspectives of the area are focused on the agricultural field, and its perspectives are directly connected and emphasize the

importance of the prompt and rational exploitation plan of the study area's water resources.

In the present study, attempts were made to develop a suitable GIS-based integration model for delineating groundwater quality zones. This was achieved by integrating different thematic layers, which have direct control on groundwater quality. There are two types of integrated outputs obtained using the (1) water quality data and (2) hydrogeochemical thematic layers. To classify the different groundwater quality zones, the overlaid premonsoon and monsoon season water quality thematic layers of calcium, magnesium, sodium, chloride, sulphate, electrical conductivity and TDS were used. As discussed, each one of the classes in the thematic layers was qualitatively placed into

Fig. 7 Final groundwater quality map

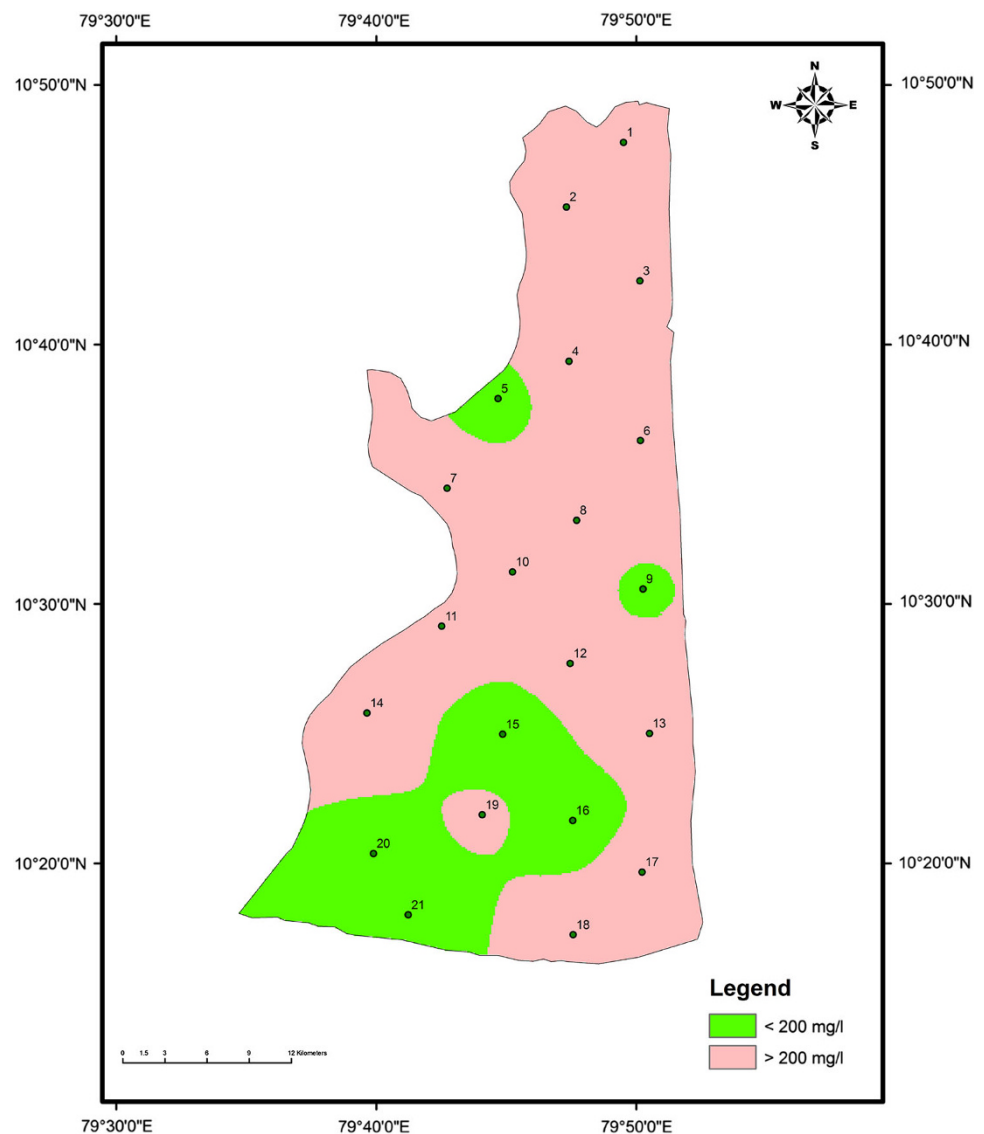


one of the categories such as desirable and undesirable with respect to drinking water quality (WHO 2008 and BIS 2000) standards. After understanding their nature with respect to groundwater quality, the different classes were made. They were assigned with suitable weights, depending upon their importance with respect to other classes in the same thematic layers. To demarcate the different groundwater quality zones, all the thematic layers were integrated with the one another through GIS using the weighted aggregation method. As per this method, the total weights of the final integrated polygons were derived as sum or product of the weights assigned to the different layers based on suitability. The categorization and the rank assigned with respect to concentration for each thematic layer are shown in the Table 4.

Integrated output of overlaid premonsoon and monsoon thematic layers of different parameters were reclassified

into two categories and assigned ranks. Table 5 shows weight assigned for different groundwater quality parameters and categories. According to water quality standards (WHO 2008 and BIS 2000), the final water quality map was classified as desirable ($EC < 1,000$, $TDS < 1,000$, $Ca < 200$, $Mg < 150$, $Na < 200$, $Cl < 500$, $SO_4 < 250$) and undesirable ($EC > 1,000$, $TDS > 1,000$, $Ca > 200$, $Mg > 150$, $Na > 200$, $Cl > 500$, $SO_4 > 250$). The groundwater quality map (Fig. 7) was produced by overlapping of the all thematic layers. Based on this final output, water quality maps of the eastern, northern and southern part of the area indicate the poor quality of the groundwater. In addition, most of the water wells have poor water quality for drinking purpose and it may be attributed to the dissolution of evaporated minerals as the region is close to the sea and large number of salt pans were in operation.

Fig. 8 Spatial distribution map of Ca



Calcium and magnesium

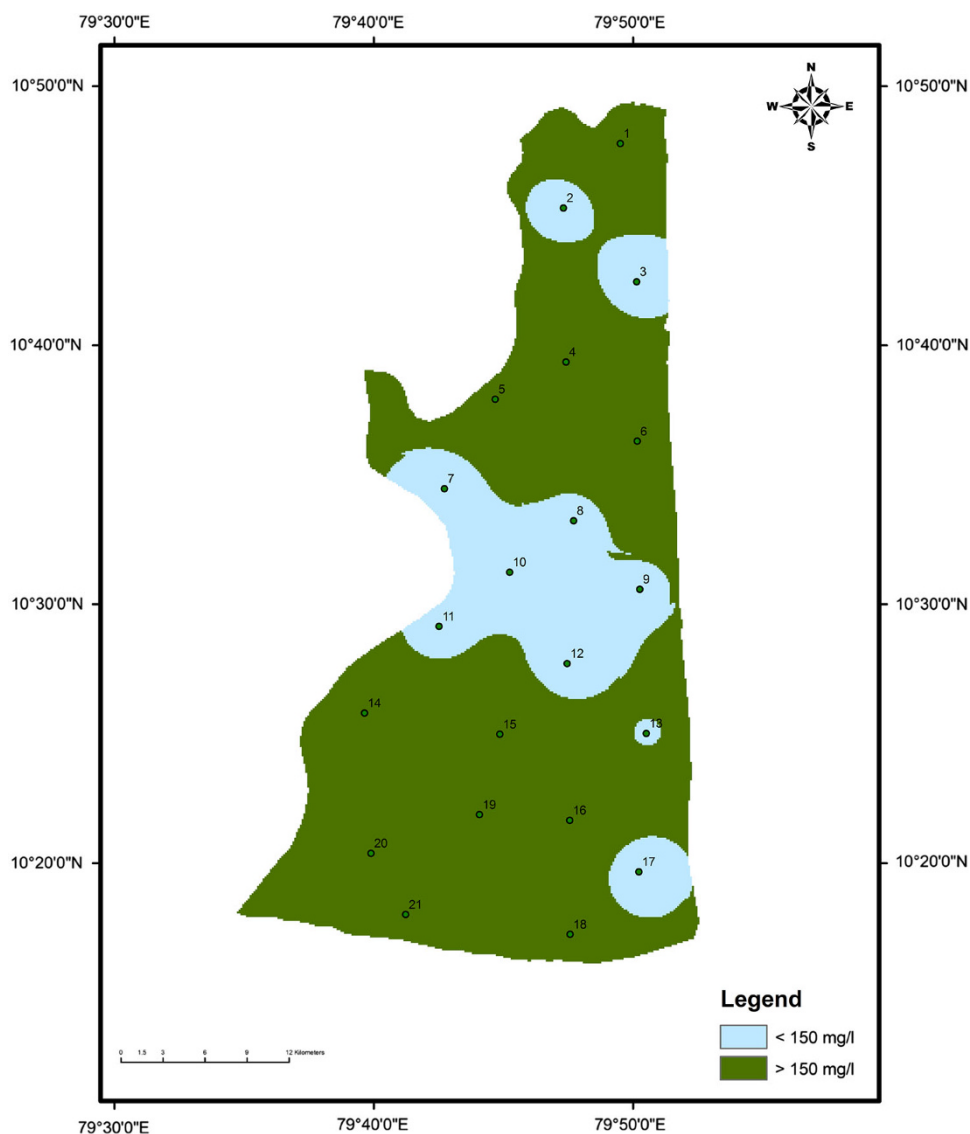
The analytical data showed that the concentration of calcium in the water samples during the study period ranged from 115.0 to 355.4 mg/l. Monsoon season recorded the maximum concentration. Premonsoon season, it ranged from 115.0 to 205.4 mg/l (sample no 5 and 2) with an average value of 205.4 mg/l and during the monsoon season, it ranged from 124.0 to 355.4 mg/l (sample no 15 and 4). In general, calcium concentration fluctuated all through the study period. Fig. 6 shows spatial diagram of calcium in study area. Calcium and magnesium are known to occur naturally in water due to its passage through mineral deposits and rock strata and contribute to its total hardness. This was observed from Karavoltzos et al. (2008) who studied evaluation of the drinking water in region Greece. The concentration of magnesium observed during the study period ranged from 95.2 to 310.0 mg/l. The highest

concentration of magnesium was observed during monsoon season. The spatial distribution map is shown in Figs. 8 and 9. The values fluctuated all through the study period. In general, the source of magnesium in the groundwater is the lime deposits, marine deposits and fossilized area and if water close to saturation in terms of calcite and dolomite, it is considered the dissolution of gypsum adds calcium to the water and causes calcite precipitation leading to a decrease in the concentration of bicarbonate. The reason for the increase in magnesium in cultivated land is the use of $MgSO_4$ as a fertilizer, which may lead to return flow into well water (Kelly et al. 1996).

Sodium

The sodium and chloride are the two important parameters in the coastal areas. The Na–Cl relationships have often used to identify the mechanisms for acquiring salinity and saline

Fig. 9 Spatial distribution map of Mg



intrusions in semi-arid regions (Magaritz et al. 1981; Dixon and Chiswell 1992; Sami 1992; Jalali 2006). The high Na^+ and Cl^- contents detected in certain samples suggest the dissolution of chloride salts. The analytical data show that the concentration of water samples in premonsoon season ranged from 109.3 to 362.4 mg/l (sample no 6, Sample no 21) with an average of 239.1 mg/l, while in monsoon season, minimum value is 115.8 mg/l and maximum value is 375.1 mg/l (sample no 6 and sample no 21). In general, the sodium concentrations fluctuated in the study period. A reason for increased level of sodium is the process, where calcium and magnesium are exchanged with sodium when absorbed on the surface of the clay minerals. The study area characterized by a sedimentary environment consisting of clay minerals which may influence the exchange process a leading to increase groundwater. In the present study, sodium concentration was found to be related to alkalinity where sodium

increases chloride concentration was also increasing. When chloride decreases, sodium also decrease, indicating the influence of sea water in this region (Fig. 10).

Chloride

Chlorides occur in all natural waters in widely varying concentrations. The chloride content normally increases as the mineral content increases (Sawyer and Mccaarty 1978). The chloride ion is the most predominate natural form of the element chlorine and is extremely stable in the water. The ranges vary between 255.6 to 576.3 mg/l for monsoon season, and premonsoon water samples ranged from 312.8 to 591.4 mg/l. A maximum chloride (591.4 mg/l) concentration was observed in premonsoon season at sample no 1. Fig. 11 shows spatial interpolation map of chloride. As per World Health Organization (WHO 2008) and Indian

Fig. 10 Spatial distribution map of Na

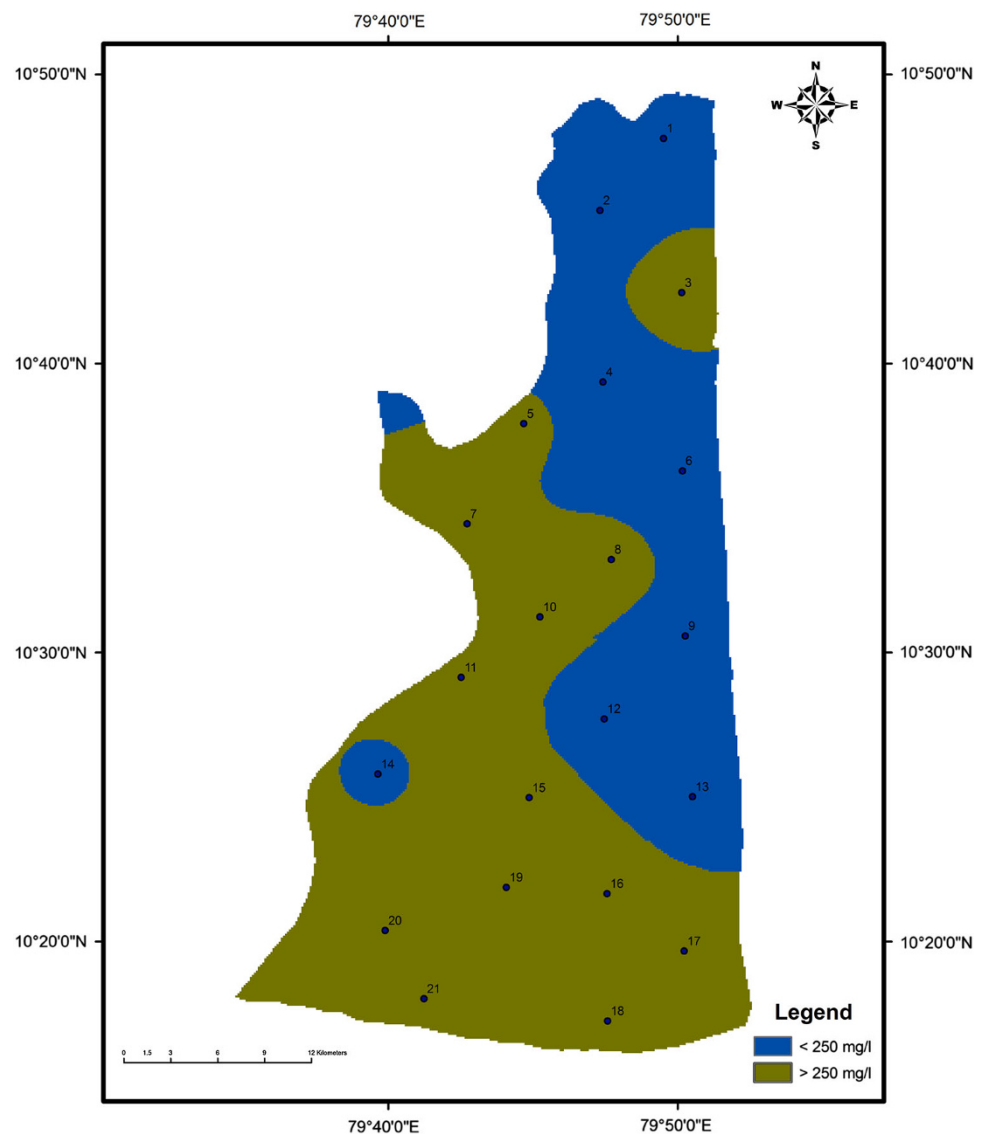
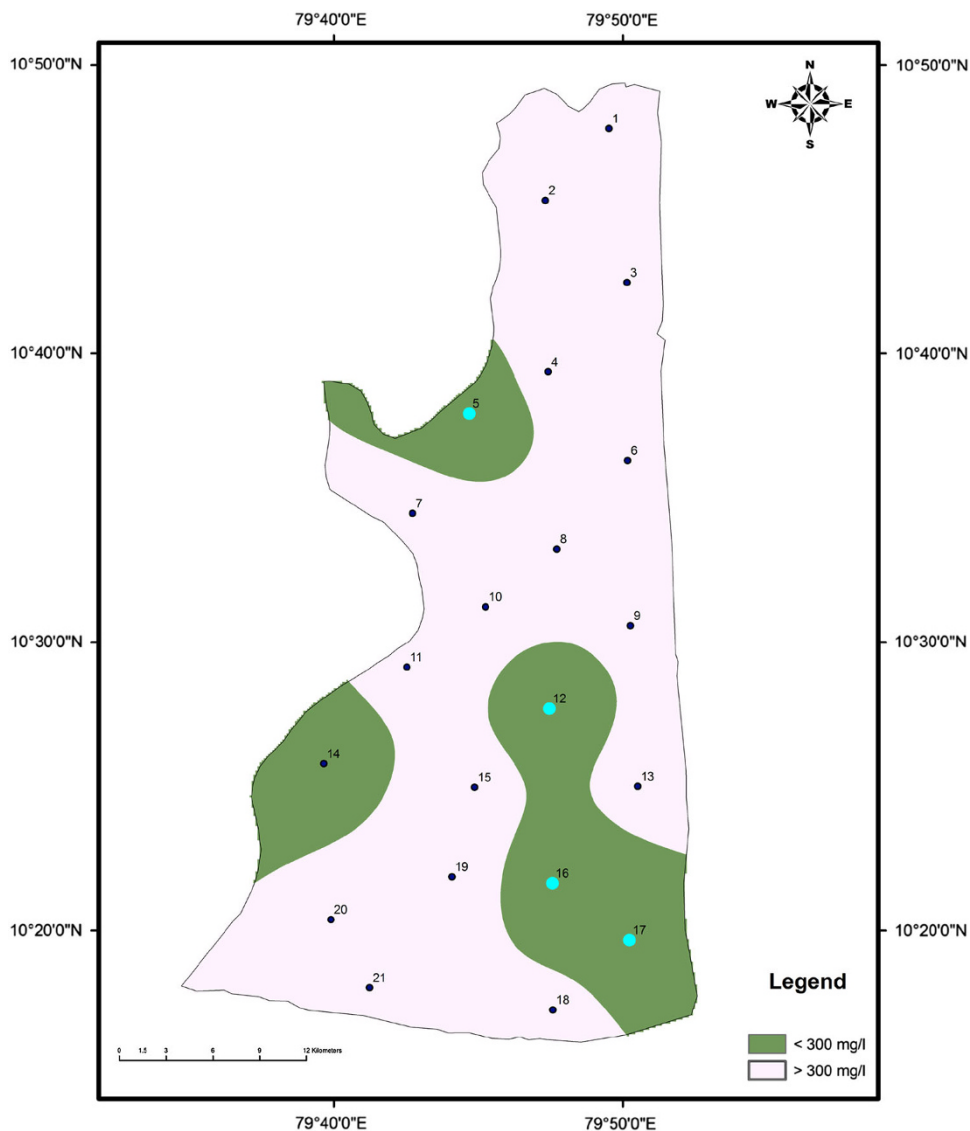


Fig. 11 Spatial distribution map of Cl



standards (BIS 2000), the desirable limit for chloride is 250 mg/l. In the study area, it has been found that in most of the locations, the chloride concentrations exceed the limit during premonsoon season. Chloride concentrations at different locations were plotted, and using the triangulation method, values were interpolated to generate thematic maps. The areas with high chloride concentrations above the desirable limit were delineated and differentiated from areas having values below the desirable limit. Weightage '1' was assigned in areas having chloride values within the desirable limit and a rank '2' for areas having chloride concentration above the desirable limit. Source of chloride originated from natural evaporite deposits of salts and brine solution. Geologically important sources of chloride are sodalite, appetite, connate water and hot springs (Freeze and Cherry 1979; Anithamary et al. 2012a, b).

Conclusion

A procedure that integrates the traditional groundwater sampling analysis methods and GIS capabilities combined with conditional overlaying techniques was adapted in order to locate the suitable areas at the lower Nagapattinam groundwater aquifer for drinking purposes. All analytical results compared with WHO, BIS standards and classified as desirable and undesirable groundwater in both seasons. The study area showed slightly saline and alkaline in nature. For the season of premonsoon, the highest concentrations of ions were observed north-east side, which indicates saline water incursion near the coastal areas. During monsoon season, the highest concentration was observed southern and western parts, indicating irrigation return flow into the coastal aquifers. The Piper trilinear diagram shows that

most of the groundwater samples fall in the field of Ca–Mg–Na facies followed by Ca–Cl₂ facies. Electrical conductivity (EC) and total dissolved solid (TDS) results show above the desirable limit. In premonsoon season, the concentration of TH was higher when compared with the monsoon season. The status of sodium and chloride ions concentration in both seasons divulges the above drinking water standards. It may be due to the influence of sea water intrusion into the coastal aquifer. To avoid these circumstances, the coastal aquifers require sustainable management in the study area. Nowadays, drilling of new deep bore holes continues in the study area to provide local supplies for public and agricultural use has to restricted or stopped. Hence, it is suggested to monitor groundwater quality on a periodic basis and plan to be worked out to prevent further deterioration of water quality.

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References

- Ahn H, Chon H (1999) Assessment of groundwater contamination using geographical information systems. *Environ Geochem Health* 21:273–289
- Anbazhagan S, Nair AM (2005) Geographic information system and groundwater quality mapping in Panvel Basin, Maharashtra, India. *Environ Geol* 45(6):753–761
- Anithamary I, Ramkumar T, Venkatramanan S (2012a) Application of Statistical Analysis for the Hydrogeochemistry of Saline Groundwater in Kodiakarai, Tamilnadu, India, *Journal of Coastal Research* 281:A89–A98
- Anithamary I, Ramkumar T, Venkatramanan S (2012b) Application of statistical analysis for the hydro geochemistry of saline ground water in Kodiakarai, Tamilnadu, India. *J Coast Res, West Palm Beach, Florida, January* 28(1A):89–98
- APHA, AWWA & WEF (1998) Standard methods for the estimation of water and waste water. American Public Health Association, Washington
- Arnos MO, Aboulela HA, Green DR (2011) Geo-environmental hazards assessment of the north western Gulf of Suez. *Egypt J Coast Conserv* 15(1):37–50. doi:10.1007/s11852-010-0118-z
- Babiker IS, Mohamed MMA, Hiyama T (2007) Assessing groundwater quality using GIS. *Water Resour Manage* 21:699–715
- Back W, Hanshaw B (eds) (1965) Chemical geohydrology advances in hydroscience. Academic Press, London, pp 49–109
- Bartels C, Beurden A (1998) Using geographic principles for environmental assessment and risk mapping. *J Hazard Mater* 61:115–124
- BIS (2000) Drinking water specification. Bureau of Indian Standards, New Delhi IS 10500
- Burrough PA, Mc Donnell RA (1998) Principles of Geographical information Systems. Oxford University Press, Oxford, p 333
- Caroll D (1962) Rainwater as a chemical agent of geological processes are view. USGS water supply. 1533:18–20
- Cheborterev II (1955) Metamorphism of natural waters in the crust of weathering-I. *Geochim Cosmochim Acta* 8:22–48
- Chidambaram S, Ramanathan AL, Srinivasamoorthy K, Anandhan P (2003) WATCLAST—A computer program for hydrogeochemical studies, recent trends in hydrogeochemistry (case studies from surface and subsurface waters of selected countries). Capital Publishing Company, NewDelhi, pp 203–207
- Chidambaram S, Ramanathan AL, Anandhan P, Srinivasamoorthy K, Prasanna MV, Vasudevan S (2008) A statistical approach to identify the hydrogeochemically active regimes in groundwaters of Erode district, Tamilnadu. *Asian J Water Environ Pollut* 5(3):123–135
- Daniela D (1997) GIS techniques for mapping groundwater contamination risk. *Nat Hazard* 20(2–3):279–294
- Daskalaki P, Voudouris K (2008) Ground water quality of porous aquifers in Greece: a synoptic review. *Environ Geol* 54:505–513
- David K, Essumang, Senu J, Fianko JR, Nyarko BK., Adokoh CK, Boamponsem L (2011) Groundwater quality assessment: a physicochemical properties of drinking water in a rural setting of developing countries. *Can J Sci Ind Res* 2:102–126
- De Figueiredo BR, Borba RP, Angelica R (2007) Arsenic occurrence in Brazilian dhumans exposure. *Environ Geochem Health* 29:109–118
- Dixon W, Chiswell B (1992) The use of hydrochemical sections to identify recharge areas and saline intrusions in alluvial aquifers, southeast Queensland, Australia. *J. Hydrology*. 130:299–338
- Dreever SA, Klir GJ (2004) Fuzzy logic in Geology. Elsevier Academic Press, Amsterdam, p 346
- ESRI (Environmental Systems Research Institute) (2001) Using Arc GIS geo statistical analyst (300p, USA)
- Fantong WY, Satake H, Aka FT, Ayonghe SN, Asai K, Mandal AK et al (2009) Hydrochemical and isotopic evidence of recharge, apparent age, and flow direction of groundwater in Mayo Tsanaga River Basin, Cameroon: bearings on contamination. *Environ Earth Sci* 60(1):107–120. doi:10.1007/s12665-009-0173-7
- Freeze RA, Cherry JA (1979) Groundwater. Prentice Hall Inc, New Jersey, p 604
- Ghodeif KO, Arnous MO, Geriesh MH (2011) Define a protected buffer zone for Ismailia Canal. *Arab J Geosci, Egypt using geographic information systems*. doi:10.1007/s12517-011-0326-3
- Gibbs RJ (1970) Mechanisms controlling world's water chemistry. *Science* 170:1088–1090
- Giridharan L, Venugopal T, Jayaprakash M (2008) Evaluation of the seasonal variation on the geochemical parameters and quality assessment of the groundwater in the proximity of River Cooum, Chennai, India. *Environmental Monitoring Assessment*. 143:161–178. doi:10.1007/s10661-007-9965-y
- Gnanachandrasamy G, Ramkumar T, Venkatramann S, Anithamary I, Vasudevan S (2012) GIS Based hydrogeochemical characteristics of groundwater quality in Nagapattinam District, Tamilnadu, India. *Carpeth J Earth Environ Sci* 7(3):205–210
- Hem JD (1959) Study and interpretation of the chemical characteristic of natural water; USGS water supply, p 269
- Hem JD (1985) Study and interpretation of the chemical characteristics of natural water, 3rd ed. Scientific, Jodhpur, p 2254
- Hong IA, Chon HT (1999) Assessment of groundwater contamination using geographic information systems. *Environ Geochem Heal* 21(3):273–289

- Isaaks EH, Srivastava RM (1989) Applied Geostatistics. Oxford University Press, New York p561
- Jalali M (2006) Chemical characteristics of groundwater in parts of mountainous region, Alvand, Hamadan, Iran. *Environ. Geology* 51:433–446
- Karavoltos S, Sakellari A, Mihopoulos N, Dassenakis M, Scoullou J (2008) Evolution of quality of drinking water in regions of Greece. *Desalination* 224:317–329
- Kaveh P, Ardeshir H (2013) Hydrogeochemical processes and chemical characteristics around Sahand Mountain, NW Iran. *Appl Water Sci* 3:479–489. doi:10.1007/s13201-013-0096-z
- Kelepertsis A (2000) Applied geochemistry (in Greek). Mache donian press, Athens, p 37
- Kelepertsis A, Alexakis D, Skordas K (2006) Arsenic, antimony and other toxic elements in drinking water of Eastern Thessaly in Greece and its possible effects on human health. *Environ Geol* 50:76–84
- Kelly J, Thornton I, Simpson PR (1996) Urban geochemistry: a study of the influence of anthropogenic activity on the heavy metal content of soils in traditionally industrial and nonindustrial areas of Britain. *Appl Geochem* 11:363–370
- Khadri Chaitanya Pande SFR, Moharir K (2013) Groundwater quality mapping of PTU watershed in Akola district of Maharashtra India using geographic information system techniques. *Int J Sci Eng Res*, Vol 4, No 9, September
- Khalifa IH, Arnous MO (2010) Assessment of hazardous mine waste transport in west central Sinai, using remote sensing and GIS approaches: a case study of UmBogma area. *ArabJ.Geosci*, Egypt. doi:10.1007/s12517-010-0196-0
- Kim TH, Chung SY, Park N, Hamm SY, Lee Kim BW (2012) Combined analyses of chemometrics and kriging for identifying groundwater contamination sources and origins at the Masan coastal area in Korea. *Environ Earth Sci*. doi:10.1007/s12665-012-1582-6
- Krishnamurthy J, Srinivas G (1995) Role of geographical and geomorphological factors in groundwater exploration: a study using IRS LISS data. *Int. J. Remote sensing* 16(4):2595–2618
- Krothe NC, Oliver JW (1982) Sulfur isotopic composition and water chemistry from the high plains aquifer, Oklahoma panhandle and south western Kansas: U.S. Geological Survey Water Resources Investigations p 28, 82–12
- Kumar M, Ramanathan AL, Rao Bhishm Kumar MS (2006) Identification and evaluation of hydro- geochemical processes in the groundwater environment of Delhi, India. *Environ Geol* 50:1025–1039. doi:10.1007/s00254-006-0275-4
- Langenegger O (1990) Ground water quality in rural areas of western Africa, UNDP project INT/81/026:10
- Limbachiya, MC, Nimavat KS, and Vyas KB (2011) Physico-chemical analysis of ground water samples of Becharji Region of Gujarat State India. *Asian J Biochem Pharm Res*, Vol. 1, No 4
- Machiwal D, Jha MK, Mal BC (2011) GIS-based assessment and characterization of groundwater quality in a hard-rock hilly terrain of western India. *Environ Monit Assess* 174(1–4): 645–663
- Magaritz M, Luzier JE (1985) Water rock interactions and seawater freshwater mixing effects in the coastal dunes aquifer. Coos bay Origin Geochem, *Cosmochim, Acta* 49:2515–2525
- Mimi Z, Assi A (2009) Intrinsic vulnerability, hazard and risk mapping for karst aquifers: a case study. *J Hydrol* 364:298–310
- Mimikou MA (2005) Water resources in Greece present and future. *Global Nest International Journal* 7:313–322
- Mohsen J (2007) Hydrochemical identification of groundwater resources and their changes under the impacts of human activity in the Chah basin in western Iran. *Environmental. Monitoring Assessment* 130:347–364
- Murray KS (1996) Hydrology and geochemistry of thermal waters in the Upper Napa Valley, California. *Ground Water* 34:1115–1124
- Nag SK, Ghosh P (2013) Variation in groundwater levels and water quality in Chhatna Block Bankura District, West Bengal—A GIS approach. *J Geol Soc India* 81:261–280
- Nas Bilgehan, Berkay Ali (2010) Groundwater quality mapping in urban groundwater using GIS, *Environ.moni. Assessment*. 160:215–227
- Olajire AA, Imeokparia FE (2001) Water quality assessment of Osun River: studies on inorganic nutrients. *Environmental Monitoring Assessment* 69(1):17–28
- Piper AM (1953) A graphical procedure in the geochemical interpretation of water analysis. *Trans Am Geophys Union* 2(5):914–928
- Prasad R (1998) Fertilizer urea, food security, health and the environments. *Curr Sci* 75:667–683
- Rahman A (2008) A GIS based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh. India. *Appl. Geogr* 28:32–53
- Ramkumar T, Venkatramanan S, Anithamary I., Mohamed Syed Ibrahim S (2011) Evaluation of hydrogeochemical parameters and quality assessment of the groundwater in Kottur blocks, Tiruvurur district, Tamilnadu, India. *Arab J Geosci*. doi:10.1007/s12517-011-0327-2
- Ran Al-Adamat, Foster IDL, Baban SMJ (2003) Groundwater vulnerability and risk mapping for the Basaltic aquifer of the Azraq Basin of Jordan using GIS, remote sensing and DRASTIC. *Appl Geogr* 23:303–324
- Richards LA (1954) Diagnosis and improvement of saline and alkali soils. U.S. Department of Agriculture, *Agriculture Handbook* 60
- Rodier J (1984) L'analyse de l'eau: eaux naturelles, eaux résiduaires, Eaux de mer. Ed. Dunod, Paris, p 1135
- Rosen M, Jones S (1998) Controls on the chemical composition of ground water from alluvial aquifers in the Wanaka and Wakatipu basins, Central Otago, New Zealand. *Hydrogeol* J6:264–281
- US. Salinity Laboratory Staff (1954) Diagnosis and improvements of saline and alkali soils. US Department of Agricultural soils. US Department of Agricultural Hand Book 60, Washington
- Sami K (1992) Recharge mechanisms and geochemical processes in a semi-arid sedimentary basin, Eastern cape, South Africa. *J. Hydrology* 139:27–48
- Sarath Prasanth SV, Magesh NS, Jitheshlal KV, Chandrasekar N, Gangadhar K (2012) Evaluation of groundwater quality and its suitability for drinking and agricultural use in the coastal stretch of Alappuzha District, Kerala, India, DOI 10.1007/s13201-012-0042-5. *Appl Water Sci* 2:165–175
- Sawyer CN, McCarty PL (1978) Chemistry for environmental engineering. New York, Mc Graw-Hill p 532
- Siegel RF (2002) Environmental geochemistry of potentially toxic metals. Springer, Berlin, p 218
- Singh DSH, Lawrence JF (2007) Groundwater quality assessment of shallow aquifer using geographical information system in part of Chennai city Tamilnadu. *J Geol Soc India* 69:1067–1076
- Singh AK, Mondal GC, Singh S, Singh PK, Singh TB, Tewary BK, Sinha A (2007) Aquatic geochemistry of Dhanbad, Jharkhand: source evaluation and quality assessment. *J Geol Soc India* 69:1088–1102
- Sofios S, Arabatzis G, Baltas E (2008) Policy for management of water resources in Greece. *Environmentalist* 28:185–194
- Srinivasamoorthy K (2005) Hydrogeochemistry of groundwater in Salem district, Tamil Nadu, India; Unpublished P.hD Thesis, Annamalai University, p 355
- Srinivasamoorthy K, Chidambaram S, Prasanna MV, Vasanthavignar M, John Peter A, Anandhan P (2008) Identification of major sources controlling Groundwater Chemistry from a hard rock terrain—A case study from Mettur taluk, Salem district,

- Tamilnadu India. *Journal of Earth System Sciences* 117(1):49–58
- Stamatis G (2010) Ground water quality of the Ag. Paraskevi Tempi valley karstic springs application of a tracing test for research of the micro-bial pollution (KatoOlympos/NE Thessaly). *Bulletin of the Geological Society of Greece* 43:1868–1877
- Subramani T, Rajmohan N, Elango L (2009) Groundwater geochemistry and identification of hydrogeochemical processes in a hard rock region, Southern India. *Environ Monit Assess*. doi:10.1007/s10661-009-0781-4
- Sullivan JP, Agardy JF, Clark JJ (2005) *The Environmental Science of Drinking Water*. Elsevier Butterworth-Heinemann, Oxford 384
- Tatawat RK, Singh Chandel CP (2008) A hydrochemical profile for assessing the groundwater quality of Jaipur City. *Environmental Monitoring Assessment* 143:337–343. doi:10.1007/s10661-007-9936-3
- Thamizoli P, Rengalakshmi R, Senthil Kumar K, Selvaraju T (2006) Agronomic rehabilitation and livelihood restoration of tsunami affected lands in Nagapattinam District of Tamil Nadu M.S. Swaminathan Research Foundation Chennai
- Tijani J (1994) Hydrochemical assessment of groundwater in Moro area. Kwarastate, Nigeria, *Environmental Geology*. 24:194–202
- Todd DK (1980) *Ground water hydrology*. Wiley & sons, New York
- USEPA (United States Environmental Protection Agency) (2006) List of drinking water contaminants and MCLs, 28 <http://www.epa.gov/safewater/mcl.html>. Accessed 31 Aug 2011
- Vasanthavigar M, Srinivasamoorthy K, Prasanna MV (2012) Evaluation of ground water suitability for domestic, irrigational, and industrial purposes: a case study from Thirumanimuttar river basin, Tamilnadu, India. *Environ Monit Assess* 184:405–420. doi:10.1007/s10661-011-1977-y
- Venkatramanan S, Ramkumar T, Anithamary I (2012) A statistical approach on hydro geochemistry of groundwater in Muthupet coastal region, Tamil Nadu, India, *Carpathian Journal of Earth and Environmental Sciences*. 7:47–54
- Voudouris K, Panagopoulos A, Koumantakis J (2004) Nitrate pollution in the coastal aquifer system of the Korinthos Prefecture (Greece). *Global Nest International Journal*. 6:31–38
- WHO (1996) *Guidelines for drinking-water quality*. 2nd ed. Vol 2: health criteria and other supporting information. World Health Organization, Geneva
- WHO (2004) *Guidelines for drinking-water quality*, world health organization (p. 515, 3rd ed.) (vol. 1) Geneva, Recommendations
- WHO (2008) *Guidelines for drinking water quality* (3rd ed.). Geneva, pp 540
- Xenixd KA, Papassiopi N, Komnitsas (2003) Carbonate rich mine tailings in Lavrion: risk assessment and proposed rehabilitation schemes. *Adv Environ Res* 7(2):207–222
- Raghunath IIM (1987) *Groundwater*, Second edition edn. Wiley Eastern Ltd., New Delhi, pp 344–369
- Yang T, Wu TN, Hsu SW, Lai CH, Ko KN, Liou SH (2002) Blood lead of primary school children in Penghu County, Taiwan: distribution and influencing factors. *Int Arch Occup Environ Health* 75:528–534