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ORIGINAL ARTICLE

Hydrogeochemical investigation of groundwater in shallow coastal aquifer of Khulna District, Bangladesh

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Abstract Groundwater acts as a lifeline in the coastal regions to meet out the domestic, drinking, irrigational and industrial needs. To investigate the hydrogeochemical characteristics of groundwater and its suitability, twenty samples were collected from the shallow tubewells of study area having screen depth 21–54 m. The water quality assessment has been carried out by evaluating the physicochemical parameters such as temperature, pH, EC, TDS and major ions i.e., Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, NO_3^-, HCO_3^-. Results found that, the water is slightly alkaline and brackish in nature. The trends of cations and anions are $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > HCO_3^- > SO_4^{2-} > NO_3^-$, respectively and Na–Cl–HCO_3 is the dominant groundwater type. The analyzed samples were also characterized with different indices, diagram and permissible limit i.e., electric conductivity (EC), total dissolved solids (TDS), chloride content (Cl), soluble sodium percentage (SSP), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), magnesium adsorption ratio (MAR), Kelley's ratio (KR), Wilcox diagram and USSL diagram, and results showed that groundwater are not suitable for drinking and irrigational use. The factors responsible for the geochemical characterization were also attempted by using standard plot and it was found that mixing of seawater with entrapped water plays a significant role in the study area.

Keywords Groundwater quality · Electric conductivity · Salinity intrusion · Hydrogeochemical processes · Coastal region

Introduction

Groundwater is the most important source of domestic, industrial and agricultural water supply in the world. It is estimated that approximately one third of the world's population use groundwater for drinking purpose (Nickson et al. 2005). It is found in aquifers that have the capacity of both storing and transmitting water, in significant quantities (Todd 1980). Generally, groundwater quality depends on the quality of recharged water, atmospheric precipitation, inland surface water and subsurface geochemical processes (Twarakavi and Kaluarachchi 2006; Kumar et al. 2014). In coastal regions groundwater quality patterns are complex, because of the input from different water sources including precipitation, seawater, ascending deep groundwater and anthropogenic sources (Steinich et al. 1998). Problems in coastal areas are typically connected to contamination of fresh water resources by saline water and include well field salinization, crop damage, and surface water quality deterioration (Karro et al. 2004).

Bangladesh lies in the northeastern part of South Asia, has 710 km coastal line and the coastal area covers about 32% of the country (MoWR 2005). Although, coastal aquifers serve as major sources of freshwater supply, the groundwater in coastal region is relatively vulnerable to contamination by seawater intrusion, which makes groundwater unsuitable (Kim et al. 2006; Jorgensen et al. 2008). Natural processes and anthropogenic activities like; over extraction, urbanization and agricultural activities are the main reason

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for seawater intrusion and water quality deterioration in coastal aquifers (Mondal et al. 2011; Selvam et al. 2013). Nowadays, almost 53% of the coastal areas of Bangladesh are affected by salinity (Hoque et al. 2003; Woobaidullah et al. 2006; Islam 2014). Salinity becomes a major problem in south-western coastal region of Bangladesh, where irrigation water quality is affected by high levels of salinity (Shammi et al. 2016a), which is a source of irrigation salinity and it mainly results from rises in the groundwater table due to excessive irrigation and the lack of adequate drainage for leaching and removal of salts (Corwin et al. 2007). The total area under irrigation in Bangladesh is 5,049,785 ha and 78.9% of this area is covered by groundwater sources including 3,197,184 ha with 1,304,973 shallow tubewells and 785,680 ha with 31,302 deep tubewells (DPHE and JICA 2010). However, most crop lands in the coastal areas of Bangladesh remain fallow in the dry season because surface water resources are saline and unsuitable for irrigation, while groundwater is not intensively utilized because of the fear of seawater intrusion into aquifers (Mondal et al. 2008). Seawater intrusion is a major threat in the coastal aquifers of Bangladesh, especially in southwestern region (Bahar and Reza 2010; Islam et al. 2015, 2016b; Islam and Bhuiyan 2016). The over dependence on groundwater for drinking, agricultural and industrial sector and different climatic and natural phenomenon causes coastal groundwater contamination (Srinivas et al. 2015). Besides, different geochemical processes in groundwater governing the chemical characteristics of groundwater, is well documented in many parts of the world by many authors i.e., Montety et al. (2008), Jalali (2009), Manjusree et al. (2009), Thilagavathi et al. (2012), Sivasubramanian et al. (2013), Nagaraju et al. (2014), Kumar et al. (2015), Islam et al. (2016a, b) and Balaji et al. (2016). Geochemical studies of groundwater provide a better understanding of water quality and possible changes (Kumar et al. 2014). However, the coastal groundwater system is fragile and its evaluation will help in the proper planning and sustainable management (Sefie et al. 2015). Therefore detailed investigations regarding the groundwater hydrogeochemistry and water quality in shallow aquifer is imperative. So the present study aims to investigate the groundwater, to determine its utility and find out the major geochemical process in study area. It also intended to delineate the spatial distribution of hydrogeochemical constituents for proper understanding and future management perspective.

Study area

Location and hydrological setting

Geographically, the study area is located between 22°28′ and 22°56′ N latitudes and between 89°12′ and 89°40′ E longitudes (Fig. 1). The investigated area falls within the western part of Faridpur Trough of Bengal Foredeep (Alam

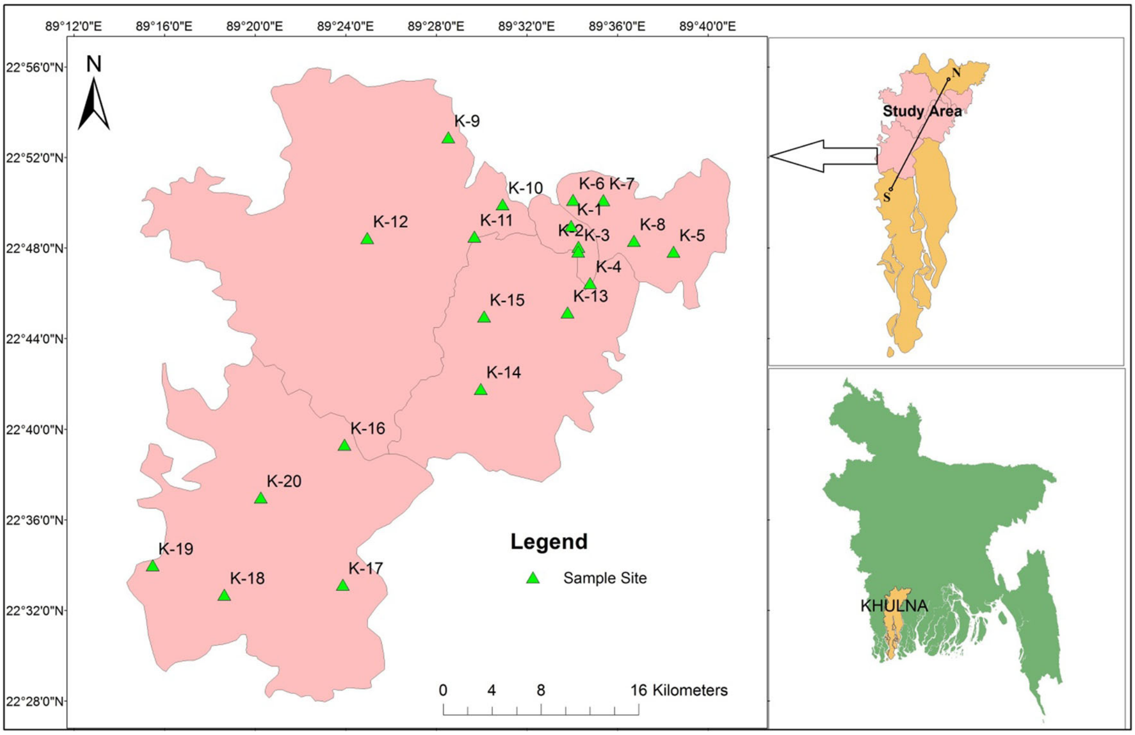

Fig. 1 Location of sampling sites in the study area

1990) and is located on a natural levee of the Rupsha and Bhairab rivers and characterized by Ganges tidal floodplains with low relief, criss-crossed by rivers and water channels, and surrounded by tidal marshes and swamps. The surface lithology of the area is of deltaic deposits which are composed of tidal deltaic deposits, deltaic silt deposits, and mangrove swamp deposits (Alam 1990). The aquifers in and around the study area are generally multilayered varying from unconfined to leaky-confined in the shallow alluvial deposits and confined in the deeper alluvial deposits (Uddin and Lundberg 1998). The aquifer systems of the study area can be classified into two major classes: the shallow aquifers ranging from depth ~10 to 150 m and deep aquifers generally >180 m depth are shown in Fig. 2. The water of this aquifer is generally brackish or saline with few isolated fresh water pockets (DPHE 2006).

Weather and climate

Climate is one of the most important factors for the occurrence and movement of groundwater (CGW Board 2009; Islam et al. 2016b). The study area falls in the south-central zone, south-western and south-eastern zone of the climatic sub-division (Fig. 3) and with bulk of rainfall occurring between the months of June to October, high temperature and excessive humidity (BMD 2014). The area comprise of three major climatic seasons includes hot summer (March–May), followed by monsoon or rainy season (June–October) and a moderate winter season (November–February). Analyzing the rainfall data from 1993 to 2012 it is observed that maximum rainfall occurs during the rainy season May to October with the peak occurring in July while during the dry period there is almost no rainfall (Iftakher et al. 2015). The mean annual rainfall of Khulna district is approximately 1816 mm. and the mean temperature is 34 °C (BMD 2014). Besides, many others natural phenomenon storm surge, tidal flood and salinity are very common in this area (Ahmed 2006; Islam and Uddin 2015; Islam et al. 2015).

Materials and methods

Field sampling and water analysis

A total 20 groundwater samples were collected from different locations of the study area (Fig. 1) from shallow tubewells. Most of the sampled wells were fitted with a standard Bangladesh number-6 hand pump. Prior to sampling each well were pumped for few minutes until it purged out approximately twice the well volume, or until steady state chemical conditions (pH, EC and temperature) were obtained. pH of the water samples were measured on spot by using pH meter (EcoScan Ion-6, Singapore); total dissolved solids (TDS) were measured by (HANNA HI8734, Romania) portable meter. Electric conductivity (EC) and salinity were measured by portable EC meter (HANNA HI8033, Romania). Temperature was also measured simultaneously by using the same TDS meter. The geographical location of each wells were determined with a GARMIN handheld global positioning system (GPS) and the approximate depth of wells were noted from the well owner's records. Samples for major ion (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, NO_3^- and HCO_3^-) analysis were collected in 500 mL polyethylene bottles. Each bottle was rinsed with distilled water before pouring the sample water. The bottles were labeled and air-tight. Two sets of samples were collected from each location and filtered through 0.45 µm cellulose nitrate hydrophilic syringe filters. Among them one was acidified using concentrated HNO_3 to reach a pH <2 for preventing absorption and chemical

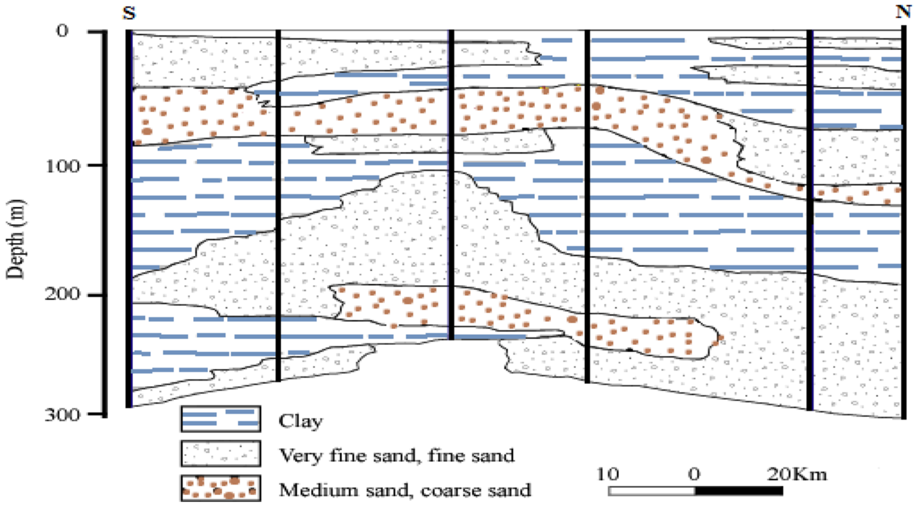

Fig. 2 N–S hydrogeological cross section of the study area. Cross-sectional lines N–S is shown in Fig. 1 (DPHE 2006)

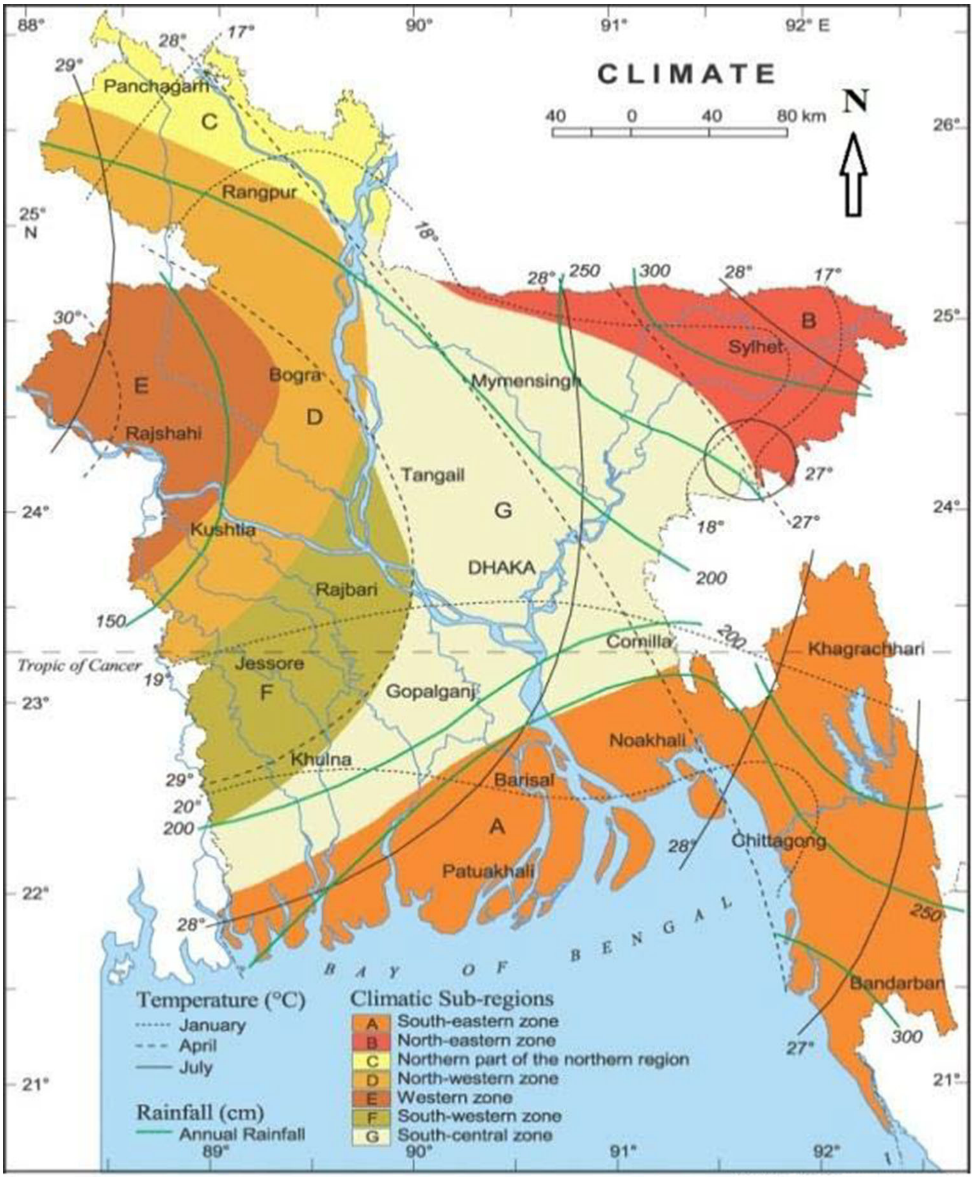

Fig. 3 Map showing the climatic zones of Bangladesh (Rashid 1991)

precipitation. For ion analysis Gallenkamp Flame Analyzer was used for Na^+ and K^+ and, ICS-5000 DIONEX SP, ion chromatography (IC) for Ca^{2+}, Mg^{2+}, Cl^-, $SO_4{}^{2-}$, and $NO_3{}^-$ analysis. Samples were diluted several times and the relative standard deviation of measured major ions was found to be within ±3%. Alkalinity ($HCO_3{}^-$) was measured by titration method with Digital Titrator (16900, HACH International, Colorado, USA) and 1.6 N H_2SO_4 cartridge.

Methods for hydrogeochemical and water quality evaluation

To assess water quality and geochemical processes the following parameters were calculated:

The total hardness (TH) in ppm (Todd 1980; Ragunath 1987; Hem 1991) was determined by following equation:

$$\mathrm{TH} = 2.497\ \mathrm{Ca}^{2+} + 4.115\ \mathrm{Mg}^{2+}. \tag{1}$$

Soluble sodium percentage (SSP) or Na % was used to evaluate the sodium hazard. Todd (1980) defined soluble sodium percentage (SSP) or Na % as:

$$\mathrm{SSP\ or\ Na\ \%} = \frac{(\mathrm{Na}^+ + \mathrm{K}^+) \times 100}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^+ + \mathrm{K}^+)}. \tag{2}$$

To evaluate the water quality for irrigation purpose, the sodium or alkali hazard expressed by sodium adsorption ratio (SAR) is widely used (Bhuiyan et al. 2015; Islam et al. 2016a, b). If water sample is high in Na^+ and low in Ca^{2+}, the ion exchange complex may become saturated with Na^+ which destroys the soil structure (Todd 1980). The SAR value of irrigation water quantifies the relative proportion of Na^+ to Ca^{2+} and Mg^{2+} (Alrajhi et al. 2015), and is computed as:

$$SAR = \frac{Na^+}{\sqrt{Ca^{2+} + Mg^{2+}/2}}, \tag{3}$$

where, Na^+, Ca^{2+} and Mg^{2+} are defined as the concentrations of Na, Ca and Mg ions in water, respectively (Ayers and Westcot 1985).

The residual sodium carbonate (RSC) is computed taking the alkaline earths and weak acids as follows (Ragunath 1987; Rao et al. 2012);

$$RSC \;=\; \left(CO_3{}^{2-} + HCO_3^-\right) - \left(Ca^{2+} + Mg^{2+}\right). \tag{4}$$

Magnesium adsorption ratio (MAR) (Ragunath 1987), also known as magnesium hazard (MH) was calculated as:

$$MAR = \frac{(Mg^{2+} \times 100)}{(Ca^{2+} + Mg^{2+})}. \tag{5}$$

Lastly, Kelley's ratio (KR) (Kelley 1963) described as:

$$KR = \frac{Na^+}{(Ca^{2+} + Mg^{2+})}. \tag{6}$$

All ionic concentrations are in milli equivalent per liter (meq/L). All these parameters and individual chemical parameters had been compared with national and international standards to assess the groundwater suitability.

Moreover, to identify the water types using major ion compositions AquaChem (version 3.7) software was used. SPSS (version 16.00) was used to statistical correlation among anion and cation of the groundwater samples and the spatial analysis were carried out using Arc. GIS (version 10.1) software.

Results and discussion

General hydrochemistry

The results of various hydrochemical parameters of groundwater samples are presented in Table 1. The depths of the sampled wells varied from 21 to 54 m. The pH of water is slightly alkaline ranging from 6.5 to 7.9 with a mean value of 7.2. The pH indicates the strength of the water to react with the acidic or alkaline material presents in water, which controls by the CO_2, $CO_3{}^{2-}$ and $HCO_3{}^-$ concentrations (Hem 1991). The mean temperature of groundwater samples was 26.7 °C ranging from 26 to 27.3 °C. Electrical conductivity (EC) of groundwater depends upon temperature, ionic concentration and types of ions present in the water. The maximum permissible limit of EC in groundwater is 1500 µS/cm (WHO 2011) where electrical conductivity (EC) of study area ranging from 498 to 5910 µS/cm with a mean value of 3018.65 µS/cm. The total dissolved solids (TDS) values range from 237 to 3112 mg/L with a mean of 1556.05 mg/L. Fetter (2001) stated that TDS values of groundwater within the range of 1000–10,000 mg/L are considered as brackish water and most of the groundwater samples in study area are falls on this group.

Concentrations of Na^+ show extremely wide range from 13.18 to 1212.61 mg/L with a mean of 647.20 mg/L, which constitute 77% of total cations (Fig. 4a). Ca^{2+} is the second dominant cation in groundwater constituting 18% with mean value 101.5 mg/L. The average Mg^{2+} concentration in groundwater is 78.28 mg/L constitutes 9% of total cation. Meanwhile, K^+ constitutes the least concentrations in all observed ground waters and forms 2% with a mean of 17.05 mg/L. The trend of major cationic concentrations of groundwater samples are $Na^+ > Ca^{2+} > Mg^{2+} > K^+$.

The groundwater is of Cl^- dominant range from 32.07 to 6270.8 mg/L. The mean chloride concentration is 1776.74 mg/L constitute 77% of total anionic compositions of collected groundwater samples in study area (Fig. 4b), where WHO limit for chloride in groundwater is <250 mg/L (WHO 2004). Surprisingly, 19 out of 20 samples were exceeds the WHO limit of chloride concentrations. Followed by, $HCO_3{}^-$ concentrations range from 261 to 808 mg/L with mean value of 510.05 mg/L that makes up 22% of total anions and remaining $SO_4{}^{2-}$ (mean 4.97 mg/L) and $NO_3{}^-$ (mean 2.61 mg/L) concentrations are very low as compared to other parameters (Fig. 4b). The anionic trend of groundwater is $Cl^- > HCO_3{}^- > SO_4{}^{2-} > NO_3{}^-$.

The results of the water quality from the study area are compared with previous study in others coastal areas of Bangladesh and standard permissible limit in Table 2. It was found that, all the parameters of water are much higher than others study in coastal areas of Bangladesh and also deep aquifer water. This indicates that, shallow aquifer of the coastal area is more vulnerable. It was also found that, most of the water quality parameters exceed the standard permissible limit for drinking and irrigational use (Table 2).

From the Pearson correlation matrix of hydrochemical parameters in groundwater (Table 3), it has been seen that EC and TDS are negatively correlated with pH but strongly correlated with Na^+ and Cl^-. EC and TDS are closely related with each other. Na^+ shows positive correlation with all variables but, strongly correlated with Cl^-, Ca^{2+} and Mg^{2+}. K^+ and Mg^{2+} are correlated with each other but show negative correlation with $NO_3{}^-$. Both have strong correlation with Ca^{2+} and Cl^-. Except pH, Ca^{2+} showed positive correlation with each variable but strongly related with Cl^-. Cl^- has strong correlation with EC, TDS, Na^+

Table 1 Physicochemical and calculated parameters of the groundwater samples from study area

Sample ID	Depth (m)	Temp (°C)	EC (µS/cm)	TDS (mg/L)	pH	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_3^- (mg/L)	HCO_3^- (mg/L)	TH	SSP	RSC	SAR	MAR	KR	Water type
K-1	24	27	4210	2262	6.5	1052.5	10.3	120.74	222.36	3728	6.23	8.2	520	1052.08	68.65	−12.51	14.11	47.23	7.71	Na–Cl–HCO_3
K-2	37	27	489	237	6.8	13.18	2.5	20.37	77.35	32.07	nd	nd	261	276.97	10.32	−1.26	0.35	30.27	0.26	Ca–Mg–Cl
K-3	21	26.1	2280	1120	7	515.42	8.78	38.74	35.32	610.7	4.21	nd	808	247.61	82.06	8.29	14.25	64.39	5.37	Na–Cl–HCO_3
K-4	52	27	3140	1602	7.9	699.01	11.32	55.16	150.78	1629.8	16.21	14.2	751	603.49	71.78	0.25	12.38	37.62	5.88	Na–Cl–HCO_3
K-5	30	26.3	4100	1830	6.9	780.92	25.31	134.69	154.75	2876.9	4.12	8.2	613	940.66	64.79	−8.76	11.07	58.92	6.66	Na–Cl
K-6	34	26.6	3400	1752	7.7	692.96	9.45	52.03	104.14	1545.9	9.3	9.2	752	474.14	76.22	2.85	13.85	45.16	7.09	Na–Cl–HCO_3
K-7	50	26	2160	1086	7.8	701.10	66.67	194.92	142	1798	14.28	nd	658	1156.67	58.20	−12.34	8.97	69.35	3.39	Na–Mg–Cl
K-8	37	26.8	2612	1228	7.6	513.02	6.81	25.21	52.1	872.31	2.4	4	564	233.84	82.79	4.57	14.59	44.37	8.11	Na–Cl–HCO_3
K-9	27	26.6	2210	1098	7.1	501.10	8.71	31.2	35.6	617	nd	nd	387	217.28	83.53	2.00	14.78	59.09	6.18	Na–Cl–HCO_3
K-10	48	27	2680	1828	7.6	534.46	6.33	31.55	30.31	1236	8.9	4.2	354	205.52	85.06	1.69	16.22	63.17	13.08	Na–Cl
K-11	27	26.8	2187	1122	7.1	494.31	14.32	35.68	47.65	748.36	2.25	4.1	342	265.81	80.45	0.30	13.18	55.23	5.29	Na–Cl–HCO_3
K-12	37	27	2295	1222	7.3	502.01	7.9	45.62	28.31	987.35	8.2	nd	456	258.42	81.01	2.30	13.59	72.65	7.40	Na–Cl–HCO_3
K-13	37	26.7	5910	3112	6.4	1212.61	68.39	296.92	285.7	6270.8	nd	nd	432	1935.22	58.48	−31.59	11.98	63.13	7.04	Na–Cl
K-14	21	26.7	2300	1164	7.6	396.31	11.32	57.84	80.85	1125.8	nd	nd	333	439.89	66.58	−3.34	8.22	54.10	5.57	Na–Cl
K-15	28	26.8	2511	1112	7.1	531.30	6.87	26.31	42.6	787.62	nd	nd	390	214.64	84.44	2.10	15.78	50.44	7.98	Na–Cl–HCO_3
K-16	21	26.2	2182	1021	7	526.10	8.78	36.74	29.32	617.37	4.21	nd	308	224.39	83.75	0.56	15.28	67.38	5.98	Na–Cl–HCO_3
K-17	54	27.3	5250	2760	7.6	922.17	14.06	95.83	131.35	3417.7	19	nd	372	722.33	73.70	−8.34	14.92	54.59	10.29	Na–Cl
K-18	30	26.6	3842	1966	6.8	980.0	24.61	124.59	147.32	2876	nd	nd	602	880.55	71.07	−7.73	14.36	58.23	7.11	Na–Cl
K-19	34	26.7	3456	1482	7	676.3	17.31	87.24	89.38	2145.3	nd	nd	547	582.18	71.90	−2.67	12.19	61.67	9.83	Na–Cl
K-20	52	27	3159	1617	7.2	699.12	11.34	54.16	142.78	1611.98	nd	nd	751	579.39	72.60	0.73	12.63	38.47	6.06	Na–Cl–HCO_3
Max.	54	27.3	5910	3112	7.9	1212.61	68.39	296.92	285.7	6270.8	19	14.2	808	1935.22	85.06	8.29	15.78	72.65	10.29	–
Min.	21	26	498	237	6.5	13.18	2.5	20.37	28.31	32.07	2.4	4	261	224.39	10.32	−12.51	0.35	30.27	0.26	–
Mean	35.05	26.71	3018.65	1556.05	7.2	647.20	17.05	78.28	101.5	1776.74	4.97	2.61	510.05	575.58	71.37	−62.93	12.64	54.78	6.82	–

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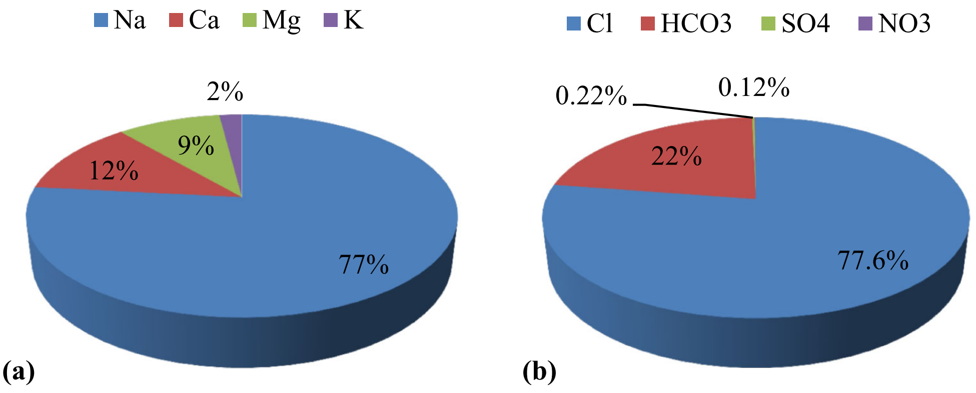


(a) (b)

Fig. 4 **a** Major cation and **b** anion proportion in groundwater samples

and Mg^{2+} and SO_4^{2-} has strong correlation with groundwater pH, which indicates that they originate from the same source or origin.

Hydrogeochemical classification of groundwater

Hydrochemical facies and water type

The values obtained from the groundwater samples were plotted by using Piper (1953) trilinear diagram (Fig. 5) to recognize the hydrochemical facies which are able to provide clues how groundwater quality changes within and between aquifers (Sivasubramanian et al. 2013). This diagram is also used to classify the water types (Wen et al. 2005), which are generally distinct zones that cation and anion concentrations are described within the defined composition categories. From the samples plotting on the Piper (1953), trilinear diagram (Fig. 5) reveals that four types; Na–Cl (35%), Na–Cl–HCO_3 (55%), Na–Mg–Cl (5%) and Ca–Mg–Cl (5%) and Na–Cl–HCO_3 are the predominant facies type (Table 4). It indicates the dominance of Na^+ in the cations and interplays of HCO_3^- and Cl^- in anions and also influence of marine water in the study area.

TDS, EC and Cl_2 content in relation groundwater salinity

Salinity is the dissolved salt content of a body of water. It used to describe the levels of different salts such as sodium chloride, magnesium and calcium sulfates and bicarbonates. The amount of chlorine is directly proportional to salinity, which originates from the dissociation of salts, such as sodium chloride or calcium chloride, in water.

$$NaCl \rightarrow Na^+(aq) + Cl^-(aq), \tag{7}$$

$$CaCl_2 \rightarrow Ca_2^+(aq) + 2Cl^-(aq). \tag{8}$$

These salts and their resulting chloride ions originate from natural minerals and mixing of seawater with fresh water (Stuyfzand 1999). Although there are some small quantities of others ions (K^+, Mg^+, SO_4^{2-}, NO_3^-); Na^+ and Cl^- present about 91% of all seawater ions. Meanwhile, Sodium and total dissolved solids (TDS) are other important parameters that can be used to observe the influence of major components and groundwater salinity. The groundwater concentrations of Na^+ and Cl^- were plotted against TDS. The plot showed that most Na^+ and Cl^- ions of the groundwater were positively correlated ($r^2 = 0.75$ and 0.76, respectively) with TDS (Fig. 6a, b). According to WHO (2004) classification of groundwater based on TDS, 60% sample falls in unacceptable, 35% poor and only 5% falls in excellent category and the spatial distribution of TDS is shown in Fig. 7. All others component i.e., Na^+, Ca^{2+}, Mg^{2+} and K^+ also well correlated with Cl^- with r^2 values 0.82, 0.79, 0.78 and 0.58 respectively (Fig. 6c–f) denotes they are originated from same sources.

According to Chloride classification by Stuyfzand (1989) 60% groundwater sample falls in brackish-salt, 35% brackish and remaining 5% falls in fresh category (Table 4). Spatial distribution of chloride concentration in groundwater shows that, the eastern and southern site of study area considered as higher saline prone area compared to northwestern site (Fig. 8). EC is other important parameters that are related with groundwater salinity. In order to diagnosis and classification, the total concentration of soluble salts (salinity hazard) in water can be expressed in terms of specific conductance (Ravikumar et al. 2011). According to WHO (2004) salinity hazard based on EC value has been classified as four groups; low salinity hazard, medium salinity hazard, high salinity hazard and very high salinity hazard. This reveals that, 5% medium, 15% high, 70% very high and remaining 10% are extremely high salinity hazard. Wilcox (1955) was also drawn classification of EC as excellent, good, permissible, doubtful and poor categories. Studies show that, 5% falls in excellent, 15% good, 70% doubtful and remaining 10% poor category. The spatial distribution of groundwater shows high EC values in eastern and southern part of the study area ranges from 2300 to 5910 µS/cm along the bank of

Table 2 Comparing the groundwater quality with others study in coastal areas of Bangladesh and standard permissible limit

Parameters	This study	Compare with others coastal areas								Compare with standard permissible limit			
		Khulna (Shammi et al. 2016a)	Gupalganj (Shammi et al.2016b)	Satkhira (Rahman et al.2011)	Bagerhat (IWM 2009)	Patuakhali (Islam et al. 2016b)	Barguna (Islam et al. 2016a)	Noakhali (Ahmed et al. 2011)	Lakshimpur (Bhuiyan et al. 2016)	FAO (1985)	UCCC (1974)	BWPCB (1976)	WHO (2011)
Aquifer depth	Shallow	Deep	Deep	Deep	Deep	Deep	Shallow	Shallow	Deep	–	–	–	–
pH	7.20	7.82	7.57	7.61	7.92	7.89	7.42	7.59	7.04	6.0–8.5	6.5–8.4	6.5–8.2	6.5–8.5
EC (µS/cm)	3018.65	1285.71	620.87	1617.75	1120.34	1165.67	8973	1940.81	1135.08	3000	700–300	–	1500
TDS (mg/L)	1556.05	–	397.36	861.34	575.00	842.00	4829	1218.11	–	2000	450–2000	1500	500
Na^+ (mg/L)	647.20	512.12	180.77	221.96	437.5	78.99	863	–	159.78	900	68–204	–	200
K^+ (mg/L)	17.05	11.34	3.47	13.40	6.15	3.80	16.16	–	10.89	2	–	–	12
Mg^{2+} (mg/L)	78.28	65.41	22.81	14.13	18.19	9.34	155	–	46.14	60	–	–	50
Ca^{2+} (mg/L)	101.5	49.74	53.08	62.80	16.77	12.47	136	–	55.76	400	–	–	75
Cl^- (mg/L)	1776.74	874.36	96.52	409.60	167.67	298.13	3513	875.61	227.20	1100	133	600	250
SO_4^{2-} (mg/L)	4.97	5.43	39.35	11.79	6.43	12.50	19.48	4.39	16.14	1000	–	400	250
NO_3^- (mg/L)	2.61	2.34	–	12.05	5.87	11.57	4.12	3.91	–	10	5	45	45
HCO_3^- (mg/L)	510.05	–	–	224.32	270.44	391.02	254	305.12	430.18	600	91	–	500

Rupsha river like; Boitaghata and Rupsha upazila (Fig. 9) possibly due to the infiltration and saline water intrusion from the river.

Total hardness (TH)

Hardness is an important criterion for determining the suitability of groundwater for domestic, agricultural and industrial uses (Vandenbohede et al. 2010). Hardness of water is related to its reaction with soap and to the scale of incrustation accumulating in containers or conducts where water is heated or transported. Since soap is precipitated by Ca^{2+} and Mg^{2+} ion. It is defined as the sum of concentration of their ion expressed an mg/L of $CaCO_3$. The classification of the groundwater of the study area based on hardness (Sawyer and McCarthy 1967) has been carried out and is presented in Table 4. Accordingly, 9 samples (45%) fall under the hard and 11 samples (55%) fall in very hard category.

Soluble sodium percentage (SSP) or Na%

Sodium is an important cation, which in excess deteriorates the soil structure and reduces crop yield (Srinivasamoorthy et al. 2005). The ratio of sodium and potassium in the sum of cation is the important factor in considering water for agriculture uses. The sodium concentration of irrigation water is of prime importance and plays a significant role in determining the permeability of soil. Na^+ absorbed on clay surface, as a substitute for Ca^{2+} and Mg^{2+} may damage the soil structure making it compact and impervious (Singh et al. 2008). Percentage of Na^+ content is a parameter to assess its suitability for agriculture purpose (Wilcox 1948) as, sodium combining with CO_3^{2-} can add to the formation of alkaline soils and sodium combining with Cl^- form saline soils. Both these soils do not helping growth of plants. According to Wilcox (1955) maximum 15% of Na^+ in groundwater is allowed for agriculture purpose, 45% samples fall in doubtful region and remaining 40% is unsuitable category (Table 4). Eaton (1950) classification also results same assumption. The plot of Na % against EC Wilcox (1955) diagram shows the suitability of groundwater samples are shown in Fig. 10.

Sodium absorption ratio (SAR)

Sodium absorption ratio (SAR) is an estimate of the extent to which sodium ion present in the water would be absorbed by the soil. The higher the SAR value, the greater the risk of sodium hazard on plant growth. Irrigation, using water with high SAR values may require soil amendments to prevent long-term damage to the soil; because the sodium in the water can displace the calcium and magnesium in the soil. This will cause a decrease in the ability of

Table 3 Pearson correlation matrix of the hydrochemical parameters of groundwater samples

Variables	EC	TDS	pH	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^-
EC	1										
TDS	0.973^{b}	1									
pH	−0.238	−0.189	1								
Na^+	0.927^{b}	0.909^{b}	−0.274	1							
K^+	0.438	0.416	−0.146	0.556^{a}	1						
Mg^{2+}	0.684^{b}	0.659^{b}	−0.344	0.756^{b}	0.922^{b}	1					
Ca^{2+}	0.747^{b}	0.727^{b}	−0.352	0.792^{b}	0.643^{b}	0.840^{b}	1				
Cl^-	0.921^{b}	0.909^{b}	−0.405	0.903^{b}	0.650^{b}	0.878^{b}	0.894^{b}	1			
SO_4^{2-}	0.211	0.279	0.625^{b}	0.217	0.102	0.081	0.111	0.110	1		
NO_3^-	0.179	0.188	0.271	0.188	−0.163	−0.062	0.255	0.092	0.418	1	
HCO_3^-	0.199	0.143	0.223	0.323	0.150	0.138	0.269	0.104	0.231	0.400	1

[a] Correlation is significant at the 0.05 level

[b] Correlation is significant at the 0.01 level

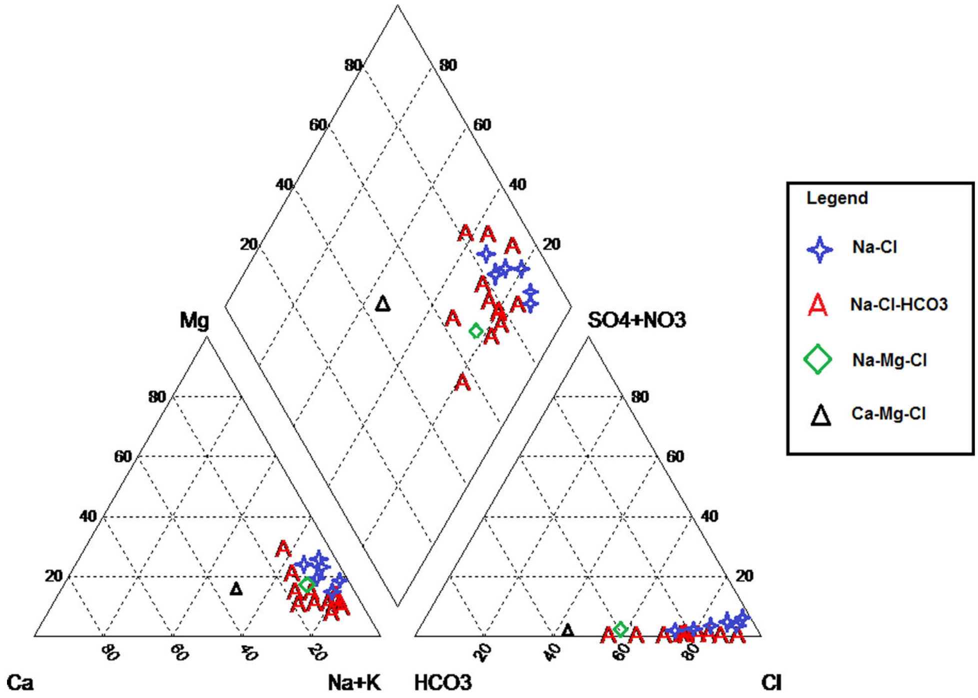


Fig. 5 Piper (1953) diagram for the groundwater samples of the study area

the soil to form stable aggregates and loss of soil structure. This will also lead to a decrease in infiltration and permeability of the soil to water, leading to problems with crop production (Chandrasekar et al. 2013). SAR values ranged from 0.35 to 15.78 in study area (Table 1). Values greater than 2.0 indicate groundwater is unsuitable for irrigation purposes (Vasanthavigar et al. 2010; Ayuba et al. 2013; Islam et al. 2016b). Study shows that, except one sample all the sample falls in unsuitable category (Table 4). Salinity and SAR determines the utility of groundwater. Salinity originates in groundwater due to weathering of rocks and leaching from top soil, anthropogenic sources along with minor influence on climate (Prasanna et al. 2011). The level of Na^+ and HCO_3^- in irrigation groundwater affects permeability of soil and drainage of the area (Tijani 1994). US salinity laboratory's (USSL) diagram proposed by Richards (1954) is used to investigate the sampled groundwater, which shows that, maximum samples fall on medium to very high salinity hazard (Fig. 11). The distribution of SAR values in the study area is shown in Fig. 12. It is observed that samples of low SAR are mainly located in the north-eastern part of the area, while high SAR dominated the southern and western part of study area.

Table 4 Hydrogeochemical classification of groundwater in the study area

Category	Grade	$N = 20$	%	Category	Grade	$N = 20$	%
Na % (Wilcox 1955)				R.S.C. (Richards 1954)			
Excellent	0–20	1	5	Good	<1.25	13	65
Good	20–40	0	0	Medium	1.25–2.5	4	20
Permissible	40–60	2	10	Bad	>2.5	3	15
Doubtful	60–80	9	45				
Unsuitable	>80	8	40				
Na % Eaton (1950)				MAR (Kacmaz and Nakoman 2010)			
Safe	<60	3	15	Suitable	<50	6	30
Unsafe	>60	17	85	Unsuitable	>50	14	70
S.A.R. (Vasanthavigar et al. 2010)				KR (Kelley 1963)			
Suitable	<2	1	5	Suitable	<1	1	5
Unsuitable	>2	19	95	Unsuitable	>1	19	95
TDS (mg/L) (WHO 2004)				Hydrochemical facies			
Excellent	<300	1	5	Ca–Mg–Cl facies		1	5
Good	300–600	0	0	Na–Mg–Cl facies		1	5
Fair	600–900	0	0	Na–Cl–HCO_3 facies		11	55
Poor	900–1200	7	35	Na–Cl facies		7	35
Unacceptable	>1200	12	60				
EC (μS/cm) (Wilcox 1955)				Chloride (Stuyfzand 1989)			
Excellent	<250	0	0	Extremely fresh	<0.14	0	0
Good	250–750	1	5	Very fresh	0.14–0.84	0	0
Permissible	750–2250	3	15	Fresh	0.84–4.23	1	5
Doubtful	2250–5000	14	70	Fresh-brackish	4.23–8.46	0	0
Unsuitable	>5000	2	10	Brackish	8.46–28.21	7	35
				Brackish-salt	28.21–282.1	12	60
				Salt	282.1–564.3	0	0
				Hyperhaline	>564.3	0	0
EC (μS/cm) (WHO 2004)				Total hardness (mg/L) (Sawyer and McCarthy 1967)			
Low salinity	0–250	0	0	Soft	<75	0	0
Medium salinity	251–750	1	5	Moderately hard	75–150	0	0
High salinity	751–2250	3	15	Hard	150–300	9	45
Very high salinity	2251–6000	14	70	Very hard	>300	11	55
Extensively high salinity	6001–10,000	2	10				
Brine	>10,000	0	0				

Residual sodium carbonate (RSC)

A relation of alkaline earths with weak acids is expressed in terms of RSC for assessing the quality of water for irrigation (Richards 1954). When the weak acids are greater than the alkaline earths, a precipitation of alkaline earths occurs in soils, which damages the permeability of soil (Rao et al. 2012). The water having excess of carbonate and bicarbonate cover the alkaline earth mainly Ca^{2+} and Mg^{2+} in excess of allowable limits affects agriculture unfavorably (Richards 1954). The variation of RSC was drawn using (Richards 1954) as good, medium and bad categories. Study shows that, 65% groundwater samples of the study area fall in good category, 20% medium and remaining 15% falls in bad category (Table 4). Spatial analysis showed that there is no significant variation of RSC distribution in studied samples. The lowest value of RSC was found in the northeastern part of the study area (Fig. 13).

Magnesium adsorption ratio (MAR)

Magnesium adsorption ratio (MAR) defines the relationship between magnesium and calcium concentration in groundwater (Ragunath 1987; Ayuba et al. 2013). The excess Mg^{2+} affects the quality of soil resulting in poor

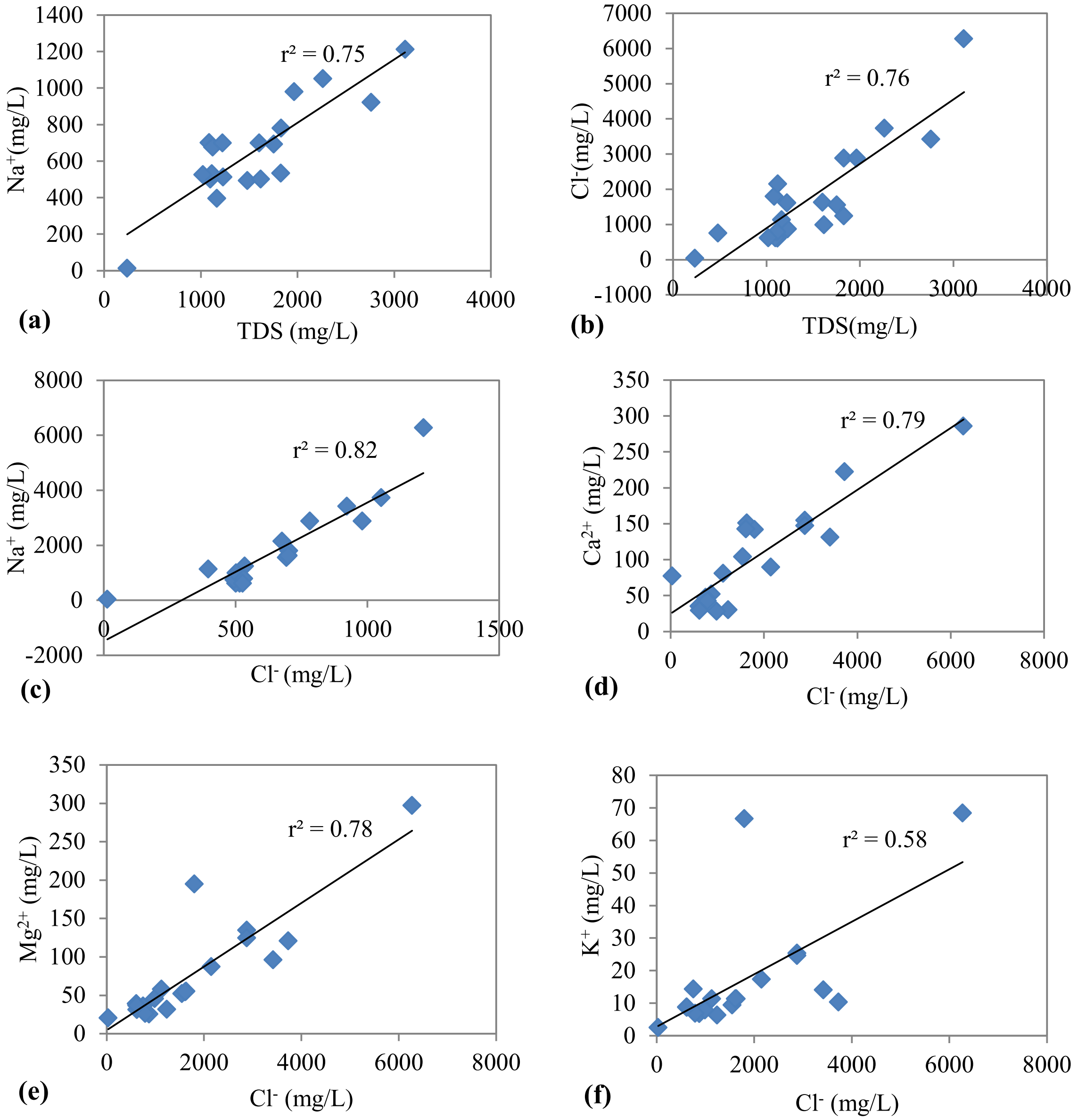


Fig. 6 Bivarate plots of **a** Na^+ versus TDS, **b** Cl^- versus TDS, **c** Na^+ versus Cl^-, **d** Ca^{2+} versus Cl^-, **e** Mg^{2+} versus Cl^-, **f** K^+ versus Cl^-

agricultural returns (Islam et al. 2016a, b). Soil containing high levels of exchangeable Mg^{2+} causes infiltration problem (Ayers and Westcot 1985). MAR greater than 50 is considered harmful and unsuitable for irrigation purposes (Kacmaz and Nakoman 2010; Islam et al. 2016b). About 70% of the studied water falls in this category and remaining 30% falls in suitable category in case of magnesium hazard (Table 4).

Kelley's ratio (KR)

The level of Na^+ measured against Ca^{2+} and Mg^{2+} is known as Kelley's Ratio, based on which irrigation water can be rated (Kelley 1963). Concentration of Na^+ in irrigation water is considered to be in excess, thereby making the water unsuitable, if Kelley's ratio is >1. Hence water with Kelley's ratio <1 is suitable for irrigation. Almost 95% water in the study area is unsuitable according to this category (Table 4). From the above investigation, it is evident that the groundwater of the study area is not suitable for drinking or irrigation purpose.

Hydrogeochemical process evaluation

A hydrogeochemical diagram proposed by Chadha (1999) has been applied in this study to identify the hydrochemical process. The same procedure was successfully applied by (Vandenbohede et al. 2010; Islam et al. 2016b) in coastal

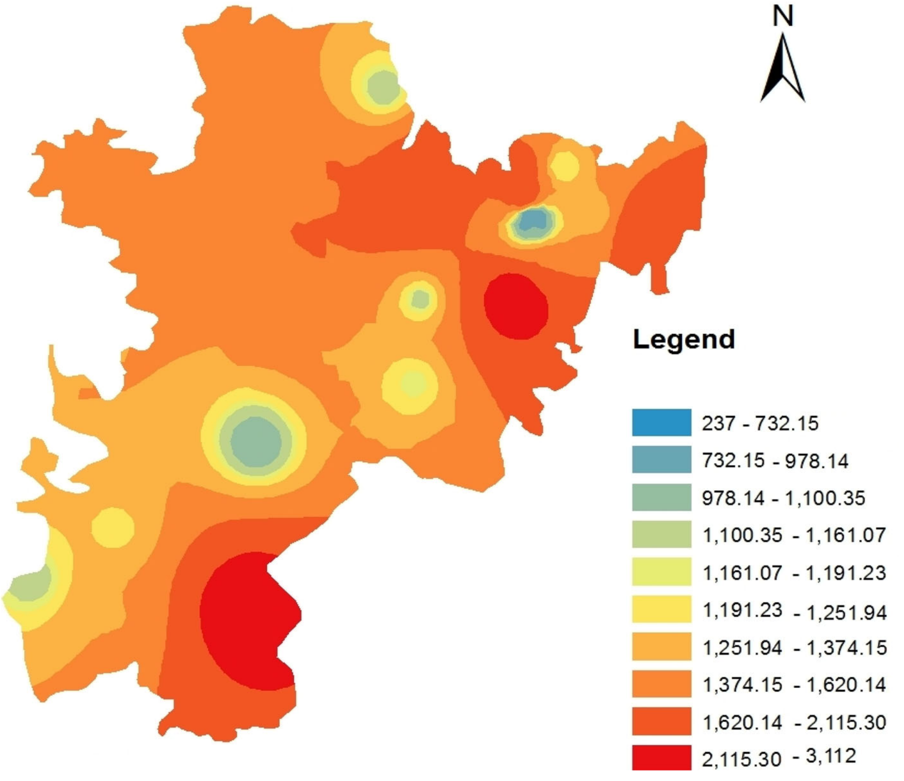


Fig. 7 Spatial distribution of TDS (mg/L) of groundwater in the study area

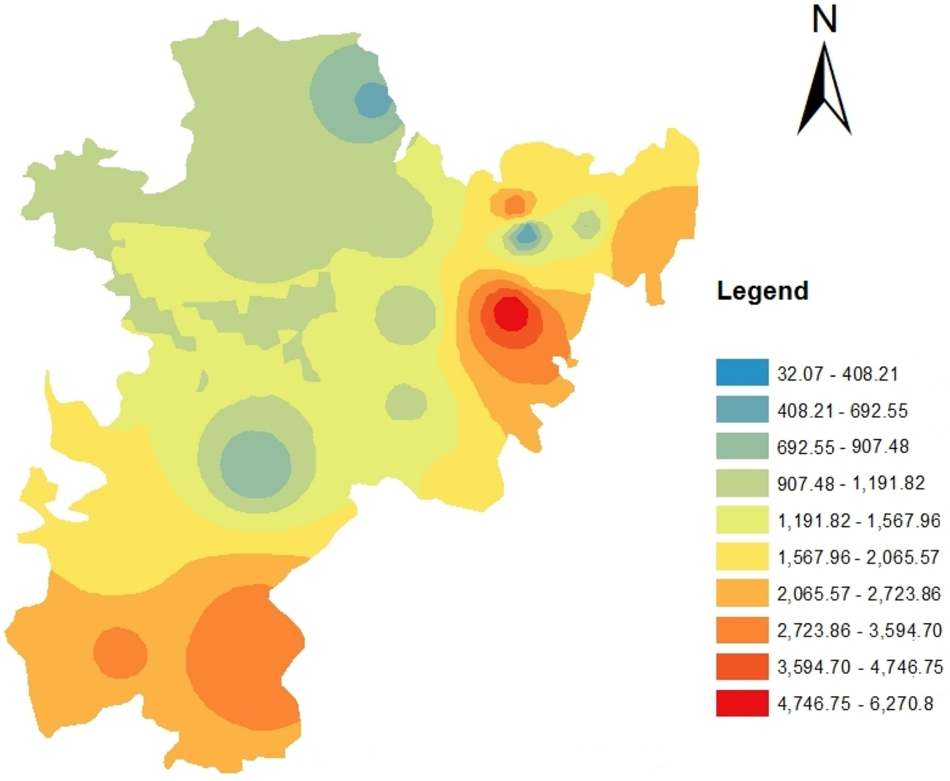
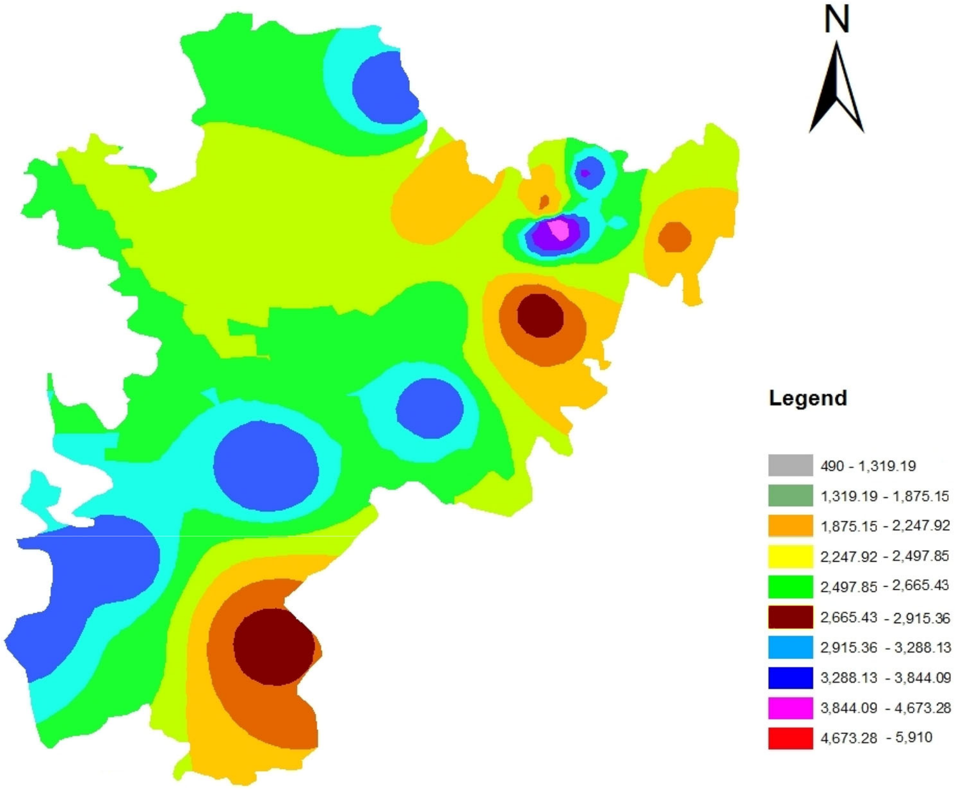


Fig. 8 Spatial distribution of Cl^- conc. (mg/L) of groundwater in the study area

aquifer to determine the evolution of different hydrogeochemical processes within a freshwater lens. For that, data was converted to percentage reaction values (milli equivalent percentages) and expressed as the difference between alkaline earths ($Ca^{2+} + Mg^{2+}$) and alkali metals ($Na^+ + K^+$) for cations, and the difference between weak

Fig. 9 Spatial distribution of EC (µS/cm) of groundwater in the study area



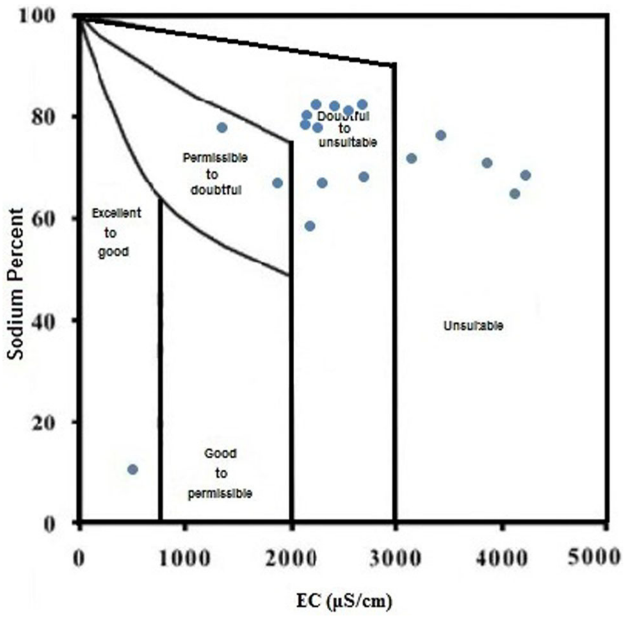


Fig. 10 Wilcox (1955) diagram for the study area

acidic anions ($HCO_3^- + CO_3^{2-}$) and strong acidic anions ($Cl^- + SO_4^2$). The hydrochemical processes suggested by Chadha (1999) are indicated in each of the four quadrants of graph. These are broadly summarized as:

Field 1 Ca-HCO_3 type recharging water.

Field 2 Ca–Mg–Cl type reverse ion exchange water.

Field 3 Na–Cl type end member waters (seawater).

Field 4 Na-HCO_3 type base ion exchange water.

The resultant diagram is exhibited in (Fig. 14). Field 1 (recharging water) when water enters into the ground from the surface it carries dissolved carbonate in the form of HCO_3^- and the geochemically mobile Ca^{2+}. Only one sample falls in this field are represented by low salinity waters. Field 2 (reverse ion exchange) it may represent groundwater where Ca^{2+}+ Mg^{2+} is in excess to Na^++ K^+ either due to the preferential release of Ca^{2+} and Mg^{2+} from mineral weathering of exposed bedrock, or possibly reverse base cation exchange reactions of Ca^{2+}+ Mg^{2+} into solution and subsequent adsorption of Na^+ onto mineral surfaces. But, there is no sample falls in this field. Most of the samples falls in Field 3 (Na–Cl) waters is typical of seawater mixing, and Field 4 (Na-HCO_3) waters represent base-exchange reactions, but surprisingly no sample falls in this field. From this it is clear that, the water quality of coastal area containing high Na^+ and Cl^- with typical seawater mixing in Field 3 and with no representation in Field 2 and Field 4 indicating the absence of ion exchange.

However, when seawater intrudes into fresh coastal aquifer, $CaCl_2$ or $MgCl_2$ type water may found (Appelo and Postma 1999). In this case, Na^+ of seawater is being replaced with either Ca^{2+} or Mg^{2+} of the clay minerals whereby, Na^+ is being adsorbed onto the clay mineral surface according to Eqs. (9) and (10) (Islam et al. 2016b).

Fig. 11 Sample water classification for irrigation according to US Salinity Laboratory's (USSL) diagram (Richards 1954)

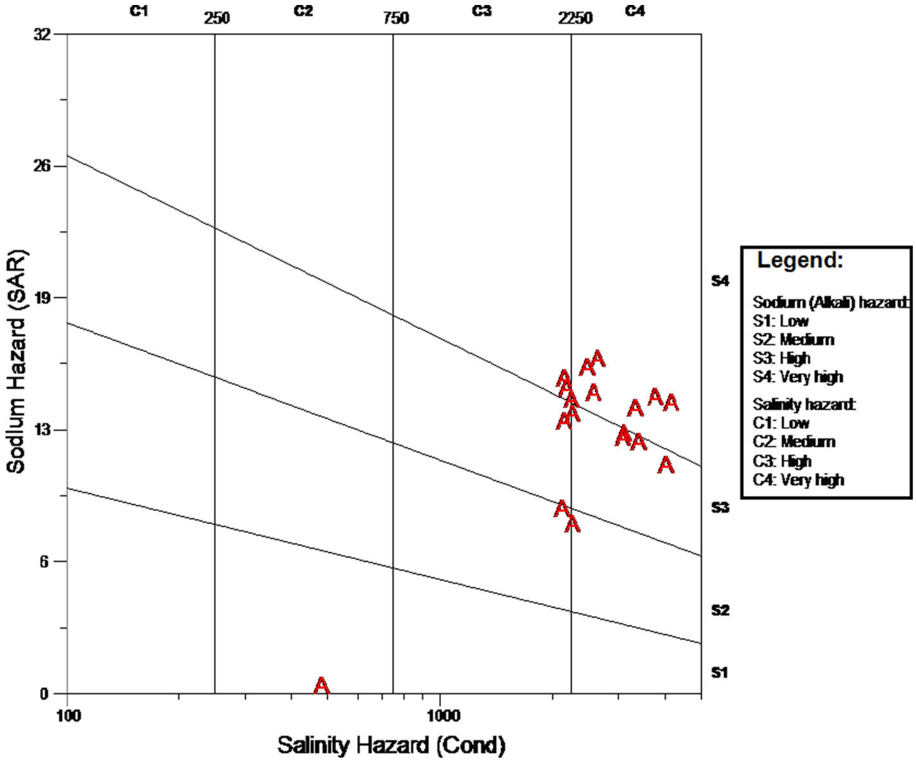


Fig. 12 Spatial distribution of SAR values in the study area

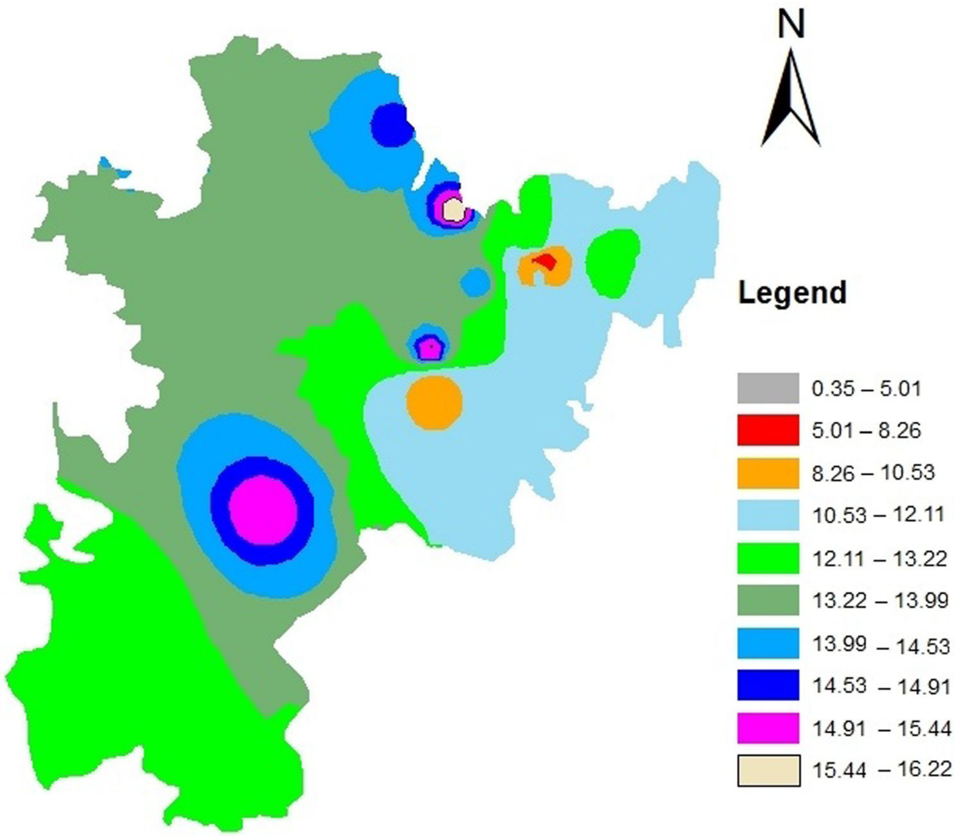
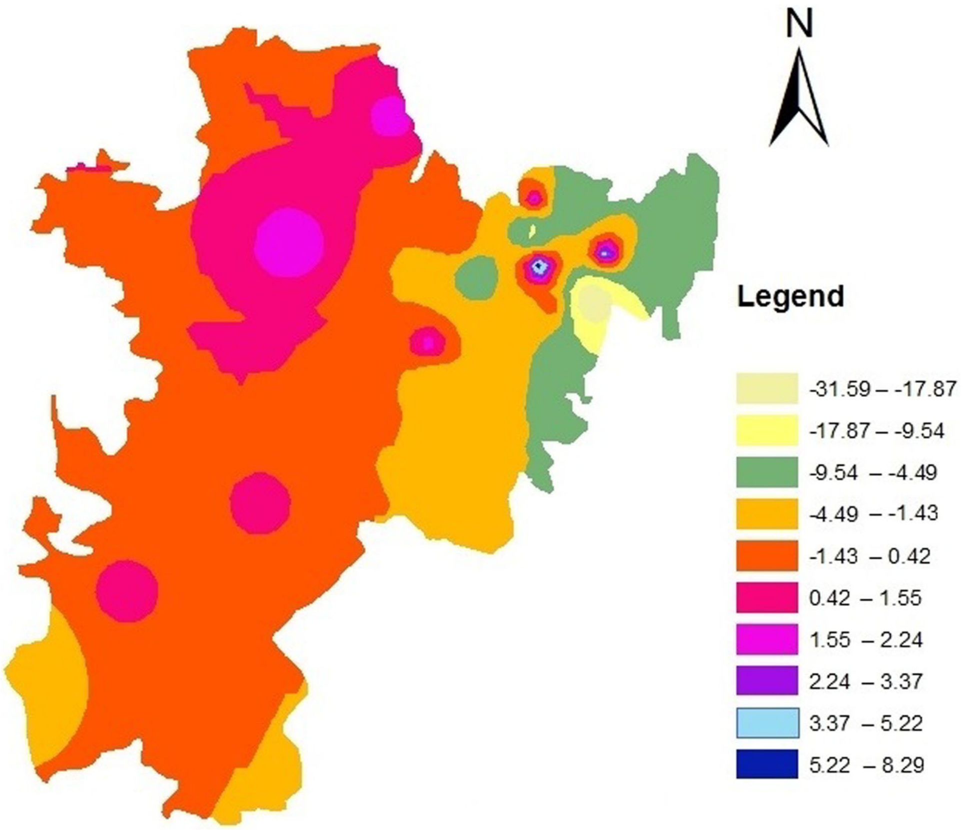


Fig. 13 Spatial distribution of RSC in the study area



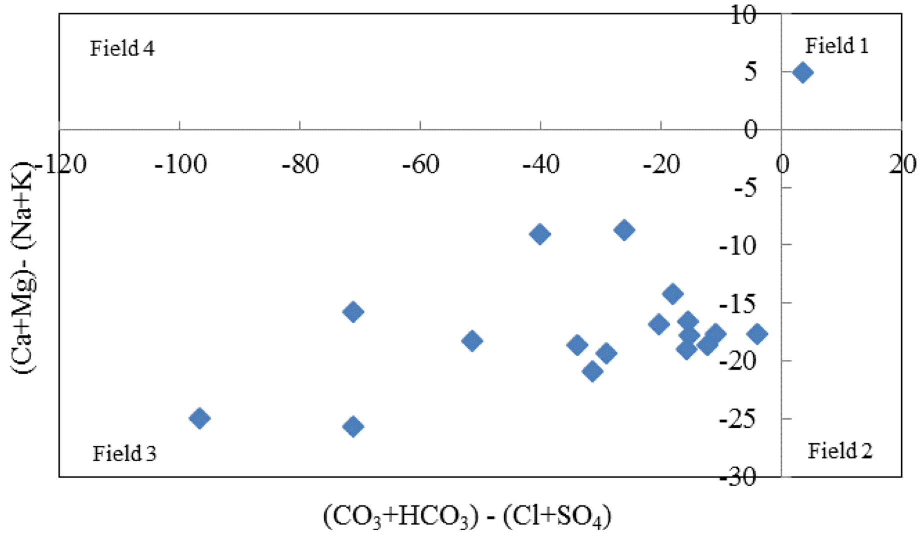
$$(Ca^{2+} + Mg^{2+}) + 4(HCO_3^-) + 2(NaX) = CaX_2 + Mg(HCO_3^-)_2 + 2NaHCO_3^-, \quad (9)$$

$$2Nacl + MgX_2 = 2NaX + MgCl_2, \quad (10)$$

where, X signifies the exchanger. So, seawater intrusion is not the fact of salinization in the study area. When seawater diluted with freshwater have create distinguished geochemical characteristics (Metcafe and Eddy 2000). Modification of the geochemical characteristics of these saline waters is caused by water–rock interaction in which three possible mechanisms may be involved: (1) base exchange reactions with clay minerals (Vengosh et al. 1994); (2) adsorption onto clay minerals and (3) carbonate dissolution-precipitation (Vengosh et al. 1994; Ghabayen et al. 2006).

Actually, the sea level in the Bengal Basin has been changed from the past (CEGIS 2006). During the holocene period, about 6 Ka is the peak period of the last highest sea level (DPHE 2006). The earliest Ganges delta development

Fig. 14 Chadda's plot of process evaluation



phase took place about 5–2.5 Ka (Allison et al. 2003). Majumder (2008) observed that the age of the deep groundwater fell along the seawater line ranged from nearly ~6 to 25 Ka. So it seems that, brackish water originated from the sea is trapped within the aquifer. The salinity of current study originates from this saline aquifer pocket with some recent intrusion. Similar observation was previously made by Sikdar et al. (2001), Rahman et al. (2011) and Islam et al. (2016a, b). Due to lack of isotopic investigation it is hurdle to delineate the actual origin of groundwater salinity in study area. But, it is clear that, shallow aquifer salinity enhances due to tidal surges and cyclone, water logging, upstream less water flow, backwater effect, shrimp culture and excess withdrawal (Islam 2014; Islam and Bhuiyan 2016).

Conclusion

The study reveals that the shallow groundwater aquifers of the study area are strongly affected by salinity. EC and TDS classification indicate majority of the samples grouped within “doubtful” to “unsuitable” with minor representation in permissible category. In SSP or Na % classification of groundwater for irrigation purposes, majority of the samples grouped in unsafe zone and minor representations also falls in safe zone. The plot of Na % against EC (Wilcox diagram) also shows that, maximum samples are doubtful to unsuitable for irrigation purpose. According to chloride classification majority of samples grouped in brackish and brackish-salt category, indicating the unsuitability of this water for agricultural activity. The ground water of this region shows chiefly in seawater characters, and few represent recharge. From spatial distribution of chloride, TDS, EC, SAR and RSC concentrations of collected groundwater, northwestern part is better than eastern and southern part of the study area which is nearer to the river channel and the coast.

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