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Groundwater quality assessment for irrigation use in the Godavari Delta region of east coast India using IRWQI and GIS

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ABSTRACT

The present work was carried out in the deltaic region of the river Godavari in coastal Andhra Pradesh of southern India to evaluate the status of groundwater quality for irrigation. Groundwater is predominantly used in these productive agricultural fields. Saline water intrusion in fresh groundwater aquifers, which is mainly due to the excess withdrawal of groundwater, was recorded in the study area. A total of 80 groundwater samples were analyzed for physical and chemical parameters using standard chemical procedures. The groundwater mainly represents Na^+–Cl^- type, which shows the mixing of fresh water with saline water. The high correlation between Na^+–Cl^- and Mg^{2+}–HCO_3^- explained that the intermixing of aquifer waters and the leaching of secondary salts influenced the region. Evaporation–fractional crystallizations are the main processes in the groundwater of the study area. The irrigation water quality index was calculated using different quality indices including Na%, sodium adsorption ratio, residual sodium bicarbonate (RSBC), permeability index (PI), magnesium hazard (MH), Kelly's ratio (KR), and potential salinity (PS), Cl^-:HCO_3^-, Mg^{2+}:Ca^{2+} and Na^+:Ca^{2+} to estimate the suitability of groundwater quality for irrigation. Spatial distribution maps were prepared using raster interpolation in GIS. The assessment revealed that the areas covering 67.6% of electrical conductivity, 100% of total dissolved solids, 57.5% of Na%, 21.3% of RSBC, 66.3% of PI, 16.3% of MH, 65% of KR, and, 100% of PS required severe to moderate restrictions. Overall, the groundwater in the study region showed potential salinity due to geogenic and anthropogenic activities, and thus it must be monitored for sustainable agriculture.

Key words: GIS, Godavari Delta, groundwater, irrigation, IRWQI, water quality indices

HIGHLIGHTS

- Geochemical evaluation of groundwater explains that evaporation is the main controlling factor of geochemistry along with rock dominance. The irrigation water quality index (IRWQI) was calculated using different quality indices to estimate groundwater quality for irrigated waters.
- The calculated indices were found to be in the moderate to unsuitable category of groundwater for irrigation.

INTRODUCTION

Agriculture is the mainstay of India's economic growth. Uncertainty about rainfall and increasing temperatures due to changing climates have become common in recent days, forcing farmers into indiscriminate exploitation of groundwater, particularly in alluvial deltaic regions for irrigation. Such exploitation can result from a lack of monitoring and scientific knowledge; an increase in population, agriculture and aquaculture; industrial demand, and also encouragement by the government to overexploit the groundwater resource.

In India, alluvial aquifers of the Beas and Ganga basins, particularly those in Punjab, Haryana and Uttar Pradesh states, and the Godavari Delta region of Andhra Pradesh, are recognized as more stressed regions because the government policies on agricultural practices related to subsidies on electrical power connections and pump sets may lead to excess groundwater withdrawals (Abhijit *et al.* 2018; CGWB 2019). In any area, irrigation methods like flooding, furrowing, sprinkling and sub-irrigating has to be selected based on the sowing crop, source of water and its availability, local topography and soil characteristics, soluble salt content of the water, and salinity status of the soil (Richards 1954).

Rapid developmental activities have put pressure on freshwater aquifers, particularly in the delta regions. Deltaic alluvial soils are more favourable for agriculture as the crops grown in these areas develop significant crop productivity. The abstraction of large quantities of groundwater can alter the surface-groundwater exchanges with the adjacent rivers, modifying not only the water fluxes from one system to another but also the hydrochemical composition of both systems. Natural processes including precipitation, evaporation, exchange of ions, mineral dissolution and anthropogenic-induced processes like irrigation, urbanization, industrialization, mining, etc. affect groundwater quality (Negrel *et al.* 2003; Mostaza-Colado *et al.* 2018).

It has been recorded that nearly 2,500 km^3 of water is consumed annually for irrigation globally (Filipovic 2020). The studies estimated that the worldwide withdrawal rate of groundwater is about 982 km^3/y, of which nearly 70% is used for irrigation. The major countries dependent on groundwater extraction are India, China and the USA. In particular, in India, about 90% of extracted groundwater is used for irrigation, which accounts for nearly 251 km^3/y (Margat & Gun 2013). When groundwater extraction is more than the natural recharge, it leads to a decline in groundwater levels, causing numerous adverse impacts on agricultural development in the irrigated area (Zektser *et al.* 2005; Singh & Kasana 2017).

The quality of groundwater is an important issue as it affects crop growth and yield. The toxic chemical parameters in groundwater not only reduce crop production through alteration of available nutrients but also soil fertility (Ayers & Westcot 1985). Therefore, knowledge of irrigation water in terms of quality and quantity needs to be enhanced for understanding agricultural practices performed in an area (Bauder *et al.* 2004).

In arid and semi-arid regions, the groundwater commonly contains high concentrations of soluble salts. The South-West Monsoon contributes more than 70% of the total rainfall during the months of June to September in the coastal areas of Andhra Pradesh. The groundwater used for irrigation contains high amounts of carbonates and bicarbonates of sodium, and hence the continuous use of such waters for irrigation increases salinity and exchangeable sodium in the soil (Bajwa *et al.* 1983).

The quality of irrigation depends on quality water in which Na^+, Ca^{2+}, Mg^{2+} and K^+ play a role in the maintenance of crop growth and development and, ultimately, their yields. Sodium hazard reduces soil permeability and can prevent crops from absorbing water through soil solution. When the osmotic pressure decreases, the water uptake in branches and leaves reduces, particularly in the summer months (Tahmasebi *et al.* 2018; Xu *et al.* 2019). To reduce the effect of salinity, gypsum can be used in clay-rich soils (BIS 2012).

Indiscriminate abstraction of groundwater from the shallow aquifers of coastal regions for agricultural, domestic and industrial purposes creates severe problems such as seawater intrusion and groundwater pollution. The pollutants from aquacultural activities, sewage discharges and industrial effluents directly released onto the ground are leached through the soil layers by precipitation into underground reservoirs, thus contaminating the freshwater resources (Melloul & Goldenberg 1997; World Bank 2010).

Salinization of groundwater occurs by the combination of diverse processes. Barlow & Reichard (2010) noted that saline water intrusion into coastal aquifers can occur through lateral intrusion from the ocean, upward intrusion from deeper waters, the flow of saline groundwater from adjacent or underlying aquifers, and downward intrusion from coastal waters. By considering critical situations in coastal developmental areas, geochemical studies of groundwater are necessary to understand the anthropogenic and geogenic sources that affect groundwater quality and determine its suitability for drinking and agricultural use.

The main objective of the present study was to evaluate the hydrochemical properties of the River Godavari Delta (RGD) alluvial aquifer of the east coast region of India. The current status of groundwater quality was assessed for irrigation purposes by adopting an integrated approach of irrigation water quality index (IRWQI) and geographic information system (GIS). The study aims to provide the data on qualitative description of groundwater and geochemical processes which are involved in shaping hydrochemistry. The impact of intensive agriculture coupled with aqua farming on groundwater can be understood through this study and it will provide baseline information to planners and local authorities for developing mitigation strategies and making an appropriate decision towards sustainable management of the area.

STUDY AREA

The study area is located between 16° 19′ and 16° 40′ N latitudes and 81° 19′ and 81° 51′ E longitudes in the coastal Andhra Pradesh state of southern India. The Godavari, the second largest river in India, flows through the alluvial deltaic soils of the study area before merging into the Bay of Bengal (Figure 1).

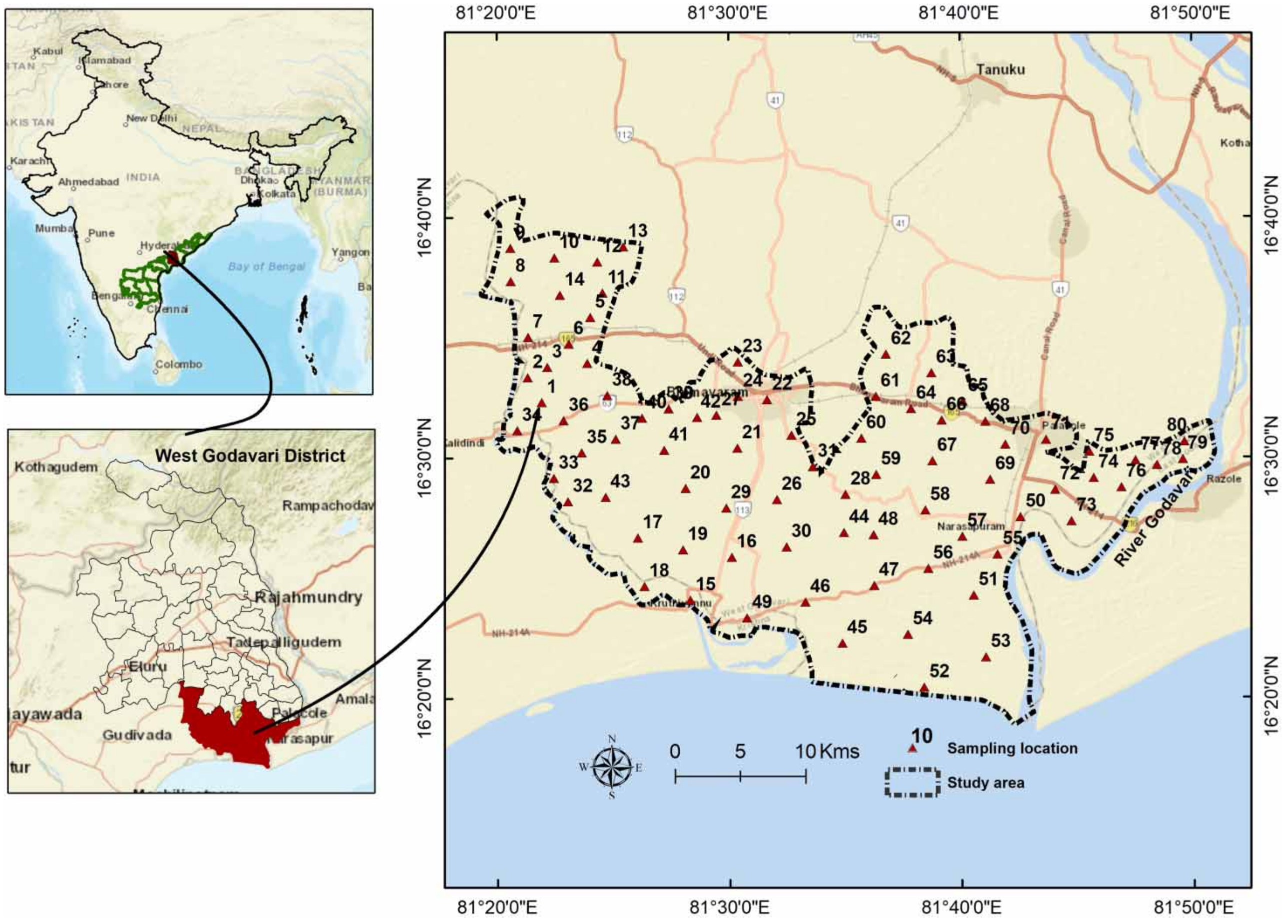

Figure 1 | Location map showing sampling stations of groundwater in the River Godavari Delta in the east coast of India.

The region around the RGD is one of the largest agriculturally grown areas in India. The area is now drastically being converted into aqua farming for good economic returns and better livelihood, which is leading to groundwater deterioration at a rapid pace. The mean annual rainfall is 1,078 mm and the temperatures vary between 20 °C (December) and 38 °C (May).

The RGD region supports a high density of population and is dependent on agriculture and aquaculture activities, as well as small-scale industries. There are several medium to large townships contributing sewage discharge, domestic wastes, industrial effluents, wastewaters from aqua ponds, etc. directly into the canals and onto the ground. Groundwater and surface water from the Godavari is used to supply water via canals for vast tracts of agriculture fields and aquaculture. The oceanic saline water from creeks and groundwater is also used extensively for aqua farming.

The area is mainly underlain by quaternary sediments with recent to sub-recent alluvium. The delta sediments of the area consist of brown, grey, gravelly sands, silty clay and clay. Dug wells and tube wells are constructed at a depth of 4–7 m below ground level and 10–65 m below ground level, respectively, for drinking and irrigation purposes as well. The water levels vary from 0.8 to 14.5 m below ground level. Groundwater development is limited in alluvium and the deeper zones are brackish to saline in nature (CGWB 2017). The rainfall, seepage from canals, return seepage through irrigation, and surface water bodies contribute to the groundwater recharge. Waterlogging is prominent in the study area due to flash floods, flat topography, poor drainage and rich clay soils.

METHODOLOGY

The groundwater samples were collected from 80 locations during May and June 2019, covering the entire study region. The 2-L pretreated polyethylene bottles were used for the collection of samples by following standard procedures (APHA 2012). The hydrochemical parameters pH, electrical conductivity (EC) and total dissolved solids (TDS) were measured by multi-parameter digital meter; calcium (Ca^{2+}) and magnesium (Mg^{2+}) analyzed using standard EDTA titration; bicarbonates (HCO_3^-) measured by titrating with HCl; chlorides (Cl^-) analyzed by titration with standard silver nitrate ($AgNO_3$) solution; sodium (Na^+) and potassium (K^+) by flame photometer; sulphates (SO_4^{2-}) measured using spectrophotometry, and colorimetric method was used for nitrates (NO_3^-) analysis (APHA 2012). The geographical coordinates along with the altitude of sampling locations were recorded using a handheld Oregon-GPS instrument. The charge balance error calculated for the data was found within ±10% accuracy. The range of analytical results is presented in Table 1.

Irrigation water quality index (IRWQI)

In the study area, groundwater is widely used for irrigation. The chemical composition of irrigation water is a measure of its quality as it affects the agricultural productivity and the properties of soils. There are several indices used to understand mechanisms controlling groundwater chemistry and determining the quality of water for irrigation purposes. The indices include Gibbs ratio I & II, chloro-alkaline indices (CAI) I & II, percentage of sodium (Na%), sodium adsorption ratio (SAR), residual sodium bicarbonate (RSBC), permeability index (PI), Kelly's ratio (KR), magnesium hazard (MH), potential salinity (PS) and other ratios which are calculated using the standard equations (Table 1). Water quality index is a numerical method that provides grades by taking the scores of all integrated quality parameters. It reflects the status of overall water quality derived from the cumulative effect of the individual parameters of groundwater (Sethy *et al.* 2017; Chaurasia *et al.* 2018). We have proposed the IRWQI by considering different water quality indices which were derived with mathematical functions based

Table 1 | The analytical results and the computed indices for determining groundwater quality for irrigation use in the study area

Parameter	Units	Minimum	Maximum	Average	Standard deviation
pH	No units	7.1	8.42	7.85	0.25
EC	µS/cm	1,510	3,808	2,607.45	574.81
TDS	mg/l	932	2,240	1,570.26	335.35
Ca^{2+}	mg/l	12	104	46.48	23.79
Mg^{2+}	mg/l	16	126	66.58	25.92
Na^+	mg/l	83	420	232.29	90.32
K^+	mg/l	15	168	91.94	34.79
HCO_3^-	mg/l	170	617	367.26	96.95
Cl^-	mg/l	112	612	361.99	134.3
SO_4^{2-}	mg/l	24	220	117.78	49.39
NO_3^-	mg/l	2	52	15.45	9.6
Na %	meq/l	30.46	88.04	60.46	11.60
SAR	meq/l	1.60	13.51	5.35	2.44
RSBC	meq/l	−0.57	8.93	3.70	1.90
PI	meq/l	43.93	98.42	69.50	11.25
KR	meq/l	0.36	6.28	1.47	0.95
MH	meq/l	8.69	71.38	30.80	15.34
PS	meq/l	4.50	19.50	11.44	3.84
Gibbs ratio-I	meq/l	0.49	0.95	0.80	0.11
Gibbs ratio-II	meq/l	0.35	0.80	0.61	0.11
CAI 1	meq/l	−0.71	0.09	−0.24	0.17
CAI 2	meq/l	−0.63	0.17	−0.25	0.19
Cl:HCO	meq/l	0.53	4.11	1.81	0.84
Mg:Ca	meq/l	0.40	10.51	3.19	2.29
Na:Ca	meq/l	0.98	17.96	5.75	3.74

on the concentrations of hydrochemical parameters in groundwater. IRWQI was calculated according to Equations (1)–(4):

$$IRWQI = \sum_{i=1}^{n} SI_i \tag{1}$$

where SI (sub-index) $= W_i q_i$ (2)

W_i is relative weight and q_i is the quality rating scale.

W_i is obtained from $W_i = \dfrac{w_i}{\sum_{j=1}^{n} w_i}$ (3)

where w_i is the assigned weight for each indices and n is the number of water quality indices.

q_i is calculated as: $q_i = \dfrac{I_v}{I_s} \times 100$ (4)

where I_v is the calculated value of water quality indices and I_s is the standard value of i^{th} indices.

In IRWQI, the assignment of weight for each index is crucial in the calculations. The recommended permissible limits of various selected water quality indices for irrigation water were taken from the standard sources. A total of ten established indices – Na%, SAR, RSBC, PI, MH, KR, PS, Cl:HCO_3, Mg:Ca, and Na:Ca – were taken into account for the development of IRWQI. Each index was assigned a suitable weight (w_i) based on the percentage of groundwater samples within the recommended limit as per the standards. If 0–25% of samples were within the permissible limits, then the weight assigned was 4; for 26–50% it was 3; for 51–75% it was 2; and for 76–100% of samples under permissible limits, the assigned weight was 1. This approach helped overcome the subjectivity of expert knowledge in choosing a rating scale for each index depending on its prominence in the irrigation water quality. The assigned weight for each index and their calculated relative weights are given in Table 2.

The overall weight of the indices range between 1 and 4, indicating excellent to unsuitable for water quality irrigation. The computed IRWQI values were grouped into four classes: no restriction for irrigation use (IRWQI $\leq$50), slight restrictions (51–100), moderate restrictions (101–200) and severe restrictions (IRWQI >200). The spatial distribution of various water quality indices and IRWQI maps were prepared using the raster interpolation technique of inverse distance weighted in the Spatial Analyst module of ArcGIS 10.6 version (ESRI 2020).

RESULTS AND DISCUSSION

Trends of hydrochemical variables

The hydrochemical data shows that the parameters EC, TDS and Mg^{2+} followed the normal distribution while other parameters pH, Ca^{2+}, Na^+, Cl^-, SO_4^{2-} and NO_3^{2-} depart from a normal distribution with skewness and outliers. The trends of

Table 2 | The assigned weights based on the percentage of samples falling below standard limits and their relative weights for each index of irrigation water used in calculating the IRWQI

			Samples within standard limit			
Sample no.	**Parameter**	**Standard limit I_s**	**Number**	**%**	**Weight w_i**	**Relative weight W_i**
1	Na%	60	35	44	3	0.136
2	SAR	10	76	95	1	0.045
3	RSBC	5	64	80	1	0.045
4	PI	25	27	34	3	0.136
5	MH	50	67	84	1	0.045
6	KR	1	31	39	3	0.136
7	PS	3	0	0	4	0.182
8	Cl^-:HCO_3^-	2	75	94	1	0.045
9	Mg^{2+}:Ca^{2+}	4	60	75	2	0.091
10	Na^+:Ca^{2+}	3	21	26	3	0.136

cations and anions follow the sequence of $Na^+ > K^+ > Mg^{2+} > Ca^{2+} = HCO_3^- > Cl^- > SO_4^{2-} > NO_3^{2-}$. The highly positive correlation (0.7–1) was identified between EC–TDS (0.994) and Na^+–Cl^- (0.93), while moderate correlation (0.5–0.7) was found between TDS–Na^+ (0.698), TDS–Cl^- (0.666), EC–Cl^- (0.671), EC–HCO_3^- (0.566), Mg^{2+}–HCO_3^- (0.543) and EC–Mg^{2+} (0.514) (Table 3).

The explains that the groundwater parameters have low to very strong influence on each other. The pH of groundwater varies between 7.10 and 8.42, with a mean of 7.85, suggesting that all the samples were within the permissible limit for irrigated water (BIS 2012). Long-term use of pH (below 6.0 and above 9.5) water damages soil structure and eventually affects crop production. The mean and standard deviation of various hydrochemical parameters recorded were 7.85 ± 0.25 for pH; EC: 2,607.4 ± 574.8; TDS: 1,570.3 ± 335.4; Ca^{2+}: 46.5 ± 23.8; Mg^{2+}: 66.6 ± 25.9; Na^+: 232.3 ± 90.3; K^+: 91.9 ± 34.8; HCO_3^-: 367.3 ± 96.9; Cl^-: 367 ± 96.9; SO_4^{2-}: 117.8 ± 49.4; and 15.5 ± 9.6 for NO_3^- (Table 1).

Natural mechanisms influencing groundwater chemistry

The geochemical evaluation of groundwater was studied using Chadha's diagram (1999). This plot is a simple modified Piper (1944) diagram that plots in milliequivalent percentages of (Ca + Mg)–(Na + K) on the x axis and ($CO_3 + HCO_3$)-(Cl + SO_4) on the y axis describes the overall character of the water by the square or rectangular field of the diagram (Figure 2).

The four quadrants of the plot explain that the hydrochemical processes of recharge water (Ca–Mg–HCO_3), reverse ion-exchange water (Ca–Mg–Cl), base ion-exchange water (Na–HCO_3) and seawater (Na–Cl). The groundwaters of the study area were mainly confined to the fields of 1, 2 and 4 according to Chadha's plot. The majority of samples revealed that the groundwater is influenced by salinity which may create problems for irrigation. The alkali metals (Na and K) exceed alkaline earths (Ca and Mg), and strong acidic anions (Cl and SO_4) exceed weak acidic anions (HCO_3) in the groundwater of the study area. The major hydrochemical facies identified were Na–Mg–Cl–HCO_3 followed by Na–Cl–HCO_3, Mg–Na–HCO_3–Cl and Na–Ca–Cl–HCO_3. The relationship between groundwater chemistry and aquifer lithology is explained by natural mechanisms which reveal that the area is influenced by evaporation and rock weathering (Gibbs 1970). The increasing trend towards evaporation dominance zone has been attributed to the marine environment close to the sea and decreasing trend of precipitation over the area (Figure 2).

The potential evapotranspiration (PET) varies from 99 mm to 162.3 mm per month, with a cumulative of 1,466 mm in a year. This high PET and the occurrence of calcareous material in the study region inclines towards the evaporation zone of groundwater chemistry (CGWB 2013). Some of the groundwater samples fall under the rock dominance category, suggesting that rock weathering and leaching are major geochemical processes influencing water types. The rock–water interaction generally includes the chemical weathering of rocks, dissolution, precipitation of secondary carbonates, and ion exchange between water and clay minerals (WHO 2012; Subba Rao 2018).

Table 3 | Pearson's correlation between the parameters showing with significant levels

Parameter	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-
pH	1	0.304**	0.314**	0.046	0.147	0.140	0.299**	0.256*	0.086	0.231*	0.100
EC	0.304**	1	0.994**	−0.103	0.514**	0.707**	0.445**	0.566**	0.671**	0.367**	0.360**
TDS	0.314**	0.994**	1	−0.107	0.527**	0.698**	0.469**	0.565**	0.666**	0.389**	0.340**
Ca^{2+}	0.046	−0.103	−0.107	1	−0.160	−0.102	−0.017	0.082	−0.070	0.053	0.053
Mg^{2+}	0.147	0.514**	0.527**	−0.160	1	−0.038	0.014	0.543**	−0.086	0.375**	0.272*
Na^+	0.140	0.707**	0.698**	−0.102	−0.038	1	0.362**	0.075	0.930**	0.136	0.245*
K^+	0.299**	0.445**	0.469**	−0.017	0.014	0.362**	1	0.159	0.379**	0.210	0.150
HCO_3^-	0.256*	0.566**	0.565**	0.082	0.543**	0.075	0.159	1	0.031	0.057	0.157
Cl^-	0.086	0.671**	0.666**	−0.070	−0.086	0.930**	0.379**	0.031	1	0.021	0.184
SO_4^{2-}	0.231*	0.367**	0.389**	0.053	0.375**	0.136	0.210	0.057	0.021	1	0.028
NO_3^-	0.100	0.360**	0.340**	0.053	0.272*	0.245*	0.150	0.157	0.184	0.028	1

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

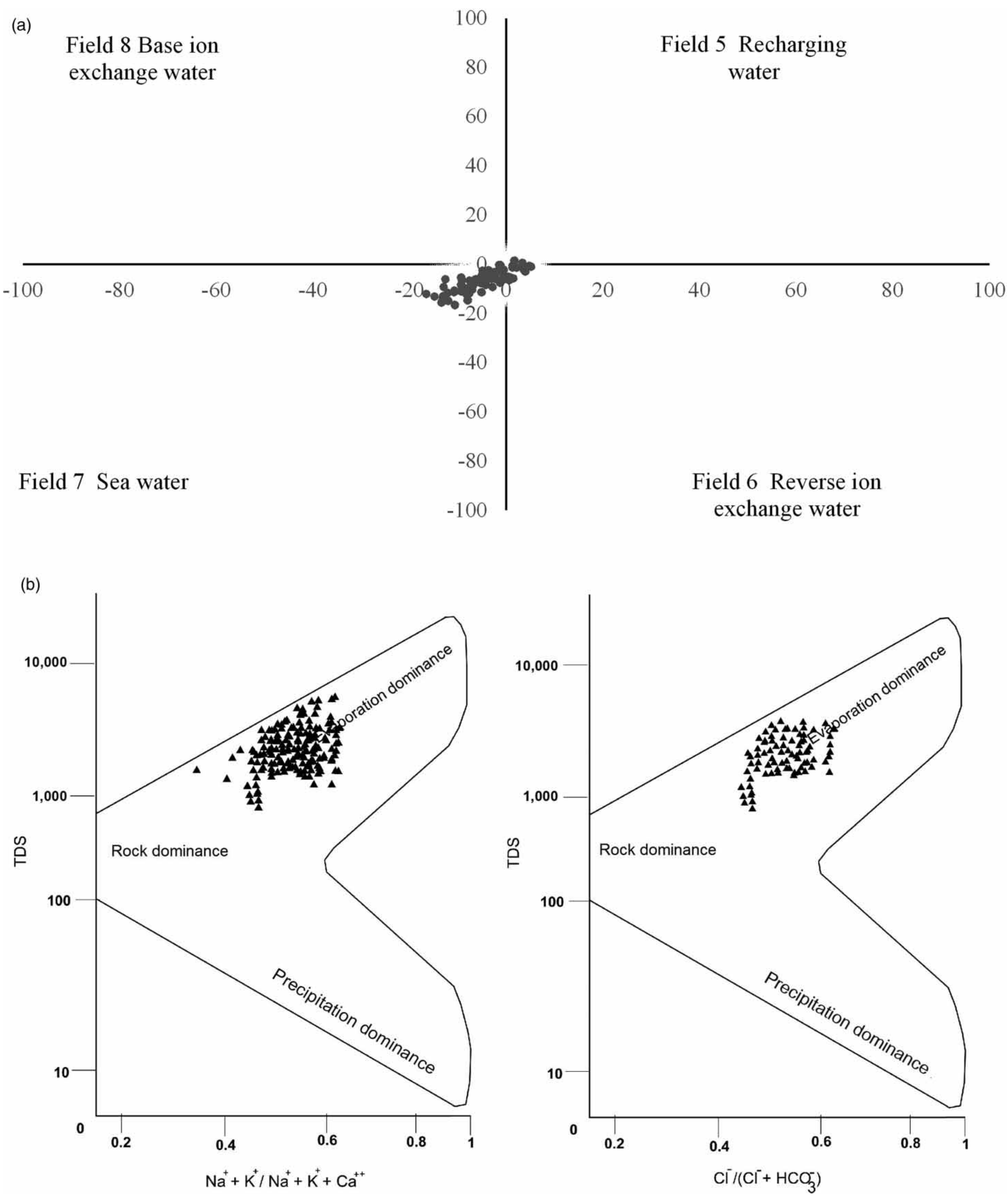

Figure 2 | (a) Chadha's diagram representing the groundwater type and (b) Gibbs diagram representing the mechanisms controlling groundwater chemistry of the study area.

Irrigation water quality indices

Salinity hazard (SAH)

The high range of EC leads to salinity which affects the plant growth and soil structure. EC in the groundwaters of the study area varied from 1,510 to 3,808 μS/cm with a mean of 2,607.4 μS/cm and TDS ranged between 932 and 2,240 mg/l with a mean of 1,570.3 mg/l. Generally, arid and semi-arid regions have high salinity in groundwater than humid-subhumid areas of the surface lands (Bauder *et al.* 2004). According to Richards (1954) classification, nearly 24 and 49% of samples recorded were unsuitable and doubtful category, respectively, hence it is doubtful for irrigation use. The remaining samples (27.5%) exhibited high salinity zones, thus the groundwater is permissible for irrigation use and it may not severely affect the agricultural productivity (Table 4).

However, there was no single sample under the low to medium salinity hazard category which explains that good drainage, high leaching and salt-tolerant plants need to be considered for irrigation (Bryan *et al.* 2007). The spatial distribution of EC in the study area is presented in Figure 3.

According to FAO (1994), nearly 87.5% of samples were shown to be suitable for moderate use; the remaining were unsuitable for irrigation because it was brackish water (Figure 4).

The ability of plants to take up water and nutrients is controlled by the saline conditions of soil as it increases due to more salts in water, poor drainage or a shallow water table. The higher the soil salinity, greater the water uptake by plants (Ayers & Westcot 1985; Filipovic 2020).

Table 4 | Classification of groundwater for irrigation purposes

Parameter/indices	Range	Classification	No. of samples	% of samples
EC μS/cm	<250	Excellent	0	0.0
	250–750	Good	0	0.0
	750–2,250	Permissible	22	27.5
	2,250–3,000	Doubtful	39	48.8
	>3,000	Unsuitable	19	23.8
TDS	<450	Safe	0	0.0
	450–2,000	Moderate to low safe	70	87.5
	>2,000	Unsuitable for irrigation	10	12.5
Na % $\left(\frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+}\right) \times 100$	<20	Excellent	0	0.0
	20–40	Good	3	3.8
	40–60	Permissible	31	38.8
	60–80	Doubtful	42	52.5
	>80	Unsuitable	4	5.0
SAR $\frac{Na^+}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$	<10	Excellent	76	95
	10–18	Good	4	5.0
	18–26	Doubtful	0	0.0
	>26	Unsuitable	0	0.0
RSBC $HCO_3^- - Ca^{++}$	<5	Safe	63	78.8
	5–10	Marginal	17	21.3
	>10	Unsuitable	0	0.0
PI $\left(\frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{++} + Mg^{++} + Na^+}\right) \times 1$	>75%	Suitable	27	33.8
	25–75%	Marginally suitable	53	66.3
	<25%	Unsuitable	0	0.0
MH $\left(\frac{Mg^{++}}{(Ca^{++} + Mg^{++})} \times 100\right)$	<50	Suitable	67	83.8
	>50	Unsuitable	13	16.3
KR $\left(\frac{Na^+}{Ca^{++} + Mg^{++}}\right)$	<1	Suitable	28	35.0
	>1	Unsuitable	52	65.0
PS $Cl^- + (0.5 \times SO_4^{2-})$	<3	Suitable	0	0.0
	>3	Unsuitable	80	100.0

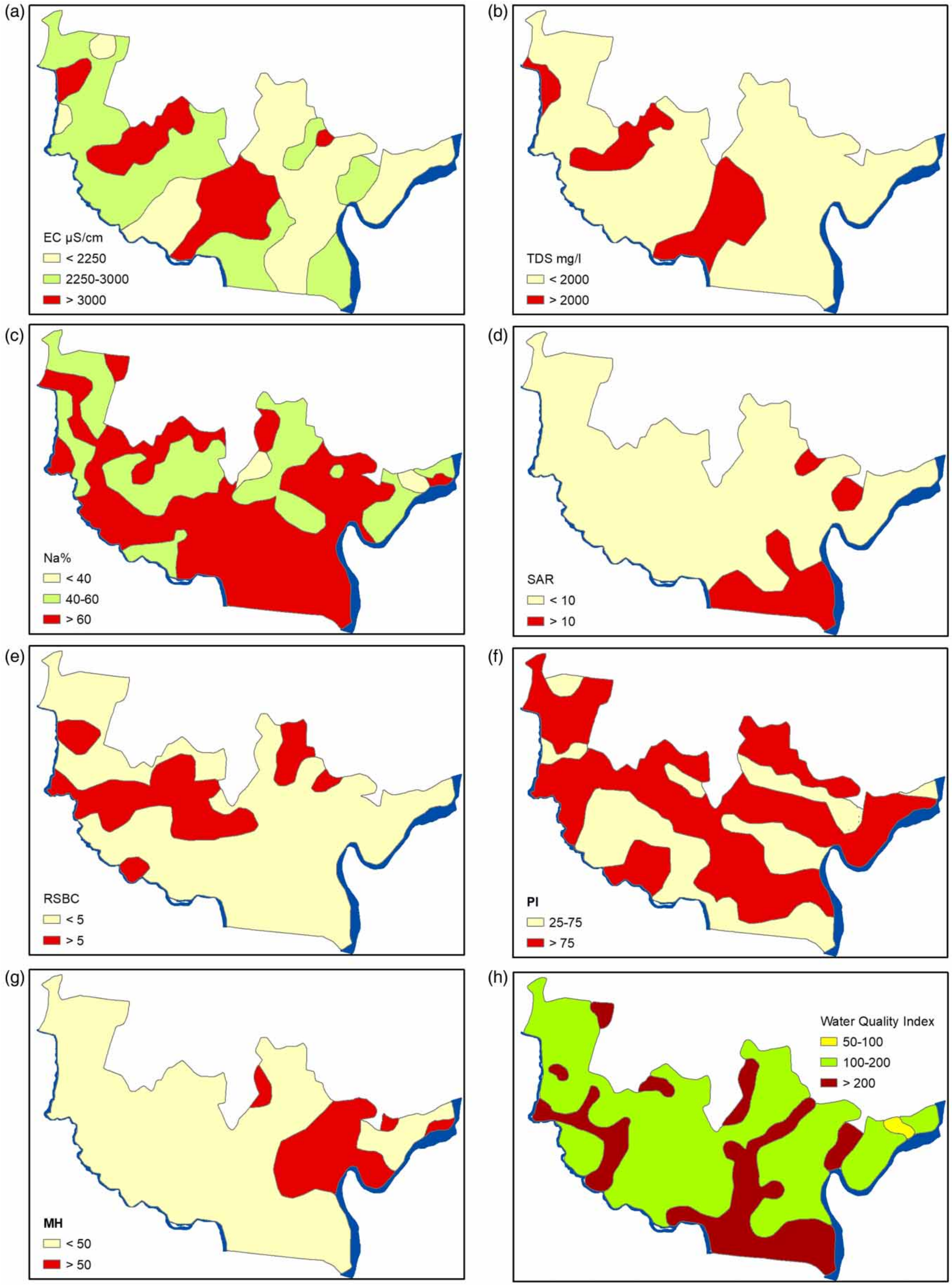

Figure 3 | Spatial distribution of various groundwater quality indices (a) EC, (b) TDS, (c) Na%, (d) SAR, (e) RSBC, (f) PI, (g) MH and (h) IRWQI representing suitability of groundwater for irrigation in the study area.

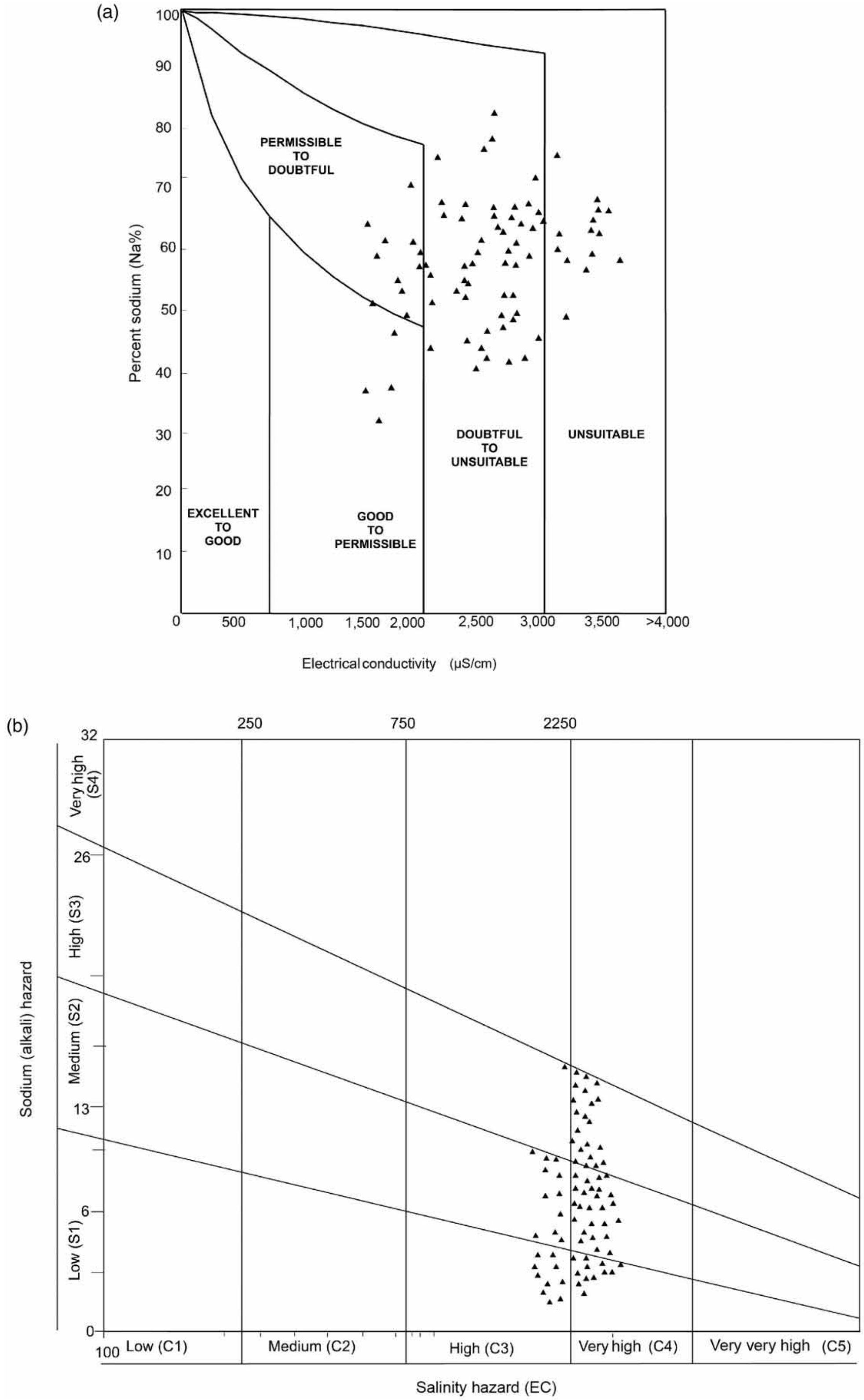

Figure 4 | The classification of groundwater water for irrigation purpose (a) Wilcox diagram and (b) USSL diagram.

Na%

Sodium occurs widely in soils, plants, water and foods that serve as essential nutrients necessary for some biogeochemical functions. The concentration of Na^+ in the study's groundwaters ranged from 83 to 420 mg/l. Sea or estuarine water intrusion may cause a high concentration of minerals and salts in groundwater (WHO 2012). The Na% or soluble sodium percentage was obtained in this study and varied between 47 and 92 meq/l (Table 1). High values of Na% in irrigated water affect the permeability of soils, leading to insufficient plant growth, thus reducing crop yield (Todd 1980). The Wilcox (1948) diagram of Na% versus EC shows that only 6% of samples fall into the good to permissible category; 13% in the permissible to doubtful; and the remaining (81% of samples) belong to the doubtful and unsuitable categories for irrigation (Figure 4). However, the groundwater can be used for agricultural purposes with 60% sodium content, which is distributed over 57.5% of the total area (Figure 3). Sodicity is different from salinity in that it causes swelling and dispersion of soil clays, surface crusting and pore plugging, resulting in high runoff. It decreases the downward movement of water into the soil, which adversely affects the root zone of plants and reduces water to the growing plants, despite sufficient water available in the root zone (Saleh *et al.* 1999; Bauder *et al.* 2014).

SAR

SAR measures the sodium or alkali hazard for crops. The activity of Na^+ in the cation exchange (with Ca^{2+} and Mg^{2+}) reactions in irrigated water destroys the soil structure due to the dispersion of clay particles. SAR assesses the potential for infiltration problems due to sodium imbalance in irrigation water. The values of SAR varied from 3.6 to 18.8 meq/l in groundwaters. All of the samples fall under the excellent to good category (Figure 3) (Bauder *et al.* 2014). USDA (1955) diagram illustrates that the samples belong to C3S1, C4S1, C3S2, C4S2 and C4S3 categories where more than 50% of total samples indicate very high salinity to medium–high alkali water (Figure 4). Hence, the use of such waters in irrigation is harmful to soil and thereby results in low permeability and poor cultivability. Good salt tolerance plants may be suitable for growing with proper drainage facilities (Todd & Mays 2005).

RSBC

Higher concentrations of carbonates and bicarbonates than calcium and magnesium in groundwater combines with sodium, leading to the formation of sodium bicarbonates. The adsorption of excess sodium in the soil leads to high residual sodium carbonate which damages soil structure and consequently reduces the permeability of soils (Eaton 1950; Richards 1954).

$$CO_3^{2-} + HCO_3^- + Na^+ + H_2O \rightarrow NaHCO_3^- + CO_3^{2-}$$

HCO_3^- varied between 170 and 617 mg/l, with a mean and standard deviation of 367 $\pm$ 96.9 in the groundwater of the present study. The calculated RSBC ranged from -0.6 to 8.9 meq/l. The negative values of RSBC were safe for irrigation (Gupta 1983). If the RSBC value is less than 5, it can be considered safe. If the value ranges between 5 and 10, it is marginal, and more than 10 indicates unsatisfactory irrigation (Gupta & Gupta 1987). According to the classification, nearly 21% of total samples indicated that the water was marginally suitable for irrigation (Figure 3). This may be due to an increase in Na^+ in the soil, which affects plant growth. Thus, best irrigation practices are necessary to use the marginal RSBC water successfully for irrigation. Application of gypsum is more effective when irrigation waters contain high residual sodium carbonate (Bajwa *et al.* 1983; Raghunath 1987).

PI

The prolonged use of irrigation water can affect the soil permeability, which is influenced by mineral-rich groundwater. The rich Na^+, Ca^{2+}, Mg^{2+} and HCO_3^- in groundwater can reduce aeration in the soil and obstruct the growth of seedlings (Ayers & Westcot 1976). The higher the PI, the lower the absorption of Na^+ in soils, resulting in an increase in plant growth. Class I, II and III represent the maximum permeability of soils with PIs of 100, 75 and 25%, respectively, corresponding to irrigation-suitable, marginally suitable and unsuitable soils (Doneen 1964). The PI of groundwater varied from 44 to 98.4%, indicating Class I and II waters (Table 4). As per the classification of PI, 34% of samples fall under suitable and the remaining 66% come under the marginally suitable category for irrigation (Figure 3).

MH

Ca^{2+} and Mg^{2+} ranged from 12 to 104 mg/l and 16 to 126 mg/l, respectively, in the study area. The high concentration of Mg^{2+} in groundwater is less harmful than Na^+, but is not as beneficial as Ca^{2+} in irrigated soils (BIS 2019). Higher Mg^{2+} than Ca^{2+} concentrations can be found in some soil types, but normally Mg^{2+} is found to be 20–50% of the Ca^{2+} concentrations (Binkley & Fisher 2019). Mg^{2+} in excess of the Ca^{2+} content can change the soil properties and damage crop growth. It is more dangerous if the water contains more Na^+ and higher salinity, which results in soil dispersion and decreased infiltration rate (Bohn *et al.* 1985). If MH is above 50 in groundwater, it is unsuitable for irrigation because it effects crop yields (Raghunath 1987). It was found that the MH ranged from 8.7 to 71.4 with 16% of total samples not suitable for irrigation (Figure 3). Mineral leaching and weathering, as well as marshy lands and gypsum, could be the cause of rising Mg^{2+} levels in groundwater.

KR

KR values ranged between 1.1 and 13.8 mg/l in the study area (Table 4). If the ratio is less than 1, then the groundwater is fit for irrigation (Kelly 1951). About 60% of groundwater samples showed a ratio more than 1, and hence the water is unsuitable for irrigation because of the high content of Na^+ against alkaline earths, which decreases soil permeability.

PS

PS is considered as an indicator for the categorization of water for agriculture use. The value of PS obtained from Cl^- and SO_4^{2-} concentrations in groundwater is below 3 suggested for irrigation use (Doneen 1964). The average concentration of Cl^- in the groundwater of the study area was 362 mg/l, indicating high limits. A very low Cl^- helps with the plant health, but high values cause sensitive crops. More than 75 mg/l Cl^- in irrigated water is toxic and also creates severe problems when it is above 350 mg/l (BIS 2019). Above 50% of samples exceeded the BIS limits, and none of the samples were found to be below the limits. On the other hand, the concentrations of SO_4^{2-} in groundwater varied from 24 to 220 mg/l. The PS can be estimated from half of SO_4^{2-} added to Cl^- concentrations, which ranges between 4.5 and 19.5 meq/l in the groundwater of the study area. All the groundwater samples fall above the limits of PS, and hence the groundwater is unsuitable for irrigation. The ratio of Cl^- and SO_4^{2-} was more than 2 in 93% of total samples, indicating necessary management practices required for minimizing the harmful effect of Cl^- in irrigation (BIS 2019).

Ionic relationship

Bivariate diagrams were drawn for hydrochemical parameters of the study area to understand the sources of ions in water (Figure 5).

The $Ca^{2+} + Mg^{2+}$ versus $SO_4^{2-} + HCO_3^-$ diagram reveals that the majority of samples nearly lie along the equiline, which indicates both carbonate and silicate weathering are the main sources for HCO_3^-, Mg^{2+} and Ca^{2+} in groundwater. The origin of high Mg^{2+} is due to the dissolution of magnesium calcite, gypsum and/or dolomite (Garrels 1976), while HCO_3^- and Ca^{2+} concentrations in groundwater may be because atmospheric CO_2 and water (carbonic acid) react with $CaCO_3$ (calcium bicarbonate) in soils.

$$CaMg(CO_3)_2 + 2H_2CO_3 \rightarrow Ca^{2+} + Mg^{2+} + 4HCO_3$$

The plot of $Ca^{2+} + Mg^{2+}$ versus HCO_3 shows that the parameters have a good relationship as samples fall along the equiline, indicating a rock–water interaction and reverse ion exchange. Na^+ and Cl^- are dominant cations and anions in the groundwater of the study area. The distribution of Na^+ and Cl^- ions along the 1:1 line reveals halite dissolution. The dominating anion, Cl^- in groundwater, results from aquifer salts and seawater intrusion. Na^+ is progressively increasing with the total mineral content of groundwater, which indicates the cation exchange process is responsible for its enrichment.

$$Ca^{2+} + Na_2 - X \rightarrow 2Na^+ + Ca - X$$

where X denotes cation exchange sites. The recharging waters exchange Ca^{2+} with Na^+ when interacting with clay lenses, leading to the development of salinization (Li *et al.* 2008). The dissolution of calcite and dolomite minerals causes an increase

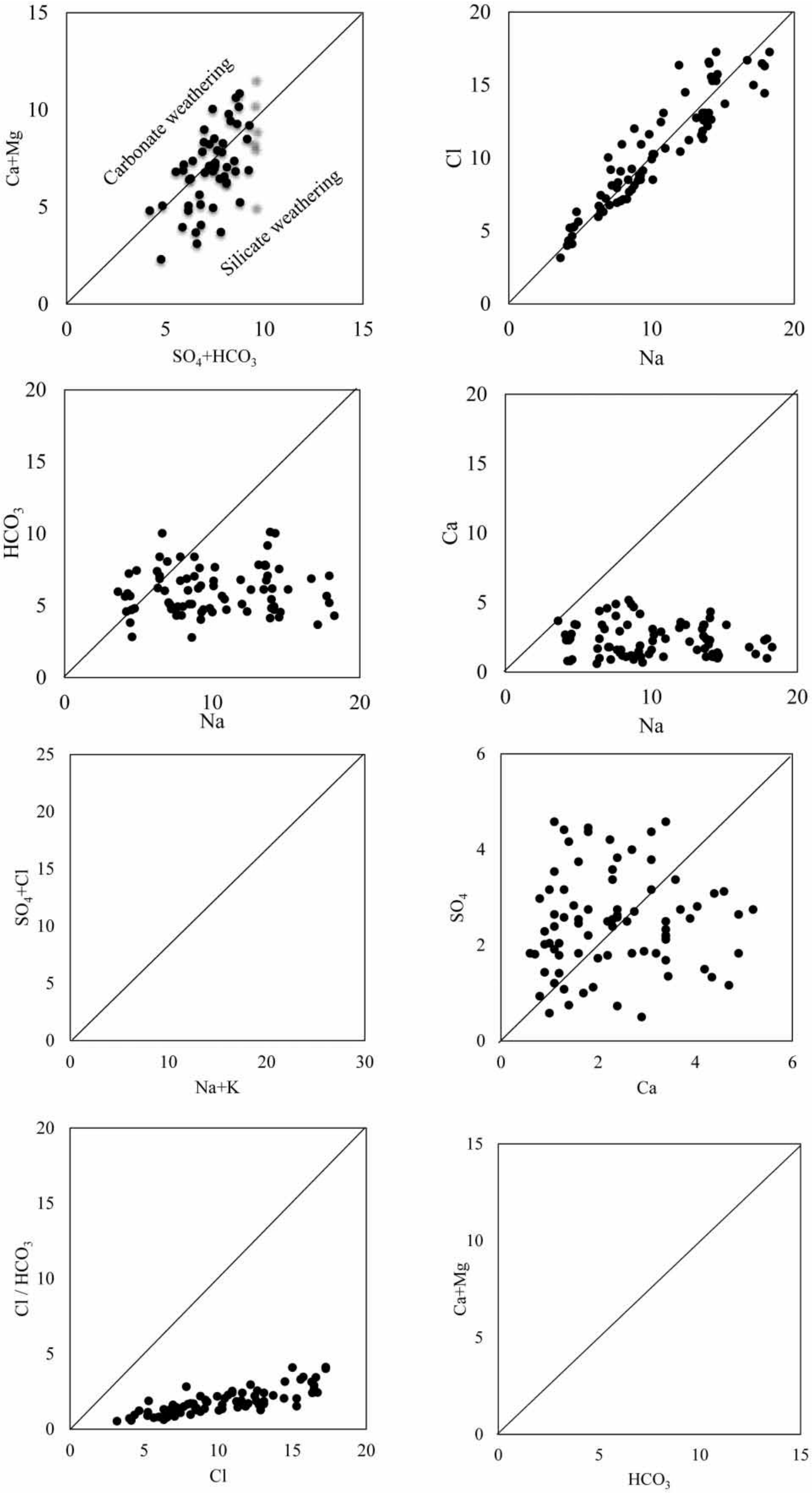

Figure 5 | Bivariate diagrams expressing the ionic relationship of groundwater.

in levels of Na^+ and HCO_3^- concentrations and low levels of Ca^{2+} in the form of:

$$CaCo_3 + CO_2(aq) + H_2O + Na_2 - X \rightarrow 2Na^+ + 2HCO_3^- + Ca - X$$

Na^+ versus HCO_3^- and Na^+ versus Ca^{2+} scatter diagrams represent the majority of samples lying below the 1:1 line, indicating less control of silicate weathering for Na^+ ions abundance. The probability of ion exchange of Ca^{2+} with Na^+ is due to the occurrence of clay soils and marine salts. When Mg^{2+} exceeds than Ca^{2+}, it indicates the dissolution of ferromagnesium minerals from the ocean floor (Mercado 1985; Hem 1991). It is supported by TDS >500 mg/l in all water samples. The association between $Na^+ + K^+$ and $Cl^- + SO_4^{2-}$ was found as a simultaneous graining with each other, indicating the dissolution of soil salts and anthropogenic sources (Srinivasamoorthy *et al.* 2011). The study area is prone to waterlogging, which transfers Cl^- salts into the soil–water interface (Drever 1988). The bivariate diagram shows that in 55% of samples SO_4^{2-} is dominant over Ca^{2+}, indicating the evaporation is responsible for the evolution of groundwater chemistry. The Ca^{2+}:SO_4^{2-} is approximately 1 in 25% of samples, indicating the dissolution of gypsum. The excess Ca^{2+} over SO_4^{2-} in a total of 45% samples might be the cause of carbonates dissolution in groundwater.

The calcite is the secondary dissolution process because fewer samples are below the 2:1 line. Cl^- is the dominant anion, followed by HCO_3^- recorded in the groundwater. High HCO_3^- leads to high alkalinity and pH in groundwaters which results in scaling and exceeding SAR. The calculated ratio of Cl^- and HCO_3^- ranges from 0.53 to 4.11, indicating that the groundwater is slightly to moderately affected by seawater because the limit of 0.5 was exceeded (Revelle 1941). Based on the ratio, the quality of water classified as good was less than 0.5; slightly contaminated was 0.5–1.3; moderately contaminated was 1.3–2.8; injuriously contaminated was 2.8–6.6 and highly contaminated was more than 6.6. The results revealed that 29% of samples were slightly contaminated, 58% were moderately contaminated and the remaining were highly contaminated (14%) (Todd 1959). The contamination of water is mainly due to a large number of aqua ponds, backwaters and salt plains, and proximity to the sea. Desai *et al.* (1979) suggested the value of 2 and above for Cl:HCO_3 for considerable seawater intrusion into the freshwater aquifers. According to this, more than 35% of samples were recorded as high in the study area due to intensive aquafarming for which pumping of saline water is necessary into the ponds (Senthilkumar *et al.* 2018).

IRWQI

The IRWQI of groundwater ranged between 78.3 and 352.6, with an average of 185.1 which was classified as good water (slight restrictions) to very poor with severe restrictions of water for irrigation purposes (Figure 3). Out of 80 samples, only three samples fell under the slight restrictions zone, while none of the samples came under the no restriction zone (excellent). The use of the majority of samples, i.e. 60%, required moderate restrictions and 36.2% of samples were very poor and cannot be used for irrigation without treatment (Table 5).

The individual indices that exceed the standard limits recorded and caused an increase in the groundwater pollution index for irrigation water were in the following sequence: PS (100%), Na:Ca (74%), PI (66%), KR (61%), Na% (56%), Mg:Ca (25%), RSBC (20%), MH (16%), Cl:HCO_3 (6%) and SAR (5%). An average of 43% of total indices exceeded the limits. The spatial distribution map of IRWQI shows a small patch of the study area in the northeast as being in good condition, while the majority of the area represents moderate to severe restrictions of use for irrigation.

CONCLUSIONS

The hydrochemical analysis of shallow groundwater was analyzed for assessing its suitability for irrigation in the agricultural west deltaic soils of Andhra Pradesh in the east coast of India. From the data analysis, the following conclusions were drawn:

1. Groundwater is used for agricultural activities in this coastal region. The water type observed was Na–Cl, and a locally mixed type of Na–Mg–Cl–HCO_3 and Na–Cl–HCO_3. The trends of cations and anions were recorded in the sequence of $Na^+ > K^+ > Mg^{2+} > Ca^{2+} = HCO_3^- > Cl^- > SO_4^{2-} > NO_3^{2-}$. The significant correlation found between EC–TDS (0.994) and Na^+–Cl^- (0.93), TDS–Na^+ (0.698), TDS–Cl^- (0.666) and EC–Cl^- (0.671) reveals that groundwater is mostly affected by anthropogenic activities and salinization.
2. Chadha's diagram revealed that alkali metals exceed alkaline earths, and strong acids exceed weak acids in the groundwater chemistry. Geochemical evaluation of groundwater explained that evaporation is the main controlling factor of geochemistry, along with rock dominance.

Table 5 | IRWQI of individual groundwater sample of the study area

Sample no.	IRWQI	Sample no.	IRWQI
1	127.9	41	233.4
2	146.1	42	214.7
3	223.8	43	180.5
4	168.4	44	208.7
5	110.3	45	285.7
6	171.7	46	182.8
7	162.7	47	248.2
8	178.0	48	303.9
9	133.8	49	264.2
10	127.4	50	226.0
11	137.0	51	171.6
12	151.0	52	242.1
13	266.2	53	352.6
14	202.4	54	182.6
15	136.7	55	150.3
16	164.0	56	245.9
17	219.5	57	143.0
18	169.3	58	137.1
19	179.7	59	158.8
20	103.6	60	91.7
21	104.0	61	218.5
22	191.6	62	242.3
23	198.7	63	141.7
24	263.5	64	184.6
25	128.3	65	155.9
26	195.2	66	179.1
27	191.5	67	235.0
28	240.5	68	283.3
29	191.6	69	123.7
30	178.7	70	126.0
31	201.5	71	208.8
32	189.6	72	311.1
33	161.7	73	135.3
34	227.4	74	149.5
35	256.4	75	121.0
36	206.6	76	138.5
37	118.3	77	78.3
38	243.1	78	96.4
39	206.8	79	198.5
40	175.9	80	103.5
Minimum	78.3		
Maximum	352.6		
Mean	185.1		

3. The groundwater samples recorded high values of EC (>2,250 µS/cm in 72.5%), Na% (>60 in 57.5%), RSBC (>5 in 21.3%), PI (66.3%), MH (>50 in 16%), KR (>1 in 65%) and PS (>3 in 100%), indicating doubtful to unsuitable conditions for irrigation use. These waters can damage crops and reduce the yields when used without treatment and good management practices. It is essential to use lime/gypsum treatment in soils with a good irrigation system, and saline or salt-tolerable crops could be used.
4. The IRWQI with a mean value of 185.1 indicated that the groundwater suitability for irrigation was very poor, hence its use must have severe restrictions. Of the groundwater samples suitable for irrigation, 96.3% of samples fell under moderate to severe restrictions. Land irrigated with such water will be exposed to salinity hazards, hence soils with good drainage and leaching conditions should control salinity.
5. The hydrochemical variations in groundwater indicate that the leaching of secondary salts, the probability of seawater intrusion, ion-exchange processes and anthropogenic activities, e.g. over-pumping and waterlogging areas, are responsible for the deterioration of groundwater quality.
6. The authorities, along with the support of local communities, must take action to arrest saline water intrusion into the alluvial aquifer systems by adopting engineering techniques, scientific monitoring and assessment, which will help towards the sustainable groundwater development of the study area for the future. The results suggest that the integrated hydrochemical indices, IRWQI and GIS methods are promising tools for the evaluation of groundwater chemistry at the local and regional level.

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DECLARATION OF INTEREST STATEMENT

The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information. All data generated or analyzed during this study are included in this article.

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