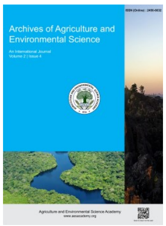
Archives of Agriculture and Environmental Science 8(4): 625-633 (2023)
https://doi.org/10.26832/24566632.2023.0804025

e-ISSN: 2456-6632

This content is available online at AESA

Archives of Agriculture and Environmental Science

Journal homepage: journals.aesacademy.org/index.php/aaes



CASE STUDY

CrossMark

Hydrochemical characterization of groundwater for consumption and agriculture: A case study from Phulpur Upazila, Bangladesh

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ARTICLE HISTORY

Received: 13 October 2023
Revised received: 29 November 2023
Accepted: 15 December 2023

Keywords

Groundwater quality
Hydrogeochemistry
Major ions
Rock-water interactions

ABSTRACT

The aim of this study was to assess the suitability of groundwater for drinking and irrigation in Phulpur Upazila, Bangladesh, based on its hydrochemical attributes. In our research, we examined twenty groundwater specimens from shallow and hand tube wells, adhering to international and national guidelines. The data showed groundwater pH levels from 5.67 to 6.84, signifying slightly acidic to neutral properties. Total dissolved solids ranged from 79 to 298 mg/l, and conductivity varied between 120 and 832 µS/cm. Notably, the primary cations and anions were sequenced as Ca > Mg > Na > K and HCO_3 > Cl > SO_4 > PO_4, respectively. A marked correlation was discerned among the physicochemical parameters, and the predominant groundwater type was magnesium-bicarbonate (Mg-HCO_3). The main geochemical activity was identified as silicate weathering, pointing to significant rock-water interactions in the region. The groundwater displayed moderate salinity and low alkalinity, qualifying them as 'excellent to good' and 'normal' in quality metrics, respectively. The soluble sodium percentage was rated as 'excellent'. On multiple assessment scales, the groundwater quality was deemed 'good' for irrigation. In line with established classification systems, most samples were suitable for drinking and irrigation. Hence, the area's groundwater is viable for consumption and agricultural utilization. Cumulatively, our research offers critical insights for sustainable groundwater stewardship in the region, providing a foundation for policymakers to guarantee the sustained provision of high-quality groundwater for diverse applications.

Citation of this article: Islam, D., Shaheen, R., Shariot-Ullah, M., Islam, M. T., Das, N., & Jahan, N. (2023). Hydrochemical characterization of groundwater for consumption and agriculture: A case study from Phulpur Upazila, Bangladesh. *Archives of Agriculture and Environmental Science*, 8(4), 625-633, https://dx.doi.org/10.26832/24566632.2023.0804025

INTRODUCTION

Water, an indispensable element for life, is a vital resource plentifully available across the planet. Groundwater, a primary source of freshwater, comprises around 30% of the world's total freshwater supply. Annually, global groundwater extraction ranges between 600–1100 km^3, but its natural replenishment is slow, ranging from 0.1% to 3% per year (Das *et al.*, 2019). Agriculture significantly draws on groundwater resources, accounting for roughly 70% to 90% of total withdrawals (Siebert *et al.*, 2010). In Bangladesh, groundwater withdrawals total about 28.48 km^3, which represents 79% of the nation's water consumption. This water is essential for irrigation, drinking, industrial, and domestic purposes (Das *et al.*, 2019; Jahan *et al.*, 2020). Approximately 87% of Bangladesh's population is engaged in agriculture either directly or indirectly, contributing substantially to the GDP (14.3% in the fiscal year 2017-18) (World Bank, 2016; BBS, 2018). The irrigated area in the country has dramatically increased from 4% in 1971 to 85% in 2013 (Shahid *et al.*, 2014).

Safe drinking water and reliable irrigation are critical for socio-economic growth and public health. Investigations into water quality are vital for ensuring agricultural efficiency, safeguarding health, and revealing geological aspects of the subsurface water (Shariot-Ullah *et al.*, 2016; Amalraj and Pius, 2018; Nemčić-Jurec *et al.*, 2019). The accessibility of ample, high-quality water is crucial for sustainable water management in sectors such as agriculture, industry, and domestic usage (Islam *et al.*, 2015; Islam *et al.*, 2017a, Das *et al.*, 2018; Rana *et al.*, 2019; Vijai and Khan, 2021; Jalil *et al.*, 2022). Groundwater quality is influenced by the geological characteristics of the soil and rock within the saturated zone (Tiwari *et al.*, 2018). The quality of recharged water can differ due to the original groundwater quality, precipitation, inland surface water, and geochemical processes below the surface (Krishna Kumar *et al.*, 2014). Chemical presence in water can affect its suitability for use. Groundwater quality variations arise from physical and chemical properties shaped by geology and human activities (Yasir and Srivastava, 2016; Ravi *et al.*, 2020; Wang *et al.*, 2021). Factors like lithology, water residence time, temperature, pH, chemical composition, and climate affect groundwater quality (Todd and Mays, 2005; Hasan *et al.*, 2016). Moreover, hydrogeochemical processes lead to spatial and temporal changes in groundwater chemistry. Understanding hydrochemistry is key for identifying water sources, chemical composition, and quality for irrigation and consumption. Such research is crucial for comprehending groundwater composition and the geochemical processes affecting water quality.

In Bangladesh, various studies have assessed groundwater quality for agricultural and domestic uses in recent years (Islam *et al.*, 2017b; Mostafa *et al.*, 2017; Akter *et al.*, 2019; Yasmin *et al.*, 2019; Islam *et al.*, 2023). Specifically, in the Mymensingh district, research has been conducted at certain sites (Das *et al.*, 2019), but there is a knowledge gap in Phulpur Upazila—an agriculturally dependent, shallow groundwater-reliant peripheral region. The shallow aquifer in this area is likely susceptible to various physicochemical influences. Through a detailed study in Phulpur Upazila, this research will provide valuable insights for sustainable groundwater management, ensuring the longevity and quality of water for both consumption and irrigation. Ultimately, this study aims to furnish essential information for decision-makers, water managers, and policymakers to devise strategies for sustainable groundwater utilization, protect public health, and enhance agricultural efficiency.

MATERIALS AND METHODS

Hydrogeologic and climatic conditions at study site

The study area, Phulpur Upazila, is under the Mymensingh district and is located between 24°44' and 25°02' north latitudes and between 90°13' and 90°33' east longitudes. The testing site is groundwater-dependent for potable and irrigation water. The soil type is silt loam to silty clay loam on the ridges and impermeable clays in the basins. The soil type consists of noncalcareous brown and gray floodplain. Phulpur is a relatively elevated region with a limited capacity for water retention (BBS, 2017). Temperatures range from 18 – 34°C, and annual precipitation averages 2541 mm (BBS, 2013). Groundwater is extracted by numerous hand, deep and shallow tube wells. The groundwater depth ranges from 4 – 6 m. The average depth of potable groundwater is between 40 and 100 m (LGED, 2013). Numerous sources of surface water are utilized for fisheries, water supply, and domestic purposes. The Kharia River is one of the region's most important irrigation supplies.

Collection and processing of water samples

Twenty shallow and hand tube wells were chosen at random from the four unions of Phulpur Upazila in the Mymensingh district, namely Bhaitkandi, Singheshwar, Rambhadrapur and Sawndhara unions, to collect groundwater samples in September 2018 (Table 1). Six samples were utilized for irrigation, whereas fourteen were used for drinking. 1000 mL of water was gathered in two properly washed 500 mL plastic bottles. Each sample was labeled with information such as the mauza number, village name, union name, and date of collection.

Table 1. Detailed information on groundwater sampling sites of Phulpur Upazila in Mymensingh district, Bangladesh.

Sample No.	Sampling location		Water sources	Depth (m)
	Union	Village		
1	Singheshwar	Bonpara	Shallow tubewell	56
2		Chanpur	Hand tubewell	14
3		Singheshwar	Shallow tubewell	87
4		Singheshwar	Shallow tubewell	43
5		Bonpara	Shallow tubewell	58
6	Bhaitkandi	Aatkuchi	Hand tubewell	20
7		Bhaitkandi	Shallow tubewell	55
8		Bhaitkandi	Shallow tubewell	50
9		Darakpur	Hand tubewell	11
10		Darakpur	Hand tubewell	27
11	Rambhadrapur	Ramnathpur	Hand tubewell	21
12		Mahadevpur	Handtubewell	23
13		Mahadevpur	Hand tubewell	14
14		Charbahadurpur	Hand tubewell	14
15		Baghedhara	Hand tubewell	15
16	Sawndhara	Hossainpur	Hand tubewell	18
17		Kandapara	Hand tubewell	20
18		Bashati	Hand tubewell	20
19		Bashati	Hand tubewell	18
20		Hatpagla	Hand tubewell	14

Analysis of physicochemical properties of groundwater samples

In situ total dissolved solids (TDS) were measured using a TDS meter (portable TDS-3 digital pen stick). Nitric acid (0.25 ml) was added to each sample to obtain the best ion concentration during the laboratory test. The water samples were appropriately filtered using Whatman No #1 filter paper. Chemical analyses were performed in two different laboratories, namely, the Humboldt Soil Testing Laboratory (for pH, EC, CO_3, and HCO_3) in the Department of Soil Science, Bangladesh Agricultural University, and in the Laboratory of the Department of Agricultural Chemistry (for Ca, Mg, Na, K, Cl, SO_4 and PO_4), Bangladesh Agricultural University. pH, electrical conductivity (EC), total dissolved solids (TDS), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), carbonate (CO_3), bicarbonate (HCO_3), sulfate (SO_4) and phosphate (PO_4) were determined by following standard methods described by Wolf (1982); Ghosh *et al.* (1983); Chopra and Kanwar (1991); APHA (1995); Tandon (1995); Singh *et al.* (1999).

Investigation of relationship between major ions and hydrochemical processes

Gibbs diagram: The Gibbs diagram is widely used to determine the relationship between water composition and aquifer lithological characteristics. Three distinct fields were assessed: precipitation dominance, evaporation dominance, and rock-water interaction dominance (Gibbs, 1970).

Piper trilinear diagram: The Piper trilinear diagram was used to infer hydrogeochemical facies. These plots included two triangles, one for plotting cations and the other for plotting anions. The cations and anion fields were combined to show a single point in a diamond-shaped field, from which inference was drawn based on the hydrogeochemical facies concept. Cations are expressed as percentages of total cations in the meq/l plot as a single point on the left triangle, while anions plot in the right triangle. These trilinear diagrams provided a more explicit representation of the chemical correlations between groundwater samples than other alternative plotting approaches. (Piper, 1944).

Estimation of water quality parameters: The soluble sodium percentage (SSP), residual sodium carbonate (RSC), and magnesium adsorption ratio (MAR) were calculated from the standard equations mentioned by Eaton (1950); Kelley (1963); Todd and Mays (1980); Ragunath (1987), where all of the ions are expressed in meq/l. The suitability of groundwater for irrigation was classified based on these selected parameters.

Correlation matrix and statistical analyses of groundwater samples: Pearson's correlation coefficient matrix (r) was utilized to analyse the association between the physicochemical variables of the groundwater (Javed *et al.*, 2019). A value of r closer to + 1 or -1 represents a great linear correlation between the two parameters, whereas zero indicates no relationship between the parameters (Islam *et al.*, 2023). If the value of r exceeds than 0.7, the parameters are deemed strongly correlated; if it spans between 0.5 and 0.7, the parameters are moderately correlated; and a negative value indicates that the worth of one parameter decreases as the value of another parameter increases (Islam *et al.*, 2023). Furthermore, factor analysis was performed using SPSS (Statistical Package for the Social Sciences) software to explain the associations between the observations. Scatter and Wilcox diagrams, as well as USSL diagrams, were drawn (Prasanth *et al.*, 2012; Zakir *et al.*, 2018).

RESULTS AND DISCUSSION

Hydrogeochemical properties of groundwater

The groundwater's pH levels within the study area were found to range from 5.67 to 6.84, averaging at 6.50 (Table 2). This suggests that the groundwater's pH leans towards slightly acidic to neutral. Drinking water standards set the pH range at 6.5-8.5 (ISI, 1983; WHO, 2004), while Ayers and Westcot (1985) proposed a pH range of 6.50-8.40 for irrigation water. All 20 groundwater samples from our study fit within this acceptable range, implying that the water is apt for both consumption and sustained crop irrigation. Such findings mirror the conclusions of past studies (Prasanth *et al.*, 2012; Mostafa *et al.*, 2017; Zakir *et al.*, 2018), yet diverge from Yasmin *et al.* (2019). The TDS in the groundwater fluctuated between 79 to 298 mg/l, with an average of 133.5 mg/l (Table 2). As per the classification by Davis and De Weist (1966), groundwater samples with TDS levels under 500 mg/l are deemed drinkable. The elevated TDS concentrations in the samples likely result from salt leaching from the soil and domestic sewage infiltration. Such observations resonate with studies by Nizam *et al.* (2016), with Zakir *et al.* (2018) reporting analogous TDS concentrations. Moreover, the EC of our groundwater samples spanned from 120 to 832 µS/cm, averaging 461.15 µS/cm (Table 2). Utilizing the guidelines proposed by Gupta (1979), each sample was rated as being "excellent to good" for irrigation. This is consistent with findings from Nizam *et al.* (2016), Yasmin *et al.* (2019), and Mostafa *et al.* (2017). However, Zakir *et al.* (2018) reported EC values that lie in the lower to mid salinity range in their groundwater research.

Major cation chemistry

Water samples showed calcium and magnesium levels ranging between 17.63-68.93 mg/l and 7.77-24.30 mg/l, respectively. Their average concentrations were 29.24 mg/l for calcium and 12.92 mg/l for magnesium. Sodium and potassium concentrations spanned 1.31 -5.47 mg/l and 0.34-1.20 mg/l, with averages of 2.35 mg/l and 0.62 mg/l, respectively, as shown in Table 2. The major cations' prevalence followed the order: calcium > magnesium > sodium > potassium. High calcium, sodium, and magnesium levels are likely due to clay minerals like montmorillonite, illite, and chlorite (Öztürk and Dişli, 2022). Importantly, all these major cation concentrations remained below WHO and Bangladesh standards (Table 2). Groundwater's calcium and magnesium ions mainly stem from limestone, dolomite, gypsum, and anhydrite dissolution, while calcium ions also arise from cation exchange processes (Öztürk and Dişli, 2022).

Table 2. Minimum, maximum, and mean values of sample parameters to drinking water specification in comparison with WHO (2011), USEPA (1992), and BBS and UNICEF (2011).

Parameters	Values of sample properties			WHO standards (2011)	US Environmental Protection Agency Secondary drinking water standards (1992)	Bangladesh National Drinking Water Quality Survey (2009)
	Minimum	Maximum	Mean			
pH	5.67	6.84	6.50	6.5-8.5	6.5-8.5	6.5-8.5
EC (µS/cm)	120	832	448.78	-	-	-
TDS (mg/l)	79	298	140.21	500	500	1000
CO_3 (mg/l)	0.0	0.0	0.0	-	-	-
HCO_3 (mg/l)	73.2	359.9	159.03	100	-	100
Cl (mg/l)	9.99	59.98	30.56	200	250	600
SO_4 (mg/l)	0.18	2.38	0.58	200	250	400
PO_4 (mg/l)	0.002	0.31	0.049	-	0.1	6
Ca (mg/l)	17.63	68.93	29.40	75	-	75
Mg (mg/l)	7.77	24.30	13.12	50	-	30-35
Na (mg/l)	1.31	5.47	2.48	200	-	200
K (mg/l)	0.48	1.20	0.69	12	-	12

Table 3. Correlation coefficient matrix of major cations and anions of the study area.

Correlation	pH	EC	TDS	HCO_3	Cl	SO_4	PO_4	Ca	Mg	Na	K
pH	1										
EC	0.0914	1									
TDS	0.0475	0.1766	1								
HCO_3	0.2366	0.2759	0.8433**	1							
Cl	-0.2546	0.0457	0.7415**	0.3748	1						
SO_4	0.0373	-0.1667	0.8905**	0.6754**	0.7792**	1					
PO_4	0.3373	-0.0352	0.3227	0.4842*	0.0221	0.3428	1				
Ca	0.2409	0.1888	0.901**	0.9571**	0.44	0.7867**	0.503*	1			
Mg	-0.0962	0.2636	0.8288**	0.7782**	0.6565**	0.7193**	0.426	0.75**	1		
Na	-0.0685	0.1209	0.8249**	0.4807*	0.8678**	0.7475**	0.0476	0.5354*	0.601**	1	
K	-0.3208	0.1096	0.6069**	0.4007	0.6245**	0.6575**	0.1787	0.4986*	0.6209**	0.4662*	1

*Significant at a 5% probability level and **significant at a 1% level of probability.

Major anion chemistry

The area under study recorded zero carbonate concentrations. Bicarbonate levels, however, spanned 73.2-359.9 mg/l with a 164.09 mg/l average (Table 2). The elevated carbonate and bicarbonate levels are attributed to carbonate minerals in recharge zones and silicate weathering (Gayathri *et al.*, 2021). Chloride concentrations varied between 8.9-59.9 mg/l (average: 26.2 mg/l). Notably, excessive chloride can harm metal infrastructure and crops. Sulfate levels ranged 0.105-2.386 mg/l with a 0.483 mg/l average. These sulfate ions likely result from sulfate and gypsum rock weathering (Van Stempvoort *et al.*, 2023). Lastly, phosphate levels ranged 0.002-0.32 mg/l, averaging at 0.06 mg/l. Based on averages, anions' dominance followed HCO_3> Cl> SO_4> PO_4.

Correlation matrix

The groundwater samples from the study area were analyzed for their chemical composition, specifically the concentrations of key cations and anions such as Ca, Mg, Na, K, Cl, SO_4, HCO_3, and PO_4. This compositional breakdown is detailed in Table 3. The crux of this analysis aimed to discern any impactful interactions among the quality indices. While no notable correlations were observed between pH and other chemical parameters like EC, TDS, and specific ions, the same was true for EC against TDS and most ions. Intriguingly, TDS manifested strong positive correlations with several ions: HCO_3 (r=0.8433), Cl (r=0.7415), SO_4 (r=0.8905), Ca (r=0.901), Mg (r=0.8288), Na (r=0.8249), and K (r=0.6069) at a confidence level of 99%. HCO_3's correlation profile revealed robust positive associations with SO_4 (r=0.6754), Ca (r=0.9571), and Mg (r=0.7782) at the 1% significance threshold. It also correlated positively with PO_4 (r=0.4842) and Na (r=0.4807) albeit at a slightly relaxed 5% confidence level. Cl, on the other hand, exhibited solid relationships with SO_4(r=0.7792), Mg (r=0.6565), Na (r=0.8678), and K (r=0.6245) at the 1% level. Moreover, SO_4 shared positive associations with Ca (r=0.7867), Mg (r=0.7193), Na (r=0.7475), and K (r=0.6575), all at the 1% significance level. PO_4, however, had a noteworthy positive tie only with Ca (r=0.503) at the 5% level. Ca itself was significantly linked to Mg (r=0.75) at the 1% level, with weaker correlations to Na (r=0.5354) and K (r=0.4986) at the 5% level. Additionally, Mg displayed robust correlations with Na and K, marked by coefficients of 0.601 and 0.6209 respectively, both significant at the 1% level. Contrarily, Na and K shared a milder yet significant relationship (r=0.4662) at the 5% level. These results echo the findings of Hasan *et al.* (2022) from their study on the Manimukta River.

Factor analysis

Factor analysis had been employed to elucidate the connections between observed data points and latent factors that weren't directly observable. The extracted factors had then been utilized to compute the primary associated factors. As seen in Table 4, the variables EC, TDS, HCO_3, Cl, SO_4, PO_4, Ca, Na, and K had shown substantial positive loadings on factor 1, whereas pH, EC, HCO_3, PO_4, and Ca had high positive loadings on factor 2. Moreover, EC, HCO_3, and Mg had significant positive loadings on factor 3. These three distinct factor variables with unique loadings provided insights into the variations in the geochemical composition of groundwater. EC, TDS, HCO_3, Ca, and Mg had favorable positive loadings, suggesting that these ions had likely come from common sources, like weathering, carbonate, and gypsum dissolution processes. The positive loadings of pH values suggested that pH fluctuations in the study area had a significant impact on the concentration of major ions, with pH being a more dominant factor than TDS. Cl, Na, and K had moderate positive loadings, indicating potential origins from rock-water interactions. Additionally, PO_4 was more associated with anthropogenic-induced pollution sources than with natural processes (Khatri and Tyagi, 2015).

Relationship between major ions and hydrochemical processes

Major ions and weathering processes

Major ions formed a substantial part of the total dissolved solids present in the groundwater. The levels of these ions in the groundwater were dependent on the hydrogeochemical processes occurring within the aquifer system. A scatter diagram (Figure 1) was constructed to illustrate the relationship between (Ca + Mg) and (HCO_3 + SO_4) in the groundwater. When calcium and magnesium predominated over bicarbonate and sulfate ions, this suggested that carbonate weathering was the dominant process. In cases where the dissolution of calcite, dolomite, and gypsum contributed to the presence of Ca, Mg, SO_4, and HCO_3, there should have been a balance between the cations and anions, which would be reflected in the scatter diagram of (Ca + Mg) versus (HCO_3 + SO_4) closely following the 1:1 line. Points that lay below the 1:1 line indicated silicate weathering. The majority of the samples fell below the equiline, signifying a substantial influence from predominant silicate weathering. Nevertheless, there were a few points on the equiline, suggesting the weathering of both carbonate and silicate minerals. Our results were juxtaposed with those from a previous study (Gayathri *et al.*, 2021), and there was a consistency in the findings.

Mechanism controlling groundwater chemistry (Gibbs diagram)

Gibbs (1970) proposed a chemical model that aimed to investigate the mechanisms governing groundwater chemistry and to understand the relationship between water's chemical components and the lithology of the underlying aquifer. The quality of the groundwater was significantly influenced by both natural weathering processes and human activities. In analyzing the groundwater samples from the research area, researchers utilized the values of total dissolved solids to plot separately the Gibbs ratios I (representing anions) and II (representing cations). Figure 2 illustrated the distribution of samples within the rock dominance area of the study site, highlighting the influence of geological formations on the groundwater composition in the aquifers. The field indicating rock-water interaction dominance suggested an interplay between the chemical composition of the rocks and the percolating waters beneath the surface, as supported by the findings of Kumar *et al.* (2020).

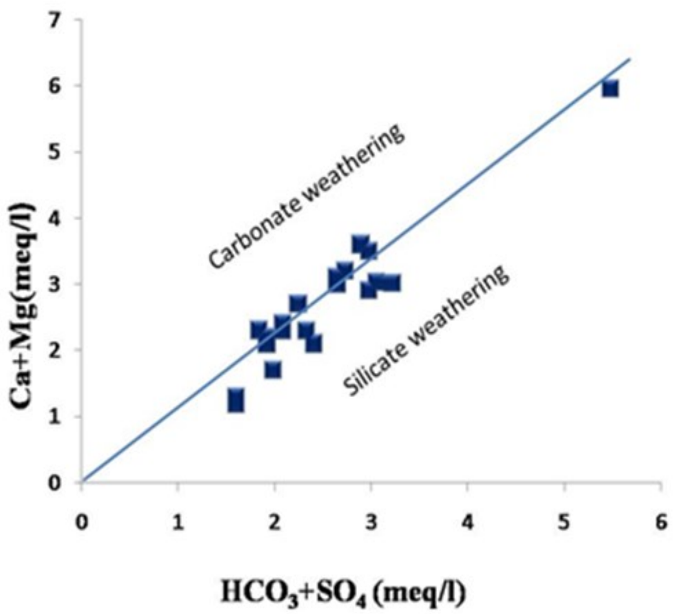

Figure 1. *Scatter plot of (Ca + Mg) vs. (HCO_3 + SO_4).*

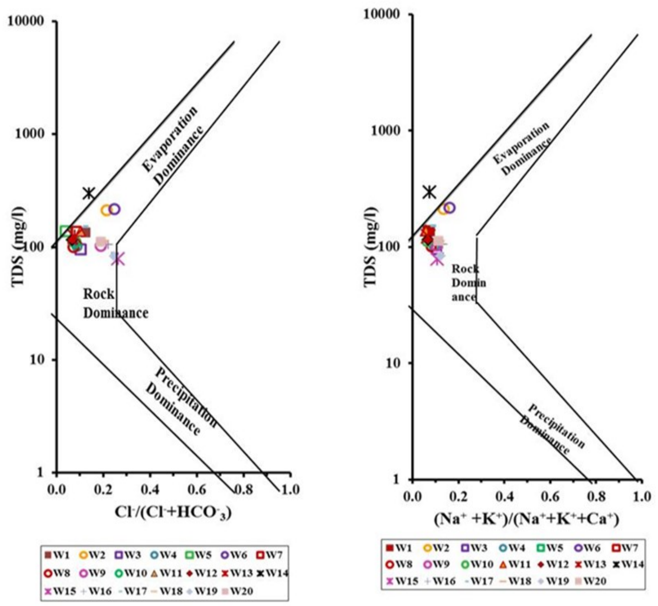

Figure 2. *Gibbs diagram (I, left and II, right) for the controlling factor of groundwater quality.*

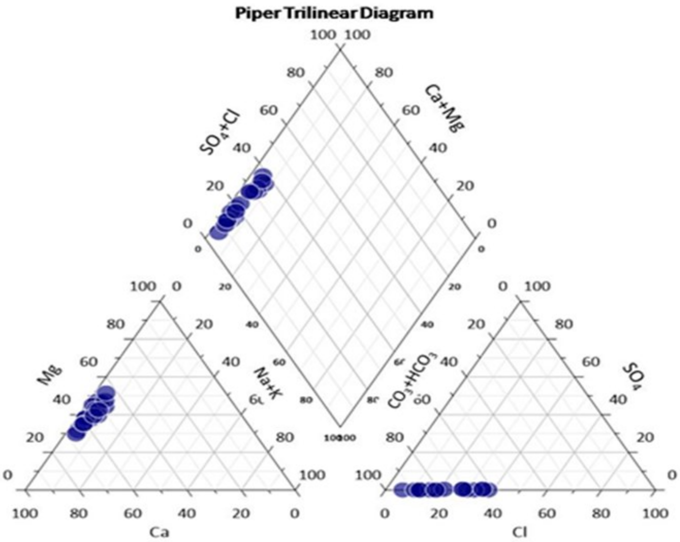

Figure 3. *Piper tri-linear diagram for hydrogeochemical facies of groundwater in the study area.*

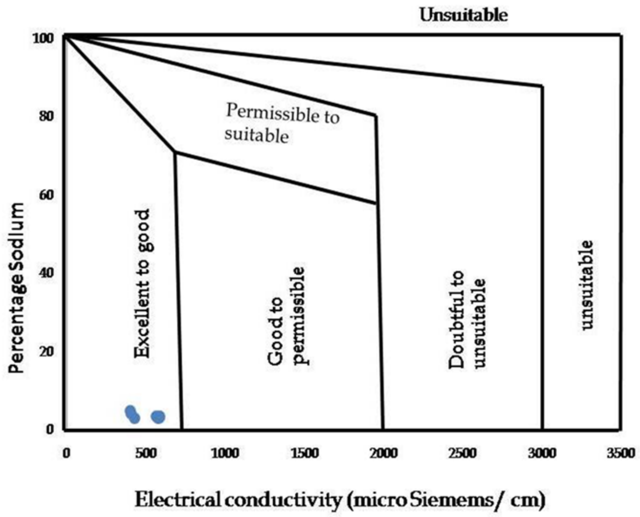

Figure 4. *Classification of irrigation water quality concerning total salt concentration and sodium percent (based on a Wilcox diagram).*

Hydrogeochemical facies (Piper tri-linear diagram)

Figure 3 displayed the Piper trilinear diagram that illustrated the variations in cation and anion concentrations of the groundwater samples in the specific area under investigation. The prevalent water type in the study area had been Mg-HCO_3. Our study's findings, when compared with values previously reported in the literature (Prasanth *et al.*, 2012), showed favorable agreement. The earlier study had also observed a similar dominance of groundwater type as was found in our research, with the majority of samples in the Rajshahi area being of the Ca-HCO_3 type.

Groundwater quality classification

Residual sodium carbonate (RSC): RSC plays a role in determining the appropriateness of water for irrigation purposes. RSC can be determined by subtracting the amount of alkaline earth (Ca + Mg) from the carbonates (CO_3+ HCO_3). If the total amount of carbonates exceeds the combined amount of calcium and magnesium, it is possible for complete precipitation of calcium and magnesium to occur. When the carbonates are lower than the alkaline earth, the RSC value is zero. Irrigation water with RSC values greater than 5.0 meq/l is considered detrimental to plant growth, while water with an RSC value above 2.50 meq/l is not deemed suitable for irrigation. Consequently, using water with high RSC levels consistently will negatively impact crop yields (Ragunath, 1987). In the study area, the RSC values ranged from -0.036 to 0.701, with an average value of 0.400 (Table 5). Based on the calculated values, all the sampled sites were found to be suitable for irrigation (Eaton, 1950). Similar results were also reported by Hasan *et al.* (2022) in their analysis of groundwater samples from Tamil Nadu, India.

Magnesium adsorption ratio (MAR): The relationship between magnesium and calcium concentrations in groundwater is defined by the MAR (Ragunath, 1987). Excessive magnesium negatively impacts soil quality, leading to low agricultural yields (Islam *et al.*, 2017c). The value of MAR exceeding 50 is considered detrimental and unsuitable for irrigation purposes (Islam *et al.*, 2016; Naidu *et al.*, 2021). The MAR values obtained ranged from 32.577 to 48.904, with an average of 41.845 (Table 5). Based on the classification by Naidu *et al.* (2021), all groundwater samples were determined to be suitable for irrigation. The results of the present study align with the findings of Islam *et al.* (2017b).

Soluble Sodium Percentage (SSP): The evaluation of sodium hazard relies on the SSP. In accordance with Wilcox (1955), SSP is a standardized parameter used to assess the suitability of natural waters for irrigation purposes. Table 5 shows that the calculated SSP values varied from 3.292 to 5.285, with an average of 3.984. Based on the standards set by Wilcox (1955), all samples were classified as excellent (SSP < 20%). The findings of this study align with the results obtained by Zakir *et al.* (2018) and Nizam *et al.* (2016).

Wilcox classification: Based on the classification system introduced by Wilcox (1955), the diagram representing the quality of water for irrigation and domestic use indicated that six samples could be categorized as being in excellent to good conditions (Figure 4). A study conducted by Zakir *et al.* (2018) in Bangladesh yielded similar findings, while Prasanth *et al.* (2012) reported the highest values falling within the range of good to permissible for irrigation in Kerala, India.

Kelley's ratio (KR): KR, a measurement comparing the levels of Na to Ca and Mg, serves as a means to evaluate irrigation water quality (Kelley, 1963). When the concentration of Na exceeds a certain threshold indicated by KR>1, the water becomes unsuitable for irrigation. Conversely, water with a KR<1 is considered suitable. In our study, the calculated values for KR ranged from 0.030 to 0.047, with an average value of 0.036 (Table 5). According to the classification reported by Kelley (1963), all groundwater samples were deemed suitable for irrigation. These findings align with the results obtained in previous studies conducted by Islam *et al.* (2017b) and Yasmin *et al.* (2019).

Table 4. Factor analysis of major cations and anions in the study area.

Variable	Factor 1	Factor 2	Factor 3
pH	0.017	0.793	-0.081
EC	0.170	0.179	0.949
TDS	0.978	0.008	0.026
HCO_3	0.839	0.410	0.118
Cl	0.774	-0.508	-0.031
SO_4	0.912	-0.095	-0.330
PO_4	0.409	0.623	-0.302
Ca	0.888	0.357	0.003
Mg	0.887	0.016	0.136
Na	0.790	-0.325	0.030
K	0.695	-0.352	0.022

Table 5. Water quality parameters in the study area.

Sample No.	EC (µS/cm)	SAR	SSP (%)	RSC (meq/l)	MAR (meq/l)	KR (meq/l)
1	579	0.074	3.292	0.518	48.904	0.030
3	396	0.092	5.285	0.448	39.371	0.047
4	400	0.083	4.534	0.306	42.557	0.041
5	583	0.078	3.510	0.701	39.131	0.032
7	561	0.086	3.867	0.464	32.577	0.037
8	421	0.065	3.416	-0.036	48.529	0.030
Maximum	583	0.092	5.285	0.701	48.904	0.047
Minimum	396	0.065	3.292	-0.036	32.577	0.030
Mean	490	0.079	3.984	0.400	41.845	0.036

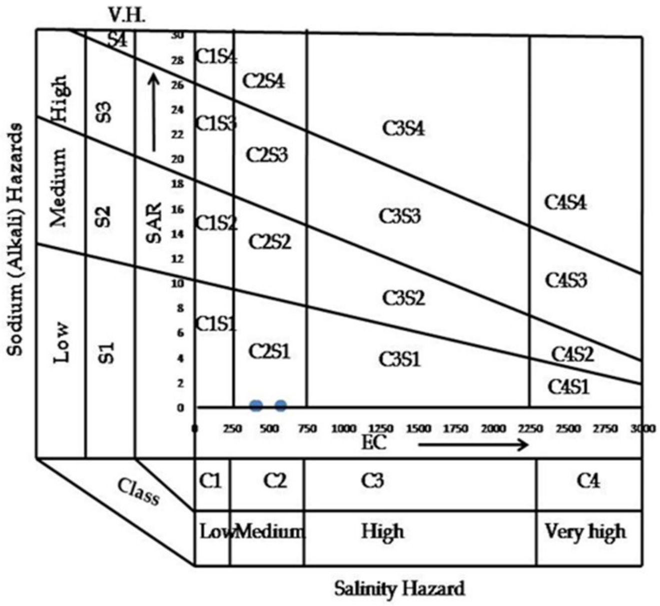

Figure 5. *Classification of irrigation water quality concerning salinity hazard and sodium hazard (based on USSL diagram).*

Sodium adsorption ratio (SAR): The SAR is a measurement used to evaluate the suitability of water for agricultural irrigation. This is because high concentrations of sodium in water can reduce soil permeability and alter soil structure (Todd and Mays, 1980). In our study, the SAR values ranged from -0.036 to 0.701, with an average of 0.400 (Table 5). According to Todd and Mays (1980), when the SAR value of water used for irrigation is less than 10, it is unlikely to have negative effects on crops. Based on the classification proposed by Gupta (1979), all groundwater samples in our study were categorized as suitable for irrigation. The results of previous studies (Prasanth *et al*., 2012; Nizam *et al*., 2016; Zakir *et al*., 2018; Yasmin *et al*., 2019) supported the findings of our current study.

United States salinity laboratory (USSL) classification

The US salinity diagram was utilized to evaluate the water samples intended for irrigation. This diagram plots the SAR against the EC. According to the US Salinity Laboratory (USSL, 1954), one of the six groundwater samples analyzed in C2S1 (medium salinity-low sodium type) exhibited satisfactory qualities (Figure 5). These groundwater samples presented moderate salinity risks but had low alkali hazards. By referring to the USSL diagram, it was determined that these groundwater samples were suitable for irrigation across various soil types. Similar findings were reported by Zakir *et al.* (2018), while Prasanth *et al.* (2012) observed partially similar results in their study.

Conclusion

The groundwater in the study area displayed a slightly acidic to neutral pH. The TDS value of the samples fell within the desirable water category. The EC value of the groundwater samples indicated excellent to good suitability for irrigation. The average concentrations of cations and anions followed the order Ca> Mg> Na> K and HCO_3> Cl> SO_4> PO_4, respectively. The predominant hydrochemical facies of the groundwater in the study area was classified as the Mg–HCO_3 type. The analysis of Gibbs plots suggested that the chemical composition of the groundwater in the region was primarily influenced by interactions between rocks and water. Scattered diagrams depicting the relationship among ions revealed that silicate weathering was the dominant weathering process. The US salinity classification of the water samples indicated that most groundwater sources belonged to the C2S1 category, representing medium salinity-low sodium water suitable for irrigation on all soil types. According to the Wilcox classification, the majority of groundwater samples were deemed acceptable for irrigation and also suitable for drinking purposes. In this study, all groundwater samples fell into the "normal" category in terms of the SAR. The groundwater was classified as "good" based on the RSC criterion. Analyzing the Wilcox diagram, the SSP values indicated that six samples were categorized as "excellent to good," signifying that the water quality was suitable for irrigation. Furthermore, the study revealed that all groundwater samples were within the "suitable" category with regard to the MAR and KR. Overall, it can be inferred that the drinking and irrigation water quality in the study area meets the necessary standards. However, it is recommended to expand the sample size to include additional regions and analyze the presence of heavy metals, while also considering changes over time. By doing so, a more comprehensive assessment of the groundwater quality throughout the Phulpur Upazila, Bangladesh can be achieved. This information would be valuable for effective planning and management of groundwater usage and treatment.

ACKNOWLEDGEMENT

The authors express their gratitude to The Ministry of Science and Technology, Bangladesh, for financially supporting this research. Additionally, the authors extend their appreciation to the anonymous reviewers whose constructive comments and suggestions greatly contributed to the enhancement of the manuscript.

Conflict of interest

The authors have declared that no competing interests exist.

DATA AVAILABILITY

Available on reasonable request.

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