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Groundwater salinization and associated co-contamination risk increase severe drinking water vulnerabilities in the southwestern coast of Bangladesh

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HIGHLIGHTS

- Groundwater was severely contaminated owing to salinity intrusion.
- High concentrations of EC, TDS, and Cl^- and low pH increased the co-contamination risk, such as from trace metals.
- High concentrations of co-contaminants in groundwater are a great concern for future drinking water security among coastal communities.
- Groundwater was completely unsuitable for drinking, which poses a significant public health risk.
- Statistical analysis showed a significant correlation between salinity and trace elements contamination, which was found to be consistent with local perceptions.

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ABSTRACT

Household drinking water security is one of the major issues among coastal communities in Bangladesh. To examine the groundwater quality and social consequences, groundwater samples and household questionnaires were administered across the study area. Instrumental and statistical tools were used to analyze the water quality and social survey data. The average concentrations of electrical conductivity (EC) (7135.67 μS/cm), total dissolved solids (TDS) (3691 mg/L), Na^+ (1569.51 mg/L), Ca^{2+} (289.5 mg/L), Mg^{2+} (340.51 mg/L), Cl^- (2940.78 mg/L), F^- (11.85 mg/L), NO_3^- (54.44 mg/L), NO_2^- (162.95 mg/L), PO_4^{3-} (105.19 mg/L), Fe (4.9 mg/L), Mn (1.22 mg/L), As (16.55 μg/L), B (833.28 μg/L), and Pb (34.22 μg/L) were observed in groundwater, and exceeded the drinking water standards from 30% to 100% depending on the sampling location. Thus, the remarkably high contents of EC, TDS, Cl^-, and Na^+ represented possible saltwater intrusion along the coastal aquifer. The positive correlations between EC and trace and toxic elements indicated the potential influence of groundwater salinization on the dissolution of more chemical contaminants in the aquifer. These results showed that 100% of samples were unsuitable for drinking purposes. Severe drinking water scarcity is a serious issue, and local people have been affected by water-related diseases owing to the long-term consumption of contaminated water. Salinity problems in drinking water and related health diseases have increased significantly in the past several years. In addition, climate change and its associated hazards, including sea-level rise, cyclonic storm surges,

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flooding, and resulting inundation problems, have intensified the drinking water scarcity and health problems at the community level. To ensure household water security, environmental exposure, hydrogeology, and anthropogenic interventions must be considered to determine future sustainable water policies.

1. Introduction

More than 844 million people presently face drinking water crises, and they have no access to good-quality potable water (WHO and UNICEF, 2017). Many of the water scarcity issues are related to diversified problems in terms of natural and anthropogenic causes. A number of causes, including increasing population, over-extraction of water resources, urban expansion, land cover change in watersheds, and climate change issues, are increasingly threatening water resources (Kim et al., 2018). In particular, climate change and its threats are now of great concern for conserving water resources. Salinity intrusion affects 11 Asian mega-deltas and other large estuaries, such as the Mississippi and Nile (Vineis et al., 2011). The availability of fresh water in large river basins, including those in East, Central, South, and Southeast Asia, is projected to decrease by the 2050s (IPCC, 2007). To meet the United Nation's Sustainable Development Goals (SDGs), safe drinking water is one of the key requirements to ensure sound public health, livelihoods, and food security (Sojobi, 2016).

In Bangladesh, approximately 99% of the total population uses groundwater as a main source of drinking water (Zahid et al., 2008), while 35 to 77 million people are considered at high risk for As contamination through drinking water sources (Edmunds et al., 2015) and 35 million people are facing serious drinking water crises because of freshwater salinization in the coastal aquifer (Talukder et al., 2016). Although Bangladesh is a low-lying deltaic country, its southwestern area is relatively flat and much lower than other parts of the country. The exposed coastal region lies approximately 1.5 m above mean sea level (Rakib et al., 2019b; Rahman and Rahman, 2015), and is highly vulnerable to climate change impacts, sea-level rise, flooding, and seawater intrusion. The frequency and magnitude of hydro-climatic extremes, such as cyclones, storm surges, and resultant inundation, have increased owing to the consequences of climate change (Penning-Rowsell et al., 2013). Mismanagement of polders[1] (Mahmuduzzaman et al., 2014; Rahman et al., 2000), flow control at the upstream barrage (Mahmuduzzaman et al., 2014; Rahman et al., 2000), land subsidence (Fakhruddin and Rahman, 2014; Bhuiyan and Dutta, 2012), and excess groundwater extraction (Chowdhury, 2010) may contribute to increasing salinization and deteriorating of groundwater quality. There is limited literature on how long-term salinity intrusion is altering the overall status of contamination in the coastal aquifer of Bangladesh. Correspondingly, the alteration of physicochemical parameters can change the chemical behavior of the aquifer composition and dissolution rate into water. In addition, the enrichment of dissolved toxic metals in water makes it unsuitable for use for drinking purposes and agricultural and industrial activities (Nazeer et al., 2014; Zhang et al., 2009; Wang et al., 2017). To control water pollution and protect water resources, it is imperative to determine the trace element concentrations, their source, distribution, and degree of health risks (Islam et al., 2014; Xiao et al., 2014; Wang et al., 2017).

Coastal communities are facing salinity crises in coastal aquifers (Bahar and Reza, 2010), and drinking water scarcity is serious. Many people regularly use contaminated water for different household activities, which is unsuitable for their health. According to the Food and Agricultural Organization (FAO) and World Health Organization (WHO), the recommended daily dietary intake of salt is less than 5 g/d (Nishida et al., 2004). The daily intake of salt is up to 16 g/d in many coastal communities through only 2 L of natural drinking water (Vineis et al., 2011). The total daily salt intake can vary according to the route of exposure, degree of contamination, pattern of household water usage, and regional environmental crises. Different routes of salinity exposure have potential links to health problems, including skin diseases, acute respiratory diseases, hypertension, diarrheal diseases, and miscarriage among pregnant women (Ministry of Environment and Forest, 2006; CDI, 2000;2005). The Safe Drinking Water Foundation (SDWF, 2018) mentioned that 80% of all the illnesses were caused by unsafe drinking water and sprawl water-borne diseases. However, today, drinking water scarcity can become a more severe condition owing to salinity intrusion and co-contamination. Few studies have emphasized the drinking water crisis owing to coastal salinity problems in terms of biophysical and social aspects (Rahman et al., 2011, 2017; Khan et al., 2008; Saha et al., 2018; Ahmed, 2011; Das et al., 2017; Sarkar and Vogt, 2015; Islam et al., 2017; Rahman and Bhattacharya, 2014; Shumaker, 2017); these studies did not explore how long-term salinity problems affect the groundwater and/or drinking water quality along the coastal belt of Bangladesh. There are a lack of studies on salinity contamination and co-contamination in groundwater and how co-contaminants, such as trace metals, and ions are spatially distributed and influenced by long-term salinization in groundwater aquifers.

The aims of this study were to assess the groundwater quality parameters and their distributions across the study area where salinization in the coastal aquifer is a principal constraint for drinking water in coastal communities; to determine how salinity influences overall groundwater quality parameters; and to determine the social perceptions of water quality and its consequences on lifestyle, such as the availability of drinking water and health impacts. This research will explain long-term salinization in coastal groundwater aquifers, and not only the creation of drinking water contamination and health impacts along the coastal belt of Bangladesh, but also the influence on aquifer steady-state conditions through the dissolution of more chemical components. In this study, inductively coupled plasma mass spectrometry (ICP-MS), atomic absorption spectrophotometry (AAS), and ion chromatography (IC) were used to analyze the water quality parameters. Statistical techniques, including the groundwater quality index (GWQI), multivariate statistics, and correlation analyses, were performed to assess the quality of drinking water and to identify the sources of contamination in groundwater aquifers. Some of the standard drinking water guideline was followed to observe the contamination status. In addition, a semi-structured household

[1] Polder is defined as "a polder is a low-lying tract of land that forms an artificial hydrological entity, enclosed by embankments known as dikes" (https://en.wikipedia.org/wiki/Polder), "In the 1960s, 123 polders (low-lying tracts of land enclosed by earthen embankments), including 49 sea-facing polders, were constructed to protect low-lying coastal areas from tidal floods and salinity intrusion in southern Bangladesh" (http://www.thenewhumanitarian.org/feature/2013/06/27/bangladesh-polders-under-threat).

questionnaire was used to examine the social perception of regional groundwater contamination and social impacts at the community level.

2. Materials and methods

2.1. Study area

This study was conducted in the southwestern part (Shyamnagar Sub-District, Satkhira District) of Bangladesh, as shown in Fig. 1. The study area was located around 22.3306°N and 89.1028°E, which was a relatively densely populated area. Shyamnagar Sub-District is very close to a mangrove forest and the Bay of Bengal. This area was considered highly vulnerable to climate change and sea-level rise because of its geographical location (the most southwestern part and its conical shape) and topographical features (mainly flat areas). The average elevation above sea level (MASL) ranged from 1 m to 2 m, and 45% of the study area was considered at high risk of a 1 m anomaly of cyclonic storm surges (Ministry of Environment and Forest, 2016). Most of the tidal channels and rivers were criss-crossed by the study area. This area was covered by the Ganges floodplain, which was mostly formed by sedimentation. The main components of the lithological units were silt to fine, medium, and coarse sands, the formations of which were less consolidated and blithely compacted (Adhikary et al., 2011). Since the last decade, sea-level rise and saltwater intrusion in the groundwater aquifer have been emerging issues in the southwestern coastal part of Bangladesh (Rakib et al., 2019a).

2.2. Sample collection

Groundwater samples were collected at 30 stations in June 2017 (Fig. 1). A total of 26 samples were collected from shallow tube wells (average depth of 30.68 m), and 4 samples were collected from deep tube wells (182.88 m). A global positioning system (GPS) was used to record the geographic locations. Before sampling, all the sampling bottles were shocked with 20% nitric acid overnight and then rinsed with deionized water to remove the internal and external contaminants. First, the hand tube wells were pumped from 3 min to 5 min to remove the aerated water from the upper part of the tube well pipe, as shown in Fig. 2. Through each of the tube wells, 1 L of water was collected in a polyethylene bottle. Airtight caps were used to avoid air exchange or contamination from the outside of the bottles. After sample collection, all the samples were sent to a laboratory of the Bangladesh Atomic Energy Commission within 21 h and kept it in a refrigerator at a temperature of under 4 °C.

2.3. Instrumental analysis

The temperatures and water quality parameters of pH, EC, and TDS were measured by following the American Public Health Organization (APHA, 1995) guideline during the sampling periods. The pH and EC were measured by using HANNA meter (model HI 98130). The pH meter was calibrated with pH 4.0, 7.0, and 10.0 standard solutions for the pH measurement. In addition, HANNA meter was calibrated with a standard solution of known conductivity to measure the EC (Rahmanian et al., 2015). Similar procedure was applied to perform the TDS analysis. The groundwater samples were processed for instrumental analysis following the standard methods of the American Public Health Association (APHA, 1998). Water quality parameters of Ag, Be, Bi, Cd, Cr, Hg, U, Th, V, Sc, Li, Pb, and B were analyzed using ICP-MS (Bruker 800), while Ca^{2+}, Na^{+}, Mg^{2+}, Zn, Fe, K^{+}, As, and Mn were analyzed using AAS (240 FS,

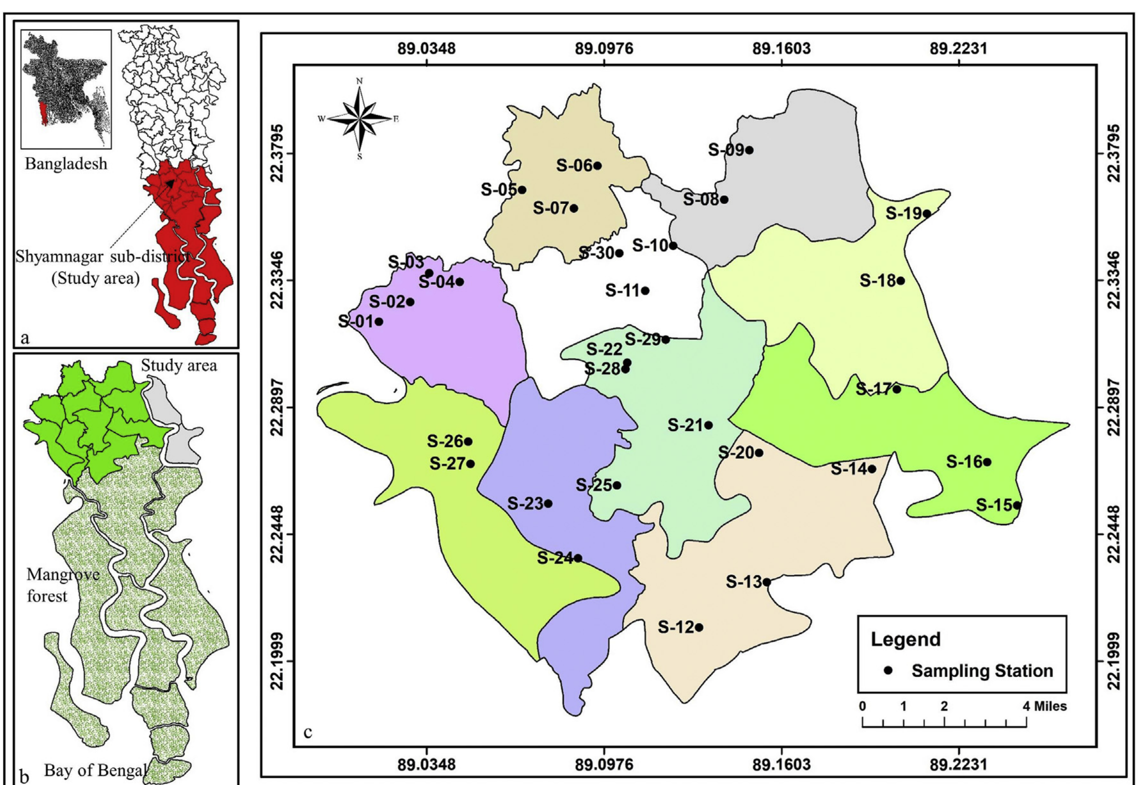

Fig. 1. Map of the study area with sampling stations.

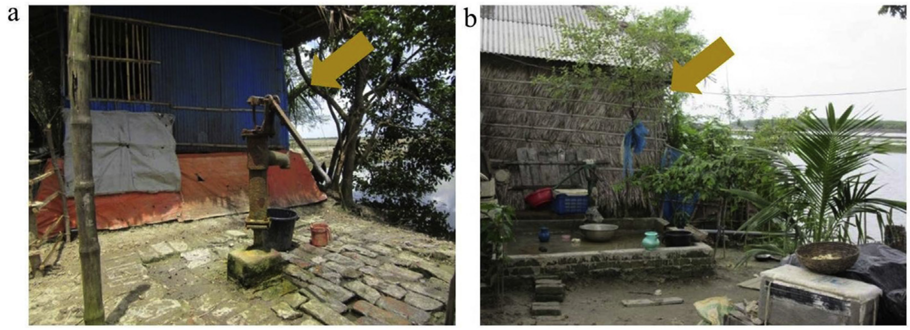

Fig. 2. Hand tube well water used for drinking purposes. (Source: Authors).

Varian). Further, F^-, Cl^-, NO_2^-, NO_3^-, Br^-, SO_4^{2-}, and PO_4^{3-} were analyzed using IC (Dionex DX-3000, USA). The National Institute of Standards and Technology standard reference material 1643e was analyzed to ensure the accuracy of the concentration measurements. All the measured (22) water quality values were compared with the drinking water standards established by the WHO (WHO, 2011), Department of Environment of Bangladesh DoE (DoE, 1997), Indian Standard (IS) (IS, 2012), United States Environmental Protection Agency (USEPA) Standard (USEPA, 2009), and European Standards (EU, 2011; Khalid et al., 2018). These comparisons were performed to evaluate the groundwater quality status for drinking purposes.

2.4. Geostatistical interpolation

To analyze the spatial distribution of water quality parameters, GIS (Geographic Information System) mapping and interpolation were performed using ArcGIS 10.4 software. To interpolate the water quality data across the study area, the ordinary kriging method was applied (Masoud, 2014; Tapoglou et al., 2014). The semivariogram is considered a principal model to determine the spatial differences between neighboring observations. The spatial distribution (Delhomme, 1978) among the random variables according to the estimation of values of unsampled locations was calculated according to the following equation:

$$\hat{z}(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \tag{1}$$

where $\hat{z}$ is the calculated value at an arbitrary point (x_0), z is the measured value at the sampling points (x_i), λ_i is a given weight at the sampling points, and n indicates the total number of sampling points (Webster and Oliver, 2001). The semivariance for each of the groundwater quality parameters was calculated as follows:

$$\gamma(h) = \frac{1}{2m} \sum_{i=1}^{m} [z(x_i) - z(x_i + h)]^2 \tag{2}$$

where m denotes the pairs of sampling points that are within a standard distance of lag h (Burrough and McDonnell, 1998).

2.5. Groundwater quality indexing

The water quality index can play an important role in setting up the demarcation of groundwater quality and suitability for drinking purposes (Tiwari and Mishra, 1985; Singh, 1992; Subba Rao, 1997; Mishra and Patel, 2001; Naik and Purohit, 2001; Avvannavar and Shrihari, 2008; Vasanthavigar et al., 2010). The GWQI is considered a robust approach to judge overall water quality while considering the composite influence of water quality parameters; it is calculated using the drinking water quality standards proposed by the WHO (2011) and EU (2011). A weight for each of the water quality parameters was determined depending on its relative importance in terms of drinking purposes (see Supplementary Table S1) (Tirkey et al., 2017; Bodrud-Doza et al., 2016; Vasanthavigar et al., 2010). The relative weight was calculated as follows:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{3}$$

where W_i is the relative weight of each parameter, w_i is the assigned weight of an individual parameter, and n is the total number of parameters. The rating of water quality (q_i) as a percentage was calculated as follows:

$$q_i = \frac{C_i}{S_i} \times 100 \tag{4}$$

Where c_i is the measured individual concentration of each of the water quality parameters and s_i is its standard value. The GWQI was calculated as follows:

$$GWQI = \sum_{i=1}^{n} W_i q_i \tag{5}$$

The GWQI was classified into five categories to justify the suitability of water for drinking purposes (see Supplementary Table S2).

2.6. Statistical analysis of measured water quality

Statistical analysis of measured water quality parameters was performed to evaluate the internal relationship using SPSS (IBM 21, Windows version). The Pearson correlation coefficient was determined using the measured parameters to identify the relationship. Multivariate statistical techniques, including principal component analysis (PCA) and cluster analysis (CA), were applied to determine the influential parameters and source apportionment by the data reduction process.

Multivariate statistics is commonly used to determine the source of environmental pollutants through correlation analysis, CA, and PCA (Mendiguchía et al., 2004; Han et al., 2006). PCA transforms the original data into a new form, namely uncorrelated variables (axes) that are linearly combined with original variables (Shrestha and Kazama, 2007). PCA is a powerful technique to reduce the dimensionality of original data sets; it aims to extract the most influential parameters through producing different components with minimum loss of original information (Helena et al., 2000). Consecutively, each component score describing the more prominent variables with their influence on all variables are given as follows:

$$y_i = a_{1i}x_1 + a_{2i}x_2 + a_{3i}x_3 + \ldots + a_{mi}x_m \tag{6}$$

where y is the component score, a is the component loading, x is the measured value of the variable, i is the component number, and m is the total number of variables. The component loadings are divided into three classes, namely strong (>0.75), moderate (0.75–0.50), and weak (0.50–0.30), depending on their absolute values (Liu et al., 2003; Gao et al., 2016; Wang et al., 2017).

CA is a reliable statistical method used to explore the internal relationships among the measured variables that exhibit similar characteristics through making an individual group. CA is preferred to assemble objects based on the similarity of internal (homogeneity within individual clusters) and external (heterogeneity among the clusters) characteristics (Shrestha and Kazama, 2007). Essentially, hierarchical agglomerative clustering is an important technique to determine the intuitive relationships among the measured objects within a cluster or entire data set, which is illustrated by a tree dendrogram (McKenna, 2003). The dendrogram itself is a visual summary of the data set that exhibits a significant reduction in the dimensionality of the original data set in relation to similarities or dissimilarities; it presents a picture and their closeness while the Euclidean distance explains the similarities between two samples and the distance represents the variation in analytical values of samples (Otto, 1998). For the source identification of water quality parameters, CA is a well-accepted technique that explores the connection between variables according to the source, abundance, and significant influence of the obtained analytical parameters.

2.7. Survey questionnaire

To understand the social impacts owing to the long-term consumption of contaminated water, information on local views was collected using a social survey. We performed a survey on household characteristics using a semi-structured questionnaire. The randomization technique was applied to perform the household survey in the coastal community. A total of 179 household questionnaires in these regions were analyzed to explore the local perceptions of groundwater quality, drinking water crisis, and its long-term consequences on health among the coastal communities. The questionnaire consisted of demographic information, groundwater quality, water access, and public health diseases.

3. Results

3.1. Concentration of chemical parameters in groundwater

The physicochemical parameters of groundwater indicate the suitability of water for drinking purposes. As displayed in Table 1, the pH of groundwater samples ranged from 4.71 to 7.53 with a mean value of 6.03. The standard pH of drinking water is between 6.5 and 8.5 (WHO, 2011). The average electrical conductivity (EC) of the groundwater samples was 7135.67 μS/cm with a range from 980 μS/cm to 14 160 μS/cm. The maximum permissible limit of EC is 400 μS/cm for drinking water (EU, 2011; Khalid et al., 2018). The average total dissolved solids (TDS) concentration in the samples was 3691 mg/L with a range from 550 mg/L to 7080 mg/L, which exceeded the drinking water standard of 500 mg/L (WHO, 2011). The average temperature of the groundwater samples was approximately 28.32 °C during the sampling period.

The average concentration of Na^+ was 1569.51 mg/L and ranged from 4.4 mg/L to 6494.3 mg/L, as shown in Table 1. The drinking water standards of the DoE (DoE, 1997) and WHO (WHO, 2011) recommended values for Na^+ concentration are both less than 200 mg/L. The measured Ca^{2+}, Mg^{2+}, and K^+ concentrations ranged from 25.11 mg/L to 889.8 mg/L, 39.69 mg/L to 1342.32 mg/L, and 2.42 mg/L to 158.3 mg/L, respectively. Among the major anions, the average concentration of Cl^- in drinking water samples was found to be 2940.78 mg/L with a range from 193.75 mg/L to 6033.81 mg/L.

Table 1
Descriptive statistics of physicochemical parameters, trace elements, cations, and anions of drinking water.

Parameters	Minimum	Maximum	Mean	Std. Deviation	Water quality standard			
					DoE (1997)	WHO (2011)	IS (2012)	USEPA (2009)
EC (μS/cm)	980	14160	7135.67	3433.58	1000[a]	400[b]	–	–
pH	4.71	7.53	6.03	0.61	6.5–8.5	6.5–8.5	6.5–8.5	6.5–8.5
Temp (°C)	18	32.2	28.32	2.87	20–30	–	–	–
TDS (mg/L)	550	7080	3691	1648.52	1000	500	500	500
Na^+ (mg/L)	4.4	6494.3	1569.51	1728.42	200	200	–	–
K^+ (mg/L)	2.42	158.3	28.54	34.78	12	–	–	–
Ca^{2+} (mg/L)	25.11	889.8	289.5	221.22	75	100	75	–
Mg^{2+} (mg/L)	39.69	1342.32	340.51	312.48	30–35	150	30	50
Cl^- (mg/L)	193.75	6033.81	2940.78	1563.53	150–600	250	250	250
F^- (mg/L)	BDL	62.93	11.85	16.83	1	1.5	1	2
Br^-(mg/L)	BDL	121.52	6.83	24.1	–	–	–	–
NO_3^- (mg/L)	BDL	376.73	54.44	80.11	10	50	45	10
NO_2^- (mg/L)	BDL	561.22	162.95	136.27	<1	0.50	–	1
SO_4^{2-} (mg/L)	BDL	2127.52	181.61	392.8	400	500	200	500
PO_4^{3-} (mg/L)	BDL	296.32	105.19	69.72	6	–	–	–
Fe (mg/L)	0.080	16.87	4.9	4.76	0.3–1.0	0.3	0.3	0.3
Zn (mg/L)	0.19	1.13	0.42	0.26	5	3	5	5
Mn (mg/L)	BDL	8.95	1.22	1.96	0.1	0.05	0.1	0.05
As (μg/L)	BDL	120.5	16.55	30.04	50	10	10	10
Li (μg/L)	BDL	1.82	0.18	0.48	–	–	–	–
B (μg/L)	110.89	2429.63	833.28	556.29	1000	500	500	–
Pb (μg/L)	BDL	159.75	34.22	40.89	50	10	10	–

BDL= Below Detection Limit.
[a] (Bodrud-Doza et al., 2016).
[b] (EU, 2011; Khalid et al., 2018).

The average concentrations of F^- and Br^- were 11.85 mg/L and 6.83 mg/L, respectively. The measured concentrations of NO_3^-, NO_2^-, SO_4^{2-}, and PO_4^{3-} were 54.44 mg/L, 162.95 mg/L, 181.61 mg/L, and 105.19 mg/L, respectively. All the mean concentrations of anions, except for SO_4^{2-}, exceeded the standard values. Moreover, the Na^+ and Cl^- concentrations were ubiquitously distributed in the groundwater samples, which may have been caused by saltwater intrusion in the coastal groundwater aquifer.

The mean concentrations of Fe and Zn were 4.9 mg/L and 0.42 mg/L, respectively, while the highest Fe concentration was 16.87 mg/L (Table 1). The ranges in As and Mn concentrations (within measured values) were from 2 μg/L to 120.5 μg/L and from 0.01 mg/L to 8.95 mg/L, respectively. In some samples, the Pb concentrations were significantly high, and ranged from 8 μg/L to 159.75 μg/L with an average concentration of 34.22 μg/L. The mean concentration of Li was 0.18 μg/L. The average concentrations of EC, TDS, Na^+, and Cl^- in shallow and deep tube-wells were found to be 7256.54 and 6350 μS/cm, 3605.77 and 4245 mg/L, 1546.05 and 1722.05 mg/L, and 2944.98 and 2913.46 mg/L, respectively. Thus, 61.90% (EC, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, F^-, NO_3^-, NO_2^-, PO_4^{3-}, Fe, and Mn) of shallow and 57.14% (EC, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, F^-, NO_2^-, PO_4^{3-}, Fe, and B) of deep tube-well water quality parameters exceeded the DoE, WHO, IS, and USEPA drinking water standards. The concentrations of the chemical components in shallow aquifer were slightly higher than the deep water.

3.2. Spatial distribution of chemical parameters in groundwater

The spatial distributions of the measured concentrations of chemical parameters are shown in Fig. 3, where deeper colors denote high concentrations. The distributions of TDS and EC had significant positive correlations across the study area. The average pH distribution across the study area was relatively low compared with the lower bounds of the drinking water standards. Similar distribution patterns were observed among Na^+, Cl^-, NO_2^-, and NO_3^-, while the individual concentrations varied. Likewise, homogeneous spatial distribution patterns were observed for EC, TDS, K^+, Ca^{2+}, Cl^-, SO_4^{2-}, NO_2^-, Fe, As, B, and Pb, whereas Ca^{2+} and F^- demonstrated similar distribution patterns.

3.3. Status of groundwater contamination

Groundwater contamination exhibits high concentrations of trace elements, major ions, and other organic matters in terms of drinking water standards. The average concentration of each element was compared with different drinking water guidelines established by the WHO (2011), DoE (1997), IS (2012), and USEPA (2009), as shown in Table 2. The concentrations of various chemical components of pH, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, F^-, NO_3^-, NO_2^-, PO_4^{3-}, Fe, Zn, Mn, As, B, and Pb exceeded their standard values by different percentages. The concentrations of EC, TDS, Ca^{2+}, Mg^{2+}, Cl^-, F^-, Br^-, NO_2^-, Fe, and Mn were significantly higher than those of the other parameters. Approximately 70% of parameters exceeded the WHO standards, and nearly 50% of the measured element concentrations (TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, F^-, NO_3^-, NO_2^-, PO_4^{3-}, Fe, Zn, and Mn) exceeded the DoE, WHO, IS, and USEPA standards. Almost all the samples exceeded the drinking water standards of the WHO, DoE, IS, and USEPA for the EC, TDS, and Cl^- concentrations. Approximately 87% of samples had the lowest level of pH, and were mostly acidic. Thirty percent of As-containing samples and 60% of Pb-containing samples also exceeded the WHO and IS standards for As and Pb concentrations, respectively, while the Zn concentrations in all the samples were lower than the standard values.

3.4. Suitability assessment of groundwater for drinking purposes

The GWQI represents the suitability of groundwater for drinking

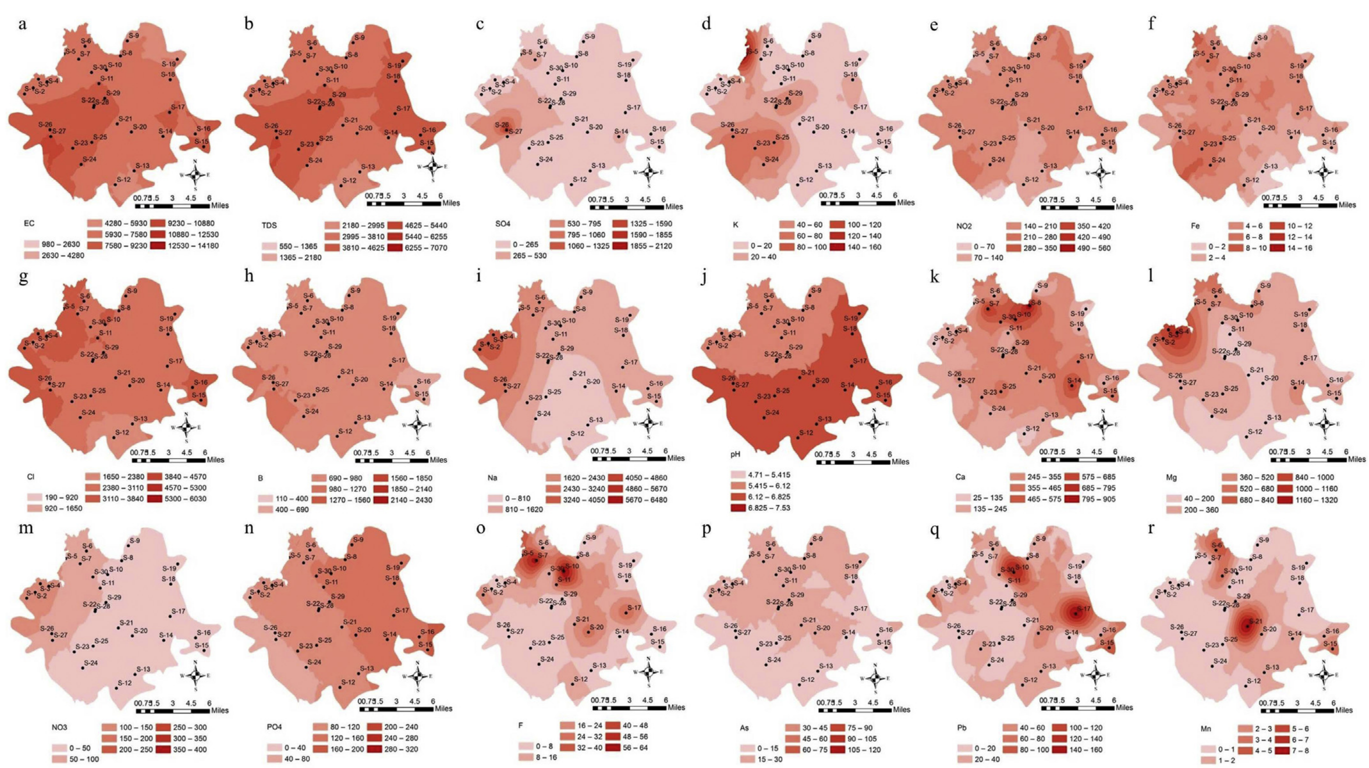

Fig. 3. Spatial distribution of salinity, trace elements, and ions.

Table 2
Comparison of measured groundwater quality parameters with global drinking water quality standards.

Parameters	Percentage of sample those exceeds DoE (1997) standard	Percentage of sample those exceeds WHO (2011) standard	Percentage of sample those exceeds IS (2012) Standard	Percentage of sample those exceeds USEPA (2009) standard
pH	86.67[a]	86.67[a]	86.67[a]	86.67[a]
TDS	93.33	100	100	100
EC	96.67[b]	100[c]	–	–
Na^+	66.67	66.67	–	–
K^+	53.33	–	–	–
Ca^{2+}	86.67	86.67	86.67	–
Mg^{2+}	100	80	100	96.67
Cl^-	90	96.67	96.67	96.67
F^-	60	60	60	60
NO_3^-	63.33	36.67	40	63.33
NO_2^-	76.67	76.67	–	76.67
SO_4^{2-}	10	6.67	23.33	6.67
PO_4^{3-}	96.67	–	–	–
Fe	63.33	86.67	86.67	86.67
Zn	100[a]	100[a]	100[a]	100[a]
Mn	73.33	76.66	73.33	76.66
As	13.33	30	30	30
B	26.67	66.67	66.67	–
Pb	20	60	60	–

[a] Below standards.
[b] (Bodrud-Doza et al., 2016).
[c] (EU, 2011; Khalid et al., 2018).

purposes, as displayed in Table 3. The GWQI score indicates the level of standard and how suitable it is for drinking. In this study, we calculated the GWQI scores at each of the sampling stations using the measured value of each water quality parameter. The estimated GWQI values mostly exceeded the standard limit score of 300 (unsuitable for drinking purposes). All the groundwater sample scores were 1–24.79 times higher than the standard GWQI values. These waters were found to be completely unfit for drinking purposes, and may enhance several waterborne diseases.

3.5. Correlation analysis

According to the results of the correlation analysis, there were correlations among the water quality parameters, which could reveal the possible sources of parameters or potential contributors of chemical components. Each pair of elements showed significant positive and negative correlations. A strong significant positive correlation was observed between EC and TDS and Cl^- (0.804–0.889; $p < 0.01$), whereas TDS also demonstrated a strong significant positive correlation with Cl^- (0.775). Each pair of elements, such as Na^+ vs. Mg^{2+}, Mg^{2+} vs. NO_3^-, pH vs. B, NO_2^- vs. SO_4^{2-}, and Fe vs. As, demonstrated strong significant positive correlations ($p < 0.01$), while their correlation coefficients varied from 0.592 to 0.701. Moreover, EC was positively correlated with K^+, Ca^{2+}, NO_2^-, Fe, As, Li, B, SO_4^{2-}, and Pb (0.209–0.424; $p < 0.05$). In addition, TDS was also positively associated with K^+, Ca^{2+}, NO_2^-, SO_4^{2-}, Br^-, Fe, As, Li, B, and Pb. Chloride demonstrated a significant positive correlation with Li ($r = 0.472$; $p < 0.05$). The internal relationships among groundwater quality parameters could be explored to determine the hydrogeochemical characteristics of the aquifer. The negative and positive correlations may have indicated the compositional variability of the contributing minerals or similarities of rock-forming minerals in the aquifer. The high abundance of saline water increased the dissolution rate of co-contaminants in the coastal aquifer, while TDS, EC, and Cl^- concentrations showed positive correlations among the co-contaminants, such as trace and toxic metals.

3.6. Multivariate analysis

The loading scores of different principal components (PCs) are shown in Table 4. In this study, eight PCs that exceeded an

Table 3
Groundwater quality index (GWQI) values and suitability status for drinking purposes.

Sampling Station	GWQI Score	Suitability Performance	Sampling Station	GWQI Score	Suitability Performance
S-01	621.02	UFD	S-16	2767.18	UFD
S-02	1562.18	UFD	S-17	3441.70	UFD
S-03	881.41	UFD	S-18	3091.83	UFD
S-04	835.57	UFD	S-19	4215.98	UFD
S-05	3507.71	UFD	S-20	2490.74	UFD
S-06	3575.78	UFD	S-21	5361.03	UFD
S-07	4120.98	UFD	S-22	361.85	UFD
S-08	2732.14	UFD	S-23	503.63	UFD
S-09	1822.98	UFD	S-24	585.23	UFD
S-10	4437.06	UFD	S-25	3637.74	UFD
S-11	3082.46	UFD	S-26	7435.80	UFD
S-12	1208.13	UFD	S-27	5540.77	UFD
S-13	362.53	UFD	S-28	3505.63	UFD
S-14	2380.53	UFD	S-29	735.89	UFD
S-15	2705.09	UFD	S-30	2874.46	UFD

UFD = Unsuitable for Drinking Purpose.

Table 4
Score loadings of varimax rotated principal component analysis for groundwater parameters.

Parameters	Components							
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
EC	0.94	−0.12	0.12	0.04	0.13	0.00	−0.11	−0.01
pH	0.02	−0.41	−0.25	−0.74	−0.00	−0.06	0.01	−0.17
Temp	−0.11	0.25	0.04	0.04	0.46	0.47	0.16	0.36
TDS	0.90	−0.11	0.10	0.01	0.22	−0.03	−0.06	−0.06
Na^+	0.03	0.88	−0.04	0.02	−0.02	0.02	−0.01	−0.25
K^+	0.27	−0.01	0.17	−0.27	−0.02	−0.21	−0.70	0.06
Ca^{2+}	0.32	−0.03	0.26	0.66	0.10	0.36	−0.05	0.03
Mg^{2+}	−0.06	0.87	−0.01	0.24	−0.15	−0.12	−0.12	0.03
Cl^-	0.89	0.073	−0.02	−0.11	0.21	0.19	0.12	−0.07
F^-	−0.03	−0.00	0.33	0.12	0.06	0.80	−0.05	−0.01
Br^-	0.11	−0.32	−0.16	0.38	0.37	−0.25	−0.00	−0.15
NO_3^-	−0.27	0.58	0.28	0.11	0.23	−0.02	−0.12	0.40
NO_2^-	0.27	−0.06	0.02	0.12	0.80	0.07	−0.03	−0.13
SO_4^{2-}	0.29	−0.05	0.09	−0.00	0.79	−0.18	−0.17	0.07
PO_4^{3-}	0.14	−0.26	0.23	−0.04	−0.20	−0.16	0.79	0.10
Fe	0.28	0.06	0.77	0.17	−0.18	0.19	−0.39	0.10
Zn	−0.06	−0.08	0.05	0.15	−0.07	−0.05	0.03	0.92
Mn	0.06	−0.30	−0.47	0.46	−0.01	−0.08	0.18	0.50
As	0.10	0.02	0.87	0.04	0.18	0.16	0.29	0.04
Li	0.43	0.12	−0.48	−0.18	−0.14	0.16	0.52	0.30
B	0.28	−0.18	0.09	−0.80	−0.10	−0.06	−0.14	−0.14
Pb	0.27	−0.17	−0.08	0.07	−0.27	0.72	0.09	−0.13
Eigenvalues	3.37	2.49	2.27	2.25	2.012	1.84	1.78	1.68
Total % of Variance	15.32	11.1	10.34	10.25	9.14	8.38	8.1	7.62
Cumulative %	15.32	26.62	36.96	47.20	56.34	64.73	72.82	80.44

eigenvalue of 1 with Kaiser normalization accounted for 80.44% of the total variance. Components whose eigenvalue was less than 1 were removed because of their low significance (Kim and Mueller, 1978). From Table 4, the first PC (PC1) explained 15.32% of the total variance, which was strongly and positively correlated with EC (0.94), TDS (0.90), and Cl^- (0.89); moderate and weak positive loadings were found for Li and Ca^{2+}, K^+, NO_2^-, SO_4^{2-}, Br^-, Fe, B, As, and Pb, respectively. The strong significant loadings score of salinity-related components may have contributed to accelerate the dissolution of more co-contaminants in the coastal aquifer. The second PC (PC2) explained 11.1% of the total variance, and strong positive loadings were found for Na^+ and Mg^{2+}; moderate positive loadings were found for NO_3^-; and weak positive loadings were found for temperature. Along with the impacts of salinization in the aquifer, inorganic fertilizer use in the aquaculture and agriculture fields led to the high ion exchange process, which may have increased the dissolution rate of ionic components, while the groundwater temperature showed a positive association with them. Similarly, 10.34% of the total variance was accounted for by PC3; strong positive loadings were observed for As and Fe and weak positive loadings were observed for F^-. According to PC3, As, Fe, and F^- may have originated from natural sources that were potential compositional unit components in some particular aquifer rocks. These contaminants could be positively influenced by salinity intrusion, which would increase the concentration of each component in the aquifer. PC4 explained 10.25% of the total variance, which showed moderate positive loadings of Ca^{2+}, while Br^- and Mn were weakly loaded. PC4 expressed the contaminants that were generally derived from natural sources. For example, the mineralogical composition and/or coastal depositions in the coastal aquifer zone were enriched with these types of chemical components. PC5 and PC6 explained 9.14% and 8.38% of the total variance, respectively, and had positive loadings of NO_2^- and SO_4^{2-} and of Br^- and Pb, respectively. Both PC5 and PC6 explored anionic contamination; ion exchange processes may increase with the salinization of the aquifer, inorganic fertilizers, pH, and geochemical reactions.

The CA exhibited the internal correlations of chemical properties of water quality parameters in relation to the source, hydrogeochemical, and mineralogical compositions. From Fig. 4a, according to the CA, three major clusters, namely Cluster-1, Cluster-2, and Cluster-3, were identified for measured water quality parameters. Cluster-1 was divided into two sub-clusters (Cluster-1a and Cluster-1b). Cluster-1a was grouped with EC, TDS, Cl^-, NO_2^-, SO_4^{2-}, Br^-, F^-, Pb, Fe, As, Ca^{2+}, and temperature; Cluster-1b was characterized by Zn, Mn, PO_4^{3-}, and Li. Cluster-1a was associated with all the components that were positively correlated with high salinity hazards in the coastal aquifer. It revealed that the characteristics of the contaminants were mostly similar in relation to abundance, source, and degree of contamination. In contrast, Cluster-1b, which consisted of chemical components, was also influenced by salinization, whereas external inputs to the aquifer, including inorganic fertilizers, may have further increased the overall dissolution mechanism.

According to the CA of sampling stations, two major clusters, namely Cluster-1 and Cluster-2, were found, as shown in Fig. 4b. Cluster-1 was divided into seven sub-clusters from Cluster-1a to Cluster-1g, which were consistently interlinked with each other. Cluster-1a was composed of almost 50% of the total sampling stations. Cluster-1 was associated with particular sampling stations with relatively high concentrations of salinity and co-contaminants. Cluster-1b to Cluster-1g were composed of the remaining sampling stations, which revealed that the natural and anthropogenic sources of contaminants originated from inorganic fertilizer and the associated impacts of salinity intrusion in the aquifers.

3.7. *Drinking water vulnerabilities and local perception*

According to the survey questionnaire, 95% of the respondents were male with ages ranging from 17 y to 65 y (Rakib et al., 2019b). Approximately 100% of respondents were locals who had lived in the southwest coastal area for a long time. According to the survey results, 94.67%, 92.33%, 97.33%, and 100% of people reported that salinity, Fe, As, and odor were consecutive threats in sub-surface

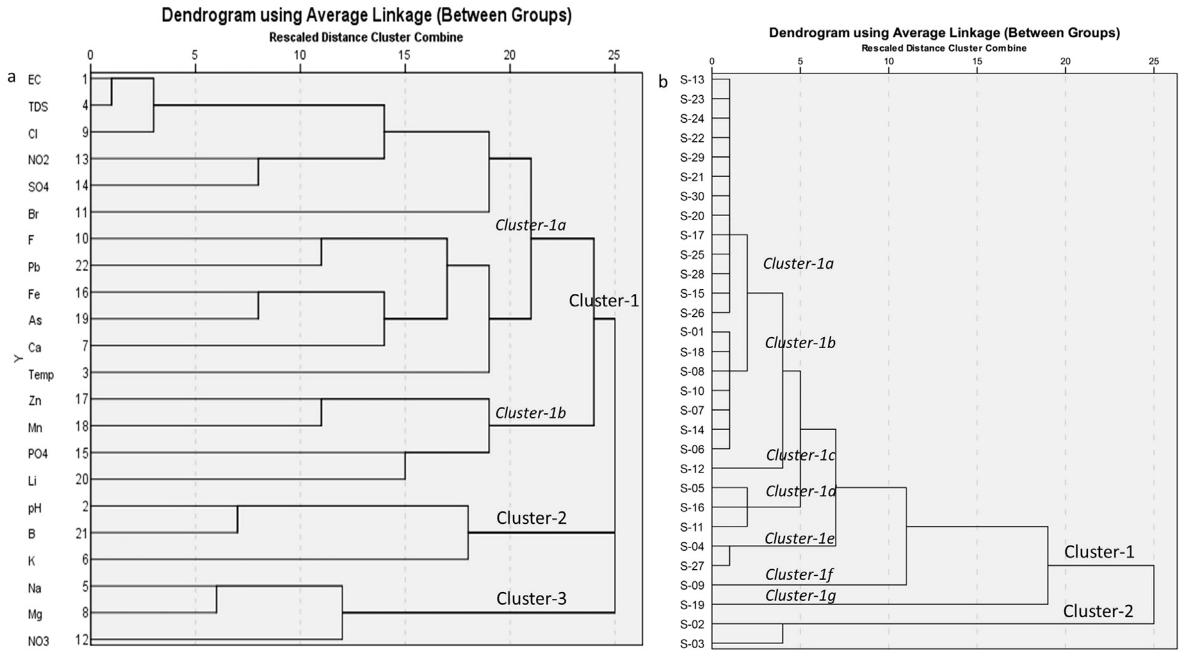

Fig. 4. Dendrogram representing the hierarchical clustering outputs. a. groundwater quality parameters and b. sampling stations.

drinking water, as shown in Table 5. According to the Likert scale results in regard to salinity hazards, most people reported that salinity in the groundwater had "highly increased" in the last few decades because of cyclonic storm surges, long dry seasons, and shrimp cultivation. Moreover, the local people stated that they had available groundwater, but was not suitable for drinking because of its high salt concentration. Salinity contamination in the groundwater aquifer has significantly increased in the last 10 y. Approximately 98% of the people reported that they had no consistent water supply system or alternative source of fresh water for drinking (Rakib et al., 2019b).

Salinity causes severe drinking water scarcity among coastal communities (Fig. 5a). Approximately 78% and 96% of the people depend on local pond and rainwater, respectively, as shown in Fig. 5b and c. According to local perceptions, people did not worry much about As and Fe contamination compared with the salinity problem in the groundwater. Local people judged drinking water contamination by symptoms, as they stated that "we feel bored when we drink saline water and sometimes it causes digest problems, while we do not feel anything for arsenic. We do not know whether it will cause health problems or not." In addition, they could not use surface water and groundwater for agriculture purposes owing to high salinity problems. One of the respondents reported that "in the last few years, high salinity has destroyed almost all fruits, trees, and vegetables. In particularly, during summer season it is impossible to grow vegetables or trees because of high salinity in the soil." In addition, local people frequently use inorganic fertilizers and other chemicals in shrimp aquaculture ponds to enhance productivity. One of the respondents reported that "we use chemicals to control pathogens and to increase productivity, but during the summer season when water level decreases in the shrimp ponds, the pond water spreads malodors to the surrounding areas."

Most of the respondents reported that some of the water-related health threats have become serious public health problems along the coastal belt. Approximately 65% and 90% of the respondents reported that chronic and acute diseases significantly increased in the last few decades. They stated that water-related problems and a high salinity environment were the principal causes of the spread of the coastal health crisis. According to the survey results, increasingly poor water governance and insufficient measures trigger worse conditions under climate change impacts.

4. Discussion

4.1. Groundwater salinization

The mean value of measured EC was found to be approximately 7100 μS/cm in the coastal aquifer, which exceeded the water quality standards for both drinking and agriculture purposes. The extremely high values of EC in the southwestern coastal area of the country indicated the occurrence of significant seawater intrusion in the aquifer. Similarly, this study found significant positive correlations between EC and TDS, Cl^- and TDS, and Cl^- and EC, respectively. To our knowledge, climate change impacts, such as sea-level rise, cyclonic storm surges, and water logging, also

Table 5
Local perceptions of groundwater threats according to the consecutive severity scale and changing status.

Groundwater Threats	First major threat (%)	Second major threat (%)	Third major threat (%)	Fourth major threat (%)	Changing status (last 10 years)
Salinity	94.67	5.33	0.0	0.0	+++
Iron	5.00	92.33	2.67	0.0	+/−
Arsenic	0.33	2.33	97.33	0.0	+/−
Odor	0.00	0.00	0.00	100	+/−

"+++" highly increased, "+/−" not confirmed.

Fig. 5. Representation of local drinking water vulnerabilities and adaptation strategies. a. collecting drinking water from a distance, b. harvesting rainwater from roofs, c. collecting drinking water from ponds, and d. collecting drinking water from desalinization plant. (Source: Authors).

increase seawater intrusion (Na–Cl type water) along the coastal belt. Thus, the salinity-contaminated water is projected to move further inland, and as a result, the intensity of contamination is expected to increase (Dasgupta et al., 2014; Nishat and Mukherjee, 2013; FAO, 2009). On the other hand, salinity values in groundwater are much higher than those in the other regions of the country, e.g., 317 mg/L, 319 mg/L, and 309 mg/L for TDS in Mokamtola (Shibgonj), Sabgram (Bogra Sadar), and Kusumdi (Sherpur), respectively (Islam and Shamsad, 2009), and from 290 to 498 μS/cm for EC in Rajshahi District in the northern part as well as from 128 to 2080 μS/cm for EC in Brahmanbaria District in the east-central part of Bangladesh (Hasan et al., 2007). Thus, a lack of availability of surface freshwater resources including downstream river flow, long dry periods, shrimp farming, and uncertainty of rainfall lead to changes in the coastal hydrogeologic environment, which creates instability in the steady-state condition of groundwater recharge, storage, and flow.

Sea-level rise and salinity intrusion in coastal aquifers are increasingly destroying the water quality in other countries, including Iran (mean EC of 3416 μS/cm) (Vesali Naseh et al., 2018), Djerba Island of southeastern Tunisia (mean EC of approximately 4560 μS/cm) (Souid et al., 2018), China (mean EC of approximately 1673 μS/cm) (Wen et al., 2019), Favignana Island of Italy (mean EC of 3979 μS/cm) (Tiwari et al., 2019), and Graciosa Island (EC ranging from 308 μS/cm to 3462 μS/cm) and Pico Island (EC ranging 186 μS/cm to 5625 μS/cm) of Portugal (Cruz and Andrade, 2017), thereby leading to a serious constraint on freshwater security. In comparison with these countries, Bangladesh is more severely affected by groundwater salinity pollution (Table 6).

4.2. Acidification of groundwater

Groundwater in the southwestern coastal area of Bangladesh was found to be mostly acidic. The mean value of measured pH in the groundwater samples from the study site was 6.03, which was lower than the standard range for pH of 6.5–8.5 (WHO, 2011), thereby indicating acidic pollution. These pH values are lower than those in the northern part of the country, e.g., 7.6 in Kuthibari (Dhunot), 7.6 in Sabgram (Bogra Sadar), and 7.3 in Kusumdi (Sherpur) (Islam and Shamsad, 2009). The pH of groundwater showed a strong positive correlation with the B concentration (0.64; $p < 0.01$), which indicated that the acidic nature of the groundwater may have increased B pollution. Lower pH values boost B desorption from mineral sites (Goldberg et al., 1996). By contrast, Wen et al. (2019) and Ha et al. (2019) reported the acidification of groundwater in the southwestern coastal areas of China (pH ranging from 6.80 to 6.96) and southern Vietnam (Ho Chi Minh City and the Mekong Delta) (average pH of 6.6). Thus, acidic pollution was found to be more serious in the southwestern coastal

Table 6
Comparison of groundwater quality parameters (pH, EC, and Cl^-) with some of recent studies on coastal aquifers in the world.

Country	pH	EC (μS/cm)	Cl^- (mg/L)	Reference
Bangladesh	6.03	7135.67	2978.40	Present study
Sri Lanka	7.69	2270	396	Bandara et al. (2018)
Mozambique	6.92	1445	–	Nogueira et al. (2019)
Tunisia	7.52	4560.54	1699.28	Souid et al. (2018)
Tamil Nadu, India	8.4	2616	705	Umarani et al. (2019)
South Africa	7.1	2687	753	Ntanganedzeni et al. (2018)
Gaza, Palestine	7.6	4189	–	Naeem et al. (2019)

*Comparison with mean values.

aquifer of Bangladesh (Table 6).

The oxidation of pyrite minerals is a possible cause of groundwater acidification (Ha et al., 2019; Appleyard and Cook, 2009; Benison and Bowen, 2015; Clohessy et al., 2013; Dickson and Giblin, 2009; Leyden et al., 2016; Mosley et al., 2014; Santos et al., 2011; Serrano et al., 2016). Similarly, acid rain (Fest et al., 2007; Franken et al., 2009; Hansen and Postma, 1995) and nitrification (Chae et al., 2004) cause groundwater acidification. Approximately 63% of the tube wells were found to be polluted with NO_3^- (Table 2), which may have decreased the groundwater pH. In addition, the occurrence of pyrite minerals in coastal aquifers is common worldwide (Dent and Pons, 1995; Schoonen, 2004). Polizzotto et al. (2006) reported that As-bearing pyrite minerals are commonly found in the groundwater aquifer of the Bengal Basin. Thus, the oxidation of pyrite minerals was another potential cause of groundwater acidification in the southwestern coastal area of Bangladesh.

4.3. Co-contamination risk

The long-term salinization in the coastal aquifer has significantly increased the co-contamination risk, which is a new threat to drinking water resources in coastal areas. According to the results of the correlation analysis, PCA, and CA, salinity was positively correlated with trace and toxic elements. Particularly, PC1 expressed that all the trace and toxic elements were positively loaded, while Cluster-1 for water quality parameters demonstrated significant similarities among this group. In addition, the CA for sampling stations and spatial distributions of these water quality parameters revealed that approximately 70% of the sampling points had pH values lower than the standard range as well as high salinity. This association is a significant concern and emerging threat for the coastal aquifer and freshwater security, as it may rapidly deteriorate the average water quality through the dissociation of other contaminants. Similarly, the impacts of groundwater salinization on trace elements have been reported in Djerba Island of southeastern Tunisia (Souid et al., 2018). Tully et al. (2019) proposed that seawater intrusion may significantly change the chemistry of tidal freshwater wetlands. Therefore, long-term or continuous salinization impacts may increase the dissolution rate of trace and toxic metals through changing the steady-state condition of the groundwater chemistry, especially physicochemical parameters. In addition, agricultural activities may contribute to groundwater contamination through leaching chemical components from the residuals of fertilizer. It is clear that both groundwater salinization and acidic pollution have led to an increase in contamination risk in the coastal belt of Bangladesh.

4.4. Groundwater suitability and scarcity

According to the GWQI results (Table 3), all the groundwater samples were completely unsuitable for drinking owing to the presence of high concentrations of measured chemical components, thereby posing a high health risk with long-term exposure. According to the survey questionnaire results, local people were only concerned with the salinity problem in their tube wells, while the majority of people did not know how it posed a long-term health risk. Rakib et al. (2019b) found that water-related problems increase the number of patients who suffer from diseases, such as high blood pressure, diarrheal, cardiovascular, acute respiratory, kidney, and skin diseases. High salinity in drinking water causes cardiovascular diseases, diarrhea, and abdominal pain (Chakraborty et al., 2019). We found that local knowledge of water contamination and disease was inadequate to cope with health problems.

Water scarcity is also becoming serious, and as a result, most of the local people stated that they have to use rainwater and polluted local pond water during water shortage crises. During these crises, only 5% of the households used treated water (desalinization plant water) to meet their emergency needs. From our observations, the socioeconomic status of the local people has been very fragile owing to frequent coastal disasters, such as cyclonic storm surges and floods; thus, most of them cannot afford to buy potable water to meet their daily needs. Rakib et al. (2019b) suggested increasing communal rainwater harvesting facilities, introducing low cost sustainable water treatment technologies, enhancing a common desalinization plant for households, and identifying a master aquifer to ensure the drinking water supply. Scheelbeek et al. (2017) recommended “managed aquifer recharge” strategy, which can provide low-sodium fresh drinking water. Thus, it is important to note that communal responses to this drinking water scarcity depends on coastal disasters, coastal geography, water access, local challenges, and economic constraints that must be taken into consideration to get the feasible drinking water sources.

Water scarcity in coastal areas has also been found in other countries. Inhabitants of Rach Gia City of the Mekong Delta in Vietnam are facing freshwater scarcity owing to groundwater salinity, and their government supports them by providing water with water supply tankers (Phuong, 2018). Tanzania is also facing freshwater scarcity owing to seawater intrusion and sanitation problems, and they are trying to adapt to the water crisis using rainwater harvesting systems (UN Environment, 2019). Panja (2019) reported that a coastal village (Mangamaripeta) of eastern India faces water scarcity problems owing to salinity intrusion in groundwater aquifers. Some villagers try to use piped water once or twice per week, while the rest use packaged water. In comparison with these countries, Bangladesh was found to be highly vulnerable to drinking water insecurity owing to seawater intrusion as well as co-contamination. To cope with these water crises, many of local people are practicing a number of drinking water adaptation techniques, which reflects a serious and vulnerable situation in terms of freshwater availability and salinity intrusion.

4.5. Water security challenges and policy implications

We found that local people did not want to use salinity-contaminated tube well water for domestic and drinking purposes. The availability of other freshwater resources was limited. We also observed that salinity intrusion led to the breakdown of coastal development trends owing to decreases in crop productivity and livelihood opportunities and increases in health risks and household costs. According to local opinions, the salinity in the surface and sub-surface waters was several folds higher than that in the past few decades, which may degrade the environmental equilibrium and living components of the freshwater ecosystems. In addition, land use changes in coastal areas, including a decrease in vegetation coverage in the inland areas, were risk factors responsible for increasing the evaporation rate during the long dry season, thereby resulting in extremely high levels of water salinity and deteriorating wetlands, communal lifestyle, and living conditions.

This study tried to explore how salinization, acidification, and chemical co-contamination affect groundwater quality and the local people, as well as their possible causes. Moreover, salinity intrusion and its recent increasing trend may be a potential constraint on future freshwater availability and development in the coastal belt of Bangladesh. To ensure sustainable, safe drinking water, it is important to formulate integrated policies considering all these concerns at the regional level. The government should also identify the potential sources of water in order to facilitate drinking water provisions. Local water resource management and conservation strategies should be redesigned in order to secure drinking water and reduce health risks. In addition, local awareness and skill management programs should be launched to enhance local adaptation techniques and knowledge to secure household and individual drinking water, thereby making the communities self-reliant and resilient, and to achieve the SDGs among the coastal communities in Bangladesh.

4.6. Limitations

Although the present study revealed the status of salinity pollution and co-contaminant along with their correlation, understanding of the detailed processes is still limited. The number of collected samples from deep wells was much fewer than that from shallow wells because ofthe difficulty in sampling; time series monitoring was not performed. In particular, a time series dataset may be required to separately evaluate the influences of climate change and anthropogenic activities, including management of agriculture and aquaculture. In terms of local perception, most of the respondents in the questionnaire were male and female perception is almost unknown. Understanding of female perception would be crucial to consider enhancing local capacity for dealing with the water scarcity problem and adapting to the increasing impact of climate change.

5. Conclusions

This study identified the groundwater quality status in the southwestern coastal part of Bangladesh by employing the interdisciplinary approach to clarify the current contamination and local drinking water scarcity problems. The GWQI results revealed that the groundwater among all the sampling points was completely unsuitable for drinking because of its high concentration of chemical components, including EC, TDS, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, F^-, NO_3^-, NO_2^-, PO_4^{3-}, Fe, Mn, As, B, and Pb. In particular, the concentrations of EC, TDS, and Cl^- were relatively high where almost all the samples exceeded the WHO, DoE, IS, and USEPA drinking water standard values. Long-term salinization of the aquifer and interference with other chemical parameters are significantly increasing the trace and toxic elements, cations, and anions. In addition, salinity intrusion in groundwater aquifers is greatly influencing physicochemical parameters, which dissolve trace elements; in particular, low pH also plays a substantial role in dissolving other contaminants.

Local people frequently used this contaminated water for several household activities. It is important to note that the local people only worried about salinity problems in drinking water and ignored or did not realize the consequences of other contaminants. Consequently, local communities are facing significant household drinking water crises and diseases. In addition, the combined impacts of salinity contamination in groundwater and its associated co-contamination may cause severe diseases in the near future. The presence of individual chemical components and their degree of contamination in groundwater, dissolution rate, exposure, and consumption rate may significantly influence disease frequency among coastal communities. Thus, groundwater contamination and health risk are associated with environmental exposure, geological conditions, lack of fresh water access and anthropogenic interventions. Further, coastal hazards and anthropogenic intervention in the coastal environment may lead to serious consequences for household drinking water and health security. The findings of this study would be helpful for decision making on the future sustainable drinking water security issues among coastal communities. The launch of integrated research along the coastal belt of Bangladesh is urgent in order to identify the cause of contamination, salinization, and severe health implications, and to determine alternative measures and/or to formulate hard and soft measures to secure fresh drinking water at the community level.

Author contributions

M.A.R. designed, planned, conceptualized, performed the analysis, drafted the original manuscript, and project administered, J.S. was involved in planning, designing, supervision, editing the manuscript, proofreading, funding acquisition, and project administration, H.M. was involved in statistical analysis, interpretation, Co-supervision, and consultation to write a draft manuscript, S.B.Q., M.J.M., M.B.D., A.K.M.A.U. and K.J.F. contributed to instrumental setup, analysis, proofreading, and validation, M.A.N. and M.A.H.B. were involved in software, mapping, proofreading and consultation during the manuscript drafting. All authors have approved the final version of the manuscript.

Declaration of competing interests

The authors declare no competing interests.

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Appendix A. Supplementary data

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