


Investigation of Groundwater Quality and Its Suitability for Drinking and Agricultural Use in the South Central Part of the Coastal Region in Bangladesh

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Abstract To examine the groundwater quality a total of 120 groundwater samples were collected from two southern districts; Barguna (27 points) and Patuakali (33 points) of Bangladesh in two seasons viz., pre-monsoon (60 samples) and post-monsoon (60 samples) in 2012. A comprehensive analysis has been conducted to explore the groundwater hydrochemistry and effects of major ions on the suitability for potable water and agricultural uses. Geochemical analyses have clearly shown that the seasonal effect does change the order of abundance of major ions in the groundwater, while principal component analysis confirmed the reasons of extreme salinity and hardness. Piper diagram showed that the predominant hydrochemical facies for the groundwater were $\text{Na}^+ - \text{Cl}^- - \text{SO}_4^{2-}$ and $\text{Na}^+ - \text{K}^+ - \text{HCO}_3^-$ types. The chloroalkaline index confirmed that

the ion exchange was governed mainly in water phase. Equiline diagram explained the relationship among the alkali with total cations and anions where cations were more dominant than anions at 1:1 ratio. The Gibb's diagram illustrated the chemical composition of water mainly influenced by precipitation from the water sources. The molar ratio $\text{Cl}^- / \Sigma \text{anions}$ and $\text{Na}^+ / \text{Na}^+ + \text{Cl}^-$ indicated that the groundwater of the study area was affected by seawater intrusion. In addition to unsuitable salinity ($>5000 \mu\text{s}/\text{cm}$), Kelly's ratio, total hardness, sodium absorption ratio, residual Sodium carbonate, and $\text{Na} \%$ clearly indicated that the groundwater in the study area were not suitable for drinking, irrigation, and domestic uses. Moreover, the spatial distribution maps were drawn to observe the spatial extent of EC, TDS, SAR, and SSP using IDW technique. Thus, considering all the above findings this area needs special attention to ensure the supply of potable water and to maintain sustainable agricultural activities.

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Introduction

The southern part of Bangladesh is vulnerable to natural disasters, and groundwater quality of this region has been deteriorating day-by-day. Groundwater (GW) has been the main source of freshwater to use in agricultural, industrial, and drinking purposes in Indian subcontinent (Azaza et al. 2011). The water quality parameters are the key concern which needs to be informed to citizens and policy makers to ensure conservation and utilization of resources (Atulegwu and Njoku 2004). Thus, it is very important to

understand the hydrochemical properties along with aquifer hydraulics to build up a suitable groundwater management planning in the study area (Nosrat Aghazadeh and Mogaddam 2011; Jiang et al. 2009). Groundwater quality usually varies widely depending on the location, recharge water quality, lithology, environmental factors and so on. The assessment of hydrochemical flow systems is based on the available information of groundwater chemistry. Concomitantly, the factors determining the quality of groundwater are the geological setting, source rocks property, recharge water composition, soil formations, lithology and the duration of time that the water body has been trapped underground (Faniran et al. 2004; Giridharan et al. 2008). These driving factors and their interrelations create critical groundwater quality. Bangladesh is a land of rivers and categorized by its intensive agricultural activities which are largely dependent on available freshwater resources such as rivers and groundwater. The soils and crops are greatly affected by the quality of irrigation, especially in the saline alkali soil areas. Salinity and sodium hazard are being considered as one of the prime indicators for irrigation water (Nishanthiny et al. 2010). During the last two decades, many researchers have been studying on groundwater quality in different parts of the world (Celik and Yildirim 2006; Partey et al. 2010). Bangladesh is considered as one of the most climate vulnerable countries in the world. In the southern part, it has approximately 710 km coastal line with highly susceptible areas to sea level rise. Water and soil salinity are regular hazards for many parts specially south east, central (Shammi et al. 2012, 2015), and south-west (Shammi et al. 2016; Bahar and Reza 2010; Halim et al. 2010) part of the coastal areas of Bangladesh are being affected by different uses of water including drinking, irrigation, household, fisheries, and functioning of the ecosystem (Egis 2001). Regarding 90 % of drinking water (Mridha et al. 1996) and nearly 75 % of irrigation water in Bangladesh (Shahid et al. 2006) are supplied from groundwater sources. There are three types of GW aquifer (UNDP 1982) in Bangladesh; upper shallow unconfined aquifer, middle confined aquifer, and deep confined aquifer. Although the main aquifer is middle confined aquifer, the most used aquifer to extract water for irrigation and drinking is the uppermost shallow aquifer almost all over the country (Shahid et al. 2006). Several water quality problems subsist in groundwater and surface water systems in Bangladesh, especially in its southwestern coastal regions, where salinity is extreme problematic issue at present (Elahi and Hossain 2011).

The coastal area of Bangladesh experienced two consecutive natural disasters cyclone Sidr and Aila in 2007 and 2009 with huge damage during and postdisaster. The coastal area of Bangladesh covers 19 districts out of total 64 districts with 140 Upazilas. In this study, two districts

namely Barguna and Patuakhali covering 12 upazilas were taken into consideration. In these coastal areas, drinking water is mainly derived from deep wells and irrigation is limited to surface water bodies. From seasonal precipitation, freshwater is also available at shallow depth sourced but turns to brackish during dry period (Datta and Ghosh 2015). This potential aquifer is also in risk from anthropogenic behavior like excessive groundwater harvesting, chemical fertilizers, etc., and its quality is deteriorating at an alarming level. Under these circumstances, a wide-range of hydrogeochemical study is needed for the assessment, identification, and evaluation of the chemical processes that governs the groundwater quality of this vulnerable area. It has been supposed that providing better water quality information with the underlying hydrochemical process, this study will be an intellectual resource to fight back against the vulnerable agriculture and susceptible public health sector in coastal areas all over the world as well as in Bangladesh. By considering suitable drinking and irrigation water, adopted climate-resilient crops, improved planning and sustainable infrastructure still we can protect the climate vulnerable societies and economies in coastal regions. Thus, the main objective of this study was to find out different hydrochemical determinants in coastal groundwater resources in order to assess the suitability of this resource for drinking and irrigation and to highlight the extent and intensity of salinity in groundwater of the study area for possible future management options of this resource.

Materials and Methods

Study Area

The study area, Barguna and Patuakhali district, is located in central south of Bangladesh (Fig. 1). The study area lies between 20°04' to 22°46' N and 89°97' to 90°60' E covering an area of 5051.46 sq. km. The population of the study area is about 2.5 million with fisheries and agriculture as major economic activity. The climate and rainfall distribution of this area is of tropical nature dominated by the south-west monsoon of the Indian Ocean. The hydrology of the coastal plain of the study area is governed by a complex interaction of fresh water flow from the upstream, the tides and tidal flows from the Bay of Bengal, tropical cyclones, storm surge, and other meteorological effect from the sea and the physiography of the coastal plains (FAO 1985). During low flow season, the tide penetrates far inland. There are river channels which carry flood water from the Ganges, Brahmaputra, Meghna, and other rivers and also act as drainage channels for rainfall and tide to the Bay of Bengal. In Bangladesh, there are three main

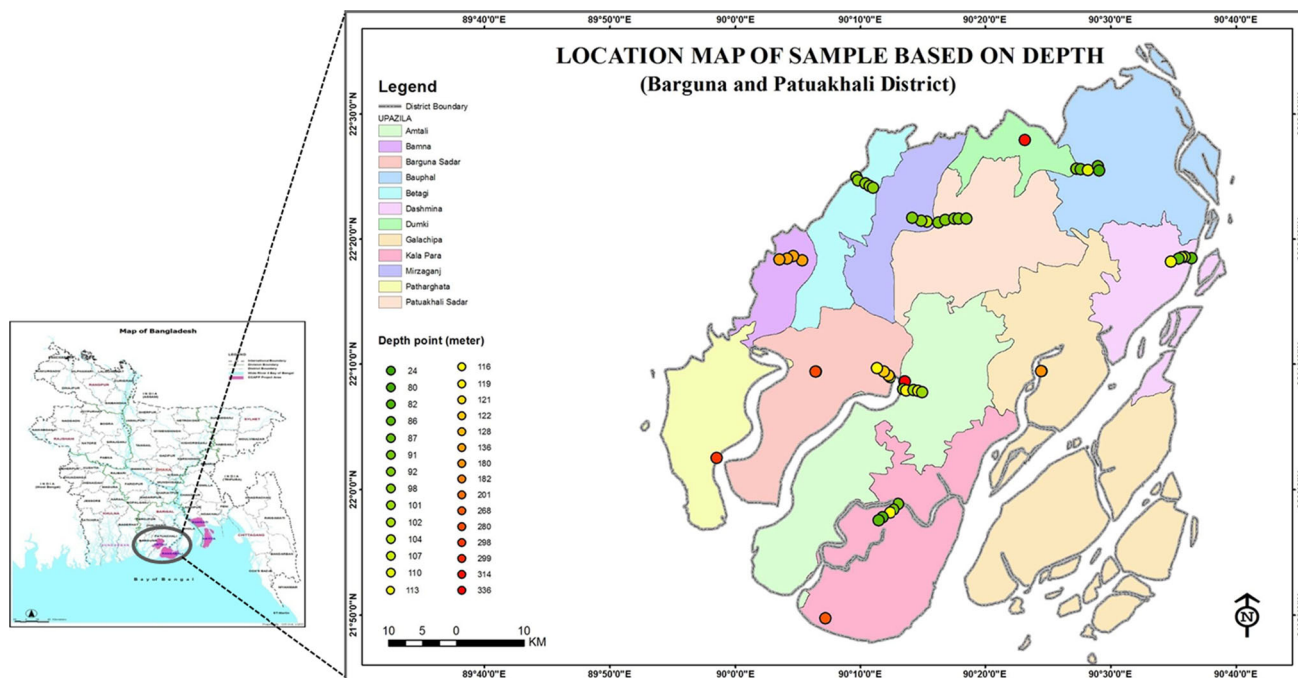


Fig. 1 GIS location map of the groundwater sampling points in the study area (Barguna and Patuakhali district), Bangladesh

seasons: each of which has its individual characteristics. The season which lasts from March throughout May is called warm season. The highest temperatures of the year occur during this period. The average annual rainfall in the coast is over 2000 mm. About 15 % of the annual rainfall occurs during this period mainly as thunder storms occurred frequently together with strong winds, and humidity is generally high throughout the period. In an average 75 to 80 % of the annual rainfall occurs during this period, and the minimum and maximum temperature are 12.1 and 33.3 °C (BBS 2011). The sampling period was March 2012 (pre-monsoon) and October, 2012 (post-monsoon). A total of 120 (60 pre-monsoon and 60 post-monsoon) groundwater samples were collected from randomly selected sampling point (Fig. 1) and sampling depth of Barguna and Patuakhali district.

Water Quality Analysis

Groundwater samples were collected for two different seasons (March 2012, pre-monsoon, September–October 2012, post-monsoon) to broadly cover the seasonal variation. Groundwater samples were collected in 500 ml plastic bottle and chemical analyses were done by following the standard guidelines (APHA 1998). The samples were collected after pumping the wells for 15–20 min and subsequent filtering through 0.45 µm membranes. Temperature (°C), pH, electrical conductivity (EC), and total dissolved solid (TDS) were measured in situ by Portable Multi-Meter

(Hach, sensION + MM150). Major anions chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-}), phosphate (PO_4^{3-}) and fluoride (F^-) were measured by ion chromatography. Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) were determined by titration with HCl. Major cations calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), were determined using AAS (Varian 680FS). The trace elements, manganese (Mn), iron (Fe), boron (B), iodine (I), bromine (Br), and silicon dioxide (SiO_2) were determined using Spectrophotometer (DR 2800). Overall data reproducibility for ions was within $\pm 10\%$. Cations and anions charge balance ($<10\%$) was an added proof for the precision of the data. Chemical analyses were carried out in Bangladesh Council of Scientific and Industrial Research (BCSIR) laboratory, Dhaka.

Statistical Analysis

Statistical analysis of groundwater quality parameters was done using SPSS (statistical package for social science) 16.60 version. For understanding the hydrochemistry of groundwater, GW Chart Software (USGS) along with Microsoft Excel 2007 was used. For the multivariate statistical analysis (PCA), Origin.9.0 (OriginLab, USA) version software was used. GIS location map was done using ArcGIS 10.1 software. Finally, to assess the suitability of groundwater for drinking and irrigation purposes the following parameters were calculated by their respective equations; chloroalkaline index (CAI), sodium absorption

ratio (SAR), percentage of sodium (Na %), residual sodium carbonate (RSC), total hardness (HT), permeability index (PI), and Kelly's ratio (KR) are discussed in the later sections.

Spatial Analysis

The spatial analysis was carried out for selected parameters (EC, TDS, SAR and TDS) for both of the pre-monsoon and post-monsoon period using ArcGIS (version 10.1). Inverse distance weighted (IDW) interpolation technique was applied for the analysis considering all the sampling points of the study area. This method estimates the values of an attribute at unsampled points using a linear combination of values at sampled points weighted by an inverse function of the distance from the point of interest to the sampled points assuming that the sampling points closer to the unsampled points are more similar to it than those further away in their values. The IDW technique calculates a value for each grid node by examining surrounding data points that lie within a user-defined search radius (Burrough and Mc Donell 1998; Sarath prasanth et al. 2012).

Results and Discussion

Chemical Properties of Groundwater in the Study Area

Summary of the hydrochemical properties of groundwater collected from of the study areas during pre-monsoon and post-monsoon period are given in Table 1 which reveals an existence of large standard deviations for most parameters, indicating chemical composition of groundwater affected by various processes. During pre-monsoon and post-monsoon, the pH was ranged from 5.50 to 9.70 and 6.86 to 8.44 with an average of 7.42 and 7.41, respectively. This result suggested that during pre-monsoon the water was slightly acidic to alkaline, on the other hand, during post-monsoon, the water fell in neutral to slightly alkaline. However, the average pH revealed that the water is overall in neutral range in both periods. This pH variation may be due to the influx of rainwater of low alkalinity or influence of chemical fertilizers in agricultural fields and leaching of dissolved constituents into the groundwater. The suggested pH values for irrigation water were from 6.5 to 8.0. Considering both sampling periods total 31 (out of 120) sampling points exhibited the pH value out of the recommended pH range (6.5–8.0) by WHO (2011). Electrical conductivity (EC) has been used as a criterion to classify the drinking and irrigation waters (Erguvanli and Yuzer 1987). EC values during pre-monsoon and post-monsoon range from 719 to 37,300 $\mu\text{s}/\text{cm}$ and 741 to

34,100 $\mu\text{s}/\text{cm}$ with corresponding averages of 8973 $\mu\text{s}/\text{cm}$ and 7887 $\mu\text{s}/\text{cm}$. According to WHO (2011) guidelines, the permissible limit of EC is 750 $\mu\text{s}/\text{cm}$. All samples exceeded the standard EC value (except 48) during pre-monsoon and post-monsoon. The enrichment of EC is liable to semi-arid climate, nutrient enrichment, and high evaporation rate. Total dissolved solids (TDS) varied from 345 to 19,490 mg/l and 422 to 18,755 mg/l in pre- and post-monsoon with a mean value of 4829 and 4436 mg/l, respectively. As per TDS classification, 50 % of the wells were of brackish water type (TDS > 1000) and 50 % wells were of freshwater (TDS < 1000) (Freez and Cherry 1979). Groundwater during pre-monsoon is subjugated by Na^+ , Ca^{2+} , Mg^{2+} , Cl^- , HCO_3^- , and SO_4^{2-} , which accounted for 98 % of total cations and anions. The concentrations mg/l of Na^+ , Ca^{2+} , Mg^{2+} , and K^+ mg/l corresponded to an average of 73.72, 13.23, 11.66, and 1.3 %, respectively. The concentration of Cl^- , HCO_3^- , SO_4^{2-} , CO_3^{2-} , NO_3^- , PO_4^{3-} , and F^- contributed on average (mg/l) of 92.49, 0.70, 0.51, 0.18, 0.10, 0.02, and 0.02 % of the total anions. Groundwater of the study area were clearly dominated by Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , and HCO_3^- during both seasons (Fig. 2), which accounted for 99 % of total cations and anions. High concentration of Na^+ , Mg^{2+} , Ca^{2+} , and Cl^- may be attributed to the landward saline water intrusion from the Bay of Bengal due to excessive withdrawal of water, lower river discharge rate and also from rock-weathering. HCO_3^- and CO_3^{2-} concentrations also varied within a long range but the anion contribution (%) showed that first one is dominated in the study area. This might be due to the weathering of carbonate as well as dissolution of the carbonic acids (Kumar et al. 2007a, b).

According to WHO (2011), most of the study area was intensively irrigated. The recommended fertilizers used for agriculture may be the source for the prominent concentration of nitrate in some locations (Chandna et al. 2010). The mean value of Mn in both pre- and post-monsoon seasons were 0.50 and 0.66 mg/l, and it was above WHO guideline for drinking water (<0.05 mg/l). The mean value of Br in pre- and post-monsoon was 1.01 and 1.16 mg/l, respectively. These higher concentrations of Fe and Mn might be responsible for the low pH value in the study area. Concentration of fluoride marginally exceeded the permissible limit of drinking water (1.5 mg/l) in about 70 % of the groundwater samples (data not shown). Fluoride in groundwater was mainly derived from the weathering of fluoride containing minerals specially like muscovite, biotite, fluorite, fluoro-apatite, besides agricultural, and industrial sources (Appelo and Postma 1996). Since, there is no major industrial setup in the study area, the cause of fluoride contamination might be from the groundwater system. The concentration of dissolved silica varied from 6.90 to 37.40 mg/l and 7.60 to 40.80 mg/l with the

Table 1 Chemical composition of groundwater samples during pre-monsoon and post-monsoon season in the study area

Parameter	Standard limit WHO (2011)	Pre-monsoon				Post-monsoon			
		Minimum	Maximum	Average	SD	Minimum	Maximum	Average	SD
Temperature*	–	26.3	31.80	27.76	1.00	26.60	31.10	28.36	0.80
Ph	6.5–8.0	5.50	9.70	7.42	1.04	6.86	8.44	7.41	0.36
EC*	750	719	37,300	8973	8860	741	34,100	7887	7946
TDS	500	345	19,490	4829	4728	422	18,755	4436	4454
Ca ²⁺	75	0.33	544	136	143	6.47	862	133	148
Mg ²⁺	30	3.53	467	155	141	1.06	467	143	132
Na ⁺	200	54.1	2857	863	759	3.20	2959	825	910
K ⁺	30	1.47	60.26	16.16	13.94	1.04	69.63	13.40	13.03
Cl ⁻	250	28.0	14,517	3513	3691	44	12,250	3068	3308
CO ₃ ²⁻	–	0.00	48.00	7.02	8.46	0.00	45.00	7.84	9.86
HCO ₃ ⁻	200	42.7	616	254	159	42.0	561	222	120
NO ₃ ⁻	45	0.20	28.77	4.12	5.20	0.05	38.92	3.73	6.09
SO ₄ ²⁻	200	0.00	629	19.48	86.53	0.00	620.5	17.24	81.38
PO ₄ ²⁻	–	0.08	5.35	0.85	0.89	0.15	5.65	0.79	1.01
F ⁻	0.6–1.5	0.01	10.7	0.76	1.40	0.02	2.12	0.71	0.59
Mn	400	0.02	4.50	0.50	0.65	0.02	5.40	0.66	0.94
Fe	0.01	0.04	21.2	5.57	5.95	0.10	21.0	5.84	5.26
B	–	0.00	3.20	1.01	0.85	0.10	3.20	1.16	0.92
I	–	0.10	2.30	0.58	0.33	0.26	2.35	0.64	0.39
Br	–	0.01	1.44	0.31	0.23	0.04	12.0	0.53	1.53
SiO ₂	–	6.90	37.4	23.92	7.67	7.60	40.8	23.36	9.10
SAR	–	3.86	473	91.27	73.96	0.50	217	70.63	61.11
Na %	–	11.4	98.2	73.38	20.48	1.09	90.4	26.34	20.53
RSC	–	–384	615	115.6	267.9	–447.5	559	91.85	222.8
HT	500	20.4	3129	977.4	886.4	20.54	3538	922.4	812.8
KR	–	0.24	110	16.97	26.37	0.08	63.2	9.38	13.53
GRA	–	0.06	0.99	0.75	0.30	0.10	1.00	0.74	0.29
GRC	–	0.20	1.00	0.83	0.18	0.11	0.98	0.76	0.23
Cl/∑anions	–			22.95					21.5
Na/Na + Cl				0.31					0.35

The units of all parameters are mg/l except * temperature (°C) and * EC (µS/cm)

respective average value of 23.92 and 23.36 mg/l in both pre- and post-monsoon. In water, the main source of the dissolved silica was the chemical breakdown of silicates during weathering processes.

To find out the interrelations among various water quality parameters, Pearson's correlation matrix was done (Table 2). According to Table 2, statistically positive significant correlations were found between EC and TDS ($r = 0.99$). Subsequently, TDS and EC showed strong significant correlation with Mg²⁺, Ca²⁺, Na⁺, K⁺, Fe, NO₃⁻, SO₄²⁻, and Cl⁻ with p value 0.01 and $r \geq 0.24$. The result attributed to the high salinity nature of the ground water, and the major contributions may be due to the sea

water intrusion into the groundwater aquifers in the study area along with precipitation from the agricultural chemicals. In additions, HT was significantly correlated with EC, TDS, Mg²⁺, Ca²⁺, Na⁺, K⁺, Fe, and Cl⁻ positively and with pH and HCO₃⁻ anion it had shown a significant negative correlation. This was further confirmed by principle component analysis (PCA). PCA is a method complementary to classical approaches of hydrogeochemical research (Morell et al. 1996) which provides quick visualization and shows correlation among different water quality variables. PCA on the combined datasets provided four factors with Eigenvalue >1 that can explain approximately 76.79 % of the variability of the data (PC 1

Fig. 2 Pie diagram to represents the contribution (%) of different cations and anions to total cations and total anions during **a** pre-monsoon and **b** post-monsoon period in the groundwater of the study area

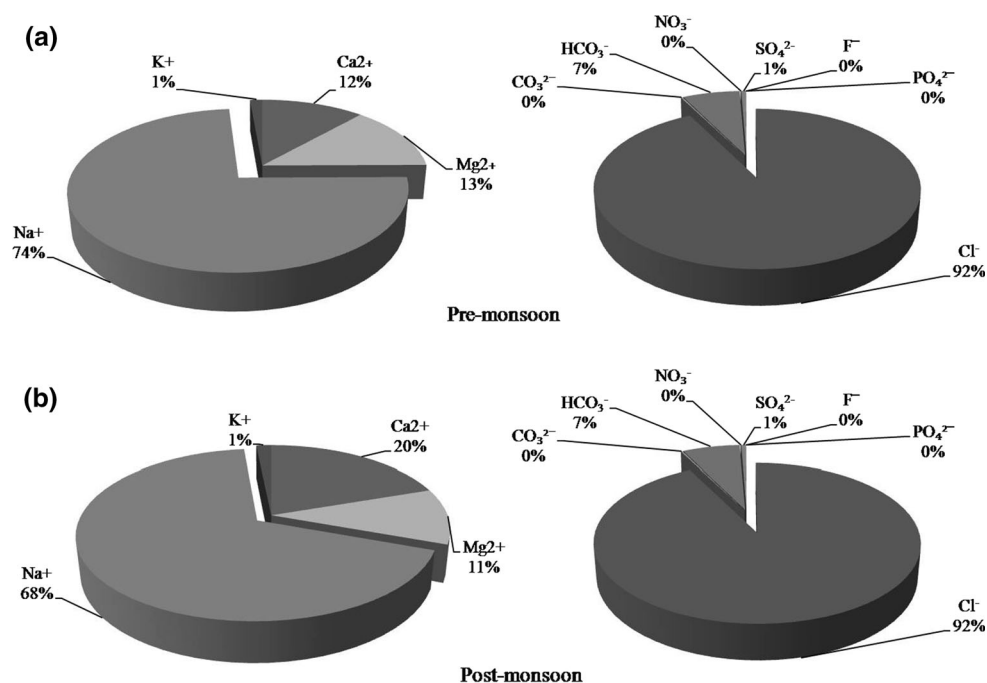


Table 2 Pearson's correlation Matrix for the chemical constituents of groundwater in both seasons ($n = 120$)

	pH	EC	TDS	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	CO ₃ ²⁻	HCO ₃ ⁻	NO ₃ ⁻	SO ₄ ²⁻	PO ₄ ³⁻	HT
pH	1													
EC	-0.36*	1												
TDS	-0.37*	0.99*	1											
Ca ²⁺	-0.34*	0.24*	0.25*	1										
Mg ²⁺	-0.49*	0.46*	0.48*	0.66*	1									
Na ⁺	-0.32*	0.42*	0.42*	0.47*	0.68*	1								
K ⁺	-0.43*	0.49*	0.49*	0.15	0.43*	0.50*	1							
Cl ⁻	-0.39*	0.88*	0.89*	0.27*	0.51*	0.44*	0.48*	1						
CO ₃ ²⁻	0.08	-0.16	-0.15	-0.02	-0.01	-0.15	-0.24*	-0.16	1					
HCO ₃ ⁻	0.41*	-0.30*	-0.31*	-0.57*	-0.58*	-0.44*	-0.31*	-0.32*	0.13	1				
NO ₃ ⁻	-0.14	0.65*	0.65*	-0.04	0.02	0.10	0.29*	0.61*	-0.18*	-0.11	1			
SO ₄ ²⁻	-0.01	0.36*	0.35*	0.03	-0.06	-0.06	-0.04	0.31	-0.13	0.06	0.12	1		
PO ₄ ³⁻	0.17	-0.04	-0.03	-0.25*	-0.10	-0.26*	-0.24*	-0.04	0.44*	0.45*	-0.005	-0.10	1	
HT	-0.48*	0.41*	0.42*	0.87*	0.94*	0.65*	0.35*	0.45*	-0.01	-0.63*	-0.005	-0.02	-0.17	1

2-tailed test of significance used

* Correlation is significant at P value <0.05

variance of 40.78 % and PC 2 variance of 17.52 %) (Table 3). From the biplot analysis of PCA, when two variables are far from the center and close to each other, then the variables are said to be significantly and positively correlated ($r = 1$). PC 1 which may be related coefficients of PC1 which are related to the total hardness of the ground water are Na⁺, Mg²⁺, and Ca²⁺. However, PC 2 may be related to the salinity of the ground water closely related to EC, TDS, and Cl⁻ (Fig. 3).

Classification of Ground Water

Groundwater classifications are used to understand the groundwater body that differs in their chemical properties and compositions (Mahlnecht et al. 2004). Depending on lithology, regional flow patterns of water and resident time hydrochemical properties of groundwater vary (Domenico 1972). From the viewpoint of chemical compounds, all waters are divided into three main

Table 3 Eigenvalues of the Correlation Matrix for principle component analysis (PCA) for all seasons

	Eigenvalue	Percentage of variance (%)	Cumulative (%)
1	5.70931	40.78	40.78
2	2.45298	17.52	58.30
3	1.50034	10.72	69.02
4	1.08802	7.77	76.79
5	0.7317	5.23	82.02
6	0.71056	5.08	87.09
7	0.56071	4.01	91.10
8	0.35645	2.55	93.64
9	0.32819	2.34	95.99
10	0.24633	1.76	97.75
11	0.17016	1.22	98.96
12	0.14404	1.03	99.99
13	0.00122	0.01	100.00
14	0	0.00	100.00

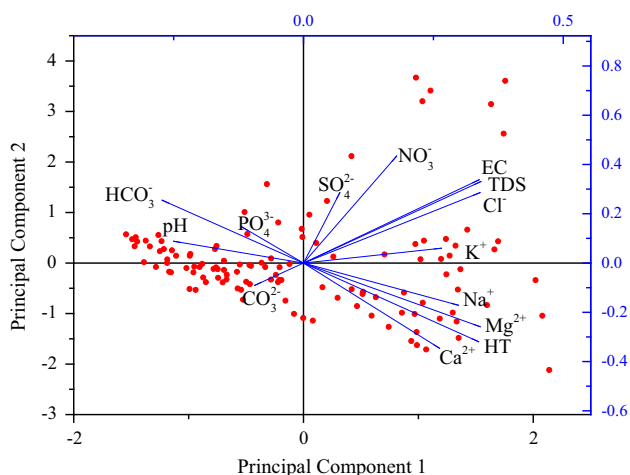


Fig. 3 Principal component analysis (PCA) biplot based on correlation matrix for both of the seasons

categories: chloride, sulfate and bicarbonate types (Chebotarev 1955). The Piper diagram can be used to identify the type of water. It consists of three parts: one diamond-shaped diagram in the middle and two trilinear diagrams along the bottom. The relative concentrations of cations (left diagram) and anions (right diagram) in each sample is shown in the trilinear diagram. For the purpose of a piper diagram, the cations are grouped into three major divisions: sodium (Na^+) plus potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). The anions are likewise grouped into three main categories: bicarbonate (HCO_3^-) plus carbonate (CO_3^{2-}), chloride (Cl^-), and sulfate (SO_4^{2-}). Each sample is represented by a point in each

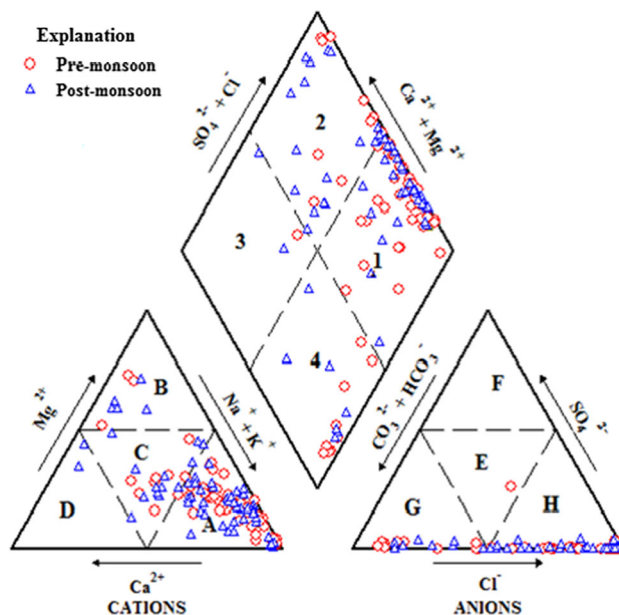


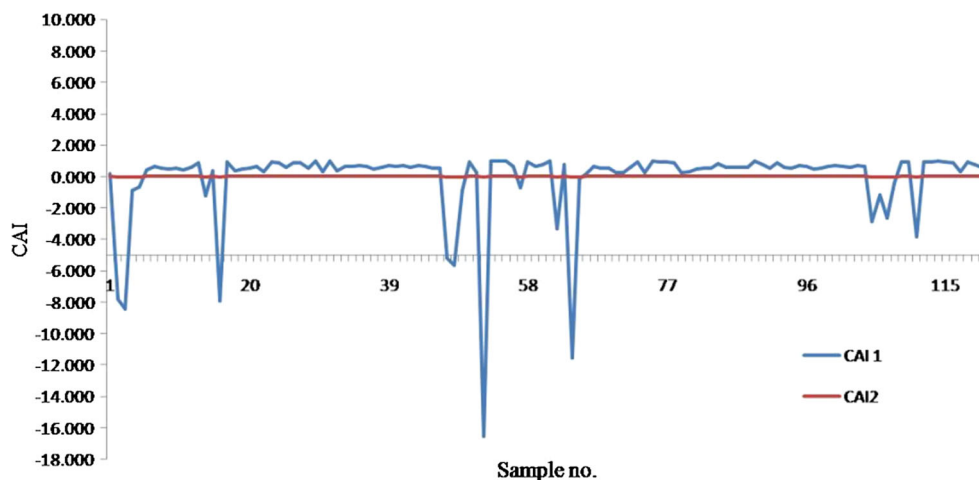
Fig. 4 Piper diagram of the groundwater samples in the study area (1) $\text{Na}^+ - \text{K}^+ - \text{SO}_4^{2-} - \text{Cl}^-$ type, (2) $\text{Ca}^{2+} - \text{Mg}^{2+} - \text{SO}_4^{2-} - \text{Cl}^-$ type, (3) $\text{Ca}^{2+} - \text{Mg}^{2+} - \text{CO}_3^{2-} - \text{HCO}_3^-$ type, and (4) $\text{Na}^+ - \text{K}^+ - \text{CO}_3^{2-} - \text{HCO}_3^-$ type

trilinear diagram; the type of water samples will qualify according to the symbolic area in piper diagram. The high variability of major ion chemistry is shown in Fig. 4. For the study area, approximately 65 % of the samples were $\text{Na}^+ - \text{Cl}^- - \text{SO}_4^{2-}$ and nearly 70 % samples were alkali and sodium–potassium type. Chloride and bicarbonate covers 98 % samples. (1) Sulfate type, (2) Calcium–Magnesium–Sulfate–Chloride type, (3) Calcium–Magnesium–Bicarbonate type, (4) Sodium Bicarbonate type, (A) Sodium Potassium type, (B) Magnesium type, (C) No-dominance, (D) Calcium type, (E) No-dominance, (F) Sulfate type, (G) Chloride type, and (H) Bicarbonate type Fig. 4. The above mentioned water types indicated that the groundwater of the study area is affected by saline water.

Chloroalkaline Index

It is very important to understand the changes in chemical composition of groundwater along with its sub-surface flow paths. The changes in chemical composition of groundwater through its way of flow can be understood by studying the chloroalkaline indices (CAIs) proposed by Schoeller (1977). He suggested two chloroalkaline indices namely CAI 1 (Eq. 1) and CAI 2 (Eq. 2) for the interpretation of the ion exchange behavior between groundwater and prevailing environment. The CAIs are used to evaluate the base exchange calculated from the following equations:

Fig. 5 Chloroalkaline indices (CAI) of groundwater in the study area



Chloro-alkaline indices, $CAI1 = [Cl - (Na + K)]/Cl$ (1)

Chloro-alkaline indices, $CAI2 = [Cl - (Na + K)] / (SO_4 + HCO_3 + CO_3)$ (2)

Positive CAIs indicate direct ion exchange between Na^+ and K^+ from the water and Mg^{+2} and Ca^{+2} from the rocks. In addition, CAIs is indirect and negative when there is an ion exchange of Mg^{+2} and Ca^{+2} from the water with Na^+ and K^+ from the rocks. In this study, CAIs (1, 2) were calculated and the results showed in Fig. 5. The results revealed that about 87.12 % of the groundwater samples of the study area possessed positive CAIs and only 12.88 % had negative CAIs for both pre-monsoon and post-monsoon period. This finding clearly indicated the ion exchange of Na^+ and K^+ from the water and Mg^{+2} and Ca^{+2} in the rocks.

Major ion Chemistry

The plot of equiline (Fig. 6) for the various ions shows the characteristics of the ions and their affinities. The plot of Na^+ versus total cations during pre- and post-monsoon shows that most of the values are on the equiline suggesting that the alkali ions are balanced by the total cations. Moreover, the ratio between the Na^+ versus total cations was 0.961, and the ratio between the $Ca^{+2} + Mg^{+2}$ versus total cations was also found to be 0.589 indicating that the most of the ions were balanced by total cations. Among the alkalis, Na^+ was the dominant and the concentration of potassium was apparently low. Relatively, the subsequent dissolution and chemical weathering of minerals of local sedimentary rocks and igneous rocks and clay minerals were the source of natural origin potassium in water (Sarin et al. 1989). These anions compensate the extra alkali ions present in the water. The ratio of $Na^+ + K^+$ versus total cations was 0.961 and $Cl^- + SO_4^{2-}$ versus total cations

was 0.224 clearly showing the dominance of alkalis over the alkaline earth metal ions.

The ratio of Cl^- versus total anions was 0.998 and HCO_3^- versus total anions was 0.081 clearly showing the bicarbonate dominance over the alkaline metal ions. The ratio of $Ca^{2+} + Mg^{2+}$ versus HCO_3^- was 0.401 and $Ca^{2+} + Mg^{2+}$ versus $HCO_3^- + SO_4^{2-}$ was 0.291. HCO_3^- ions in groundwater normally arise from the reaction of carbonate ions with water molecules releasing hydroxyl ions into the water, increasing the pH of the water indicates alkalinity.

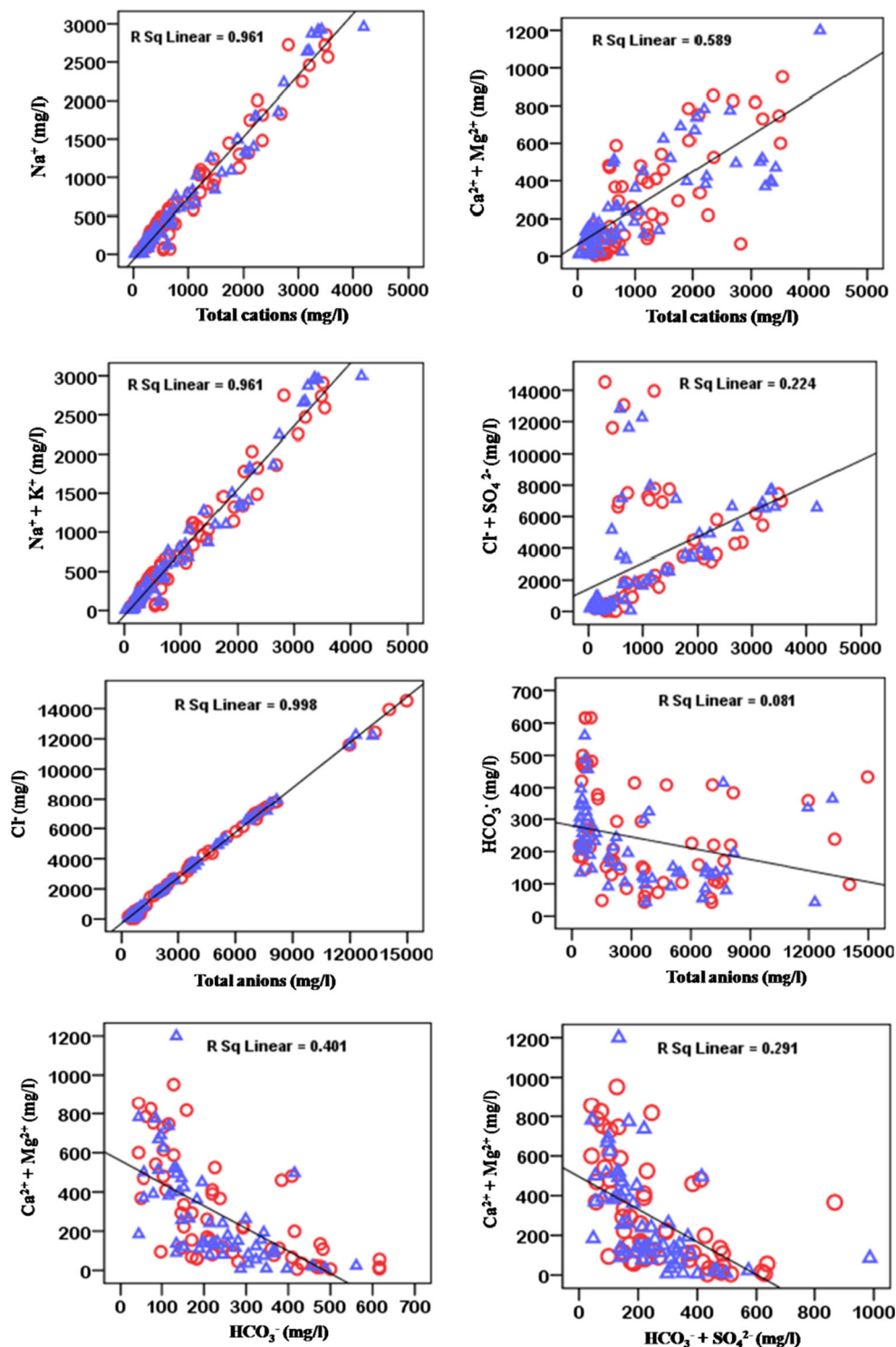
Gibb's diagram explains the mechanism of chemical reactions which lead to changes in the composition of groundwater and sources (Gibb's 1970). Two plots (Fig. 7a) represent TDS versus $(Na^+ + K^+) / (Na^+ + K^+ + Ca^{2+})$ and TDS versus $Cl^- / (Cl^- + HCO_3^-)$. Figure 7b shows that about 75 % of the water samples during pre-monsoon and post-monsoon fell in the precipitation dominance region. It is interesting to note that both the cation and anion plots clearly describe the occurrence of weathering reaction in the study area.

To check the seawater intrusion, the molar ratio of $Cl^- / \sum anions$ and $Na^+ / (Na^+ + Cl^-)$ for the groundwater of the study area was also investigated. According to Hounslow (1995), groundwater samples having $Cl^- / \sum anions$ ratio greater than 0.8 and having $Na^+ / (Na^+ + Cl^-)$ ratio less than 0.5 suggest that the groundwater was derived from the seawater. In this study, 81 % samples having $Cl^- / \sum anions$ ratio greater than 0.8 followed by 85 % samples having $Na^+ / (Na^+ + Cl^-)$ ratio less than 0.5 (Table 1). This result clearly indicates the seawater intrusion in the groundwater of the study area.

Drinking and Irrigation Water Suitability

To check the suitability of the groundwater for drinking and irrigation uses, a set of determinants were studied and

Fig. 6 Ion scatter diagram showing relationships among major ions in the groundwater samples of the study area (*solid line* denotes 1:1) (O = Pre-monsoon, Δ = Post-monsoon)



scaled in Table 4. The results obtained from the chemical analyses of groundwater in the study area were further evaluated to check the suitability for drinking and agricultural uses. The drinking water quality was compared to the specifications of World Health Organization (WHO 1996, 2011). In case of TDS, the optimum level is 500 mg/l

and the maximum permissible limit is 1500 mg/l. In the study area TDS ranged from 345–19,490 mg/l and 422–18,755 mg/l in pre-monsoon and post-monsoon (Table 1), respectively, which exhibited 84 % of water samples were out of the guideline limit (500 mg/l) (Data not shown). In terms of total hardness (TH), the

Fig. 7 The Gibb's Ratios (weight ratio) of **a** TDS versus $(\text{Na}^+ + \text{K}^+)/(\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+})$ and **b** TDS and $\text{Cl}^-/(\text{Cl}^- + \text{HCO}_3^-)$ (O = Pre-monsoon, Δ = Post-monsoon)

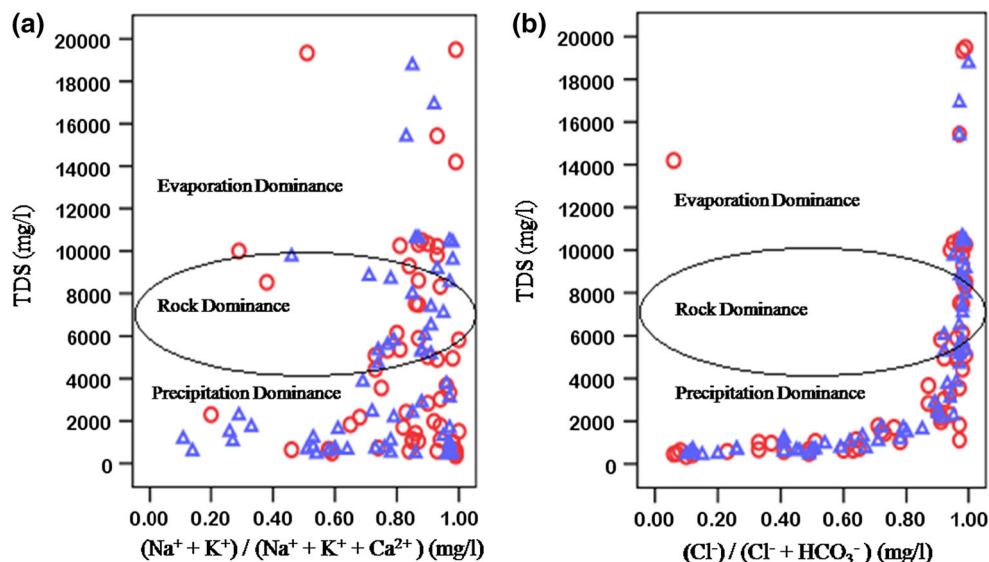


Table 4 Classification of groundwater based on suitability determinants (EC, SAR, TDS, TH, RSC, KR, and % Na) for irrigation or drinking purposes

Parameters	Reference	Range	Classification	Number of sample within standard range	
				Pre-monsoon	Post-monsoon
EC	Wilcox (1955)	$<250 \mu\text{Scm}^{-1}$	Excellent	0	0
		$250\text{--}750 \mu\text{Scm}^{-1}$	Good	1	1
		$750\text{--}2250 \mu\text{Scm}^{-1}$	Permissible	18	21
		$2250\text{--}5000 \mu\text{Scm}^{-1}$	Doubtful	9	9
		$>5000 \mu\text{Scm}^{-1}$	Unsuitable	32	29
SAR	Richards (1968)	$<10 \text{ mg/l}$	Excellent	4	11
		$10\text{--}18$	Good	3	3
		$18\text{--}26$	Doubtful	3	2
		>26	Unsuitable	50	44
TDS	Freeze and Cherry (1979)	$0\text{--}1000 \text{ mg/l}$	Freshwater	13	19
TH	Sawyer and McCarty (1967)	$0\text{--}75 \text{ mg/l}$	Soft	8	5
		$75\text{--}150 \text{ mg/l}$	Moderately hard	1	1
		$150\text{--}300 \text{ mg/l}$	Hard	3	6
RSC	Eaton (1950)	$<1.25 \text{ meq/l}$	Suitable	18	21
Kelly's ratio	Kelly (1940)	<1	Suitable	3	7
% Na	Wilcox (1955)	<20	Excellent	3	19
		$20\text{--}40$	Good	1	27
		$40\text{--}60$	Permissible	7	3

groundwater was classified according to Sawyer and McCarty (1967). The most desired limit for TH was $80\text{--}100 \text{ mg CaCO}_3/\text{l}$ (Freeze and Cherry 1979). The TH ranged from 20.37 to 3129.19 and 20.54 to 3538.47 mg/l with an average of 977.45 and 922.40 mg/l, respectively, during pre- and post-monsoon seasons tending to be very hard water categories (Table 4). It is, therefore, confirmed that 90 % of the water samples were not suitable for the domestic use in both seasons. In addition to these, EC also

exhibited extreme salinity level, only 2 samples out of 120 fell into the medium salinity range, and no sample was in the low salinity range (Wilcox 1955) (Table 4).

Crop yield and soil fertility deteriorate due to using irrigation waters pumped from wells containing considerable chemical constituents derived from natural environment and anthropogenic activities (Jalali 2009). The success of irrigation projects mostly depends on the supply of irrigation water to the land along with the optimum control of

salts and alkali in the soils (Haritash et al. 2008) The application of irrigation water helps supplies salts into the root zone (Jalali and Mohsen Jalali 2011a, b). Parameters such as sodium absorption ratio (SAR), sodium percentage (% Na), residual sodium carbonate (RSC), and permeability index (PI) are being considered as determinants for the irrigation water suitability test (Raju 2007).

Salt water is a good conductor of electricity, and thus EC is a measurement of the degree of electrical conductance in water. Based on the chemical analysis results, it was found that the degree of salinity in the study area was classified (Table 4) based on the US salinity laboratory (Wilcox 1955). According to the classification, no sample in both seasons was in the excellent range. However, 32 samples in pre-monsoon, 29 samples in post-monsoon were unsuitable; each 9 (pre- and post-monsoon) samples were doubtful; 18 pre-monsoon and 21 post-monsoon samples were in permissible range, and only 1 sample each for pre- and post-monsoon was medium salinity range.

Sodium Percentage (Na^+ %)

Sodium is a major ion used for the classification of irrigation water due to its reaction with soil that reduces its permeability. Percentage of Na^+ is generally used for assessing the suitability of water for irrigation purposes (Wilcox 1955). Na^+ is expressed as percent sodium or soluble-sodium percentage (Na^+ %) using Eq. 3. Where, all ionic concentrations are expressed in mg/l. The classification of samples is shown in Table 4. As per the (Wilcox 1955) classification, 8 and 49 % of groundwater during pre-monsoon and post-monsoon represent excellent category; 54 and 35 % represent good quality; 24 % during pre-monsoon and 2 % represents permissible limit at post-monsoon (Table 4). The effect of dilution is well observed during post-monsoon season by an increase in number of samples representing excellent category, and a decrease in samples from good and permissible category for irrigation purposes. In general, higher Na^+ % was observed during pre-monsoon, indicating the ion exchange and weathering from lithological units.

$$(\%)\text{Na}^+ = \left(\frac{\text{Na}^+ + \text{K}^+}{\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+ + \text{Na}^{2+}} \right) \times 100 \quad (3)$$

Residual Sodium Carbonate (RSC)

The total of carbonate and bicarbonate over the total of calcium and magnesium in water affects the suitability of groundwater for irrigation purposes. An excess sodium bicarbonate and carbonate influence the physical characteristics of soil by dissolution of organic matter in soil that

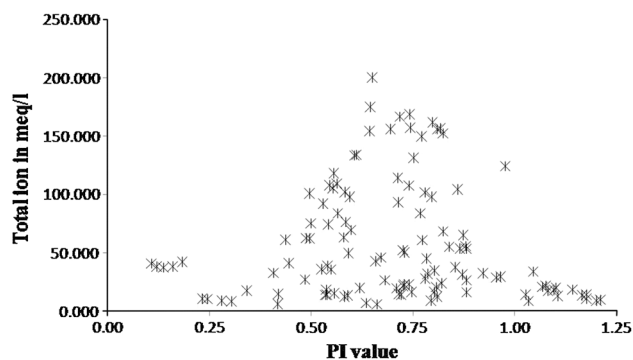


Fig. 8 Permeability index (PI) scale showed maximum PI value ranges from 0.25 to 1.00 during both pre- and post-monsoon period in the study area

leaves a black stain on soil surface on drying (Kumar et al. 2007a, b). This excess is called RSC and determined by the formula proposed by Ragunath (1987) Eq. 4. Where, all ionic concentrations are expressed in mg/l. RSC ranged from -384.58 to 615.31 mg/l and -447.53 to 559.36 mg/l with an average of 115.64 and 91.85 mg/l during pre-monsoon and post-monsoon, respectively (Table 1). From the results, it was distinctively clarified that 70 % of the samples during pre-monsoon, and 65 % of the samples during post-monsoon were unsuitable for irrigation (Table 4).

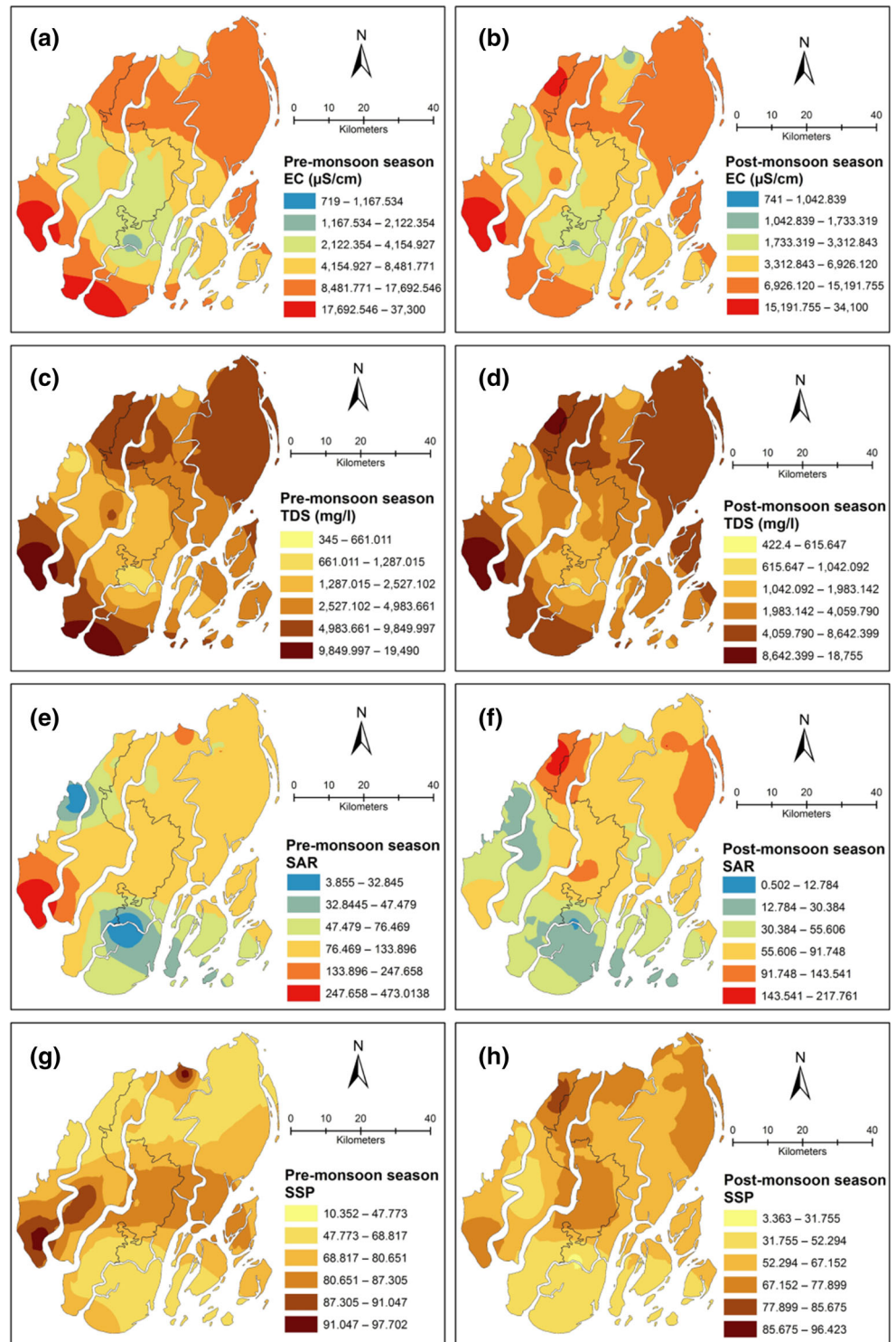
$$\text{RSC} = (\text{CO}_3^{2-} + \text{HCO}_3^-) - (\text{Ca}^{+2} + \text{Mg}^{+2}) \quad (4)$$

Sodium Adsorption Ratio (SAR)

To determine the quality of water used for irrigation, sodium adsorption ratio (SAR) is an essential parameter and is expressed as sodium or alkali hazard. Higher salinity reduces the osmotic activity of plants as well as prevents water to reach to the branches and leaves of plants resulting in inferior production (Deepali et al. 2011). Moreover, irrigation water with high Na^+ and low Ca^{2+} favors ion exchange by saturation of Na^+ and destroys the soil structure due to scattering of clay particles (Todd 1980) resulting in minor production because of difficulty in cultivation (Subba 1998). Based on the SAR value the groundwater suitability classification is shown in Table 4. It was found that during pre-monsoon 83 % of the groundwater sample fell in the unsuitable range and during post-monsoon 73 % sample was in the unsuitable range, and rest 17–27 % samples were within suitable-doubtful range during pre- and post-monsoon, respectively. The SAR is calculated using the following equation (Eq. 5):

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}} \quad (5)$$

Fig. 9 Spatial distribution maps for EC, TDS, SAR and SSP during pre-monsoon and post-monsoon. **a** EC pre-monsoon; **b** EC post-monsoon; **c** TDS pre-monsoon; **d** TDS post-monsoon; **e** SAR pre-monsoon; **f** SAR post-monsoon; **g** SSP pre-monsoon and **h** SSP post-monsoon



Permeability Index (PI)

Sodium, magnesium, calcium, and bicarbonate content influence the permeability of soil which in turn influence the quality of irrigation water on uses for a long time.

Doneen (1964) evolved a criterion for assessing the suitability of water for irrigation based on permeability index (PI) and calculated by the Eq. 6, where all the ions were expressed in meq/l. According to the PI, water can be classified as class I, Class II, and Class III levels. Class I

and Class II water are categorized as good for irrigation with 75 % or more maximum PI and Class III water are unsuitable with 25 % of maximum permeability. This study calculated the PI and it ranged from 12 to 105 % and 16 to 187 % with an average of 76 and 72 % during pre-monsoon and post-monsoon, respectively. It was confirmed that the maximum PI values ranged between Class II and Class I, so in terms of PI groundwater were more suitable for irrigation; however, only 7 sample showed the unsuitable range with PI value <25 % Fig. 8.

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

Kelly's Index (KI)

Kelly's index is used for the classification of water for irrigation purposes. The value of KI (>1) shows an excess of sodium and KI (<2) signifies its deficit in waters (Kelly 1940). The KI was calculated using Eq. 7. The waters with low KI (<1) are fit for irrigation while those with greater ratio are considered as unsuitable (Sundaray et al. 2009). KI ranged between 0.24–110.95 mg/l and 0.08–63.29 mg/l during pre-monsoon and post-monsoon seasons (Table 1). A sum of 10 and 43 % of samples during pre-monsoon and post-monsoon represent its suitability and rest of the samples fell under unsuitable range (Table 4).

$$KI = Na^+ / (Ca^{2+} + Mg^{2+}) \quad (7)$$

The KI values indicated that higher percentage of Na⁺ can be derived from weathering of Feldspars from the litho units of the study area (Vasanthavigar et al. 2012). The groundwater was not suitable for irrigation as well as drinking purposes.

Spatial Distribution Maps for Selected Parameters

To observe the spatial extent of the water quality parameters through the entire study area, spatial distribution maps were sketched using the IDW technique with ArcGIS software (Fig. 9a–h). From Fig. 9a–b, it is shown that the EC values were higher in the north and south part of the study area than the central part. There is a noticeable variance also observed between two seasons. A similar pattern of distribution was observed in case of TDS values in the study area (Fig. 9c–d). This may be caused by the depth of the sampling points along with the flow of the coastal rivers. The shallow aquifer can be easily affected by seawater intrusion but the deep aquifer is quite stable to get polluted. However, the river flow and anthropogenic activities might also have influenced in this regard. Consequently, the SAR values have

also significant spatial variations during both seasons (Fig. 9e–f). In the pre-monsoon, the highest SAR observed in south-west region; on the other hand, it was on the north-east during post-monsoon. A quite similar distribution pattern was noticed in case of SSP (Fig. 9g–h). Nevertheless the SSP value showed higher occurrences in the central part of the study area in pre-monsoon. But it changed to north-eastern in the post-monsoon. Overall, the spatial distribution of the above parameters indicated that the area is affected by high saline water from the sea, and central part of the study area is comparatively better than other area.

Conclusions

Geochemical assessment of the study area has been evaluated using different techniques. Results clearly demonstrate that the seasonal effect imposes a serious impact on the concentration of ions due to the dilution of water in post-monsoon. The ranks of the abundance of the ions are as follows: the extent of cations was found to be in the order of Na⁺ > Ca²⁺ > Mg²⁺ > K⁺ and Na⁺ > Mg²⁺ > Ca²⁺ > K⁺ during pre-monsoon and post-monsoon, respectively. On the other hand, the order of anions is Cl⁻ > HCO₃⁻ > SO₄²⁻ > CO₃²⁻ > NO₃⁻ > PO₄³⁻ > F⁻, and Cl⁻ > HCO₃⁻ > SO₄²⁻ > CO₃²⁻ > NO₃⁻ > PO₄³⁻ > F⁻ for the pre-monsoon and post-monsoon, respectively. The TDS was mainly due to Mg²⁺, Na⁺, K⁺ and Cl⁻. The EC values are extremely high in most of the sampling points. In general, the concentrations of cations and anions are high in the pre-monsoon indicating excessive evaporation, silicate weathering, and anthropogenic activities. The high salinity and %Na along with hardness makes the groundwater unsuitable for irrigation. Although water quality is in critical status in the studied regions, farmers are forced to use this water for agriculture practices. Also groundwater quality in these areas is not suitable for drinking and could be hazardous to public health. This coastal area requires special water resource management plans to ensure agricultural activities and/alternative strategy to combat against the present situation. This study can be used as a very good resource for the groundwater management programs in the coastal area of Bangladesh.

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Compliance with Ethical Standards

Conflict of Interests This is an original manuscript that has not been submitted elsewhere for publication. All authors have read the manuscript and agreed that the work is ready for submission to the journal with no conflict of interests. The author Md. Mostafizur Rahman will represent for all correspondence.

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