



Assessment of groundwater quality in hard rock aquifer of central Telangana state for drinking and agriculture purposes

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Abstract

Quality assessment of groundwater for drinking and irrigation was evaluated in parts of Nalgonda district of Telangana state, India. The overall groundwater quality and the suitability to drinking and irrigation were evaluated by hydrochemical analysis of 78 groundwater samples. The water quality parameters were compared with that of the limits set by World Health Organisation (WHO) and Bureau of Indian Standards (BIS). Groundwater is found to be contaminated by fluoride and nitrate ions. The water quality indices (WQI) suggest that during pre-monsoon, 72.5% samples are suitable for drinking while 86.8% are suitable during post-monsoon. Indicators like sodium absorption ratio (SAR), electrical conductivity (EC), percent of sodium (Na %), residual sodium carbonate (RSC), permeability index (PI), magnesium ratio (MR), residual sodium bicarbonate (RSBC), salinity hazard (SH), potential salinity (PS), soluble sodium percentage (SSP), and magnesium ratio (MR) were estimated for assessing the irrigation suitability of the groundwater samples. Wilcox, United States Salinity Laboratory diagrams (USSL diagram) and Doneen's chart infer that most of the samples are suitable for irrigation purpose and the suitability improves during post-monsoon. The geochemical evolution of the groundwater was also studied using Piper's and Chadha's diagrams. The major facies found in groundwater are Na–Mg–HCO₃–Cl, Na–Mg–HCO₃, Na–HCO₃, Mg–Ca–HCO₃, Mg–Na–HCO₃ and Na–Cl. Rock-water interaction, ion exchange and evaporite dissolution were found to be the major geochemical processes governing the groundwater chemistry.

Keywords Water Quality Index · Hydrochemistry · Hard rock aquifers · Drinking and irrigation suitability

Introduction

Among the different sources of fresh water that can be used for drinking purpose, groundwater is the widely used resource due to quality and quantity considerations. Groundwater, in general, is not vulnerable to surface contamination since the contaminants are either decayed or diluted in unsaturated zone before reaching the water table while surface water is susceptible to contamination (Hounslow 1995; Sharma et al. 2017). Increased population and industry have led to a rapid decline in groundwater level due to over-exploitation and also resulted in quality deterioration. According to Ramesh and Elango (2012), the water

resources available in India are not sufficient to fulfil the needs of the whole population. The per capita water availability in India has dropped by 15% from 2001 to 2011 (from 1816 cubic metres to 1545 cubic metres in 2011; *Source: Ministry of statistics and programme implementation, India*). This scenario is further severe in arid and semi-arid regions (Scanlon et al. 2006; Vasanthavigar et al. 2010). In this context, the groundwater quality assessment has become crucial in arid and semi-arid regions where rainfall is irregular and major water supplies to drinking and irrigation are met by groundwater.

Nalgonda district of Telangana state (India) falls under semi-arid region with an annual rainfall of 674 mm (CGWB 2013) and frequent draughts. The groundwater recharge is very less and occurs through fractures present in the hard rock formations. The groundwater quality is also reported to be poor due to the impact of chemical fertilisers, animal wastes and natural contaminants (Brindha et al. 2011; Keesari et al. 2014a, b; Venkateshwarlu et al. 2014). It is reported that parts of this district fall under semi-critical

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to over-exploited category (CGWB 2013). Many studies have reported the presence of high fluoride and salinity in groundwater of this region (Kota et al. 2016; Lakshmi et al. 2016; Venkateshwarlu et al. 2014). Heavy exploitation of groundwater was found to be reason for the quality deterioration in this district (Venkateshwarlu et al. 2014; Lakshmi et al. 2016). In the most recent studies, researchers found that rock–water interaction and evaporation are the main reasons for the water quality deterioration in this region (Das et al. 2017; Narsimha and Sudarshan 2017; Venkateshwarlu and Reddy 2017). Findings from studies by Vasu et al. (2017) and Adimalla and Venkatayogi (2018) also suggest the influence of rock–water interaction in addition to silicate weathering and reverse ion exchange towards the groundwater chemical evolution. In most instances, the groundwater was found to be unsuitable for household uses and marginal for irrigation purpose (Unnisa and Bi 2017). Most of the earlier studies were focused on the F^- contamination and deterioration of water quality due to few parameters while studies on the overall chemistry of groundwater and its quality index are very limited. In this study, the overall geochemistry and water quality was studied using water quality index (WQI) in addition, suitability to drinking and irrigation was also evaluated. The suitability of the groundwater for domestic purpose was assessed in relation to WHO (2011) and BIS (2012) standards, while agricultural suitability was assessed by sodium absorption ratio (SAR), electrical conductivity (EC), percent of sodium (Na %), residual sodium carbonate (RSC), permeability index (PI), magnesium ratio (MR), residual sodium bicarbonate (RSBC), salinity hazard (SH), potential salinity (PS), soluble sodium percentage (SSP), and magnesium ratio (MR). Chadda's and Piper's classifications were adopted to determine the geochemical facies and evaluate the governing geochemical processes.

Study area description

Study area is located in Nalgonda district between 16.91° and 17.36° North latitudes and 78.77° and 79.59° East longitudes spreading an area of about 50 km^2 (Fig. 1). This area falls under semi-arid category with an annual average rainfall of 674 mm (CGWB 2013) which is mostly received during south west monsoon (i.e. June to September). The study area comprises of a hard terrain physiography with low to moderately dissected hills and valleys of both structural and denudational origin (Fig. 2). The average elevation is about 480–800 m above mean sea level (CGWB 2013). The study area has structural and geomorphic lineaments with dykes, joints and fractures (Fig. 2). River Krishna along with the tributaries Musi, Aler, Dindi, Halia and Peddavagu rivers form the drainage for this area which is dendritic to sub-dendritic in nature. The geology of the study area comprises Archaean crystalline rocks of granites, gneisses,

schists and intrusive. Formations such as limestones, quartzites and shales are also encountered in the study area. Top zone mostly comprises of weathered formation ranging from 5 to 10 m while the deeper zones are dominated by fractured granitic rocks (Brindha et al. 2011; CGWB 2013). Most of the water supply to irrigation is met by shallow groundwater, streams or tanks. Wells tapping shallow weathered zone range from 5 to 12 m below ground level (bgl) while deeper wells tap up to 100 m bgl (CGWB 2013; Keesari et al. 2014b).

Sample collection and methodology

Samples from bore well, hand pump and open wells of different depths covering entire study area were collected. A total of 40 samples were collected during pre-monsoon and 38 samples during post-monsoon season of 2012 (Fig. 1). Sampled water was passed through $0.45 \mu\text{m}$ pore size membrane filters and stored in acid-washed polyethylene bottles. For cation measurements, samples were acidified by adding ultrapure nitric acid to pH 2. Physical parameters like temperature, electrical conductivity, pH, DO were measured in the field using portable metres (Hanna, Make). Alkalinity was measured in field by titration of 10 ml of water sample with $0.02 \text{ N H}_2\text{SO}_4$, the mixed indicator (Bromocresol green–Methyl red) was used for indicating the end point of the titration. Major anions viz., Cl^- , SO_4^{2-} , NO_3^- and F^- and major cations viz., Na^+ , K^+ , Mg^{2+} and Ca^{2+} were analysed using ion chromatography (DX-500) with electrochemical detector (ED 40) in conductivity mode. The accuracy of the analysis was checked using charge balance error, which is calculated for each sample using the equation below. The error was within the allowed limit of $\pm 5\%$ (Hounslow 1995).

$$\% \text{ CBE} = \frac{\text{meq (cations)} - \text{meq (anions)}}{\text{meq (cations)} + \text{meq (anions)}} \times 100 \quad (1)$$

Results and discussion

General water quality

A summary of hydrochemical data is given in Table 1. The seasonal variations of hydrochemical data is represented in the box whiskers plots (Fig. 3a–k). The temperature varies from 28.7 to 36.3°C , with an average of 30.9°C , and the pH values range from 5.52 to 7.6 with an average of 7.17 during pre-monsoon and 7.33–8.77 with an average of 7.9 during post-monsoon season (Table 1). Most of the groundwater samples indicate alkaline nature ($\text{pH} > 7$). The increased pH in the post-monsoon can be attributed to dissolution of carbonate minerals present in the unsaturated zone. The pH

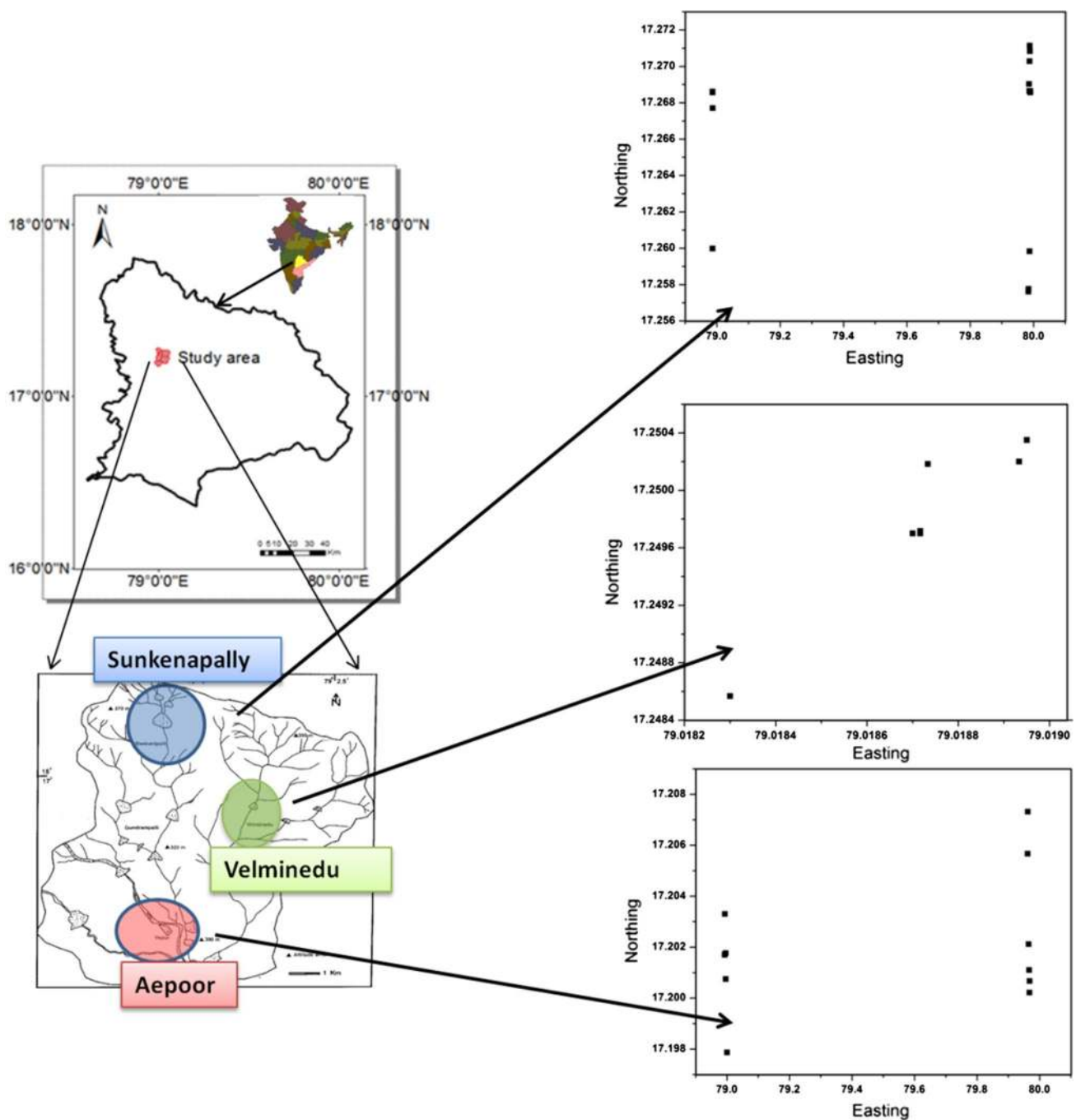


Fig. 1 Sampling location map

value of all the samples are within the permissible limit of 6.5–8.5 prescribed for drinking water by BIS (2012) and WHO (2011) except for few samples given in Table 2. Dissolved ions and salinity is represented by EC and it varies from 499 to 1999 $\mu\text{S}/\text{cm}$ with an average of 887 $\mu\text{S}/\text{cm}$ in pre-monsoon and from 291 to 1897 $\mu\text{S}/\text{cm}$ with an average of 870 $\mu\text{S}/\text{cm}$ in post-monsoon season (Table 1). From the bar diagram of variation of EC (Fig. 4), it is clear that in 54% of the samples show a decrease in EC during pre-monsoon

compared to post-monsoon, which could be due to addition of salts to groundwater through unsaturated zone. During the infiltration of rainwater, the salts that are accumulated in unsaturated zone leach into shallow groundwater leading to higher salinity. Total dissolved solid (TDS in mg/L) was calculated from the EC measured by using the formula (Weiner 2013; Sharma et al. 2017):

$$\text{TDS (mg/L)} = 0.67 \times \text{EC } (\mu\text{S}/\text{cm}) \quad (2)$$

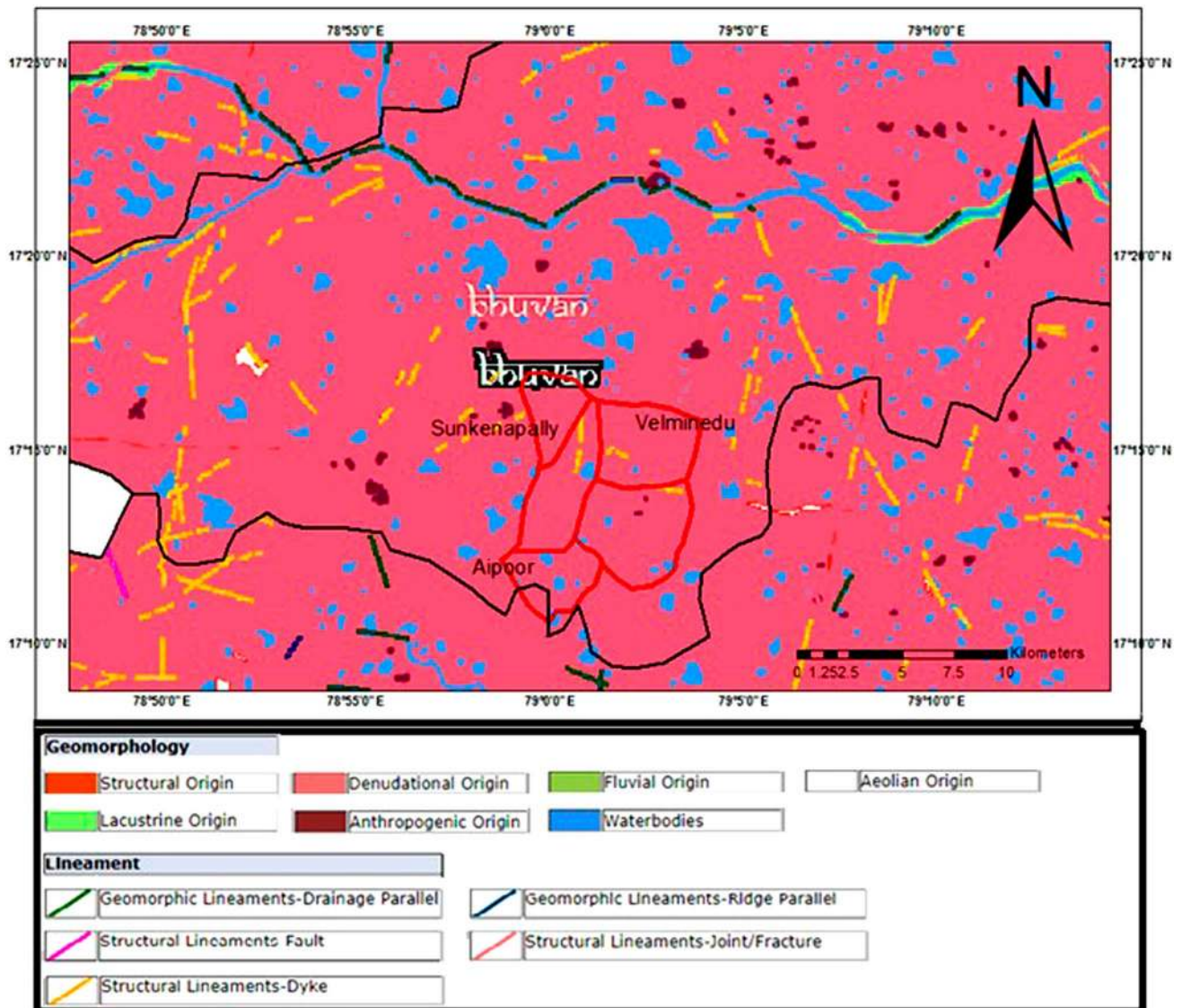


Fig. 2 Geomorphology and Lineament map of the study area (modified after GSI and NRSC 2012)

The TDS values vary from 334 to 1339 mg/L with an average of 594 mg/L during pre-monsoon and from 195 to 1271 mg/L with a mean of 583 mg/L during post-monsoon (Table 1). TDS is mainly contributed by dissolution of salts present in the unsaturated zone through rainwater percolation (Sharma et al. 2017). DO levels in water are maintained by dissolution of atmospheric oxygen as well as photosynthesis by aquatic plants and it decreases with higher temperature, salinity and elevation. DO values vary from 0.13 to 1.74 mg/L with a mean of 1.13 mg/L (Table 1).

Suitability for drinking

Table 2 shows the percentage of samples exceeding the Maximum Permissible Limits (MPL) set by WHO and BIS for each parameters. It is clear from the table that in the pre-monsoon the dominant contaminant is F^- with 30% samples exceeding the permissible limit of 1.5 mg/L (Table 2). Other parameters like NO_3^- , total alkalinity and total hardness are also higher than permissible limits in 27.5, 15 and 27.5% of samples, respectively (Table 2). F^- and NO_3^- contamination is seen in fewer samples (10 and 26.3%, respectively) during

Table 1 Physicochemical parameters for both pre and post-monsoon season

Parameter	Season	Minimum	Maximum	Median	Average	SD
EC	Pre	499	1999	797.5	887.88	299.26
	Post	291	1897	824.5	870	431.74
pH	Pre	5.52	7.6	7.17	7.17	0.33
	Post	7.33	8.77	7.9	7.9	0.4
T	Post	28.7	36.3	30.1	30.9	2.23
DO	Pre	0.13	1.74	1.27	1.13	0.42
TA	Pre	0	923.8	251.7	330.7	270.3
	Post	18	954.7	360.5	406.4	311.1
TDS	Pre	334	1339	534	594	200
	Post	195	1271	552	583	289
TH	Pre	7.5	1458	231.4	404	354
	Post	56.3	1621.3	416.5	584.3	417.43
Na ⁺	Pre	16.2	708.9	156.7	233.0	183.5
	Post	21.7	659	239.2	261.2	170.16
K ⁺	Pre	0.1	16.3	2.99	4.2	3.99
	Post	1.1	22.5	2.5	3.3	3.58
Ca ²⁺	Pre	1	336	24.95	61.7	77.54
	Post	0	336	81.63	104.7	92.66
Mg ²⁺	Pre	0	170	38.09	60.8	44.93
	Post	7.9	209	68.38	78.5	52.8
F ⁻	Pre	0.18	3.4	0.7	1.12	0.94
	Post	0	2.6	0.5	0.72	0.62
Cl ⁻	Pre	10.2	529	79.48	154	143.5
	Post	11	740	97.83	178.9	168.32
SO ₄ ²⁻	Pre	9.5	177.8	37.5	59	43.53
	Post	8.4	201	44.09	62.4	51.26
NO ₃ ⁻	Pre	3.3	236	34	48.9	48.69
	Post	6.4	302	26.23	48.9	59.62
HCO ₃ ⁻	Pre	0	1878.4	511.88	672.6	549.63
	Post	36.6	1941.4	733.2	826.3	632.66

TDS, total dissolved solids (mg/L); DO, dissolved oxygen (mg/L); T, temperature (°C); EC, electrical conductivity (μs/cm); TA, total alkalinity (mg/L); TH, total hardness (mg/L); SD standard deviation; Ca²⁺, calcium (mg/L); Mg²⁺, magnesium (mg/L); Na⁺, sodium (mg/L); K⁺, potassium(mg/L); F⁻, fluoride (mg/L); HCO₃⁻, bicarbonate(mg/L); Cl⁻, chloride (mg/L); SO₄²⁻, sulphate (mg/L); NO₃⁻, nitrate (mg/L)

post-monsoon, while alkalinity and total hardness increased up to 36.8 and 44.7%, respectively (Table 2; Fig. 3g, i, k).

TDS and Total Hardness (TH) are the common indicators of drinking water suitability. As per BIS limits all samples show TDS values within permissible limit in both the seasons but as per WHO guidelines 5% samples (pre-monsoon) and 10.5% samples (post-monsoon) are above limits (Table 2). The higher percentages during post-monsoon can be attributed to addition of salts through percolating rainwater. Classification of groundwater based on TDS is shown in Table 3.

Hardness of the water increases due to the increase of alkaline earths such as calcium and magnesium (Narsimha and Sudarshan 2017). The presence of calcite and dolomite

minerals are the main reasons for increased Ca²⁺ and Mg²⁺ concentrations in groundwater (Adimalla and Venkatayogi 2018; Sharma et al. 2017). High TH in drinking water causes many disease viz. calcifications problem of arteries, urinary calculus, kidney or bladder diseases and stomach problems (Sengupta 2013). TH (mg/L of CaCO₃) was determined by the following equation (Todd 1980):

$$TH = 2.497 \times Ca^{2+} + 4.115 \times Mg^{2+} \quad (3)$$

where TH, Ca²⁺, Mg²⁺ concentrations are expressed in mg/L. TH values vary from 7.5 to 1458 mg/L with an average of 404 mg/L during pre-monsoon and 56.3–1621 mg/L with an average of 584 mg/L (Table 2). Classification of groundwater done by Durfor and Becker (1964) on the basis of TH is given in Table 3. From the table, it can be seen

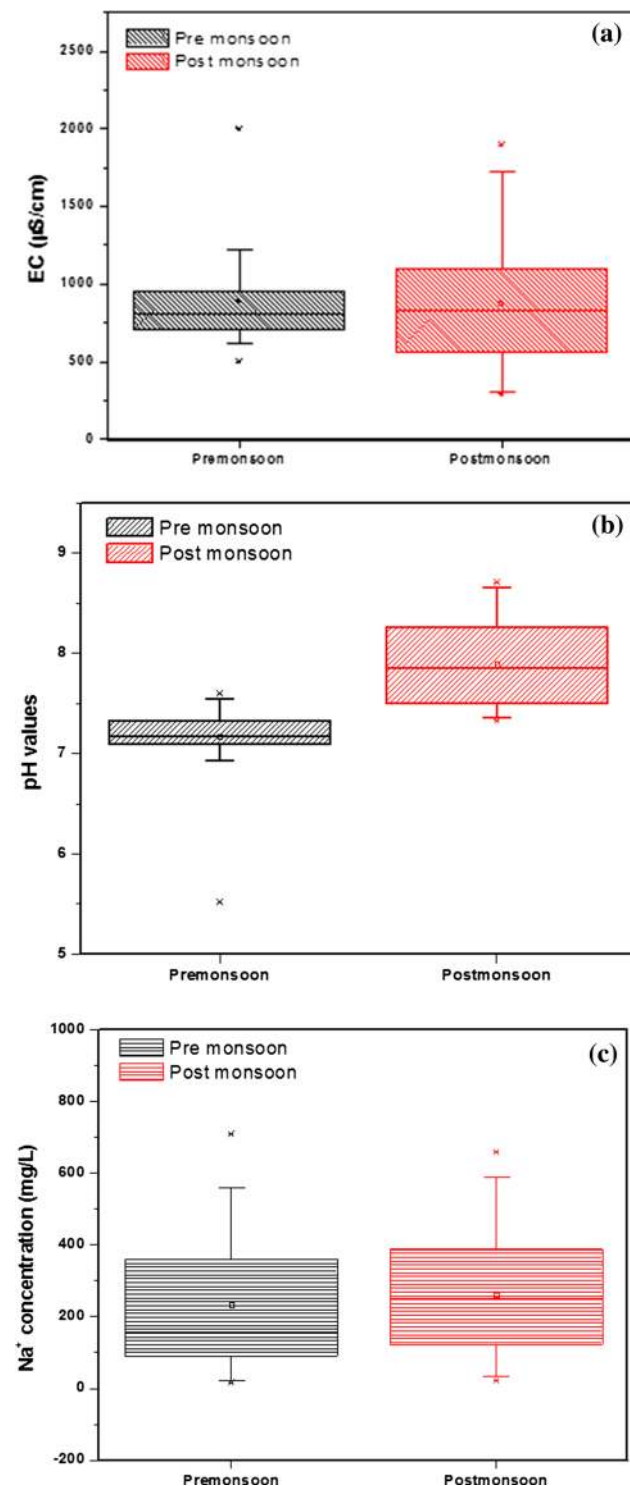


Fig. 3 Box-Whisker Plots showing seasonal variation in **a** EC ($\mu\text{S}/\text{cm}$); **b** pH; **c** Na^+ concentration (mg/L); **d** K^+ concentration (mg/L); **e** Mg^{2+} concentration (mg/L); **f** Ca^{2+} concentration (mg/L); **g** F^- concentration (mg/L); **h** Cl^- concentration (mg/L); **i** NO_3^- concentration (mg/L); **j** SO_4^{2-} concentration (mg/L); **k** Alkalinity as CaCO_3 (mg/L)

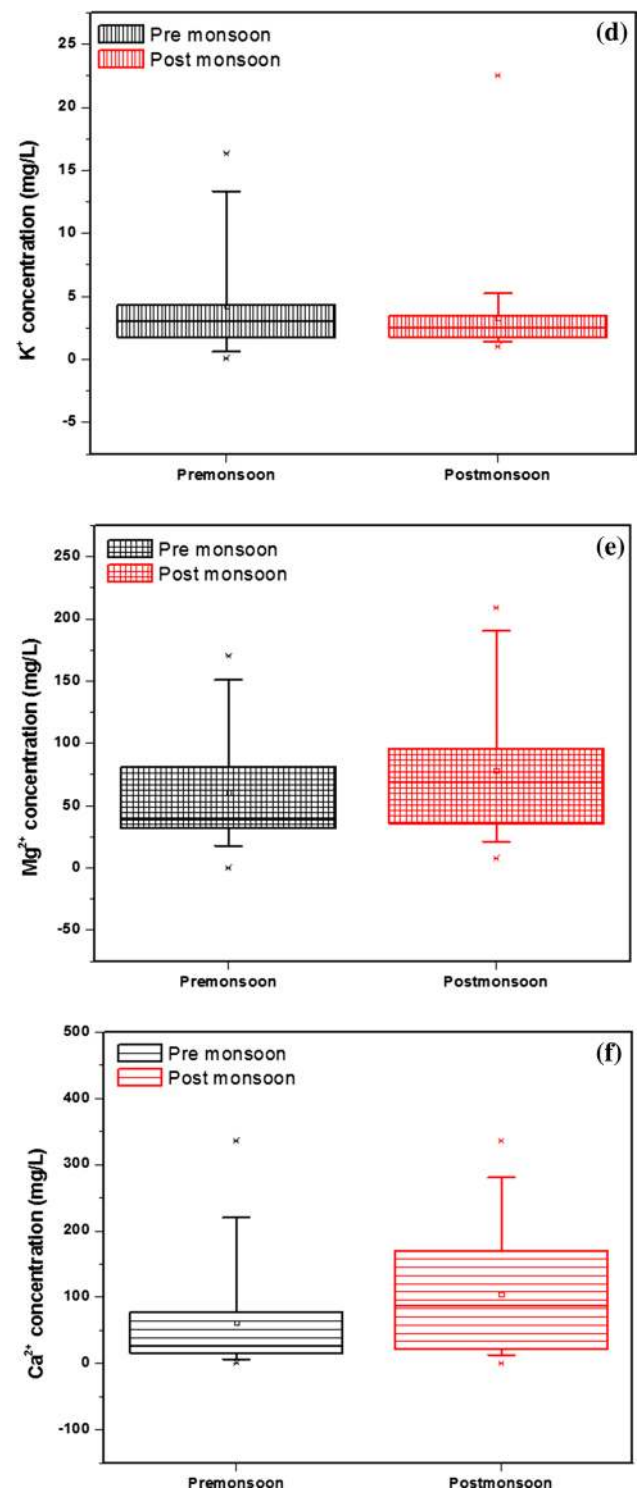


Fig. 3 (continued)

that 67.5 and 84.2% samples from pre and post-monsoon respectively fall in very hard category.

Sodium (Na^+) in water comes mainly from feldspar like mineral and anthropogenic sources (Kumar et al. 2009). Na^+ values vary from 16.2 to 709 mg/L during pre-monsoon with

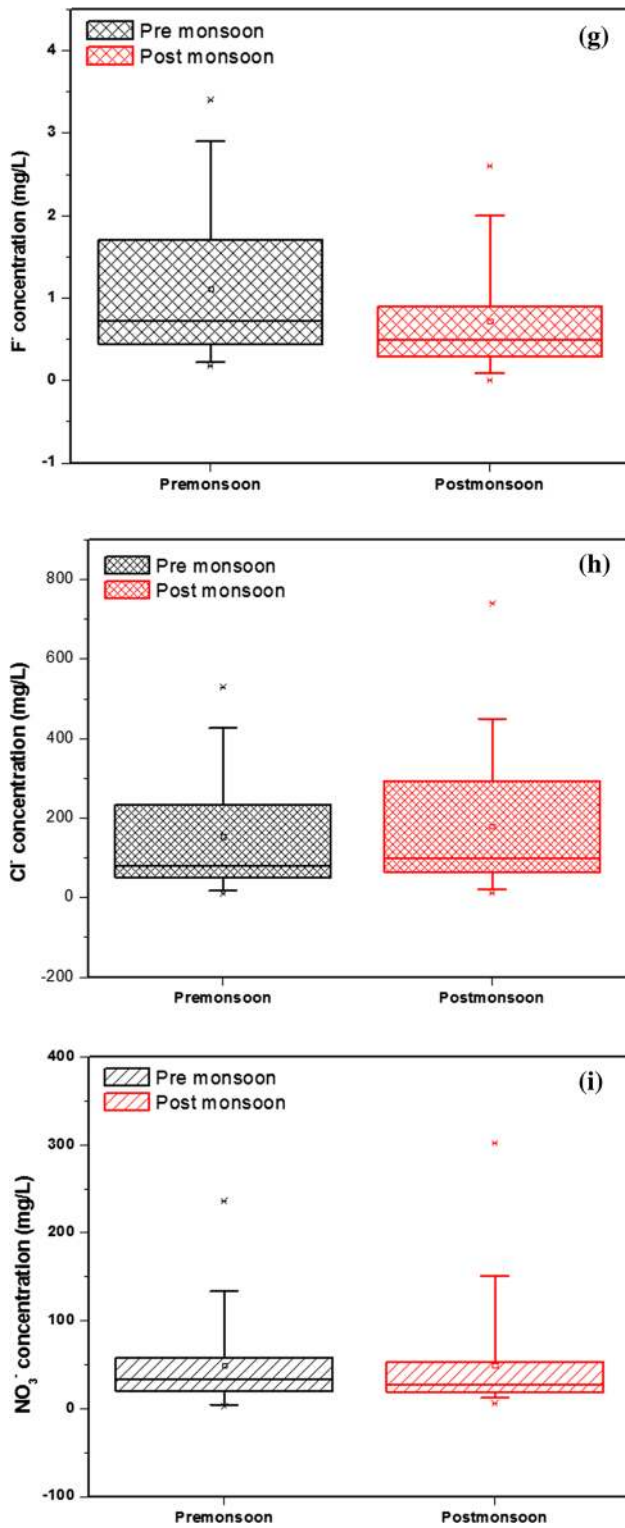


Fig. 3 (continued)

an average value 233 mg/L and from 21.7 to 659 mg/L during post-monsoon with an average of 261 mg/L (Table 1; Fig. 3c). Potash feldspar acts as an anthropogenic source

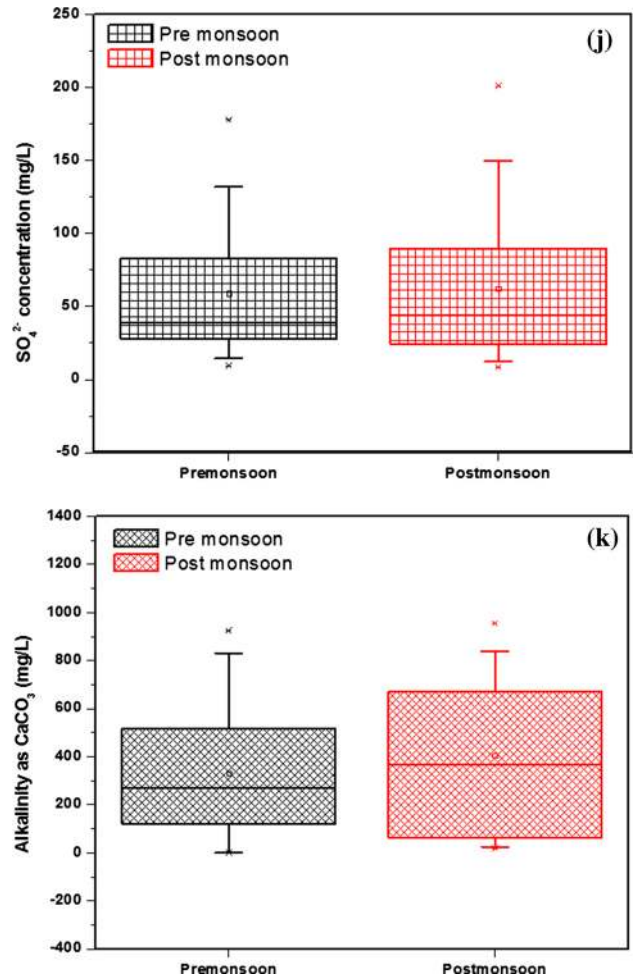


Fig. 3 (continued)

of K⁺ in water. Orthoclase, microcline and clay minerals are major sources of K⁺ in groundwater, and it may also be derived through ion-exchange process (Hem 1985). K⁺ concentration varies from 0.1 to 16.3 mg/L with an average of 4.2 mg/L for pre-monsoon samples and from 1.1 to 22.5 mg/L with an average of 3.3 mg/L during post-monsoon samples (Table 1, Fig. 3d). There are no guidelines prescribed for Na⁺ and K⁺ for drinking water, but for people with heart conditions excess Na⁺ intake can be a matter of concern (WHO 2011) and high K⁺ concentration is harmful for human digestive and nervous system due to its laxative effect (Keesari et al. 2016) (Fig. 3d).

Other important water quality parameters are Ca²⁺ and Mg²⁺ which control the TH of water. The desirable level (DL) of Ca²⁺ in drinking water is 75 mg/L, and the MPL permissible limit is 200 mg/L (BIS 2012). Deficiency in Ca²⁺ results in rickets, while higher levels might cause accumulation in different body parts and kidney problems. The Ca²⁺ concentration in the samples varies from 1 to 336 mg/L with a mean value of 61.7 mg/L in pre-monsoon

Table 2 Suitability to drinking purpose, comparison of pre- and post-monsoon samples on the basis of BIS and WHO standards

Parameter	BIS (2012)		WHO (2011) guideline value	Percentage samples having higher values than BIS (2012)		Percentage samples having higher values than WHO (2011)		Effect on human body when greater than maximum permissible limit
	DL	MPL		Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	
T	–	–	–	–	–	–	–	Temperature affects usefulness of water for different purposes. Uniformly low temperature water is usually preferred by users. With increasing depth of aquifer the temperature of groundwater is increased
DO	–	–	–	–	–	–	–	Basic requirement of higher forms of aquatic life
pH	6.5–8.5	No relaxation	6.5–8.5	0	0	0	0	Affects the taste of water and also mucous membrane
TH	200	600	500	27.5	44.7	30	44.7	Causes Calcification at arteries. Kidney and Stomach problems also common
TDS	500	2000	1000	0	0	5	10.5	May cause gastrointestinal irritation and decreases palatability
TA	200	600	–	15	36.8	–	–	Unpleasant taste
Na ⁺	–	–	–	–	–	–	–	Large concentration affects irrigation and industrial use. Give water salty taste when combined with chloride. Harmful for people with heart conditions
K ⁺	–	–	–	–	–	–	–	High K ⁺ concentration is harmful for human digestive and nervous system due to its laxative effect
Ca ²⁺	75	200	300	7.5	10.5	2.5	5.3	Deficiency causes various type of rickets and increased level may cause kidney and bladder problems and urination disorder
Mg ²⁺	30	100	100	20	23.7	20	23.7	Salts are cathartic and diuretic high concentration poses problems of laxative effect less amount may affect functions of enzymes
F ⁻	1	1.5	1.5	30	10	30	10	Dental carries may occur above 1.5 mg/L, high F ⁻ results crippling skeletal fluorosis
NO ₃ ⁻	45	No relaxation	50	27.5	26.3	27.5	26.3	Methemoglobinemia in infants
SO ₄ ²⁻	200	400	250	0	0	0	0	Causes gastrointestinal irritation
Cl ⁻	250	1000	250	0	0	25	31.6	Injurious to heart and kidney patients other than this taste, palatability and digestion is effected
HCO ₃ ⁻	–	–	–	–	–	–	–	Combined with calcium and magnesium forms carbonate hardness

DO, dissolved oxygen (mg/L); T, temperature (°C); TDS, total dissolved solids (mg/L); TA, total alkalinity as CaCO₃ (mg/L); TH, total hardness as CaCO₃(mg/L); Ca²⁺, calcium (mg/L); Mg²⁺, magnesium (mg/L); Na⁺, sodium (mg/L); K⁺, potassium(mg/L); F⁻, fluoride (mg/L); Cl⁻, chloride (mg/L); SO₄²⁻, sulphate (mg/L); NO₃⁻, nitrate (mg/L); HCO₃⁻, bicarbonate(mg/L)

and from 0 to 336 mg/L with a mean value of 104.7 mg/L in post- monsoon (Table 1; Fig. 3f). Mg²⁺ is an essential activator for enzymes and various biochemical reactions in body but excess Mg²⁺ is cathartic and diuretic (WHO 2009). Mg²⁺ values range from 0 to 170 mg/L with a mean value

60.8 mg/L during pre-monsoon and from 7.9 to 209 mg/L with a mean 78.5 mg/L during post-monsoon (Table 1, Fig. 3e).

Bicarbonate concentration (HCO₃⁻) in groundwater of the study area ranges from 0 to 1878.4 mg/L

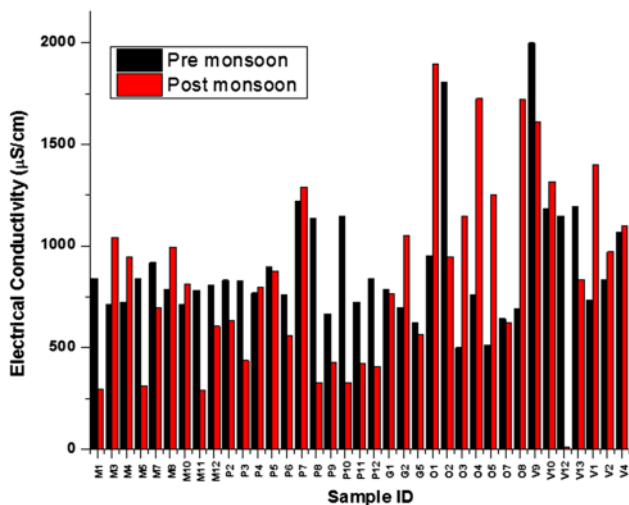


Fig. 4 Seasonal variations in electrical conductivity of water samples (µS/cm)

during pre-monsoon with an average of 673 and 36.6 to 1941 mg/L with an average of 826mg/L during post-monsoon (Table 1). The higher alkalinity due to higher bicarbonate ion concentration can be attributed to silicate weathering and carbonate mineral dissolution in the presence of soil CO₂ (g) releasing HCO₃⁻ in the groundwater (Hem 1985, 1986; Narsimha and Sudarshan 2017). During pre-monsoon Cl⁻ concentration in the area varies from 10.2 to 529 mg/L with an average of 154 mg/L and from 11 to 740 mg/L with an average of 178.9 mg/L during post-monsoon (Table 1; Fig. 3h). Natural and anthropogenic, both act as the sources of Cl⁻ in groundwater. High concentration of chloride in water causes health problems in human like hypertension, ventricular hypertrophy, osteoporosis, renal stones and asthma (McCarthy 2004; Raviprakash and Krishna 1989). SO₄²⁻ amount in the area ranges from 9.5 to 178 mg/L with mean value 59 mg/L

in pre-monsoon and from 8.4 to 201 mg/L with an average value of 62.4 mg/L during post-monsoon (Table 1; Fig. 3j). The presence of gypsum (CaSO₄·2H₂O), anhydrite (CaSO₄) and oxidation of sulphide minerals are the main reasons of higher concentration of SO₄²⁻ in groundwater (Han et al. 2016). The anthropogenic sources of SO₄²⁻ in the region are fertilisers, industrial effluents etc. (Lakshmi et al. 2016). Excess SO₄²⁻ with Mg²⁺ or Na⁺ causes gastrointestinal problem in the consumers (WHO 1997).

A major portion of the study area shows contamination by NO₃⁻ and F⁻ (Table 2). NO₃⁻ concentration in the area varies between 3.3 and 236 mg/L with an average of 48.9 mg/L in pre-monsoon and between 6.4 and 302 mg/L with an average of 48.9 mg/L (Table 1; Fig. 3i). Nitrate in groundwater is derived mainly from poultry farms, animal wastages and septic tank leakages, agricultural activities, and decaying of organic domestic wastes (Jalali 2005; Lee et al. 2003; Narsimha and Sudarshan 2017). High NO₃⁻ in drinking water causes methemoglobinemia (blue baby syndrome) in infants (WHO 1997). F⁻ Concentration in the area varies between 0.18 and 3.4 mg/L with an average of 1.12 mg/L for pre-monsoon samples and between 0 and 2.6 mg/L with an average of 0.72 mg/L for post-monsoon samples (Table 1; Fig. 3g). Granites/gneisses are the major rock types in this study area which have the highest fluoride containing minerals viz. fluorite (0–3.3%), biotite (0.1–1.7%), and hornblende (0.1–1.1%). So, the major reason for elevated level of fluoride concentration in the groundwater in this region could be due to water rock interaction and weathering of F⁻ rich minerals. Anthropogenic activities such as, application of fertilisers and industrial activities like brick kilning also add to fluoride levels in the aquifers (Brindha and Elango 2011; Datta et al. 1996; Hem 1986; Pickering 1985). Consumption of fluoride rich water causes dental fluorosis (Heller et al. 1997; Viswanathan et al. 2009) and aids weakening

Table 3 Groundwater classification on the basis of TDS and TH

Values of parameters	Class of water	% of samples in pre-monsoon	% of samples in post-monsoon
TDS (mg/L)			
< 500	Desirable for drinking	35	39.5
500–1000	Permissible for drinking	60	50
1000–3000	Useful for irrigation	5	10.5
> 3000	Unfit for drinking and irrigation	0	0
TH (mg CaCO₃/L)			
< 60	Soft	2.5	2.6
60–120	Moderately hard	7.5	2.6
121–181	Hard	22.5	10.52
> 181	Very hard	67.5	84.2

of bones and skeletal fluorosis (National Research Council 1993).

Water Quality Index (WQI)

In order to provide overall the quality of groundwater for drinking purpose, WQI was estimated. All the measured parameters in this study were considered for estimating the WQI and the weighted arithmetic index method suggested by Brown et al. (1970) was used for WQI calculation. The equation used for the calculation is:

$$q_n = 100[V_n - V_{i0}]/[S_n - V_{i0}] \tag{4}$$

where n is defined as the number of water quality parameters and q_n refers to the quality rating of the n th parameter which reflects the relative contribution towards the polluted water with respect to the standard value.

- q_n = Quality rating for the n th parameter of water quality
- V_n = Measured value of n th parameter for a particular sample
- S_n = Standardised permissible value of n th parameter
- V_{i0} = Ideal value of n th parameter in pure water (i.e. 0 for all parameters except pH which has neutral value of 7)

WQI is calculated using this equation:

$$WQI = \frac{\sum q_n W_n}{\sum W_n} \tag{5}$$

where W_n = unit weight of n th parameters, which is calculated by:

$$W_n = K/S_n \tag{6}$$

K = Constant of proportionality and calculated as:

$$K = \frac{1}{\sum \left(\frac{1}{S_n}\right)} \tag{7}$$

Table 4 Relative weight of chemical parameters for WQI Index

Parameters	Relative weight (W_i)
EC	0.000802
pH	0.141576
TDS	0.001203
TH	0.002407
TA	0.002006
Ca ²⁺	0.004011
Mg ²⁺	0.012034
F ⁻	0.802265
NO ₃ ⁻	0.024068
SO ₄ ²⁻	0.004814
Cl ⁻	0.004814
$\sum W_i =$	1.000000

Table 5 Water Quality Index (WQI) for pre- and post-monsoon

Sample		WQI	
Pre	Post	Pre	Post
M1	M1	19.9	90.1
M3	M3	37.5	47.8
M4	M4	46.6	50.1
M5	M5	47.2	61.5
M7	M7	27.7	88.8
M8	M8	175.5	52.6
M10	M10	88.1	144.4
M11	M11	34.8	42.7
M12	M12	25.7	33.5
	P1		18.4
P2	P2	15.6	9.5
P3	P3	20.6	27.6
P4	P4	18.2	27.6
P5	P5	143.9	30.0
P6	P6	45.1	25.5
P7	P7	31.2	35.3
P8	P8	38.7	53.0
P9	P9	47.1	20.7
P10	P10	18.6	26.4
P11	P11	15.1	39.3
P12	P12	34.0	33.5
G1	G1	127.7	20.1
G2	G2	86.2	69.2
G3		128.9	
G4		102.9	
G5	G5	17.7	39.5
O1	O1	102.2	120.9
O2	O2	59.4	114.8
O3	O3	37.7	31.9
O4	O4	31.4	49.3
O5	O5	13.3	32.2
O7	O7	62.9	118.7
O8	O8	190.3	59.0
V9	V9	123.6	146.7
V10	V10	131.9	63.0
V11		159.1	
V12	V12	85.2	13.8
V13	V13	121.4	93.2
V1	v 1	50.7	44.8
V2	v 2	37.3	19.8
V4	v 4	20.6	12.1

Table 4 lists the relative weights of chemical parameters for WQI calculation. The calculated WQI for each sample is given in Table 5 and description of the classification of water on the basis of WQI is given in Table 6. According to the WQI values 27.5% of samples in pre-monsoon and 13.2% of samples in post-monsoon are unsuitable for drinking.

Table 6 Classification of groundwater on the basis of Water Quality Index (WQI)

WQI	Classification of pre- and post-monsoon samples based on WQI	Percentage of pre-monsoon samples	Percentage of post-monsoon samples
0–25	Excellent water quality	22.5	18.4
26–50	Good water quality	35	42.1
51–75	Poor water quality	7.5	18.4
76–100	Very poor water quality	7.5	7.9
> 100	Unsuitable for drinking	27.5	13.2

Good-to-excellent quality is found in 57.5% of samples during pre-monsoon and 60.5% in post-monsoon.

Irrigation suitability

In addition to different irrigation suitability indicators (SAR, EC, Na %, RSC, PI, MR, RSBC, SH, PS, SSP and MR), Doneen’s chart, Wilcox and USSL diagrams were also used to assess the groundwater suitability for irrigational use in this area. Groundwater classification based on EC values (Richards 1954) and the percentage of samples falling in each class is given in Table 7. 35% samples in pre-monsoon and 39.5% samples in post-monsoon fall in the good category and the rest in permissible category. The groundwater samples were also classified as per salinity hazard (SH) (Richards 1954). Table 7 shows that 35 and 39.5% of the samples fall in good category during pre- and post-monsoon seasons, respectively. None of the samples fall in the excellent or unsuitable categories.

Soluble sodium percentage (SSP) is an important parameter to assess the sodium hazard towards irrigation. It is defined by Todd (1960) as shown below:

$$SSP = \frac{Na^+}{Ca^{2+} + Mg^{2+} + K^+} \times 100 \tag{8}$$

where all the concentrations are in meq/L. Table 7 enlists the classification of the samples on the basis of SSP values. Table 7 shows that 77.5% of the pre-monsoon samples fall in the doubtful to unsuitable category, while 82% of the samples fall in the doubtful to unsuitable category during post-monsoon.

High sodium ion concentration in water causes low permeability of soil and hence infiltration of water becomes difficult. The presence of calcium and magnesium in soil allows easy cultivation and makes soil more permeable. The increase in sodium in soil replaces calcium and magnesium from soil and soil becomes hard and compact leading to reduced infiltration and poor internal drainage (Karanth 1987). The SAR values are calculated using the following equation (Richards 1954):

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \tag{9}$$

where the concentrations are expressed in meq/L. The SAR values vary from 0.6 to 25.8 during pre-monsoon and from 0.5 to 14.8 during post-monsoon, 82.5% of the pre-monsoon samples fall in the excellent category and only one sample in doubtful category. During post-monsoon, 94.7% samples fall in the excellent category (Table 7). High sodium concentration also leads to alkaline soils by combining with CO₃²⁻ and HCO₃⁻ and saline soils by combining with Cl⁻. Both alkaline and saline soils are unfavourable for irrigation. Sodium hazard is expressed as percentage sodium (Na %, Wilcox 1948). The following equation is used to calculate the Na% parameter (Wilcox 1955):

$$Na\% = \frac{(Na^+ + K^+) \times 100}{Na^+ + K^+ + Ca^{2+} + Mg^{2+}} \tag{10}$$

All units are in milliequivalents per litre. Na% values for the pre-monsoon samples varied from 18.2 to 91.5, while in post-monsoon season, it ranged from 12.1 to 84.9. Values suggest that a majority of samples from both the seasons fall in excellent-to-permissible zones, while 32.5% samples in pre-monsoon and 26.3% of samples in post-monsoon fall in doubtful to unsafe category (Table 7). High Na⁺ and EC reduce the osmotic pressure in the plants limiting the intake of nutrients present in water for proper growth (Keesari et al. 2016). To study the integrated effect of EC and Na%, Wilcox diagram is used (Wilcox 1955). From the diagram (Fig. 5), it can be observed that groundwater is more suitable for irrigation during post-monsoon season because 76.3% samples fall in excellent-to-good and good-to-permissible categories in comparison to 67.5% samples during pre-monsoon. The quality of groundwater in pre-monsoon season is degraded mainly because of high amount of Na⁺, HCO₃⁻ and TDS due to extreme evaporative conditions.

The United States Salinity Laboratory diagram was used to describe the irrigation suitability of groundwater of this region in a detailed way (USSL 1954). Based on the USSL classification, the study area is classified into major five zones, C2S1, C2S2, C3S1, C3S2 and C3S3 (Fig. 6). Samples falling in the C2S1 and C2S2 region are good for irrigation while samples falling in C3S1 and C3S2 region are marginally suitable for irrigation because of high salinity hazard values. Samples falling in the C3S3 region are unsuitable

Table 7 Irrigational suitability of groundwater

Parameters	References	Classification based on parameters	% of samples from pre-monsoon	% of samples from post-monsoon
EC ($\mu\text{s}/\text{cm}$)	Richards (1954)			
< 250		Excellent	0	0
250–750		Good	35	39.5
750–2000		Permissible	65	60.5
2000–3000		Doubtful	0	0
> 3000		Unsuitable	0	0
Alkalinity hazard (SAR)	Richards (1954)			
< 10		Excellent	82.5	94.7
10–18		Good	15	5.3
18–26		Doubtful	2.5	0
> 26		Unsuitable	0	0
Per cent sodium (Na %)	Wilcox (1955)			
> 20		Excellent	2.5	2.6
20–40		Good	20	18.4
40–60		Permissible	45	52.6
60–80		Doubtful	15	23.7
> 80		Unsafe	17.5	2.6
Residual sodium carbonate (RSC)	Eaton (1950)			
< 1.25		Good	42.5	50
1.25–2.5		Doubtful	10	7.9
> 2.5		Unsuitable	47.5	42.1
Salinity hazard (SH) (EC values in $\mu\text{s}/\text{cm}$)	Richards (1954)			
100–250		Excellent	0	0.0
250–750		Good	35	39.5
750–2250		Doubtful	65	60.5
> 2250		Unsuitable	0	0.0
Residual sodium bicarbonate (RSBC)	Gupta (1983)			
< 5		Satisfactory	42.5	39.5
5–10		Marginal	30	18.4
> 10		Unsatisfactory	27.5	42.1
Potential salinity (PS)	Doneen (1962)			
< 5		Excellent to Good	62.5	55.3
5–10		Good to Injurious	20	28.9
> 10		Injurious to satisfactory	17.5	15.8
Soluble sodium percentage (SSP)	Todd (1960)			
0–20		Excellent	0	2.6
20–40		Good	12.5	7.9
40–60		Permissible	10	7.9
60–80		Doubtful	12.5	15.8
> 80		Unsuitable	65	65.8
Magnesium ratio (MR)	Raghunath (1987)			
< 50		Suitable	12.5	36.8
> 50		Unsuitable	87.5	63.2
Kelley ratio (KR)	Kelley (1963)			
< 1		Suitable	42.5	52.6
1–2		Marginally suitable	30	34.2
> 2		Unsuitable	27.5	13.2

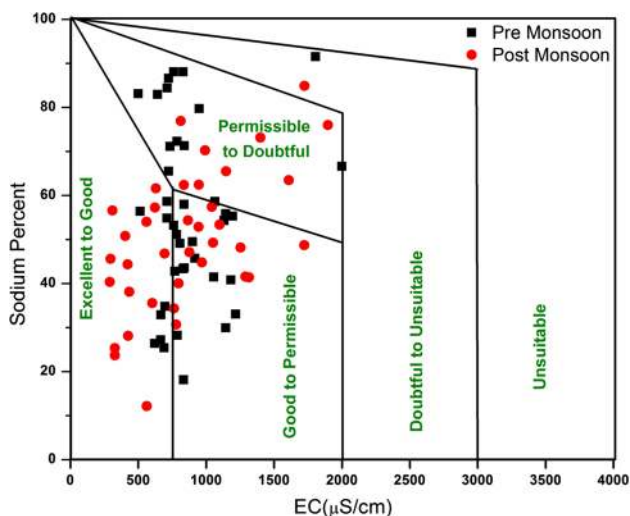
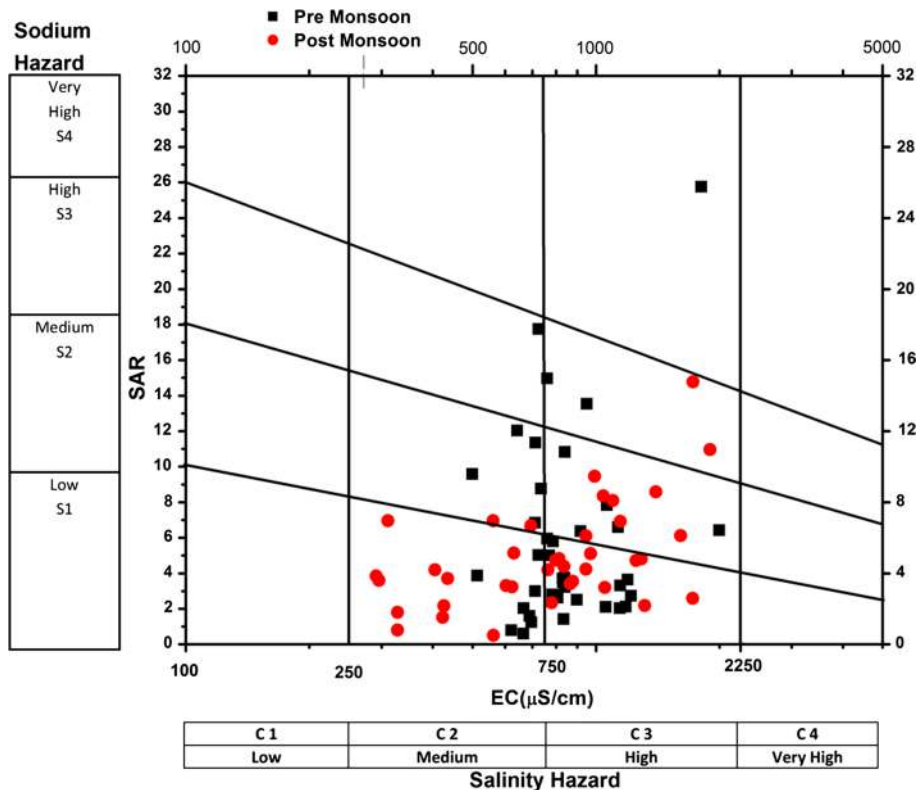


Fig. 5 Wilcox diagram of groundwater samples of the study area for two seasons

for irrigation because of high salinity hazard and high SAR values. The SH values indicate that 65% of the pre- and 60.5% of the post-monsoon samples belong to high salinity zone. The SAR values indicate 82.5% of the pre- and 95% of the post-monsoon samples belong to the low SAR (Fig. 6). Overall, 10% of the pre- and 5.3% of the post-monsoon samples were found to be unsuitable for irrigation (Fig. 6).

Fig. 6 USSL diagram of groundwater samples of the study area for two seasons



RSC is also an important parameter for assessing the groundwater suitability for irrigation, it is defined as (Eaton 1950):

$$RSC = (\text{HCO}_3^- + \text{CO}_3^{2-}) - (\text{Ca}^{2+} + \text{Mg}^{2+}) \quad (11)$$

where all the concentrations are in meq/L.

RSC < 1.25 indicate suitability of water for irrigation while 1.25–2.5 is in doubtful category and greater than 2.5 is not useful for irrigation (Lloyd and Heathcote 1985). During pre-monsoon RSC values in this area range from –12.22 to 15.79 and during post-monsoon, it varies from –7.3 to 13.9. 52.5% of samples during pre-monsoon and 58% during post-monsoon fall under good-to-doubtful category, while rest fall in unsuitable category (Table 7).

Similar to RSC, RSBC is another factor determining the quality of water on the basis of bicarbonate ion concentration. RSBC is defined as (Gupta 1983):

$$RSBC = \text{HCO}_3^- - \text{Ca}^{2+} \quad (12)$$

where all the concentrations are in meq/L. From the summary of Table 7, it can be seen that 60% of sample in post-monsoon samples show marginal to unsatisfactory values, while 58% of samples during pre-monsoon have marginal to unsatisfactory values.

Potential salinity (PS) is defined as the chloride concentration plus half of the sulphate concentration (Doneen 1962);

$$PS = \text{Cl}^- + \frac{1}{2}\text{SO}_4^{2-} \quad (13)$$

where all the concentrations are in meq/L. Table 7 shows that 82.5% of the pre-monsoon and 84.2% of the post-monsoon samples fall in excellent-to-good and good-to-injurious categories, while rest of the samples (17.5% during pre- and 15.8% during post-monsoon season, respectively) falls under injurious to satisfactory category.

Excess magnesium in waters affects the soil quality by increasing the alkalinity and it subsequently decreases the crop yield. The hazard posed by excess Mg^{2+} in groundwater is indicated by magnesium ratio (MR) defined as (Raghunath 1987):

$$MR = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100 \quad (14)$$

All the concentrations are expressed in meq/L. Table 7 shows that 87.5% of the pre-monsoon samples belong to the unsuitable category while 63% of the post-monsoon samples fall in this category.

Kelly's ratio (KR) was also estimated to evaluate the groundwater quality for irrigation purposes (Kelley 1963). It is defined as:

$$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \quad (15)$$

where all the concentrations are in meq/L. $KR > 2$ indicates an excess level of sodium in waters and not suitable for irrigation. From Table 7, it can be seen that 72.5% of the pre- and 87% of the post-monsoon samples belong to suitable to marginally suitable category. The rest of the samples belong to the unsuitable category.

Long-term use of groundwater for irrigation purposes affect the permeability index (PI) of groundwater, which in turn is influenced by Na^+ , Ca^{2+} , Mg^{2+} and HCO_3^- concentrations. PI is defined by:

$$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100 \quad (16)$$

where all concentrations are expressed in meq/L. Doneen (1964) has classified water into three groups based on the PI values (Fig. 7). Class I category is considered to be 100% of maximum permeability and have good prospect for irrigation, class II considers 75% of maximum permeability and considered to be marginally suitable for irrigation, while class III is associated with 25% maximum permeability and is unsuitable for irrigation. From the Doneen's chart, it is clear that post-monsoon groundwater is better for irrigation with only one sample in class III unsuitable for irrigation whereas five samples from pre-monsoon fall in class III (Fig. 7).

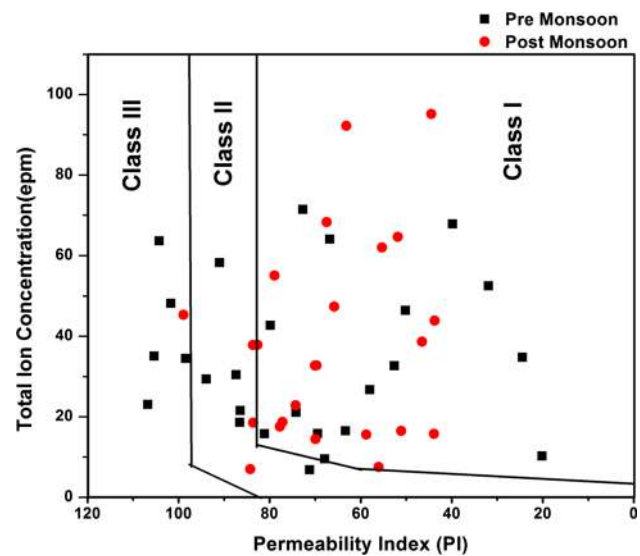


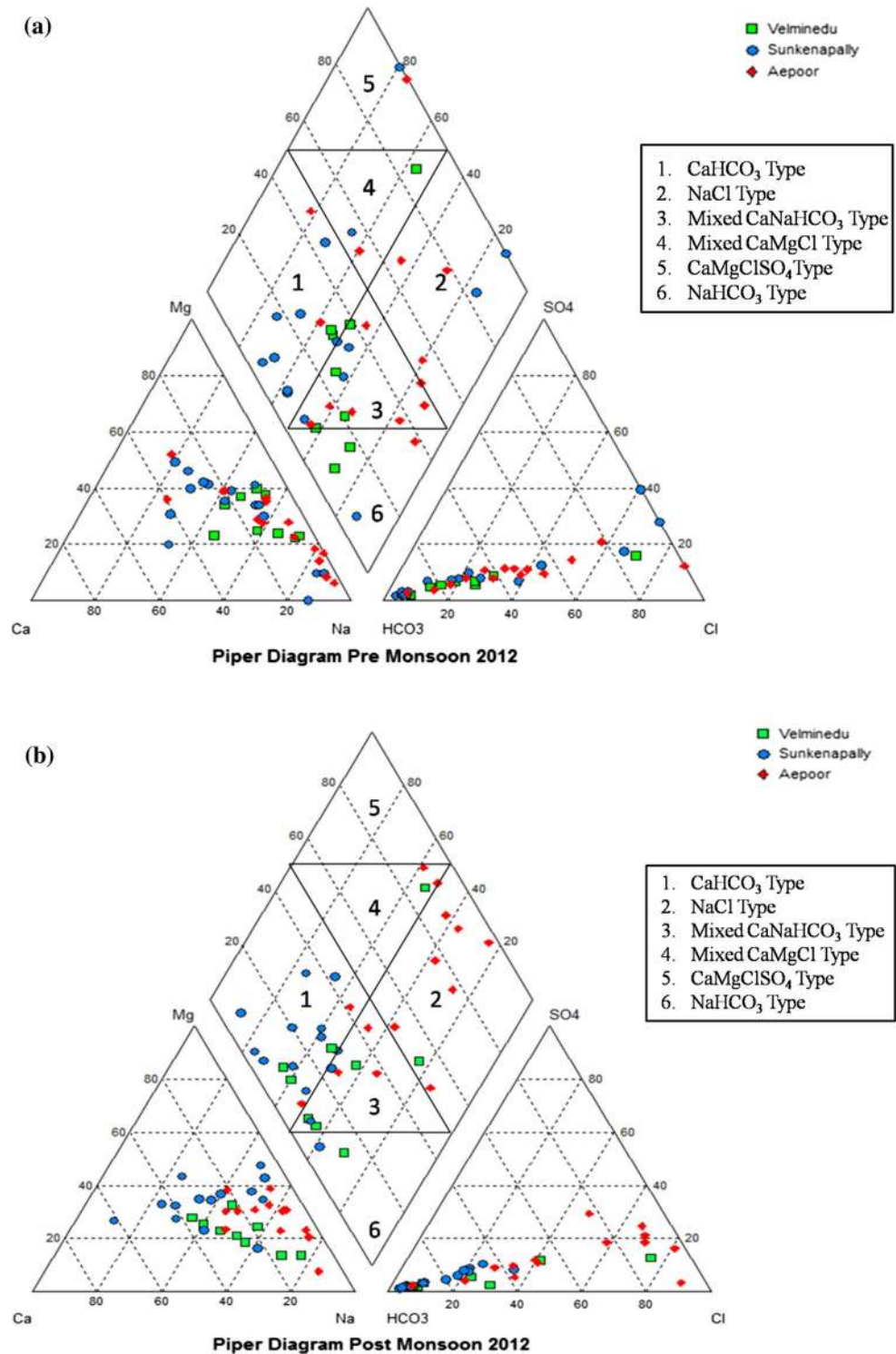
Fig. 7 Doneen's chart for groundwater samples of study area for two seasons

From the evaluation of the groundwater quality with respect to drinking and irrigation purposes, it can be seen that the quality of post-monsoon samples is better than the pre-monsoon samples. The higher levels of F^- and NO_3^- in groundwater are the major concern of this region. However, this study infers that the post-monsoon samples have reduced level of contaminants and also are better for drinking water and irrigation purposes. Hence, increasing the groundwater level through rainwater harvesting can be a viable option to mitigate the water quality problems of this region to a greater extent. Better rainwater harvesting can be achieved through construction of artificial structures and also by desilting the natural tanks available in this region.

Geochemical study of groundwater samples

Chemical data of major ions are plotted in piper tri-linear diagram (Piper 1944) (Fig. 8a, b) to determine the types of groundwater as well as the geochemical characteristics of the groundwater in the study area. The diagram consists of two triangular fields for cation and anion separately and a diamond shaped field. The diamond field is divided into six major groups representing a characteristic water type. These water groups are (1) $CaHCO_3$, (2) $NaCl$, (3) mixed $CaNaHCO_3$, (4) mixed $CaMgCl$, (5) $CaMgClSO_4$ and (6) $NaHCO_3$ type. Piper diagram shows that Na^+ and HCO_3^- are the dominant species in both the seasons. The major water types of the study area are found to be: $Na-Mg-HCO_3$, $Na-Mg-HCO_3-Cl$, $Na-HCO_3$, $Mg-Na-HCO_3$, $Mg-Ca-HCO_3$ and $Na-Cl$ (Fig. 8a, b). The comparative analysis of the number of samples falling in each of these groups in the diamond field suggests

Fig. 8 **a** Piper diagram of the groundwater samples collected in pre-monsoon 2012. **b** Piper diagram of the groundwater samples collected in post-monsoon 2012



that 40% samples in the pre-monsoon fall in the group 1 and 2 while 63% of samples fall in these groups during post-monsoon. This confirms the influence of the rainwater recharge and subsequent dissolution of the salts in the unsaturated zone during post-monsoon season.

Geochemical characteristics of the groundwater are also evaluated by Chadha’s plot (Chadha 1999). In order to construct this plot, all the data were transferred to milliequivalent percentages and the difference between Ca²⁺ + Mg²⁺ and Na⁺ + K⁺ for cations, and between HCO₃⁻ + CO₃²⁻ and

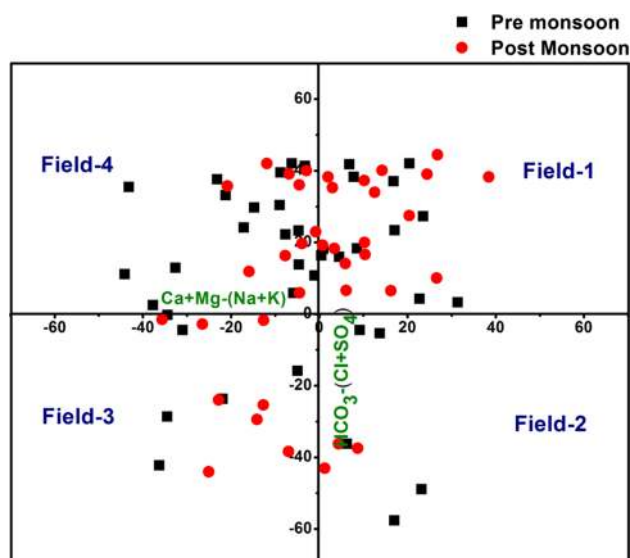
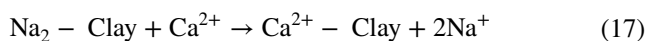


Fig. 9 Geochemical classification based on Chadha's diagram

$\text{Cl}^- + \text{SO}_4^{2-}$ for anions was calculated. This each quadrant of the plot infers a different hydrochemical process, e.g. Field-1 represents recharging waters (Ca– HCO_3 type), Field-2 represents reverse ion-exchange waters (Ca–Mg–Cl type), Field 3 represents end member waters (seawater Na–Cl type) and Field 4 represents base ion-exchange waters (Na– HCO_3 type). Majority of samples fall in the fields 1 and 4 for both of the seasons, but the relative proportion indicates that more number of post-monsoon samples fall in the field 1 as compared to pre-monsoon. This again corroborates the finding from Piper's diagram that the post-monsoon samples are originated from precipitation, while pre-monsoon samples show base exchange reaction as the governing reaction as indicated below (Hounslow 1995; Keesari et al. 2016) (Fig. 9):



A few samples fall in field 3 indicating Na–Cl type water. Dissolution of the salts deposited in the unsaturated zone by rainwater can result in Na–Cl type water. These samples are also characterised by relatively high EC (1897 $\mu\text{S}/\text{cm}$).

Conclusion

A current update on the status of groundwater quality and the geochemical characters of the hard rock aquifers of central parts of Telangana State, India, is presented. Suitability of the groundwater for domestic and irrigation purposes was evaluated from the measured hydrochemical parameters in accordance with guideline values prescribed by WHO (2011) and BIS (2012). The overall water quality is assessed

using WQI, which indicates that more number of samples have better quality during post-monsoon compared to pre-monsoon. F^- and NO_3^- were found to be the main inorganic contaminants in groundwater, while high HCO_3^- concentration renders the water quality poor by increasing the total hardness. Seasonal variation of the hydrochemical data clearly suggests that dissolution of salts in the unsaturated zone by infiltrating rainwater adds to major ions into the groundwater, while F^- and NO_3^- show a reduction in concentration due to rainwater dilution. All the indicators and diagrams depicting the irrigation suitability suggest that post-monsoon samples are more suitable for irrigation than pre-monsoon samples. The geochemical characteristics of groundwater determined by Piper's diagram and Chadha's plot show that post-monsoon groundwater has significant contribution from rain and the chemistry is governed by salt dissolution in unsaturated zone. During pre-monsoon, water rock interaction and ion-exchange processes were found to be more dominating. The study area (Nalgonda District) being a known fluoride contaminated region, implementing rainwater harvesting by constructing suitable artificial structures and desilting the natural tanks available in this area can help increase the groundwater availability and also limit the fluorosis incidences among local population.

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