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A synoptic assessment of groundwater quality in high water-demand regions of coastal Andhra Pradesh, India

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ABSTRACT

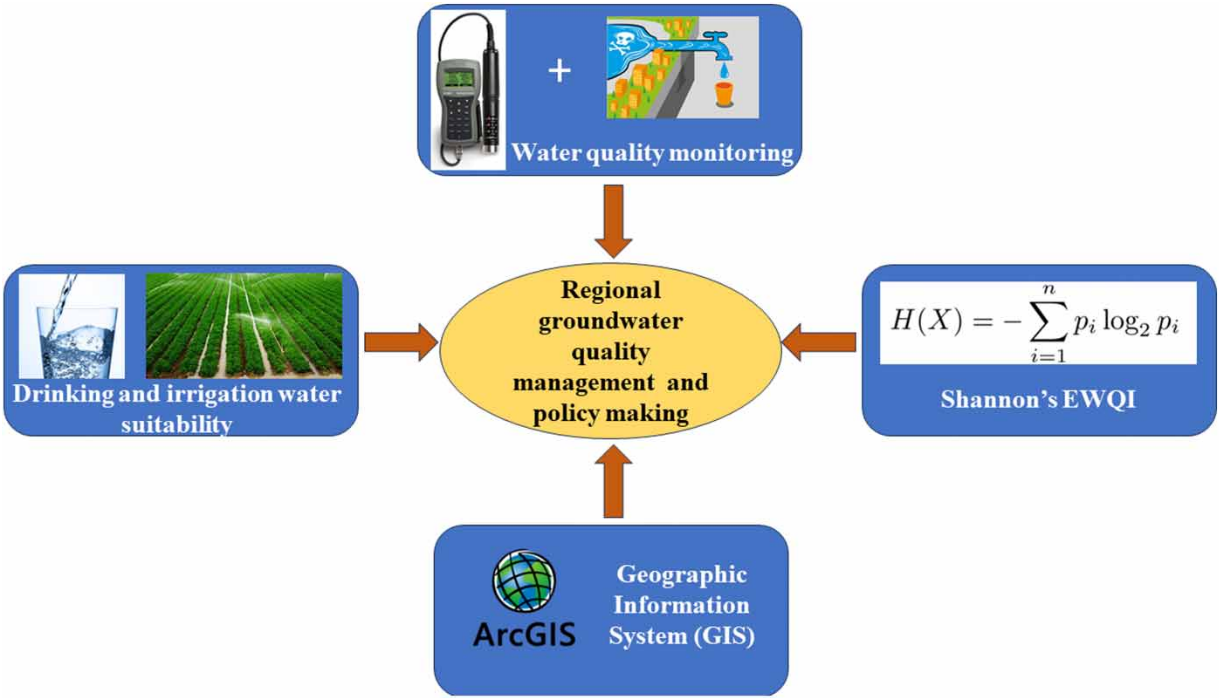
In this article, a coastal region of India having high water demand for irrigation supply was studied for its groundwater quality in temporal and spatial domains. The statistical tests (Shapiro–Wilk *W* and Anderson–Darling *A*) of the chemical data of over 100 groundwater samples of the study area indicate the non-parametric nature of the distribution. High concentrations of F^- and NO_3^- ions above drinking water permissible limits were present in 12% and 28% of samples, respectively. Similarly, Cl^- ion, and total hardness were higher while Ca^{2+}, Mg^{2+}, and Na^+ ions were marginally higher compared to drinking water limits. Kruskal–Wallis (ANOVA) test results indicate that seasonal variations are not very significant among chemical species. Based on irrigation water quality indicators, groundwater samples fall under the excellent to doubtful category during premonsoon and permissible to unsuitable category during postmonsoon season. These inferences were verified by using the Entropy Water Quality Index (EWQI). The spatial contours of the EWQI values clearly suggest that the impact of anthropogenic activities on groundwater is greater in the northern parts of the study area. Optimizing fertilizer application and effluent treatment can improve the groundwater quality thereby achieving sustainable groundwater management in this region.

Key words: Coastal India, Entropy Water Quality Index, hydrochemistry, SDG-6, Srikakulam

HIGHLIGHTS

- Hydrochemistry of the groundwater suggests a high vulnerability to nitrate contamination in the northern parts.
- Seasonal variations in water quality data infer that the premonsoon season is better than postmonsoon season.
- Indicators representing the water quality for irrigation show that groundwater is in the excellent to doubtful category excepting magnesium hazard and Kelley's ratio.

GRAPHICAL ABSTRACT



INTRODUCTION

Safe water, sanitation, and hygiene form the most basic needs for human health and wellbeing. The United Nations Development Programme has set a goal of achieving clean water and sanitation by 2030 under Sustainable Development Goal 6 (SDG-6). Groundwater is one of the most important and reliable resources of freshwater but it is limited. Climate change and human interference have been impacting both the quality and quantity of groundwater in many parts of the world. A recent report on the assessment of climate change over the Indian sub-continent has highlighted that monsoonal rainfall intensity has been decreasing due to climate change leading to poor recharge of ponds, lakes, and other surface water bodies. From the current water level fluctuation data, it is estimated that 37.3% of the assessment units (Blocks/Taluks/Mandals/Districts) fall under the unsafe category, i.e. semi-critical to over-exploited in India (CGWB 2017). Another major concern is the degradation of water quality by both geogenic and anthropogenic sources. Dumping untreated industrial wastes, sewage, and agricultural wastes is a major factor degrading the surface and groundwater quality in India (Khatri & Tyagi 2015). In addition, geogenic contamination such as fluoride (Keesari *et al.* 2007, 2021; Jha & Tripathi 2021), arsenic, and other metals (Poonia *et al.* 2021), as well as salinization of freshwater aquifers (Pant *et al.* 2020), are some major concerns. Many coastal regions have been impacted by saline water either due to seawater intrusion or the upcoming deep-seated saline pockets (Prusty & Farooq 2020). Among anthropogenic contamination, nitrate contamination is most prevalent in many parts of India, which is mainly attributed to the contribution of agricultural and industrial wastes (Jain & Sharma 2008).

Srikakulam district of Andhra Pradesh is among the coastal districts of India with a high dependence on groundwater resources (Figure 1(a)–1(d)). This district has a coastline of 129 km, and groundwater in some pockets is found to be saline (Rao *et al.* 2011). Due to the high water demand for drinking, irrigation and industrial needs, the groundwater is being extracted more than the natural recharge in several parts of this district leading to a lowering of water levels. Degradation of water quality is another major issue in this district. Several studies reported that groundwater is impacted by high levels of total dissolved solids (TDS), chloride (Cl^-), total hardness (TH), magnesium (Mg^{2+}), nitrate (NO_3^-), and fluoride (F^-) concentrations (Kumar *et al.* 2010; Rao *et al.* 2022). Considering the freshwater demand and dependency on groundwater, three mandals, G. Sigdam, Laveru, and Ranasthalam, of this district are designated as water-stressed, and water conservation efforts have been initiated by water authorities. The available literature on the water quality of this region is

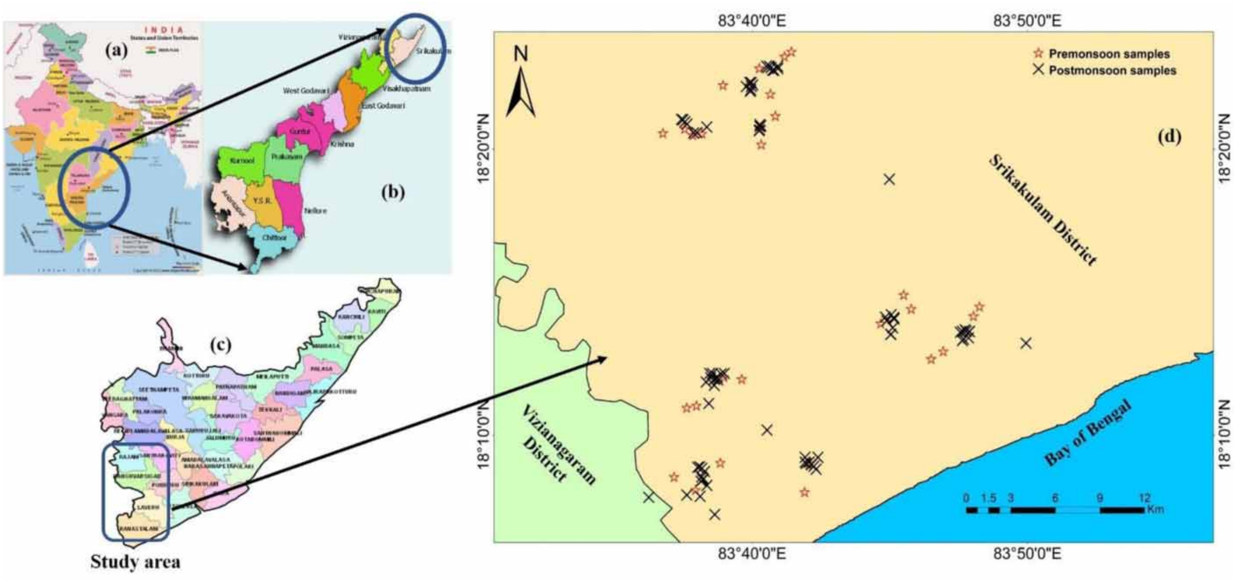


Figure 1 | (a) India political map, (b) district map of Andhra Pradesh, (c) mandal map of the Srikakulam district, and (d) locations of groundwater samples collected during pre- and postmonsoon seasons.

limited and does not provide an in-depth analysis of groundwater quality. In this study, the overall quality of groundwater from the study area has been evaluated with objectives to (i) evaluate suitability for drinking and irrigation and (ii) estimate the composite water quality index (WQI). The objectives are achieved through the measurement of hydrochemical parameters of the groundwater samples collected across the study area covering different well depths and seasons. Suitability for drinking is assessed using TDS, TH, and electrical conductivity (EC) while suitability for irrigation is assessed using sodium adsorption ratio (SAR), percent sodium (Na%), residual sodium carbonate (RSC), magnesium hazard (MH), permeability index (PI), EC, Kelly's ratio (KR), and corrosivity ratio (CR). The computed values for different indicators were compared with World Health Organization (WHO) and Bureau of Indian Standards (BIS) guidelines for drinking water suitability. Shannon's entropy technique was used to estimate the composite water quality due to its low biases and capacity to capture uncertainty (Amiri *et al.* 2014). Geographic information system (GIS) is normally employed to develop distribution maps of ionic concentrations or any water quality parameter (WQP) so that monitoring and interpretation of the groundwater quality is done in a reliable manner (Adimalla & Qian 2020). Flexibility in data handling and ease and speed of data processing enable the GIS methods as superior tools over the conventional approaches. GIS studies have been undertaken by many researchers to infer the groundwater quality and resource potential of a given region (Elumalai *et al.* 2017). In this study, we have integrated both Shannon's entropy technique and GIS to arrive at more reliable water quality distribution contour diagrams for the study area. The outcome of this study would provide a baseline for future studies as well as act as a guide to establish the impact of water conservation measures being carried out by water departments.

METHODOLOGY

Study area

The study area falls in the southern part of Srikakulam district, Andhra Pradesh state of India and extends from latitudes 18.110° to 18.412° N and longitudes 83.582° to 83.865° E encompassing a total area of 1,153 km^2 (Figure 1(d)). This area is agrarian and the irrigation water needs are met mainly by groundwater. The study area is categorized as semi-critical to over-exploited. The major perennial rivers are Vamsadhara and Nagavali, both of which are east-flowing rivers and drain into the Bay of Bengal. The drainage pattern of the study area is dendritic with a drainage density varying from <0.2 to 1 km/km^2. The study area receives rainfall of about 1,067 mm/a, in which about 70% of the rainfall occurs during the southwest monsoon and 20% during the northeast monsoon. The maximum temperature is about 34 °C during May and the minimum is about 17.5 °C during December/January (APSAC 2018).

The geology of the study area belongs to the Archaean group and alluvium. Khondalites and Charnockites of the Eastern Ghat Super Group constitute the Archaean group of rocks and the Migmatite group includes Granitic Gneisses. Khondalites and Charnockites formations have low yields in the order of 10–20 m^3/d in the weathered zones while granitic gneiss formation has higher yields of about 10–40 m^3/d. Sandstone formation with limited extension is also present in the Ranasthalam mandal located in the western part of the district. The main types of soils found in the district are red soil, red loams, sandy loams, sandy soil, black soil, and alluvial soil (APSAC 2018).

Sampling and measurement

Samples were collected from the existing hand pumps (HP), dug wells (DW), and tube wells (TW) in the study area, with a total of 114 samples. During the premonsoon season, 32 samples were collected to get an initial overview of the groundwater quality, however, during postmonsoon season, a detailed sampling was carried out (82 numbers) covering a wider network of wells so that monsoon-induced water quality changes can be perceived clearly. In addition, power failure and drying up of wells also limited sample availability during the premonsoon season. The sample location map is provided in Figure 1(d). The physicochemical parameters (EC, pH, and TDS) were measured *in situ* using a multiparameter kit (Hanna Make, HI 9829 11042). Total alkalinity describes the capacity of the sample to neutralize acids and is commonly measured at the site using titrimetric analysis, where the equivalent of acid used to reach a pH of 4.2 corresponds to the total alkalinity of the sample. In natural water samples, bicarbonate and carbonate ions are the predominant ions that determine the pH of the water. Therefore, alkalinity is expressed as (i) P-alkalinity, which refers to carbonate concentration (acid titration with phenolphthalein indicator) and (ii) M-alkalinity, which refers to the sum of carbonate and bicarbonate concentration (acid titration with methyl orange indicator). Alkalinity can also be computed using total inorganic carbon (TIC) that can be determined by wet chemical analysis where a measured sample is injected with a percentage of 1 N hydrochloric acid. The carbonates are reduced to CO_2 and are detected using a non-dispersive infrared detector (NDIR). These methods are described by Michałowski & Asuero (2012), Hassoun *et al.* (2015), Boyd *et al.* (2011) and references therein. In this study, acid-base titration is applied for total alkalinity measurement. A 10 mL water sample was titrated against 0.02 N H_2SO_4 and the end point was determined using methyl orange indicator.

For major ion chemistry, approximately 60 mL water sample was filtered through a 0.45 μm cellulose filter in the field and transferred into the Tarsons® bottles. Ultra-pure concentrated nitric acid was added to the filtered samples for cation measurements to avoid precipitation and wall adsorption. Ion chromatography system (DX-500, Dionex Corporation) was used to measure anions (F^-, Cl^-, NO_3^-, and SO_4^{2-}) and cations (Na^+, K^+, Mg^{2+}, and Ca^{2+}). The accuracy of the chemical measurements was verified using charge balance error (CBE) (Equation (1)). The calculated CBE of the water samples was within the allowed limit of $\pm 5\%$.

$$\text{CBE}\ (\%) = \frac{M_{\text{eq}}(\text{cations}) - M_{\text{eq}}\ (\text{anions})}{M_{\text{eq}}(\text{cations}) + M_{\text{eq}}\ (\text{anions})} \times 100 \tag{1}$$

Evaluation of drinking water and irrigation suitability indicators

The drinking water suitability was evaluated by comparing EC, TDS, and TH with the permissible limits set by WHO (2011) and BIS (2012).

TDS (in mg/L) is calculated from measured EC using Equation (2) after Hem (1985).

$$\text{TDS}(\text{mg/L}) = 0.64 \times \text{EC}\ (\mu\text{S/cm}) \tag{2}$$

Ca^{2+} and Mg^{2+} ions are responsible for hardness in water (TH) which is expressed as mg/L of $CaCO_3$ using Equation (3) (Todd 1980).

$$\text{TH}\ (\text{mg/L}) = 2.497 \times \text{Ca}^{2+} + 4.115 \times \text{Mg}^{2+} \tag{3}$$

The irrigation suitability was examined using SAR, Na%, PI, RSC, MH, KR, and CR.

The SAR for water is calculated using Equation (4) (Richards 1954).

$$SAR = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \quad (4)$$

Percent sodium (Na%) is calculated using Equation (5) (Wilcox 1955).

$$Na\% = \frac{(Na^{+} + K^{+}) \times 100}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} \quad (5)$$

PI was proposed by Doneen (1966) to evaluate the possible impact of water quality on the physical characteristics of soils because crop productivity depends upon soil fertility. PI is divided into three classes, 100% permeability as Class I, 75% permeability as Class II, and 25% permeability as class III. Class I, Class II, and Class III indicate suitability, marginal suitability, and unsuitability for irrigation, respectively. PI is calculated using Equation (6) (Doneen 1966);

$$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{Ca^{2+} + Mg^{2+} + Na^{+}} \times 100 \quad (6)$$

The alkalinity hazard of water is represented by RSC and estimated using Equation (7) (Eaton 1950). The water with RSC < 1.25, 1.25–2.5, and >2.5 are considered suitable, doubtful, and unsuitable for irrigation, respectively (Lloyd & Heathcote 1985).

$$RSC(meq/L) = (HCO_3^{-} + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}) \quad (7)$$

MH is another indicator used to examine irrigation water quality. MH is calculated using Equation (8). MH < 50 is considered as safe and >50 as unsafe for irrigation.

$$MH = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100 \quad (8)$$

CR represents the effect of water on the metal surface and the metal vulnerability to corrosion. The CR is calculated by Equation (9) and water samples with CR < 1 are considered to be safe while >1 is unsafe for the supply of water using metallic pipe (Balasubramanian 1986).

$$CR = \frac{(Cl/35.5) + 2\,(SO_4/96)}{2\{(CO_3 + HCO_3)/100\}} \quad (9)$$

Kelley's ratio (KR) is an indicator to check the suitability of water for irrigation. KR is estimated using Equation (10) (Kelley 1946) in which concentrations of Na^{+} and Mg^{2+} are in meq/L. Water samples with KR < 1, 1–2 and > 2 are considered as suitable, marginally suitable, and unsuitable, respectively.

$$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}} \quad (10)$$

Entropy Water Quality Index

This technique is used to calculate the WQI of groundwater samples collected from the study area to understand and assess the suitability for drinking and irrigation (Amiri *et al.* 2014). For normalization of the parameters, Equation (11) is used.

$$Y_{ji} = \frac{C_{ji} - (C_{ji})_{\min}}{(C_{ji})_{\max} - (C_{ji})_{\min}} \quad (11)$$

where $(C_{ji})_{\max}$ and $(C_{ji})_{\min}$ are the maximum and minimum measured value of ith parameter among all the samples (N), C_{ji} is the measured value of ith parameter of the jth groundwater sample.

Probability P_{ji} is calculated using Equation (12):

$$P_{ji} = \frac{(1 + Y_{ji})}{\sum_{j=1}^{N} (1 + Y_{ji})} \tag{12}$$

e_i is the information entropy calculated using probability factor P_{ji} (Equation (13)).

$$e_i = -\frac{1}{\ln(N)} \sum_{j=1}^{N} P_{ji} \ln(P_{ji}) \tag{13}$$

W_i is the entropy weight of the ith parameter, calculated using Equation (15);

$$w_i = (1 - e_i) \tag{14}$$

$$W_i = \frac{w_i}{\sum_{j=1}^{N} w_i} \tag{15}$$

q_i is the quality rating scale of ith parameter

for pH, $q_i = (C_{\mathrm{pH}} - 7)/(S_{\mathrm{pH}} - 7)$, while for other WQPs

$$q_i = \left(\frac{C_i}{S_i}\right) \times 100 \tag{16}$$

C_i is the measured value of the ith WQPs; S_i stands for the permissible standard limit defined by BIS (2012) and WHO (2011) of the same parameter, C_{pH} is the measured pH value of a groundwater sample and S_{pH} is the standard value of pH.

The Entropy Water Quality Index (EWQI) is calculated using Equation (17);

$$\mathrm{EWQI} = \sum_{i=1}^{n} W_i \cdot q_i \tag{17}$$

where n represents the number of WQPs.

On the basis of EWQI, groundwater can be divided into five categories, excellent (<25), good (25–50), moderate (50–100), poor (100–150), and extremely poor (>150).

Geostatistical approach

A geostatistical approach was employed to understand spatio-temporal variation of the EWQI values. The Spatial analyst module of ArcGIS 10.8 software was used for this purpose. The inverse distance weighted (IDW) technique was used for preparing the spatial distribution maps. ArcGIS software has long been used for geospatial and geostatistical analysis of WQPs (Mukherjee & Singh 2022). Kriging, Ordinary Kriging, Empirical Bayesian Kriging, and IDW techniques are some of the interpolation methods used for the preparation of spatial distribution maps. IDW method is often found to be the best model for interpolation of WQPs. IDW is a type of deterministic method for multivariate interpolation with a known scattered set of points. IDW determines cell values using a linear-weighted combination set of sample points. It weighs the points closer to the prediction location greater than those farther away (Elumalai *et al.* 2017). IDW is generally applied to highly variable data, and it is highly possible to return to the original collection site and record a new value that is statistically different from the original value but is within the general trend for the area (Khouni *et al.* 2021). However, IDW assumes stationarity, i.e., the relationship between distance and influence remains constant across the study area and therefore would not provide precise information in the case where study areas exhibit large variations in water quality. For IDW interpolation power value 2 and variable search radius with 12 number of neighbor points were used. The spatial distribution maps were finally reclassified using the Raster analysis tool in ArcGIS 10.8 according to the EWQI categories.

Temporal variation of the WQPs

A normality test was performed on the WQPs as well as calculating the EWQI using Shapiro–Wilk and Anderson–Darling tests. Based on the normality results, parametric one-way analysis of variance (ANOVA) or non-parametric Kruskal–Wallis tests were performed to evaluate seasonal variation of the means or medians of the WQPs and EWQI values, respectively. The statistical calculations were done using a python programming language.

RESULTS AND DISCUSSION

Physicochemical parameters

The summary of the hydrochemical parameters of the groundwater of pre- and postmonsoon seasons is provided in Table 1. The pH of the groundwater samples ranges from 6.9 to 8.4 (mean value: 7.7) and 6.6 to 9 (mean value: 7.5) in premonsoon and postmonsoon seasons, respectively (Table 1). The pH of all the groundwater samples in both seasons is within the permissible limit (pH 6.5–8.5) as per WHO (2011) and BIS (2012), except for a few samples during postmonsoon season. Generally, the pH of the groundwater is influenced by the CO_2 released from different biological activities and the atmosphere as well as toxic compounds. The seasonal variations in pH values of groundwater are depicted in the Box–Whisker plot (Figure 2(a)). From the mean values of pH during pre- and postmonsoon seasons, it can be inferred that premonsoon samples are slightly alkaline compared to postmonsoon samples. This could be due to the addition of root zone CO_2

Table 1 | Physicochemical and chemical parameters for both premonsoon (32) and postmonsoon (82) seasons

Parameters	Seasons	Minimum	Maximum	Median	Average	SD
EC	Premonsoon	469	3,483	936	1,136	661
	Postmonsoon	245	4,400	1,236	1,413	785
pH	Premonsoon	6.9	8.4	7.8	7.7	0.3
	Postmonsoon	6.6	9.0	7.5	7.5	0.4
Alkalinity	Premonsoon	195	488	354	339	75
	Postmonsoon	171	976	512	518	140
TDS	Premonsoon	236	1,744	468	567	334
	Postmonsoon	123	2,200	618	706	393
TH	Premonsoon	92.4	633	199	240	125
	Postmonsoon	77.1	948	255	301	160
Na^+	Premonsoon	2.82	597	127	158	143
	Postmonsoon	19.6	504	137	160	104
K^+	Premonsoon	0.54	315	2.69	25.3	63.5
	Postmonsoon	0.12	246	6.2	26.7	45.6
Ca^{2+}	Premonsoon	2.95	134	23.4	28.6	26.4
	Postmonsoon	6.15	162	33.8	44	32.8
Mg^{2+}	Premonsoon	7.3	91.5	38.3	41	18.9
	Postmonsoon	5.4	132	42.1	46.4	24.5
F^-	Premonsoon	0.55	1.96	1.1	1.12	0.35
	Postmonsoon	0.1	4.6	1	1.14	0.792
Cl^-	Premonsoon	11.2	740	90.6	169	176
	Postmonsoon	10.6	995	131	194	187
SO_4^{2-}	Premonsoon	3.9	220	25.6	44.0	46.0
	Postmonsoon	4.54	200	36.2	49.1	41.8
NO_3^-	Premonsoon	0	240	17.5	41.0	53.67
	Postmonsoon	0.6	210	27.1	49.3	52.1

Note: EC (μS/cm), rest of the parameters in mg/L; SD, standard deviation.

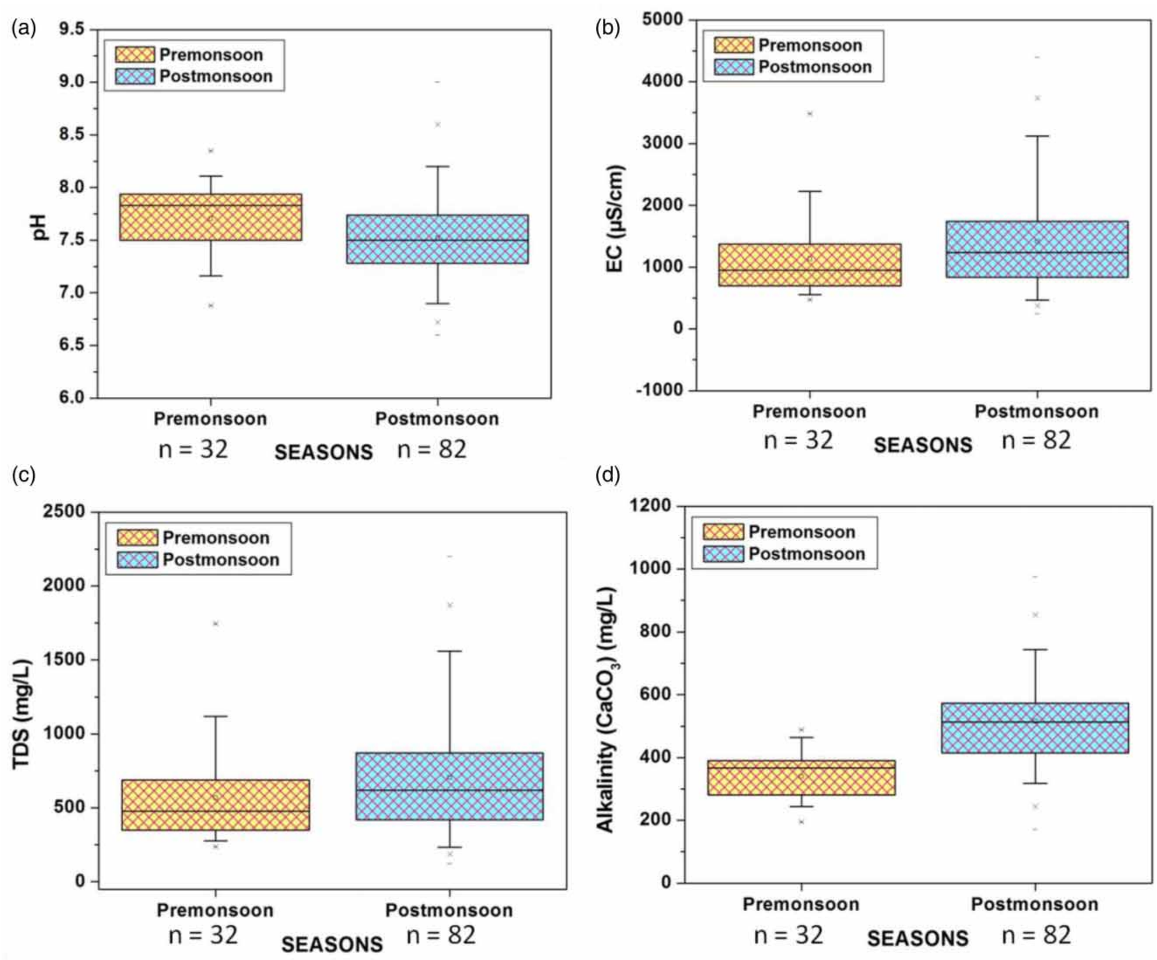


Figure 2 | Box–Whisker plots showing seasonal variations of (a) pH, (b) EC, (c) TDS, and (d) alkalinity.

during postmonsoon, which reduces pH to lower values. In the previous study, a narrow range of pH values was observed in groundwater samples, i.e. 7.4–8.6 (Keesari *et al.* 2020).

EC depends on the concentration of dissolved ions in groundwater (Hem 1985). During premonsoon, the EC is in the range of 469–3,483 µS/cm with a mean value of 1,136 µS/cm, while during postmonsoon it is in the range of 245–4,400 µS/cm with a mean value of 1,413 µS/cm (Table 1, Figure 2(b)). The temporal trends in EC suggest that postmonsoon samples have slightly higher EC values compared to premonsoon. This could be attributed to the addition of salts from the soil zone. The TDS of groundwater samples is found to be in the range of 236–1,744 mg/L with a mean value of 567 mg/L in premonsoon and 123–2,200 mg/L with a mean value of 706 mg/L during postmonsoon (Table 1, Figure 2(c)). Unlike pH, large fluctuations in the TDS values (71–3,115 mg/L) are reported in earlier studies (Lal *et al.* 2020). Temporal trends of TDS and EC were found to be similar and the plausible reason for higher values during postmonsoon could be the leaching of salts from the unsaturated zone with the infiltrating rainwater. Total alkalinity present in groundwater during premonsoon is in the range of 195–488 mg/L with a mean value of 339 mg/L and 171–976 mg/L with a mean value of 518 mg/L during postmonsoon (Table 1, Figure 2(d)). High alkalinity gives an unpleasant taste to water (Roy *et al.* 2018).

The normality test results of the WQPs suggest that the majority of the parameters during both seasons do not follow normal distribution except F^- ion during premonsoon season (Table 2). Non-parametric Kruskal–Wallis (ANOVA) test was performed to understand the seasonal variation in median values of WQPs. The results of the test are presented in Table 3. The table suggests that the majority of the parameters do not show significant seasonal variation (p-value > 0.05)

Table 2 | Results of normality test on the premonsoon and postmonsoon samples

	N	Shapiro–Wilk W	*p* (normal)	Anderson–Darling *A*	*p* (normal)
Ca^{2+}_post	82	0.8617	3.13×10^{-7}	3.631	3.82×10^{-9}
Ca^{2+}_pre	32	0.7803	1.77×10^{-5}	1.743	1.43×10^{-4}
Cl^{-}_post	82	0.8185	1.21×10^{-8}	4.190	1.65×10^{-10}
Cl^{-}_pre	32	0.7951	3.30×10^{-5}	2.319	5.15×10^{-6}
EWQI_post	82	0.9079	2.16×10^{-5}	1.907	6.60×10^{-5}
EWQI_pre	32	0.7730	1.32×10^{-5}	2.496	1.85×10^{-6}
F^{-}_post	82	0.8402	5.79×10^{-8}	3.456	1.03×10^{-8}
F^{-}_pre	32	0.9650	3.73×10^{-1}	0.3729	3.98×10^{-1}
K^{+}_post	82	0.5974	1.18×10^{-13}	11.480	8.34×10^{-28}
K^{+}_pre	32	0.4312	4.99×10^{-10}	7.159	6.19×10^{-18}
Mg^{2+}_post	82	0.9222	9.99×10^{-5}	1.970	4.60×10^{-5}
Mg^{2+}_pre	32	0.9310	4.17×10^{-2}	0.894	1.98×10^{-2}
Na^{+}_post	82	0.9012	1.09×10^{-5}	2.281	7.85×10^{-6}
Na^{+}_pre	32	0.8120	6.90×10^{-5}	1.560	4.10×10^{-4}
NO_3^{-}_post	82	0.8360	4.24×10^{-8}	4.779	6.16×10^{-12}
NO_3^{-}_pre	31	0.7524	7.61×10^{-6}	2.452	2.35×10^{-6}
SO_4^{2-}_post	82	0.8431	7.23×10^{-8}	3.684	2.84×10^{-9}
SO_4^{2-}_pre	32	0.7289	2.42×10^{-6}	2.586	1.10×10^{-6}

Table 3 | Results of Kruskal–Wallis non-parametric ANOVA test

Parameter	*H* (χ^2)	*Hc* (tie corrected)	*p* (same)	Remark
F^{-}	1.655	1.656	0.1982	Not significant
Cl^{-}	0.6929	0.6929	0.4052	Not significant
NO_3^{-}	1.8	1.8	0.1797	Not significant
SO_4^{2-}	0.9007	0.9008	0.3426	Not significant
Na^{+}	0.6364	0.6365	0.425	Not significant
K^{+}	4.072	4.073	0.04359	Significant
Ca^{2+}	7.456	7.459	0.006312	Significant
Mg^{2+}	0.7087	0.709	0.3998	Not significant
EWQI	0.4468	0.4468	0.5038	Not significant

in the median values except the Ca^{2+} (*p*-value 0.006312) and K^{+} ions (*p*-value 0.04359) which show significant seasonal variation. This can be attributed to processes such as silicate weathering and cation exchange operating in the subsurface (Hem 1985).

Suitability for drinking

Among major cations, alkaline earth metals (Ca^{2+} and Mg^{2+}) are very important ions for evaluating the drinking water quality of groundwater. Ca^{2+} ion concentration is in the range of 2.95–134 mg/L (mean value: 28.6 mg/L) during premonsoon and 6.15–162 mg/L (mean value: 44 mg/L) during postmonsoon (Table 1, Figure 3(a)). About 6% and 20% of samples show concentrations above the BIS limit of 75 mg/L during pre- and postmonsoon seasons, respectively (Table 4). Consumption of Ca^{2+} ion deficit water causes rickets while the excessive concentration of Ca^{2+} ion in water creates several health issues like kidney disease, stones in the bladder, and difficulty in urinary passage. Mg^{2+} ion concentration is in the range of 7.3–91.5 mg/L (mean value: 41 mg/L) during premonsoon and 5.4–132 mg/L (mean value: 46.4 mg/L) during postmonsoon (Table 1,

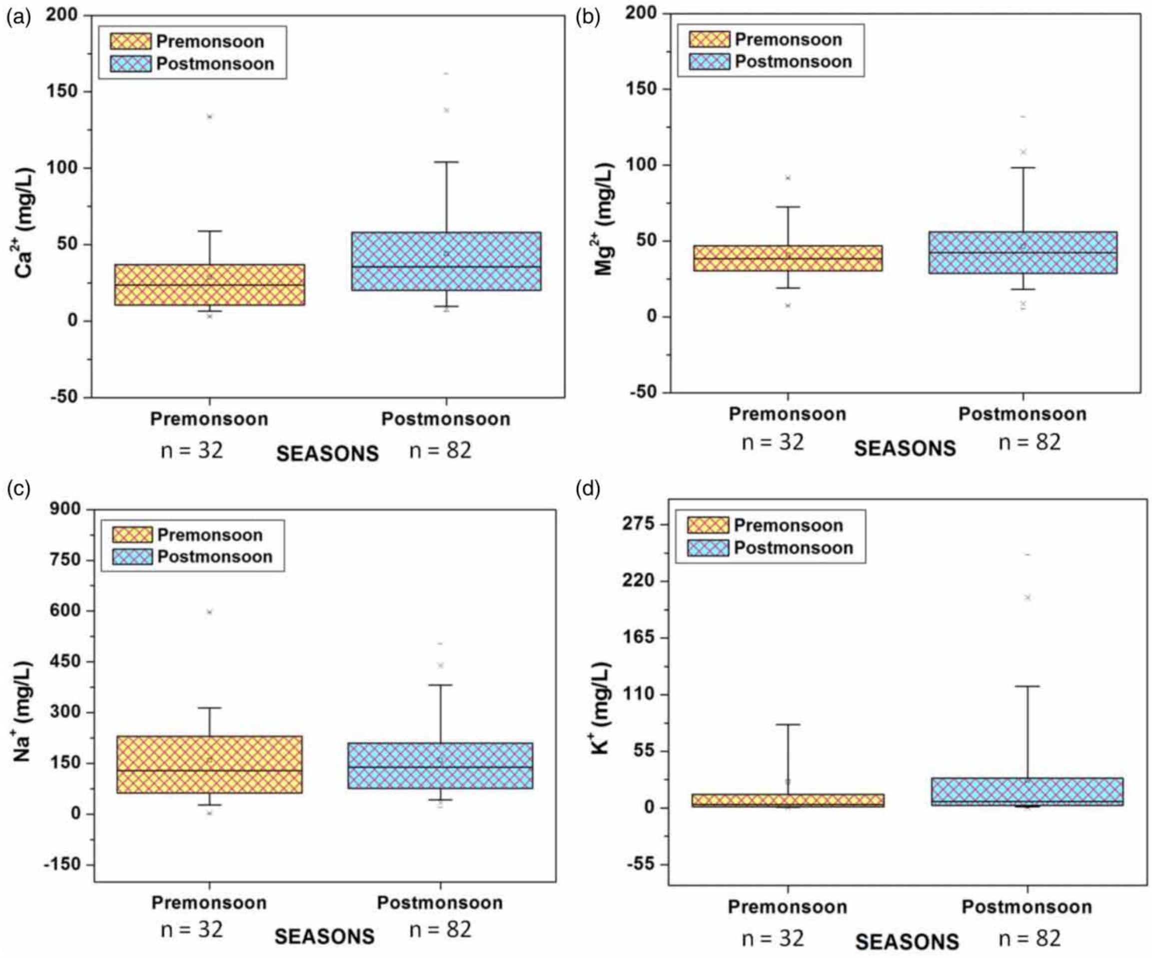


Figure 3 | Box–Whisker plots showing seasonal variations in cations: (a) Ca^{2+}, (b) Mg^{2+}, (c) Na^{+}, and (d) K^{+}.

Figure 3(b)). Higher concentration of Mg^{2+} ion i.e. above 30 mg/L (BIS limit), is observed in groundwater during both seasons (premonsoon 75% and postmonsoon 68%). Based on WHO (2011) limits, only 3% of groundwater has a high concentration of Mg^{2+} ion during postmonsoon (Table 4). Magnesium is important for diverse biochemical reactions in the human body and is also an activator of enzymes, but high Mg^{2+} ion levels have cathartic and diuretic effects (WHO 2009).

Na^{+} ion concentration in groundwater ranges from 2.82 to 597 mg/L (mean value: 158 mg/L), and 19.6–504 mg/L (mean value: 160 mg/L) during pre- and postmonsoon seasons, respectively (Table 1). The concentration of Na^{+} is slightly higher during postmonsoon compared to premonsoon period (Figure 3(c)). The major sources of Na^{+} ions in this region are minerals like feldspars and clays (APSAC 2018). K^{+} ion concentration is in the range of 0.54–315 mg/L (mean value: 25.3 mg/L) in premonsoon and 0.12–246 mg/L (mean value: 26.7 mg/L) during postmonsoon (Table 1, Figure 3(d)). The major sources of K^{+} ions in the groundwaters are feldspar minerals as well as fertilizers (Hem 1985). Excessive Na^{+} ion intake is a matter of concern for the person suffering from heart disease while high K^{+} ion concentration impacts human digestive and nervous systems (WHO 2011). There are no health-based standards prescribed for Na^{+} and K^{+} ions and they are not considered as drinking water indicators (BIS 2012).

Among anions, nitrate and fluoride are the major contaminants impacting groundwater resources in various parts of India. The F^{-} ion concentration ranges from 0.55 to 1.96 mg/L (mean value: 1.12 mg/L) and 0.1 to 4.6 mg/L (mean value: 1.14 mg/L) during pre- and postmonsoon seasons, respectively (Table 1, Figure 4(a)). F^{-} ion contamination is observed in about 65% and 47% of samples as per BIS limit (2012) during pre- and postmonsoon seasons, respectively. Based on the WHO limit (2011), about 12% and 21% of samples are found to be contaminated with F^{-}ions during pre- and postmonsoon, respectively (Table 4). Both anthropogenic and geogenic activities contribute to excess F^{-} ions in groundwater. Consumption of

Table 4 | Percentage of water samples exceeding drinking water limits based on BIS (2012) and WHO (2011)

Parameter	BIS (2012) DL	BIS (2012) MPL	WHO (2011) Guideline value	Percentage samples exceeding BIS (2012) Premonsoon ($n = 32$)	Percentage samples exceeding BIS (2012) Postmonsoon ($n = 82$)	Percentage samples exceeding WHO (2011) Premonsoon ($n = 32$)	Percentage samples exceeding WHO (2011) Postmonsoon ($n = 82$)	Negative impacts of high and low concentrations of parameters (Roy *et al.* 2018)
pH	6.5–8.5	No relaxation	6.5–8.5	0	2	0	2	Effect on taste of water, causes skin dryness, itchiness, and stomach upset
Total hardness as $CaCO_3$	200	600	500	46	69	3	12	Calcification at arteries, kidney stone, and heart-related disease
Total dissolved solids	500	2,000	1,000	44	69	9	15	Constipation and laxative effect on human body
Total alkalinity as $CaCO_3$	200	600	–	0	21	0	0	Unpleasant taste
Ca^{2+}	75	200	300	6	20	0	0	Low concentration causes rickets, high level causes kidney disease and stone in bladders
Mg^{2+}	30	100	100	75	68	3	0	Cathartic and diuretic effects
F^-	1	1.5	1.5	65	47	12	21	Excessive concentration causes crippling skeletal fluorosis
NO_3^-	45	No relaxation	50	28	36	28	36	Blue-baby syndrome
SO_4^{2-}	200	400	250	3	0	3	0	Exceeds a concentration of 250 mg/L, give bitter and unpleasant taste of water, stomach upset and gastrointestinal irritation
Cl^-	250	1,000	250	25	28	25	28	Kidney disease, dehydration

Note: All concentrations are in mg/L, except pH; DL, desired limit; MPL, maximum permissible limit.

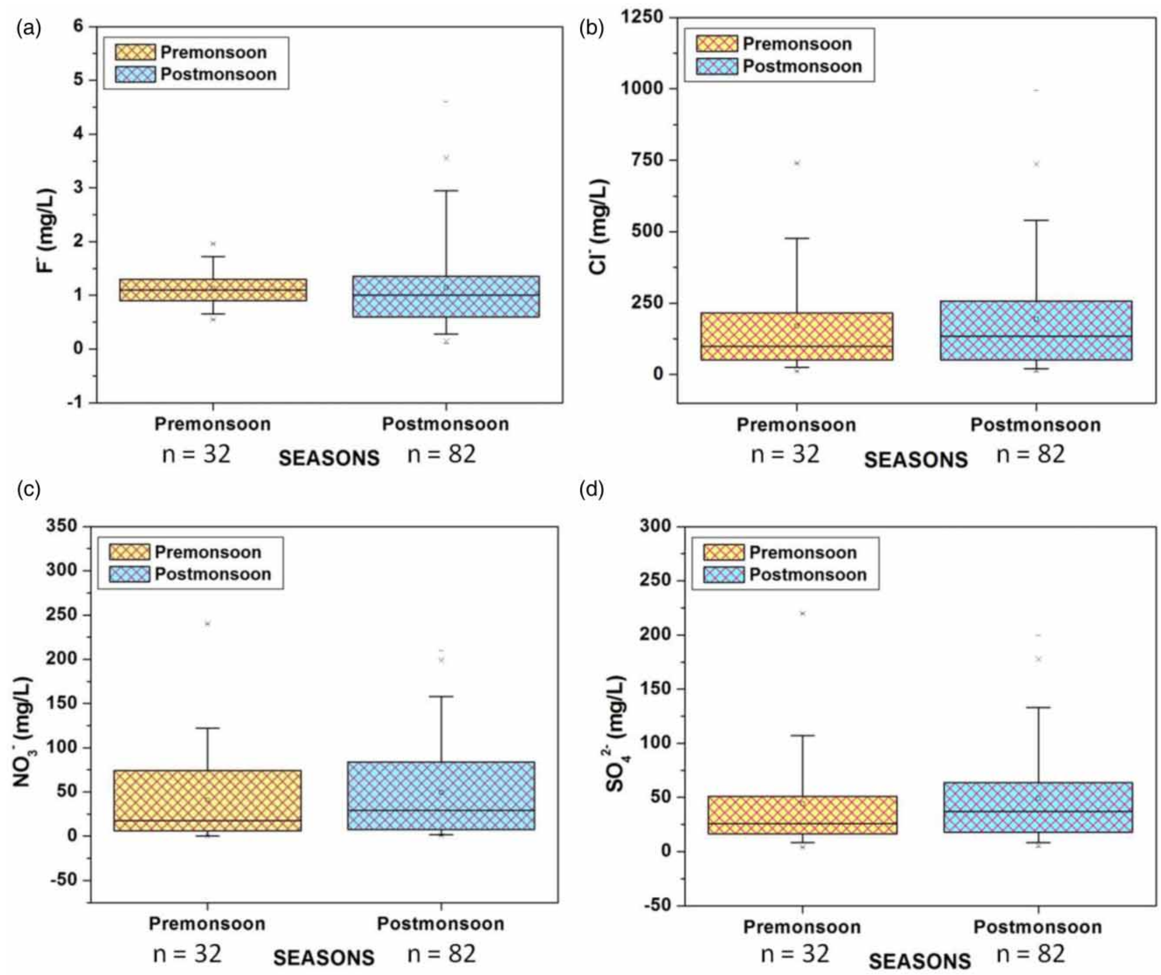


Figure 4 | Box–Whisker plots showing seasonal variations in anions: (a) F^-, (b) Cl^-, (c) NO_3^-, and (d) SO_4^{2-}.

fluoride-rich water affects the teeth, causing dental fluorosis, and long-term exposure to high-fluoride water causes the weakening of bones and ultimately skeletal fluorosis (Ray *et al.* 1981). The NO_3^- ion concentration is found to be in the range from below desirable limit to 240 mg/L (mean value: 41 mg/L) and 0.6–210 mg/L (mean value: 49.3 mg/L) during pre- and postmonsoon seasons, respectively (Table 1, Figure 4(c)). About 28% and 36% of samples are contaminated with high NO_3^- ion (>45 mg/L) as per BIS (2012) guideline value during pre- and postmonsoon, respectively (Table 4). Leguminous species of vegetation may increase the concentration of NO_3^- ion naturally, while other sources of NO_3^- ion in groundwater are mainly agricultural activity (use of NPK fertilizers) and domestic and industrial effluents. Activated sludge plant effluents usually contain 25 mg/L of nitrogen in the form of ammonia. Nitrogen > 1 mg/L in water bodies is toxic to aquatic ecosystems. About 1 mg/L of NO_3^--N in any aquatic system may result in the eutrophication of uncontaminated water bodies (Alexander 1995). High NO_3^- ion concentration in water causes methemoglobinemia (blue-baby syndrome) in infants (WHO 1997). Biological-nitrification and denitrification may help to reduce the content of NO_3^--N in wastewater. Algae, vegetation and other microorganisms through photosynthetic activity provide aerobic condition which is the most essential parameter for nitrification. After nitrification, denitrification occurs and nitrogen is remove in the form of NH_4^+ or NO_3^-, which are consumed by microorganisms, algae and vegetation (Champagne *et al.* 2017).

Cl^- ion concentration varies from 11.2 to 740 mg/L (mean value: 169 mg/L) and 10.6–995 mg/L (mean value: 194 mg/L) during pre- and postmonsoon seasons, respectively (Table 1, Figure 4(b)). High Cl^- ion concentration i.e. more than 250 mg/L is observed in 25% and 28% of the samples in pre- and postmonsoon seasons, respectively (WHO 2011; BIS 2012). High Cl^- ion concentration in waters can interrupt the microbial process of denitrification and also cause hypertension, asthma, kidney disease, and dehydration (Raviprakash & Krishna 1989). The SO_4^{2-} ion concentration ranges from 3.9 to 220 mg/L (mean value: 44 mg/L) and 4.54–200 mg/L (mean value: 49.1 mg/L) in pre- and postmonsoon seasons, respectively (Table 1, Figure 4(d)). As per permissible limits ascribed by BIS (2012) and WHO (2011), only 3% of samples are sulfate-rich during premonsoon, while none of the samples fall above limits in postmonsoon (Table 4).

The presence of dissolved solids changes the taste of water, and consumption of high TDS water may lead to laxative and constipation effects in humans (WHO 2011). The suitability of groundwater for drinking based on TDS values is provided in Table 5. It is observed that, as per the TDS values 56.3% and 30.1% of groundwater samples fall in the desirable category and 31.2% and 54.2% of the samples fall in the permissible category during pre- and postmonsoon seasons, respectively. Based on the above observations, it can be inferred that most of the groundwater samples are suitable for drinking. Based on BIS (2012) guidelines, about 56% and 31% of the samples are suitable for drinking purposes during premonsoon and postmonsoon seasons, respectively. As per WHO limits about 87% and 84% of the samples are suitable for drinking purposes during premonsoon and postmonsoon seasons, respectively (Table 4).

TH is caused by dissolved salts of Ca^{2+} and Mg^{2+} ions and it is used as an indicator to check the potability of water. During premonsoon (Table 1), the TH is in the range of 92.4–633 mg/L (mean value: 240 mg/L) and in postmonsoon 77.1–948 mg/L (mean value: 301 mg/L). Water classification based on TH is given in Table 5 (Durfor & Becker 1964). It is observed that none of the samples fall in the soft water category (TH < 60 mg/L). About 12.5% and 7.2% samples fall in the moderately hard category (TH 60–120 mg/L) during pre- and postmonsoon seasons, respectively. About 18.7% and 15.7% of samples fall in the hard water category (TH 121–181 mg/L) in pre- and postmonsoon seasons respectively (Table 5). About 68.8% and 77.1% of samples fall under very hard type (TH > 181 mg/L) in pre- and postmonsoon seasons, respectively (Figure 5(c) and 5(d)). Based on BIS limits about 53% and 31% of the groundwater samples are suitable for drinking while 97% and 88% of groundwater samples are suitable for drinking as per WHO (2011) during pre- and postmonsoon seasons, respectively (Table 4). Temporal variations suggest that groundwater samples indicate higher TH values in postmonsoon than in premonsoon, which could be due to the addition of Ca^{2+} and Mg^{2+} carbonates in groundwater. Earlier studies have indicated that the northern part of this district has higher TH values and the local population is affected by kidney stones and heart-related disease (Tatapudi *et al.* 2019).

Suitability for irrigation

The summary of indicators for irrigation water quality suitability is provided in Table 6. In addition, USSL, Wilcox diagrams, and Doneen's chart are also used in this study for better presentation of groundwater suitability for irrigation. EC classifies the irrigation suitability of groundwater into five different categories, in the excellent category (250 μS/cm) only 1.2% of samples fall in postmonsoon. About 34.4% and 15.4% of samples fall in the good (250–750 μS/cm) category during pre- and postmonsoon, respectively. Most of the samples fall in the permissible (750–2,000 μS/cm) category, premonsoon (53.1%) and postmonsoon (67.5%) as shown in Table 6. SAR measures the relative concentration of Na^+ over Ca^{2+} and Mg^{2+} ions. The calculated SAR values of the groundwater range from 0.09 to 14.3 (mean value: 4.3) and 0.8 to 20.3 (mean value:

Table 5 | Classification of groundwater samples based on TDS and TH for suitability to drinking and irrigation

Parameters	Water class	% of samples in premonsoon ($n = 32$)	% of samples in postmonsoon ($n = 82$)
TDS (mg/L)			
<500	Desirable for drinking	56.3	30.1
500–1,000	Permissible for drinking	31.2	54.2
1,000–3,000	Useful for irrigation	12.5	15.7
>3,000	Unfit for drinking and irrigation	0.0	0.0
TH (mg $CaCO_3$/L)			
<60	Soft	0	0
60–120	Moderately hard	12.5	7.2
121–181	Hard	18.7	15.7
>181	Very hard	68.8	77.1

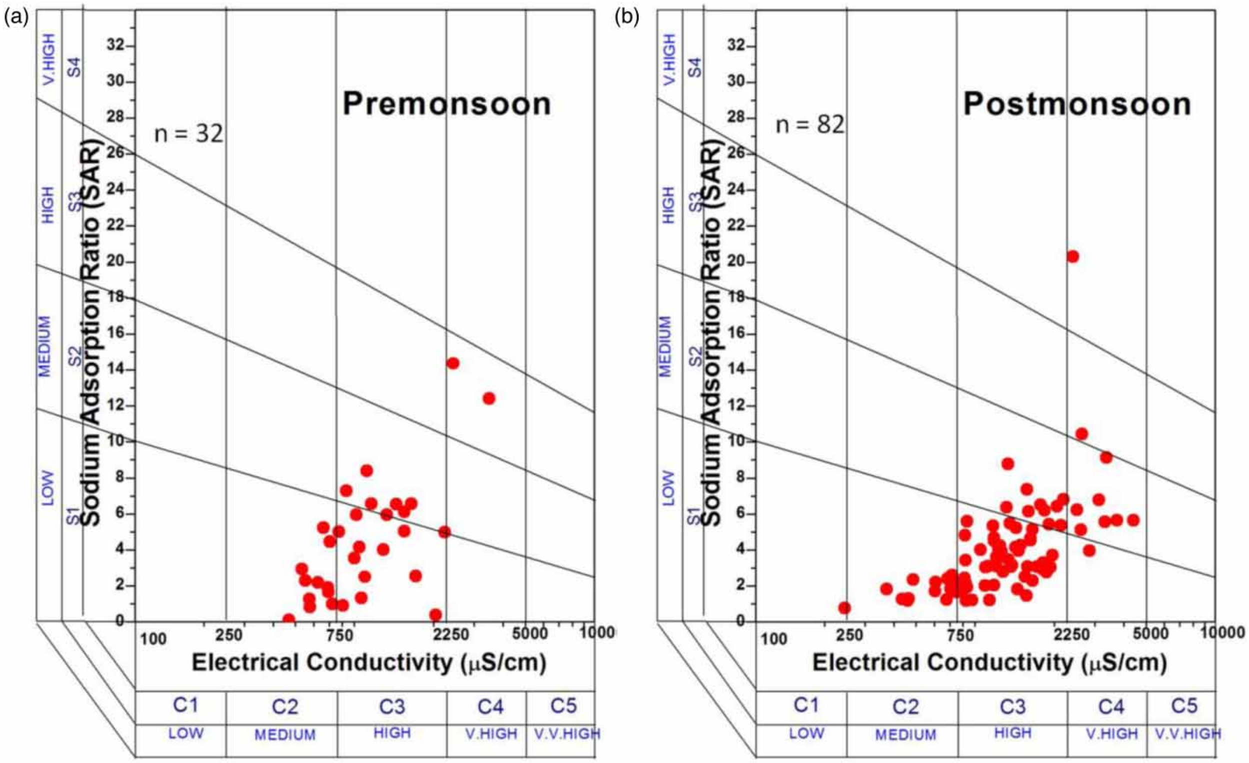


Figure 5 | USSL plot of groundwater samples collected during (a) premonsoon and (b) postmonsoon seasons.

4.01) in pre- and postmonsoon seasons, respectively. About 93.8% and 97.6% of samples fall in the excellent category for irrigation in pre- and postmonsoon samples, respectively (Table 6). About 6.2% and 2.4% of samples fall in the good category in pre- and postmonsoon seasons, respectively (Table 6). From SAR values, it can be inferred that groundwater quality is excellent for irrigation purposes.

Percent sodium is also one of the very important indicators for checking the irrigation suitability of water. The use of Na^+ ion-rich water for irrigation leads to changes in the pH of soil. Interaction of Na^+ ion with CO_3^{2-} and HCO_3^- ions results in high alkalinity (pH $>$ 7), while its reaction with Cl^- ions increases the salinity of soil. Binding and compaction due to the interaction of ions reduce water movement capacity in soil. Percent sodium of premonsoon water samples is in the range of 3.6–81.1 (mean value: 53.2), and 36.4–94.1 (mean value: 60.4) in postmonsoon. Only 6% of the groundwater samples fall in the excellent category in premonsoon, but none of the samples fall in the excellent category during postmonsoon. Groundwater samples in the good category are 22% and 7.3% for premonsoon and postmonsoon, respectively (Table 6). In order to reduce the Na% measures such as mulching of soil, drip or sprinkle irrigation, crop rotation and use of organic manures can be recommended. These measures will help in improving the water movement capacity and permeability of soils.

RSC is an essential parameter for the determination of the suitability of water for irrigation as it impacts the growth of crops because of soil sodication (Eaton 1950). RSC of the groundwater samples was in the range of –6.6 to 5.4 meq/L (mean value: 0.75 meq/L) and −7.7 to 24.2 meq/L (mean value: 7.5 meq/L) in pre- and postmonsoon seasons, respectively. According to the findings, 56.2% of premonsoon samples and 7.3% of postmonsoon samples fall in the good category while about 25% and 7.3% of samples are in the doubtful category during pre- and postmonsoon seasons, respectively (Table 6).

High levels of magnesium negatively impacts the soil with increasing alkalinity, making the soil unsuitable for irrigation, and also decreases crop yield, hence MH is used as an indicator for irrigation water quality. MH of groundwater samples range from 27 to 94.3 (mean value:72.6) and 19.7 to 90.9 (mean value: 54) during pre- and postmonsoon seasons, respectively. It is observed that 6.2% of groundwater samples are suitable (MH $<$ 50) and 93.8% are unsuitable (MH $>$ 50) for irrigation in the premonsoon season. About 24.4% of groundwater samples are suitable and 75.6% are unsuitable for irrigation in the postmonsoon season (Table 6).

Table 6 | EC, SAR, RSC, MH, KR, CR, and Na% values for the groundwater samples

Parameters	Water classification	Premonsoon (%) ($n = 32$)	Postmonsoon (%) ($n = 82$)
EC (μS/cm)			
<250	Excellent	0.0	1.2
250–750	Good	34.4	15.7
750–2,000	Permissible	53.1	67.5
2,000–3,000	Doubtful	9.4	9.6
>3,000	Unsuitable	3.1	6.0
Alkalinity hazard (SAR)			
<10	Excellent	93.8	97.6
10–18	Good	6.2	2.4
18–26	Doubtful	0.0	0.0
>26	Unsuitable	0.0	0.0
Percent sodium (Na%)			
<20	Excellent	6.0	0
20–40	Good	22	7.3
40–60	Permissible	22	41.5
60–80	Doubtful	47	46.2
>80	Unsafe	3.0	5.0
Residual sodium carbonate (RSC)			
<1.25	Good	56.2	7.3
1.25–2.5	Doubtful	25	7.3
>2.5	Unsuitable	18.8	85.3
Magnesium hazard (MH)			
<50	Suitable	6.2	24.4
>50	Unsuitable	93.8	75.6
Kelley's Ratio (KR)			
<1	Suitable	40.6	26.8
1–2	Marginally unsuitable	34.	48.8
>2	Unsuitable	25.0	24.4
Corrosivity ratio (CR)			
<1	Suitable for pipe	62.5	81.7
>1	Unsuitable for pipe	37.5	18.3

KR represents the variation in the amount of Na^+ ion concentration (Karanth 1987) and a high concentration of sodium ions in groundwater is not acceptable for irrigation purposes. In this study, KR values of the groundwater range from 0.03 to 4 (mean value:1.4) and 0.5 to 16 (mean value: 1.72) during pre- and postmonsoon seasons, respectively. It is observed that 40.6% and 26.8% of samples are suitable for irrigation ($KR < 1$) in pre- and postmonsoon seasons, respectively. About 34.4% and 48.8% of samples are marginally unsuitable (KR: 1–2) in pre- and postmonsoon seasons, respectively. About 25% and 24.4% of samples are unsuitable ($KR > 2$) during pre- and postmonsoon seasons, respectively (Table 6). The CR provides the vulnerability of metal pipes to corrosion. The CR values range from 0.04 to 3.1 (mean value: 0.8) and 0.08 to 2.35 (mean value: 0.57) during pre- and postmonsoon seasons, respectively. In this study, 37.5% and 18.3% of samples are found to be unsuitable according to CR values during pre- and postmonsoon seasons, respectively, i.e. $CR > 1$ (Table 6). The decreased nature of corrosiveness in groundwater during postmonsoon can be attributed to dilution by rainwater infiltration. PI is also used for assessing the irrigation water quality (Doneen 1966). The PI values range from 46.4–120 (mean value: 81) and 57–201 (mean value: 115) during pre- and postmonsoon seasons. According to Doneen's chart, most of the groundwater samples of premonsoon fall in Classes I and II (75–100% maximum permeability), while postmonsoon samples fall in both Class II and Class III categories (25–75%, maximum permeability) (Figure 6).

A combination of two quality indicators can provide a better representation of the water quality required for irrigation. USSL diagram is used for the assessment of water quality for irrigation purposes (USSL 1954). This diagram is plotted between SAR/sodium hazard and EC/salinity hazard and 16 classes are identified in the diagram. Based on the USSL classification (Figure 5(a) and 5(b)), water samples fall under the medium to high salinity hazard and low to medium sodium hazard categories in premonsoon while medium to very high salinity and medium sodium hazard categories during postmonsoon. Previous data from the northern region of the Srikakulam district indicated that groundwater samples fall under the low to medium-hazard category (Keesari *et al.* 2020). This trend suggests that the quality of groundwater is further degrading in the study area compared to the northern part of the district, and this would pose a serious concern considering the high demand for groundwater in this region.

Wilcox plot helps in the evaluation of groundwater suitability for irrigation based on the combined effect of EC and Na% (Wilcox 1955). From the plots, it can be observed that a maximum number of groundwater samples falls in the excellent to permissible category for irrigation in premonsoon while in postmonsoon samples are widely distributed in all the categories from excellent to unsuitable (Figure 7(a) and 7(b)). About 3% and 6% of samples are unsuitable for irrigation purposes in

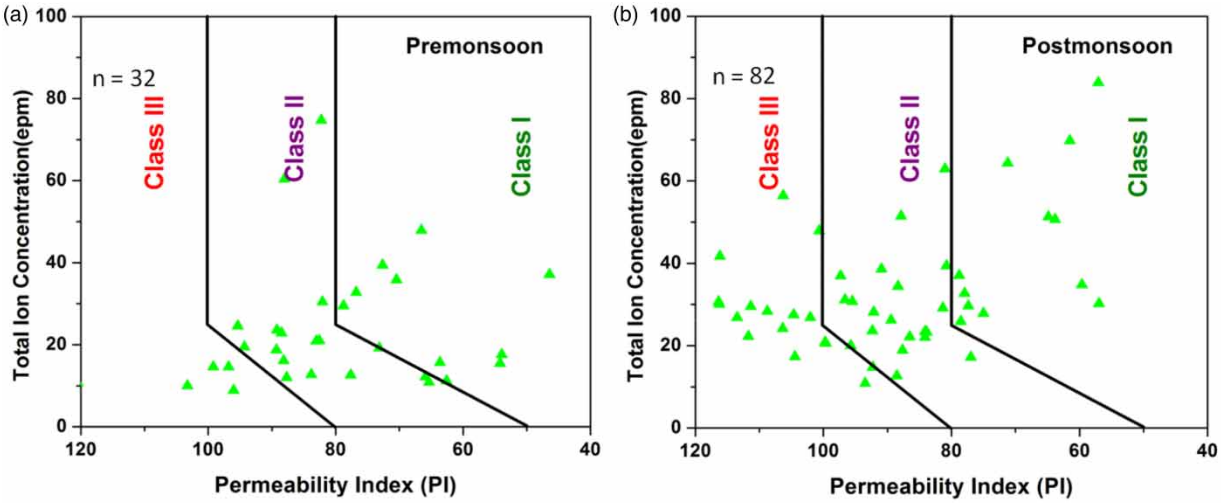


Figure 6 | Doneen's diagram of groundwater samples collected during (a) premonsoon and (b) postmonsoon seasons.

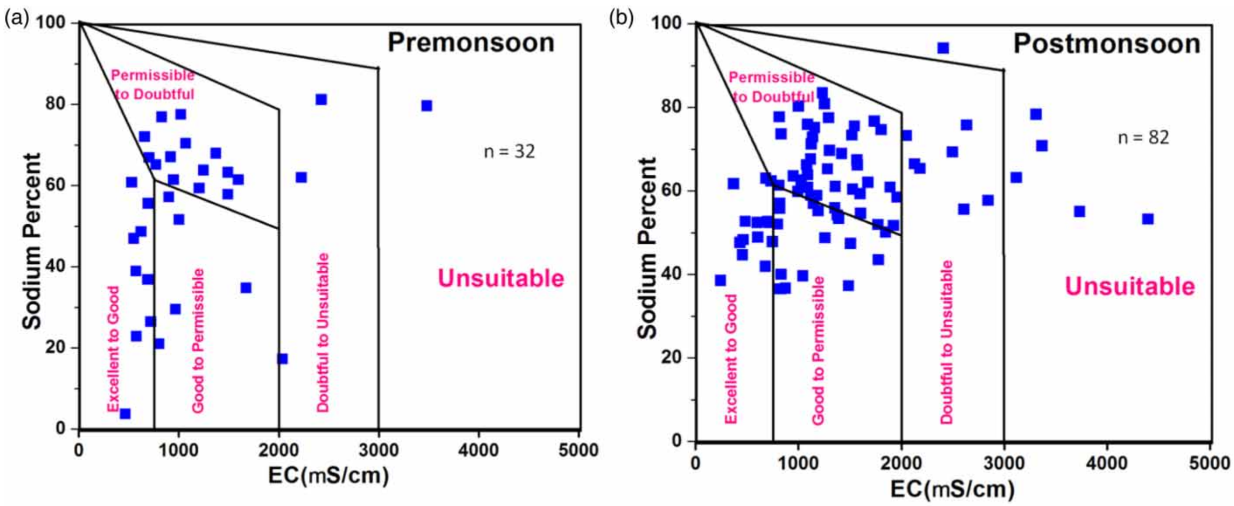


Figure 7 | Wilcox diagram of groundwater samples collected during (a) premonsoon and (b) postmonsoon seasons.

premonsoon and postmonsoon seasons, respectively (Figure 7(a) and 7(b)). In an earlier study, most of the groundwater samples of the district were found to be in the excellent to good category for irrigation (Keesari *et al.* 2020). The trends again suggest that the groundwater quality degradation is more pertinent in northwestern and southwestern parts of the district and this might continue to happen considering the rising water demand for irrigation.

The EWQI

The WQI is a popular and valuable rating model that allows aggregation and conversion of the positive and negative footprints of different WQPs into single index (Kumar & Maurya 2023). In this study, water quality evaluation of the samples was carried out using the EWQI. The relative weights of different parameters such as TH, NO_3^-, SO_4^{2-}, Ca^{2+}, Cl^-, Mg^{2+}, F^-, Na^+, K^+, alkalinity, pH, and TDS are calculated based on their validity for water quality indexing. Parameters with relative weight values greater than 0.10 are considered critical while weight values between 0.05 and 0.10 are considered semi-critical. According to this classification, TH in both seasons, SO_4^{2-} in premonsoon, and NO_3^- in postmonsoon are found to be critical parameters while TDS, alkalinity, F^-, Cl^-, Mg^{2+}, Ca^{2+} and pH are identified as semi-critical parameters. Based on the importance, the parameters can be arranged in the following order: $TH > SO_4^{2-} > Cl^- > NO_3^- > F^- > TDS > alkalinity > Ca^{2+} > Mg^{2+} > pH$ during the premonsoon and $TH > NO_3^- > SO_4^{2-} > Ca^{2+} > Cl^- > TDS > Mg^{2+} > F^- > pH > alkalinity$ during the postmonsoon (Table 7). The calculated EWQI values range from 22.6 to 116 (mean value: 43.26) in the premonsoon season and 7.05 to 139 (mean value: 43.03) in postmonsoon season. From the EWQI values, it can be inferred that most of the groundwater samples fall in excellent to poor quality during both seasons but during postmonsoon some samples fall in unsuitable quality (Table 8). The error estimates of IDW interpolation are provided in Table 9. From the table it can be found that the IDW errors do not show significant variations with power value; however, considering the spatial variations observed in the groundwater quality of the study area, interpolations by IDW might not be very precise and care should be taken to infer the results.

The spatial distribution of water quality suggests that a very small percentage of the area (~0.7%) is found to be in the excellent category in premonsoon and 3.7% of the area in the excellent category in postmonsoon. About 78.6% of the study area falls in the good category during premonsoon while only 73.3% of the area falls in the good category during postmonsoon. About 19.8% and 1% of the study area fall in the poor category during pre- and postmonsoon, respectively. About 0.9% and 5.1% of the study area fall in the very poor category during pre- and postmonsoon, respectively, which is not safe for potable use (Table 10, Figure 8(a) and 8(b)). Overall, nearly all of the study area is in the good category during premonsoon, except for a few places in the northern part, which fall in the poor category. Majority of the area falls in the good category during postmonsoon with few places in southeastern and southwestern parts falling in the poor category.

Table 7 | Relative weight of hydrochemical parameters for EWQI

	Relative weight (W_i)	
Parameters	**Premonsoon ($n = 32$)**	**Postmonsoon ($n = 82$)**
TDS	0.076	0.068
Alkalinity	0.076	0.048
F^-	0.079	0.062
Cl^-	0.091	0.077
NO_3^-	0.083	0.125
SO_4^{2-}	0.121	0.092
Na^+	0.085	0.086
K^+	0.074	0.081
Mg^{2+}	0.063	0.067
Ca^{2+}	0.065	0.088
TH	0.127	0.152
pH	0.060	0.053
ΣW_i	1	1

Table 8 | Groundwater classification on the basis of the EWQI

Interval	Classification of samples based on the EWQI	(% of samples) WHO (2011)	
		Premonsoon ($n = 32$)	Postmonsoon ($n = 82$)
0–25	Excellent water quality	3	30
26–50	Good water quality	72	34
51–75	Poor water quality	19	26
76–100	Very poor water quality	6	6
>100	Unsuitable for drinking	0	4

Table 9 | Estimated error of IDW interpolation

Power	Root mean square	
	Premonsoon	Postmonsoon
1	19.38	25.61
2	17.89	25.61
3	18.65	26.09

Table 10 | Area percentage of water samples falling under different EWQI categories

EWQI category	% of area (premonsoon, $n = 32$)	% of area (postmonsoon, $n = 82$)
Excellent	0.7	3.7
Good	78.6	73.3
Poor	19.8	17.8
Very poor	0.9	5.1
Unsuitable	0.1	0.0

Summary and conclusions

A comprehensive water quality evaluation was undertaken in parts of the coastal Srikakulam district, which has witnessed high water demand in recent times. Water samples were collected covering both spatial and temporal variations in the study area. The indicators employed for evaluating drinking water suitability were TH, TDS, EC, and chemical species including NO_3^- and F^-, while irrigation suitability was examined using SAR, RSC, MH, PI, Na%, CR, and KR indicators. In addition, diagrams such as Wilcox, USSL, and Doneen's chart were used to further evaluate the water quality for irrigation use. Statistical tests were conducted on the obtained data using Shapiro–Wilk W and Anderson–Darling A tests and it was found that chemical parameters do not follow normal distribution except F^- ions in premonsoon. Chemical data indicate that a significant percentage of groundwater samples showed higher concentrations in Cl^- and TH above drinking water permissible limits, whereas Ca^{2+}, Mg^{2+}, and Na^+ ions were marginally higher. High concentrations of F^- and NO_3^- ions were present in 12% and 28% of samples and the contamination levels increased during postmonsoon season. The statistical significance of seasonality in chemical ion concentration was verified using a non-parametric Kruskal–Wallis (ANOVA) test, which concluded that the majority of the parameters do not show significant seasonal variation (p-value > 0.05) except Ca^{2+} and K^+ ions (p-value < 0.05). Based on SAR (premonsoon range: 0.09–14.3 and postmonsoon range: 0.8–20.3), groundwater falls in the excellent category during both seasons, whereas, based on RSC (premonsoon range: −6.6 to 5.4 and postmonsoon range: −7.7 to 24.2) and Na% (premonsoon range: 3.6–81.1 and postmonsoon range: 36.4–94.1), groundwater falls in the excellent to doubtful category during premonsoon and permissible to unsuitable category during postmonsoon. PI values signify that water quality is better during the premonsoon season (range: 46.4–120) compared to postmonsoon season

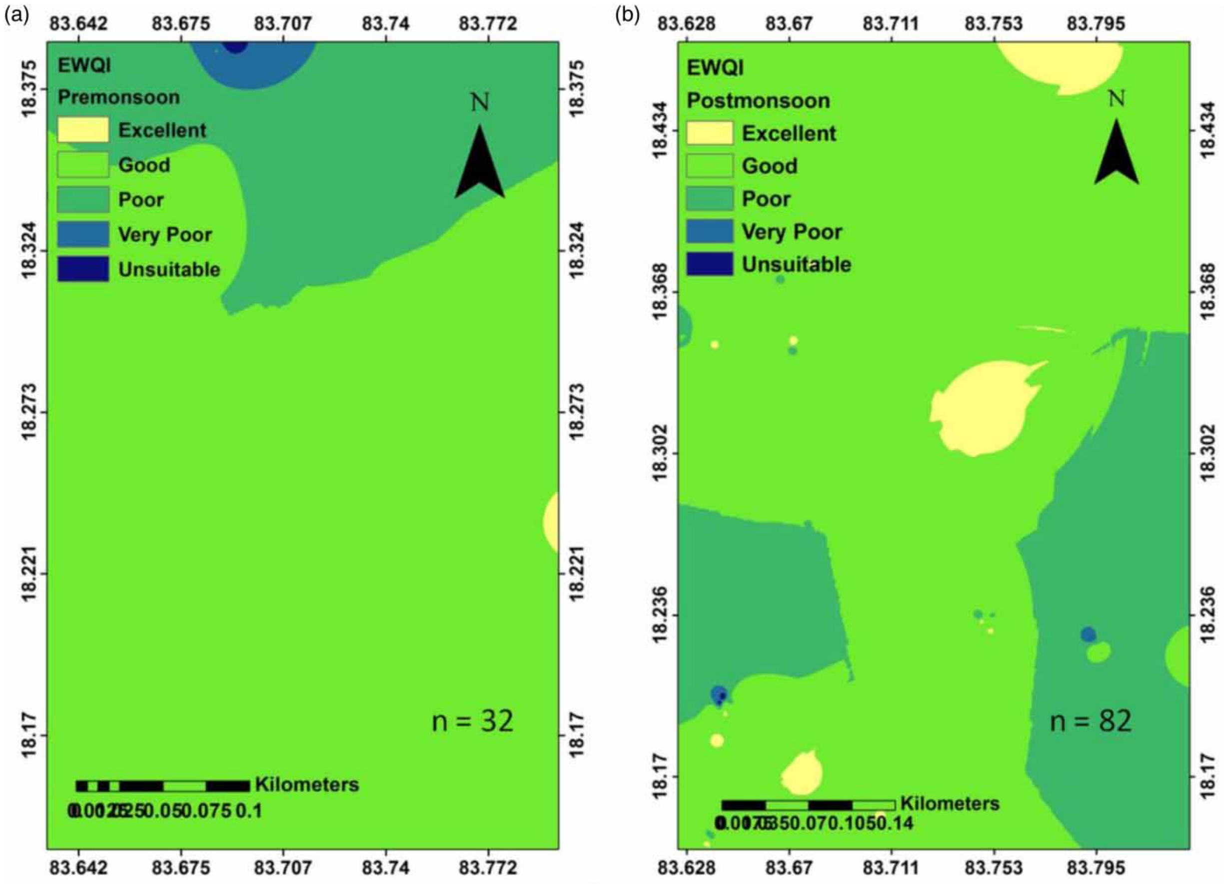


Figure 8 | GIS maps depicting spatial distribution of the EWQI in the study area: (a) premonsoon and (b) postmonsoon seasons.

(range: 57–201). On the other hand, based on MH (premonsoon range: 27–94.3 and postmonsoon range: 19.7–90.9) and KR (premonsoon range: 0.03–4 and postmonsoon range: 0.5–16), indicators demonstrate unsuitable nature of groundwater during premonsoon but suitable to marginally unsuitable nature during postmonsoon. CR values are higher during premonsoon (range: 0.04–3.1) but reduce during postmonsoon (range: 0.08–2.35). Based on the above observations, it can be inferred that the overall water suitability for irrigation is better in premonsoon than in postmonsoon. Shannon's entropy technique was used to estimate the EWQI to provide better appraisal of water quality. It was found that TH was the critical parameter for both seasons, followed by SO_4^{2-} and NO_3^- ions. Spatial contours of the EWQI were prepared using the IDW interpolation method by ArcGIS software. The contours suggest that the southern part consists of good quality water compared to the northern parts during premonsoon. However, during postmonsoon the water quality is excellent to poor throughout the study area, which can be attributed to recharge by rainwater infiltration. Spatial trends in the EWQI clearly suggest that excess use of fertilizers and pesticides, as well as domestic waste discharges, play a critical role in impacting the groundwater quality of the study area. Adoption of traditional organic farming and treatment of domestic and industrial waste can improve the groundwater quality, thereby achieving sustainable groundwater management in this region.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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