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ORIGINAL PAPER

Evaluation of groundwater quality and its suitability by applying the geospatial and IWQI techniques for irrigation purposes in the southwestern coastal plain of Bangladesh

Mohammad Tofayal Ahmed[1] · Md Yeasir Hasan[1] · Minhaj Uddin Monir[1] · Biplob Kumar Biswas[2] · Chowdhury Quamruzzaman[3] · Md Junaid[4] · Md Abdus Samad[5] · Md Mominur Rahman[1]

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Abstract

The groundwater quality for irrigation and drinking purposes has become a great concern because of salinity intrusion in the coastal zone of Bangladesh. The aim of this study is to investigate an irrigation water quality index (IWQI) by using the model of geostatistics and multivariate indices in the southwestern coastal part of Bangladesh. The spatial distribution of major cation (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anion (HCO_3^{-}, SO_4^{2-}, Cl^{-}) maps have been made by the interpolation of GIS based on the WHO standard. Principal component analysis and cluster analysis diagram have been used to explain the hydrochemical procedure in the aquifer. The analytical results show that aquifer water of this coastal study area is primarily of high salinity (NaCl rich). The IWQI, geostatistical analysis, and multivariate statistics (analysis of regression model) have revealed the areas of the spatial distribution and indicated the suitable-unsuitable areas for irrigation. According to IWQI, the total study area has split into 34.15% (good areas), 23.84% (permissible areas), 17.07% (dubitable areas), and 24.94% (severe areas), respectively, and no excellent groundwater areas have been identified. There was a vast relation with (NaCl) or salinity and the other effective parameters or higher amount of EC and TDS which was represented by the regression and geostatistical analysis model. Finally, remediation measures have also been suggested for the prediction of unsuitable zone.

Keywords Groundwater quality · Salinity · Irrigation · IWQI · PCA · Geostatistics

Nomenclature

ASN	Asia Arsenic Network
AAS	Atomic absorption spectrophotometer
BADC	Bangladesh Agricultural Development Corporation
CA	Cluster analysis
EC	Electro conductivity
GIS	Global information system
GPS	Global pensioning system
GW	Ground water
HCA	Hierarchical cluster analysis
IWQI	Irrigation water quality index
KI	Kelly's index
KR	Kelly's ratio
ME	Mean error
MH	Magnesium hazard
MSE	Mean square error
OK	Ordinary kriging
PC1	Principle component 1
PC2	Principle component 2
PC3	Principle component 3
PCA	Principle component analysis
PI	Permeability index

Responsible Editor: Amjad Kallel

✉ Mohammad Tofayal Ahmed
tofayal74@yahoo.com

1 Department of Petroleum and Mining Engineering, Jashore University of Science and Technology, Jashore 7408, Bangladesh

2 Department of Chemical Engineering, Jashore University of Science and Technology, Jashore 7408, Bangladesh

3 Department of Geology, University of Dhaka, Dhaka 1000, Bangladesh

4 Department of mathematics, Jashore University of Science and Technology, Jashore 7408, Bangladesh

5 Lab of Bangladesh Agricultural Development Corporation (BADC), Jashore, Bangladesh

RME	Minimum mean error
RMSE	Root mean squared error
RMSSE	Root mean square standardized error
RSC	Residual sodium carbonate (RSC)
SAR	Sodium adsorption ratio (SAR)
SSP	Soluble sodium percentage
TDS	Total dissolved solid
TH	Total hardness
WHO	World Health Organization
APHA	American Public Health Association

Introduction

The quality of groundwater in the southern part of Bangladesh has been deteriorating by increasing disasters and rising sea level (Morshed et al. 2016). Groundwater (GW) has been considered the prime origin of freshwater for farming, manufacturing, and purposes of drinking (Tanjil et al. 2019). Bangladesh is the highest user of groundwater for irrigation in the Indian subcontinent (around 65%) reported by Kaur and Kaur (2016). The coastal areas of Bangladesh have covered around 3.22 million ha where 2.00 million ha is suitable for potential agricultural uses. However, by increasing salinity with sea level, the soil of groundwater is considered the main limiting factor. During several decades, the traditional practices of farming in the coastal zone of Bangladesh have been hampering. The increasing of salinity in groundwater has become responsible for this. Moreover, new areas of coastal regions have been affected by the problem of salinity which had increased higher in the few decades. These problems also have affected the production of crops in coastal areas (Ahmed et al. 2019a). Solangi et al. (2019) reported that surface water and groundwater of Indus delta were not suitable for drinking and agricultural purposes. The groundwater in the coastal areas has been mainly polluted by the continuous high tides of sea and intrusion of saline water from the sea through different rivers and canal (Biswas et al. 2017). Direct flooding with saline or brackish water in the wet season and upward or lateral movement of groundwater in the dry period has made the soils into salinity. As a result, the continuous process of leaching intrusions on wet saline soil water increases the salinity of groundwater (Ahmed et al. 2020b).

The coastal area of Bangladesh comprises approximately 32% of the total land of the country. Kabir et al. (2009) researched the south-central region of Bangladesh and reported on lithopathy and hydrogeological conditions but did not indicate the hydrochemical conditions of groundwater. Moreover, there have been insufficient research to assess whether or not the areas are ideal for groundwater irrigation. Previous research also stated on the salinity of irrigation in Sagardari, Jashore (Ahmed et al. 2019a; Ahmed et al. 2020c). All previous work has been conducted in the southwestern part, which is a long way from the coastal area. In addition, Shammi et al. (2016) stated that the coastal districts of Bangladesh were seriously impacted by salinity. However, no inquiries have been established in these coastal areas for irrigation purposes. It is also important to carry out an investigation here.

Although simulation techniques and conceptual models have been reported to be used in assessing groundwater for domestic and irrigation uses, the wide-spread application of the water quality index is still effective to understand the suitability of groundwater for irrigation purpose (Hussain and Abed 2019; Sharma et al. 2020). Irrigation water quality index (IWQI) and multivariate statistical are performed in a technique of rating that identified the combined dominance of particular irrigation quality by hydrochemical parameters on the whole quality of the utilization of groundwater (Ahmed et al. 2020a). Multivariate statistical (regression analysis and principal component analysis) (Bodrud-Doza et al. 2016) and cluster analysis techniques (Ghodbane et al. 2016) have considered an effective connection with the hydrochemical parameters. It is considered by means of managing, interpreting, and representing to the constituents and hydrochemistry. The characteristics of physical, chemical, biological, and radiological properties of groundwater have been encompassed by the water quality (Monir et al. 2011). The hydrochemical flow of groundwater systems has originated on the setting of geological correlation, the property of source rocks and aquifers, and the composition of groundwater recharge, soil formations, lithological facies, and duration of groundwater recharge time (Ahmed et al. 2019b; Hasan et al. 2020). Therefore, in the study area, the IWQI shows a different form. Shamsuddin et al. (2019) and Matta et al. (2020) studied the estimation of the overall hydrochemical parameters of the IWQI. It is considered as a unitless individual number which has been distilled through a complex mathematical procedure from a large number of hydrochemical parameters of irrigation water quality. Most of the hydrologist and researchers have preferred IWQI technique to assess the groundwater hydrochemical condition. The IWQI has been developed several times by different authors and agencies. However, most of them have been developed through the U.S. National Sanitation Foundation, 2007 (Attuquayefio et al. 2017).

According to the previous investigations (Ahmed et al. 2019a; Ahmed et al. 2020a; Ahmed et al. 2020b; Hasan et al. 2020) and the causes of severity on the salinity on irrigation at Sagardari, Jashore, this study has been driven on the Bagerhat district, the coastal belt, located in the Khulna division. The aquifers of this area have been affected by higher salinity due to its morphological condition as well as close proximity of the Bay of Bengal. The main objective of this study has been performed on the assessment of hydrochemical properties on groundwater, determination of groundwater quality for irrigation purposes according to the IWQI, and has been recommended on a suitable place for irrigation with poorly affected areas. This study also has been evaluated by various farming hydrochemical parameters such as soluble sodium percentage (SSP), sodium adsorption ratio (SAR), permeability index (PI), Kelley's ratio (KR), and magnesium hazard (MH), respectively.

Study area

Location

The investigated area is situated in the Bagerhat district which is the most southern coastal parts of Bangladesh. This area is located between 21° 49′ and 22° 59′ latitude and between 89° 32′ and 89° 98′ longitude covering 3959.11 km^2. The studied area (Bagerhat district) is surrounded by Pirojpur and Barguna districts in the east, Gopalganj and Narail districts in the north, and Khulna district in the west while the Bay of Bengal (saline source) stands at the south. However, more than half of the areas of Sundarbans, the largest Mangrove forest in the world, belong to Bagerhat district (Fig. 1). The Bay of Bengal controls the distribution of monsoon climate of this region. June to August rainy period and severe rainfall occurs during this period in the study area. Humidity also remains generally higher during this time. The annual average precipitation in Bagerhat is 1934 mm, and the annual average temperature is 26.0 °C. Rivers and hydrology of the investigated areas are controlled by a complex system of the freshwater flow, tidal flow, tropical cyclones, and storm surge from the Bay of Bengal and have been affecting the fresh water-bearing zone.

Geology

The investigated area is in the coastal plain, and it is associated with one of the largest deltas, Ganges Delta. According to some authors (Dola et al. 2018; Nahin et al. 2020), this deltaic plain of the region consisted of Holocene alluvium forming the largest Ganges Delta with the terrace, meander, and swamp deposits.

The Maghna flood plain unit has become center for continuous sediment accumulation. This process has made different lithological distribution, and clay, silt, and fine to medium and occasionally coarse sands are considered as the main components of the sediments of the study area. The individual sedimentary units are very complex, and it has made a lack of horizontal continuity on a local scale. The freshwater is mainly found in the wetlands of the Upper Delta plain and in the lower part fresh groundwater mixes with saline seawater. The landward boundary of the Upper Delta plain is associated with the initiation of distributary boundary along the Ganges plain of the coastal area. The river process of the study area is very complex, and all are connected to the sea. Some rivers have crossed the Mangrove forest and fall into the sea. The geology and hydrology of the area are regulated by the interaction of river and sea, storm surges, and flooding processes.

Hydrological setting of the study area

The characteristics of the hydrochemical parameters in study area have indicated the hydrochemical properties, and lithology is correlated with the aquifer system. The bore log data of the study area indicate that the aquifer systems can be divided into three parts/units. Bangladesh Agricultural Development Corporation (BADC) drilled boreholes in the study area for the investigation of hydrology of the coastal plain. The subsurface of the studied area consists of higher upper clay and silt with higher porosity and lower permeability. Higher porosity with moderate permeability is considered as the main characteristic of composite aquifer (mention its depth level, lithology, thickness range, and water quality). Higher porosity and permeability in moderate to higher have been associated with the main aquifer. It is considered the most significant aquifer that produces the highest quantity of groundwater in the study area. This deeper aquifer has consisted of fine to medium sands, and it has been located 200 m lower from the upper level. This is caused by the presence of different coastal plain from the other topography (Dola et al. 2018).

Material and methods

Sampling procedure

The groundwater samples were collected from March to November 2019. This study analyzed the results of rainy seasonal crops like grain, maize, bajra, ragi, soybean, groundnut, cotton, and all kharif crops in March–November 2019 as a result of the Bangladesh monsoon period. The sampling station/points were selected depending on uniform spaces and geographic situation (Fig. 1). The coordinates of the sampling point/stations were recorded by Global Positioning System (GPS). The groundwater samples were collected in 100-ml plastic bottles, which were then placed in an airtight container and shipped to the laboratory at a favorable temperature (< 4 °C) (Baird et al. 2017). The sampling number was added in the plastic bottle containing GPS readings. However, the sample bottles were prewashed with 1:1 HNO_3. After that, it was washed again by distilled water. The tube wells were pumped continuously 1/2 min or up to 30 times for collecting the accurate sample. The research methodology is shown in Fig. 2. A total of 70 groundwater samples were collected from the whole area of Bagerhat (except the mangrove forest).

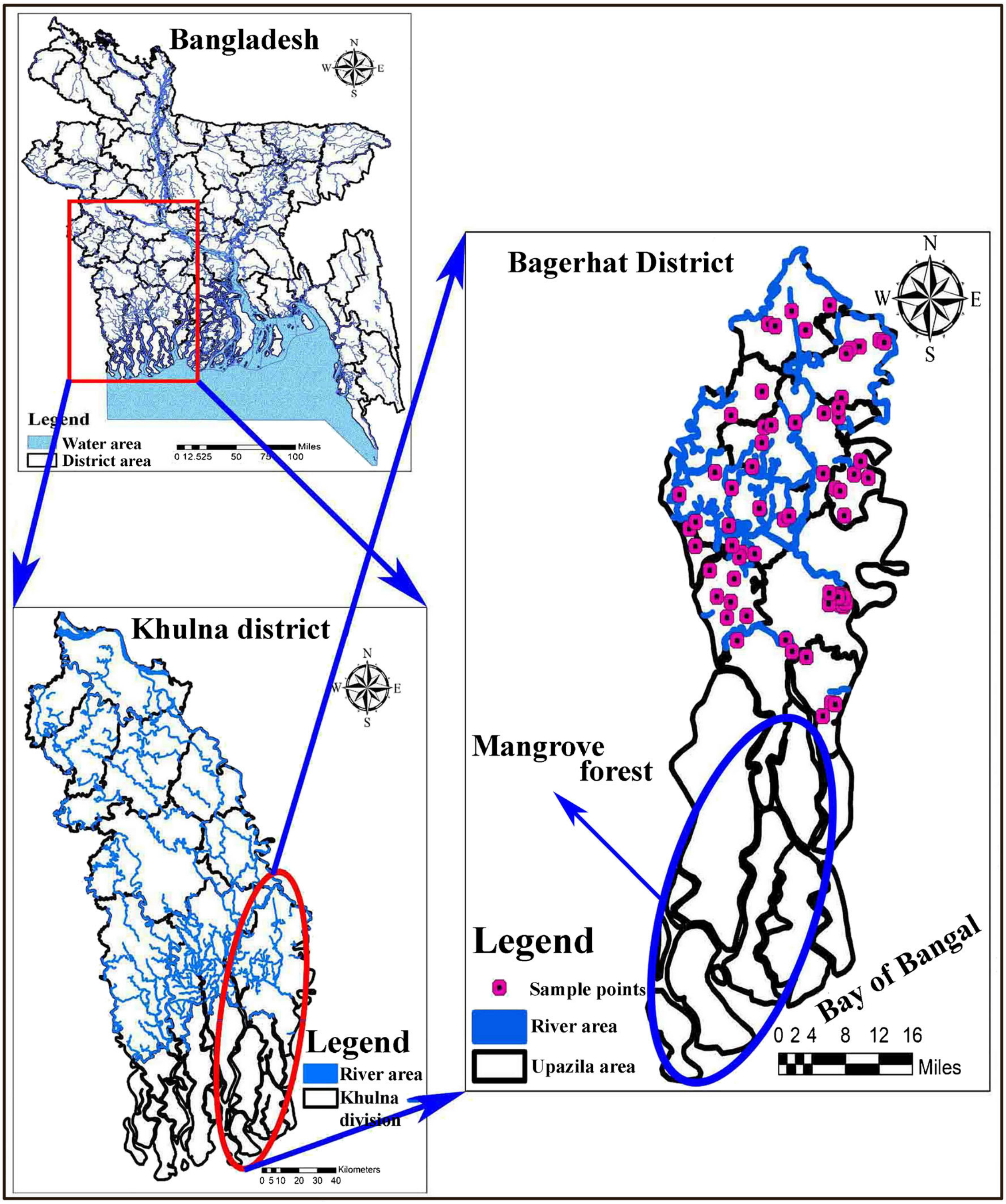


Fig. 1 The location and bore well map in the hydrochemical investigation area by showing various sampling points.

Analytical procedure in laboratory

The chemical analysis of water samples was carried out in the water research laboratory of Bangladesh Agricultural Development Corporation (BADC) Jashore, Bangladesh, following the standard guidelines (Table 1) (Baird et al. 2017). Every time after running 10 groundwater samples, each instrument was recalibrated. The total reproducibility of data for major and non-major ions was within ± 10%.

Evaluation of irrigation groundwater quality indices

The respective equations of hydrochemical parameters on irrigation purposes of water quality parameters such as total hardness (TH), sodium absorption ratio (SAR), soluble sodium percentage (SSP), residual sodium carbonate (RBC), permeability index (PI), magnesium hazard (MH), and Kelley's ratio (KR) are mentioned below:

The TH has been calculated by the following Eq. 1 (Raghunath 1987):

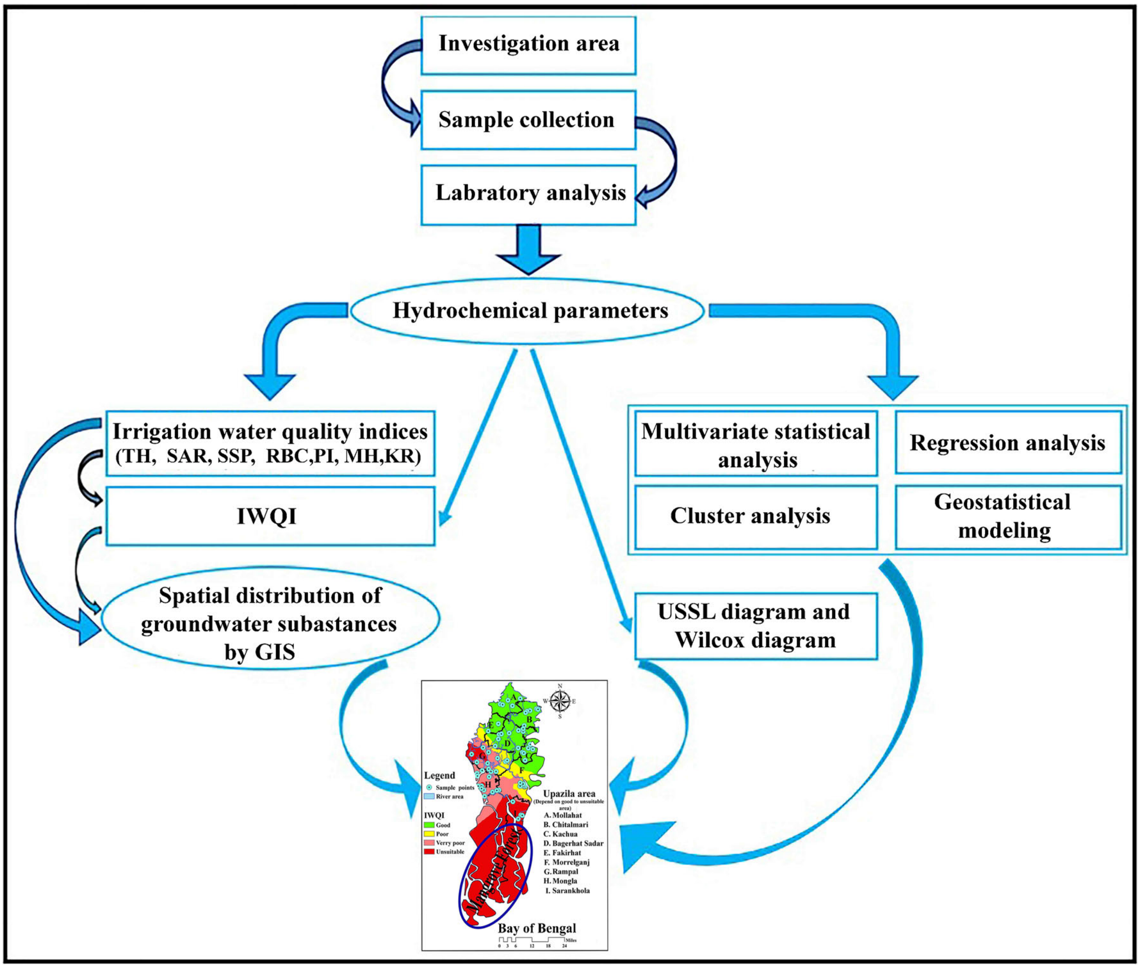


Fig. 2 Flow chart of methodology on this investigation area

$$[\mathrm{TH} = 2.497\mathrm{Ca}^{2+} + 4.11\mathrm{Mg}^{2+}] \quad (1)$$

The sodium absorption ratio (SAR) has been developed by the subsequent formula (Eq. 2) (Richards 1954):

Table 1 The analytical procedures hydrochemical approaches of different groundwater parameters in the investigation region (Ahmed et al. 2019a; Khan et al. 2019; Raghunath 1987)

Properties (groundwater)	Progression
Hardness	EDTA titrimetric method
Iron (Fe)	Ferrozine iron reagent method (0.009–1.4 mg/L) using a spectrophotometer (DR 2800 HACH Germany) at 562 nm
Total dissolved solids	Conductivity bridge method
Major cations [(Na^+), (K^+), (Mg^{2+}), (Ca^{2+})]	Atomic absorption spectrophotometer (Varian AAS, 680FS)
Chloride (Cl^-)	Ion chromatography
Electrical conductivity (EC)	Portable Multi-Meter (Hach, sensION + MM150)
Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-)	HCl titration
Major anions [(Cl^-), (SO_4^{2-}), (CO_3^{2-})]	Ultraviolet spectrophotometer (UV) method
Temperature	Technique of thermometric
Total dissolved solids	Conductivity bridge method

$$\mathrm{SAR} = \left[\frac{\mathrm{Na}^+}{\left(\sqrt{\frac{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}{2}}\right)}\right] \quad (2)$$

Permeability index (PI) has been defined by Doneen (1962) through the following formula (Eq. 3):

$$\mathrm{PI} = \left[\left(\frac{\mathrm{Na}^+ + \sqrt{\mathrm{HCO}_3}}{\mathrm{Ca}^{2+} + \mathrm{Na}^+ + \mathrm{Mg}^{2+}}\right) \times 100\right] \quad (3)$$

Soluble sodium percentage (SSP) (Islam et al. 2018; Todd and Mays 2005) has been expressed by the following formula (Eq. 4):

$$\mathrm{SSP} = \left[\frac{\mathrm{Na}^+}{\left(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^+\right)}\right] \quad (4)$$

Residual sodium carbonate has been defined by Gupta (1983) as the formula is calculated by Eq. 5.

$$\text{Residual sodium carbonate (RSC)} = \left[\left(\mathrm{HCO}_3^- + \mathrm{CO}_3^{2-}\right) - \left(\mathrm{Mg}^{2+} + \mathrm{Ca}^{2+}\right)\right] \quad (5)$$

Kelley (1940) has proposed the formula of the Kelley index (Eq. 6):

$$\text{Kelly inedx (KI)} = \left[\frac{\mathrm{Na}^{2+}}{\left(\mathrm{Mg}^{2+} + \mathrm{Ca}^{2+}\right)}\right] \quad (6)$$

Magnesium hazard (MH) has been reported by the following formula (Eq. 7) (Raghunath 1987):

$$\text{Magnesium hazard (MH)} = \left[\frac{\mathrm{Mg}^{2+}}{\left(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}\right)}\right] \quad (7)$$

Sodium percentage (% Na) has been calculated by the following formula (Eq. 8) (Acharya et al. 2018; Meireles et al. 2010):

$$\text{Sodium percentage (\%Na)} = \left[\frac{(Na^+ + K^+)}{\left(Ca^{2+} + Mg^{2+} + Na^+ + K^+\right)}\right] \quad (8)$$

Regression analysis

The regression analysis is a statistical technique that estimates the relationships among the key variables and the other numbers of factors. It has been narrated the causative effect between one variable with the other hydrochemical variables (Ahmed et al. 2020a; Yan et al. 2018). The regression analysis has been efficiently applied to state the association of various hydrochemical parameters. The linear regression model has been represented by the following equation (Eq. 9):

$$y_1 = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots\ldots\ldots\ldots\ldots\ldots\ldots \beta_m x_{im} + \varepsilon_i \quad i = 1, 2, 3 \ldots\ldots\ldots\ldots n \quad (9)$$

where $x_{i1}, x_{i2} \ldots\ldots\ldots x_{im}$, m has indicated the independent variables, which are connected with the dependent variables linearly (y_i), ε_i has indicated the errors on the random with $\varepsilon_i \sim N(0, \sigma^2)$, $C_{ov}(\varepsilon_i, \varepsilon_j) = 0$, $i \neq j$ *and* $i, j = 1, 2 \ldots\ldots n$ where the variances are indicated by σ. $\beta_0\beta_2 \ldots\ldots\ldots \beta_m$ are represented as regression coefficients, and these have been used to estimate the application of least-squares technique. Equation (1) has been applied to make the model of regression analysis.

Cluster analysis

Cluster analysis has been called as an assortment process that can be performed to classify the assigning observation on a group. It has indicated the comparison of homogeneous groups that have been separated from other groups. It evaluates particularly grouping or the unknown groups with its object. There are two types of processes in the cluster analysis, such as (1) R and (2) Q-modes, respectively (Rana et al. 2017). In this study, the R-mode of cluster analysis has been performed on the hydrochemical of groundwater data to the individual groups of the water quality samples. In the majority cases, hierarchical cluster analysis (HCA) is used to measure the sample parameter distances. The cluster analysis signifies a group of hydrochemical parameters on the same areas, and the cluster formation has been repeated till all other points have belonged to one another (Almasoud et al. 2015). All the samples of hydrochemical parameters have been converted on a cluster diagram statistically by applying the SPSS (V. 22) software. The 2D plotting map has been made from the resulting hydrochemical parameters, and it is also called the dendrogram (Fig. 3).

Irrigation water quality index

The irrigation water quality index (IWQI) has been considered as an effective hydrogeological mean to evaluate comprehensively groundwater quality for irrigation. The parameters of IWQI have been applied to develop a single index value. The irrigation quality index has been divided according to Table 2. Some researchers from different

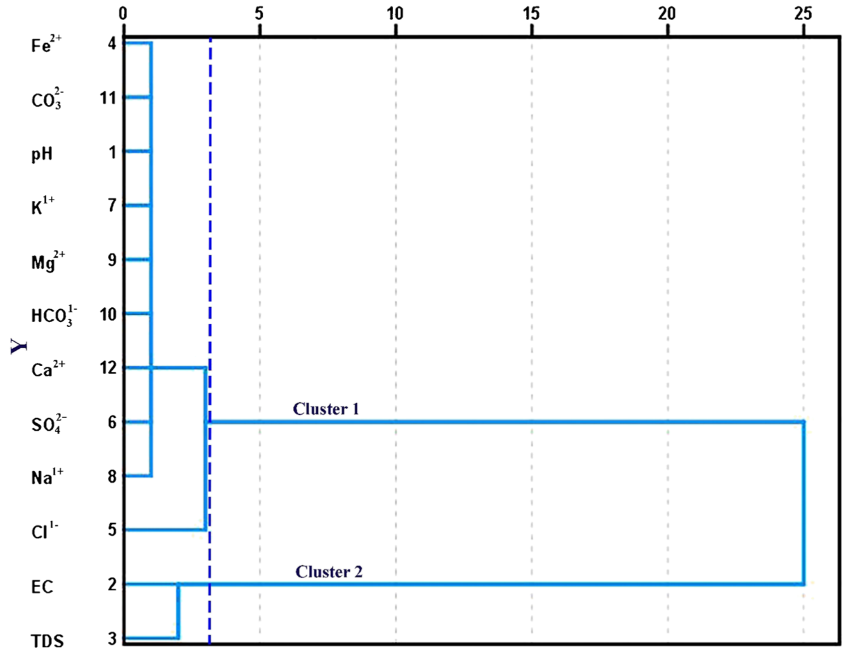


Fig. 3 The groundwater samples Cluster analysis diagram on the investigation area

countries proposed various IWQIs considering various parameters of groundwater quality, and these types of indices have been used worldwide. During the present study, the IWQI model has been proposed based on integration with eight hydrogeological groundwater quality parameters: they are SAR, RSC, Na, EC, pH, TDS, Na, and Cl. This irrigation groundwater quality parameter has been calculated depending on recommendation reported by Meireles et al. (2010). The details of IWQIs used in the present study have been described in the literature (Ahmed et al. 2020a). The groundwater quality index for irrigation has been calculated using the following equations (Eqs. 10–12):

$$\text{Qrv} = \left[\frac{(Cv) \times 100}{(RSv)}\right] \tag{10}$$

$$\text{Wcv} = \left[\frac{1}{RSv}\right] \tag{11}$$

$$\text{IWQI} = \left[\frac{\left(\sum_{1=0}^{n} Wcv \times Qrv\right)}{\left(\sum_{1=0}^{n} Wcv\right)}\right] \tag{12}$$

In this water quality calculation, Qrv is the characterization of rating the values on quality, Cv is considered as the concentration of laboratory values observed from the analytical area, and RSv is the characterization of the standard values of irrigation purposes on groundwater. However, Wcv has indicated the weight of co-efficient on relative values of the variables, IWQI has also considered irrigation water quality index and the quantity of groundwater quality variables has been indicated by n. Category of dimensionless variables of IWQI ranged from 0 to 100 (Table 2).

Multivariate statistical analysis

Principal component analysis (PCA) is largely used as a tool of statistics and a large number of variables can be reduced by it so that the latent factors of the simple set make an exploration of the interrelationships between the variables. The analytical hydrochemical factors on the groundwater data have been performed on SPSS version 22. At first, the matrices of correlation have been created applying the R mode. In the step of the second part, the principal components (PCs) have been expelled by eigenvalue. Accordingly, all factors with eigenvalue higher than 1 were included in the estimation. For ensuring better interpretation, the extraction of components has rotated. The rotation has not been affected by the goodness solution fit of factors. Factor 1 has been considered the highest eigenvalue and represents the longest variation in the set of data. Again, a factor of 2 has been considered as the 2nd highest eigenvalue (Jiang et al. 2009). Depending on the approach of Liu et al. (2003), the terms "stronger," "moderate," and "weaker" have been used to the factor of loadings, and it also mentioned to the values of absolute loading (0.75, 0.75–0.50, and 0.50–0.30). This scale is used to identify the component's variance relationship between different components.

Geostatistical modeling

The ordinary Kriging (OK) and semivariogram models have been applied on the major dominant hydrochemical parameters and irrigation water quality indexes to determine the spatial distribution in the investigation area. These techniques have documented indifferent present hydrochemical

Table 2 The parameter rating of hydrochemical substances on groundwater quality for irrigation according to various indices such as EC, SAR, KR, SSP, PI, MH, Na, T.H, IWQI, TDS (Ahmed et al. 2020a; Baird et al. 2017; Monir et al. 2012; Organization 1993; Raghunath 1987; Todd and Mays 2005)

Parameters	Range	Water class
	< 250	Excellent
	250–750	Good
EC	750–2250	Permissible
	> 2250	Doubtful
	0–10	Excellent
SAR	10–18	Good
	18–26	Doubtful
	> 26	Unsuitable
	< 1	Suitable
KI	1–2	Marginal suitable
	> 2	Unsuitable
SSP	< 50	Good
	> 50	Unsuitable
	> 75	Class-I
PI	25–75	Class-II
	< 25	Class-III
MH	< 50	Suitable
	> 50	Harmful &Unsuitable
	< 20	Excellent
Na	20–40	Good
	40–60	Permissible
	60–80	Doubtful
	> 80	Unsuitable
	< 75	Soft
T.H	75–150	Moderately Hard
	150–300	Hard
	> 300	Very Hard
	85–100	Excellent
	70–85	Good
IWQI	50–70	Permissible
	40–55	Doubtful
	0–40	Severe
	< 450	Excellent
TDS	450–750	Good
	750–2000	Permissible
	> 2000	Unsuitable

investigation (Ahmed et al. 2011). The model helps to understand the large hydrographic portion with the scenario of pollution. The model of semivariogram $\gamma(h)$ has been determined by applying Eq. 13 (Journel and Huijbregts 1978):

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}\left[z(x_i)-z(x_i+h)\right]^2 \quad (13)$$

Here, n is the pair number of sample point, and when it has divided, the standard distance is called lag h (Journel and Huijbregts 1978). $z(x_i)$ is the variable of the x_i locations at each point. The model of semivariogram $\gamma(h)$ has been tested as the model of best fit, and nugget (C_0), sill (C), and ranges (A_0) of the parameters have been used to describe the actual major ranges of the model. In the second portion, the appropriate model of semivariogram (e.g., circular, spherical, exponential, and Gaussian) has been approved on the basis of the resultant experimental semi variogram (Webster and Oliver 2007).

In this investigation, the model of OK has been applied to evaluate the hydrochemical parameters of their spatial changes, and it has calculated by Eq. 14 that has approved the estimation unbiased and has shown the weights have to be equal (Ghanbarpour et al. 2013).

$$\widehat{\ddagger}(x_o) = \sum_{i=1}^{n} z(x_i) \quad (14)$$

where $\widehat{\ddagger}$ has calculated the x_o value of the sample point; the observation value of x_i point is z; the point of weight is λ_i, and the sample numbers have been measured represented as n (Webster and Oliver 2007). The model of ordinary kriging has been applied to calculate the local means of constant (Goovaerts 1997). Each parameter of variables has been engaged to measure the best variability prediction when it has to interpolate for the model of spatial process (Goovaerts 1997). The performance prediction of the fitted model has been identified by the tests of cross-validation. To establish the best-fit model, it has been evaluated by the mean error (ME), mean square error (MSE), root mean square error (RMSE), average standard error (ASR), and root mean square standardized error (RMSSE). Minimum mean error (ME), root mean error (RME), and mean squared error (MSE) values have been considered as the best goodness resulting values and the root mean squared error (RMSE) and average squared error (ASE) values that have been helped to attain good unity of the best fit models (Scott and Janikas 2010).

The following equation has been applied to determine the errors, according to Eqs. 15–18:

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(p_i - o_i) \quad (15)$$

$$\mathrm{RMSE} = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}(p_i - o_i)^2\right]} \quad (16)$$

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(p_{si} - o_{si})^2 \quad (17)$$

$$\mathrm{ASE} = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}\left(p_i - \frac{\sum_{i=1}^{n} p_i}{n}\right)^2\right]} \quad (18)$$

Here, the observed point has been considered as n numbers; the observation and prediction values have been indicated as *o* and *p* where the location point is *i*; the standardized observation values are *os*; and the standardized predicted values are indicated as *ps*.

Results and discussion

Descriptive statistics

The general characteristics of hydrochemical parameters on the investigation area have been summarized with the values of maximum, minimum, average, standard deviation, and variance values in Table 3. The total samples (n = 72) show the values of pH ranged from 7.97 to 6.48, standard deviation 93.7421, and variance 17,327.573. The pH indicated moderate acidic to alkaline in groundwater nature which is consistent with the literatures (Ahmed et al. 2020a). In the study area, the EC value (Fig. 6a) was found within the ranges from 608 to 30,500 µS/cm with an average value in the range 11,016.2 µS/cm, standard deviation 9009.01 µS/cm, and variance is 86,509,036.23 µS/cm. The value of EC indicates the salinity rate of the investigation area. The cation concentrations of the sampling resign are Na^+, K^+, Ca^{2+}, and Mg^{2+}ions, and it is found in the range of 172.409 to 3915.66mg/l, 3 to 800 mg/l, 41.32 to 413.8 m/l, and 29.5809 to 602.701 mg/l with the values of average 51.1857 mg/l, 1588.88 mg/l, 182.657mg/l, and 140.802 mg/l, respectively. The dissolved anions of the groundwater sample are found main dominant ions of Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-} in a range of 600 to 14,000 mg/l, 10–1500mg/l, 63.5809 to 636.701 mg/l, 6.35 to 63.6 mg/l with the average values in 3729.85 mg/l, 315.285 mg/l, 216.657 mg/l, and 21.6162 mg/l, respectively. The sequential order of main cations and anions of the groundwater sampling areas is found in categorical ranges of $Na^+ > K^+ > Mg^{2+} > Ca^{2+} > Fe^{2+}$and $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^{2-}$, respectively. In recent, it is noted by several authors (Ahmed et al. 2020a; Shammi et al. 2017) that Ca^{2+}, Mg^{2+}, HCO_3^-, Na^+, Cl^-, and SO_4^{2-} are the major dominant cations and anions in the present investigation area and the southern part of Bangladesh. The highest rate of concentration Cl^- and Na^+ ions in this investigation area has influenced the groundwater.

Evaluation of ionic relationships by cluster analysis

The cluster analysis (CA) on R-mode has been applied to the groundwater hydrochemical parameters (Fig. 3). It has exhibited the ionic relationship on the different particular groups on the datasets of groundwater. The cluster analysis (CA) has been estimated the major dominant hydrochemical factors in the individual terms. In the present work, the CA has been indicated two major clusters for the hydrochemical interrelationship between the parameters of the study area. Figure 3 has been represented as the hydrochemical relationship of cluster analysis. The hydrochemical parameters that have belonged from the same cluster have been originated from the similar origin (Grande et al. 2003; Hussain et al. 2008). In the analysis of cluster, it has indicated that Cl^-, Na^+, EC, TDS, Ca^{2+}, and SO_4^{2-} (Cluster 1 and Cluster 2) are the major dominant hydrochemical parameters, respectively, as shown in Fig. 3. However, Cl^-, Na^+, Ca^{2+}, and SO_4^{2-} (cluster 1) have

Table 3 The resultant value of descriptive statistical analysis of hydrochemical properties in the investigation area

Parameters	Max	Min	Average	Std. deviation	Variance	Standards	
						WHO (2011)	BMAC (1997)
Temperature (°C)	31.2	27.1	29.4785	1.15001	1.364	–	–
pH	7.97	6.48	18.3224	93.7421	17,327.573	6.5–8.0	6.5–8.5
EC (µS/cm)	30500	608	11016.2	9009.01	86,509,036.23	750	1000
TDS (mg/L)	21350	425.6	7711.35	6306.3	42,389,427.75	500	600
Hardness (mg/L)	1600	180	388.971	195.165	58,745.77	–	–
Iron (Fe) (mg/L)	6	0.1	0.52142	1.16642	1.78	–	–
Chloride (mg/L)	14000	600	3729.85	3264.57	12,143,033.68	250	600
Sulfate (mg/L)	1500	10	315.285	356.557	146,901.77	200	400
Potassium (mg/L)	100	3	51.1857	96.0696	17,126.88	30	12
Sodium(mg/L)	3915.66	172.409	1588.88	1106.232	1,300,002.97	200	200
Magnesium(mg/L)	602.701	28.5809	182.657	134.535	20,584.95	30	30-35
Calcium	413.8	41.32	140.802	87.436	8694.86	75	75
HCO_3 (mg/L)	636.701	63.5809	216.657	134.535	20,584.95	200	600
CO_3 (mg/L)	63.6	6.35	21.6162	13.446	205.62	–	–

BMAC Bangladesh maximum admissible concentration, *WHO* World Health Organization showed that these are the main groundwater controlling of hydrochemical parameters. These hydrochemical parameters have indicated (Danielsson et al. 1999) the sign of salinity (NaCl) and excessive amounts of sodium (sodium hazard). Another sign of salinity has been indicated by EC (cluster 2) which is connected with TDS. These salinity indicators have connected with other (salinity and sodium hazard) hydrochemical parameters and show the same sign according to (cluster 1) salinity in the groundwater. In other cases, Mg^{2+}, K^{+}, pH, Fe^{2+}, CO_3^{2-}, and HCO_3^{-} have connected with each other in the same series of cluster analysis on the groundwater parameters, respectively. These have shown the lower dominant characteristics of groundwater parameters. The result (cluster 1) indicates that the probability of mixing or infiltration of hydrochemical parameters in this study area from various sources, such as intrusion of salinity or seawater into the aquifer zone, aquifer-level weathering of the bedrock, geographical circumstances, and other factors, is the leaching of higher residual crops in the process of farming that goes into the levee (Bodrud-Doza et al. 2016). Cluster 2 also showed the same sources of salinity in cluster 1 with hydrochemical parameters (EC, TDS). Again, the effect of the hydrochemical (cluster diagram) may be due to the domestic impact and contamination of agriculture, such as the increased use of fertilizers on excess chemical and other agrochemicals in the outer regions, or the dissolution of minerals in the initial circumstances (Bodrud-Doza et al. 2016).

Multivariate statistics

Analysis of regression model

The results of geochemical analysis indicated that the salinization of groundwater of the aquifer system of Bagerhat occurred from the southern coastline of Bangladesh. Concentrations of major ions and TDS indicate regeneration model shown in Fig. 9. Correlation of TDS and other (major-minor) dominant ions has been evaluated by the regression model. The relationship between TDS with major anions Cl^{-}, (HCO_3^{-}+ CO_3^{2-}), and major cations (Mg^{2+}, Ca^{2+}, K^{+}, and Na^{+}) has been developed by the hydrochemical regression model. The correlation coefficient of TDS and major anions Cl^{-}, (HCO_3^{-} + CO_3^{2-}) and major cations (Mg^{2+}, Ca^{2+}, K^{+}, and Na^{+}) are 0.6618, 0.3365, 0.40123, 0.4112, 0.0726, and 0.4946, respectively (Fig. 9 a–f). These relationships of hydrochemical properties have found the major dominant ions series as $Cl^{-} > Na^{+} > Ca^{2+} > Mg^{2+} > K^{+} > (HCO_3^{-}\ CO_3^{2-})$ with the coefficient value of TDS (0.6618 > 0.4946 > 0.41123 > 0.4012 > 0.3365 > 0.0726). The correlation value of r in the substances (Cl^{-} and Na^{+}) has been found 0.6618 and 0.4946, which is the higher value of major dominant (anion and cations) with the co-relations of TDS, respectively. Therefore, the salinity or mixing of seawater (NaCl) has been considered as the main dominant substance in the groundwater, and salt element has controlled the groundwater in this aquifer system. According to the regression model, the mechanisms of groundwater salinization have been analyzed by the correlation of major anions and cation with each other. The relationship of Na^{+}/Cl^{-} has shown the higher concentrations of hydrogeochemistry in these coastal areas (Fig. 10b). It has been compared with other higher concentration which has crossed the limit of WHO because of the intrusion of saline water. The higher concentration of Na^{+} co-relative to Cl^{-} has the potential to narrate ion-exchange spread from seawater to groundwater in this region, such as cation exchange. These were caused by the fraction of clay in the aquifer system in this study area (Ahmed et al. 2020a). All the samples in this study area, Ca^{2+}, have shown a positive correlation with the dominant ion by Cl^{-} in the aquifer system (Fig. 10a). The higher cation exchange process has been mostly responsible in this area, and these ions have been connected by a relative deficiency with each other. The dissolution process of dolomite is probably responsible for the higher concentration of (Mg^{2+} and Ca^{2+}) versus Cl^{-} in the aquifer system (Fig. 10 a and e). The correlation plot of Cl^{-} versus (HCO_3^{-} + CO_3^{2-}) has shown the exchange of ions with (Ca^{2+} and Mg^{2+}) that has regulated the rate of salinity, and the hydrochemical parameters have been effected by the mixing of salinity with the mineralization of groundwater by gypsum dissolution (Fig. 10c) (Sarker et al. 2018). In the same way as Na^{+}/Cl^{-}, the ratio of plotting K^{+}/Cl^{-} has been affected on aquifer system of groundwater level by the ion exchange in a 1:1 ratio in the molar ratio of K^{+}/Cl^{-} (Fig. 10d) (Bodrud-Doza et al. 2016). The overall groundwater samples with the co-relation of Fig. 9 (a–f) and Fig. 10 (a–e) have indicated that the salinity mixing of salinity or the ion exchanging process from the seawater is responsible for these types of aquifer system in the coastal line.

Principal component analysis

Principal component analysis (PCA) has been represented on the quality of groundwater data applying Varimax rotation through Kaiser normalization. It is applied to explain the observed relationship with the parameters in a simple process (Raju 2007). This method shows a complex hydrochemical procedure in the zone laterally with the interaction of ion altercation, material leaching and fertilizer of farming, sewage of domestic case, and mineral weathering (Masoud 2014). The correlation of hydrochemical parameters is shown in Table 4 by the factor analysis of pH, EC, TDS, Na^{+}, K^{-}, Ca^{2+}, Mg^{2+}, Fe^{2+}, Cl^{-}, CO_3^{2-}, and HCO_3^{-}, respectively. Three factors have expelled for the groundwater quality data depending on eigenvalues over 1, which illustrated the total % of variance on PC1, PC2, and PC3, respectively (74.907%) in the investigation area (Fig. 4a, b). The explanations of variance on

Table 4 The principal component analysis (PCA) with extracted eigenvectors of coefficients for the groundwater samples of the Bagerhat district

Parameters	Component		
	PC1	PC2	PC3
pH	− 0.084	0.468	0.277
EC	0.845	− 0.386	0.038
TDS	0.845	− 0.386	0.038
Hardness	0.473	− 0.145	− 0.601
Fe	− 0.25	0.097	− 0.339
Cl	0.805	− 0.356	− 0.09
SO4	0.49	− 0.513	0.272
Ca	0.954	0.279	− 0.023
K	0.313	− 0.024	0.658
Na	0.954	0.279	− 0.023
Mg	0.954	0.279	− 0.023
HCO_3	0.954	0.279	− 0.023
CO_3	0.954	0.279	− 0.023
Eigenvalues	7.257	1.325	1.074
% of variance	55.83	10.192	8.258
Cumulative %	55.83	66.019	74.277

PC1, PC2, and PC3 have been indicated as 55.83%, 10.192%, and 8.258%, respectfully. EC, TDS, Na^+, K^+, Mg^{2+}, Cl^-, and SO_4^{2-} have shown a strong correlation with the PC1. Hardness, HCO_3^-, and CO_3^{2-} have indicated a strong corelationship in PC2. EC, TDS, and pH have a strong load of the hydrochemical parameters in PC3 (Table 4). From Fig. 4a, the scree plot has been used to describe the PCA number of being retained to understand the structure of the underlying parameters. The calculated factor of dominance, % of cumulative, and % of variance stated by each factor are shown in Table 4. About 9.62% of the total variance was represented in the first three (Table 4) PC1, PC2, and PC3 eigenvalues, respectfully, as 7.257, 1.325, and 1.074, and this process has been found in the 13 components of hydrochemical properties (Fig. 4a). The total % of cumulative is 196.126, and the PC1, PC2, and PC3 have been found as 55.83%, 66.019%, and 74.277%, respectively. The loading factors of the study area (Ahmed et al. 2020b; Shammi et al. 2017) have been shown as the Cl^- and Na^+ which are the main dominance factors of the groundwater samples (Fig. 4b).

Spatial distribution of groundwater substances

Concentration of electro conductivity (EC) values and its spatial variation are shown in Fig. 7a. The spatial distribution of EC divided into three distribution levels. It has mainly crossed the WHO limit, and there is no good and excellent distribution like chloride (Sarker et al. 2018). The higher mixing or salinity intrusion is the main cause of EC. Increasing of chloride and higher mixing of salinity, it divided the total area on permissible, doubtful, and severe. According to Fig.7a, the severe level of EC distributed on the total mangrove forest, Mongla, Rampal, and Sarankhola Upazila. As a result, a total of 70% of the total district is covered in severe distribution. In the Wilcox diagram, (EC vs %Na^+) has indicated that most of the samples (around 74.43% samples) have been found in the unsuitable zone. The mangrove forest, Mongla, Rampal, and Sarankhola, has been located in this unsuitable zone. The key factors of these forms of groundwater are the persistent

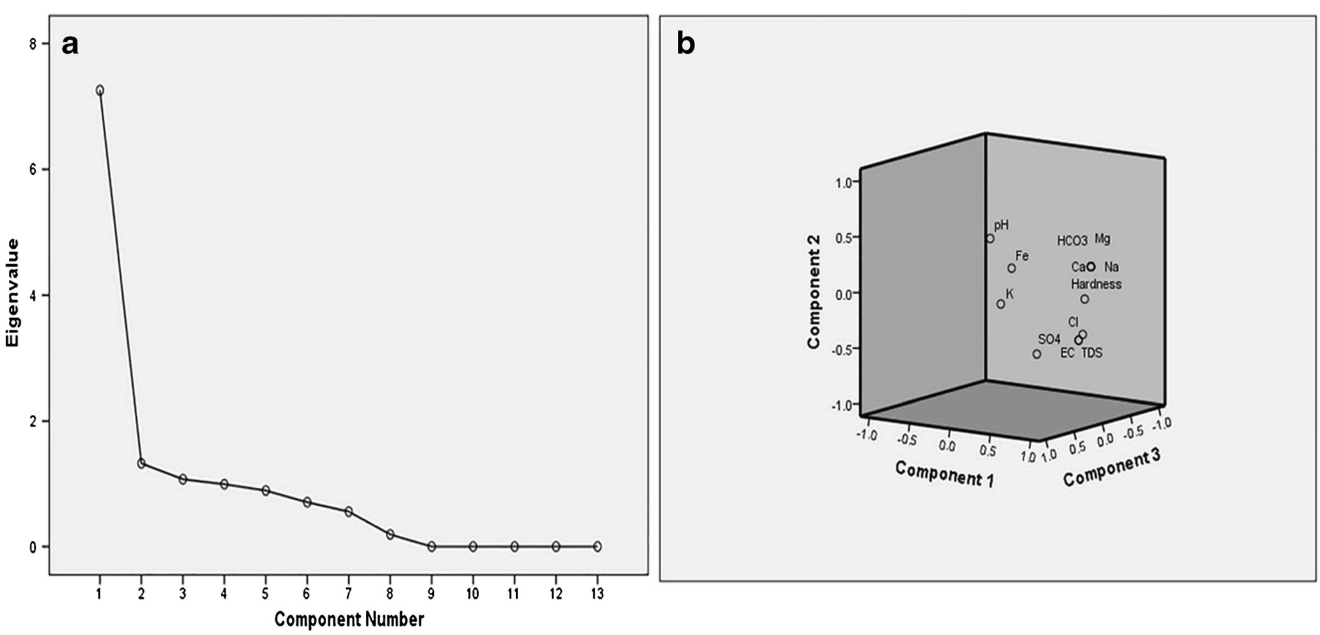


Fig. 4 Principal component analysis has been shown the scree plot (**a**) of the characteristic roots (eigenvalues) (**b**) component plot in rotated space

intrusion of salinity from the ocean regions by the tidal wave (Abbasnia et al. 2018). The other samples have been found on the zone of doubtful to unsuitable (around 21.56%) and permissible to doubtful (around 4.02 %), respectively. There have no samples found in the zone of excellent to good and good to permissible. The concentration and its concentration spatial variation map of total dissolved solid (TDS) are shown in Fig. 7d. As the mixing of salinity is higher, the value of TDS is also higher. According to the chloride, TDS also controlled groundwater suitability. Most of the area TDS level is higher, and it crossed the WHO limit. This also converted the freshwater into the unsuitable level. The Ca^{2+} and Mg^{2+}

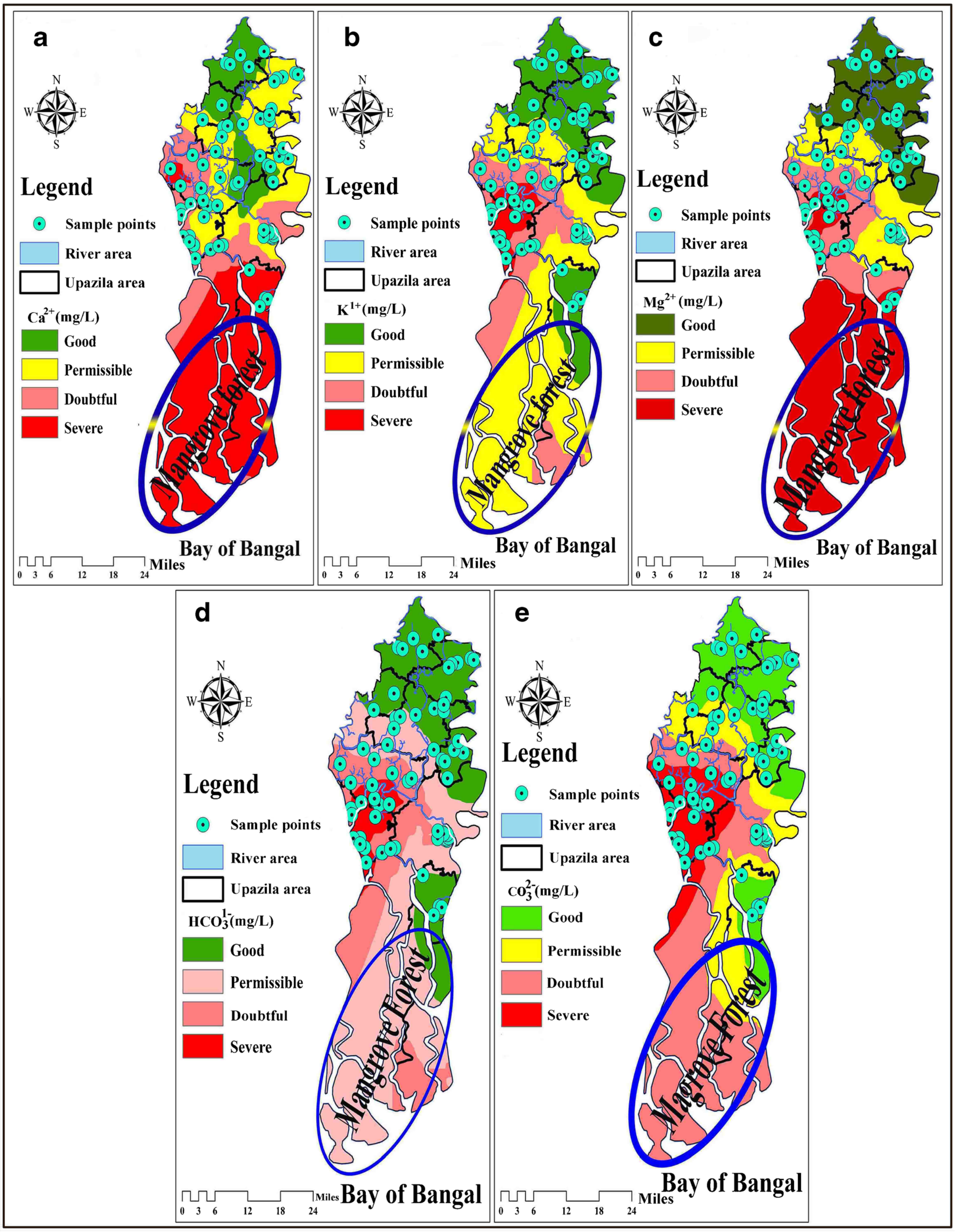


Fig. 5 The spatial distribution maps for major ions (anions and cations) in the investigation area

concentration and its spatial distribution maps in groundwater are shown in Fig. 5 a and c, respectively. From the spatial distribution map, Fig. 5a of Ca^{2+} concentration has shown that most of the investigation area is located on the severe and doubtful area which is very higher. Based on Ayenew (2005), the higher concentration of Ca^{2+} and Mg^{2+} in groundwater is derived from simple sand and silicate acquisition. As this region has formed near the coastal areas, the same forms of formation have been reported. The concentrations of calcium and magnesium are higher in the coastal area. In the upper

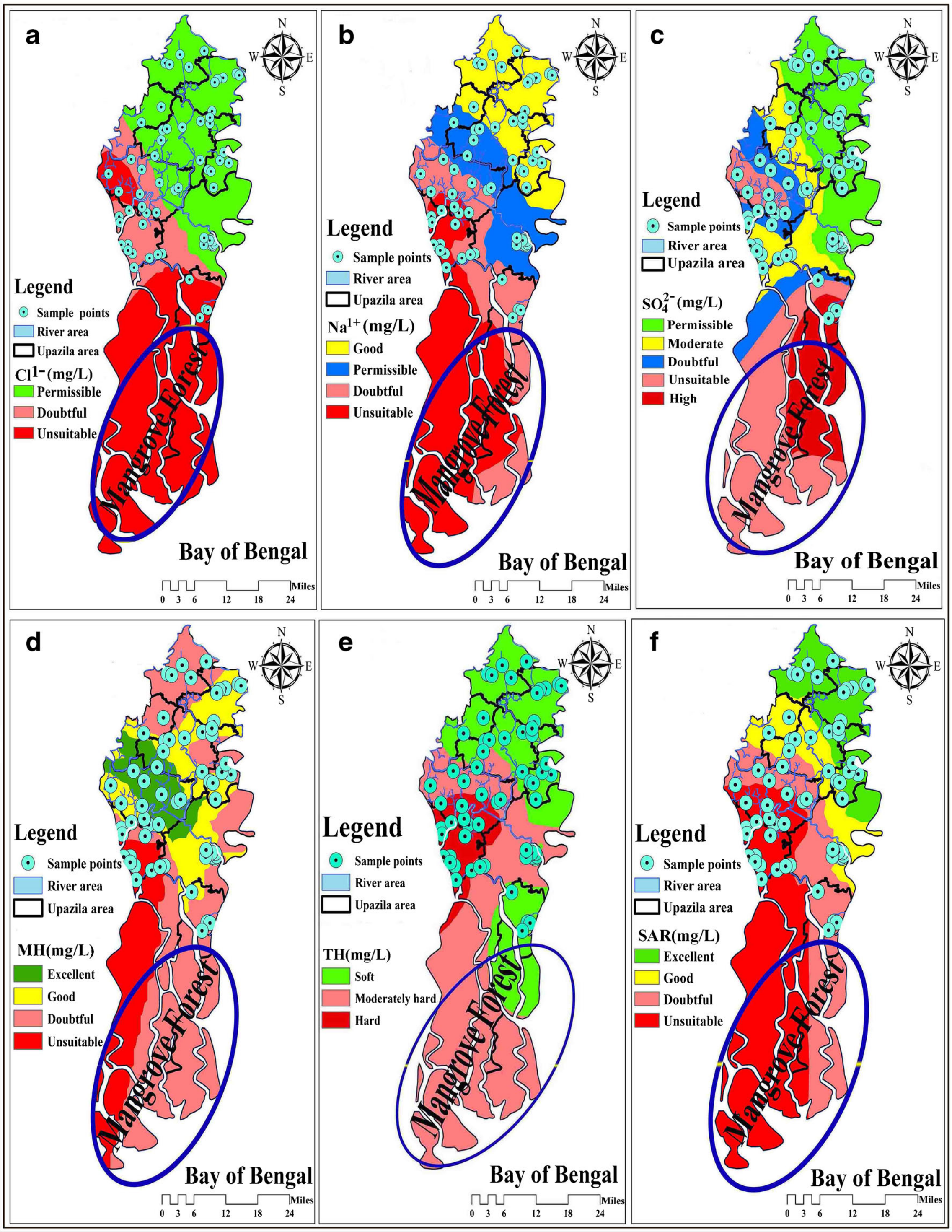


Fig. 6 The spatial distribution maps for the irrigation major ions (anions-cations) and groundwater quality indexes in the investigation site

area of Bagerhat district, this two-ion concentration is very lower, and it has been found in good distribution level areas. The majority of the investigation areas have been found in the lower level of the WHO standard (Organization 1993) of the two ions in the study areas (Fig. 5a–c). The Na^+ and K^+ concentration and its spatial distribution maps in groundwater are shown in Figs. 5b and 4b, respectively. According to the WHO guideline (Organization 1993), the concentrations of Na^+ and K^+ are 200 and 12 mg/l, respectively. If the concentration level is higher than 200 mg/l, it is indicated unacceptable for use. From Fig. 6b, the concentration of sodium majority crosses the WHO level (Organization 1993), and there is no excellent area. In comparison, the strong concentration area is also much smaller due to extreme Na^+ ions and is also

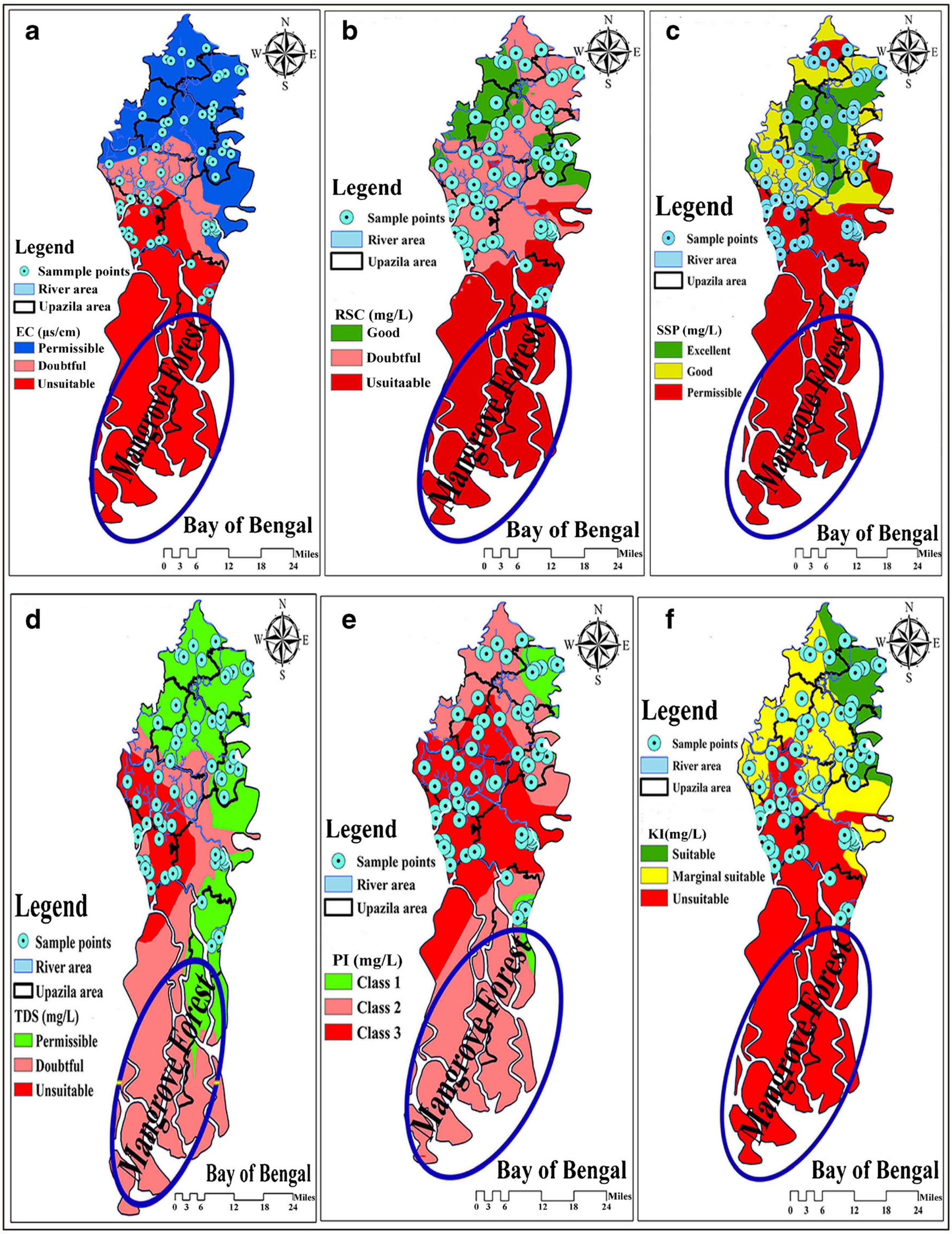


Fig. 7 The spatial distribution maps for the irrigation water quality indexes in the investigation site

higher than another K^+ ion. From Fig. 5b, the potassium concentration is covered in higher areas of good distribution level. In the middle middle-west of the sample area is the higher or severe distribution of (Na^+) sodium and potassium (K^+), and this area exceeds the WHO limit (Organization 1993). The chloride (Cl^-) concentration and its spatial distribution map in the investigation area are shown in Fig. 6a. These are the most prevalent contaminants of groundwater due to the mixing of salinity from the coastal region. The majority of the chloride sample crossed the permissible limits of the WHO (Organization 1993). Figure 6 a indicates that there is no good and excellent area for the spatial distribution of chloride. The total mangrove forest and middle Bagerhat district are considered as high salinity of the groundwater. This substance controlled the irrigation and other agricultural activities in this coastal area. The concentration of SO_4^{2-} and its spatial distribution maps in groundwater have been shown in Fig. 6c. The concentration of the sulfate is not higher than the anions of Cl^-. Very lower area exceeds the WHO limits. From Fig. 6c, it indicated that the west mangrove forest is considered as the higher SO_4^{2-} concentration, and the upper area of the district has been considered the area excellent distribution of SO_4^{2-}. The concentration of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}), its spatial distribution map, has been shown in Fig. 5d, e. Bicarbonate and carbonate severe distribution areas are very lower. Silicate minerals are found higher here. Therefore, the bicarbonate and carbonate are also higher in this area. The total mangrove forest, Mongla Rampal Morrelganj in total, is carbonate and bicarbonate which is higher (Fig. 5d, e). However, the upper area of Bagerhat district is considered as excellent and good distribution of carbonate and bicarbonate.

The evaluation of irirrigation quality indexes and dominant parameters

The samples of groundwater are categorized depending on irrigation indexes (Table 5). The growth of a plant depends on the types of soil and water quality, where water is considered as the essential element. When poor quality of water is used for cultivation purposes, it affects the production of the crop. Intense practices of agricultural and higher rate of chemical fertilizers using salinity on the coastal area mixing with the groundwater has made a serious effect on the quality of groundwater. Sodium adsorption ratio (SAR), soluble sodium percentage (Na%), permeability index (PI), magnesium hazard ratio (MH), Kailly index (KI), total hardness (TH), and resedual sodium carbonate (RSC) have been used for the evaluation of groundwater in this area for the purposes of irrigation. According to the SAR values in Table 2 (Richards 1954), the water is classified for the purpose of irrigation. It is the main tolerant component for the irrigation. Depending on Richard's classification (Richards 1954), the spatial distribution (Fig. 6f) indicated 23% as "excellent" for irrigation, 17% is found as good area, 34% is found as doubtful, and 26% is found as the severe distribution areas. In Fig. 8a, the USSL diagram has indicated the groundwater classification (salinity hazard (EC) vs sodium hazard). The concentration of EC is so much higher that there is no sample found on the zone (C1) and (C2) of excellent and good but in the other two zones, these are found; the sample is higher (the zone of high and very high). Figure 8 b indicates that most of the sample has been found on the zone of C4-S4, and it means high salinity and high sodium concentration. Then, the sample is found in these higher to lower position in the zone of (C4-S3) > (S2-C4) > (S3-C3), respectively. Most

Table 5 The classified area of irrigation water quality (IWQI) index in the Bagerhat district

IWQI classes	Zone (Upazila)	Restrictions	Recommendation
Excellent	No area is found		
	Mollahat		
	Chitalmari		
Good	Kachua	Lower	Avoid salt sensitive plants
	Bagerhat Sadar		
	Fakirhat		
	Morrelganj (27%)		
Permissible	Morrelganj (38%)	Moderate	Moderate tolerance to salts may be grown
	Rampal (32%)		
	Morrelganj (35%)	High	Moderate to high tolerance to salinity plant
Doubtful	Rampal (45%)		Control of special salinity plant
	Mongla (83%)		
	Sarankhola	Irrigation is	Higher salt and (Na, Cl and HCO_3) tolerance
Severe	Mongla (17%)	not suitable	
	Rampal (23%)		

of the sample is located on the zone of (C4-S4) and (C4-S3) which means the groundwater of the investigation area is found on higher salinity with sodium hazard. The groundwater suitability is affected by additional concentration of bicarbonates with carbonates over calcium and magnesium. The extra bicarbonate concentration has become to cause different harmful physical properties of soil (Das and Nag 2015). The RSC has been calculated by the subsequent equation (Doneen 1962). In the investigation area, a total of 20% are found in good areas, 42% areas are doubtful, and 38% areas are considered as severe (Table 2; Fig. 7b). The combination of Ca^{2+} and Mg^{2+} is the multiplicating value (Table 2), and its spatial distribution is shown in Fig. 6e. It mainly controls the soil quality (Todd and Mays 2005). It is divided into three parts: soft, moderately hard, and hard. Crop production directly or indirectly depends on total hardness (TH). From Fig. 6e, it is indicated that 44% area is found in the soft distribution, 38% is found in moderately soft, and 18% is found in hard distribution. Kelly's index indicated the relative quantity of sodium against the concentration of calcium and magnesium, and it assets to identify the water suitability for irrigation purposes. According to the Kailly classification (Kelley 1940) (Table 2) that is shown in Fig. 6c, where about 10% are considered suitable distribution areas, 31% of areas are located on the marginally unsuitable areas and 61% are considered as the unsuitable distribution areas for the purpose of groundwater on irrigation. The values of the permeability index (PI) and its spatial distribution are shown in Fig. 7b. According to Table 2, Doneen (1962) classified irrigation water quality based on pi. It is divided on three parts. It determined the water passing rate in the soil. It has made a higher impact on the soil in long-term irrigation practice. It is mainly controlled by the influence of HCO_3^-, Ca^{2+}, and Mg^{2+} in the groundwater. From Fig. 7b, it indicated that class 2 and class 3 have been covered in the higher distribution of the study area. About 14% are found in class 1 area, 39% are found in class 2 distribution area, and about 50% are found in class 3 distribution area. The higher rate Mg^{2+} ion concentration of recent study area affected the crop yield and the soil, and magnesium hazard (MH) has been also evaluated by Raghunath (1987). The MH is considered as the combination

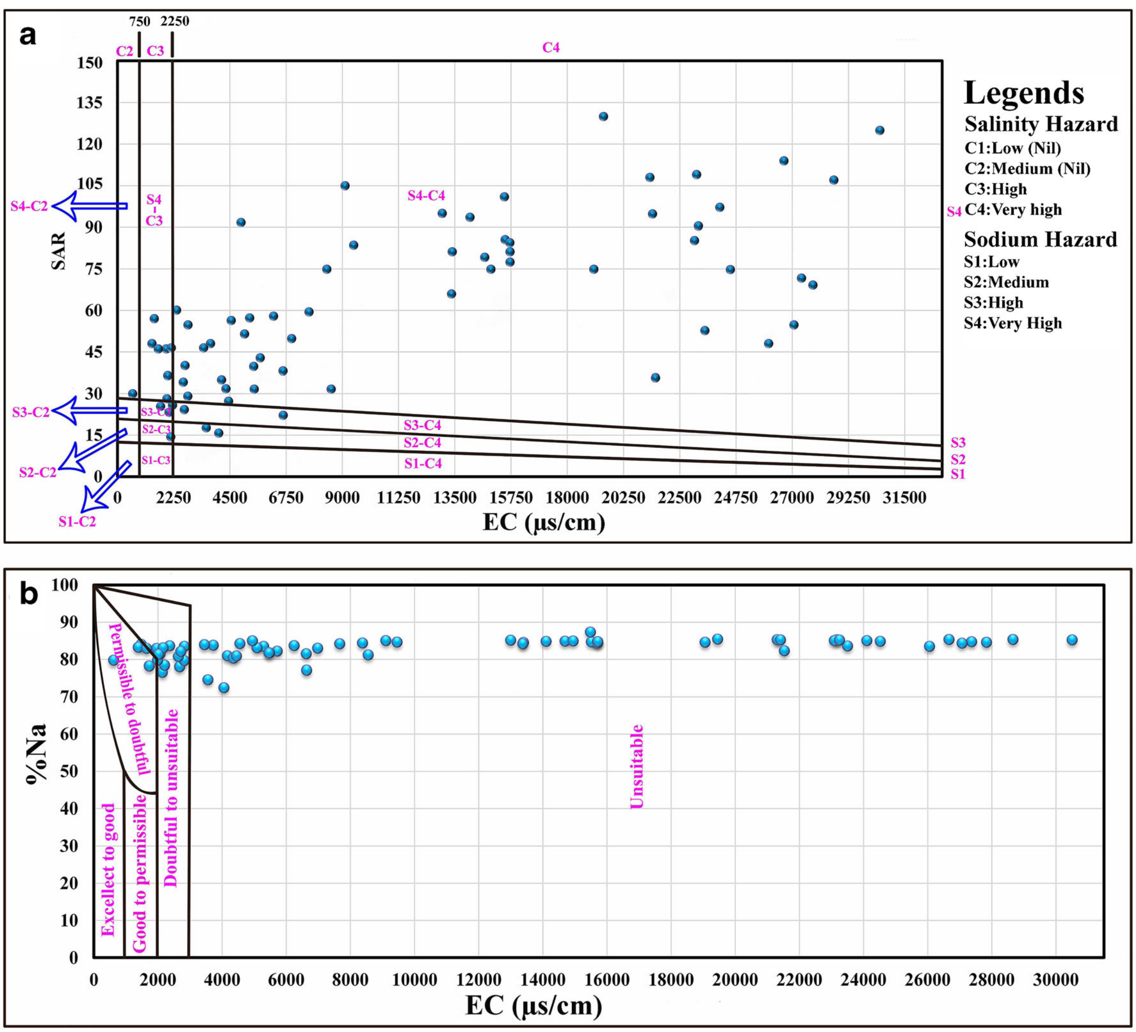


Fig. 8 The plot of **a** USSL diagram (Salinity Hazard (EC) vs Sodium Hazard) and **b** Wilcox diagram (EC vs % Na) has classified the investigation area

of Ca^{2+} and Mg^{2+}. It is divided on four distributional areas according to Table 2. From Fig. 6d, it is indicated that about 18.34 % are found in excellent class and 25% are found in good class, 45 % are found in permissible class, and at last, 12% are found in severe class.

Irrigation water quality index

Irrigation water quality index (IWQI) is interpreted as the technique that provides the appropriateness of plant life and soil substances. It has also represented that the composite influences the effect of mineral constituents monitoring the groundwater (Doneen 1962; Ghodbane et al. 2016). The assessment of irrigation suitability for the purpose of groundwater quality depends on the international standard (Matta et al. 2020; Raghunath 1987), and Bangladesh standard values have followed Eqs. 10, 11, and 12, and the results have been presented on different categories according to Table 2. The hydrochemical consequences from the chemical analytical process of groundwater in the study area have been further evaluated to identify the suitability for human consumption and purposes of agriculture. The general criteria for measuring the quality of irrigation on the purpose of groundwater are considered as the concentration of higher (Fig. 8, 9, and 10) salt (sodium and chloride). Sodium adsorption ratio (SAR), sodium percentage (SSP) and residual sodium carbonate

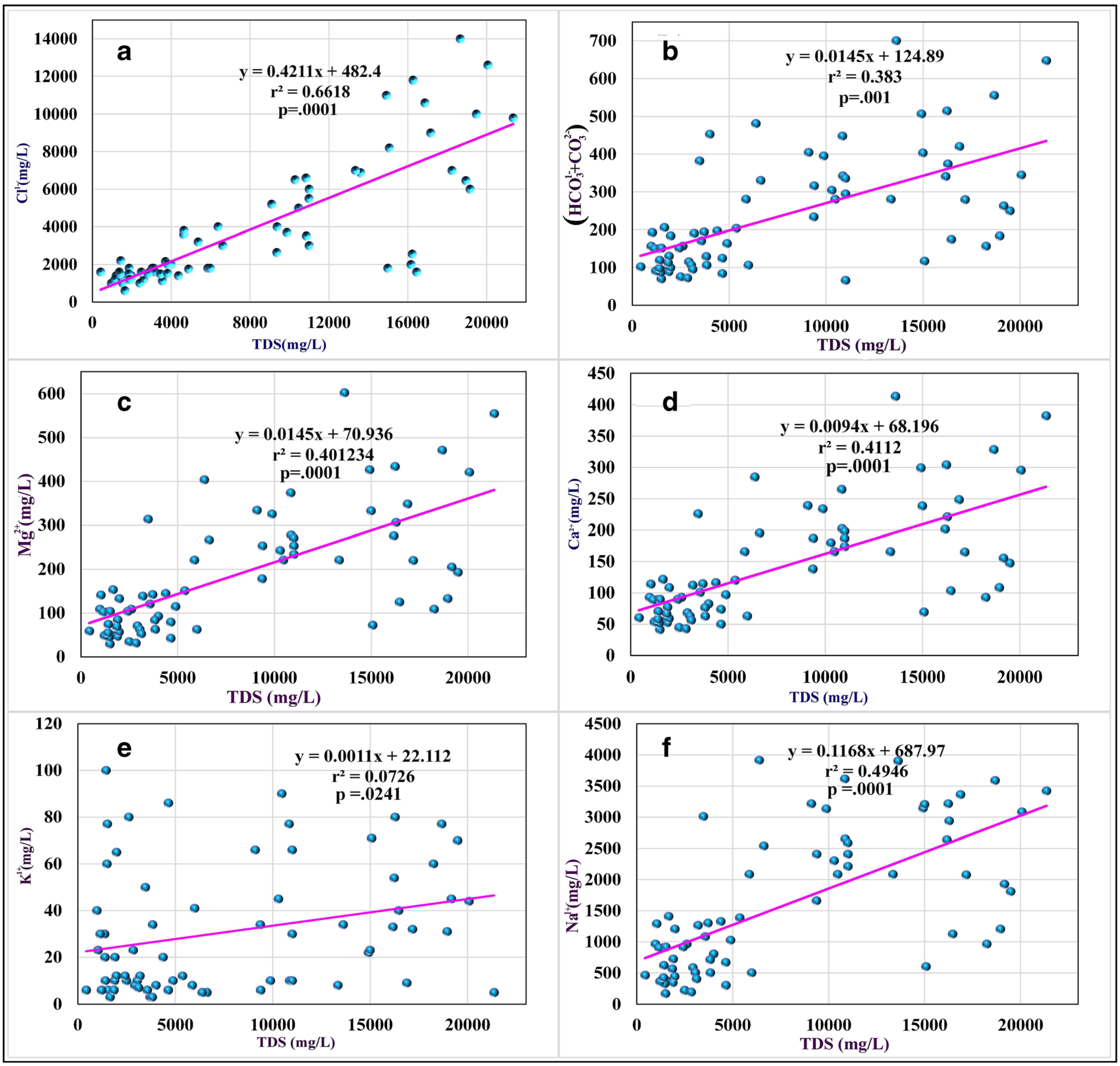


Fig. 9 Relationships among TDS and other major and minor hydrochemical ions (cations and anions) (**a**–**f**)

(RSC), KI (Kelly index), PI (permeability index), EC (Electro-conductivity), Cl (chloride), and Na (sodium) also controlled the irrigation suitability of groundwater. Some experiments (Ahmed et al. 2019a; Shamsuddin et al. 2019) suggest that sodium percent and electrical conductivity are important variables that can control the use and classification of groundwater for irrigation purposes. According to the quality ranges (Table 2), the establishment of groundwater quality of the Bagerhat district, the coastal plane is developed and is shown on Fig. 11 and Table 5. However, it is very concerning that there is no area that is in the groundwater category of the excellent zone (Table 5).

Geostatistical analysis

The investigation has been regarded as the spatial distribution on the indexes of water quality and major hydrochemical data, and it has been carried out through the spatial arrangement of geostatistical modeling in the investigation area. Arc GIS (V. 10.2) has been applied to calculate the models of semivariogram in the normalizing process on sets of data. In Fig. 12 according to this series (a) Cl^-, (b) EC, (c) K^+, (d) Na^+, (e) TDS, (f) SAR, (g) SSP, (h) TH, (i) MH, and (j) Fe have been shown the semivariogram of experimental process (points of scattered), respectively. It has indicated that around 80% of the plots (red points) of semivariogram have been found around near the omnidirectional areas (blue line). Table 6 illustrates the nugget; the major range's value of the semivariogram models for its best fit on hydrochemical and water quality indexes in the investigation area according to Fig. 12a–j. The range is defined by the distance of the hydrochemical area. It first fitted the model, and it is shown in various models with the fitted according to the semivariogram (Table 6). When the model has attained the

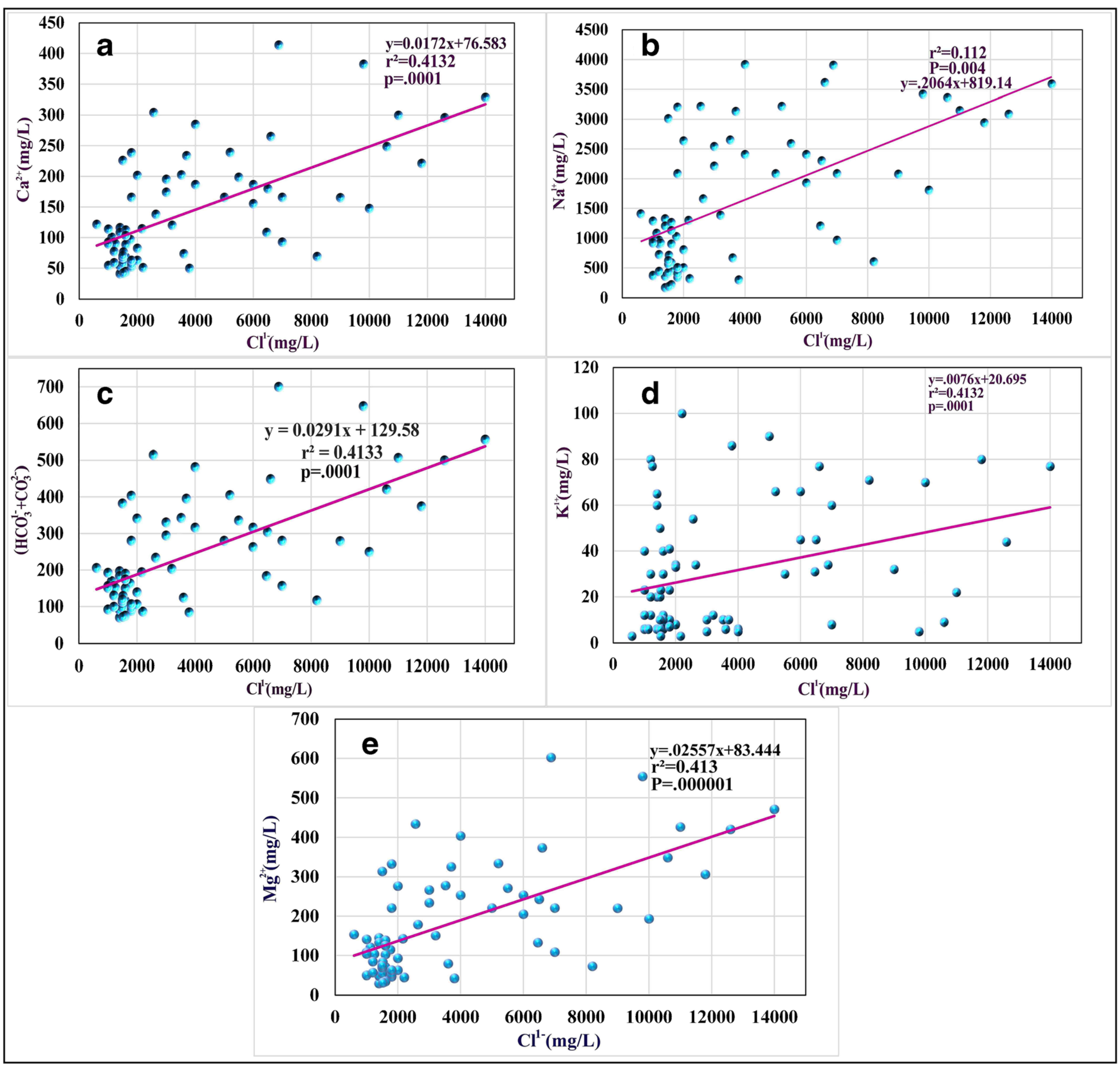


Fig. 10 The relationships between Cl with major cations and actions, such as **a** Cl^- versus Ca^{2+}, **b** Cl^- versus Na^+, **c** Cl^- versus ($HCO_3^- + CO_3^{2-}$), **d** Cl^- versus K^+, and **e** Cl^- versus Mg^{2+}

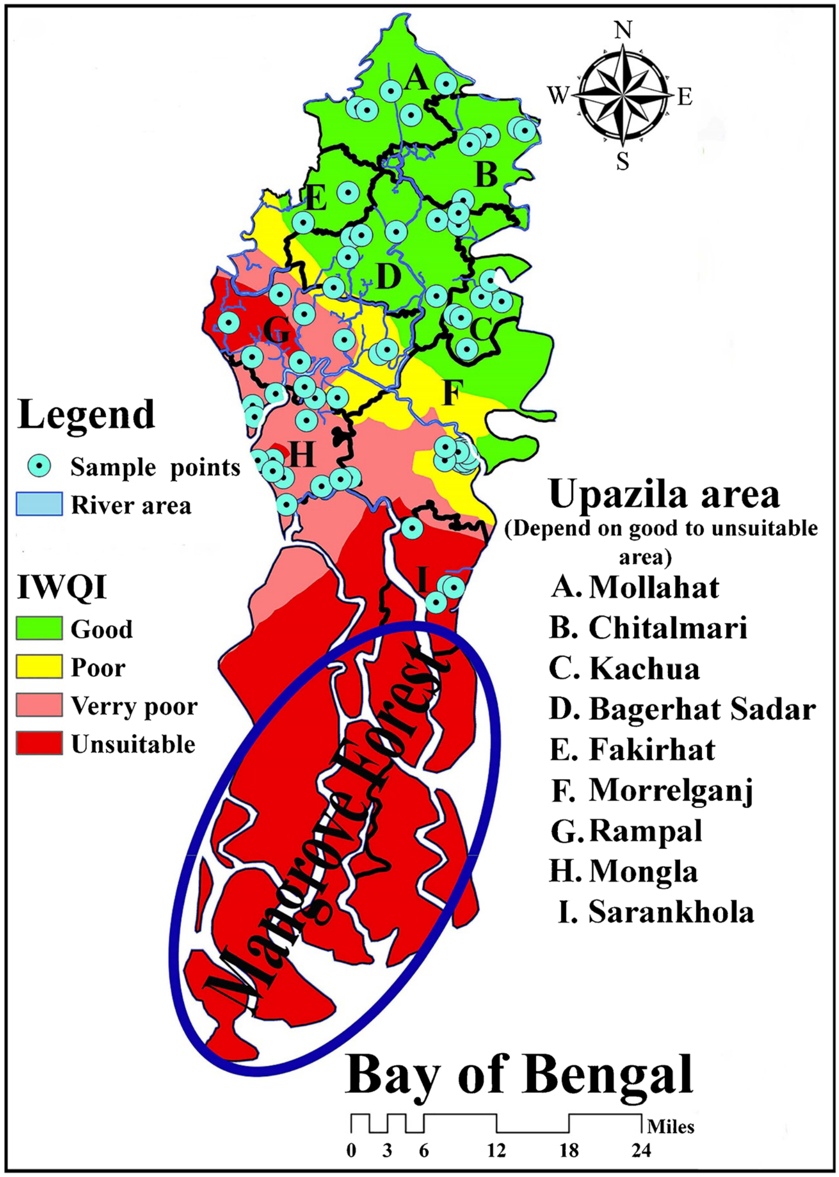
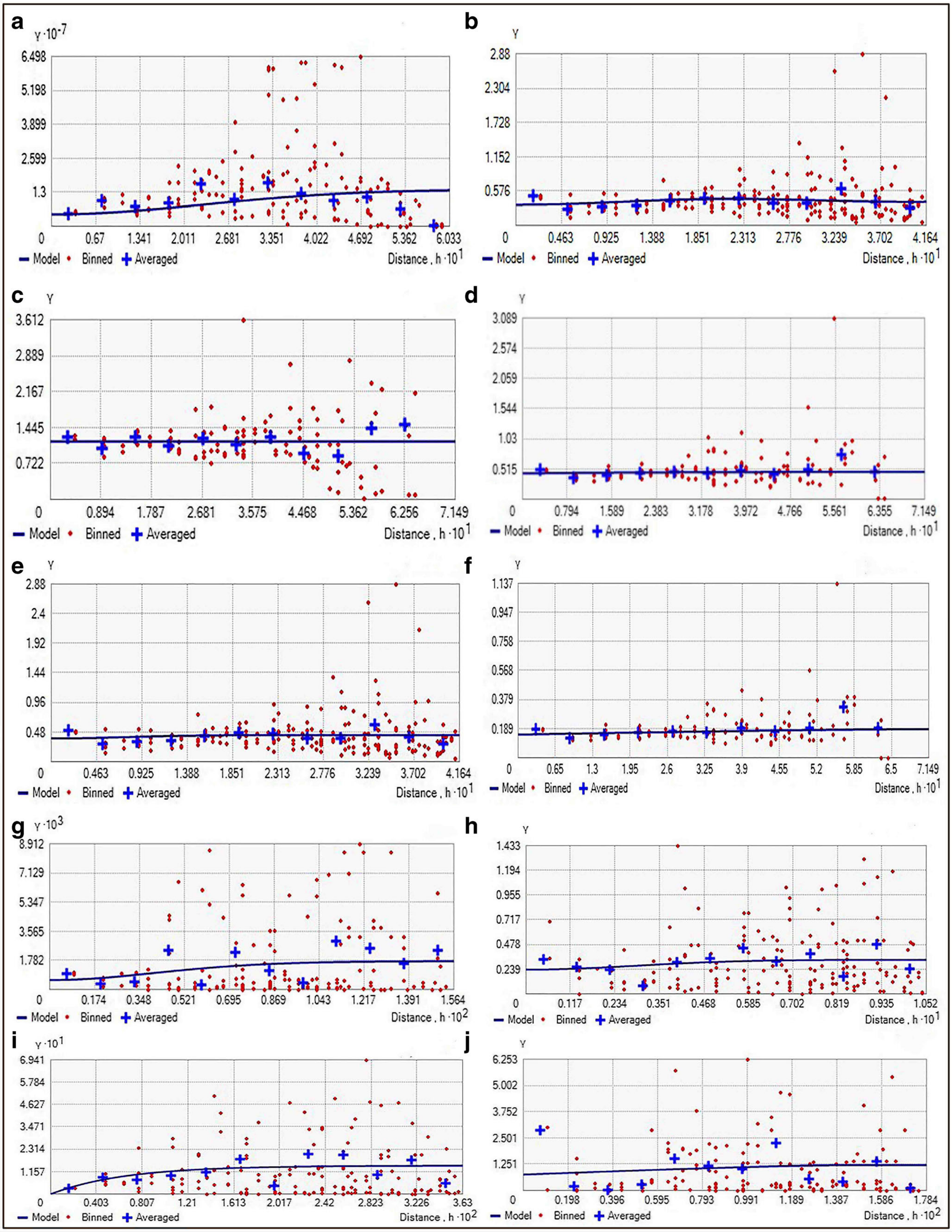


Fig. 11 The spatial distribution on IWQI and the indicated area for irrigation in the Bagerhat district

actual ranges, then the value has been called the sill. When the model has intercepted the direction of the y-axis, then it has been called nugget (Scott and Janikas 2010). The model is indicated as robust and accurate when the value of ME and

Table 6 The most suitable and best-fitted semivariogram models of hydrochemical parameters and their changes

Parameters	Model type	Nugget	Major range	Lag size	Mean	RMS	MS	RMSSE	ASE
SAR	Spherical	0.152	0.714	0.059	1.5539	47.06674	− 0.061	1.126	55.95701
Na	Exponential	0.438	0.714	0.059	85.887	1116.826	− 0.079	1.149	1642.32
TH	Gaussian	0.235	0.07	0.008	19.052	236.4642	− 0.075	0.815	303.076
MH	Exponential	0	0.036	0.003	− 0.164	16.24	− 0.049	0.848	21.56008
TDS	Gaussian	0.376	0.161	0.034	631.63	4147.361	− 0.02	0.901	7829.929
SSP	K-Bessel	0	0.015	0.001	0.0553	2.624515	0.0093	0.791	3.532121
Cl	Gaussian	36341	0.603	0.05	− 53.98	2686.636	− 0.027	1.15	2237.752
EC	J-Bessel	0.347	0.416	0.034	762.56	6186.523	− 0.064	0.984	10676.9
Fe	Exponential	0.017	0.884	0.001	− 0.02	1.201149	− 0.128	1.579	1.101257
K	Exponential	1.165	0.266	0.059	2.5008	94.39158	− 0.016	0.696	117.5677


a
Y ·10-7
6.498
5.198
3.899
2.599
1.3
0
0.67 1.341 2.011 2.681 3.351 4.022 4.692 5.362 6.033
Model Binned Averaged
Distance , h ·10¹
b
Y
2.88
2.304
1.728
1.152
0.576
0
0.463 0.925 1.388 1.851 2.313 2.776 3.239 3.702 4.164
Model Binned Averaged
Distance , h ·10¹
c
Y
3.612
2.889
2.167
1.445
0.722
0
0.894 1.787 2.681 3.575 4.468 5.362 6.256 7.149
Model Binned Averaged
Distance , h ·10¹
d
Y
3.089
2.574
2.059
1.544
1.03
0.515
0
0.794 1.589 2.383 3.178 3.972 4.766 5.561 6.355 7.149
Model Binned Averaged
Distance , h ·10¹
e
Y
2.88
2.4
1.92
1.44
0.96
0.48
0
0.463 0.925 1.388 1.851 2.313 2.776 3.239 3.702 4.164
Model Binned Averaged
Distance , h ·10¹
f
Y
1.137
0.947
0.758
0.568
0.379
0.189
0
0.65 1.3 1.95 2.6 3.25 3.9 4.55 5.2 5.85 6.5 7.149
Model Binned Averaged
Distance , h ·10¹
g
Y ·10³
8.912
7.129
5.347
3.565
1.782
0
0.174 0.348 0.521 0.695 0.869 1.043 1.217 1.391 1.564
Model Binned Averaged
Distance , h ·10²
h
Y
1.433
1.194
0.955
0.717
0.478
0.239
0
0.117 0.234 0.351 0.468 0.585 0.702 0.819 0.935 1.052
Model Binned Averaged
Distance , h ·10¹
i
Y ·10¹
6.941
5.784
4.627
3.471
2.314
1.157
0
0.403 0.807 1.21 1.613 2.017 2.42 2.823 3.226 3.63
Model Binned Averaged
Distance , h ·10²
j
Y
6.253
5.002
3.752
2.501
1.251
0
0.198 0.396 0.595 0.793 0.991 1.189 1.387 1.586 1.784
Model Binned Averaged
Distance , h ·10²

◀ **Fig. 12** The suitable-fitted of semivariogram models for the evaluation of groundwater on irrigation water quality indices in the investigation area: **a** Cl, **b** EC, **c** K, **d** Na, **e** TDS, **f** SAR, **g** SSP, **h** TH, **i** MH, **j** Fe

MSE is found close to 0; the value of RMSE and ASE is found lesser and RMSSE is close to 1. Mainly, the best model of semivariogram has been chosen by criteria of ME, MSE, RMSE, RMSSE, and ASE (Hu et al. 2004). According to Table 6, the variation hydrochemical parameters and indexes have been calculated. There were found three kinds of classifications that have been used to evaluate the total models: (a) when the ration is < 26%, it indicated the strong spatial dependence; (b) the range of 26 to 74% indicated the moderate impedance; (c) when the has been found > 75%, the spatial distribution has been mentioned as weak impedances. The strong spatial dependencies have been exhibited on TDS, EC, Na^+, Cl^-, SAR, and SSP (Fig. 12) of the hydrochemical parameters of the investigation area. The trace metals of Fe and K have been found to lower spatial impedances sp spatial distribution. Mainly, the major spatial distribution has evaluated the EC and Cl are considered as higher spatial impedances. The dependences of weak spatial distribution are presented (Fig. 12): Fe, K, total hardness, and magnesium hazard only in the monsoon and post monsoon both seasons. These have not found the best fit of spatial distribution. The major range has been varied from 0.07 to 0.88 km that is measured for the major dominant parameters Cl^-, EC, and Na^+ in the study area. The range of this variation has been influenced by topographic and geometric influences for the wide distance of the area of investigation. These factors have also affected groundwater samples (Ahmed et al. 2020a; Masoud 2014).

Remediation process of groundwater for coastal irrigation

Nineteen (19) districts of Bangladesh are in the coastal belt, and Bagerhat district, selected for this research, is one of them. There is a high impact on groundwater hydrochemical properties for the purposes of irrigation and in the coastal area, which is controlled by salinity. It is not possible to be totally controlled, but only proper remediation can be controlled. Depending on the Maas and Nieman (1978)'s suggestion, it has recommended that the crops from upper salt resistance to lower salt resistance have been represented in a sequence.

The crops series with its common and botanical name of higher to lower salinity resistance series (Ahmed et al. 2020a; Maas and Nieman 1978): barley > cotton > sugar beet > sorghum > safflower > wheat > beet, red > cowpea > alfalfa > tomato > cabbage > maize > lettuce > onion > rice > bean.

In addition, these are another series of crop's botanical name: *Hordeum vulgar*e > *Gossypium hirsutum* > *Beta vulgaris* > *Sorghum bicolor* > *Carthamus tinctorius* > *Triticum aestivum* > *Beta vulgaris* > *Vigna unguiculata* > *Medicago sativa* > *Lycopersicon lycopersicum* > *Brassica oleracea* capitata > *Zea mays* > *Lactuca sativa* > *Allium cepa* > Oryza sativa > *Phaseolus vulgaris*.

Conclusion

The hydrostatistical analyses and spatial distribution maps based on IWQI and geostatistical analysis have been used for the evaluation of irrigation quality in the coastal district of Bagerhat. This process has clarified the actual areas for the proper irrigation in Bagerhat district and which crops are proper in different lower to higher salinity areas have been also mentioned. This study has also been indicated that salinity has become a vital part in this district, and it has been a long-term effect on irrigation. The quality of groundwater on the purpose of irrigation has been proved by IWQI and geostatistical analysis. Therefore, the irrigation water indices (EC, SAR, TDS, TH, RBC, KI, SSP, and MH) were used to identify the suitable irrigation areas in this study. The irrigation sustainability in coastal Bangladesh has become in peril because of the intrusion of seawater, higher trial flow from the seawater, and sudden change of climate. The mixing of higher salinity in groundwater is damaged of soil substances and crop production. It is apparent that good quality of the water mainly controls the large production of the agricultural sector. However, as the salinity trend increases in the coastal areas of Bangladesh, people of many areas have started to understand the effect of using poor-quality water for the purpose of irrigation. It is not possible to control totally the mixing of salinity in the groundwater. Remediation is the main key process so that the effect of salinity can be minimized. The identification of suitable areas for irrigation purposes is considered as the main remediation process. The cluster analysis diagram and hydrochemical statistics showed that groundwater of this investigation area has become affected by higher salinity. In total, IWQI and geostatistical analyses have been used to show the areas of severe to excellent irrigation. It is very concerning that there is no excellent area for irrigation. Water quality in this area is closely related and influenced by the hydrogeological condition, sampling process and periods, laboratory, and statistical analysis of the samples and environmental factors. These mathematical and environmental issues have limited the entire method of water quality for irrigation purposes. The irrigation series of the Bagerhat district is showed from higher to lower quality of irrigation: Mollahat > Chitalmari > Kachua > Bagerhat Sadar > Fakirhat > Morrelganj > Rampal > Mongla > Sarankhola. According to the investigation of this study area, the following recommendations have been included.

- The total irrigation plan in the coastal area should be developed effectively. The plan should cover full coastal region at a period. In this regard, an artificial tank should be built in the study area for every farming land to preserve the water.

- The rice which is the main crop of Bangladesh could be cultivated in this coastal area due to the higher amount of water needed for its cultivation.
- During the rainy season, water could be stored by artificial ponds and lakes. In the dry season, this water could be used for irrigation purposes.
- For the proper irrigation, adaptation is considered very significant to accomplish groundwater resources. Crop (mainly the rice patterns) and salinity tolerance variation would be wanted to be broadly cultivated. Future research could be helpful and higher salinity tolerance crops could be provided to the farmers for proper irrigation. These are the salinity tolerance crops (Abedin and Shaw 2013): BRRI-dhan 47 (Boro dhan), BRRI dhan 40, BRRI dhan-41, (T. Aman varieties), Bari tomato.
- For irrigation purposes, deep fresh water could be used to avoid saline water which is available in the surface water. It has been recommended that the land edge size could be 1 m higher above the high tide level that would be protected from the land saline water intrusion.
- This study strongly suggested to monitor and control the affection level over the water table, to maintain proper groundwater management system, to control the drainage network and used the dams to monitor the connection with coastal areas to prevent the leakage of coastal channels.
- Finally, it should be monitored the agro-climatic zone, and various technologies could be applied according to the expert consultation and proper use of water.

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