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ORIGINAL ARTICLE

Evaluation of groundwater quality for domestic and irrigation purposes in a coastal alluvial aquifer using multivariate statistics and entropy water quality index approach: a case study from West Godavari Delta, Andhra Pradesh (India)

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Abstract

The present study investigates the groundwater quality for domestic and irrigation purposes in a coastal aquifer in the West Godavari delta region based on geochemical evaluation, integrated multivariate statistical analysis and entropy water quality index (EWQI). The study area is underlain by the Quaternary sediments with unconsolidated to semi consolidated sand, silt and clay formation. In the study, the significant hydrochemical facies of groundwater observed were Na-Mg-Cl-HCO_3^-, Na-Cl-HCO_3^- and Mg-Na-Cl-HCO_3^-. The results revealed that the area occupies high salinity groundwater controlled mainly by evaporation and also by rock weathering-solubilization to some extent. The concentrations of major cations and anions decreased in the order: $Na^+ > K^+ > Mg^{2+} > Ca^{2+} = Cl^- > HCO_3^- > SO_4^{2-} > NO_3^-$. The chemical constituents of the samples TA (85%), TDS (100%), TH (83%), Mg^{2+} (91%), Cl^-(81%) and SO_4^2 (12%) exceeded the limits, making them unfit for drinking. Based on EWQI (53.3–143.4), nearly 70% of groundwater samples were of poor to very poor quality for drinking, which required treatment, and the remaining 30% of samples were unsuitable for domestic purposes. Some samples of the irrigation suitability parameters (Na%, SAR, RSC, PI, CAI, KR and CCR) exhibit moderate to good categories, which can be used for irrigation with proper management. The multivariate statistical analysis was performed to understand the relationships among the chemical constituents present in groundwater. TDS is highly correlated with EC, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^- and Cl^-. Principal component analysis (PCA) applied to the datasets showed that the first three PCs accounted for 65% of total variance cumulatively 94.5% for a total of 7 PCs. The PCA results indicate that the variation of groundwater quality is possibly attributed to various anthropogenic and geogenic factors, rock–water interactions and ion exchange processes in groundwater. The uncontrolled drawl of subsurface waters and aqua forming at an advanced rate when compared with recharge has led to this coastal aquifer being in a critical stage.

Keywords Groundwater quality · Alluvial aquifer · Hydrochemical indices · PCA/FA · Multivariate statistics · Godavari delta · Coastal Andhra Pradesh · India

Introduction

Groundwater is a vital natural resource and has a significant role in the global economy. For irrigation purposes, groundwater is a reliable source of water and can be used in a flexible manner (USGS 2001). According to the World Bank (2012), the largest consumer of groundwater in the world is India, with an estimated annual groundwater use of 230 km^3. Owing to the pressure created on hydrologic and hydrogeologic systems, the quality of groundwater is being degraded particularly in coastal areas across the globe. In coastal regions, seawater intrusion and salinization of groundwater because of overexploitation of freshwater aquifers will establish a negative water balance (Ferguson and Gleeson 2012). Hydrochemical studies of groundwater have vigorously been conducted by several researchers globally to identify and interpret the human-induced impact on groundwater chemistry (Sahu and Sikhdar 2008; Gibrilla et al. 2011; Aly et al. 2014; Brindha and Kavitha 2015;

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Sarikhani et al. 2015; Li et al. 2016; Diana et al. 2017; Wagh et al. 2018; He et al. 2019; Loh et al. 2020). The multiusage of groundwater for drinking, agricultural and industrial purposes, fisheries and energy production depends considerably on its quality (Iscen et al. 2008). The soil structure and crop yields are adversely affected by the presence of salts in irrigation waters. Arid and semi-arid climate regions are particularly vulnerable to salinity because of variations in rainfall and temperatures that lead to high evaporation (Jalali 2007; Houatmia et al. 2016). The soils of agricultural areas have created environmental problems like water resource contaminants and health risks for human beings due to the vigorous usage of fertilisers and agrochemicals (Shindo et al. 2006; Scanlon et al. 2007; Jiang et al. 2009). Zakaria et al. (2021) conducted groundwater quality studies in the Anayari catchment area, which is predominantly dependent on groundwater for agricultural purposes. They found that the water containing a low percentage of Na^+ with moderate salinization can usually be used for irrigation purposes without any prior treatment. In the recent years, with an increasing number of chemical and physical variables in groundwater, a wide range of conventional tools and techniques of statistical methods have been applied for proper analysis and interpretation of data (Belkhiri et al. 2010; Machiwal and Jha 2010). Hierarchical cluster analysis, being a simple but efficient approach, was applied by researchers to distinguish the multivariate similarities in groundwater quality. Principal Component Analysis (PCA)/Factor Analysis (FA) and Cluster Analysis (CA) explains the dataset matrixes for understanding environmental systems and the quality of water influenced either by natural or anthropogenic conditions (Lee et. al. 2001; Subyani and Ahmadi 2010; Dudeja et al. 2011; Guggenmos et al. 2011; Blake et al. 2016; Ravikumar et al. 2017; Sayad et al. 2017; Khelif and Boudoukha 2018; Paul et al. 2019; Sandeep et al. 2020). Multivariate statistical techniques can be employed to analyze large datasets on water quality with the minimum loss of vital information (Simeonov et al. 2003; Jauhir et al. 2011; Gulgundi and Shetty 2018). The alluvial aquifer system is the dominant type of aquifer in the coastal area. The coastal alluvial aquifer is relatively vulnerable to contamination by seawater. It is hard to restore its fresh groundwater condition which makes groundwater unsuitable for drinking as well as agriculture use (Jeen et al. 2001; Chidambaram et al. 2009; Mohapatra et al. 2011; Swarna Latha and Nageswara Rao 2012; Guler et al. 2012; Reddy 2013; CGWB 2014; Sajjil Kumar 2016; Alfrrah et al. 2018; Sivakarun et al. 2020). The conversion of agriculture and marshy lands into aquaculture, which uses large scale saline water from creeks and urban industrialization lead to the alteration of freshwater aquifers in coastal regions. Therefore, understanding the hydrochemical characteristics of the coastal groundwater is essential to prevent saline intrusion and its associated problems (Prasanna et al. 2011; Thilagavathi et al. 2019). The residents of coastal regions in India are facing severe drinking water quality problems in comparison with other regions.

Keeping this in to consideration, the present study was carried out to evaluate the hydrochemical characteristics and quality of groundwater and its suitability for domestic use and irrigation in an alluvial coastal aquifer using multivariate statistical techniques. The main aim of the present study is to assess the quality of water based on the entropy weighted water quality index (EWQI) for drinking purposes.

Study area

The study area is located in the West Godavari delta region of coastal Andhra Pradesh (AP) in Southern India. The district of West Godavari in AP is bounded by the districts of East Godavari in the North and Krishna in the South, Telangana State in the West and the Bay of Bengal in the East. The area under research lies between 16° 19' N to 16° 40' N latitudes and 81° 19' E to 81° 43' E longitudes (Fig. 1). It has a 23 km coastline covered with natural vegetation, cashew, casuarina and coconut plantations on its sandy tracts. The study area receives rainfall mostly from the south-west monsoon (June to September) and the average annual rainfall recorded is about 875 mm. The climate is maritime tropical humid with the maximum of 38 °C in May. The River Godavari is a major river and its tributaries, namely the Tammileru, Yarrakalva and Ramileru, flow through the West Godavari district, providing an abundant water supply for vast tracts of agriculture fields and aquaculture ponds. The river Godavari bifurcates into Gautami Godavari and Vasishta Godavari in the district region. The Gautami Godavari river marks the district boundary on the right side and drains through the present study area before ultimately debouching into the Bay of Bengal at Antarvedi.

The delta area is aided by the large canal system and numerous other drains. The oceanic saline water from creeks is also extensively used for aqua farming near the coastal tracts. The largest shallow freshwater lake in Asia is Kolleru Lake, in the southwestern part of the study area, and is designated as a wetland of international importance under the international Ramsar Convention. The study area accommodates nearly 0.5 million people, spread over several villages. Agriculture and aquaculture are the predominant activities found in the study area. The area is known for the large scale production of paddy, sugarcane, pulses, oilseeds, coconuts, etc. and it is considered to be one of the largest aqua farming regions of the country. The study area has been infested by a huge number of fish and prawn ponds during the last three decades, resulting in an ecological and environmental imbalance (Swarna Latha and Hema Malini 2018).

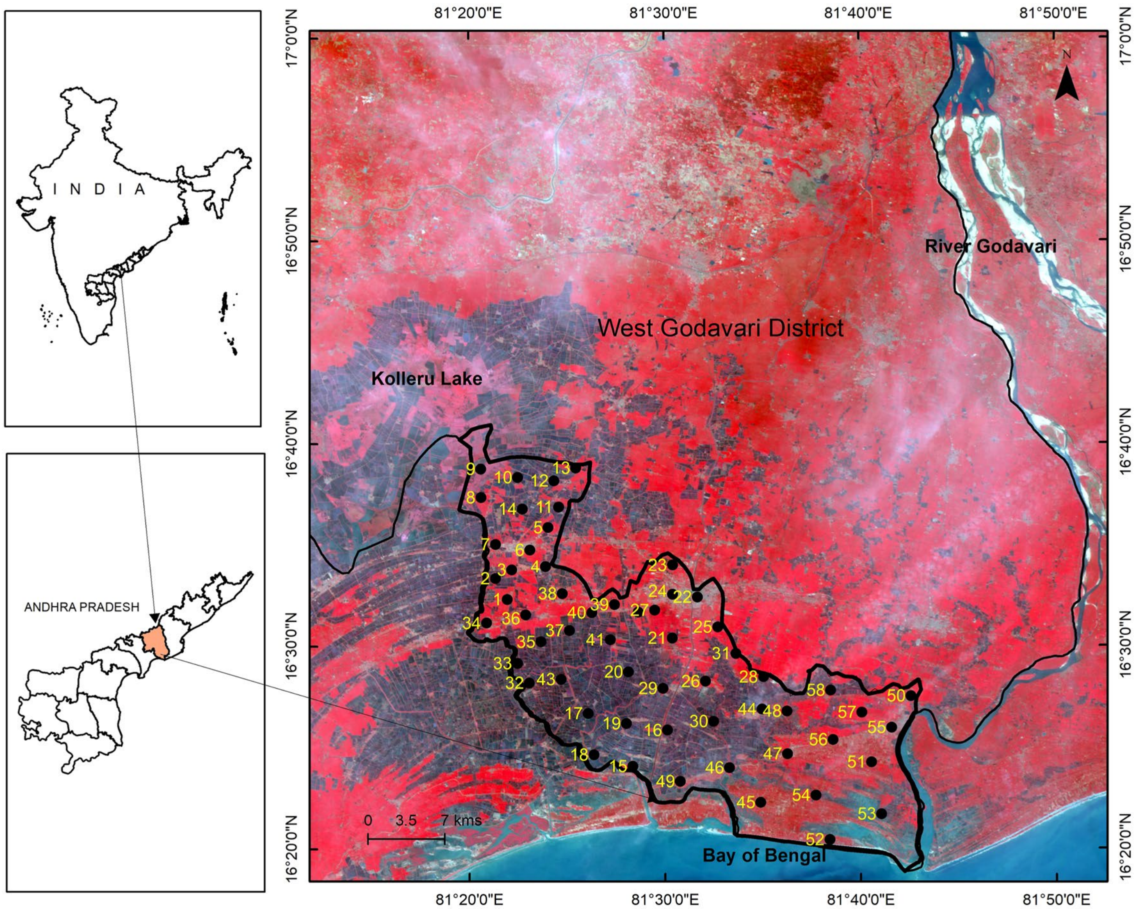


Fig. 1 Location map of the study area

General geology and geomorphology

Geologically, the study area is underlain by the quaternary sediments with unconsolidated to semi consolidated sand, silt and clay formations. In general, the delta sediments consist of brown, grey, gravelly sands and silty clay. The thickness of the sediments gradually increases towards the sea and is of the order of 400 m in the Godavari delta (Raju et al. 1994; Ramesh 2008). The quaternary sediments comprise thick layers of alluvium, gravel and colluvial deposits, beach sand, kankar and soils of various types. Different geomorphic features such as flood plains, alluvial plains, levees, paleochannels, beach ridges, active tidal flats, mudflats, swamps and backwaters etc. are observed. Flood plains are built up of alluvium carried by the river during floods and is deposited in the sluggish water. The flat or nearly level sloping ground of these flood plains yields high groundwater potential zones. Beach ridges are low dunes formed as continuous mounds of beach materials (sand, gravel, shingle, etc.) parallel to the shoreline. Another important feature is tidal flats, which are characteristically extensive, nearly horizontal, marshy or barren stretches of land alternately covered and uncovered by the rise and fall of the tides. It consists of unconsolidated sediments, mostly mud and sand. Soils predominantly are deep black clay and sandy; and to some extent, gravelly, dark brown and silty soils. Groundwater extraction structures in the study region are mainly open, bore or tube wells. The average depth of the dug well recorded is 7 m below ground level (m bgl). The borewell depth varies from 10 to 65 m. The average fluctuation of the water table is recorded at 0.91 m in the study area (CGWB 2017).

Materials and methods

A total of fifty eight (58) groundwater samples were collected with proper care from the bore wells covering the entire study area during May 2017 (Fig. 1). The 1L polyethylene bottles were used for collecting groundwater and were properly rinsed with distilled water before carrying out the sampling. At the sampling location, the bottles were rinsed several times with the same bore well water to avoid any contamination before filling. These samples were cautiously sealed and labelled and taken to the laboratory to carry out the analysis within a week. The samples were preserved by adding appropriate reagents in the laboratory by adopting standard protocols (APHA 1998). The pH, electrical conductivity (EC) and total dissolved solids (TDS) were analyzed using a multi parameter digital meter. Total alkalinity (TA), total hardness (TH), calcium (Ca^{2+}), bicarbonates (HCO_3^-) and chlorides (Cl^-) were measured by the titration method, sodium (Na^+) and potassium (K^+) by flame photometer whereas sulphates (SO_4^{2-}) were analyzed by spectrophotometry. Magnesium (Mg^{2+}) was estimated by the formulae [TH-(2.5 × CaH)]/4.1 (Todd and Mays 2005). The result of ionic balance shows that the error for groundwater samples was ≤ 10%. The analytical results of chemical parameters of groundwater are presented in Table 1. The Bureau of Indian Standards (BIS 2012) was considered for comparing chemical constituents in groundwater for its utilization for both domestic and agricultural purposes.

Entropy weighted water quality index (EWQI)

The water quality index methods provide better and more valid information to ascertain quality issues more accurately. The entropy weighted water quality index (EWQI) is one such method which explains the quality of water with a numerical number by integrating all the analyzed hydrochemical parameters. This improved water quality index model is considered to be more reliable and accurate as it greatly reduces the biased weight assignment to the quality parameters. EWQI is calculated as explained below in five steps (Wu et al. 2018; Subba Rao et al. 2020; Adimalla 2021):

Step 1 The eigenvalue matrix "X" which is associated with the water quality parameters estimated by the following equation:

$$X = \begin{bmatrix} x_{11}, x_{12}, x_{13}, \ldots ..x_{1n} \\ x_{21}, x_{22}, x_{23}, \ldots ..x_{2n} \\ . \\ . \\ . \\ x_{m1}, x_{m2}, x_{m3}, \ldots ..x_{mn} \end{bmatrix}$$

where, m ($i = 1, 2, 3, 4, \ldots, m$) represents water samples and n ($j = 1, 2, 3, 4, \ldots\ldots, n$) represents the total number of hydrochemical parameters of each sample.

Step 2 The standardization process "y_{ij}" is evaluated and then standard evaluation matrix "Y" is obtained as:

$$y_{ij} = \frac{x_{ij} - \left(x_{ij}\right)_{\min}}{\left(x_{ij}\right)_{\max} - \left(x_{ij}\right)_{\min}}$$

$$Y = \begin{bmatrix} y_{11}, y_{12}, y_{13}, \ldots ..y_{1n} \\ y_{21}, y_{22}, y_{23}, \ldots ..y_{2n} \\ . \\ . \\ . \\ y_{m1}, y_{m2}, y_{m3}, \ldots ..y_{mn} \end{bmatrix}$$

where x_{ij} is the initial matrix; $(x_{ij})_{\min}$ and $(x_{ij})_{\max}$ are the minimum and maximum values of the hydrochemical parameters of the samples, respectively.

Step 3 The entropy "(e_j)" and entropy weight "(w_j)" are computed using the equations as follows:

The entropy weight function is based on the discrete probability distribution.

$$e_j = \frac{-1}{\ln(m)} \sum_{i=1}^{m} n_{ij} \ln\left(n_{ij}\right)$$

where, $n_{ij} = -\frac{(1+y_{ij})}{\sum_{i=1}^{m}(1+y_{ij})}$.

The degree of diversity (d) possessed by each criteria is evaluated as:

$$d_j = 1 - e_j, j = 1, 2, 3, \ldots$$

The weight for each criteria is given by

$$w_j = -\frac{d_j}{\sum_{i=1}^{m} d_j}$$

Step 4 The quality rating scale "q_j" of the "j" parameter is calculated as:

$$q_j = \frac{V_j}{S_j}$$

where, "V_j" is the concentration value of chemical parameter "j" and "S_j" is the standard limit of BIS of parameter "j".

Step 5 EWQI is calculated by using the following equation.

$$\text{EWQI} = \sum_{J=1}^{m} w_j q_j$$

The computed EWQI for each sampling station has been grouped into five categories, namely, excellent (EWQI < 25), good (between 25 and 50), poor (50–100), very poor (100–150) and extremely poor (EWQI > 150) for human consumption. The standard values and the corresponding entropy weights are presented in Table 2.

Irrigation suitability parameters

The following selected parameters were computed for assessing the groundwater suitability for irrigation purpose.

Table 1 The analytical results of physico-chemical parameters of groundwater samples in the study area

Sample No.	pH	EC	TA	TDS	TH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	NO_3^{-}	Water type
1	7.8	2421	283	1424	512	64	86	159	102	304	248	186	12	Mg–Na–Cl–HCO_3
2	7.9	2482	245	1460	382	33	73	160	98	265	236	204	8	Na–Mg–Cl–HCO_3
3	7.7	2468	312	1452	306	32	55	316	84	265	436	42	22	Na–Mg–Cl–HCO_3
4	7.9	2460	284	1447	412	64	61	235	102	265	356	145	36	Na–Mg–Cl–HCO_3
5	7.8	2185	198	1285	422	25	87	146	54	259	210	143	14	Mg–Na–Cl–HCO_3
6	7.9	2332	312	1372	464	17	102	188	53	278	255	168	8	Mg–Na–Cl–HCO_3
7	8.7	3451	356	2030	688	56	133	236	112	466	364	188	9	Mg–Na–Cl–HCO_3
8	8.2	3222	306	1895	312	47	47	224	102	401	342	212	12	Na–Cl–HCO_3–SO_4
9	7.7	2766	288	1627	592	46	111	162	93	377	264	152	17	Mg–Na–Cl–HCO_3
10	8.0	2691	312	1583	618	46	122	146	87	409	248	132	29	Mg–Na–Cl–HCO_3
11	7.8	2587	278	1522	542	66	92	196	93	364	302	122	36	Na–Mg–Cl–HCO_3
12	7.6	2470	216	1453	508	34	103	172	34	283	295	120	24	Mg–Na–Cl–HCO_3
13	7.6	3024	212	1779	384	26	78	324	126	278	541	57	15	Na–Mg–Cl
14	8.1	3592	364	2113	356	62	49	302	142	477	456	112	18	Na–Cl–HCO_3
15	7.2	2202	292	1295	364	33	68	143	64	383	236	42	7	Na–Mg–Cl–HCO_3
16	7.6	2460	302	1447	342	36	61	202	63	396	294	56	2	Na–Mg–Cl–HCO_3
17	7.6	2470	236	1453	312	42	50	321	29	309	444	123	3	Na–Mg–Cl–HCO_3
18	8.0	2630	312	1547	338	26	66	181	103	409	312	33	16	Na–Mg–Cl–HCO_3
19	7.9	2853	232	1678	342	64	44	268	112	304	376	164	4	Na–Cl–HCO_3
20	8.4	2681	354	1577	504	69	81	110	102	464	202	112	12	Mg–Na–Ca–HCO_3
21	7.8	2706	336	1592	456	42	85	98	103	440	156	156	19	Mg–Na– HCO_3–Cl
22	7.7	2577	292	1516	396	42	71	294	88	383	402	88	18	Na–Mg–Cl–HCO_3
23	7.9	3177	288	1869	384	64	54	316	109	377	426	212	22	Na–Cl–HCO_3
24	7.8	3145	466	1850	493	26	104	326	32	610	554	113	33	Na–Mg–Cl–HCO_3
25	7.8	2729	387	1605	484	42	92	178	94	507	248	98	39	Na–Mg–HCO_3–Cl
26	7.7	3528	364	2075	384	56	75	304	76	477	424	126	41	Na–Mg–Cl–HCO_3
27	8.1	2924	384	1720	512	16	115	212	65	503	294	108	12	Mg–Na–Cl–HCO_3
28	7.8	3589	422	2111	632	24	139	306	104	553	464	88	6	Na–Mg–Cl–HCO_3
29	7.9	2761	284	1624	256	25	47	201	93	372	312	126	5	Na–Mg–Cl–HCO_3
30	8.0	3055	364	1797	508	64	85	303	88	477	412	103	12	Na–Mg–Cl–HCO_3
31	8.0	2722	224	1601	325	22	66	223	106	293	412	58	8	Na–Mg–Cl–HCO_3
32	7.9	2754	218	1620	322	42	53	249	143	286	372	180	26	Na–Mg–Cl–HCO_3
33	8.1	2912	388	1713	420	16	92	144	141	508	210	143	9	Mg–Na–K–HCO_3
34	8.0	3135	364	1844	412	36	78	312	144	477	458	188	7	Na–Mg–Cl–HCO_3
35	7.8	3386	344	1992	399	24	82	334	121	451	532	196	12	Na–Mg–Cl–HCO_3
36	7.8	2978	211	1752	404	16	88	223	124	276	391	227	8	Na–Mg–Cl–SO_4
37	7.8	3208	464	1887	538	64	92	148	115	608	223	103	5	Mg–Na–HCO_3–Cl
38	7.8	3021	228	1777	344	25	68	323	128	299	450	144	6	Na–Mg–Cl–HCO_3
39	7.6	3665	312	2156	444	62	36	263	113	366	584	87	14	Na–Cl–HCO_3
40	7.9	2519	198	1482	354	26	70	181	84	259	395	120	22	Na–Mg–Cl–HCO_3
41	7.8	3881	326	2283	412	48	71	400	122	427	573	107	37	Na–Mg–Cl–HCO_3
42	7.8	3378	464	1987	398	46	69	323	98	608	456	126	5	Na–Mg–Cl–HCO_3
43	7.7	2978	346	1752	354	32	67	216	112	453	302	133	9	Na–Mg–Cl–HCO_3
44	7.6	3410	278	2006	414	64	62	346	128	364	486	214	11	Na–Mg–Cl–HCO_3
45	7.9	3145	168	1850	312	26	60	394	94	220	536	204	8	Na–Mg–Cl
46	7.3	2200	212	1294	364	30	70	232	79	278	346	68	4	Na–Mg–Cl–HCO_3
47	7.9	3188	146	1875	414	22	87	406	142	191	584	178	22	Na–Mg–Cl
48	7.9	3777	234	2222	424	18	92	402	124	307	574	96	38	Na–Mg–Cl
49	7.6	3653	198	2149	519	32	107	414	97	259	602	212	4	Na–Mg–Cl

Table 1 (continued)

Sample No.	pH	EC	TA	TDS	TH	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Water type
50	7.9	2312	188	1360	164	46	12	312	80	246	428	83	4	Na–Cl–HCO_3
51	7.7	2083	214	1225	217	60	33	316	46	280	592	123	13	Na–Cl–HCO_3
52	8.0	2028	224	1193	248	22	47	173	86	293	243	86	6	Na–Mg–Cl–HCO_3
53	8.0	2038	188	1199	114	26	12	324	94	246	594	28	18	Na–Cl
54	7.9	1675	134	985	195	22	34	192	59	176	264	68	23	Na–Mg–Cl–HCO_3
55	7.9	1714	124	1008	188	36	24	208	67	162	282	58	36	Na–Cl
56	7.9	2540	320	1494	154	46	10	315	104	419	446	35	16	Na–Cl–HCO_3
57	7.6	2185	202	1285	195	28	38	194	103	265	326	88	5	Na–Mg–Cl–HCO_3
58	7.9	2317	232	1363	140	11	29	192	113	304	272	127	18	Na–Cl–HCO_3

*All parameter concentrations are in mg/L except pH (no units) and EC (μS/cm)

Table 2 The water quality standards and calculated entropy weights used in the assessment of EWQI

Hydrochemical parameter	Standard value (S_j)	$\sum n_{ij}$	e_j	d_j	w_j
pH	8.5	– 4.060	1.000	0.001	0.001
TA (mg/l)	200	– 4.019	0.990	0.010	0.062
TDS (mg/l)	500	– 4.043	0.996	0.004	0.026
TH (mg/l)	300	– 4.006	0.987	0.013	0.083
Ca^{2+} (mg/l)	75	– 3.970	0.978	0.022	0.136
Mg^{2+} (mg/l)	30	– 3.969	0.978	0.022	0.138
Cl^- (mg/l)	250	– 4.009	0.987	0.013	0.077
SO_4^{2-} (mg/l)	200	– 3.966	0.977	0.023	0.143
NO_3^- (mg/l)	45	– 3.839	0.945	0.055	0.336

$$\text{Percent sodium (Na\%)} = \left(\frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+}\right) \times 100$$

$$\text{Sodium adsorption ratio (SAR)} = \frac{Na^+}{\sqrt{\frac{Ca^{++}+Mg^{++}}{2}}}$$

$$\text{Residual sodium carbonate (RSC)} = \left(CO_3^{2-} + HCO_3^-\right) - \left(Ca^{++} + Mg^{++}\right)$$

$$\text{Permeability index (PI)} = \left(\frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{++} + Mg^{++} + Na^+}\right) \times 100$$

$$\text{Chloro alkaline indice 1(CAI1)} = \left[Cl^- - \left(Na^+ + K^+\right)/Cl^-\right]$$

$$\text{Chloro alkaline indice 2(CAI2)} = \frac{\left[Cl^- - \frac{(Na^+ + K^+)}{Cl^-}\right]}{\left(SO_4^{2-} + HCO_3^- + CO_3^{2-} + NO_3^-\right)}$$

$$\text{Kelly ratio (KR)} = \left(\frac{Na^+}{Ca^{++} + Mg^{++}}\right)$$

$$\text{CCR} = \frac{\left(\frac{Cl^-}{35.5}\right) + \left(\frac{SO_4^{2-}}{48}\right)}{\left(\frac{CO_3^{2-}+HCO_3^-}{50}\right)}$$

where the concentration of ions used in the calculations are in meq/L except for KR and CR for which mg/L used.

The results of all irrigation quality parameters are given in Table 3. Multivariate statistical analysis methods, including principal component analysis, factor analysis, and correlation, were used to analyze the groundwater chemistry characteristics. XLSTAT 2018 was utilized for preparing graphs and data table analysis. The Piper, USSL, Wilcox diagrams were generated using Aquachem 2014 software.

Results and discussion

The box plot helps in summarizing the distribution of a data set by the median, the variation, the skewness, outliers and extreme values in a graphical form. From Fig. 2, it is noted that TA, EC, TDS, Mg^{2+}, HCO_3^-, SO_4^{2-} are approaching normality. The data for the variables Ca^{2+}, Na^+, Cl^- and NO_3^- depart from a normal distribution only in skewness. There are outliers for pH, TH and K^+ but the data departs from a normal distribution only in the skewness. The unexpected outliers may be due to the usage of fertilizers in agricultural and aqua pond regions. The abundance of chemical parameters is as follows: $Na^+ > K^+ > Mg^{2+} > Ca^{2+} = Cl^- > HCO_3^- > SO_4^{2-} > NO_3^-$.

Table 3 The calculated values of chemical parameters for analyzing their suitability for irrigation

Sample No.	Na%	Cl^-/HCO_3^-	SAR	RSC	PI	KR	CR
1	48.2	1.4	3.1	− 5.2	53.4	1.1	1.8
2	55.4	1.5	3.6	− 3.3	62.0	1.5	2.1
3	72.2	2.8	7.9	− 1.8	79.7	3.6	2.5
4	60.9	2.3	5.0	− 3.9	66.7	1.9	2.5
5	47.8	1.4	3.1	− 4.2	56.9	1.3	1.7
6	50.7	1.6	3.8	− 4.7	59.1	1.6	1.9
7	48.9	1.3	3.9	− 6.1	54.3	1.2	1.5
8	66.5	1.5	5.5	0.3	77.0	2.4	1.8
9	45.2	1.2	2.9	− 5.3	51.6	1.0	1.4
10	41.0	1.0	2.6	− 5.6	47.8	0.9	1.2
11	50.2	1.4	3.7	− 4.9	56.7	1.2	1.5
12	45.1	1.8	3.3	− 5.5	54.6	1.3	1.9
13	69.3	3.3	7.2	− 3.1	74.6	3.1	3.0
14	70.2	1.6	7.0	0.7	78.7	2.7	1.6
15	51.9	1.1	3.3	− 1.0	64.7	1.4	1.0
16	60.3	1.3	4.8	− 0.3	72.6	2.1	1.2
17	70.2	2.5	7.9	− 1.2	80.3	3.5	2.4
18	60.9	1.3	4.3	− 0.1	71.5	2.0	1.2
19	68.0	2.1	6.3	− 1.9	75.1	2.5	2.3
20	42.3	0.7	2.1	− 2.5	50.8	0.7	0.9
21	43.1	0.6	2.0	− 1.9	52.0	0.8	0.9
22	65.5	1.8	6.4	− 1.6	73.9	2.6	1.7
23	68.3	1.9	7.0	− 1.5	75.8	2.7	2.2
24	60.4	1.6	6.4	0.1	72.2	2.5	1.5
25	51.2	0.8	3.5	− 1.4	61.0	1.3	0.9
26	62.8	1.5	6.2	− 1.2	72.2	2.3	1.5
27	51.5	1.0	4.1	− 2.0	62.2	1.6	1.0
28	55.8	1.4	5.3	− 3.6	62.9	1.9	1.3
29	68.5	1.4	5.5	1.0	80.9	2.8	1.5
30	60.3	1.5	5.9	− 2.3	68.5	2.0	1.4
31	65.6	2.4	5.4	− 1.7	73.4	2.5	2.2
32	69.2	2.2	6.0	− 1.7	75.3	2.6	2.5
33	55.5	0.7	3.1	− 0.1	62.4	1.3	0.9
34	65.8	1.7	6.7	− 0.4	75.1	2.7	1.8
35	68.9	2.0	7.3	− 0.6	76.7	3.1	2.1
36	61.5	2.4	4.8	− 3.5	66.5	2.1	2.9
37	46.6	0.6	2.8	− 0.8	55.8	0.9	0.7
38	71.6	2.6	7.6	− 2.0	77.7	3.5	2.6
39	70.2	2.7	6.6	− 0.1	79.3	2.7	2.5
40	58.6	2.6	4.2	− 2.8	66.5	1.9	2.6
41	71.4	2.3	8.6	− 1.2	78.2	3.4	2.2
42	67.6	1.3	7.0	2.0	78.2	2.8	1.3
43	63.4	1.1	5.0	0.4	73.6	2.2	1.2
44	68.9	2.3	7.4	− 2.3	75.0	2.8	2.5
45	75.8	4.2	9.7	− 2.6	81.5	4.6	4.4
46	62.5	2.1	5.3	− 2.7	70.4	2.3	2.0
47	72.0	5.3	8.7	− 5.1	74.9	3.7	5.3
48	70.9	3.2	8.5	− 3.4	76.0	3.7	3.0
49	66.4	4.0	7.9	− 6.1	70.7	3.0	4.1
50	82.7	3.0	10.6	0.8	92.5	5.4	2.8

Table 3 (continued)

Sample No.	Na%	Cl^-/HCO_3^-	SAR	RSC	PI	KR	CR
51	72.2	3.6	8.1	− 1.1	81.6	3.4	3.4
52	66.2	1.4	4.8	− 0.2	77.9	2.5	1.5
53	87.9	4.2	13.2	1.8	98.4	8.5	3.5
54	71.7	2.6	6.0	− 1.0	82.1	3.4	2.5
55	74.1	3.0	6.6	− 1.1	83.4	3.5	2.8
56	84.2	1.8	11.0	3.8	97.3	5.7	1.6
57	71.1	2.1	5.6	− 0.2	81.4	3.0	2.1
58	79.2	1.5	6.9	2.0	93.7	4.8	1.7

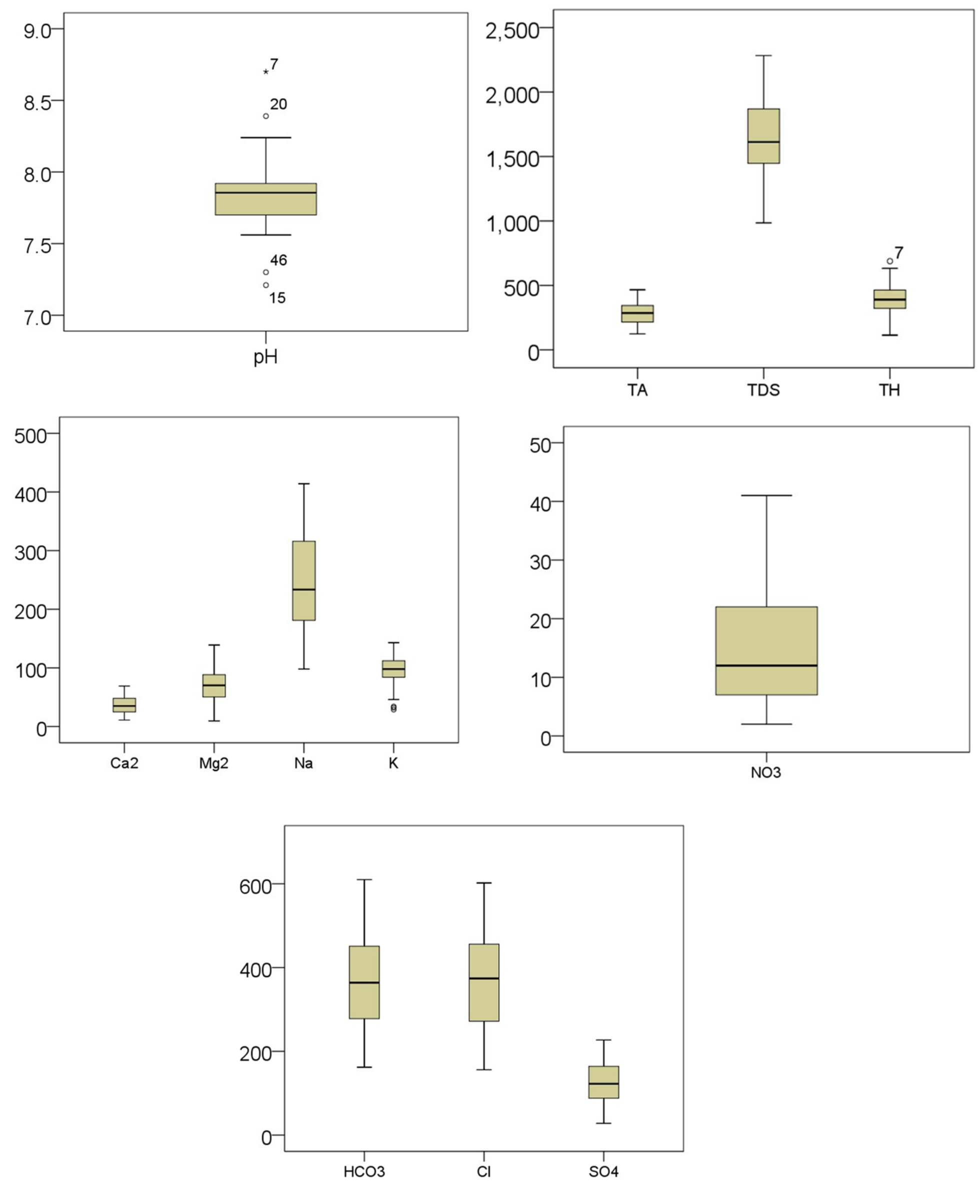


Fig. 2 Data normality of water quality parameters explaining by the box plot

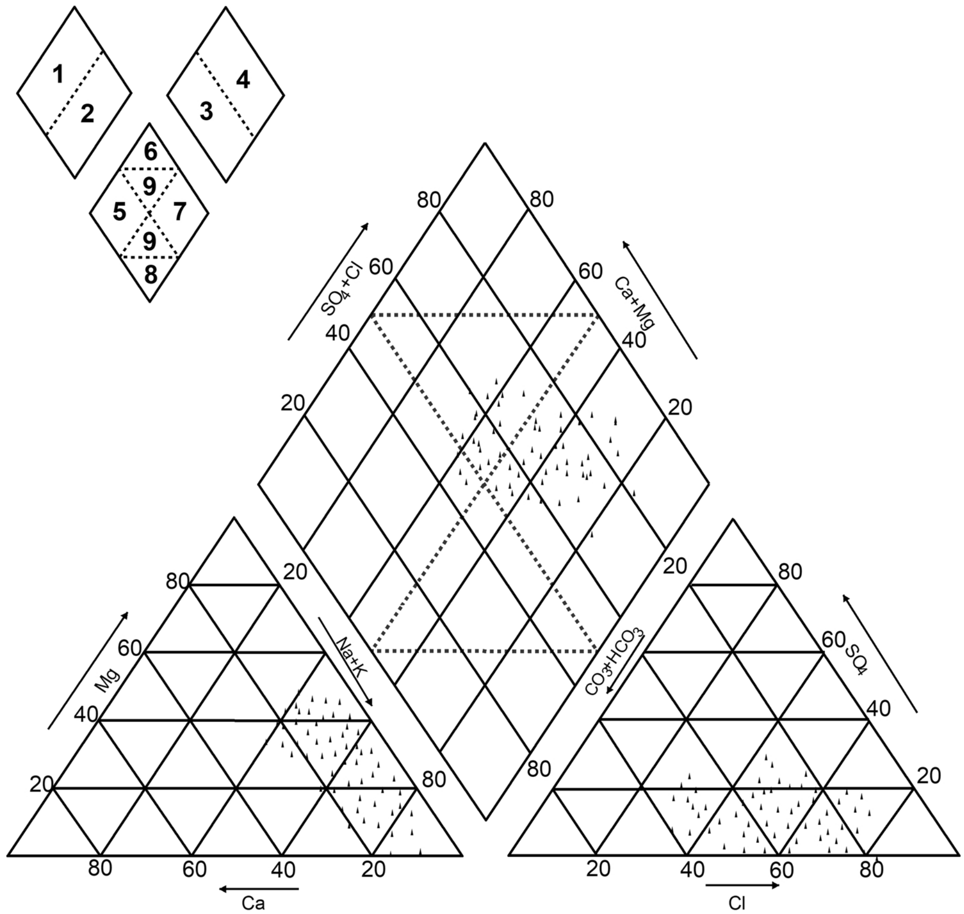


Fig. 3 Classification of hydrochemical facies using the Piper plot

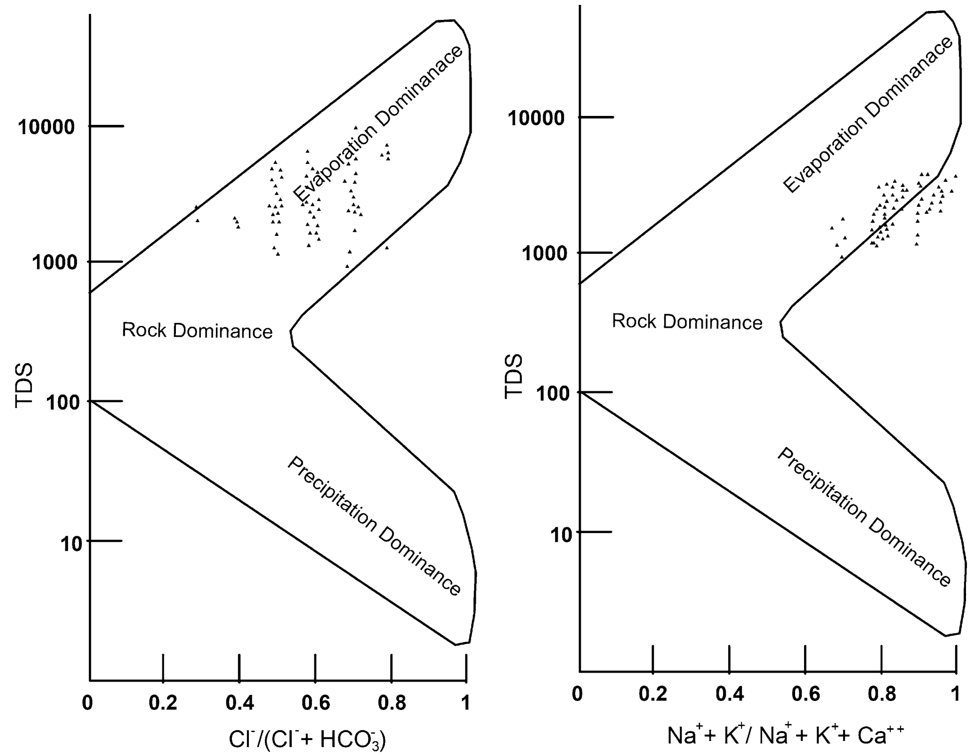
Table 4 Groundwater classification based on the Piper diagram

Subfield	Chemical characteristics	No. of samples in different fields	Total
1	Alkaline earths (Ca + Mg) exceed alkalies (Na + K)	1, 5, 6, 7, 9, 10, 11, 12, 14, 15, 20, 21, 25, 27, 33, 37	16
2	Alkalies exceed alkaline earths	2, 3, 4, 8, 13, 14, 16, 17, 18, 19, 22, 23, 24, 26, 28, 29, 30, 31, 32, 34, 35, 36, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58	43
3	Weak acids (CO_3 + HCO_3) exceed strong acids (SO_4 + Cl)	9, 14, 15, 20, 21, 25, 27, 33, 37	
4	Strong acids exceed weak acids	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 16, 17, 18, 19, 22, 23, 24, 26, 28, 29, 30, 31, 32, 34, 35, 36, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58	49
5	Carbonate hardness (secondary alkalinity) exceeds 50%	-Nil-	–
6	Noncarbonate hardness (secondary alkalinity) exceeds 50%	-Nil-	–
7	Noncarbonate alkali (primary salinity) exceeds 50%	2, 3, 4, 8, 13, 14, 16, 17, 18, 19, 22, 23, 24, 26, 28, 29, 30, 31, 32, 34, 35, 36, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58	43
8	Carbonate alkali (primary salinity) exceeds 50%	-Nil-	–
9	None of the cation or anion pairs exceed 50%	1, 5, 6, 7, 9, 10, 11, 12, 14, 15, 20, 21, 25, 27, 33, 37	16

Hydro chemical processes

The Piper (1944) plot explains the evolutionary trends of water quality parameters in order to classify the similarities and differences in the chemical composition of water into certain water types. The groundwaters were categorized into different hydrochemical facies based on major cations Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and major anions HCO_3^{-}, Cl^{-}, SO_4^{2-} using Piper's trilinear diagram (Fig. 3). The prominent types shown are Na-Mg-Cl-HCO_3^{-}, Na-Cl-HCO_3^{-} and

Fig. 4 Gibbs plot showing the geochemical process of groundwaters



Mg–Na–Cl–HCO_3^-. It can be observed from the plot that the majority of groundwater samples fall into the field of 4 suggesting that strong acids exceed weak acids. The exceeding primary salinity (field 7) and alkalies exceeding alkaline earths (field 2) are also found (Table 4). The samples in the Na–Mg–Cl facies indicate the leaching of primary/secondary salts and exchange of ions from the clay deposits. The mechanism controlling the geochemical process of groundwater with respect to atmospheric precipitation, rock–water interaction and evaporation, has been presented by Gibbs plot (1970) for the present study (Fig. 4). The ratio of dominant cations ($Na^+ + K^+$)/($Na^+ + K^+ + Ca^{2+}$) and anions (Cl^-/($Cl^- + HCO_3^-$)) against TDS was plotted. It is found that most sampling points fall towards evaporation dominance, indicating that the groundwater has high salinity controlled by evaporation and also rock weathering solubilization. Cation exchange is the influencing factor controlling hydrochemical processes. The limited interaction of rock water generally includes the chemical weathering of the rocks, the precipitation dissolution of secondary carbonates and the exchange of ions between the water and the clay minerals.

Suitability of groundwater use for drinking

The chemical constituents present in the groundwater show a wide variation in different individual parameters (Table 1). The pH of groundwater samples ranged from 7.2 to 8.7, with a mean of 7.8, indicating the slightly alkaline nature of groundwater in the study area. The concentrations of chemical constituents in groundwater and their effects on human health are presented in Table 5. The minimum and maximum values of alkalinity ranged from 124 to 466 mg/L with a standard deviation of 81.8. Above 250 mg/L, the concentration of total alkalinity in the water gives an unpleasant taste (BIS 2012). Nearly 85% of the water samples in the study area contain alkalinity values higher than the desirable limits. The high alkalinity values in the study area are raised due to the action of carbonates on the basic materials in the soil, which gives water an unpleasant taste. EC fluctuated from 1675 to 3881 μS/cm, with a mean of 2800 μS/cm while TDS ranged between 985 and 2283 mg/L, with a mean of 1647 mg/L. High EC is probably resulted from the dissolved inorganic substances largely present in the water (Hem, 1985). All groundwater samples recorded TDS levels above the desirable limits (more than 500 mg/L) and 84% of samples had TDS levels greater than 2000 mg/L, indicating that they are unfit for drinking (BIS 2012).TH as CaCO3 varied from 114 to 688 mg/L with a mean of 386. There are ten samples that fall within the desirable limits and the remaining samples (83% of total samples > 300 mg/L) fall into the very hard water category. The cations Ca^{2+}, Mg^{2+}, Na^+ and K^+ ranged between 11–69 mg/L, 10–139 mg/L, 98–414 mg/L, 29–143 mg/L, respectively. The anions HCO_3^-, Cl^-, SO_4^{2-} and NO_3^- from 162 to 610 mg/L, 156–602 mg/L, 28–227 mg/L, 2–41 mg/L, respectively.

Table 5 The range of concentrations of chemical constituents in groundwater and their effect on human health

Parameter	Bureau of Indian Standards (2012)		Min	Max	Mean	Std	CV	Groundwater samples exceeds the desirable limit		Effect on human health
	Desirable limit	Permissible limit						No. of samples	% of samples	
pH	6.5–8.5	–	7.2	8.7	7.8	0.2	0.03	1	1.7	Bitter taste (WHO 2003a, b)
EC (µS/cm)	NR	NR	1675	3881	2800.7	517.4	0.18	–	–	–
TA (mg/L)	200	600	124	466	283.3	81.1	0.29	49	84.5	Gastrointestinal issues, Nausea and skin irritations (Wei et al. 2017)
TDS (mg/L)	500	2000	985	2283	1647.4	304.4	0.18	58	100	Salty and bitter taste, lung irritation, rashes, vomiting, dizziness (Meride and Ayenew 2016)
TH (mg/L)	300	600	114	688	386.1	123.8	0.32	48	82.8	Cardiovascular problems, diabetes, neural diseases, and renal dysfunction (Lalitha, et al. 2004)
Ca^{2+} (mg/L)	75	200	11	69	38.6	16.3	0.42	–	–	Hypercalcaemia and renal insufficiency (WHO 2009)
Mg^{2+} (mg/L)	30	100	10	139	70.4	28.6	0.41	53	91.4	Hypermagnesaemia, diarrhoea, etc. (WHO 2009)
Na^{+} (mg/L)	NR	NR	98	414	249.8	81.2	0.32	–	–	–
K^{+} (mg/L)	NR	NR	29	143	95.6	27.8	0.29	–	–	–
HCO_3^- (mg/L)	NR	NR	162	610	361.7	109.1	0.30	–	–	–
Cl^- (mg/L)	250	1000	156	602	380.0	121.3	0.32	47	81	Congestive heart failure (WHO , , 2003a; b)
SO_4^{2-} (mg/L)	200	400	28	227	124.3	52.5	0.42	7	12.1	Bitter taste and laxative effect (WHO 2004)
NO_3^- (mg/L)	45	NR	2	41	15.6	10.7	0.68	–	–	Blue baby syndrome (Knobeloch et al. 2000)

Calcium bicarbonate is the prime cause of the hardness in water. Concentrations of Ca^{2+} and Mg^{2+} are well below the permissible limits. In seawater, magnesium is present in large quantities. High magnesium in the groundwater causes scaling in boilers, pipes and water heaters and abdominal disorders etc. and is not desirable for domestic use. Higher values of Na^{+} (mean 250 mg/L) and K^{+} (mean 95.2 mg/L) were found in the groundwater and may be attributed to saline water intrusion, discharge of aquaculture wastewaters and domestic sewage (Thilagavathi, et. al. 2019; Sivakarun et. al. 2020). Normally, these ions are not toxic to humans, but excess intake causes hypertension and vomiting, etc. Whereas K^{+} is an essential element for plants and animals. Cl^{-} directly relates to the mineral content of water and is mostly identified by the salt taste in potable water. Only 19% of groundwater samples showed less than 250 mg/L which are acceptable for drinking as per BIS. It explains that the probable cause for the abnormal concentration of chloride is the seawater intrusion and rocks in the study region. SO_4^{2-} concentrations in 7 locations were recorded as slightly high and all the samples of NO_3^{-} fell under the permissible limits of BIS. Overall, the majority of water quality parameters of the groundwater samples analyzed in the study area were recorded above desirable levels.

Table 6 Categorization of groundwater based on EWQI in the study area

Permissible limit	Category	No. of samples	% of samples
25	Excellent	0	0
25–50	Good	0	0
50–75	Poor	9	16
75–100	Very poor	20	34
> 100	Unfit	29	50

Groundwater quality based on EWQI

The results of the entropy weighted water quality index (EWQI) to quantify the quality of groundwater for the purpose of drinking in each location of the study area are given in Table 6. The spatial distribution of EWQI is presented in Fig. 5. The computed EWQI values for groundwater samples in the study ranged between 53.3 and 143.3 with an average of 99. Overall, the results indicate that the quality of groundwater is poor to extremely poor category. Fifty percent of total groundwater samples have shown more than 100 EWQI value, indicating that they are unfit for drinking or domestic use (Wu et al. 2018). The remaining 34% of samples were

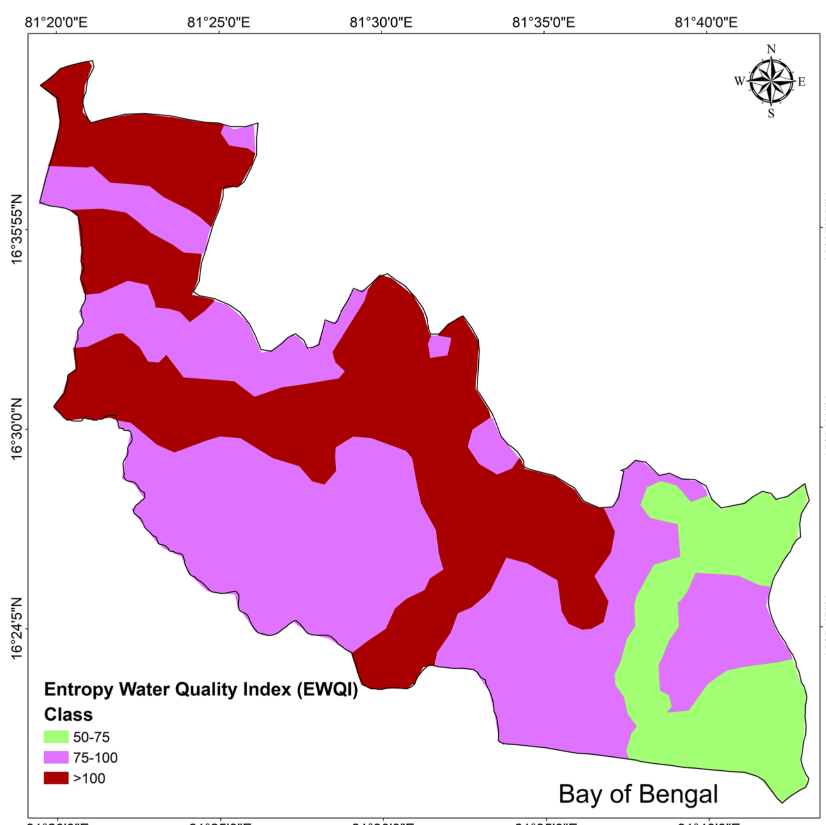


Fig. 5 Groundwater categorization and its spatial distribution based on EWQI in the study area

classified as very poor quality water, which is also unsuitable for drinking. Only 16% of samples show poor quality, which indicates that these sampling location's groundwater may be marginally utilized for domestic use. None of the samples were found in the excellent to good quality of groundwater category.

Suitability of groundwater use for irrigation

In the study area, the groundwater samples were analyzed for monitoring the suitability of quality for irrigation purposes. It can be observed from Table 7, the groundwater recorded as high to very high salinity condition (Richards 1954). About 85% of total samples have recorded electrical conductivity that is very high (> 2250 µS/cm). High EC in the water proportionate to the salt content explains that the groundwater can severely affect the plants and soils, thus reducing productivity. The Na% ranged between 41 and 87.9 meq/L with a mean of 63 meq/L. Nearly 69% of water samples were found to have high levels of sodium (> 60%), thus not suitable even for irrigation (Swarna Latha and Nageswara Rao 2012). The ratio of Cl^-/HCO_3^- of groundwaters can provide the level of salinization effect in a region (Weiner 2000). The Cl^-/HCO_3^-ratio is shown above 2 in twenty-four samples out of 58, indicating the possible signatures of seawater intrusion into the land as the area is adjacent to the coast and the aqua ponds are continuously pumped by saline water (Desai et al. 1979).

High sodium content may destroy the soil structure and affect plant growth (Wilcox 1948). Only two samples (Nos. 54 and 55) fall under the permissible to doubtful category and the remaining samples are in the doubtful to unsuitable category (Fig. 6 and Table 8). The SAR values in the study area vary from 2.0 to 13.2 meq/L and nearly 45% of samples exhibit increased problems as SAR > 6 meq/l (Herman Bouwer 1978).

The influence of evaporation can be examined with the help of Na^+ vs Cl^- plots. The graph (Fig. 7a) provides a strong evidence of halite dissolution which results from aquifer salts and seawater intrusion. It was found that the dominant anion and cation present in water are Cl– and Na +, respectively. The enrichment of Na^+ and K^+ concentrations is accompanied by the increase of Cl^- ions that probably occurs due to dissolution of soil salts (Manusree et al. 2009; Srinivasamoorthy et al. 2011; Rao et al. 2017; Senthilkumar et al. 2018). The majority of samples fall in injuriously contaminated by saline water intrusion indicating the mixing of fresh water aquifers with the saline water (Fig. 7b). The enrichment of Na + groundwater samples may due to cation exchange process. The progress in the salinization can occur with the groundwater recharge through Ca^{2+} exchange with Na^+ as the clay soils and marine salts dominate the region. The Durov diagram (Fig. 8) explains that the $Na^+ + K^+$ enrichment with HCO_3^- dominance in the groundwater of study region may be influenced by the dissolution of clays and marine salts and the subsequent replacement of alkaline earths with the alkalis. The high TDS in groundwater also indicated the dissolution of soil salts and anthropogenic sources in the study region (Manjusree et al. 2009; Chidambaram et al. 2018).

According to the U.S. Salinity Laboratory Diagram (USDA 1955), more than 80% of the water samples come under the fields of C4S2, C4S1, C4S3 and C3S2, indicating high-very high salinity and low–high alkali water (Fig. 9 and Table 9). The groundwater is not suitable for irrigation in the drainage restriction as it leads to low permeability and poor cultivability. RSC varied from − 6.1 to 3.8 meq/L with a mean of − 1.8 meq/L in the study area. More than 82% of samples show negative values and are safe for irrigation purposes. The best irrigation practises must be adopted to use the marginal RSC water for irrigation. The high concentration of Na^+, Ca^{2+}, Mg^{2+} and HCO_3^- in irrigation water can affect the soil's permeability condition. More than 80% of the groundwater samples are not suitable for irrigation purposes. (Donen 1964). The range of KR values is 0.7–8.5 mg/L and most groundwater samples (91%) are recorded above 1, hence the groundwater is fit for irrigation (Kelley 1951). The CR values (0.7–5.3 mg/L) recorded in the study area indicate the corrosive nature of water, thus it cannot be transported through the metal pipes.

Principal component and factor analysis

The dataset of analyzed parameters was verified for variable reduction by PCA and FA using Kaiser–Meyer–Olkin and Bartlett's sphericity tests. The results of the KMO and ρ

Table 7 Classification of groundwater based on the Wilcox (1948) diagram

Category	Sample numbers	Number of samples	Percentage of samples
Permissible to doubtful	54, 55	2	3.4
Doubtful to unsuitable	1, 2, 3, 4, 5, 6, 9, 10, 11, 12, 15, 16, 17, 18, 19, 20, 21, 22, 25, 27, 29, 31, 32, 33, 36, 40, 43, 46, 50, 51, 52, 53, 56, 57, 58	35	60.3
Unsuitable	7, 8, 13, 14, 23, 24, 26, 28, 30, 34, 35, 37, 38, 39, 41, 42, 44, 45, 47, 48, 49	21	36.2

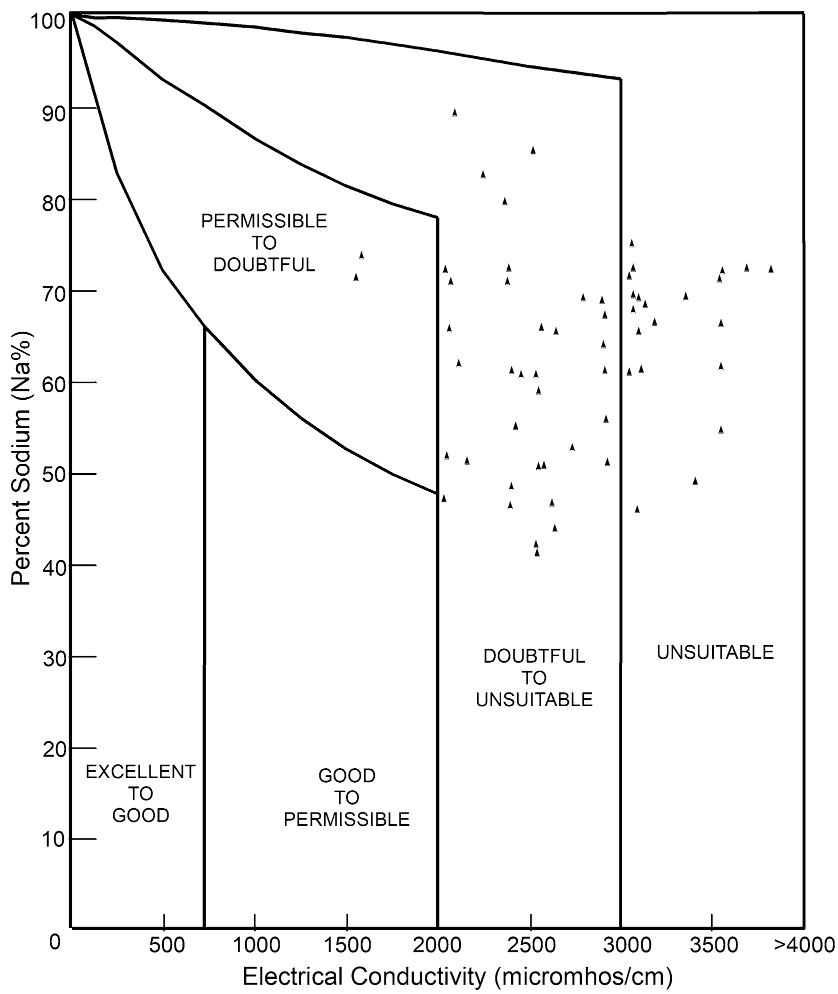


Fig. 6 Wilcox (1948) diagram represents the presence of sodium content in the groundwaters

Table 8 Classification of groundwater based on USSL diagram (USDA 1955)

Classification	Sample numbers	Number of samples	Percentage of samples
C3S1	5, 15	2	3.4
C3S2	46, 51, 52, 54, 55, 57	6	10.3
C3S3	53	1	1.7
C4S1	1, 2, 6, 9, 10, 12, 20, 21, 25, 33, 37	11	19.0
C4S2	3, 4, 7, 8, 11, 13, 14, 16, 17, 18, 19, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 34, 35, 36, 38, 39, 40, 42, 43, 44, 58	31	53.4
C4S3	41, 45, 47, 48, 49, 50, 56	7	12.1

were 0.58 and less than 0.001, respectively, hence the dataset was used for analysis (Wang et al. 2013). The results of the principal factors, eigenvalues, explained variance and varimax–rotated loads are summarized in Table 7. EC (0.92), TDS (0.92), HCO_3^- (0.71), TA (0.69), TH (0.69), Mg^{2+} (0.6) in factor 1 while in factor 2, Na^+ (0.88) and Cl^- (0.88) were recorded. The first three PCs accounted for 65% of total variance cumulatively 94.5% for a total of 7 PCs. The scree plot showing the positive component loadings of all PCs is presented in Fig. 10. The first factor explained 33.3% of the total variance with strong positive loadings on EC, TDS, TH, HCO_3^-, TA and limited loading on NO_3^-. This could be due to the influence of carbonate weathering as the main source of these minerals. Factor 2 contributed 20.3% of the total variance with high positive loadings on Na^+ and Cl^- which probably due to seawater intrusion. Factor 3 accounts for 10.8% of the total variance. The closely related parameters were SO_4^{2-} and K^+; this was probably due to

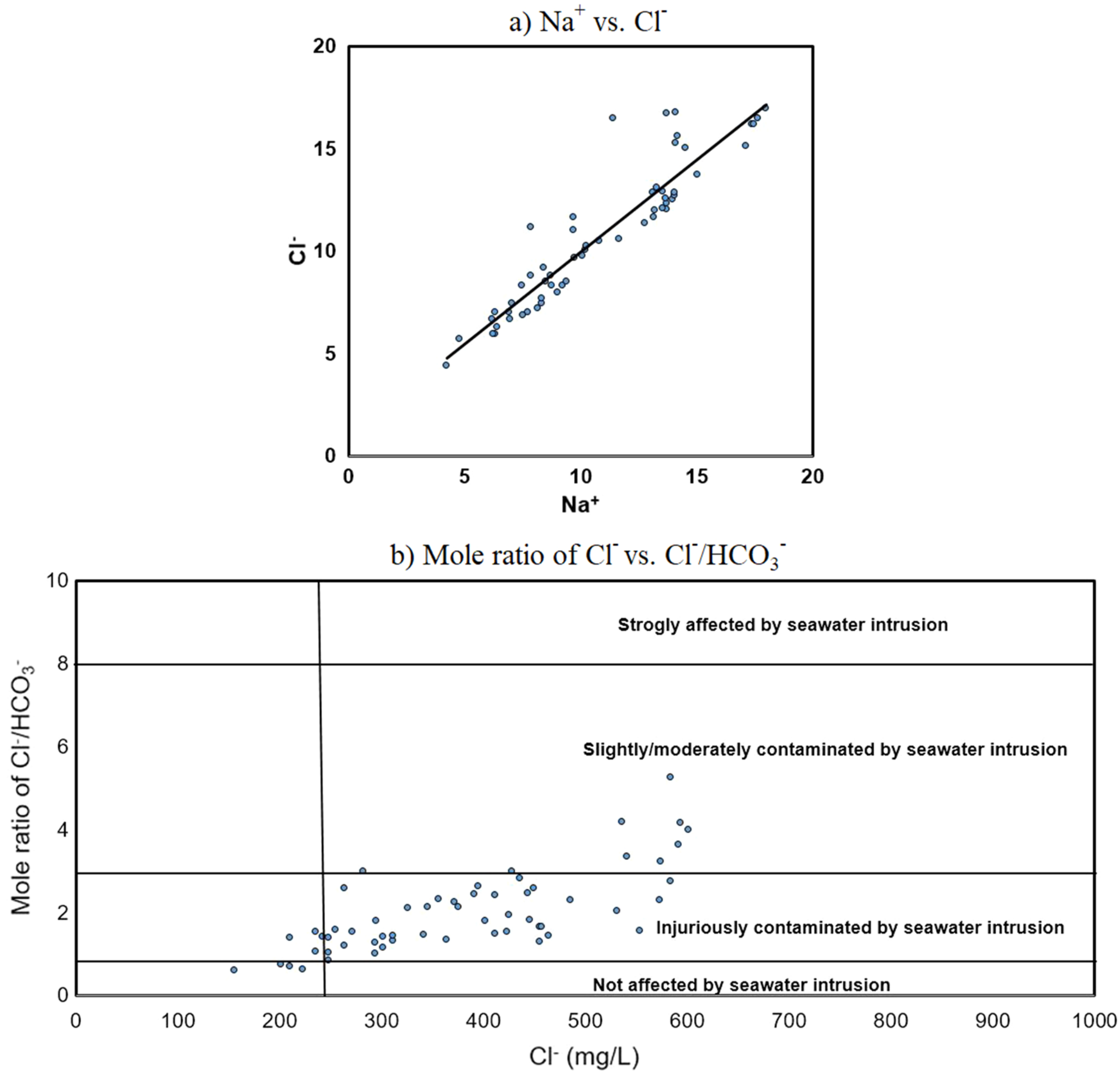


Fig. 7 Ionic relationship of groundwaters **a** Na^+ vs. Cl^- and **b** Cl^- vs. Cl^-/HCO_3^-

the application of organic and inorganic fertilizers, manure and sewage. With the loading of Mg^{2+}, factor 4 contributed 9.74% to the total variance; this indicates the impact of clay minerals and rock weathering. All the hydrochemical parameters applied by Pearson's correlation indicating that TDS was significantly correlated with EC, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^- and Cl^- (Table 10). The Na^+ and Cl^-, TA and HCO_3^- are correlated highly significant and are the main source of TDS.

Conclusions

The evolution of groundwater chemistry was explained through geochemical plots, ionic ratios, bivariate scatter plots, principal component and factor analysis for the coastal aquifer of Southern India. The chemical constituents in the groundwater were determined through EWQI for their suitability for drinking purposes. The average ionic concentration found in the study area is $Na^+ > K^+ > Mg^{2+} > Ca^{2+} = Cl^- > HCO_3^- > SO_4^{2-} > NO_3^-$. The following observations made during the study:

- The high concentrations of Na^+, Cl^- and SO_4^{2-} found in the groundwater may be attributed to the dissolution of mineral phases in the aquifer systems.
- The result of PCA and FA analysis revealed that the factors responsible for the variation in the groundwater chemistry are weathering, leaching of secondary salts, reverse ion exchange, seawater intrusion and agricultural return flow.

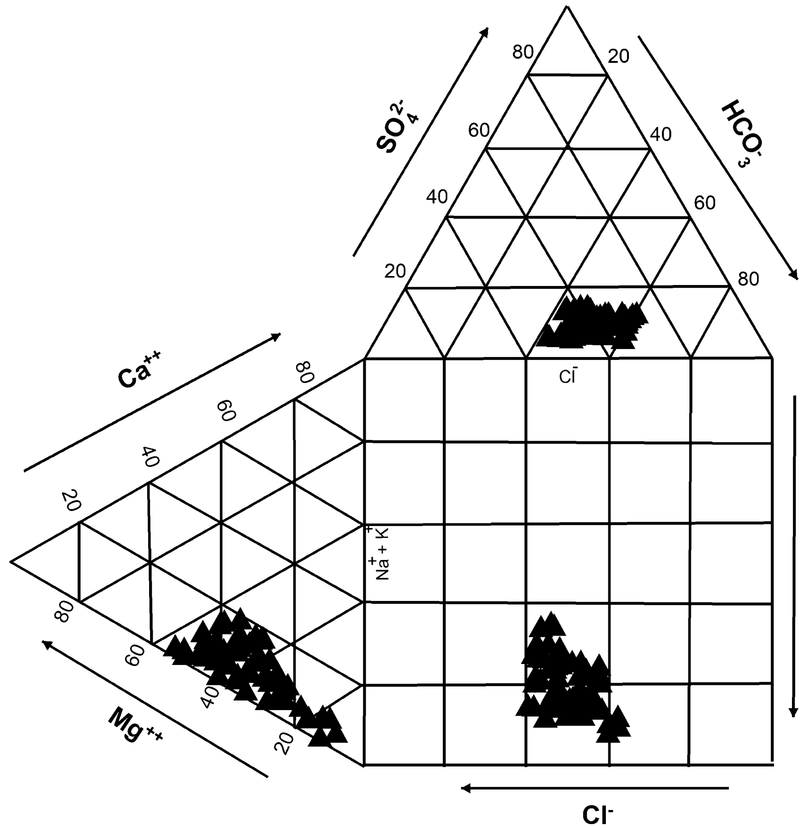


Fig. 8 Durov diagram depicting hydrochemical processes of groundwaters

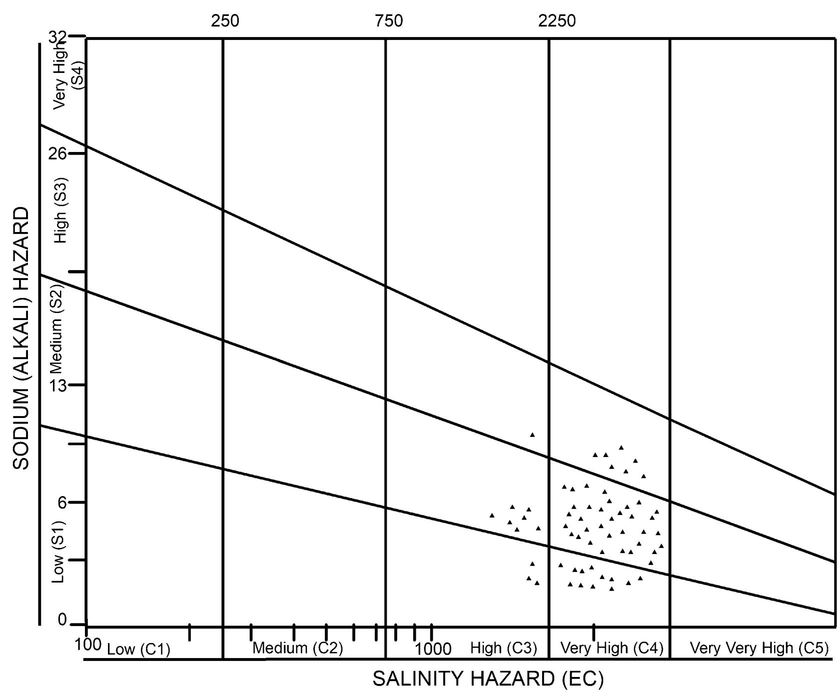


Fig. 9 The suitability of groundwater for irrigation exhibiting by USSL diagram

Table 9 The results of principal components and factors of groundwater samples

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12
Eigenvalue	4.332	2.659	1.407	1.262	1.092	0.896	0.651	0.424	0.157	0.070	0.038	0.010
Variability (%)	33.323	20.456	10.825	9.711	8.397	6.891	5.011	3.264	1.210	0.540	0.291	0.080
Cumulative %	33.323	53.779	64.605	74.316	82.714	89.604	94.615	97.879	99.089	99.629	99.920	100
Variable	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12
pH	0.262	− 0.205	0.433	− 0.518	0.074	− 0.370	− 0.523	− 0.131	0.026	− 0.002	− 0.002	0.000
TA	0.706	− 0.426	− 0.431	− 0.172	− 0.214	− 0.036	− 0.057	0.157	− 0.114	0.009	− 0.131	− 0.013
EC	0.917	0.332	0.008	0.017	− 0.055	− 0.036	0.077	0.024	0.195	− 0.011	− 0.009	− 0.006
TDS	0.917	0.332	0.008	0.017	− 0.055	− 0.036	0.077	0.024	0.195	− 0.011	− 0.009	− 0.006
TH	0.734	− 0.452	0.106	0.335	0.227	0.107	0.024	− 0.250	− 0.031	0.024	− 0.027	0.069
Ca^{2+}	0.312	− 0.085	− 0.137	− 0.543	0.347	0.653	0.018	− 0.182	− 0.006	− 0.016	0.014	− 0.024
Mg^{2+}	0.634	− 0.452	0.154	0.547	0.136	− 0.118	− 0.019	− 0.152	− 0.087	− 0.028	0.034	− 0.064
Na^{+}	0.301	0.878	− 0.166	0.124	0.034	0.021	− 0.211	− 0.021	− 0.134	− 0.178	0.000	0.015
K^{+}	0.427	0.316	0.419	− 0.415	− 0.155	− 0.245	0.499	− 0.117	− 0.156	0.004	0.004	0.001
HCO_3^-	0.717	− 0.390	− 0.430	− 0.182	− 0.252	− 0.061	− 0.051	0.155	− 0.058	0.012	0.135	0.019
Cl^-	0.275	0.878	− 0.208	0.126	0.039	0.012	− 0.194	− 0.105	− 0.089	0.188	0.006	− 0.009
SO_4^-	0.422	0.063	0.705	0.105	0.068	0.347	− 0.104	0.410	− 0.071	0.027	0.004	0.004
NO_3^-	0.079	0.042	− 0.230	− 0.098	0.866	− 0.344	0.129	0.213	− 0.011	0.006	0.002	0.002

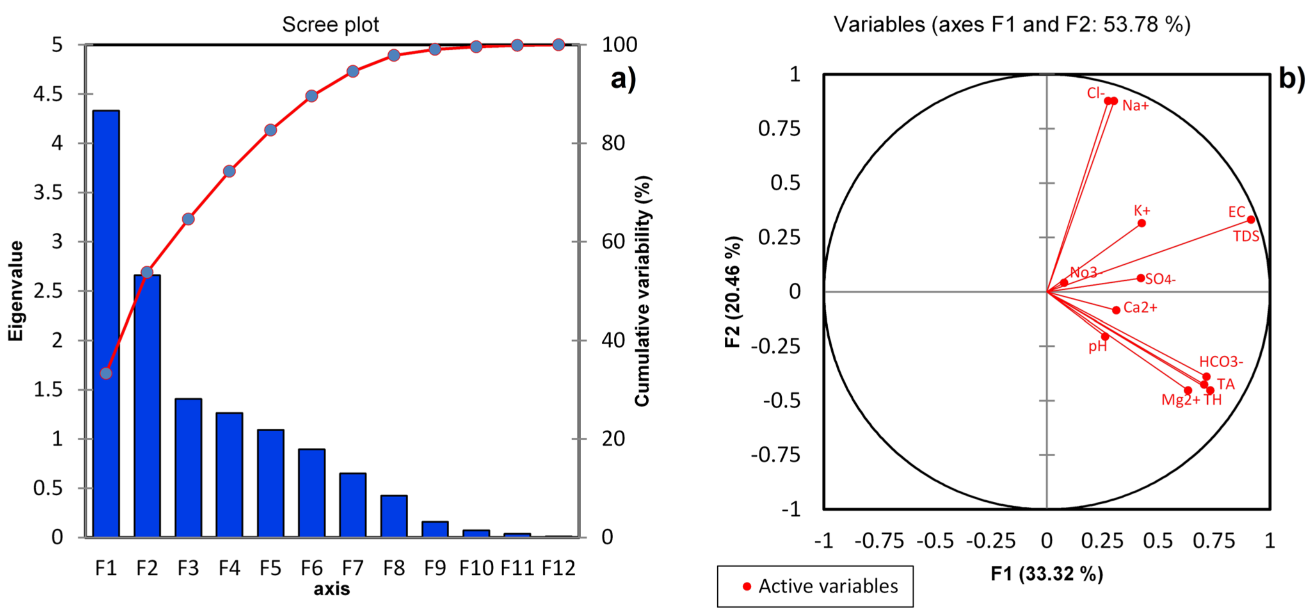


Fig. 10 Scree plot showing dominance of ions

- All the groundwater samples when compared with BIS for potability indicating the groundwater in the study area is unfit for drinking in the majority of the areas.
- The entropy water quality index values shown that nearly 85% of groundwater samples indicating very poor quality of water. Hence, remedial measures must be taken for utilizing groundwater for drinking purpose.
- The quality indices for irrigation reveal that the groundwater studied in the locations ranges between the good and moderate categories, hence the water can be used for irrigational purposes with proper management.

Various anthropogenic activities such as intense agricultural and aquaculture practices, aquaculture waste discharge without treatment etc. are also the probable causes of deterioration of the quality of water. This research database

Table 10 Correlation matrix of different parameters of groundwater samples

Variable	pH	TA	EC	TDS	TH	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^-	NO_3^-
pH	1												
TA	0.179	1											
EC	0.137	0.490	1										
TDS	0.137	0.490	1	1									
TH	0.154	0.520	0.502	0.502	1								
Ca^{2+}	0.119	0.280	0.200	0.200	0.263	1							
Mg^{2+}	0.123	0.438	0.417	0.417	0.923	− 0.082	1						
Na^+	− 0.133	− 0.097	0.525	0.525	− 0.141	0.004	− 0.139	1					
K^+	0.272	0.070	0.514	0.514	0.061	0.092	− 0.005	0.192	1				
HCO_3^-	0.185	0.961	0.524	0.524	0.491	0.260	0.423	− 0.074	0.098	1			
Cl^-	− 0.152	− 0.115	0.505	0.505	− 0.137	0.006	− 0.159	0.926	0.177	− 0.088	1		
SO_4^-	0.224	0.001	0.387	0.387	0.343	0.147	0.319	0.107	0.267	− 0.009	0.033	1	
NO_3^-	0.059	0.008	0.060	0.060	0.092	0.145	0.065	0.077	− 0.017	− 0.013	0.078	− 0.122	1

provides baseline information that may be used for detecting significant trends more precisely with the help of modern tools like the Geographic Information System. Further research need to be conducted to identify both geogenic and anthropogenic sources of the contamination of groundwater, so that it will help the authorities in implementing an appropriate water management programmes at local level.

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Data availability All data generated or analyzed during this study are included in this article.

Declarations

Conflict of interest The author declares that there is no conflict of Interest.

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