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Hydrochemical Characterization and Quality Assessment of Groundwater in Hatiya Island, Southeastern Coastal Region of Bangladesh

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Abstract: Groundwater is a vital source of fresh water for drinking and agricultural purposes in the region of Hatiya Island, Bangladesh, yet it is subject to contamination by natural and anthropogenic activities. Over time, the contamination has resulted in a variety of negative effects on human health. This research aims to examine groundwater hydrogeochemical characterization and suitability for irrigation and drinking purposes on different indices utilizing a combined geochemical method, multivariate statistical approaches, and geospatial analysis. Results of hydrogeochemical analyses of 15 groundwater samples from the intermediate aquifer (60–90 m depth) represent the order of cations, anions, and metal concentrations as $Na^+ > Mg^{2+} > Ca^{2+} > K^+$, $Cl^- > SO_4^{2-} > HCO_3^- > NO_3^-$, and $Fe > I > Br > Mn > As$, respectively. Saltwater intrusion has been determined to be the most important hydrogeochemical process influencing the chemistry of groundwater. Principal component analysis, Pearson's correlation matrix, and hierarchical cluster analysis indicate that groundwater quality is highly governed by geogenic influences. This information has been evaluated using a drinking water quality index map, which found that six (40%) of the groundwater samples are suitable for human consumption, whereas the other nine (60%) are unfit for drinking. The analysis of irrigation quality parameters revealed that eight (54%) of the groundwater samples are in excellent or good condition for agricultural uses; however, the other seven (46%) samples are unsuitable.

Keywords: groundwater geochemistry; quality assessment; coastal aquifer; Hatiya Island; Bangladesh

1. Introduction

Globally, groundwater is regarded as one of the most significant sources of potable water [1,2]. Over the course of the most recent few decades, there has been an enormous increase in the need for a supply of clean water. This demand has been brought on by a significant rise in population as well as an increase in industry, urbanization, and agricultural activity. Water is a primary natural resource that is required for various activities, including industrial, drinking, household, agricultural, recreational, and environmental ones [3–5]. Previous studies estimate that roughly one-third of the world's population relies on groundwater for drinking, and in Asia alone, millions of people are directly dependent upon groundwater supplies [6,7]. Yet, because it is a renewable natural resource and an essential component of the ecosystem, it is subject to both natural and human-caused consequences that may threaten the quality of groundwater and the health of those who use it [8].

Evaluations of drinkable and agricultural water focus on the chemical and physical properties of the water. Groundwater's level of danger or viability is established by the concentrations and types of ions it contains [9–11]. Chloride, sodium, and boron concentrations are often used to measure the hazard potential for irrigation, as they are toxic to many crops, even in low quantities. Research generally utilizes several parameters to quantify the quality of irrigation water, including the sodium absorption ratio (SAR), the

soluble sodium percentage (SSP), the residual sodium carbonate (RSC), and the electrical conductivity [12]. In addition, the water quality index (WQI) is a metric used to evaluate water quality with a numerical expression, making it possible to summarize vast volumes of complex water quality data quickly and easily. It is an important factor for assessing the human-use suitability of groundwater [13,14].

In Bangladesh, roughly 90 percent of drinking water and 75 percent of agricultural water originate from untreated sources of groundwater [15,16]. Given the geologic characteristics and potential for saltwater intrusion, there is potential for an excessive number of various cations, anions, and salts to be present in the groundwater [17]. Where the latter is concerned, the abundance of salts depends on the coastal environment, the source and movement of groundwater, and the freshwater channels [18].

Bangladesh has various sources for water supply; hence, analysis of water quality is often overlooked, and that is why an adequate amount of water is required for the purpose of irrigating agriculture. Irrigation with low-quality water diminishes soil production and modifies its physical and chemical qualities [19]. The quality of the water is significantly influenced by a variety of anthropogenic factors, including rapid population increase, unplanned urbanization, and rapid industrialization [20–22]. Excessive groundwater withdrawals and the use of fertilizers and pesticides in agricultural activities may also negatively impact water quality, primarily through chemical leaching into the groundwater [23,24]. In addition, the presence of heavy metal concentrations typically reduces agricultural land's yield. Low pH causes the dissolving and leaching of underlying rock, which has devastating effects on aquatic life and the surrounding area [25].

Most of Bangladesh's surface freshwater resources and shallow aquifers are susceptible to saltwater intrusion because the low-lying coastal zones are often inundated by seawater [26]. An increase in salinity in the coastal aquifer is typically the result of a variety of human activities affecting coastal water resources. These activities may involve a reduction in the flow of freshwater to estuaries, a modification of the mixing processes in estuaries, and an extension of marine influences further inland [27]. Contamination of freshwater resources by saltwater increases crop damage and deteriorates the quality of surface water [28]. As a result, the accessibility of water that is both of a sufficient quantity and of a quality that can be maintained is currently the primary concern in the coastal region. The diversity of pollutant sources suggests the need to study both the quality and geochemistry of groundwater supplies. The geogenic enrichment of arsenic (As) in groundwater as well as a saltwater intrusion in Bangladesh pose a major threat to the country's clean water supplies [29–33]. The coastal regions are at risk of groundwater contamination due to both geogenic and other anthropogenic activities [34].

Previous studies on Bangladesh's groundwater in urbanized and coastal areas focused mostly on hydrogeological and hydrogeochemical elements, particularly delineation and spatio-temporal assessment of groundwater potential zones [35–37], hydrochemical characteristics and quality assessment of groundwater [38–42], evaluating the quality and sustainability of groundwater using GIS and multivariate statistical methods [43,44], and vulnerability of arsenic-contaminated aquifers in Bangladesh due to geogenic sources [45–47]. Additionally, several studies on groundwater have been performed to evaluate its suitability for irrigation and drinking usage in Bangladesh [48–50]. Recent work has explored the health risks associated with heavy metal contamination on Hatiya Island [51]. However, the work conducted so far has barely focused on the relationship between groundwater quality assessment in coordination with hydrogeochemical characterization. This research aims to fill that gap by assessing the impacts of both natural and anthropogenic actions on groundwater chemistry and calculating groundwater quality indices to determine the suitability of groundwater resources for agricultural and drinking use.

2. Materials and Methods

2.1. Study Area

The study island (Figure 1) is in the delta, which is situated at the estuary's mouth of the Meghna River. The island is administratively located in the Noakhali district, which is composed of seven unions and has a total area of 849 km^2 [52]. These unions are named Char Ishwar union, Burir Char union, Nalchira union, Jahajmara union, Sonadia union, and Tamaruddin union. The region of interest spans the latitude range of 22.077° to 22.4° North and the longitude range of 91.0023° to 91.197° East. The study location is a part of the GBM delta, which is formed by the massive confluence of the Ganges, Brahmaputra, and Meghna (abbreviated as GBM). The study region is a low-lying and gradually sloped landmass, and it has a mean elevation of about 2.4 m [53]. Each year, billions of tons of sediment pour into the Bay of Bengal through the western and eastern channels of Hatiya Island. A minor percentage of these sediments settle in the south and southeast portions of the area [54].
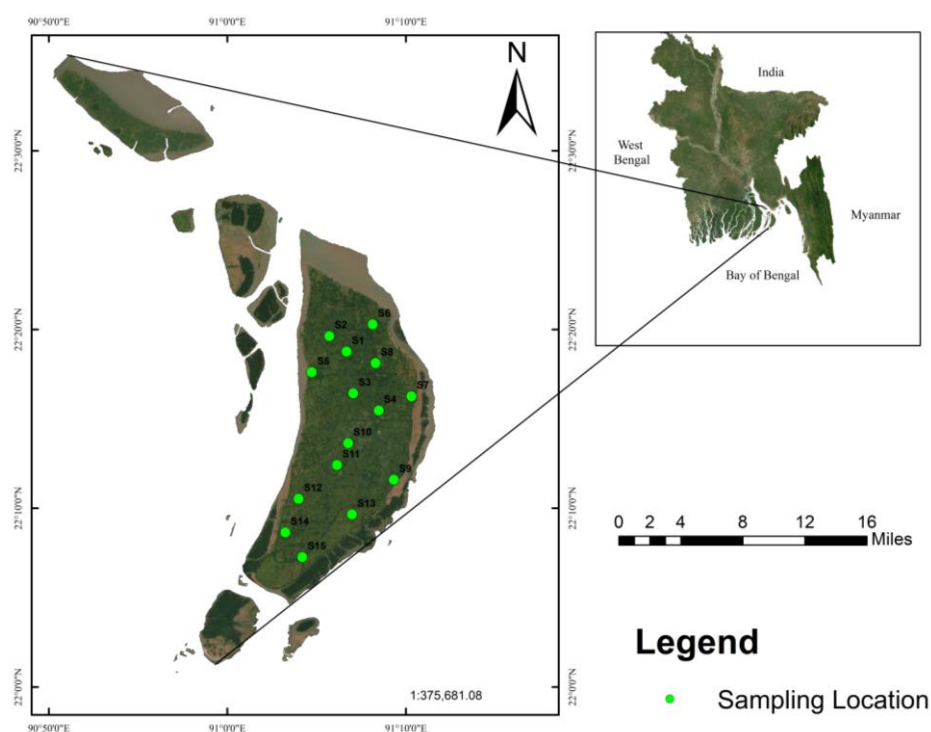

Figure 1. Map of the study area.

Upstream freshwater flows, Bay of Bengal tides, storm surges, tropical cyclones, and other marine meteorological happenings all contribute to the hydrogeology of Bangladesh's coastal plains [55]. The development of the aquifer along the shore was significantly aided by the presence of thick sedimentary deposits that date back to the Quaternary [56]. Based on groundwater composition, the aquifer has been classified or divided into three groups based on groundwater ages. These groups include a shallow aquifer with a depth of 10–30 m, an intermediate aquifer with a depth of 70–140 m, and a deep aquifer with a depth of 180–300 m [57].

Figure 2 depicts a lithologic succession of approximately 300 m in the study region, which can be used to evaluate the distribution, extent, and interconnection of aquifers and aquitards [58]. The lithology of the region consists of various sedimentary layers, including silty clay, silt, very fine sand, and fine sand. Groundwater is not drawn from the shallow aquifer because it is highly contaminated [51]. The shallow aquifer is surrounded by a layer composed of silt and silty clay, which is unsuitable for groundwater extraction. The

intermediate aquifer is bounded by silty clay layers. Below 180 m lies the deep aquifer, which is separated from the intermediate aquifer by a thick layer of silty clay.
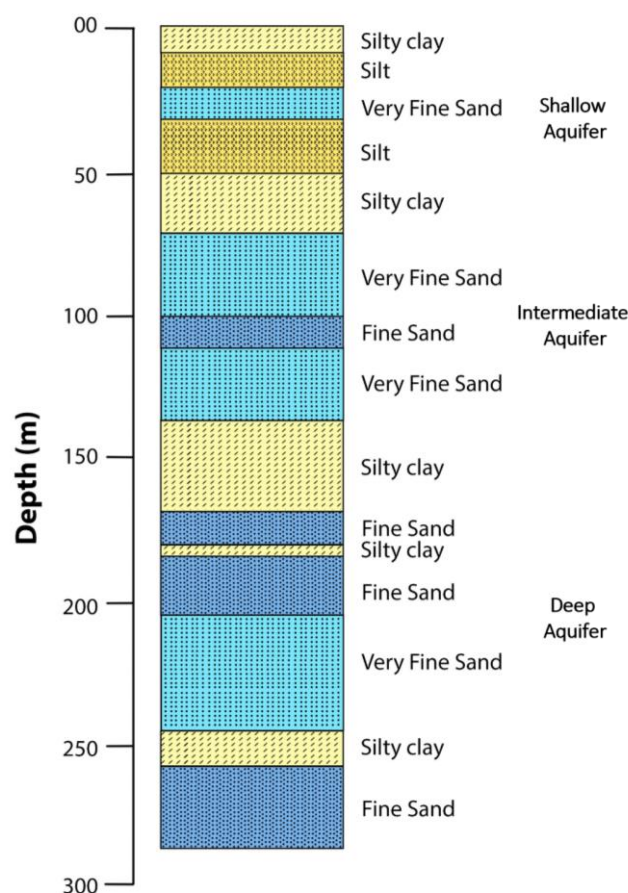
Figure 2. Cross-section of the underlying lithology.

2.2. Groundwater Sampling and Chemical Analyses

Fifteen samples of groundwater were taken from tubewells (LTW) with depth levels varying from 60 to 90 m (Figure 2). Sampling, preservation, and analysis were conducted based on the American Public Health Association's [59] standard protocols. Prior to sample collection, the tubewells were pumped to remove stagnant water [60]. Each location yielded two bottles of groundwater samples: one was acidified with concentrated HNO_3 (1% *v/v*), while the other remained unacidified. A syringe-head membrane filter with a 0.45-micron pore size was utilized to filter each of the samples. During the sampling process, calibrated portable multiparameter (Aquaread Water Monitoring Instruments — The AP-700 & AP-800 Water Monitoring Probe) equipment was used to measure index parameters, such as temperature (T), pH, electrical conductivity (EC), and total dissolved solids (TDS). The major cations, Mg^{2+}, Ca^{2+}, K^+, and Na^+, were evaluated in the laboratory by atomic absorption spectroscopy (AAS) (Thermo Scientific iCE 3000 Series), and the anions, SO_4^{2-} and NO_3^-, by UV-VIS spectrophotometer (HACH DR3900). The concentration of Cl^- and HCO_3^- was assessed by the method of standard titration (manual drop counted titrator) with H_2SO_4 (0.05 N) as titrant. Metals, such as Fe, Mn, and As, were evaluated by atomic absorption spectroscopy (AAS) (Thermo Scientific iCE 3000 Series), whereas I and Br were measured by a UV-VIS spectrophotometer (HACH DR3900).

Samples were handled with clean latex gloves and lab coats free of talc. During the analysis, analytical blanks and the standard reference were evaluated using the same method as the samples. In addition, functioning standards were evaluated for every ten

samples. To verify the analytical precision, an ion-balance calculation was conducted for the main ions using the following equation:

$$Ion\ Balance = [(\Sigma\ Cations - \Sigma\ Anions)/(\Sigma\ Cations + \Sigma\ Anions)] \times 100 \qquad (1)$$

2.3. Hydrogeochemical Data Analyses

The Piper trilinear diagram [61] and the Gibbs diagram [62], which show the equivalency ratios of $Na^+/(Na^+ + Ca^{2+})$ and $Cl^-/Cl^- + HCO_3^-$ with TDS, were employed to determine the hydrogeochemical facies and main hydrogeochemical activities in the aquifer [63,64]. Diagrammatically, Wilcox [65] proposed a system for classifying groundwater for agricultural use based on the percentage of electric conductivity (EC) and salt. Wilcox [65] categorized the suitability of water for irrigation into five distinct categories: excellent to good, good to permissible, permissible to questionable, doubtful to unsuitable, and unsuitable. The US Salinity Laboratory's (USSL) diagram for classified agricultural water, in which SAR is shown alongside EC, is widely used [12]. In the USSL diagram, SAR is a sodium hazard catalog, and EC is a salinity hazard catalog, displaying the classification of groundwater samples with respect to sodium hazard and salinity hazard, respectively. S1 refers to low, S2 medium, S3 high, and S4 very high sodium hazard levels. C1 refers to low, C2 medium, C3 high, and C4 very high salinity hazard levels.

2.4. Geostatistical Data Analyses

The origin of the solutes in the groundwater was determined using several multivariate statistical methods. Pearson's correlation matrix was utilized to evaluate the similarity or dissimilarity of the origin of parameters recorded in the collected samples of groundwater. Analyses such as a principal component analysis (PCA) and a hierarchical cluster analysis (HCA) were put to use in order to categorize groundwater samples in accordance with the geochemical characteristics of those samples [66–68]. PCA is one of the most widely used techniques for identifying the geochemical weathering processes associated with the mineralization process in groundwater and distinguishing the primary anthropogenic and natural processes impacting groundwater quality [66,69–72]. HCA was then applied to distinguish between groups of samples with comparable hydrochemical properties [73,74]. The software SPSS was used to perform all statistical analysis (version 20).

2.5. Spatial Data Analyses

To evaluate the spatial distribution of both water quality and associated health indices, we utilize several geospatial analysis techniques. Kriging was applied to interpolate sample data and estimate values between measurements [75]. Mapping the water quality index (WQI) is a straightforward approach to assessing whether water is suitable for drinking [13,76]. This index is composed of water quality indicators related to human consumption [77].

2.6. Water Quality Indexing

The water quality index (WQI) is a method for summing together complex water quality data to create a given level of quality indicator [16,78]. It is very critical in determining the suitability of groundwater for human consumption. WQI calculates an index value for each water quality metric to reflect the water's general quality at a particular location and time [79–82]. In this study, 13 parameters were taken into consideration: Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, Fe, Mn (all in mg/L), EC, pH, and TDS.

Each of the thirteen factors was given a relative weight (w_i) based on its relative importance for drinking and its effect on human health [83,84]. The allocated weight varied between 1 and 4. Health-affecting parameters are allocated 4, those responsible for diminishing the physical qualities of water and having minor effects on water quality are assigned a value of 3, while parameters with less significant effects are assigned a value of 2 [85–87].

The relative weight W_i was calculated as follows:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \text{,} \tag{2}$$

where w_i represents the weight of parameter i and n represents the total number of parameters in use. Table A1 provides both the individual and relative weights, as well as the WHO standards.

Then a quality rating qi was determined for each parameter by dividing the observed concentration by its appropriate WHO norm and multiplying the result by 100:

$$q_i = \left(\frac{C_i}{S_i}\right) \times 100 \tag{3}$$

where C_i is the concentration of chemical i in water (mg/L) and S_i is the drinking-water standard for each chemical (mg/L) according to WHO [78] recommendations; both numbers are in milligrams per liter.

In order to compute the WQI, SI_i was initially calculated for each of the chemical parameters using Equation (4). Then the WQI was calculated by adding up all the SI_i.

$$SI_i = W_i \times q_i \text{,} \tag{4}$$

$$\text{WQI} = \sum_{i=1}^{n} SI_i, \tag{5}$$

The sodium adsorption ratio (SAR), the sodium soluble percentage (SSP), and the residual sodium carbonate (RSC) are the three metrics that were used to measure the quality of irrigation water [88]. In order to compute the following indices, the concentration of each of the different ions was first translated into milliequivalents per liter (meq/L).

The sodium adsorption ratio (SAR) is a measurement of Na^+ in relation to Ca^{2+} and Mg^{2+} that is used to evaluate the hazard posed by sodium. The SAR is provided by [12]:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \tag{6}$$

The sodium soluble percentage (SSP), which is another essential benchmark for groundwater in relation to its suitability for use in irrigation, is calculated by using this formula [89]:

$$SSP\,(\%) = \left\{ \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \right\} \times 100. \tag{7}$$

This is the formula for calculating the amount of residual sodium carbonate (RSC) in groundwater [90,91]:

$$\text{RSC} = (HCO_3^- + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}). \tag{8}$$

## 3. Results and Discussion

3.1. Groundwater Chemistry

The variability of groundwater index characteristics is a leading indicator of the quality, type, and composition of the water [92]. The temperature of groundwater is approximately consistent through the year; however, it could experience a modest rise with increasing depth. The temperature of the groundwater in the area surrounding Hatiya Island was determined to be in the range of 23.8 to 28.2 degrees Celsius and did not display a significant amount of variance. Overall, most of the groundwater samples were neutral; however, the pH did range from slightly acidic to slightly alkaline (mean 7.5). Both the EC and TDS readings are interconnected, and it is possible to infer the salinity of the groundwater from their high levels. The electrical conductivity values of the groundwater samples range

from 412 to 14,930 μS/cm, and such high EC values suggested the presence of saline in the groundwater as a result of saltwater intrusion. The total dissolvable solids (TDS) in the groundwater samples varied from 272 to 9854 mg/L, which is indicative of the existence of salty groundwater. The concentration of significant ions in groundwater is mostly the product of water-rock interaction and gives insight into the ongoing hydrogeochemical mechanisms in the aquifer system. The main anions and cations present in the examined groundwater were $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and $Cl^- > HCO_3^- > NO_3^- > SO_4^{2-}$. Minor and trace metals in groundwater, such as manganese (Mn), iron (Fe), lead (Pb), chromium (Cr), arsenic (As), and cadmium (Cd), are necessary not only for the public health community but also for human health and the environment [93]. Minor and trace metal concentrations in groundwater indicate that the average abundance of metals in the region of Hatiya Island is in the following order: Fe > I > Br > Mn > As.

3.2. Hydrogeochemical Facies and Processes

3.2.1. Piper Diagram

Using Piper's [61] trilinear diagram (Figure 3), the values derived from the groundwater samples were plotted to find the hydrochemical facies that can provide insight on how the quality of groundwater differs between and within aquifers. [94]. Two prominent facies types can be identified: Na-Cl (85%) and Na-Cl-HCO$_3$ (15%). It reveals the dominance of Na^+ in cations, the interactions between HCO$_3$ and Cl^- in anions, and the influence of seawater in the studied area.
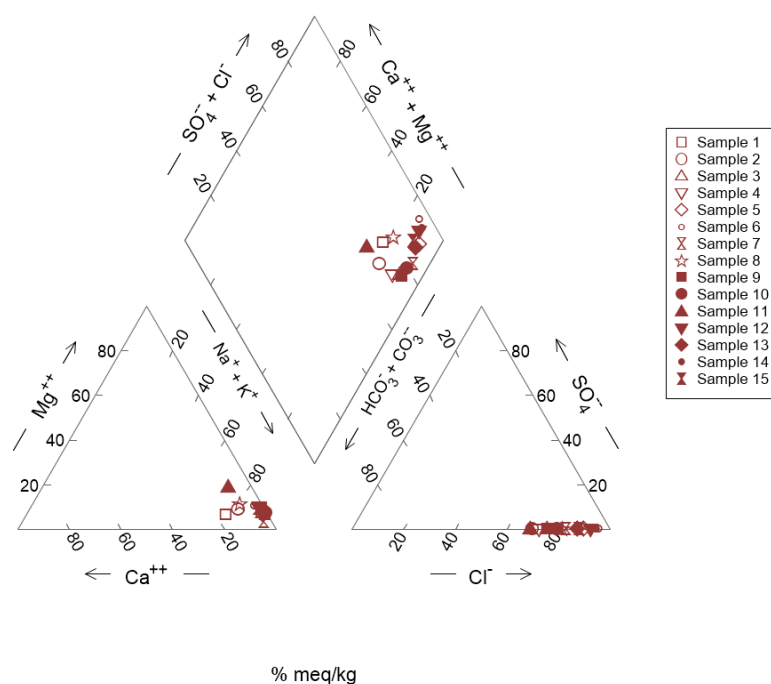
Figure 3. Piper trilinear diagram of the major ions representing hydrogeochemical facies.

3.2.2. Gibbs Diagram

According to the Gibbs diagram [62], the majority of samples are located in the upper portion, which is considered an evaporation-dominated zone. Controlling the groundwater chemistry in the aquifer framework involves saltwater intrusion [38]. However, some of the samples were found to be distributed toward the rock-water interaction dominant zone (Figure 4).
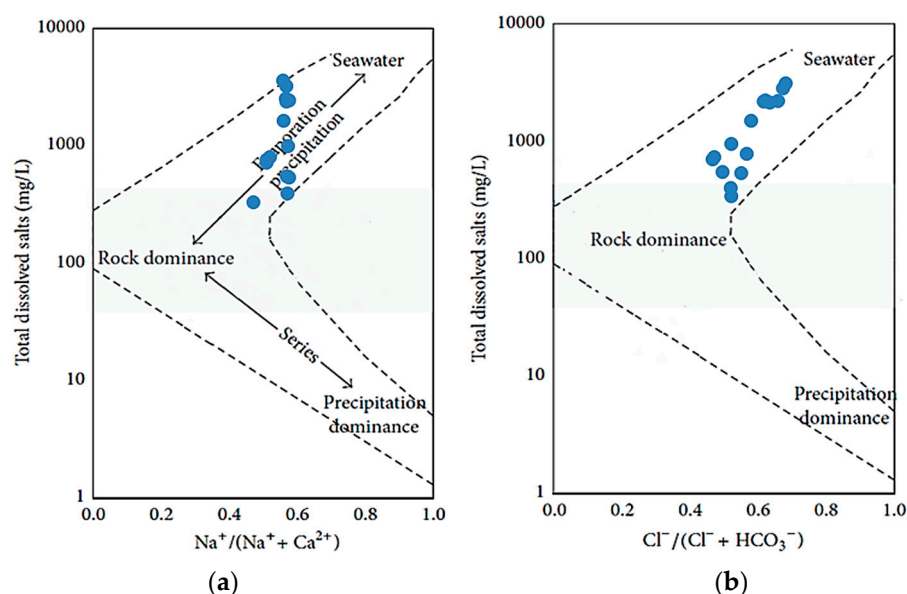
Figure 4. Gibbs diagram depicting dominant hydrogeochemical processes: (**a**) TDS vs. $Na^+/(Na^+ + Ca^{2+})$; (**b**) TDS vs. $Cl^-/(Cl^- + HCO_3^-)$.

3.2.3. Wilcox's Diagram

EC and Na play a key role in determining the suitability of groundwater for agricultural use. The increasing concentration of sodium in agricultural water will raise the sodium content of cropland, resulting in altered soil permeability that makes the soil difficult to irrigate [95]. Percent sodium is an expression used to determine the Na concentration in water used for irrigation. When classified based on %Na vs. EC, out of 15 samples, 1 was excellent to good, 5 were good to permissible to doubtful, 2 were doubtful to unsuitable, and the rest of the sampled locations do not fall within the diagram due to high values of EC (Figure 5).
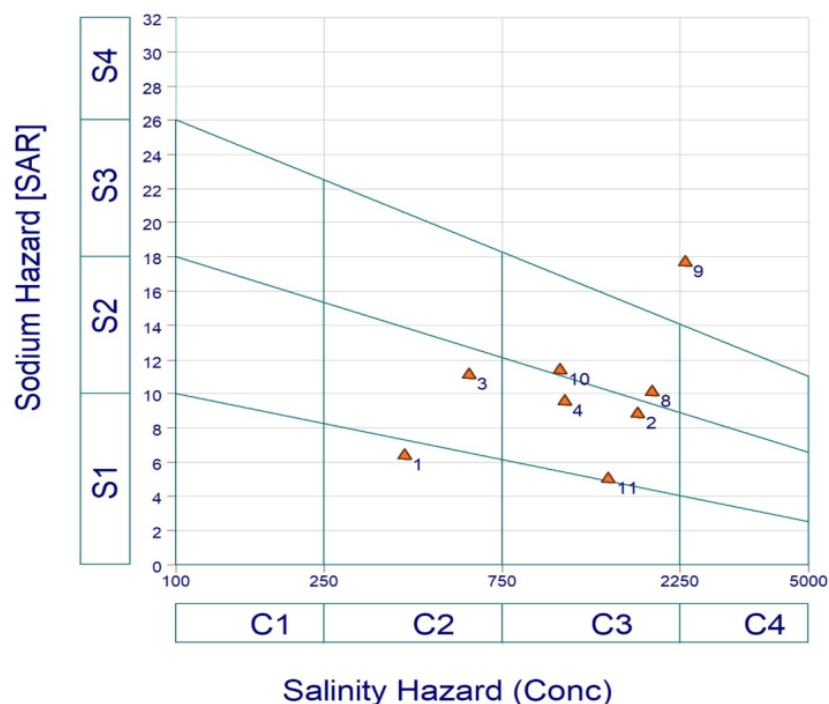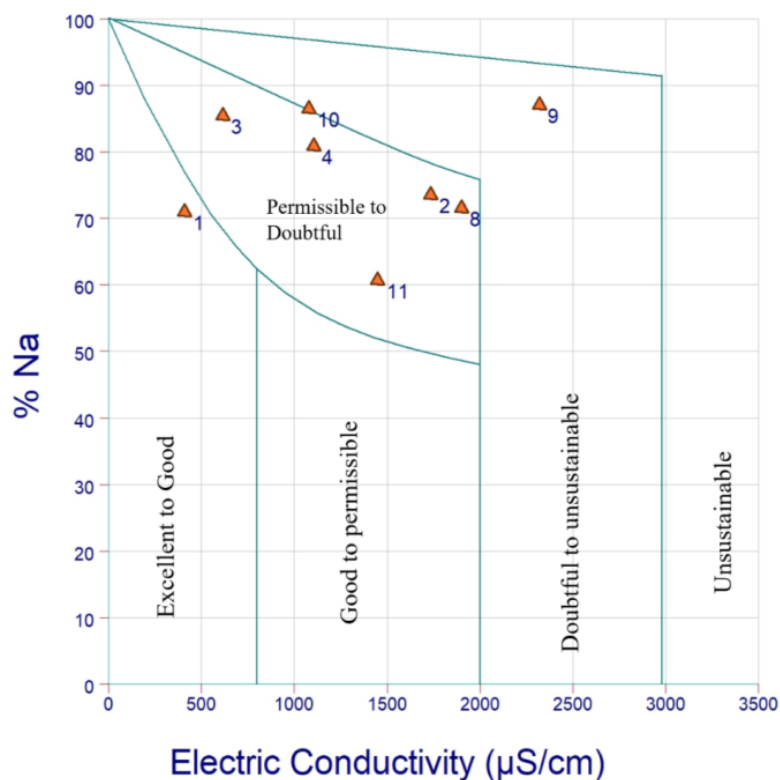

Figure 5. Classification of groundwater samples on the basis of electric conductivity and percent sodium [65].

3.2.4. U.S. Salinity Diagram

The analytical data shown on the graphic of the U.S. Salinity Laboratory (Figure 6) reveal that one water sample falls within the zone of C2S1 (suited for all plants but drainage should be good), four samples lie in the field of C3S2 (require drainage), two samples are in the field of C3S3 (unsuitable), one sample is in C4S4 (unsuitable), and the rest of the samples have EC values that are too high to fall into the USSL categories.

Figure 6. Classification of groundwater samples in relation to salinity and sodium hazards [96].

3.3. Geostatistical Analyses

3.3.1. Correlation-Matrix Analysis

Ca is moderately associated with Mg^{2+} (0.531), Na^+ (0.454), Cl^- (0.504), and Mn (0.491). Mg has a significant positive correlation with Na, Cl^-, Fe, EC, and TDS, but a strong negative correlation with pH. The EC (0.954) and TDS (0.954) had a significant positive correlation with the concentrations of Cl^- (0.95) and Na^+ (0.919), were negatively correlated to pH (−0.811), and had a moderate correlation with Fe (0.779) and Mn (0.621) (Table 1). Typically, Na^+ and Cl^- were the predominant ions in groundwater and the primary contributors to EC and TDS values. A significant association between the Na^+ (0.919), Mg^{2+} (1.0), and Cl^- (0.95) values suggests a common origin, namely the entry of saltwater. The moderate association between Na^+ and HCO_3 concentrations suggests that they may have originated from the same source, most likely rock weathering. The significant positive association between the Na^+ concentration and the Fe concentration (0.726) and the moderately positive correlation between the Na^+ concentration and the Mn concentration (0.518) suggest that reductive dissolution of Fe and Mn oxyhydroxides may occur in Na^+-Cl^- saltwater [97]. A moderate connection between Mn and Fe contents suggests reductive dissolution of Mn and Fe oxyhydroxides in the aquifer [98,99]. Poor relationships between As, NO_3^-, and the other parameters, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, and HCO_3^-, suggest anthropogenic causes [100,101].

Table 1. Correlations between the physiochemical parameters.

Ca	Mg	Na	K	HCO$_3$	Cl	SO$_4$	NO$_3$	Fe	Mn	As	I	Br	pH	EC (μS/cm)	TDS
1															
0.531	1														
0.454	**0.919**	1													
0.07	0.287	0.269	1												
0.19	0.361	0.58	0.155	1											
0.504	**0.95**	**0.993**	0.273	0.495	1										
−0.127	0.097	0.329	0.234	0.105	0.296	1									
0.157	0.347	0.286	0.412	−0.246	0.333	0.569	1								
0.325	**0.779**	**0.726**	0.075	0.11	**0.767**	−0.028	0.166	1							
0.491	0.621	0.518	0.108	0.099	0.561	0.205	0.4	0.496	1						
0.064	0.226	0.364	0.403	0.39	0.329	0.522	0.289	0.085	0.245	1					
−0.108	0.052	0.006	−0.095	0.203	−0.012	0.005	0.135	−0.007	0.332	0.125	1				
−0.076	0.017	−0.065	−0.095	0.098	−0.071	−0.048	0.187	−0.043	0.29	0.05	**0.984**	1			
−0.471	**−0.811**	**−0.766**	−0.207	−0.139	**−0.802**	−0.211	**−0.571**	**−0.752**	−0.648	−0.07	−0.136	−0.133	1		
0.48	**0.954**	**0.97**	0.242	0.403	**0.988**	0.27	0.378	**0.832**	0.571	0.302	−0.002	−0.051	**−0.825**	1	
0.48	**0.954**	**0.97**	0.242	0.403	**0.988**	0.27	0.378	**0.832**	0.571	0.302	−0.002	−0.051	**−0.825**	**1**	1

3.3.2. Principal Component Analysis

The measured physicochemical parameters (Ca^{2+}, Na$^+$, Mg^{2+}, K$^+$, Cl$^-$, SO$_4^{2-}$, HCO$_3^-$, NO$_3^-$, Fe, As, Mn, I, Br, pH, and EC concentrations) were subjected to principal component analysis (PCA) to evaluate the connections between the component levels and the significant factors that impact the groundwater quality and hydrogeochemical processes of the aquifer. The first four principal components have been selected because the eigenvalues are greater than one [102]. A total eigenvalue sum of 10.4 for the four principal components was calculated, which indicated a significant influence on the groundwater hydrogeochemical processes. The four components explain 79.94% of the total variance in the data. Table 2 is a tabular representation of the factor loadings, variance percentages, eigenvalues, and cumulative percentages of variance that are related to each of the four principal components. The retained PCA number has been visualized as a scree plot (Figure 7) to better comprehend the underlying parameter structure.

PC1 indicated 37.9% of the variance in the groundwater's physicochemical characteristics overall, influenced by the high positive loading of the Na$^+$ (0.968), Mg^{2+} (0.945), Cl$^-$ (0.982), Fe (0.785), Mn (0.667), and EC (0.978) concentrations and negatively loaded by pH (−0.84). High amounts of dissolved ions in the groundwater were responsible for the EC's loadings. The high values of Mg^{2+}, Na$^+$, and Cl$^-$ loading indicate seawater intrusion [38]. Both the redox state of the groundwater and the chemical weathering of Mn- and Fe-bearing rocks in the aquifer are believed to be responsible for the substantial loading of iron and manganese concentrations found in PC1 [43,99]. Fe and Mn enrichment in groundwater may also be caused by the microbial decomposition of Fe- and Mn-bearing minerals [103–106].

PC2 represented 16.87% of the total accounted variance, which was due to the positive loading of NO$_3^-$ (0.864) and As (0.813) concentrations. The greater concentrations of NO$_3$ and As are thought to be the result of agricultural operations, the outflow of urban wastewater, and effluent from the chemical and dyeing industries. [100,106–108]. Enrichment of arsenic in the groundwater may also be caused by natural processes [99,104].

Table 2. Factor loading of each physicochemical parameter of the groundwater with their eigenvalues and variance.
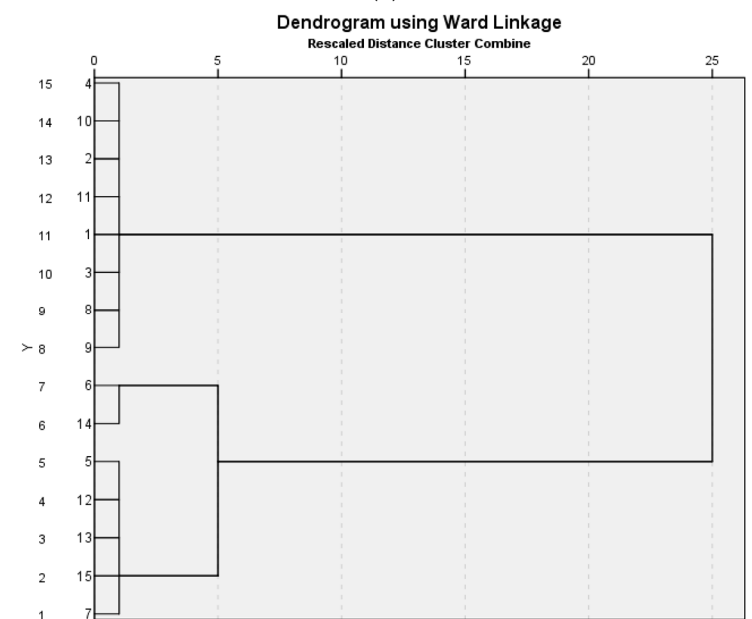
Variable	PC1	PC2	PC3	PC4
Ca	0.533	−0.294	0.004	0.254
Mg	**0.945**	−0.201	0.045	0.041
Na	**0.968**	−0.005	−0.093	0.149
K	0.317	0.344	−0.309	−0.135
HCO3	0.458	0.358	0.003	**0.661**
Cl	**0.982**	−0.074	−0.082	0.082
SO4	0.309	0.589	−0.247	−0.446
NO3	0.362	**0.864**	−0.173	−0.013
Fe	**0.785**	−0.347	0.053	−0.116
Mn	**0.667**	0.018	0.373	−0.326
As	0.407	**0.813**	−0.201	−0.005
I	0.078	0.366	**0.917**	0.045
Br	0.022	0.297	**0.935**	−0.004
pH	**−0.84**	0.25	−0.187	0.259
EC	**0.978**	−0.123	−0.05	0.008
Eigenvalue	4.927	2.193	1.884	1.388
% variance	37.9	16.87	14.49	10.68
Cumulative %	37.9	54.77	69.26	79.94
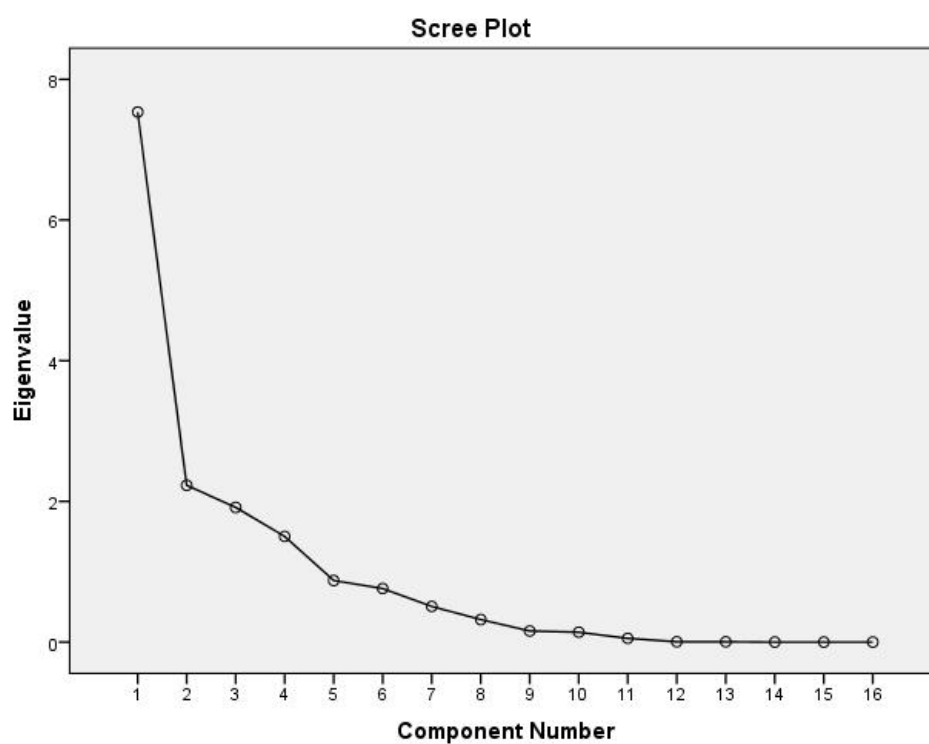
Figure 7. Scree plot.

PC3 accounted for 14.49% of the total variance; it was positively loaded by the I (0.917) and Br (0.935) concentrations, indicating a geogenic origin of groundwater pollution [109].

PC4 accounted for 10.68% of the total variance and was loaded by the HCO_3^- (0.661) concentration. Silicate mineral weathering is regarded as the primary source of HCO3 in groundwater [30]. However, bacterial decomposition of organic contaminants in aquifers can also produce HCO3 [31,98,101].

3.3.3. Hierarchal Cluster Analysis

Hierarchical cluster analysis (HCA) (Figure 8) was used to figure out how far apart the clusters or groups are based on the farthest distance between any two objects in different clusters or groups. The HCA clusters and groups are used to get a better understanding of the chemical data based on chemical variables (R-mode) and groundwater samples (Q-mode), respectively.

(a)

(b)

Figure 8. Dendrogram showing the clustering of samples: (**a**) R-mode cluster analysis; (**b**) Q-mode cluster analysis.

The R-mode HCA split the groundwater variables into three distinct clusters, indicating that values related to the same cluster may have come from a similar source [101,110]. Cluster 1 consisted of the EC concentrations and the TDS concentrations, which have a similar correlation. Cluster 2 consisted of the Cl concentrations, the Na+ concentrations, and the pH, which represents the contribution of saltwater intrusion in the groundwater [43]. Cluster 3 included the Ca^{2+}, Mg^{2+}, SO_4^{2-}, HCO_3^-, As, pH, NO_3^-, Br, I, K^+, Fe, and Mn concentrations, indicating the influence of both anthropogenic activities and natural processes [101].

On the basis of the amounts of several physicochemical parameters, cluster analysis (Q mode) was used to determine the spatial similarity or variability between the groundwater samples [111]. The results group the 15 sampling sites into three major clusters. Cluster 1 is composed of about 53.3% (8 samples) of the total sampling sites. Cluster 1 was dominated by moderate concentrations of Ca^{2+}, Mg^{2+}, Na^+, HCO_3^-, and Cl^-, which signifies the influence of rock weathering as well as a saltwater intrusion in the aquifer system [101]. Cluster 2 was characterized based on the extreme levels of Na^+, Cl^-, Mg^{2+}, and Fe concentrations. The excessive level of Na^+ and Cl^- concentrations in cluster 2 might have resulted from an exceptionally high intrusion of saline water. Cluster 3, which is composed of about 33.3% (5 samples) of the total sampling sites, also consists of high average concentrations of Na^+, Cl^-, and Mg^+, which might have been caused by the interaction of saline water.

3.4. Water-Quality Assessment

3.4.1. Drinking-Water Quality

In order to determine whether or not the groundwater in the study area is acceptable for human consumption, the physicochemical parameters of the groundwater in the study region were evaluated according to the guidelines provided by the WHO [78]. The values of the water quality index (WQI) for human consumption are categorized into the following five classes: excellent, good, bad, extremely poor, and unsuitable for human drinking [112] (Table 3). Based on the analysis of the WQI data for groundwater, six of the samples were in good condition, two were poor, one was very poor, and the groundwater from six other sampled locations was deemed unsuitable for drinking purposes (Figure 9).

Table 3. Classification of the groundwater based on the WQI.

Range	Class	Frequency % (Counts)	Reference
<50	Excellent	0% (0)	
50−100	Good	40% (6)	
100.1−200	Poor	13.33% (2)	[14,78]
200.1−300	Very poor	6.66% (1)	
>300	Unsuitable for drinking	40% (6)	

3.4.2. Irrigation Water Quality

A number of standard indices have been taken into account in this study (Table 4): electric conductivity (EC); sodium absorption ratio (SAR); soluble sodium percentage (SSP); residual sodium carbonate (RSC); and total dissolved solids (TDS) to evaluate the whole irrigational water quality of the study region [86,113,114]. The classification of groundwater for the purpose of irrigation is provided based on these parameters. According to SAR, SSP, RSC, EC, and TDS values, the groundwater in sample locations 1, 3, 4, and 10 is in excellent to good condition for the use of irrigation, as these regions are in the green colored zone. Regions 2, 8, 9, and 10 are suitable for use because the groundwater is in good condition based on water quality. However, groundwater quality in locations 5, 6, 7, 12, 13, 14, and 15, which are in the red colored zone, is hazardous and unsuitable for agricultural purposes (Figure 10).
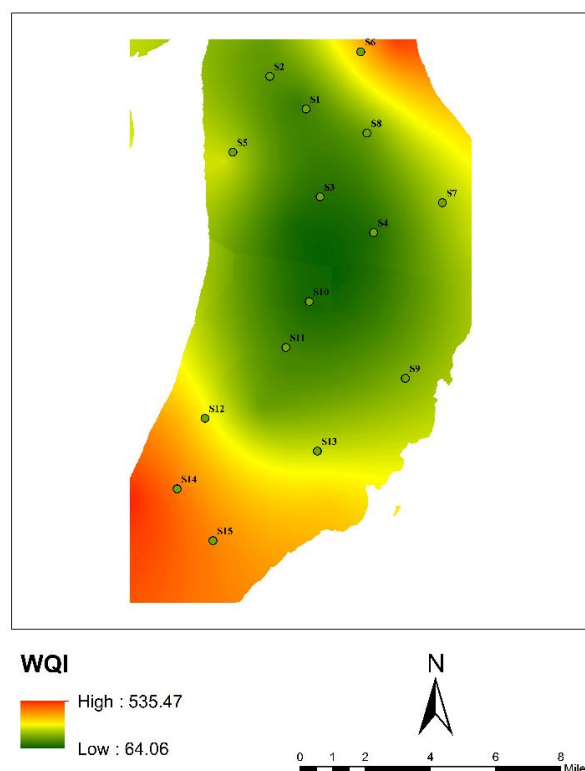
Figure 9. Water quality index map of the groundwater for drinking purposes.

Table 4. Suitability of the groundwater for irrigation purposes.

| Parameter	Range	Class	Frequency % (Counts)	Reference
Electrical conductivity (EC)	<700	No hazard	13.3% (2)	
	700−3000	Slight-to-moderate hazard	40% (6)	[115]
	>3000	Severe hazard	44.7% (7)	
Sodium absorption ratio (SAR)	<10	Excellent	26.66% (4)	
	10−18	Good	26.66% (4)	[12,116]
	18−26	Poor	6.66% (1)	
	>26	Unsuitable	40% (6)	
Soluble sodium percentage (SSP)	<20	Excellent	0% (0)	
	20−40	Good	0% (0)	[117]
	40−80	Fair	53.3% (8)	
	>80	Unsuitable	44.7% (7)	
Residual sodium carbonate (RSC)	<1.25	Safe	13.3% (2)	
	1.25–2.5	Marginally suitable	33.3% (5)	[12]
	>2.5	Unsuitable	53.3% (8)	
TDS	<500	Excellent	13.3% (2)	
	500–1000	Good	33.3% (5)	[118]
	1000–3000	Suitable	6.66% (1)	
	>3000	Unsuitable	44.7% (7)	
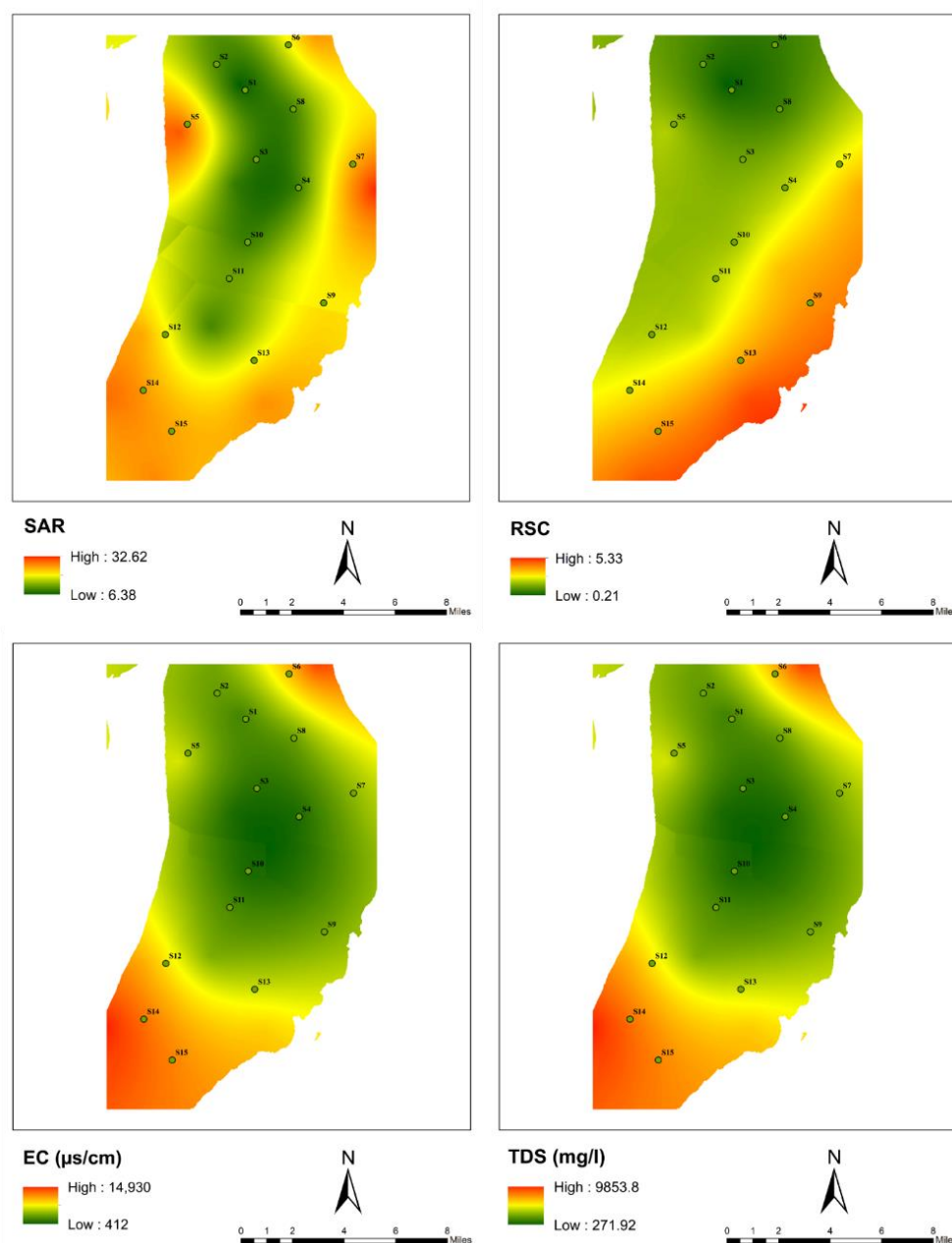
Figure 10. Water quality index map of the groundwater for irrigation purposes.

4. Conclusions

This study's principal objective was to comprehend the hydrogeochemical conditions and assess the quality and suitability of the groundwater on an island in Bangladesh that relies significantly on agriculture. In order to obtain specific information on hydrogeochemical facies, the Piper diagram was utilized, which revealed that approximately 80% of the examined samples belong to the $Na^+ Cl^-$ facies, which represent saline groundwater. On the basis of the Gibbs diagram, the saline water intrusion process dominates the groundwater chemistry. According to Wilcox's diagram and the U.S. Salinity diagram, just 34% of the samples are acceptable, and only two are in excellent to good condition. According to a main component analysis, the principal process influencing the hydrogeochemistry of groundwater is the infiltration of saltwater. Cluster analysis indicated the ion sources, and correlation matrices showed similar results. Kriging analysis delineated the spatial extent of the saltwater contamination surrounding the island. WQI and comparison with the WHO and Bangladesh criteria revealed that six of the groundwater samples can be considered

suitable for human consumption. Eight water samples can be considered suitable based on the irrigational water quality indices, of which four fall under the excellent to good quality categories. Alongside high values of SAR and SSP due to high concentrations of Na and Cl in groundwater, some relatively high concentrations of EC, RSC, and As in the groundwater in some samples suggest recharge of the groundwater with contaminated water from water bodies that receive agricultural runoff. This research provides a baseline state of groundwater quality on Hatiya Island. Despite the outcomes of this study's findings, significant limitations must be addressed. Even though we have 15 groundwater samples for hydrogeochemical characterization and quality evaluation, more samples from nearby locations, densely spread around the island and neighboring regions, could provide a more comprehensive outlook of the current groundwater quality state. In addition to measuring the influence of recharge discharge, seasonal fluctuations in groundwater chemistry are also a significant component. Future studies surrounding this region, where groundwater is the dominant water source for the inhabitants' livelihoods, should incorporate these concerns.

Appendix A

Table A1. Weight and relative weight of the physiochemical parameters. EC is in μs/cm, the rest in mg/L.

Parameter	BD Standard (Si)	Weight (Wi)	Relative Weight (Wi)
Na	200	4	0.1
K	12	2	0.05
Ca	75	3	0.075
Mg	35	2	0.05
HCO$_3$	200	3	0.075
Cl	600	4	0.1
SO$_4$	400	3	0.075
NO$_3$	10	4	0.1
Fe	1	3	0.075
Mn	0.1	3	0.075
pH	8.5	2	0.05
TDS	1000	3	0.075
EC	1000	4	0.1

Table A2. The mean and standard deviation of groundwater composition.

Parameter	Mean	Std. Deviation	Analysis N
Ca	28.32	21.11	15
Mg	93.61	79.58	15
Na	949.15	742.82	15
K	11.77	4.63	15
HCO_3	230.13	99.43	15
Cl	1658.5	1351.6	15
SO_4	0.12	0.056	15
NO_3	1.77	0.83	15
Fe	3.51	2.17	15
Mn	0.24	0.112	15
As	0.014	0.008	15
I	0.419	0.335	15
Br	0.256	0.23	15
pH	7.59	0.28	15
EC (μS/cm)	5187.2	4790.59	15
TDS	3423.55	3161.79	15

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