

Groundwater Chemistry and Quality in an Intensively Cultivated River Delta

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Abstract The deltaic region of Cauvery River in Tamil Nadu, India is one of the intensively cultivated regions of India. The present study was carried out with the objective of assessing the groundwater quality and to evaluate the suitability of water for domestic and agricultural use in the deltaic region of this river. Groundwater samples were collected from 44 wells once in two months from July 2007 to September 2009. EC, pH, Eh and concentrations of ions (Na, K, Ca, Mg, Cl, SO₄, HCO₃ and NO₃) were determined. Groundwater occurs in the alluvial formation generally in unconfined condition in this area. Na, Cl and HCO₃ are the dominant ions in groundwater. Groundwater is unsuitable for drinking in the coastal part and in few locations in the southwestern part of the area. Relatively high concentrations of fluoride and nitrate near the surface suggest the impact of fertilizers. Groundwater in the coastal region is unsuitable for irrigation due to sodium hazard. High concentration of ions in groundwater of the coastal region is due to poor flushing of groundwater into the sea and due to fine-grained nature of sediments in the aquifer. Hence proper management strategy is required to control salinity buildup either by increasing the rainfall recharge or by maintaining the river flow over a long period.

Keywords Groundwater quality · Coastal area · Salinity · Cauvery River delta · Tamil Nadu · India

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Introduction

Groundwater is exploited to meet the ever increasing demand for domestic, agricultural and industrial needs. The quality of groundwater is very important in evaluating its suitability for agricultural, domestic and industrial purposes. Hence, protection and management of groundwater quality are emerging as a great concern around the world and especially in India. Exploitation of groundwater has increased greatly in the past few decades in Asian countries where it is used for agricultural and drinking purposes (Gupta et al. 2004). The assessment of the effect of agricultural activities on groundwater systems is a major issue in intensively irrigated regions (Gerhart 1986). Human activities and agriculture had direct and indirect effects in contamination of groundwater due to the dissolution and transport of excess quantities of fertilizer and also through changes in water–rock reactions in the soils and aquifers (Elhatip et al. 2003). Sujatha and Reddy (2003) reported that the groundwater quality is affected by industrial and agricultural pollution in some parts of Andhra Pradesh, India. Jalali and Kolahchi (2007) studied that pollution of groundwater due to the application of fertilizers, irrigation practice, mineral dissolution and discharge of domestic sewage in an agricultural area of northern Malaysia, Western Iran. Harter et al. (2002) reported that the nitrate concentration is extremely high in the unsaturated zone due to fertilizer application. Since irrigation is one of the major sources for the economic development in most of the countries, the groundwater quality is an important criterion to decide the use of water for irrigation activities. Numerous studies evaluated the suitability of groundwater for irrigation using various parameters, e.g. Na%, SAR, RSC, USSS classifications, etc (Rajmohan et al. 1997; Elango et al. 1998; Elango et al. 2003; Al-Bassam and Al-Rumikhani 2003; Vetrinurugan and Elango 2007; Brindha and Elango 2011a).

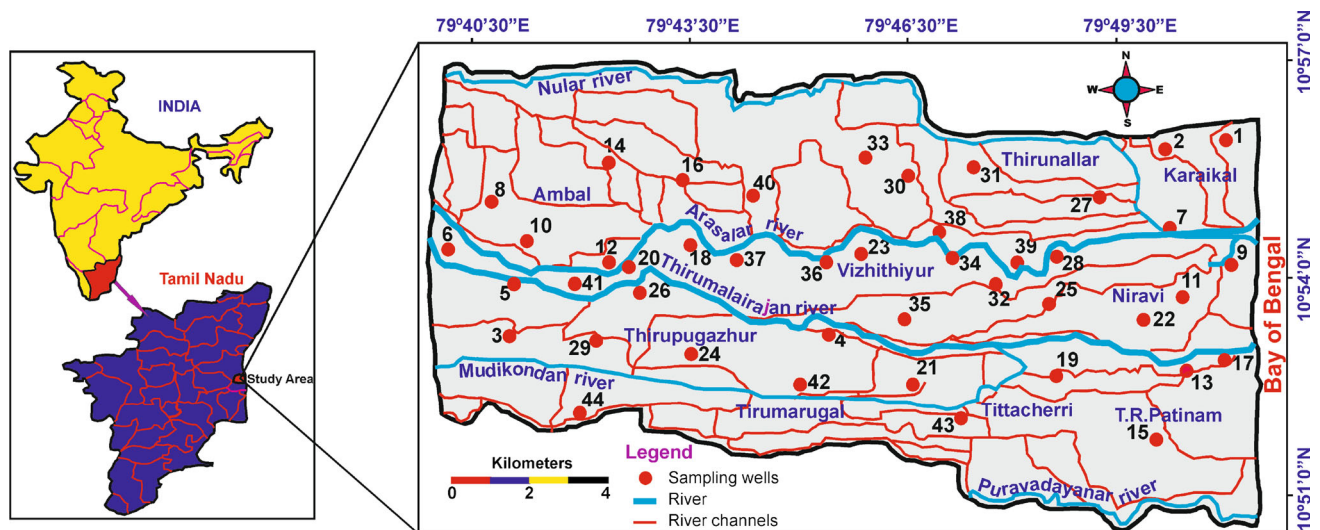


Fig. 1 Location of study area

In southern India, dependence on groundwater has increased due to limited surface water resources, non perennial rivers and frequent failure of monsoonal rain. In the state of Tamil Nadu, southern India, the dependence on groundwater is increasing as the rivers that drain into the Bay of Bengal are non perennial. These rivers flow only for about 60 days in a year. The deltaic region of Cauvery River in Tamil Nadu, India is one of the major agricultural regions in southern India. Since olden days the Cauvery Delta is called the Rice Bowl of Southern India as rice is cultivated over hundreds of square kilometres. Studies in this part of the region were carried out by [Sukhija et al. \(1993\)](#) on differentiation of palaeomarine and modern seawater intrusion based on inorganic chemistry, organic biomarker fingerprints and radiocarbon dating. Other studies in this area include seasonal and spatial variations in magnesium and chloride concentration in groundwater of this deltaic region by [Rajmohan et al. \(1997\)](#), [Vetrimurugan and Elango \(2007\)](#) and [Vetrimurugan et al. \(2013\)](#). In spite of large-scale utilization of groundwater of this basin for irrigation and drinking purposes, the lack of appropriate water management measures has seemingly deteriorated the water quality due to increasing anthropogenic activities ([Solairaj et al. 2010](#)). It is essential to understand the variation in groundwater quality in this region and understand the implication of anthropogenic activities. Earlier studies carried out in this area have not attempted to identify the causes for variation in groundwater quality of this region. As this area is intensively cultivated, it is important to identify the causes for variation in groundwater quality and to identify the implication of hydrogeology on water quality. Earlier studies have not studied the possible effect of deltaic sediments consisting of fine-grained material near the coast on the groundwater quality. Therefore, the present study was

carried out with the objective of assessing the groundwater quality and to evaluate the water suitability for domestic and agricultural use in the deltaic region of Cauvery River, India and also to understand the reasons for saline groundwater near the coast.

Methodology

Description of the Study Area

The study area covers around 160 sq.km forms a part of deltaic region of Cauvery river basin, Tamil Nadu. This area falls between latitude of $10^{\circ}49'30''$ and $10^{\circ}57'0''$ N and longitude of $79^{\circ}40'30''$ and $79^{\circ}51'0''$ E. It is bounded by Bay of Bengal on the east and the puravadayanan river on the south. The Cauvery River originates on Brahmagiri Hill of the Western Ghats in southwestern Karnataka state, flows in a southeasterly direction for 475 miles (765 km) through the states of Karnataka and Tamil Nadu, and descends the Eastern Ghats in a series of great falls. Before emptying into the Bay of Bengal, the river breaks into a large number of distributaries forming a wide delta called the “garden of southern India” (Fig. 1). The climate of the region is humid and tropical. Mean monthly temperature varies between 31.8 and 21.7 °C. The relative humidity is generally high above 70 % during August to April, and minimum humidity varies from 60 to 65 % during the months of June and July. The 120 annual average rainfall of the region is 1207 mm of which the north east monsoon (October–December) contributes 69 % and the southwest monsoon (July–September) contributes 21 %. The area receives maximum rainfall during the month of November.

Cauvery is the major river flowing in this area, and has five main tributaries namely Noolar, Arasalar, Thirumalairayanar, Mudikondan and Puravadayananar draining towards Bay of Bengal (Fig. 1). These rivers are non-perennial and flow only during the north east monsoons. Agriculture in this region chiefly depends upon the availability of water in the river channels during monsoons, and the groundwater for rest of the period. The main crops grown are paddy and pulses. Groundnut, cotton, sugarcane, coconut, flowers and vegetables also are cultivated. Normally, the river water is available from June to February.

Field and Laboratory Methods

Initially well inventory survey was performed and electrical conductivity (EC) of groundwater samples of the wells located in this region was measured. Based on this survey, 44 representative wells were selected for periodical groundwater sampling (Fig. 1). Most of these wells are shallow in nature and they are used for irrigation. Groundwater samples were collected once in two months from July 2007 to September 2009. A total of 413 groundwater samples were collected during the study period. About 244 groundwater samples were collected during pre-monsoon seasons from 2007 to 2009 (July 2007, September 2007, June 2008, August 2008, June 2009 and September 2009) and about 168 groundwater samples were collected during post-monsoon season from 2007 to 2009 (December 2007, March 2008, November 2008 and February 2009). During certain periods, some well samples could not be collected as the wells were dry or inaccessibility. The samples were collected in 500 ml of high-density polyethylene containers washed with acid and before sampling containers must rinsed 3–4 times using the sample collected. EC, pH and oxidation reduction potential (Eh) were measured in situ using digital meters (YSI 556 MPS). Total dissolved solids (TDS) of the samples were estimated using the relation $TDS = 0.64 \times EC$. Samples were transported to the laboratory within the same day. Samples for chemical analysis were filtered through 0.45 μm cellulose membranes (Nupore) before analysis.

Except alkalinity, concentrations of other major ions (Na, K, Ca, Mg, Cl, SO_4 and NO_3) were analysed by ion chromatograph (Metrohm 861 Advanced Compact IC). Alkalinity (HCO_3) was determined by the titration technique as per the methods suggested by APHA (1995). Blanks and standards were run intermittently to check the analytical procedures. Overall, measurement reproducibility and precision for each analysis were less than 2 %. The analytical precision for the total measurements of ions was checked again by calculating the ionic balance error and it was generally within ± 5 %.

Results and Discussion

Groundwater Occurrence

The geology and hydrogeology of this region are described by Natarajan (1982), Central Ground Water Board (CGWB) (1991), Sankaran and Natarajan 1980, Varadaraj and Natarajan 1988, CGWB (1993) and Vetrimurugan et al. (2013). The study area consists of formations of age ranging from the Archaean to recent alluvium. Quaternary formations, which are fluvial and semi-marine in origin are present along the coast and also occupy most of the study area with thickness varying from about 1 to 50 m from west to east (Vetrimurugan et al. 2013). Groundwater occurs in the alluvial formation in unconfined and semi confined condition in this area. The alluvium is directly recharged by precipitation and during flow of water in river canals. During the hot weather period, the depth to water table is about 7 m from the ground level. After the intense monsoonal rains in November and December, the groundwater level raises and it occurs at a depth from 2 to 3 m below ground level.

General Groundwater Chemistry

The most common physical parameters that are measured in the field at the time of sampling are pH, Eh and EC. They often give us the preliminary information that is required in any groundwater study. pH is a negative logarithm of the hydrogen ion concentration in an aqueous solution. pH is temperature dependent and measurements should be taken in-situ, and the actual temperature of the water should be noted for the sample along with the pH measurement. The hydrogen ion is very small and is able to enter and disrupt mineral structures so that they contribute dissolved constituents to groundwater. Consequently, the greater the H^+ availability, i.e. the lower the pH, the higher the TDS in the water. Eh is a measure of the reduction–oxidation (redox) potential of a water sample, means ability of an environment to supply electrons to an oxidizing agent, or to take up electrons from a reducing agent. The solubility of some elements in water depends on whether they are oxidized or reduced. The redox potential can be correlated with the amount of dissolved oxygen. As the oxygen content drops, the environment becomes more reducing (the redox potential drops). The minimum and maximum ranges of pH, Eh and EC measured in the groundwater samples collected from the study area are given in Table 1. The pH of groundwater of this area varies from 6.7 to 8.7. Thus the groundwater of this area is generally neutral. The Eh of groundwater of this area varies from 42 to 390 mV, with mean value of 140 mV. Thus the groundwater of this region is mostly in oxidized condition.

EC is a measure of the total salt content of water which is based on the flow of electrical current through the sam-

Table 1 Minimum, maximum and average values of physical parameters

	pH	Eh (mV)	EC ($\mu\text{S}/\text{cm}$)
Min	6.67	42	326
Max	8.74	390	7,850
Mean	7.50	140	2,201
Median	7.50	147	1,941
STD	0.39	95	1,358
<i>n</i>	413	413	413

Table 2 Statistical analysis of various chemical parameters

	Na	K	Ca	Mg	Cl	SO ₄	HCO ₃	NO ₃	F
Min	37	0.51	9	0.35	23	11	85	0.0	BDL
Max	1,390	559	385	164	2,365	514	1,043	854	1.67
Mean	348	74	80	41	529	120	388	42	0.30
Median	300	32	63	32	394	97	360	3	0.25
STD	254	100	58	29	463	92	152	104	0.23
<i>n</i>	413	413	413	413	413	413	413	413	413

Units = mg/l

ple, i.e. higher the salt content, greater is the flow of electrical current. EC is the reciprocal of resistivity (R) and is expressed as $\mu\text{S}/\text{cm}$. In the study area, EC of groundwater varies between 326 to 7,850 $\mu\text{S}/\text{cm}$ with the mean value of 2201 $\mu\text{S}/\text{cm}$ ($n = 413$). Lowest EC was measured during June 2008 and highest EC during September 2007. The regional distribution of EC in groundwater for the pre-monsoon falls under unsuitable to permissible range. The rainfall recharge after the monsoon improves the groundwater quality which can be seen by reduction in area of unsuitable water quality.

The study of major ion concentration of the groundwater of this area will provide information about the hydrochemical status of an aquifer. The concentrations of dissolved major cations and anions in the groundwater vary both spatially and seasonally in this region. Statistical results of various ions are presented in Table 2. The range of concentration, spatial variation and temporal variation in the concentration of major ions are discussed in the following section. The order of dominance of cations in the groundwater of the study area is $\text{Na} > \text{Ca} > \text{K} > \text{Mg}$ and anions is $\text{Cl} > \text{HCO}_3 > \text{SO}_4$. Thus Na, Cl and HCO₃ are the dominant ions present in groundwater of this area.

Hydrochemical Facies

The geochemical nature of groundwater can be understood by plotting the concentrations of major cations and anions in the Piper trilinear diagram. The trilinear diagram of Piper (1953) is very useful in bringing out the chemical relationship

in groundwater. This is useful to understand the total chemical character of groundwater samples in terms of cations and anions pairs. The Piper trilinear plot of groundwater samples collected from the study area from July 2007 to September 2009 indicates the hydrochemical facies (Fig. 2). Four major hydrochemical facies have been identified from the Piper diagram based on the major ion chemistry of groundwater 215 of this area. They are: Na-Cl facies, Ca-Na-HCO₃ facies, Ca-Mg-Cl facies, Ca-HCO₃ facies. Na-Cl and Ca-Na-HCO₃ types of water are predominant in the study area. Na-Cl facies type of groundwater generally occurs in the coastal part of this area. This type of water might have been derived due to the mixing of seawater with groundwater. Durov plot (Fig. 3) also indicates the dominance of Na and Cl in groundwater of this area.

Drinking Water Quality

The analytical results of physical and chemical parameters of groundwater were compared with the standard guideline values as recommended by the WHO (1996) and BIS (1991) for drinking and public health purposes (Table 3). The table shows the most desirable limits and maximum allowable limits of various parameters. pH value exceeded the limits in 1.2 % of samples.

Total Dissolved Solids

The suitability of the groundwater for any purpose is determined by classifying its hydrochemical properties based on the concentration of TDS (Catroll 1962; Freeze and Cheery 1979). Based on TDS, 39.5 % of groundwater samples out of the total 413 samples exceeded the limit suggested by WHO (1993) (Table 3). The classification of groundwater of the study area during September and December 2007 based on TDS is given in Table 4. This shows that groundwater is fresh to brackish in December 2007. In certain part of the coastal region, groundwater is not suitable for drinking purpose with respect to TDS as WHO (1993) recommended range is from 500 to 1500 mg/L (Fig. 4).

Total Hardness

Calcium, magnesium, and carbonate are the major components of hardness, which is the amount of dissolved minerals in water. Water hardness in most groundwater naturally occurs due to minerals dissolved from bedrock and soil as water passes through them. Calcium and magnesium along with their sulphate, chloride, bicarbonate and carbonate make the water hard in nature. Hardness is an important criterion to determine the suitability of groundwater quality for domestic, drinking and many industrial supplies (Karanth 1987). Hardness is classified as temporary due to carbonate and

Fig. 2 Spatial variation in groundwater level (m msl) during August 2008 and November 2008

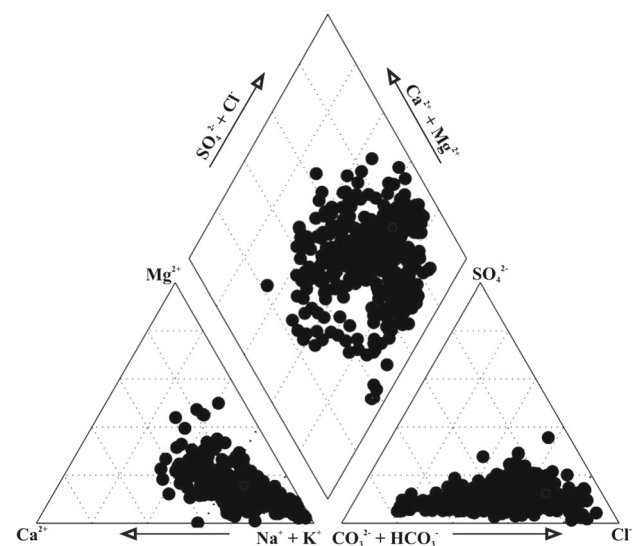
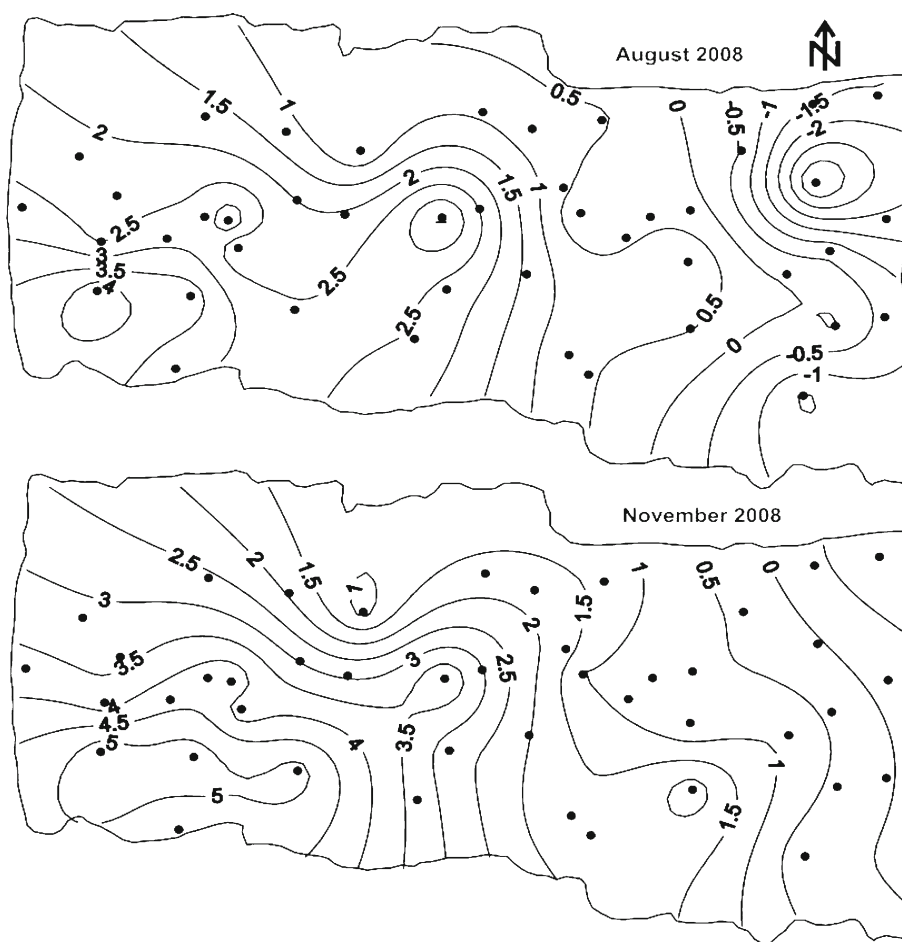


Fig. 3 Piper trilinear diagram showing hydrochemical facies

bicarbonates or permanent due to sulphate and chlorides of calcium and magnesium. Hardness reduces lather formed by soap and causes formation of scales in pipes and on plumbing fixtures. Magnesium is important constituent in determining

hardness of water which may be cathartic and diuretic (WHO 1997). Excessive hardness may indicate the presence of other chemicals such as nitrate. TH of the groundwater was calculated using the formula given below (Hem 1985, Rangunath 1987).

$$TH \text{ (as CaCO}_3\text{) mg/l} = (\text{Ca} + \text{Mg}) \text{ meq/l} \times 50$$

The maximum allowable limit of TH for drinking is 500 mg/l, and the most desirable limit is 100 mg/l as per the WHO (1997). The classification of groundwater (Table 5) based on total hardness (TH) shows that majority of the groundwater samples are in the hard water category. The zonation map based on the total hardness for the months of September and December 2007 is shown in Fig. 5. During the month of September 2007, total hardness ranges from very hard to average and in December, total hardness ranges from soft to average due to rainfall recharge.

Cations

The concentration of major cations measured in groundwater of the study area was compared with the WHO (1993) and BIS (2012) (Table 3). Based on the recommended limits of

Table 3 Groundwater quality evaluation using WHO and Indian Standards for drinking purpose

Water quality parameters	WHO (1993)		Indian Standard (IS 10500, 2012)		Total no. of samples exceeding the standards		Percentage of samples exceeding the standards	
	Desirable limit	Max. allowable limit	Desirable limit	Max. permissible limit	According to WHO (1993)	According to ISI (1991)	According to WHO (1993)	According to ISI (1991)
pH	6.5	8.5	6.5–8.5	6.5–9.5	5	0	1.2	0.0
TDS	500	1,500	500	2,000	163	83	39.5	20.1
TH (as CaCO ₃)	100	500	300	600	96	66	23.2	16.0
Ca ²⁺	75	200	75	200	16	16	3.9	3.9
Mg ²⁺	50	150	30	100	3	22	0.7	5.3
Na ⁺	–	200	–	200	276	276	66.8	66.8
K ⁺	–	12	–	–	261	–	63.2	–
Cl [–]	200	600	250	1,000	139	53	33.7	12.8
NO ₃ [–]	45	–	45	45	82	82	19.9	19.9
SO ₄ ^{2–}	200	400	200	400**	4	4	1	1

Units = mg/l, except pH **upto 400 mg/l if Mg does not exceed 30 mg/l

Table 4 Classification of groundwater based on TDS

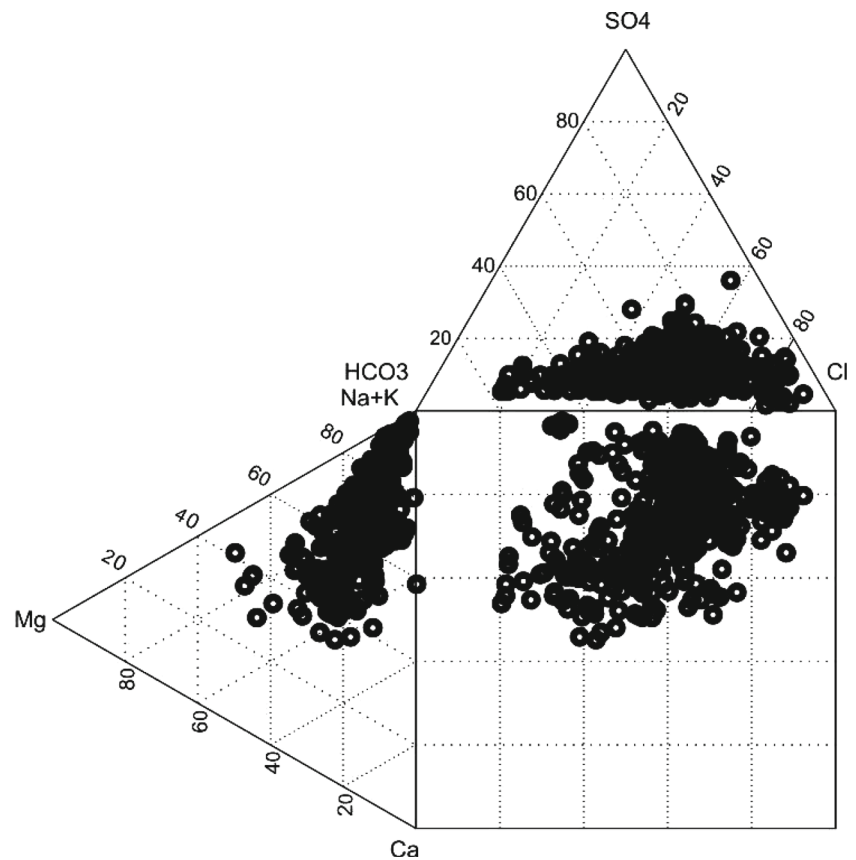
TDS (mg/l)	Nature of water	Pre-monsoon (September 2007)		Post-monsoon (December 2007)	
		Total no. of wells	Percentage of wells	Total no. of wells	Percentage of wells
< 1000	Fresh water	13	32.5	15	36.6
1000–10,000	Brackish water	27	67.5	26	63.4
10,000–1,00,000	Saline water	Nil	–	Nil	–
> 1, 00, 000	Brine water	Nil	–	Nil	–

WHO (1993), the calcium concentration in groundwater of this area exceeded in 3.9 % of total samples. The groundwater of the region is generally suitable for drinking purpose with regard to magnesium. Potassium concentration has exceeded the limits in 63.2 % of the samples. Potassium level in can be reduced by the use of treatment process by activated carbon method. Sodium concentration exceeded the recommended limits in 66.8 % of samples.

Sodium concentration of groundwater of this area varies from 37 mg/l to 1390 mg/l, with an average value of 348 mg/l. The sodium ion is the dominant cation of the study area as mentioned earlier. The concentration of sodium varies spatially and it increases towards east. Fig. 6 shows the spatial variation of sodium during June 2008 and February 2009. High concentration of sodium ion is found in groundwater along the eastern part of the study area indicating the influence of the Bay of Bengal. It was found that the sodium concentration of groundwater in certain wells located in southwestern part of the study area also has relatively higher concentration. The spatial variations in the concentration of other major cations are also similar to that of sodium.

Anions

With regard to the concentration of bicarbonate the groundwater of this region suitable for drinking purpose. Chloride ion is a minor constituent of the earth's crust; but it is found to be a major dissolved constituent of most natural waters. The amount of chloride is a good indicator of water quality. The concentration of chloride exceeded the recommended limits in 33.7 % of samples (Table 3). Figure 7 shows the spatial variation of chloride during June 2008 and February 2009. The chloride concentration in this region varies from 23 to 2365 mg/l, with an average value of 529 mg/l. The coastal parts of the region contain relatively more chloride. In agricultural fields, approximately half to two thirds of water applied is consumed through evapotranspiration and the remaining part infiltrates and joins the groundwater. The infiltration water will have high salinity due to evaporation and evapotranspiration, and thus increases the groundwater salinity (Elango and Ramachandran 1991). In the southwest region, the concentration of chloride is high similar to sodium.

Fig. 4 Durov's classification of groundwater**Table 5** Classification of groundwater based on total hardness

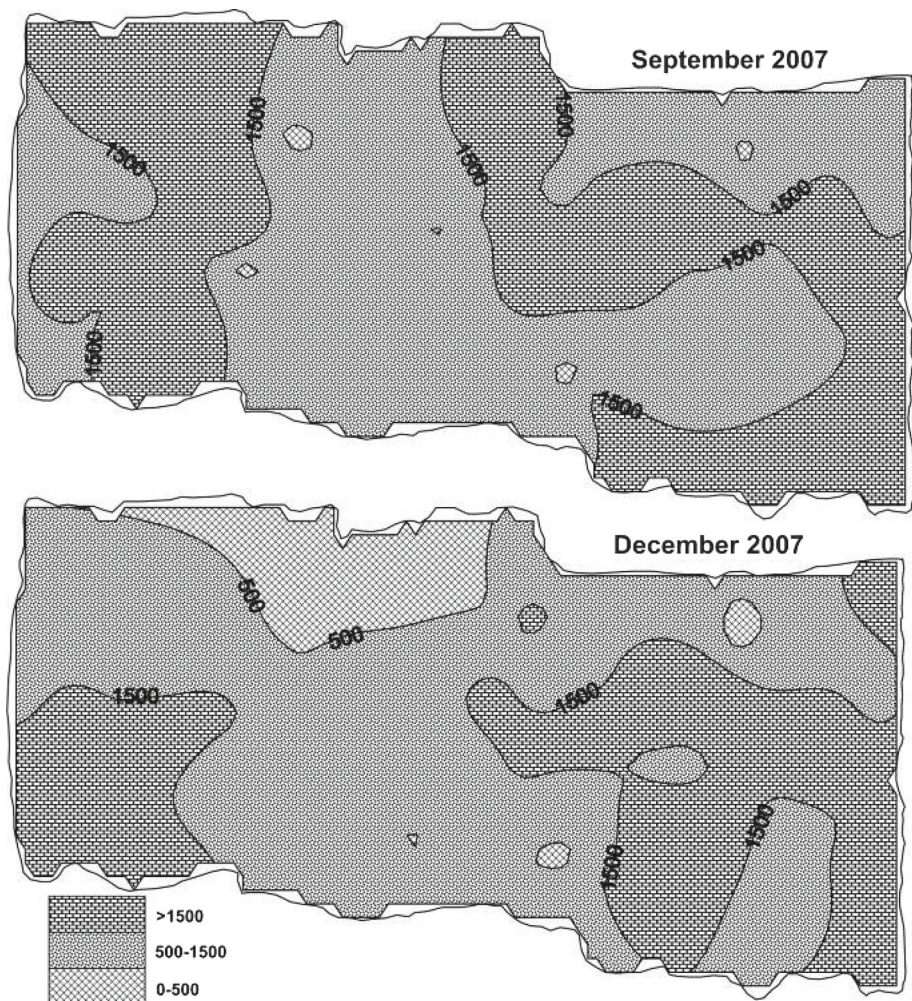
Total hardness as CaCO ₃ (mg/l)	Classification of water	Pre-monsoon		Post-monsoon	
		Total no. of wells	Percentage of wells	Total no. of wells	Percentage of wells
< 50	Very Soft	2	0.82	2	1.2
50–150	Soft	29	11.89	31	18.5
150–250	Average	64	26.23	45	26.8
250–500	Hard	89	36.48	54	32.1
> 500	Very hard	60	24.59	36	21.4

Sulphate is widely distributed in reduced form in various rocks as metallic sulphide and it is not a major constituent of the earth's outer crust. Sulphate concentration in groundwater of this area varies from 10.87 to 514 mg/l, with an average value of 120 mg/l. Figure 8 shows the spatial variation of sulphate during June 2008 and February 2009. Sulphate concentration in this area is influenced by the agriculture patterns, since the man-made chemical fertilizers are used for enriching the nutrient contents of soil.

The fluoride concentration of the groundwater of the study area ranges from Below Detectable Limit (BDL) to 1.67 mg/l with a mean value of 0.3 mg/l. The allowable World Health Organization (WHO 1996) standard for fluoride is 1.5 mg/l.

Thus the groundwater of this area is suitable for drinking, based on the concentration of fluoride. The spatial variation of fluoride concentration in groundwater of this area is shown in Fig. 9. In general, fluoride is mostly originated from the geogenic sources and processes (Apambire et al. 1997; Ayoob and Gupta 2006; Edmunds and Smedley 2005; Reddy and Prasad 2003; Brindha and Elango 2011b). However, in the study area, there is no possibility of geogenic source as the region comprises only alluvial deposits. Hence, fluoride is likely to be derived from the use of fertilizers. Usage of phosphatic fertilizers in the paddy field seems to be the sources for fluoride (Brindha et al. 2011). Relatively high concentrations of fluoride near the surface also suggest the impact of

Fig. 5 Spatial variation in TDS during September and December 2007



use of fertilizers and also it is due to different depths of wells (Fig. 10).

High concentration of nitrate in drinking water is toxic. The nitrate ion is the most oxidized form of nitrogen in nature and is relatively non-toxic to fishes (Zhang and Chen 2004). However, when the concentration becomes excessive along with phosphate, eutrophication can become a serious environmental problem. Several authors (Hill 1982; Flipse et al. 1984; Houzim et al. 1986; Kolaja et al. 1986; Vrba 1986; Brindha et al. 2012) related the nitrate in groundwater to different sources as leaching of organic and inorganic fertilizers from agricultural land by infiltration of precipitation, irrigation water, animal waste and leakage from sewers. The concentration of nitrate in groundwater of this area ranges from BDL to 854 mg/l, with a mean concentration of 42.5 mg/l. The highest desirable (WHO 1996) and maximum permissible limit of nitrate are 45 mg/l for drinking water purpose. The concentration of nitrate is exceeded in 19.9 % of the samples (Table 3). The groundwater is unsuitable for drinking with regard to the concentration of nitrate in coastal part and a few locations in southwestern part of the area (Fig. 11).

The variation in the concentration in nitrate with depth of wells indicates the effect of application of fertilizers, such as ammonium chloride, muriate of potash in cultivated areas increases potassium nitrate in groundwater. That is the concentration of nitrate in groundwater from the upper region of the aquifer is relatively high (Fig. 12).

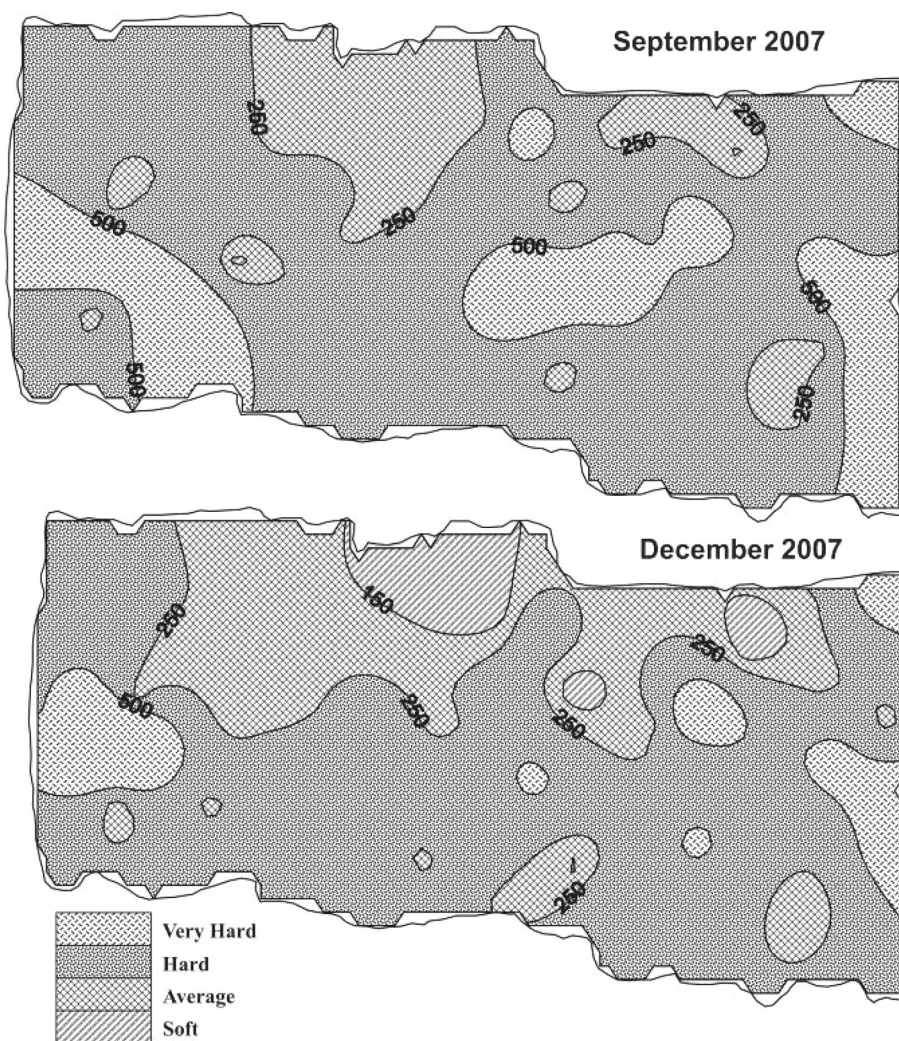
Irrigation Water Quality

The groundwater of the study area is extensively used for irrigation purposes. The suitability of groundwater for irrigation depends upon the mineral constituents present in the water. Irrigation water of good quality is essential to maintain the soil for higher crop productivity.

Salinity Hazard

EC is a good measure to evaluate salinity hazard of groundwater used for irrigation. It is a measure of the degree of the mineralization of the water, which is dependent on rock water interaction, the residence time of the water in the rock

Fig. 6 Spatial variation in CaCO_3 (mg/l) during September and December 2007



(Eaton 1950). Based on EC, the water can be classified as excellent, good, permissible, doubtful, unsuitable and highly unsuitable. EC of the irrigation water becomes one of the important parameters to evaluate the overall chemical quality of groundwater and it is being used to compare the water in any region. During pre-monsoon and post-monsoon periods of September 2007, about 12.5 and 12.2 % of groundwater samples 359 fall under good category of EC, respectively (Table 6). Most of the groundwater samples in the study area fall under permissible to unsuitable category. The spatial variation in EC of groundwater of the study area is shown in Fig. 13.

Alkalinity Hazard

The sodium adsorption ratio (SAR) is an important parameter for determining the suitability of groundwater for irrigation because it is a measure of alkali/sodium hazard to crops and extent to which sodium is adsorbed by the soils (Fig. 14). SAR is given by the relationship

$$\text{SAR} = \text{Na} / \{(\text{Ca} + \text{Mg}) / 2\}^{1/2}$$

where the concentrations are in meq/l.

The irrigation water containing a high proportion of sodium will increase the exchange of sodium content of the soil, effecting the soil permeability, and makes the texture of soil hard to plough and unsuitable for seedling emergence (Trivedy and Goel 1984).

The SAR and EC values of water samples of the study area are plotted in diagram suggested by the U.S. Salinity Laboratory (1954) for evaluating suitability of waters for irrigation purpose (Fig. 15). In this diagram, waters of the study area are classified into C1, C2, C3, C4 and C5 types on the basis of salinity hazard and S1, S2, S3 and S4 types on the basis of sodium hazard. Some samples have been located in C4S2 and C4S4. Compared to other water types, few samples are of C5S4 types which are not suitable for irrigation.

In addition, the soil of study region exhibits higher amount of clay and silt content leading to restricted drainage. The irrigation return flow of the surface soil due to agriculture

Fig. 7 Spatial variation of sodium (mg/l) in groundwater during June 2008 and February 2009

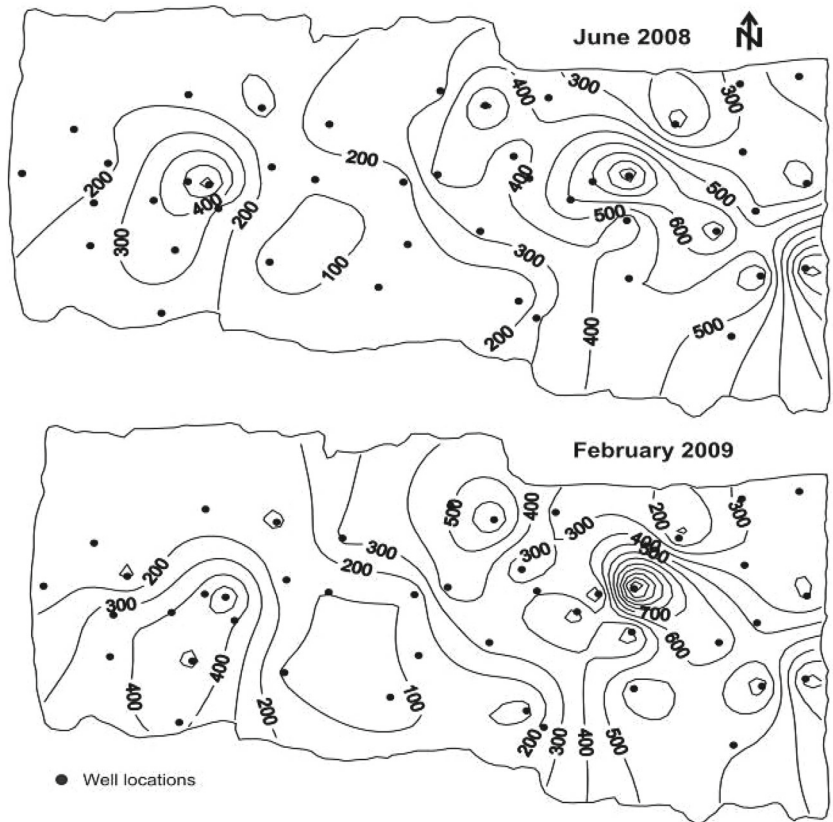


Fig. 8 Spatial variation of chloride (mg/l) in groundwater during June 2008 and February 2009

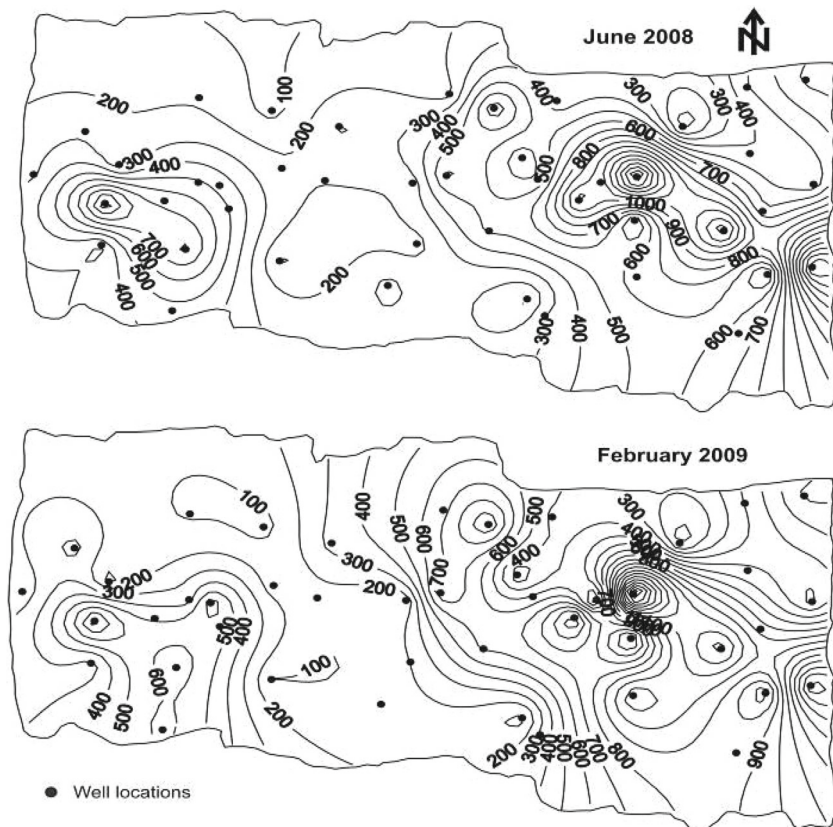


Fig. 9 Spatial variation of sulphate (mg/l) in groundwater during June 2008 and February 2009

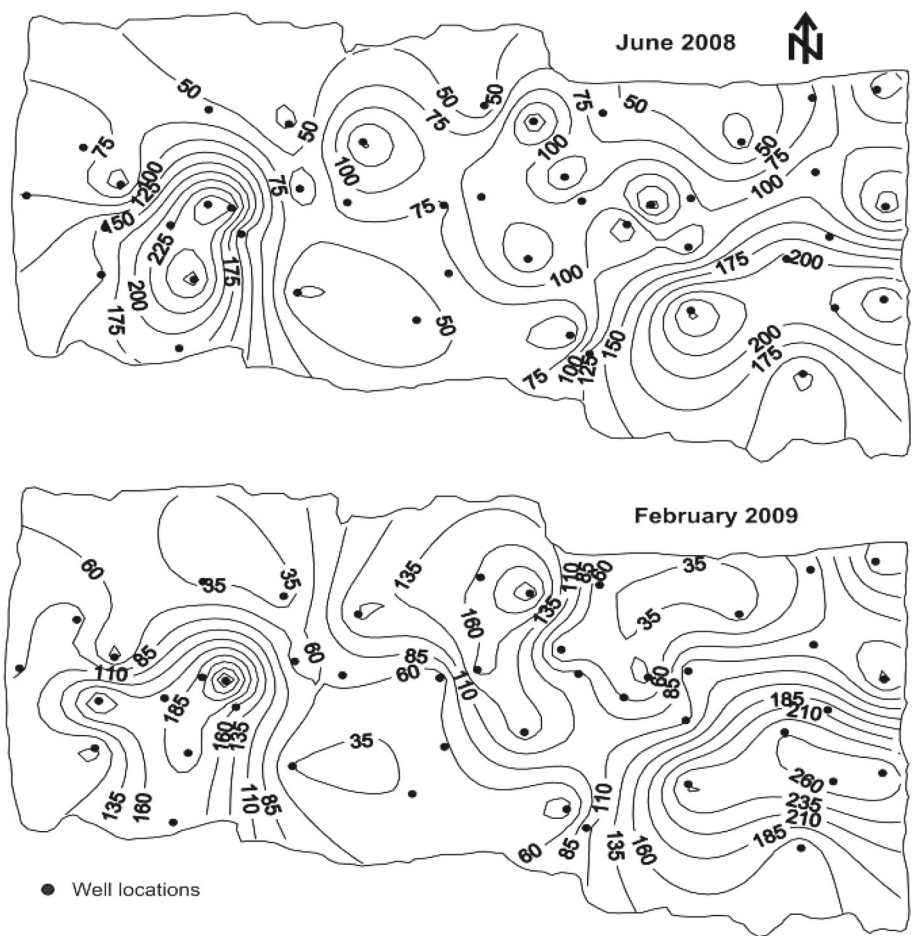
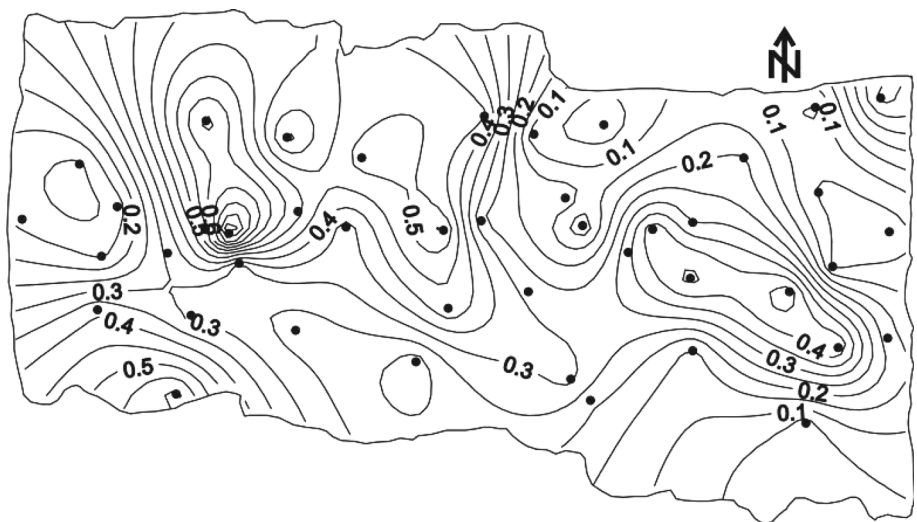


Fig. 10 Spatial variation of fluoride (mg/l) in groundwater during August 2008



activities and storage of animal waste and local pollution may be the reason behind high salinity in the study area. If the SAR value is greater than 6, the irrigation water will cause permeability problems on shrinking and swelling types

of clayey soil (Saleh et al. 1999). Therefore, special management strategy for salinity control is needed and selection of salt tolerance crops is important.

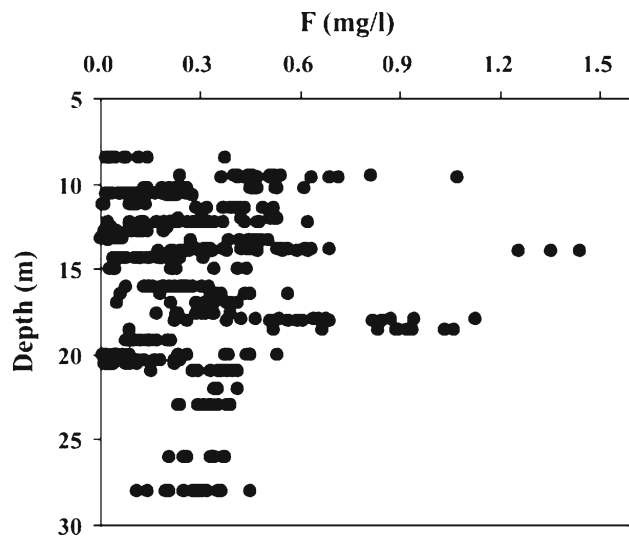


Fig. 11 Variation in concentration of fluoride with depth of wells

Percent Sodium

Sodium is important in classifying irrigation water, because sodium reacts with soil thereby reducing the permeability. Percent sodium in water is a parameter computed to evaluate the suitability of water quality for irrigation (Wilcox et al.

1948). The percentage of sodium (%Na) is calculated using the formula given below:

$$\%Na = \frac{(Na + K) \times 100}{(Ca + Mg + Na + K)}$$

where, all the concentrations are expressed in meq/l.

The percentage sodium has been computed for all wells for the entire sampling period. Generally, %Na 398 should not exceed 60 % in irrigation waters. Wilcox (1955) used %Na and specific conductance in evaluating irrigation waters using the Wilcox diagram as given in Fig. 16. It has been observed that most of the samples have fallen under the category of permissible to doubtful and doubtful to unsuitable. Some samples are plotting in the unsuitable region for irrigation use which are located in near coastal area. Thus the concentration of sodium is high in groundwater, and hence the sodium ions tend to be absorbed by clay particles, displacing Mg and Ca ions. This exchangeable process of Na in water for Ca and Mg in soil reduces the permeability and eventually results in soil with poor internal drainage. Hence, air and water circulation is restricted even during wet conditions and such soils are usually hard when dry (Collins and Jenkins 1996; Saleh et al. 1999).

Fig. 12 Spatial variation of nitrate (mg/l) concentration in groundwater during August 2008

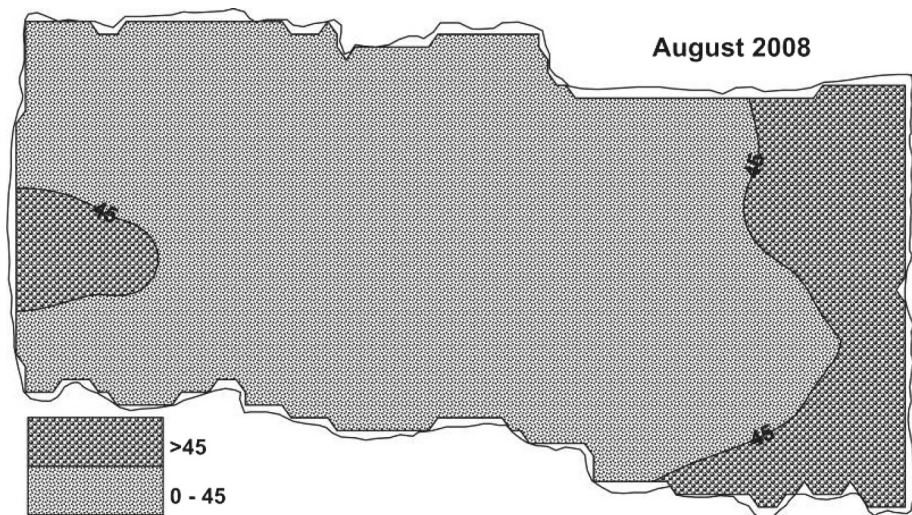


Table 6 Irrigation water quality based on electrical conductivity

EC ($\mu\text{S}/\text{cm}$)	Classification of water	Pre-monsoon (September-2007)		Post-monsoon (December-2007)	
		Total No. of wells	Percentage of wells	Total No. of wells	Percentage of wells
< 250	Excellent (C1)	0	0	0	0
250–750	Good (C2)	5	12.5	5	12.2
750–2,250	Permissible (C3)	16	40	20	48.8
2250–5,000	Unsuitable (C4)	17	42.5	13	31.7
5000–10,000	Highly Unsuitable (C5)	2	5	3	7.3

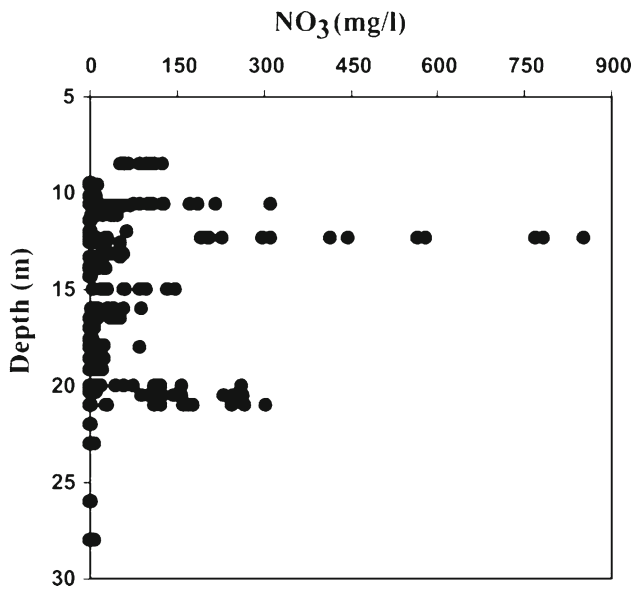


Fig. 13 Variation in concentration of nitrate with depth of wells

Residual Sodium Carbonate

In addition to the SAR and Na%, the excess sum of carbonate and bicarbonate in groundwater over the sum of calcium and magnesium also influences the unsuitability of groundwater for irrigation. Residual sodium carbonate (RSC) value is computed, where ions are expressed in meq/l using the following formula (Ragunath 1987):

$$RSC = (CO_3 + HCO_3) - (Ca + Mg)$$

where, all the concentrations are expressed in meq/l. The classification of irrigation water according to the RSC values is presented in Table 7, for the pre-monsoon and post-monsoon periods. Around 15 and 7.3 % of samples comes under unsuitable category during the month of September and December 2007.

Fig. 14 Spatial variation in Electrical Conductivity ($\mu S/cm$) of groundwater during September and December 2007

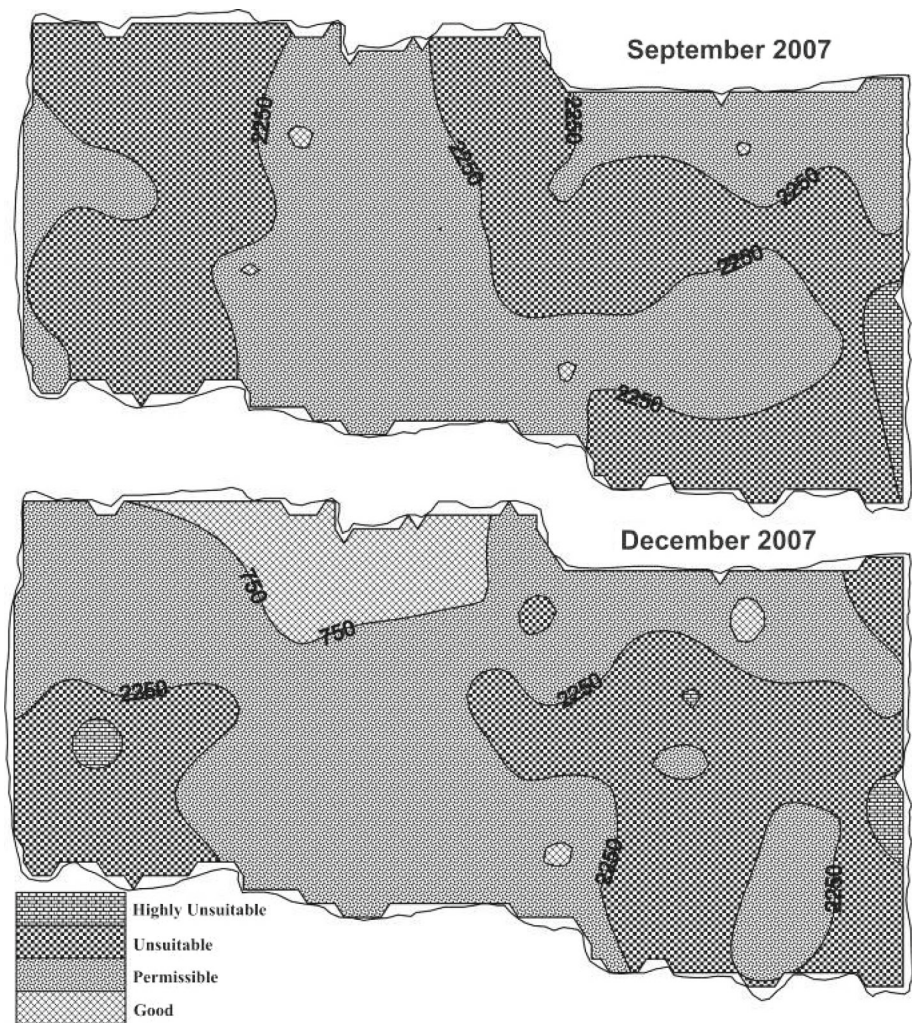


Fig. 15 USSL Classification of groundwater in the study area

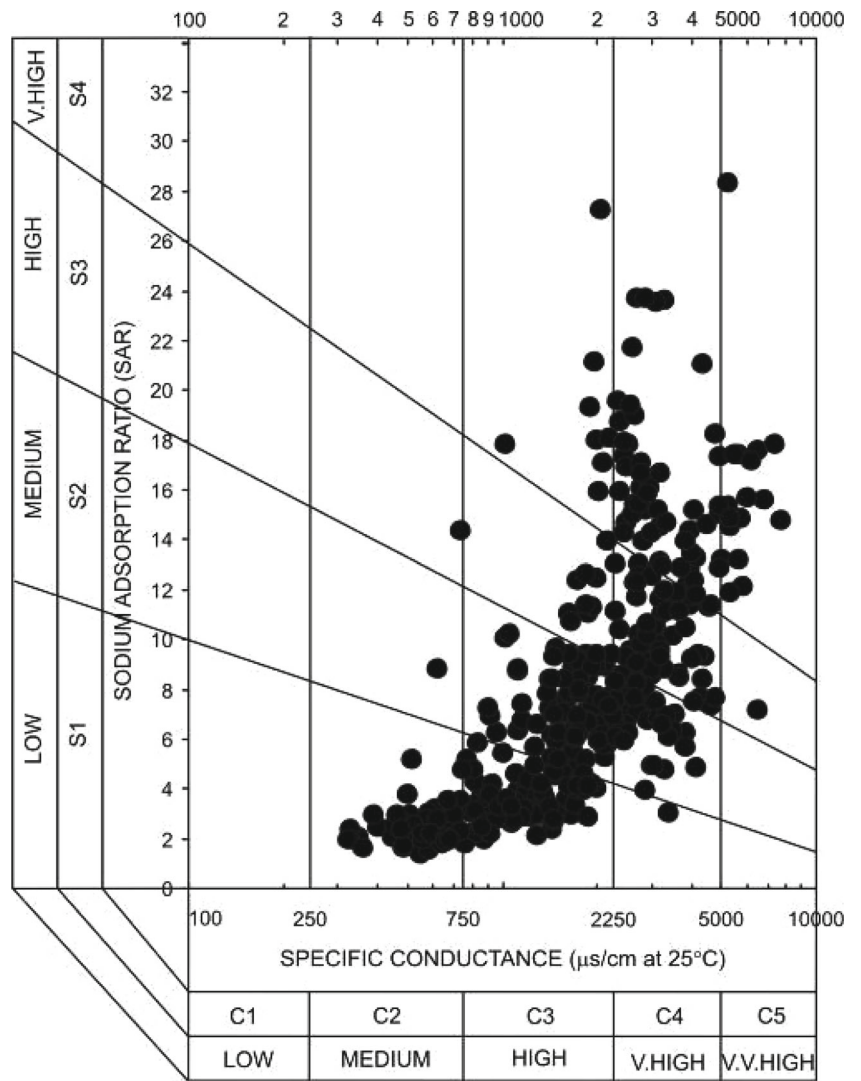


Fig. 16 Wilcox diagram showing irrigation water quality

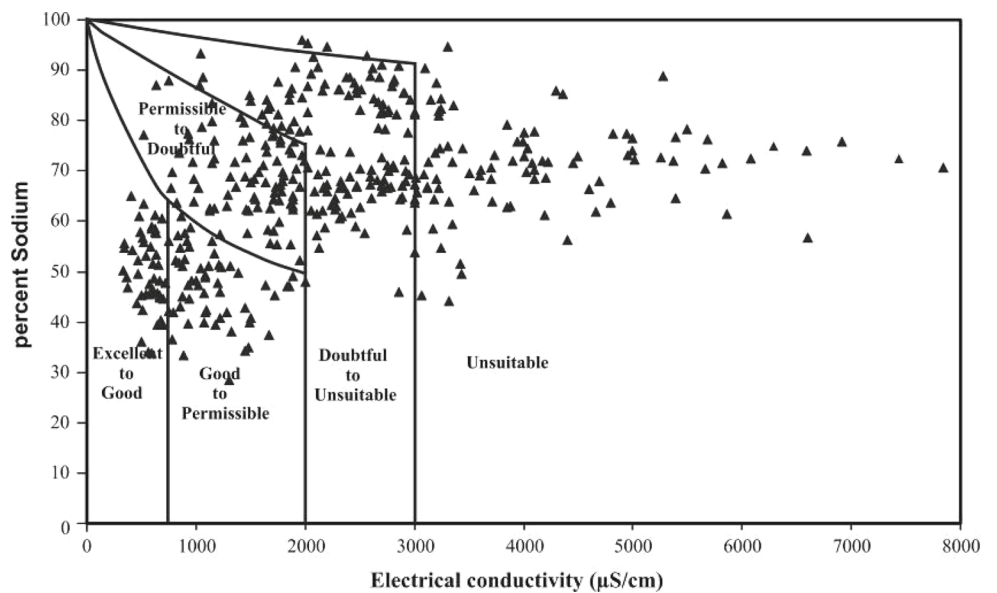


Table 7 Quality of groundwater based on residual sodium carbonate

RSC (meq/l)	Suitability for irrigation	Pre-monsoon (September-2007)		Post-monsoon (December-2007)	
		Total no. of wells	Percentage of wells	Total no. of wells	Percentage of wells
< 1.25	Safe	32	80	35	85.4
1.25–2.5	Moderate	2	5	3	7.3
> 2.5	Unsuitable	6	15	3	7.3

Permeability Index

The soil permeability is affected by long-term irrigation influenced by Na, Ca, Mg, K and HCO_3 contents of the soil. The soil permeability index (PI) is also used to determine the suitability of groundwater for irrigation purposes. It is defined by Rangunath (1987) as

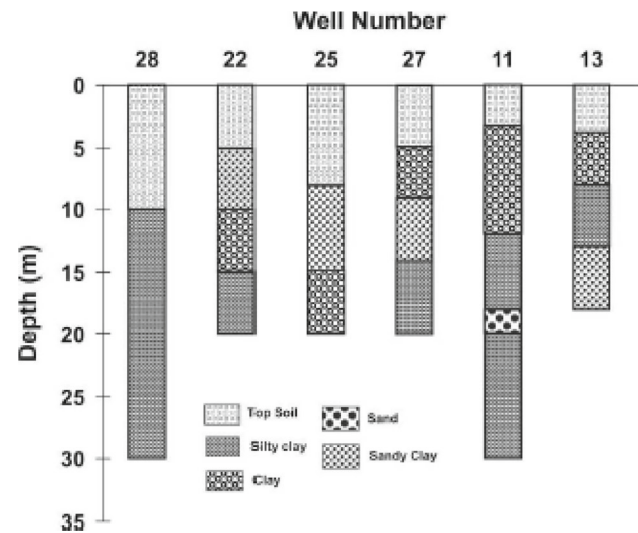
$$\text{PI} = (\text{Na} + (\text{HCO}_3) 0.5) * 100 / (\text{Ca} + \text{Mg} + \text{Na} + \text{K})$$

The concentrations are expressed in meq/l. PI ranged from a minimum of 32.4 to a maximum of 99.9 with an average value of 73.1. The PI is greater than 50 in 97 % of samples.

Causes for Salinity

The study area of Cauvery deltaic region is formed by the deposition of sediments carried by the river and is covered by thick quaternary and recent alluvial deposits comprising of sand and clay. In the coastal region, the thickness of the sediments is more when compared to that of the western side and fine grained material constitutes majority of the aquifer material. Cauvery River is a non-perennial river and flows only during the monsoon periods generally for a period of two months in a year.

From the study period of three years, numerous spatial variation maps were drawn and it has been identified that the ionic concentration is high in the coastal region. Although, small scale anthropogenic activities such as salt evaporation ponds and aquaculture farms are practiced which cause some degree of pollution, this alone could not explain the cause for poor groundwater quality in the coastal part. High concentration of ions in groundwater of the coastal region is due to poor flushing of groundwater into the sea due to fine-grained nature of sediments. This could be confirmed by the study of lithological logs which shows the presence of fine-grained materials in the coastal area (Fig. 16). That is the contaminants from the western side of the study area have been transported and build up in ionic concentration is recorded in the coastal regions. Concentration of major and minor ions like Na and Cl in coastal region can be due to the mixing of seawater. The concentration of nitrate and potassium ions is very less in seawater but high in groundwater of the coastal part (Fig. 17).

**Fig. 17** Lithologs of wells near the coast

Conclusion

Groundwater occurs in the alluvial formation in unconfined to semiconfined condition in this area. The pH of groundwater of this area generally neutral and in certain region, it is alkaline. The groundwater of this region is in oxidized condition. Groundwater in the study area is of brackish water type. Based on EC, the groundwater is found to be unsuitable for drinking in certain areas. The classification of groundwater based on total hardness shows that majority of the groundwater samples fall in the hard water category. Poor groundwater quality along the eastern part of the study area is due to mixing of seawater. The groundwater is also unsuitable for drinking with regard to the concentration of nitrate in coastal part and a few locations in southwestern part of the area. Relatively high concentrations of fluoride and nitrate near the surface suggest the impact of use of fertilizers. The concentration of sodium is high in groundwater and hence the sodium ions are tending to be absorbed by clay particles. Thus groundwater is unsuitable for irrigation due to sodium hazard especially in the coastal region. The PI is greater than 50 in 97 % of samples. High concentrations of ions like Na and Cl in groundwater of coastal regions can be due to the mixing of seawater. However, relatively high concentration

of nitrate and potassium ions in groundwater of the coastal part is due to the use of fertilizers as their concentration in seawater is very less. Hence, high concentration of ions in groundwater of the coastal region is due to poor flushing of groundwater in to the sea due to fine-grained nature of sediments in the aquifer. Proper management strategy is required to control salinity buildup either by increasing the rainfall recharge or by the maintaining the river flow for sufficiently longer period.

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