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A Hydrogeochemical Characterization and Quality Assessment of Groundwater from the Sadar Upazila, Khagrachhari District, Bangladesh for Irrigation and Drinking Uses

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Abstract: Water scarcity in the hill tract districts of Bangladesh becomes acute in the dry season as most of the streams, the primary source of water, dry up. However, groundwater, where available, can supply water throughout the year. In this study, a total of 37 water samples were collected and analyzed from shallow (34) and deep (3) wells in Khagrachhari Sadar to assess their geochemical type and suitability for drinking using a multiparameter groundwater quality index (GWQI), as well as their suitability for irrigation uses using the sodium adsorption ratio (SAR), residual sodium carbonate (RSC), sodium percentage (SP), and the Riverside and Wilcox classifications. The physicochemical parameters of the groundwater were characterized by relatively low EC, low pH, positive redox potentials (Eh) in millivolts, and mostly soft water. Shallow wells were dominated by Ca–HCO_3- and Ca–Na–HCO_3-type water, and deep wells by Na–HCO_3-type water. Among major and trace ions, there were higher concentrations, exceeding safe water standards, of HCO_3^- in deep wells and NO_3^-, Fe^{2+}, and Mn^{2+} in shallow wells. Irrigation water quality assessments and GWQI results reveal that most shallow wells can be considered good and safe options for both drinking and irrigation, while groundwater from deep wells requires additional caution prior to use for agricultural purposes.

Keywords: groundwater geochemistry; irrigation water quality; drinking water quality index; Khagrachhari Sadar; hill district; Bangladesh

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1. Introduction

Groundwater is considered one of the safest and most important sources of water for domestic, agricultural, and industrial uses in the present world [1]. In Bangladesh, around 98% of potable water and about 80% of the irrigation water supply in the dry season is from groundwater [2]. However, groundwater is not equally available across the country. Among the four major physiographic units in Bangladesh, the Tertiary Hills in the northern and eastern fringes of the country occupy about 18% of the land and are home to 1.11% of the population [3]. Hill tract communities have long been experiencing a safe drinking water crisis, particularly during the dry period, when most of the surface water sources deplete [4,5]. Generally, groundwater is not used to its full potential in the hilly region due to the geological complexity, the greater depth of aquifers at the top of hilly surfaces, the inadequate availability of data, and inaccessibility that prevents conducting rigorous investigations on groundwater. Thus, these hilly regions in Bangladesh have remained underprivileged zones compared to the other parts of the country in terms of sustainable groundwater development.

A few water quality investigations [6–13] have been performed in the hill districts of south-eastern Bangladesh up to this point. However, no groundwater quality assessment study has yet been conducted in the town of Khagrachhari in the Sadar Upazila, which is considered a significant area in this hill district due to its role as the center of local administration, its importance for the livelihood of a large hill tract community, and its extensive agricultural activity due to having relatively flat land surrounded by hills. The town is situated in a syncline, where the Pleistocene Dupi Tila Formation constitutes a very productive aquifer [14]. Consequently, groundwater provides most of the water supply for about 111,833 people living in this area [3]. A detailed assessment of groundwater quality for drinking and irrigation uses in this area is, therefore, very important. Groundwater chemistry, i.e., the composition and concentrations of dissolved constituents in water, play a significant role in determining the quality of water [15,16]. Anthropogenic actions may alter water composition extensively through the direct effects of contamination and the indirect consequences of water development [15]. Fundamental data used in different water quality assessments are obtained by chemical analyses of water samples in the laboratory as well as onsite measurements of the physicochemical parameters of water in the field [15]. A number of scientists and organizations have established benchmarks for different water quality parameters based on drinking and irrigation uses [16–25]. Irrigation water quality mainly depends on the type and amount of dissolved salts present in the water supply and their effects on crop growth and development. There are some basic criteria for assessing groundwater quality for irrigation purposes [26]. For example, measures of electrical conductivity are used to address the salinity hazard; estimates of the relative proportion of Na^+ to Ca^{2+} and Mg^{2+} ions, which is referred to as the sodium adsorption ratio (SAR), are used to address the sodium hazard; and estimates of residual sodium carbonates (RSCs) that take into account the HCO_3^- and CO_3^{2-} anions and Ca^{2+} and Mg^{2+} cations in irrigation water are used to address the alkalinity hazard. Drinking water quality has long been evaluated by using the groundwater quality index (GWQI) method [23–25,27–34].

This study characterizes the groundwater types and assesses the groundwater quality for drinking and irrigation uses in the Khagrachhari Sadar. The results of this study can be considered as the baseline groundwater investigation for this area and be insightful for future water resource development and water quality management planning in this hill district of south-eastern Bangladesh. Moreover, as the major delta part of the country has long been extensively studied in terms of groundwater quality and development, and since the hill tract districts rarely have received proper attention on this issue, this groundwater study can also contribute to further investigations on the complex hilly aquifers of the country.

2. Materials and Methods

2.1. Study Area

Khagrachhari Sadar is located in a syncline in the eastern Tertiary hilly regions in the Chattogram Division in south-eastern Bangladesh (Figure 1) [35]. The eastern Tertiary hilly regions of Bangladesh are composed of alternating anticlines and synclines trending in a north-to-south direction [14]. The study area occupies a land area of 298 sq km, with 24,316 households [3,35]. The annual average rainfall in the study area is 3031 mm, and the annual average temperature varies from 34.6 °C (summer) to 13 °C (winter) [3]. The Chengi River is the main river in Khagrachhari Sadar, and there are about 592 local ponds, which are sometimes used for domestic and agricultural water supply [35]. According to the BWDB [36], there is no available groundwater table hydrograph data for Khagrachhari Sadar. However, since these ponds contain water almost throughout the year [35], it can be assumed that the fluctuation in groundwater levels between the wet and dry periods is not very high. About 78.3% of households obtain their drinking water supply from groundwater wells, 1.7% from the tap, and the rest from surface water bodies and springs [3]. Both surface water irrigation, using the main river, canals, ponds, and other water bodies, as well as groundwater irrigation, with water lifted by shallow tube wells, deep tube wells, and other traditional devices, are common in the Khagrachhari area [35].

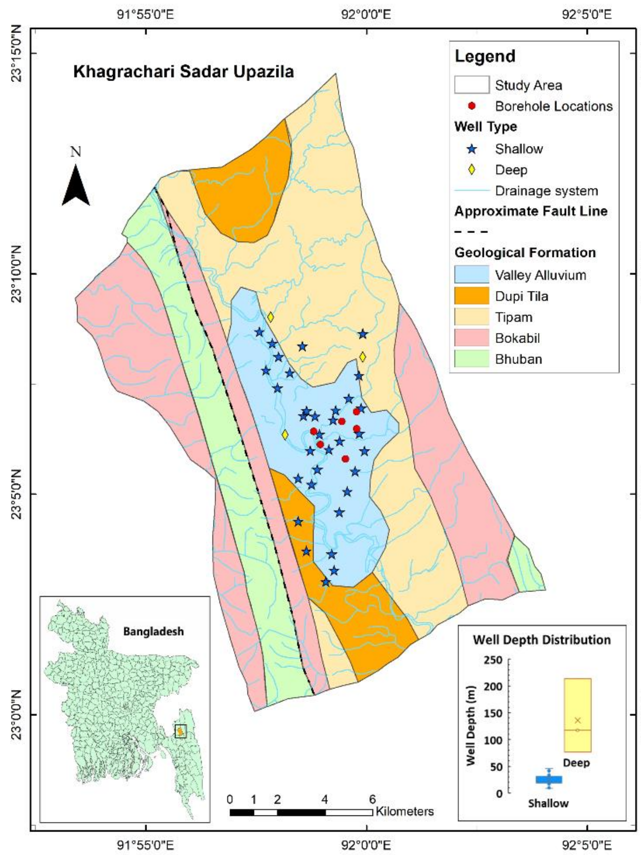

Figure 1. Geology and groundwater sampling and borehole locations in the study region, with the distribution of water well depths.

2.2. Groundwater Sample Collection and Laboratory Analyses

Groundwater samples were collected in February 2020 (dry season) from 37 tube wells distributed in the study area (Figure 1). The depth of the water wells ranged from 9 m to 213 m. Based on well depth, these 37 wells were divided into shallow (<50 m) and deep (>50 m) wells in this study. Before sampling, the wells were purged for a short duration to avoid stagnant water in the tube well. Sample bottles were washed properly, and a 0.45 µm membrane filter was used to remove colloidal substances and suspended particles from the water samples. From each well, an acidified (concentrated HNO_3^-) and a non-acidified sample were collected in two 120 mL plastic bottles. Acidifying the water sample with concentrated HNO_3^- is required to lower the pH value to slow down the precipitation of the dissolved constituents and to act as a preservative. The collected water samples, with appropriate labels, were transported to the Geochemistry Laboratory of the Department of Geology, University of Dhaka; this was performed cautiously, and samples were preserved in a temperature-controlled refrigerator before the lab analyses.

Several physicochemical parameters of the water, such as temperature, EC (electrical conductivity), Eh (oxidation–reduction potential), and pH (potential of hydrogen), were measured at the field site using a portable EC meter (HANNA, model DIST HI 198300/4) and a portable waterproof pH/°C meter (pHep by HANNA, model HI 98127). Total hardness (TH) was calculated in terms of the $CaCO_3$ equivalent by the following Equation (1) [21], where Ca^{2+} and Mg^{2+} are measured in mg/L.

$$TH = 2.5\,(Ca^{2+}) + 4.1\,(Mg^{2+}) \tag{1}$$

In the laboratory, cations, such as Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, and Mn^{2+}, were analyzed using an atomic absorption spectrometer (AAS), and anions, such as SO_4^{2-}, NO_3^-, NO_2^-, F^-, Br^-, and PO_4^{3-}, were measured using ion chromatography from the acidified samples.

The non-acidified samples were analyzed for HCO_3^- and Cl^- ions through the acid–base titration method using standard H_2SO_4. The accuracy of the water analysis was estimated using the ionic charge balance error (ICBE) equation [37], where all cation and anion concentrations are converted into milliequivalents per liter (meq/L).

$$\text{ICBE}\ (\%) = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} \times 100 \quad (2)$$

All the water samples were estimated to have ICBE values within ±10%, which is generally considered an acceptable limit [37].

2.3. Hydrogeochemical Characterization

The physicochemical parameters of the water samples were analyzed to characterize the groundwater. The chemical analyses of the groundwater samples can be represented using a variety of graphical methods, which help to show the groundwater types in an area based on chemical composition and chemical relationships among ions or groups of ions [15]. In this study, Piper diagrams, Stiff diagrams, and box plots are used to understand the hydrochemical characteristics of the groundwater.

2.4. Groundwater Quality Assessment for Irrigation

The assessment of groundwater quality for irrigation depends on the dissolved salts and their concentrations. These dissolved salts have a great influence on the productivity and quality of crops. The evaluation of the water quality was performed based on various indicators, such as the sodium adsorption ratio (SAR), the residual sodium carbonate (RSC), and the sodium percentage (SP).

The sodium adsorption ratio (SAR) provides a useful index of the possible sodium hazard in irrigation water. Sodium hazard can reduce the permeability of the soil and hinder the absorption of water by crops [38]. The SAR is related to the amount of Na^+ relative to Ca^{2+} and Mg^{2+}, measured in meq/L, in water and is determined by the following Equation (3) [18,20]:

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+}+\text{Mg}^{2+}}{2}}} \quad (3)$$

Groundwater can be classified based on SAR values as follows: excellent (<10), good (10–18), doubtful (18–26), and unsuitable for irrigation (>26) [18,20,39–42]. Water with a very high SAR value is considered to be unsuitable for irrigation because of the tendency toward long-term damage to the soil structure [26,39].

The residual sodium carbonate (RSC) index of the water defines the alkalinity hazard for the soil by measuring the relative concentrations of HCO_3^- and CO_3^{2-} compared to the concentrations of Ca^{2+} and Mg^{2+} [43,44]. RSC values are calculated using the following Equation (4), as given by Eaton and Richards [17,18], where all ions are in meq/L:

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

Irrigation water can be classified based on RSC values as follows: <1.25 meq/L is good for irrigation, 1.25–2.5 meq/L is doubtful, and >2.5 meq/L is considered to be unsuitable for irrigation [17,18,41,45]. Water with an excess of CO_3^{2-} and HCO_3^- that is over the levels of Ca^{2+} and Mg^{2+} and beyond permissible limits can be harmful to crops and is unsuitable for irrigation [17,18].

The sodium percentage (SP) (%Na) is another indicator that relates to sodium hazard. The SP plays a significant role in crop productivity as excess Na^+ ions in water may cause permeability reductions by being absorbed by clay particles and replacing Ca^{2+} and

Mg^{2+} ions, which results in poor internal drainage within the soil [40]. The SP is calculated by the following formula, which includes Na^+, K^+, Ca^{2+}, and Mg^{2+} ions [21].

$$SP\ (\%) = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100 \quad (5)$$

According to Wilcox [19], irrigation water can be classified based on the SP as follows: excellent (<20), good (20–40), permissible (40–60), doubtful (60–80), and unsuitable for irrigation (>80). A high %Na in the soil can have adverse effects on soil structure, aeration process, and water infiltration [41,46]. Agricultural activities, such as the application of fertilizer and pesticides, can increase the sodium content in irrigation water [40].

Groundwater suitability for irrigation can also be assessed using the Riverside classification [18] and the Wilcox classification [19], which are based on water salinity (electrical conductivity) vs. SAR value and sodium percentage (%Na) vs. electrical conductivity, respectively.

2.5. Groundwater Quality Index (GWQI) for Drinking

To assess drinking water quality, GWQI was calculated using several water quality parameters. The calculation of GWQI involves several steps. First, the weight values were assigned for each parameter (pH, TDS, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe^{2+} Mn^{2+}, HCO_3^-, SO_4^{2-}, Cl^-, F^-, Br^-, NO_3^-, NO_2^-, and PO_4^{3-}) depending on their importance for the water quality assessment and risk to human health; e.g., a value of 5 for health-based criteria, 3 for aesthetic criteria, and 1 for the criteria that pose less risk to health and aesthetic objectives (Table 1) [16].

Although arsenic is considered a significant water quality constituent, it was not included in the analysis and evaluation of GWQI in this study. Naturally occurring elevated levels of arsenic are often found in shallow Holocene aquifers in the Bengal basin [47–49]; in contrast, despite the lack of sufficient data and testing, the hill districts of Bangladesh are known as a low-arsenic zone, perhaps due to the geological setting that differs from that of the delta part of the country. In addition, a recent environmental monitoring report published by the Chittagong Hill Tracts Rural Development Project-II showed that the arsenic concentrations in 12 tube wells from Khagrachhari Sadar Upazila were $\leq$0.001 mg/L, which is within the Bangladesh standard limit (<0.05 mg/L) [50]. Microbial testing was also excluded from this study because the risk of bacteriological contamination in the groundwater of Bangladesh is more likely associated with the infrastructure of the hand tube wells and problems with the different stages of water collection and end-use, including the use of unhygienic containers for collection, transport, storage, and drinking [51]; such issues do not necessarily connect to the actual aquifer water quality. However, a further study that includes arsenic and microbial testing should be undertaken before the drinking water is considered completely safe.

Table 1. List of groundwater quality parameters, with their standards, according to recommended drinking water quality guidelines [16,52] and the assigned and relative weights that were used in the calculation of GWQI.

Groundwater Quality Parameter	Unit	Standard (Si)	Weight (wi)	Relative Weight (Wi)
NO_3^-	mg/L	10	5	0.102
NO_2^-	mg/L	<1	5	0.102
F^-	mg/L	1	5	0.102
TDS	mg/L	1000	3	0.061
[1] TH	mg/L	200–500	3	0.061
[1] pH	-	6.5–8.5	3	0.061

Table 1. *Cont.*

Groundwater Quality Parameter	Unit	Standard (Si)	Weight (wi)	Relative Weight (Wi)
SO_4^{2-}	mg/L	400	3	0.061
Cl^-	mg/L	600	3	0.061
Ca^{2+}	mg/L	75	3	0.061
Mg^{2+}	mg/L	35	3	0.061
Fe^{2+}	mg/L	1	3	0.061
Mn^{2+}	mg/L	0.1	3	0.061
Na^+	mg/L	200	3	0.061
PO_4^{3-}	mg/L	6	1	0.020
HCO_3^-	mg/L	200	1	0.020
Br^-	mg/L	6	1	0.020
K^+	mg/L	12	1	0.020
Total			49	1.000

Note: [1] A pH standard of 7 and a TH standard of 350 mg/L were used for the calculation.

In the second step, the relative weights were calculated from the assigned weight for each parameter (wi) and the sum of the weights assigned for the parameters, using the following equation:

$$\mathrm{Wi} = \frac{\mathrm{wi}}{\sum_{i=1}^{n} \mathrm{wi}} \tag{6}$$

where Wi = relative weight, wi = weight for each parameter, i = individual parameter, and n = total number of parameters. In the third step, the quality rating (Qi) for each parameter was derived by taking its concentration in each water sample (Ci) divided by its respective standard and then multiplied by 100.

$$\mathrm{Qi} = \frac{\mathrm{Ci}}{\mathrm{Si}} \times 100 \tag{7}$$

where Qi = quality rating, Ci = concentration of each groundwater quality parameter, Si = water quality standard for each parameter, and i = individual parameter. The standard for each parameter was chosen according to the water quality parameters in the Bangladesh Standards [52], except bromide (Br^-). For Br^-, the WHO guideline for drinking water [16] was used as this parameter was not included in the Bangladesh Standards.

The final GWQI score for each water sample was obtained by taking the sum of the quality rating scores of each parameter (Qi) multiplied by their relative weight (Wi).

$$\mathrm{GWQI} = \sum_{i}^{n} \mathrm{QiWi} \tag{8}$$

where GWQI = groundwater quality index, Qi = quality rating, Wi = relative weight, n = total number of parameters, and i = individual parameter.

GWQI scores make it possible to categorize the suitability of groundwater for human consumption according to the following categories: excellent (<50), good (50–100), poor (101–200), very poor (201–300), and unsuitable for drinking purposes (>300) [24,33].

3. Results and Discussion

3.1. Aquifer Delineation

The aquifer was delineated based on data from six borehole logs from the Department of Public Health Engineering (DPHE) of Bangladesh (Figures 1 and 2a). Based on the borehole logs, a very thick sandy aquifer dominates in the shallow subsurface ranging from 40 to 160 m, which is sometimes separated by a thin layer (20–45 m) of clayey deposits at variable depths (Figure 2b). There are two major aquifers present in the study area: the Plio-Pleistocene-aged Dupi Tila sandstone formation and the Pliocene-aged Tipam sandstone formation (Figures 1 and 2b) [14,53]. Although recent valley alluvium covers the central part of the Khagrachhari Sadar region, both sand-dominated formations are exposed in other parts of the area (Figure 1). Moreover, the medium to fine-grained Dupi Tila aquifer and the fine to coarse-grained Tipam aquifer can both be found at shallow depths (Figure 2b); however, it is often difficult to distinguish these two aquifers [14]. At greater depths, interbeds of sandstone from the Bokabil or Bhuban formations may act as the deeper aquifer [14]. However, the DPHE boreholes collected data for up to 183 m of the subsurface, which results in a focus mainly on the shallow aquifers (Figure 2b).

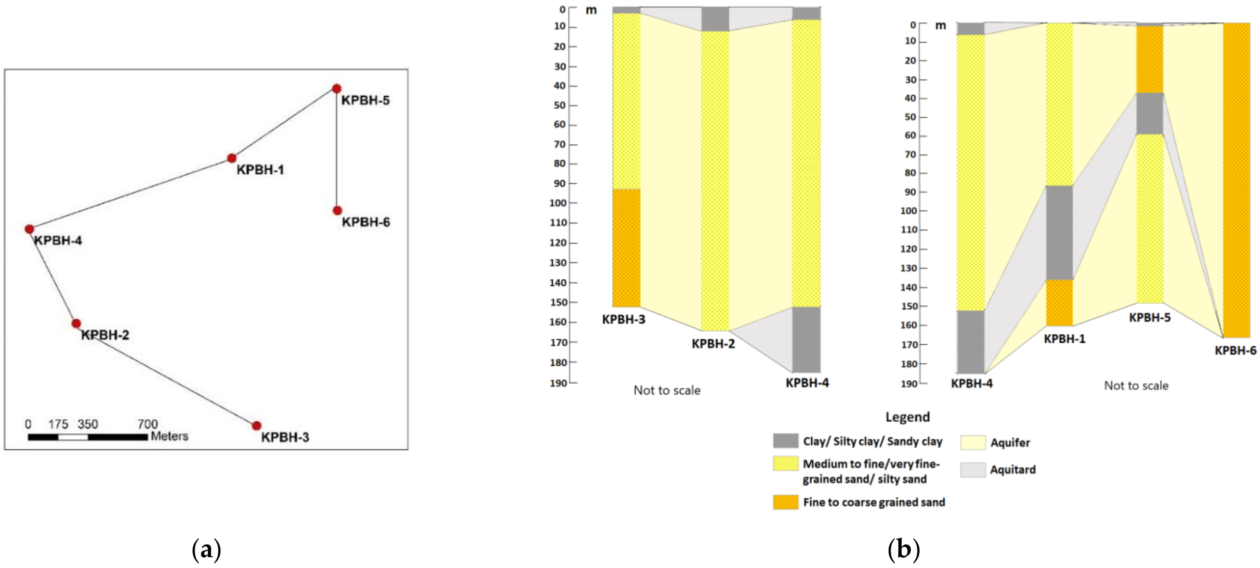

Figure 2. Delineation of aquifers based on the DPHE borehole logs: (**a**) cross-section line through the borehole locations shown in Figure 1; (**b**) two cross-sections showing the subsurface aquifers and local aquitard.

3.2. Physicochemical Characterization of Groundwater

The results for each of the physicochemical parameters are discussed in the subsequent sections.

3.2.1. Electrical Conductivity (EC)

Electrical conductivity (EC) is the measurement of the ionic concentration of the groundwater samples; it varies according to the temperature and type of ions present [15,23]. EC is an important parameter in groundwater quality assessment for both drinking and irrigation. In general, the EC of groundwater increases with depth, but high EC in water samples from shallow aquifers may be an indicator of contamination due to anthropogenic activities [54]. However, the maximum EC value found was 460 µS/cm (Table A1 in Appendix A), which is below the safe drinking water limit of 1500 µS/cm [16]. All EC values for the water samples collected from the Khagrachhari Sadar ranged from excellent (81.1%) to good (18.9%) (Table 2) [19].

Table 2. Classification of water samples based on EC, pH, and TH values.

Classification Parameter and Range	Type of Water	No. of Sample	% of Samples
EC (µS/cm) [19]			
<250	Excellent	30	81.1
250–750	Good	7	18.9
750–2000	Permissible	0	0.0
2000–3000	Doubtful	0	0.0
>3000	Unsuitable for drinking	0	0.0

Table 2. *Cont.*

Classification Parameter and Range	Type of Water	No. of Sample	% of Samples
pH [16]			
<6.5	Acidic	32	86.5
6.5–8.5	Neutral	4	10.8
>8.5	Alkaline	1	2.7
TH (in mg/L as $CaCO_3$) [22]			
<60	Soft	30	81.1
60–120	Moderately hard	6	16.2
120–180	Hard	1	2.7
>180	Very hard	0	0.0

3.2.2. Potential of Hydrogen (pH)

pH is another important operational quality parameter of groundwater; it indicates the state of acidity and alkalinity of the water. The normal pH range for drinking water is considered to be between 6.5 and 8.5 [16]. The mean pH value of the groundwater in the study area was 5.98, which indicates acidic groundwater; the maximum and minimum pH values were 8.55 and 4.08, respectively (Table A1 in Appendix A). A total of 86.5% of wells, including three deep wells, had acidic water, while 10.8% had neutral and 2.7% had alkaline water (Table 2; Figure A1a in Appendix A). Although slightly acidic or alkaline water has no direct impact on health, lower pH (acidic) water has the tendency to be corrosive and can damage water pipes [16].

3.2.3. Redox Potential (Eh)

The redox potential is a numerical index of the intensity of the oxidizing or reducing environments within an aquifer system, where positive and negative potentials indicate the relative oxidizing and reducing conditions of the system, respectively [15]. This potential is measured as Eh, with the millivolt as its unit. The groundwater samples collected from the Khagrachhari Sadar all showed positive Eh values, ranging from 23 to 323 millivolts (Table A1 in Appendix A), indicating the presence of relatively oxidizing conditions in the aquifers.

3.2.4. Total Hardness (TH)

The maximum and minimum values for total hardness calculated from the concentration of Ca^{2+} and Mg^{2+} were 144.4 and 15.89 mg/L as $CaCO_3$, respectively (Table A1 in Appendix A). A TH above 200 mg/L, along with other interacting parameters, such as higher pH and alkalinity, may cause scale deposition in pipe distribution systems and water tanks [16]. Hence, there are very low chances of scale accumulation in the pipelines in the study area.

In addition, based on the TH value, water can be categorized as soft (<60), moderately hard (60–120), hard (120–180), or very hard (>180) [22]. According to this classification system, 81.1% of the water wells in Khagrachhari Sadar contain soft water, 16.2% moderately hard water, and 2.7% hard water (Table 2; Figure A1b in Appendix A). The spatial map indicates that one deep well has hard water, and six shallow wells have moderately hard water, while the rest of the wells, including two deep wells, have soft water (Figure A1b in Appendix A). Corrosion is typically associated with soft and acidic water [16]; therefore, wells containing both soft and low-pH water, shown in Figure A1a,b in Appendix A, should be under observation and monitoring.

3.2.5. Water Quality Constituents

The box plots depict the statistical distributions of the concentration of different water quality constituents in shallow and deep wells, including major and trace ions, such as HCO_3^-, Cl^-, SO_4^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+}, NO_3^-, NO_2^-, PO_4^{3-}, F^-, Br^-, Fe^{2+}, and Mn^{2+} (Figure 3a). These plots provide a visual representation of the interquartile range, mean, median, and outliers, i.e., the occurrence of disproportionate concentration values for the constituents [55]. Water quality standards for each constituent [16,52] were also included in the plots to compare their concentrations against safe drinking water limits.

Among the measured samples, the concentrations of Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+, NO_2^-, PO_4^{3-}, F^-, and Br^- were found to be within safe limits in both shallow and deep wells (Figure 3a). The distribution of relatively higher concentrations of Na^+ was noticeable in the deep wells compared to the shallow wells; this was possibly caused by the replacement of Ca^{2+} ions through the cation exchange process at a greater depth. For HCO_3^- ions, the interquartile range, mean, and median values from shallow wells were within safe limits; however, one outlier from a shallow well and all three values from deep wells exceeded the safe water limit of 200 mg/L (Figure 3a). Higher concentrations of HCO_3^- in deeper wells were probably due to either the presence of deeper aquifer materials [56] through the weathering of carbonate and silicate minerals or the mixing of freshwater with ancient seawater. Although the interquartile range, mean, and median values for NO_3^- concentrations were below the safe water limit (<10 mg/L) in the shallow wells, five outliers showed higher values (>10 mg/L) that could have been released into the groundwater by fertilizer application in the agricultural fields [57]. Fe^{2+} and Mn^{2+} both had some outliers exceeding the safe water limit, with values of 1 mg/L and 0.1 mg/L, respectively, in the shallow wells (Figure 3a). Such results are usually natural, due to the geochemical conditions of the aquifer, e.g., the acidic (low pH) and low-dissolved-oxygen conditions [58].

3.3. Hydrochemical Facies and Groundwater Types

In Figure 3b, the plots of major ions from 37 wells show that water samples were dominated by the Ca–HCO_3 and mixed Ca–Na–HCO_3 types of groundwater, which are labeled as 1 and 3, respectively, in the diamond of the Piper plot [59]. Samples from two deep wells and four shallow wells contained Na–HCO_3 and NaCl–SO_4 types of water, respectively (Figure 3b).

Ca–HCO_3 water at a shallow depth is usually the result of the dissolution of aquifer materials through the action of CO_2 derived from the air and soil in the presence of organic matter [56]. If shallower water is of the Ca–HCO_3 type, and clay minerals are present in the deeper formation with no organic matter, Na^+ ions adsorbed to the clay surfaces are successively replaced by Ca^{2+} ions, and the groundwater alters to the Na–HCO_3 type at depths of not less than 30 m and sometimes more than 50 m [56]. HCO_3^- ions may also be released from carbonate minerals and the weathering of silicate minerals [60]. In addition, there is another hypothesis to explain the presence of Na–HCO_3 water in the deeper aquifers due to marine transgression in the Bengal Basin during the Holocene epoch [61,62]. When fresh groundwater invades a deeper aquifer that previously contained seawater (NaCl) or an Na-rich brine derived from seawater, Na–HCO_3 type water can be naturally formed from the mixing of freshwater with saline water [15,63]. A study conducted on groundwater quality in different locations in Bangladesh included hydrochemical data for one deep tube well located in the Khagrachhari District [11]. This study also showed that the groundwater collected from the deep well was of Na–HCO_3 type. In contrast, the NaCl-type water found in one of the shallow wells was likely due to the agricultural practices in the study area [15,64].

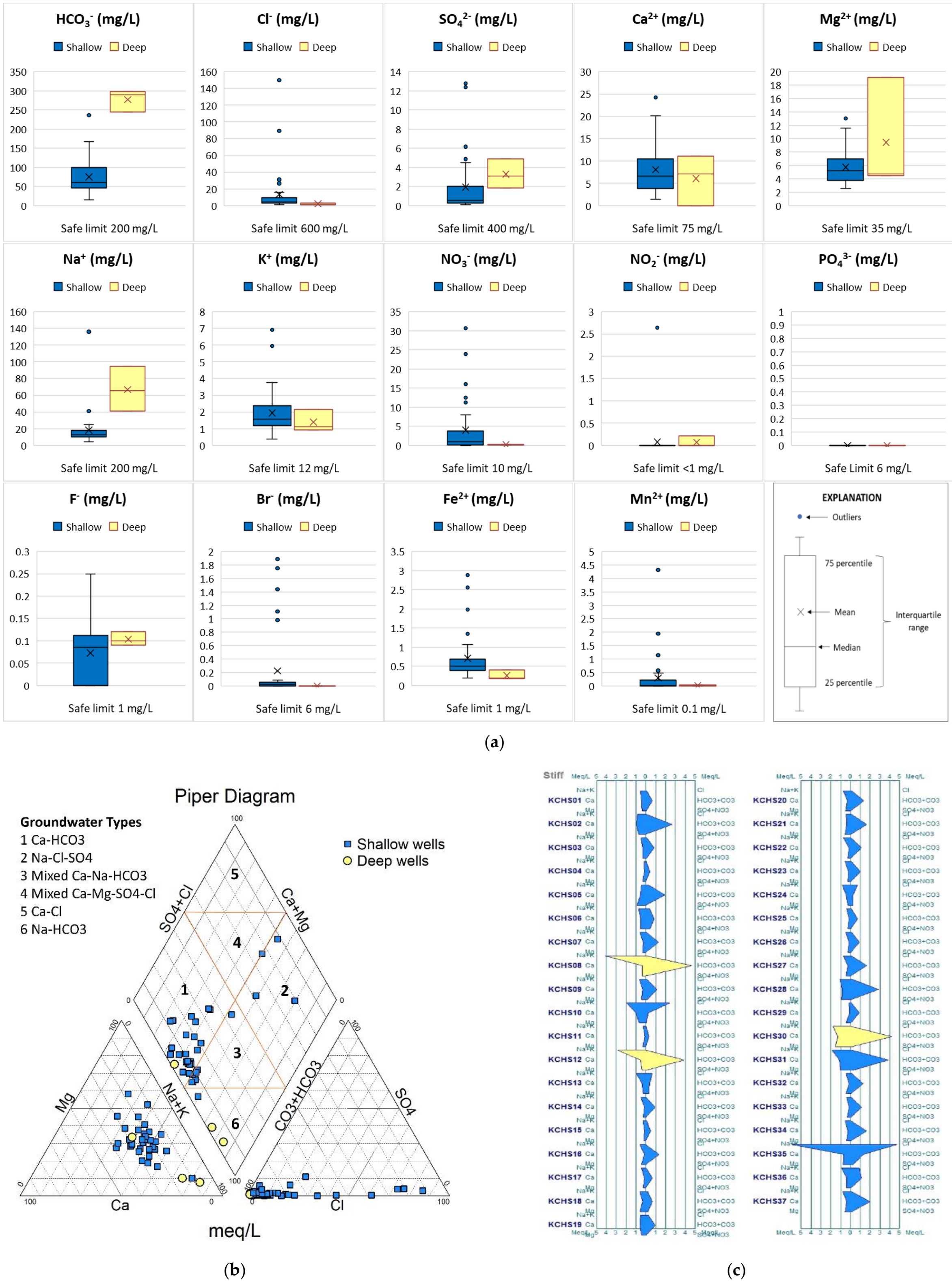

Figure 3. (**a**) Box plots showing the statistical distribution of the concentrations of different water quality constituents in groundwater, with their safe limits [16,52]; (**b**) Piper diagram showing the groundwater types based on the plots of major ions; and (**c**) Stiff diagram showing the major cation and anion concentrations analyzed from the water samples collected from shallow and deep wells in the Khagrachhari Sadar.

In Figure 3c, most of the water samples display approximately the same polygonal shapes, with relatively low to moderate concentrations of cations (Na^+, K^+, Mg^{2+}, and Ca^{2+}) and anions (Cl^-, HCO_3^-, CO_3^{2-}, and SO_4^{2-}) in meq/L. Stiff diagrams usually help in making a rapid visual comparison between groundwater samples with high ion concentrations [65]. Water samples from all three deep wells, i.e., KCHS-08, 12, and 30, and from two shallow wells, i.e., KCHS-31 and 35, showed variations in major ion concentrations (Figure 3c). Among them, the three deep wells had relatively high Na + K and HCO_3 + CO_3 concentrations that might have been released into the groundwater from the deeper aquifer materials. One of the shallow wells (KCHS-35) demonstrated remarkably high levels of Na + K and Cl, which may indicate surface contamination caused by agricultural activities.

3.4. Groundwater Quality Assessment for Irrigation

The results of the irrigation water quality assessment methods are discussed in the subsequent sections.

3.4.1. Sodium Adsorption Ratio (SAR)

The calculated SAR values for the water samples ranged from 0.350 to 6.737 (Table A2 in Appendix A). Therefore, all the groundwater samples collected from the Khagrachhari Sadar region were excellent for irrigation purposes (100%) (Table 3), with low SAR values that result in a positive effect on soil permeability and crop yields [40].

Table 3. Classification of irrigation water quality based on the evaluations of SAR, RSC, and SP.

Classification Parameter and Range	Type of Water	No. of Sample	% of Samples
SAR [18,20]			
<10	Excellent	37	100.0
10–18	Good	0	0.0
18–26	Permissible	0	0.0
>26	Unsuitable for irrigation	0	0.0
RSC (meq/L) [17,18]			
<1.25	Good	34	91.9
1.25–2.5	Doubtful	1	2.7
>2.5	Unsuitable for irrigation	2	5.4
SP (%) [21]			
<20	Excellent	0	0.0
20–40	Good	10	27.0
40–60	Permissible	24	64.9
60–80	Doubtful	2	5.4
>80	Unsuitable for irrigation	1	2.7

3.4.2. Residual Sodium Carbonate (RSC)

According to the RSC values calculated for the collected samples (Table A2 in Appendix A), 91.9% of the water samples were safe and good for irrigation, 2.7% were doubtful (one shallow well), and 5.4% (two deep wells) were unsuitable for irrigation purpose (Table 3; Figure 4a).

3.4.3. Sodium Percentage (SP)

Based on the calculated SP values (Table A2 in Appendix A), 27% of the groundwater samples from Khagrachhari Sadar were good for irrigation, around 64.9% were within the permissible range, 5.4% of wells (one shallow well and one deep well) were in doubtful condition, and 2.7% (one deep well) was unsafe and unsuitable for irrigation (Table 3; Figure 4b).

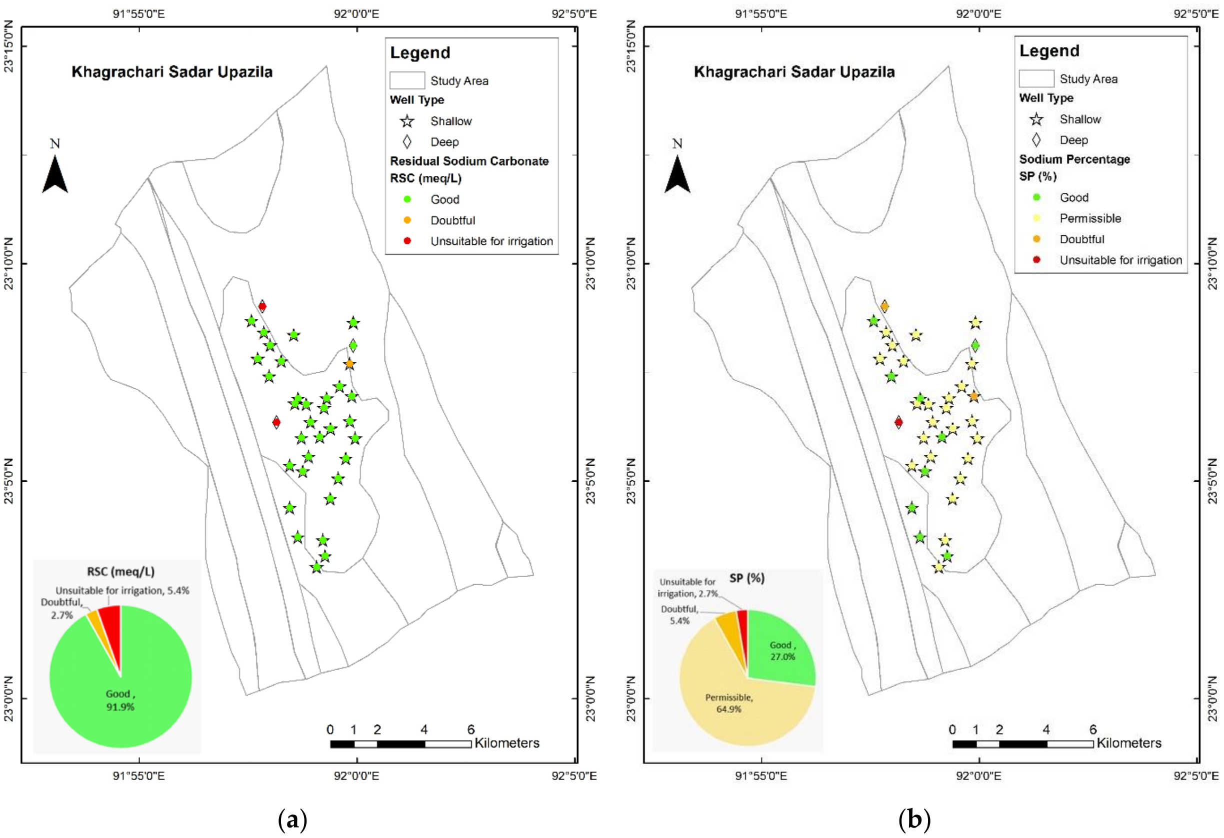

Figure 4. Spatial distribution of the measurements for (**a**) RSC and (**b**) SP in shallow and deep wells of the Khagrachhari Sadar for irrigation water quality assessment.

3.4.4. Riverside Classification

In Figure 5a, all groundwater samples are located within the low SAR and low to medium EC areas in the Riverside graph, which is recommended for irrigation on almost all soils with little danger of sodium hazard [18].

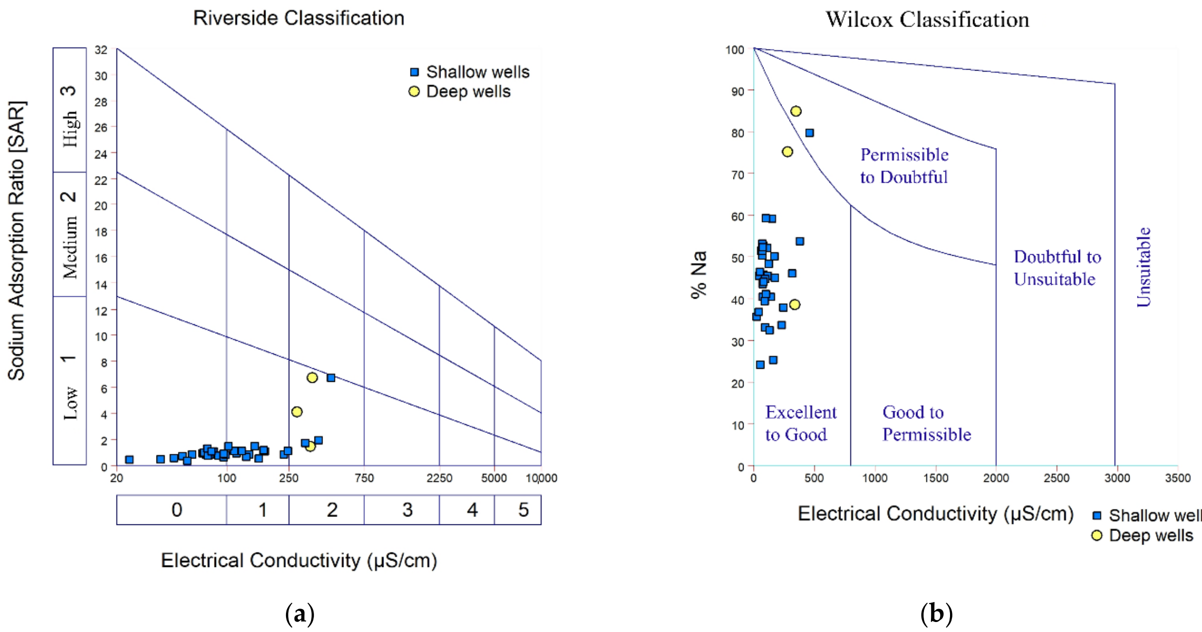

Figure 5. (**a**) Riverside classification and (**b**) Wilcox classification for assessing irrigation water quality.

3.4.5. Wilcox Classification

In the Wilcox diagram (Figure 5b), most of the water samples fall in the 'Excellent to Good' quality range with respect to salinity (EC) and sodium percentage (%Na). One shallow well and one deep well were within the 'Permissible to Doubtful' range. In addition, one deep well sample was located close to the border between the 'Excellent to Good' and 'Permissible to Doubtful' ranges. Incessant irrigation with these three water wells may lead to the accumulation of more Na^+, which may have negative effects on the soil and the sustainability of crop production in the long term [44].

3.5. Groundwater Quality Index (GWQI) for Drinking

The calculated GWQI values for each groundwater sample are listed in Table A3 in Appendix A. According to the classification shown in Table 4 and Figure 6, 86.5% of the collected groundwater samples for the study region were excellent for drinking, 8.1% of the samples fell into the good quality groundwater category, and there were 2.7% of samples in both the poor and very poor water quality categories. The spatial map shows that the poor- and very-poor-quality water samples were both collected from shallow wells (Figure 6), while the water from the three deep wells was excellent for drinking purposes.

Table 4. Classification of drinking water quality based on the GWQI [24,33].

GWQI Score	Type of Water	No. of Sample	% of Samples
<50	Excellent	30	81.1
50–100	Good	5	13.5
101–200	Poor	1	2.7
201–300	Very poor	1	2.7
>300	Unsuitable for drinking	0	0.0

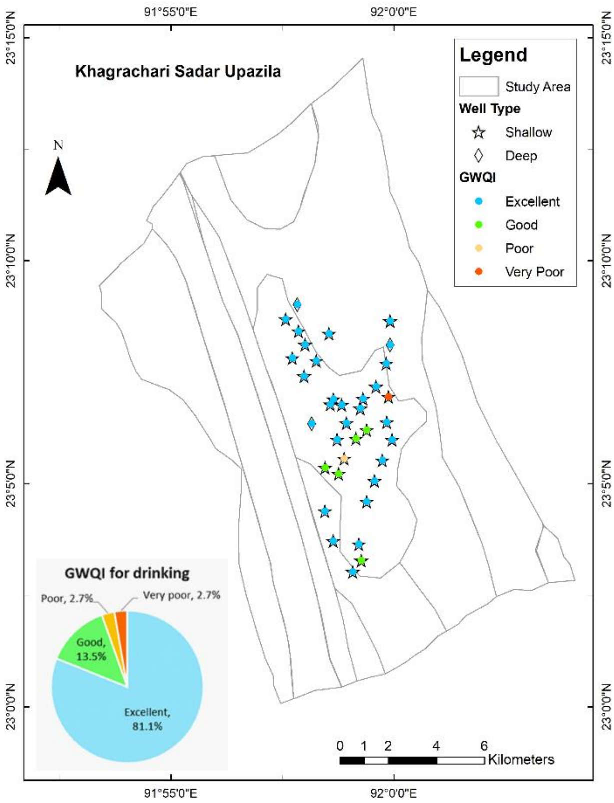

Figure 6. Spatial distribution of the GWQI values in shallow and deep wells of the Khagrachhari Sadar for drinking water quality assessment.

The groundwater quality index (GWQI) for drinking purposes adopted in this paper is not an absolute indicator of safe water. Rather, it is a factor that a person may choose to consider in evaluating drinking water quality based on the chemical parameters of the water. Excellent or good quality groundwater may still not be safe to drink due to several factors that were not considered in the evaluation of GWQI, e.g., bacteriological effects, contamination due to poor infrastructure or poor maintenance of the tube wells, and other unexpected occurrences that may occur from time to time.

4. Conclusions

For water quality management in a particular area, it is primarily essential to understand the groundwater composition and characterize the hydrochemical facies. In this study, water samples were collected from 34 shallow wells and 3 deep wells in the Khagrachhari Sadar area, measured at the field site, and analyzed in the lab. Samples were also evaluated for drinking and irrigation water quality using different water quality assessment methods. Spatial distribution maps were produced to obtain a better understanding of the distribution of shallow and deep wells in the study area, along with their physicochemical parameters and water quality assessment results.

In this investigation, the groundwater EC values were observed to be within the excellent to good range. Water wells were dominated by low-pH acidic water (86.5%). Positive redox potential (Eh) values were found in all wells, ranging from 23 to 323 millivolts. Most of the wells contained soft water (81.1%) in terms of total hardness. Shallow wells in the study area were dominated by the Ca–HCO_3 and mixed Ca–Na–HCO_3 types of groundwater, while two out of three deep wells contained Na–HCO_3-type water. In addition, box plots were used to display the statistical distribution of the major and trace ions present in the water samples, and the concentrations of Cl^-, $SO_4{}^{2-}$, Ca^{2+}, Mg^{2+}, Na^+, K^+, $NO_2{}^-$, $PO_4{}^{3-}$, F^-, and Br^- were observed to be below the safe drinking water limit. Higher concentrations of HCO3-, exceeding the safe water limit (>200 mg/L), were found in deep wells; this result may be derived from either the weathering of carbonate and silicate minerals or the mixing of freshwater with ancient seawater. Na^+ also showed relatively higher concentrations in the deep well water samples, but values were within safe water limits. Some of the shallow wells contained high levels of $NO_3{}^-$, Fe^{2+}, and Mn^{2+} that were above the safe water limits, i.e., 10 mg/L, 1 mg/L, and 0.1 mg/L, respectively. Excess NO_3- was possibly released from agricultural activities in the study region, and the slightly high values observed for Fe^{2+} and Mn^{2+} may be naturally present in shallow aquifers in favorable geochemical environments.

According to the SAR measurements, 100% of the water wells were in excellent condition for irrigation. The Riverside classification also showed that all the water samples were within the low SAR and low to medium EC range. A total of 91.9% of the water samples were found to be good in quality; groundwater results from one shallow well and two deep wells were doubtful and unsuitable for irrigation, respectively, based on the RSC method. The calculations associated with the SP method showed that one shallow well and two deep wells were not safe for irrigation since they fell into the doubtful and unsuitable categories. This result was also supported by the Wilcox classification, where SP (%Na) was measured against the EC of the water samples. According to the GWQI results, groundwater from 81.1% of the wells, including the three deep wells in the Khagrachhari Sadar, was of excellent quality for drinking purposes. Two shallow wells were found to contain only poor- or very-poor-quality groundwater for human consumption. The results can be summarized as follows: the groundwater of deep wells in the study area was less suitable, and more caution is needed before using it as irrigation water. However, deep groundwater was not found to be harmful for drinking purposes. In contrast, although some water samples from the shallow wells were of doubtful or poor quality, the majority of the shallow wells in the Khagrachhari Sadar area were relatively safe for both drinking and irrigation water uses. However, further investigation, including arsenic and microbiological tests, is recommended to obtain a more acceptable assessment of safe drinking water quality in the study region.

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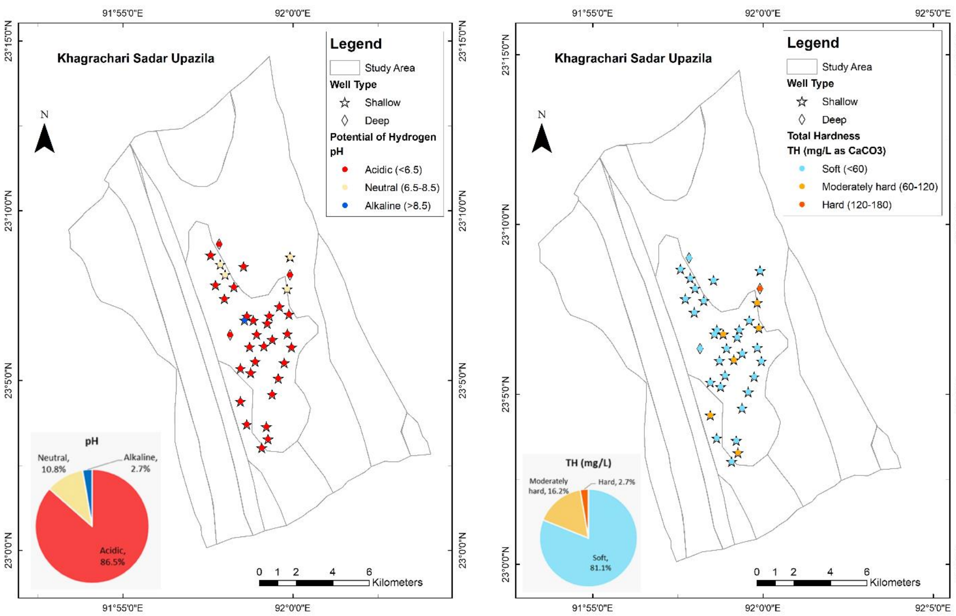
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Physical parameters of the water samples collected from the shallow and deep wells in the Khagrachhari Sadar with the mean, maximum, minimum, standard deviation value, and water quality standard.

Parameter	Unit	Mean	Maximum	Minimum	Std Deviation	Water Quality Standard
Temperature	°C	27.08	29.3	24	1.23	25
EC	µS/cm	143.46	460	24	107.82	1500
pH	-	5.98	8.55	4.08	0.853	6.5–8.5
Eh	millivolt	182.16	323	23	69.78	-
TH	mg/L as $CaCO_3$	46.36	144.4	15.89	27.85	200

Note: Water quality standard [16].



(**a**) (**b**)

Figure A1. Spatial distribution of (**a**) pH and (**b**) TH in shallow and deep wells of the Khagrachhari Sadar.

Table A2. Calculated values of SAR, RSC, and SP along with the water classifications based on these three methods for irrigation water quality assessment in the study area.

SAMPLE ID	SAR	Comment-SAR	RSC (meq/L)	Comment-RSC	SP (%)	Comment-SP
KCHS01	0.831	Excellent	−0.09	Good	40.45	Permissible
KCHS02	0.882	Excellent	1.08	Good	33.69	Good
KCHS03	0.832	Excellent	0.29	Good	45.77	Permissible
KCHS04	0.466	Excellent	0.09	Good	35.74	Good
KCHS05	0.535	Excellent	0.60	Good	25.30	Good
KCHS06	0.878	Excellent	−0.24	Good	40.42	Permissible
KCHS07	1.086	Excellent	0.81	Good	52.65	Permissible
KCHS08	6.737	Excellent	3.99	Unsuitable for irrigation	84.84	Unsuitable for irrigation
KCHS09	0.981	Excellent	0.42	Good	45.49	Permissible
KCHS10	1.944	Excellent	−1.35	Good	53.65	Permissible
KCHS11	0.512	Excellent	−0.04	Good	36.88	Good
KCHS12	4.129	Excellent	3.03	Unsuitable for irrigation	75.13	Doubtful
KCHS13	1.502	Excellent	−0.18	Good	59.19	Permissible
KCHS14	0.980	Excellent	0.57	Good	53.07	Permissible
KCHS15	0.597	Excellent	0.20	Good	45.47	Permissible
KCHS16	1.125	Excellent	0.82	Good	52.09	Permissible
KCHS17	0.877	Excellent	0.35	Good	51.48	Permissible
KCHS18	0.789	Excellent	−0.17	Good	39.46	Good
KCHS19	0.653	Excellent	−0.06	Good	33.19	Good
KCHS20	1.078	Excellent	0.43	Good	45.03	Permissible
KCHS21	0.675	Excellent	0.55	Good	32.431	Good
KCHS22	1.492	Excellent	0.57	Good	59.33	Permissible
KCHS23	1.017	Excellent	0.43	Good	50.27	Permissible
KCHS24	1.174	Excellent	−0.61	Good	50.16	Permissible
KCHS25	0.752	Excellent	0.26	Good	46.47	Permissible
KCHS26	1.002	Excellent	0.34	Good	51.39	Permissible
KCHS27	1.142	Excellent	0.78	Good	48.24	Permissible
KCHS28	1.122	Excellent	1.00	Good	37.90	Good
KCHS29	0.350	Excellent	0.20	Good	24.12	Good
KCHS30	1.468	Excellent	1.24	Good	38.55	Good
KCHS31	1.756	Excellent	1.57	Doubtful	45.94	Permissible
KCHS32	0.828	Excellent	0.57	Good	41.11	Permissible
KCHS33	0.770	Excellent	0.54	Good	43.46	Permissible
KCHS34	0.932	Excellent	0.88	Good	44.78	Permissible
KCHS35	6.731	Excellent	−0.24	Good	79.74	Doubtful
KCHS36	1.329	Excellent	0.26	Good	52.28	Permissible
KCHS37	1.088	Excellent	0.93	Good	44.00	Permissible

Note: KCHS-Khagrachhari Sadar.

Table A3. Calculated GWQI scores and types of groundwater for drinking water quality assessment in the study area.

SAMPLE ID	GWQI Score	Type of Groundwater	SAMPLE ID	GWQI Score	Type of Groundwater
KCHS01	20.45	Excellent	KCHS20	17.27	Excellent
KCHS02	67.01	Good	KCHS21	137.14	Poor
KCHS03	20.81	Excellent	KCHS22	57.03	Good
KCHS04	11.16	Excellent	KCHS23	12.22	Excellent
KCHS05	21.93	Excellent	KCHS24	12.54	Excellent
KCHS06	51.02	Good	KCHS25	28.45	Excellent
KCHS07	12.55	Excellent	KCHS26	11.78	Excellent

Table A3. *Cont.*

SAMPLE ID	GWQI Score	Type of Groundwater	SAMPLE ID	GWQI Score	Type of Groundwater
KCHS08	21.03	Excellent	KCHS27	12.25	Excellent
KCHS09	27.54	Excellent	KCHS28	51.27	Good
KCHS10	22.07	Excellent	KCHS29	92.11	Good
KCHS11	13.46	Excellent	KCHS30	25.80	Excellent
KCHS12	16.59	Excellent	KCHS31	26.00	Excellent
KCHS13	41.89	Excellent	KCHS32	35.41	Excellent
KCHS14	15.43	Excellent	KCHS33	18.14	Excellent
KCHS15	13.83	Excellent	KCHS34	13.81	Excellent
KCHS16	15.37	Excellent	KCHS35	31.85	Excellent
KCHS17	16.39	Excellent	KCHS36	288.45	Very Poor
KCHS18	33.20	Excellent	KCHS37	17.23	Excellent
KCHS19	20.45	Excellent			

Note: KCHS-Khagrachhari Sadar.

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