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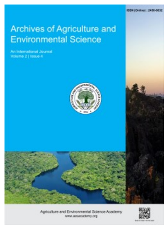


ORIGINAL RESEARCH ARTICLE

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# Utilizing geographic information system and indexing to evaluate irrigation suitability of groundwater in Kalihati Upazila, Bangladesh

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**ABSTRACT**

The aim of this research was to evaluate groundwater quality for irrigation in Kalihati Upazila, Bangladesh, a region that is significantly reliant on groundwater for crop development, especially during dry periods. By combining hydrochemical analysis and Geographic Information System (GIS), the research examined the physicochemical attributes and their spatial distribution. Fifteen groundwater samples from various locations were analyzed to measure parameters such as sodium adsorption ratio (SAR), soluble sodium percentage (SSP), residual sodium carbonate (RSC), magnesium adsorption ratio (MAR), electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), Kelly's ratio (KR), permeability index (PI), and potential salinity (PS). The pH of the groundwater ranged between 5.51 and 7.53, indicating slightly acidic to moderately alkaline conditions suited for irrigation. The EC ranged between 115.7 and 458 µS/cm, mostly falling into the "excellent" or "good" categories. Groundwater displayed irrigation suitability with TDS below 182 ppm and low SAR values, but variable RSC and MAR values indicated localized water quality issues. Based on the irrigation water quality index, all samples were within the "permissible" range. However, GIS-generated maps showed disparities in groundwater quality across the study area. Correlation matrices revealed significant links between various factors. Both the Piper and Gibbs diagrams displayed a prevalent Ca-$HCO_3$ groundwater type influenced by geological formations. Overall, the study confirmed groundwater's appropriateness for irrigation while recommending periodic evaluations due to a few uncertainties. In conclusion, the study found that hydrochemical analysis, GIS mapping, and correlation matrices reveal groundwater quality and spatial trends, allowing for sustainable water resource management and agricultural advancement.



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## INTRODUCTION

The escalating global populace and expanding agricultural demands underscore an urgent requirement to harmonize the equilibrium between water supply and demand. As the influence of climate change persists in altering precipitation patterns and the accessibility of surface water, relying exclusively on surface water reservoirs for agricultural needs becomes increasingly precarious (Lal *et al.*, 2018). Groundwater, subject to appropriate governance, holds the potential to act as a safeguard against water scarcity and ameliorate the deleterious consequences of climatic shifts. This subsurface water resource, constituting approximately 30% of the planet's freshwater reserves, has amassed over geological epochs and exhibits a recharge rate spanning from 0.1 to 3% annually (Das *et al.*, 2019). Despite its finite availability, groundwater presently caters to a quarter of the global water demand. In nations with inadequate river and drainage systems, groundwater has emerged as the predominant water source, presenting a notable concern for both crop cultivation and agricultural security (Iqbal *et al*., 2020). For instance, in the context of Bangladesh, nearly 95% of groundwater is harnessed for potable consumption, with roughly 75% allocated for irrigation (Akhter *et al*., 2019; Yasmin *et al*., 2019; Iqbal *et al*., 2020). The remaining 25% of irrigation is facilitated through alternative means, such as precipitation during the monsoon season or the utilization of lakes, rivers, and ponds. However, groundwater is susceptible to contamination stemming from diverse sources, including wastewater discharge, the application of fertilizers and pesticides, product disposal, mining operations, and the disposal of nuclear energy byproducts, all of which pose hazards to human health (Bodrud-Doza *et al*., 2019). Consequently, the escalating deterioration in groundwater quality for irrigation has emerged as a burgeoning concern in recent times.

Water suitability for irrigation displays variability, demanding adherence to specific quality benchmarks to enhance agricultural output (Das *et al*., 2019). Groundwater presents added complexities due to its potential for heightened concentrations of dissolved chemical components in contrast to surface water. Therefore, the cautious utilization of groundwater for irrigation is imperative to avert the accumulation of harmful ions in the soil and crops, which could degrade the soil ecosystem and detrimentally impact agricultural yields (Nikolaou *et al*., 2020). However, the attainment of environmentally friendly and sustainable crop production mandates the evaluation of diverse water quality parameters to ensure conformity with acceptable thresholds. Water quality encompasses traits spanning the physical, chemical, and biological domains. Among these, physicochemical attributes including the sodium adsorption ratio (SAR), soluble sodium percentage (SSP), residual sodium carbonate (RSC), magnesium adsorption ratio (MAR), electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), Kelly's ratio (KR), permeability index (PI), and potential salinity (PS) predominantly serve as yardsticks for assessing irrigation water appropriateness (Hasan *et al*., 2016; Eyankware *et al*., 2018; Das *et al*., 2019; Yasmin *et al*., 2019). This holistic approach ensures informed decision-making regarding water resource utilization in agriculture.

While the evaluation of water quality commonly relies on various hydro-chemical parameters, an element of uncertainty arises when certain parameters conform to guideline limits while others do not, underscoring the need for modern and pragmatic techniques to appraise the spatial diversity of physicochemical attributes and aptly portray water quality (Hussain and Abed, 2019). While earlier studies have acknowledged the utilization of simulation methodologies and conceptual models for assessing the appropriateness of groundwater for domestic and agricultural use, the widely adopted water quality index maintains its efficacy in comprehending the suitability of groundwater specifically for irrigation purposes (Hussain and Abed, 2019). The irrigation water quality index (IWQI) serves as an evaluative tool that gauges the collective impact of hydrochemical measures on the overall utility of groundwater in irrigation practices (Ahmed *et al*., 2021). Furthermore, in conjunction with the IWQI, a contemporary technique like Geographic Information System (GIS) is employed to scrutinize the spatial variance of physicochemical parameters and effectively depict water quality patterns (Moharir *et al*., 2019; Pandey *et al*., 2020). This combined approach offers a comprehensive understanding of groundwater suitability for irrigation, aiding in informed decision-making regarding water usage and management strategies.

Recent investigations in Bangladesh have primarily concentrated on appraising groundwater quality for domestic and agricultural applications within select urban areas (Das *et al*., 2019; Yasmin *et al*., 2019; Iqbal *et al*., 2020). However, such studies have disregarded the considerable heterogeneity in groundwater quality across diverse locales. Importantly, there exists a conspicuous gap in research concerning the evaluation of groundwater suitability for agricultural use in the Kalihati Upazila of Bangladesh. This void is particularly critical due to the region's heavy reliance on groundwater for crop cultivation, especially during dry spells. Given the burgeoning population and escalating food demands, it becomes imperative to evaluate the appropriateness of groundwater for irrigation within this locality. Additionally, the Paikara Union within the Kalihati Upazila is believed to be susceptible to various physicochemical constituents present in the shallow aquifer. In response, our study aims to employ GIS approach to delineate concentrations of groundwater quality and assess its aptness for irrigation, utilizing the IWQI technique in conjunction with correlation matrix analysis. Collectively, this research not only carries significant implications for promoting sustainable water management practices and enhancing agricultural yield but also underscores the well-being of local populations. The amalgamation of indexing methodologies and GIS-based evaluations presents an efficacious strategy for steering decision-making processes and fostering judicious and efficient exploitation of groundwater resources.

## MATERIALS AND METHODS

### Water sample collection and laboratory analysis

Figure 1 depicts the sampling site within the study region, Paikara Union, located in the Kalihati Upazila of the Tangail District in Bangladesh. The geographical coordinates of the research area span from 24°18'40"N to 24°24'00"N in terms of latitude and 89°46'40"E to 90°05'20"E in terms of longitude. The groundwater quality within this geographical region is impacted by the Jamuna, Dhaleshwari, and Louhajang Rivers flowing through Bangladesh. In the month of April 2019, a total of fifteen samples of groundwater were gathered in a random manner to ensure comprehensive coverage of the study area. The selection of sampling sites was accomplished using a handheld Global Positioning System (GPS) device. Subsequently, the collected samples were carefully preserved within 500 ml bottles that had been pre-treated with mild HCl acid, followed by triple rinsing

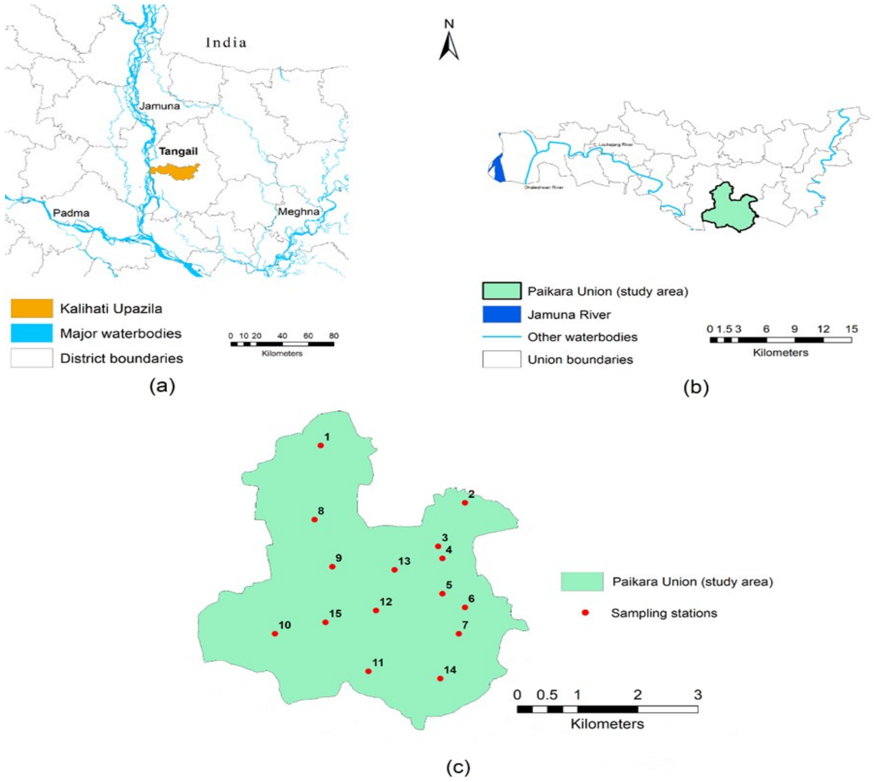



**Figure 1.** *(a) Kalihati Upazila, Bangladesh mapping, and (b) study area with sampling stations highlighted on the Kalihati Upazila map.*

with the water samples themselves. These bottles were meticulously labeled for identification purposes. Prior to undergoing laboratory analysis, the samples were maintained at a temperature lower than 4°C. To eliminate unwanted particulates and suspended matter, the samples were meticulously filtered using Whatman No. 1 filter paper.

The investigation of groundwater samples was executed at the Department of Agricultural Chemistry and the Interdisciplinary Institute for Food Security, Bangladesh Agricultural University, Bangladesh, adhering to the established protocols outlined by APHA (2012). The assessment encompassed parameters such as pH, EC, TDS, and major ionic components including calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), sodium ($Na^{+}$), potassium ($K^{+}$), chloride ($Cl^{-}$), sulfate ($SO_4^{2-}$), nitrate ($NO_3^{-}$), alkalinity as carbonate ($CO_3^{-}$), bicarbonate ($HCO_3^{-}$) and phosphate ($PO_4^{3-}$). pH values were gauged by subjecting a 50 ml water sample to measurement using a pH meter, following the methodology elucidated by Singh and Narain (1980). EC was ascertained by immersing the electrode of a conductivity meter into a 100 ml water sample, employing the technique outlined by Tandon (1993). TDS was determined through the evaporation of a 100 ml water sample to dryness and the subsequent measurement of the residue's weight, in accordance with the procedure recommended by Chopra and Kanwar (1982). The concentrations of Ca and Mg ions were assessed through a complexometric titration method utilizing $Na_2EDTA$ as the titrant. The concentration of Cl was determined by means of a titration assay utilizing $AgNO_3$. $CO_3^{-}$ and $HCO_3^{-}$ were quantified through titrimetry against a standard 0.01 N HCl acid solution. Na and K contents were measured using a Flame Photometer, while the concentrations of $SO_4^{2-}$ and $NO_3^{-}$ were analyzed using a spectrophotometer. This meticulous approach ensures a comprehensive understanding of the groundwater composition and quality, which holds significant implications for various agricultural and environmental considerations.

## Quality parameters for irrigation suitability

The assessment of groundwater suitability for agricultural use encompassed the analysis of different indicators pertaining to water quality (Nijesh *et al.*, 2021). Among these indicators, the SAR emerges as significant, elucidating the interplay between soluble sodium ($Na^{+}$) and soluble divalent cations, notably calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$). Computation of the SAR was accomplished through the utilization of the following equation outlined by Richards (1954).

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

where all the ions are expressed in meq/L or epm (equivalents per million).

The assessment of sodium hazard relies on the measurement of SSP, which can be determined using the following equation provided by Todd and Mays (2004):

$$SSP = \frac{(Na^{+}+K^{+})}{Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}} \times 100$$

Where all the ions are expressed in epm.

The excessive influence of $Na^{+}$ in groundwater can be significantly mitigated by the presence of $Mg^{2+}$ in groundwater. The determination of the $Mg^{2+}$ adsorption ratio (MAR) was performed using the equation proposed by Raghunath (1987):

$$MAR = \frac{Ma^{+}}{Ca^{2+} + Mg^{2+}} \times 100$$

Where all the ions are expressed in epm.

The equation (Eaton, 1950) mentioned below was utilized to assess the potential harm caused by carbonate and bicarbonate in water intended for agricultural use, by calculating the RSC.

$$RSC = (CO_3^{-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$$

Where all the ions are expressed in epm. The following equation used to determine the TH was as stated by Sawyer and McCarty (1967):

$$TH = (2.5 \times Ca^{2+}) + (4.1 \times Mg^{2+})$$

Where all the ions are expressed in mg/l or ppm (parts per million). KR is a significant factor for assessing the quality of irrigation water. It can be determined using the formula introduced by Kelly (1963) as follows:

$$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}}$$

Where all the ions are expressed in epm.
Doneen (1964) developed a method to evaluate the appropriateness of water for irrigation using the PI. The PI value was determined using the following equation proposed by Doneen (1964):

$$PI = \frac{(Na^{+} + \sqrt{HCO_3^{-}})}{Ca^{2+} + Mg^{2+} + Na^{+}} \times 100$$

Where all the ions are expressed in epm.

Potential salinity (PS) refers to the sum of chloride concentration and half of the sulfate concentration, as defined by Doneen (1954) in the provided equation:

$$PS = Cl^{-} + \frac{1}{2} SO_4^{2-}$$

Where all the ions are expressed in epm.

### Irrigation water quality index (IWQI)

The calculation of the IWQI involved the utilization of five subsequent water quality indicators, namely EC, SAR, $Na^{+}$, $Cl^{-}$, and $HCO_3^{-}$. To ensure consistency, the concentration units were initially converted from ppm to epm using the conversion factors outlined by (Abbasnia *et al.*, 2018) prior to the commencement of data analysis. Within this section, the evaluation of the IWQI centered on the computation of water quality measurement parameter values ($q_i$) and the cumulative witness ($W_i$). The predetermined threshold values for the five chosen parameters were summarized in the earlier study conducted by Abbasnia *et al.* (2018). The specific qi values corresponding to each of the five water quality parameters (qEC, qSAR, $qNa^{+}$, $qCl^{-}$, and $qHCO_3^{-}$) were determined through the application of equation, as presented in the formula below. For the assessment of $x_{imap}$, the upper limit of the parameter range, as stipulated in prior research (Abbasnia *et al.*, 2018), was established based on the highest value observed among the samples.

$$q_i = q_{max} - \left(\frac{(x_{ij} - x_{inf}) \times q_{imap}}{x_{amp}}\right)$$

Where, the symbol $q_{max}$ signifies the upper limit within a specific $q_i$ class. The notation $X_{ij}$ is employed to denote the data points pertaining to the chosen parameters, representing the actual observed values for each respective parameter. Moreover, $X_{inf}$ is indicative of the lower boundary value associated with the class to which the given observed parameter pertains. The terms $q_{imap}$ and $x_{imap}$ are utilized to express the amplitude of the class within the qi classes and the parameter's corresponding class amplitude, respectively. Finally, the IWQI was calculated using the following equation:

$$IWQI = \sum_{1}^{n} q_i w_i$$

Here, n signifies the count of parameters under examination, which equates to 5 within this instance. The assigned values of $q_i$ underwent a multiplication process by their respective weights, denoted as $w_i$, as outlined in the methodology pioneered by Meireles *et al.* (2010).

### Geographic information system (GIS)-based spatial mapping

The geographic information system (GIS) technique for comprehensive environmental management and monitoring integrates spatio-temporal factors, which are critical in the evaluation and decision-making processes (Ahmed *et al.*, 2021). In the present investigation, the analysis of groundwater's diverse physicochemical parameters' spatial distribution was conducted utilizing ArcGIS 10.5 software. To predict values for unmeasured or unsampled sites from a set of measured values, the deterministic inverse distance weighted technique was employed. This technique involves predicting values for unobserved points by computing a weighted average of known points, providing estimations for unknown ones. The resolution of the raster maps utilized to portray the spatial arrangement of physicochemical parameters and IWQI was standardized at 10 m × 10 m.

### Pearson's correlation coefficient analysis

The correlation among the physicochemical attributes of groundwater was evaluated through Pearson's correlation coefficient matrix (r) as indicated by Javed *et al.* (2019). A correlation coefficient (r) nearing +1 or -1 signifies a precise linear interdependence between the variables, whereas a value of zero implies the absence of any association between the parameters, as discussed by Das *et al.* (2019). The strength of correlation is categorized as robust when r surpasses 0.7, moderate when it ranges between 0.5 and 0.7, and an inverse value indicates that as one parameter increases, the other parameter decreases, as noted by Paul *et al.* (2019). This methodology enables a comprehensive understanding of the intricate relationships governing groundwater attributes.

## RESULTS AND DISCUSSION

Understanding the chemical composition of groundwater is of paramount importance due to its pivotal role in evaluating its suitability for diverse uses, including drinking, household consumption, farming, and industrial activities. The tabulated data in Table 1 offers statistical insights encompassing ranges, averages, and standard deviations of physicochemical components and quality indicators for a set of 15 groundwater samples collected specifically for irrigation intentions. The subsequent sections thoroughly analyze and discuss these results.

### Spatial distribution of the selected water quality parameters

**pH:** The pH scale is employed to measure the acidity or alkalinity of water by indicating the concentration of hydrogen ions (Yasir and Srivastava, 2016). The pH values obtained for the water samples under examination ranged from 5.51 to 7.53, with an average of 6.14 (Table 1). This pH range suggests that the subterranean water analyzed displayed a slightly acidic to slightly alkaline nature. Notably, the majority of groundwater samples exhibited pH levels suitable for irrigation, falling within the recommended pH range of 6.0 to 8.5 for agricultural use (Ayers and Westcot, 1985). These findings partially align with the results reported by Akter *et al.* (2019). Figure 2a, depicting the geographic distribution, illustrates the spread of groundwater pH values across the study area. In a substantial part of the research area, an acidic pH range (5.51-5.9) was the prevailing condition, whereas slightly acidic water (pH 5.9-6.3) was detected in the southern, eastern, and northern regions. This pattern can be ascribed to the scarcity of alkaline substances in the groundwater, which leads to the buildup of acidity (Das *et al.*, 2019).

**Electrical conductivity (EC):** EC functions as an indicator of water's conduction capacity, primarily dependent on the presence of dissolved ions. Increased amounts of ionizable solids are directly linked to higher EC values (Kumar *et al.*, 2021). This measurement is valuable for assessing water purity and reliably assessing the potential impact of salinity on crops (Çadraku, 2021). Analyzing groundwater samples revealed EC levels ranging from 115.7 to 458 µS/cm, with an average of 266.31 µS/cm. When these EC values were compared with established standards using the Wilcox classification (Table 2), it became evident that 7 groundwater samples fell within the 'excellent' category, while 8 samples were classified as 'good'. Spatial examination of the distribution of EC in groundwater samples highlighted localized areas with elevated EC concentrations, primarily located in the north-eastern and south-western regions (Figure 2b). In general, the study area maintained a consistent and moderate EC profile.

**Total dissolved solids (TDS):** The composition of natural TDS in water primarily consists of a diverse range of salts such as chlorides, nitrates, phosphates, carbonates, bicarbonates, calcium, sodium, potassium, and magnesium sulfates, in addition to other particulate matter (Das *et al.*, 2019). The classification of irrigation water based on its TDS content indicated three categories: low-salinity (<450 ppm), which was suitable for agricultural irrigation; mildly to moderately saline (450–2000 ppm); and highly saline (>2000 ppm), which was not suitable for agricultural use (FAO, 2006). During the present investigation, TDS levels ranged from 48 to 182 ppm (Table 1), all comfortably within the irrigation standards set by FAO. Moreover, in accordance with the classification provided by the World Health Organization (WHO), all water samples fell within the excellent range (Table 2). The spatial distribution of TDS was illustrated in Figure 2c, revealing that the groundwater within the study area consistently maintained a low TDS concentration, except for a minor section in the southeastern region.

**Table 1.** Chemical composition and quality parameters of groundwater samples from the study area.

| Chemical composition and parameters | Range | Average | Standard deviation | Bangladesh Standard (1997) |
|---|---|---|---|---|
| pH | 5.51-7.53 | 6.14 | 0.59 | 6.5 – 8.5 |
| EC (µS/cm) | 115.70-458 | 266.31 | 109.34 | 1000 |
| TDS (ppm) | 48-182 | 83.40 | 33.71 | 600 |
| Calcium (ppm) | 2.41-24.05 | 12.77 | 6.15 | 75 |
| Magnesium (ppm) | 0.97-31.60 | 8.63 | 8.80 | 30–35 |
| Sodium (ppm) | 3.10-18.63 | 5.99 | 4.09 | 200 |
| Potassium (ppm) | 0.31-2.39 | 0.84 | 0.64 | 12 |
| Chloride (ppm) | 5.98-65.46 | 24.53 | 16.81 | 600 |
| Sulphate (ppm) | 0.19-7.05 | 2.06 | 1.77 | 400 |
| Nitrate (ppm) | 0.87-11.09 | 3.36 | 2.97 | - |
| Carbonate (ppm) | 15.22-30.54 | 20.58 | 4.94 | - |
| Bicarbonate (ppm) | 152.22-305.37 | 205.81 | 49.44 | 600 |
| TH (ppm) | 33.95-189.66 | 67.34 | 42.26 | - |

EC = electrical conductivity; TDS = total dissolved solids; TH = total hardness.

**Table 2.** Classification of groundwater samples for irrigation purposes based on some selected quality parameters and IWQI.

| Parameters | Max. | Min. | Average | Range | Water class with its developer | No. of sample | % of sample |
|---|---|---|---|---|---|---|---|
| EC (µS/cm) | 458 | 115.7 | 266.31 | <250 | Excellent | 15 | 100 |
| | | | | 250-750 | Good | - | - |
| | | | | 750-2250 | Doubtful | - | - |
| | | | | >2250 | Unsuitable | | |
| | | | | | Wilcox (1955) | - | - |
| TDS (ppm) | 182 | 48 | 83.40 | <300 | Excellent | 15 | 100 |
| | | | | 300-600 | Good | - | - |
| | | | | 900-1200 | Fair | - | - |
| | | | | >1200 | Unacceptable | | |
| | | | | | WHO (1996) | - | - |
| SAR | 0.59 | 0.18 | 0.31 | <10 | Excellent | 15 | 100 |
| | | | | .0-18 | Good | - | - |
| | | | | 18-26 | Doubtful | - | - |
| | | | | >26 | Unsuitable | - | - |
| | | | | | Richards (1954) | | |
| SSP (%) | 24.61 | 11.99 | 17.31 | <20 | Excellent | 12 | 80 |
| | | | | 20-40 | Good | 3 | 20 |
| | | | | 40-60 | Permissible | - | - |
| | | | | 60-80 | Doubtful | - | - |
| | | | | | Wilcox (1955) | | |
| RSC (epm) | 5.34 | -0.45 | 2.70 | <1.25 | Safe | 2 | 13.33 |
| | | | | 1.25-2.50 | Marginal | 4 | 26.67 |
| | | | | >2.50 | Unsuitable | 9 | 60 |
| | | | | | WHO (1989) | | |
| TH (ppm) | 189.66 | 33.95 | 67.33 | 0-75 | Soft | 13 | 86.67 |
| | | | | 75-150 | Moderately Hard | 1 | 6.67 |
| | | | | 150-300 | Hard | 1 | 6.67 |
| | | | | >300 | Very Hard | - | - |
| | | | | | Sawyer and McCarty (1967) | | |
| MAR | 88.99 | 6.73 | 48.02 | <50 | Suitable | 9 | 60 |
| | | | | >50 | Unsuitable | | |
| | | | | | Haritash *et al.* (2016) | 6 | 40 |
| PI (epm) | 280 | 53.54 | 156.87 | > 75 | Class-I (suitable) | 15 | 100 |
| | | | | 25–75 | Class-II (good) | - | - |
| | | | | < 25 | Class-III (Unsuitable) | - | - |
| | | | | | Doneen (1964) | | |
| KR | 0.66 | 0.12 | 0.32 | <1 | Suitable | 15 | 100 |
| | | | | >1 | Unsuitable | | |
| | | | | | Karakus and Yidiz (2020) | - | - |
| PS (epm) | 1.87 | 0.17 | 0.72 | <5 | Excellent to Good | 15 | 100 |
| | | | | 5-10 | Good to Injurious | - | - |
| | | | | > 10 | Injurious to Unsatisfactory | - | - |
| | | | | | Doneen (1954) | | |
| IWQI | 77.5 | 56.49 | 69.04 | 50–70 | Permissible | 15 | 100 |
| | | | | 40–55 | Doubtful | - | - |
| | | | | 0–40 | Severe | - | - |
| | | | | | Ahmed *et al.* (2021) | | |

## Appraisal of calculated water quality appropriates with spatial distribution

**Sodium adsorption ratio (SAR):** SAR emerges as a critical parameter in assessing the suitability of groundwater for irrigation. In cases where irrigation water exhibits elevated SAR values, the sodium content in the water can displace vital calcium and magnesium within the soil matrix. Conversely, inadequate SAR values lead to a decrease in the soil's ability to form durable aggregates, potentially resulting in soil structure degradation. This degradation subsequently triggers reduced water infiltration and soil permeability, ultimately posing challenges for achieving optimal crop yield (Laonamsai *et al.*, 2023). The study's findings indicated that the highest recorded SAR value in the investigated area was 0.59, with an average SAR value of 0.31 (Table 2). When utilizing the classification by Richards (1954) (Table 2), it is important to note that all groundwater samples in the experimental region were classified as excellent for irrigation purposes. The spatial distribution of SAR values across the study area was effectively depicted in Figure 2d. This visual representation highlighted that, except for a small portion in the central and eastern zones, the majority of the area showcased low SAR values.

Moreover, to comprehensively assess the suitability of groundwater for irrigation, the study integrated both EC and SAR parameters to construct the US Salinity Laboratory diagram (USSL), as outlined by Mukonazwothe *et al.* (2022). In this representation, EC served as an indicator of salinity hazard, while

SAR embodied the alkalinity hazard. The resulting USSL diagram revealed that 40% of the analyzed samples fell into the C1S1 classification, indicating water of exceptional quality for irrigation applications (Figure 3a). On the other hand, the remaining 60% of samples were categorized under C2S1, suggesting moderately saline irrigation water with low alkali content, making it suitable for irrigation purposes with minimal associated risk.

**Soluble sodium percentage (SSP):** The concentration of sodium within irrigation water holds significant significance, exerting a notable impact on soil permeability. In the study area, the SSP displayed a range of variability from 11.99% to 24.61%, with an average value of 17.31% (Table 2). When compared to the classification by Wilcox (1955), it became clear that 80% of the samples were categorized as 'excellent,' while the remaining 20% were classified as 'good' (Table 2). These results showed partial agreement with the findings presented by Nizam *et al.* (2014). The spatial distribution of SSP, as depicted in Figure 2e, showed an upward trend from north to south. The graphical representation of the relationship between EC and the proportion of sodium (SSP), commonly known as the Wilcox diagram (Figure 3b), clearly indicated that all water samples fell into the 'excellent' category, suggesting their suitability for irrigation without any potential risks (Figure 3b).

**Residual sodium carbonate (RSC):** The investigation into RSC values in the study region demonstrated a range from -0.45 to 5.34 epm, with a mean of 2.7 (Table 2). According to the RSC classification (Table 2), approximately 60% of groundwater samples were characterized as unsuitable for irrigation, while only 13% were considered suitable. The increased concentration of carbonate and bicarbonate ions was associated with the inherently alkaline nature of the soil, making it unsuitable for agricultural purposes, as highlighted by Das *et al.* (2019). The spatial distribution map of RSC (Figure 2f) showed predominantly moderate RSC values throughout the study area, except for a relatively high RSC value observed in a small portion of the southwestern and eastern regions. Therefore, caution was necessary when using groundwater from the study area for irrigation. It was advisable to avoid utilizing groundwater sources falling into the unsuitable category based on the assessment.

**Magnesium adsorption ratio (MAR):** The relationship between Magnesium and Calcium concentrations in groundwater, as explained by Raghunath (1987), underscores the intricate link between these two elements. By leveraging insights from the Magnesium-Calcium relationship, groundwater can be categorized effectively into two distinct groups: 'suitable' and 'unsuitable'. According to Haritash *et al.* (2016), the former is distinguished by a MAR value less than 50, whereas the latter exceeds this threshold. This classification system disclosed that about 60% of the samples fell into the 'suitable' category, while the remaining 40% were classified as 'unsuitable', as indicated in Table 2. A geospatial analysis of MAR distribution in groundwater showed a predominance of elevated MAR values in the eastern region of the study area, as depicted in Figure 2g. Therefore, prudent consideration was essential when considering the use of groundwater for irrigation purposes in this particular geographic area.

**Total hardness (TH):** Groundwater's suitability for various applications, encompassing domestic, agricultural, and industrial sectors, hinges significantly on its hardness (Singha *et al.*, 2020). The TH of the analyzed groundwater samples covered a quantitative range from 33.95 to 189.66 ppm, with an average of 67.33 ppm, as presented in Table 2. Among these 15 samples, one exhibited moderate hardness, another indicated hardness, while the remaining samples were categorized as having soft hardness, as indicated in Table 2. Figure 2h illustrated the spatial distribution of TH across the study area, emphasizing the prevalence of hard groundwater occurrences, especially in the northwestern region. This highlighted the importance of comprehending patterns of groundwater hardness for efficient resource management.

**Kelly's ratio (KR):** The metric designated as KR, utilized to gauge the proportion of sodium relative to calcium and magnesium within irrigation water, has been established as a quantifiable parameter by Kelly (1963). This metric holds significant importance as an evaluative indicator in the assessment of groundwater suitability for irrigation applications, as highlighted by Ravi *et al.* (2020). As per the findings presented by Karakus and Yidiz (2020), KR values below 1 indicate favorable water conditions for irrigation, whereas values surpassing 1 denote unsuitability. When KR exceeds 1, it signifies an excessive sodium concentration in irrigation water, rendering it inappropriate for use. The present investigation revealed KR values ranging from 0.12 to 0.66, with an average of 0.32, as detailed in Table 2. Based on this criterion, the groundwater within the study area was determined to be well-suited for irrigation purposes. The spatial distribution of KR across the research area, as depicted in Figure 2i, showed a prevalence of lower KR values in the northwestern part.

**Permeability index (PI):** Groundwater suitability assessment for irrigation primarily hinges on the PI, a significant parameter, which elucidates the relationship between dominant cations and bicarbonate in hydrochemical dynamics. Over prolonged periods of agricultural irrigation, soil permeability experiences decline. This decline, fortunately, is counteracted by key water ions such as Na, $HCO_3^-$, $Ca^{2+}$ and $Mg^{2+}$, which work to mitigate this reduction (Haritash *et al.*, 2016). The dataset of the present study showcased a variety of PI values for groundwater samples, which ranged from 53.54% to 280%, with an average value of 156.87% (Table 2). Following the framework set forth by Doneen (1964), all groundwater samples were categorized as 'class I,' indicating their suitability for irrigation. The spatial representation of the distribution of PI values was depicted in Figure 2j, revealing lower values in the northern study area.

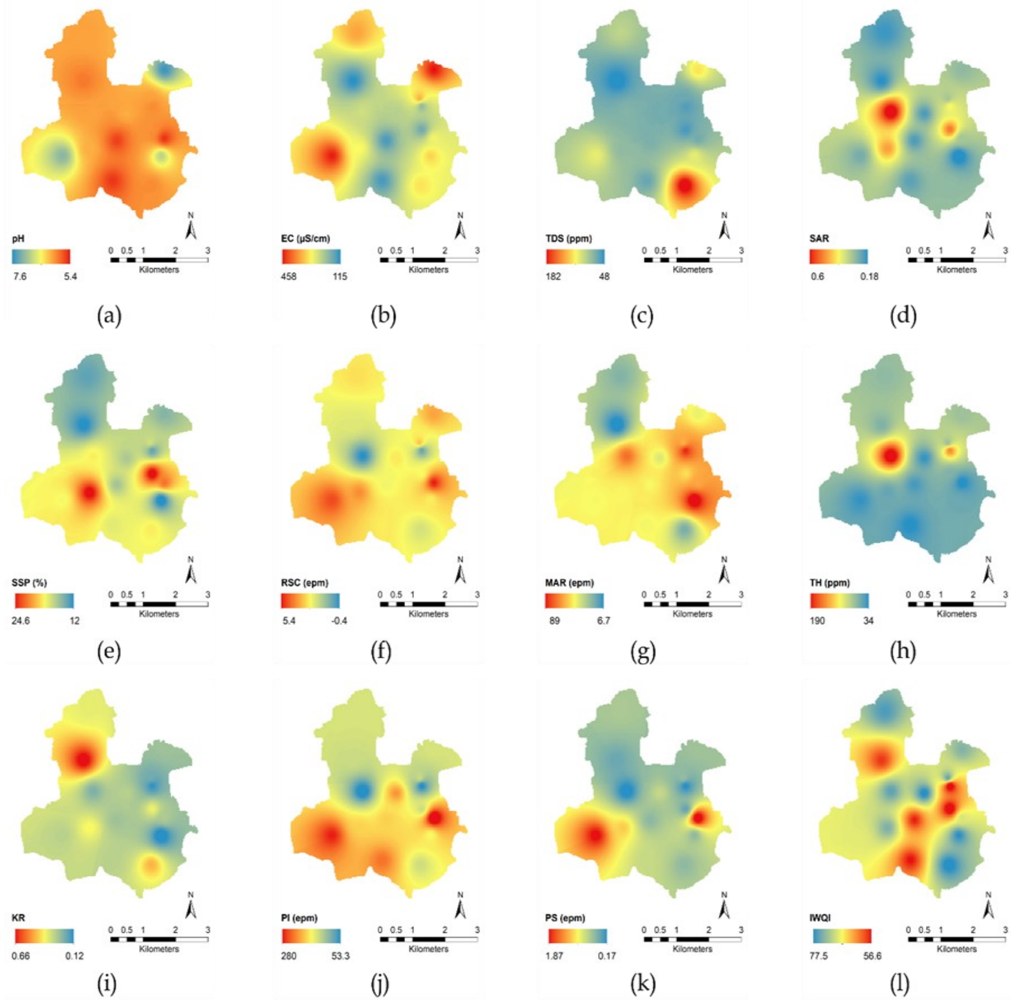



**Figure 2**. *Spatial distribution maps of various water quality parameters in the study region: (a) pH, (b) EC, (c) TDS, (d) SAR, (e) SSP, (f) RSC, (g) MAR, (h) TH, (i) KR, (j) PI, (k) PS, and (l) IWQI.*

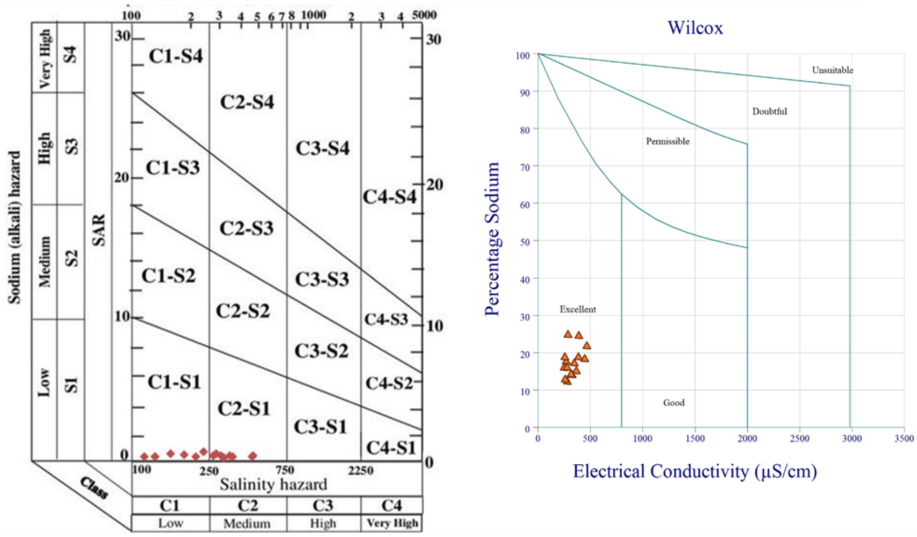
**Potential salinity (PS):** The evaluation of groundwater suitability for irrigation purposes encompasses the assessment of a crucial parameter, PS, as highlighted by Doneen (1954). Doneen's framework classifies PS into three distinct categories: 'Excellent to Good (<5)', 'Good to Injurious (5-10)', and 'Injurious to Unsatisfactory (>10)' (Table 2). The recorded PS values from the groundwater samples covered a spectrum ranging from 0.17 to 1.87 epm (Table 2). In accordance with this categorization, all the groundwater samples that were analyzed fell within the 'Excellent to Good' range. The results of Das *et al.* (2019) indicated a certain level of agreement with our study, which is now in the past. In terms of spatial distribution, the depiction in Figure 2k demonstrated that higher PS values were predominantly clustered in the central and south-eastern regions of the study area.

### Irrigation water quality index (IWQI)

The application of the IWQI facilitated the amalgamation of various parameters, which augmented the comprehensive understanding of overall water quality within the designated study region. Within this experimental framework, the IWQI was computed through the assessment of five pivotal physicochemical attributes of groundwater. As elucidated by Ahmed *et al.* (2021), the IWQI-centered approach allowed for the classification of irrigation water quality into distinct categories: Permissible (50-70), Doubtful (40-55), and Severe (0-40). The acquired IWQI values in this specific investigation indicated favorable irrigation water quality across all samples, demonstrating full compliance with the permissible standards. The spatial distribution of the IWQI, as portrayed in Figure 2l, illustrated that while higher IWQI values were noticeable in the southern and eastern sectors of the study area, they consistently remained within the acceptable thresholds.

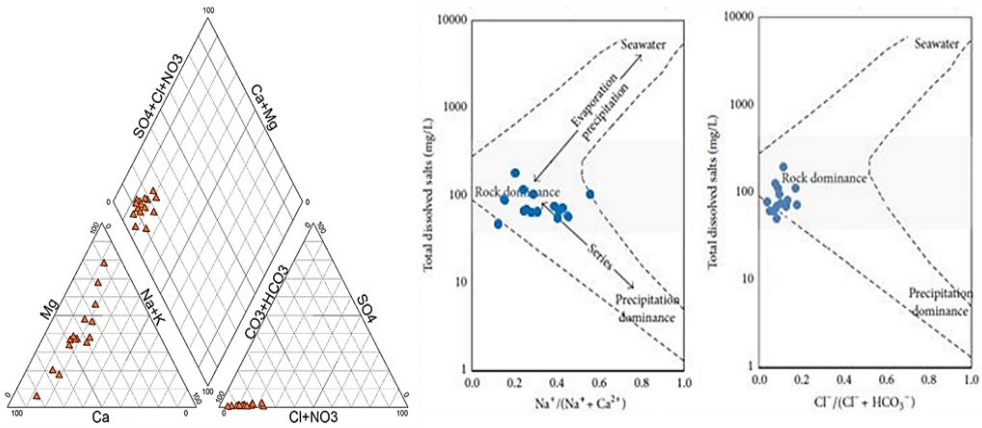
### Interrelationship among different water quality parameters and index

The correlation coefficient matrix, denoted as "r," was calculated to elucidate the interconnections and coherence patterns among various groundwater quality parameters and irrigation water quality indices, as presented in Table 3. A value of "r" approaching zero indicates the absence of a clear relationship between the parameters (Aravinthasamy *et al.*, 2020). Conversely, a value close to 1 suggests a strong correlation between the parameters. A "r" value exceeding 0.7 signifies a robust correlation, while a range of 0.5 to 0.7 indicates a moderate correlation between the parameters. Conversely, a negative "r" value signifies a decrease in one parameter with an increase in another (Paul *et al.*, 2019).




(a) (b)

**Figure 3.** *(a) US Salinity Laboratory diagram and (b) Wilcox diagram for classification of irrigation water.*




(a) (b)

**Figure 4.** *Classification results of the groundwater using (a) Piper diagram and (b) Gibbs diagram.*

A notable and robust correlation emerged between EC and pH (r = 0.78). All quality parameters displayed negative correlations with each other. Specifically, the pollution index (PI) exhibited a strong positive correlation (r = 0.87) with the RSC and a substantial negative correlation (r = -0.81) with TH. In contrast, the PS showed a pronounced and significant positive correlation with RSC (r = 0.87) and PI (r = 0.88), while KR demonstrated a strong negative correlation with the MAR (r = -0.89). In the current study, the SAR displayed negative correlations with most parameters, with correlation coefficients below 5. Notably, no significant relationship was observed between pH and TH, with a correlation coefficient of 0. The pairs of TDS-RSC, TDS-PI, TDS-SSP, TDS-KR, and TDS-PS exhibited extremely weak correlations, nearly approaching 0. The majority of parameter pairs demonstrated correlations ranging from weak to moderately strong.

## Classification of groundwater type

For the purpose of elucidating the groundwater quality, hydrochemical data are utilized in various diagrams. In this study, renowned graphical methods such as the diagrams of Piper (1953) and Gibbs (1970) were utilized for categorization purposes, allowing for a deeper understanding of hydrochemical processes within the groundwater flow system.

**Piper diagram:** Hydrochemical examination provides analytical information to create a diagram as per the method introduced by Piper (1953). This diagram organizes groundwater categorizations based on the dispersion of cations and anions. Concentrations of major cations and anions from collected water samples are depicted on the Piper diagram, illustrated in Figure 4a. In this study, the groundwater samples were specifically classified as Ca-$HCO_3$. Notably, the dominance of cations in the plot indicated a prevalence of Ca or Mg, while the anionic plot emphasized the supremacy of $CO_3$+ $HCO_3$. This water type, characterized by Ca-$HCO_3$, was likely the outcome of rainfall recharge processes, which were linked to low EC values. The calcium ions in the groundwater of the study area were potentially generated from the dissolution of $CaCO_3$ and Ca Mg $(CO_3)_2$ precipitates during recharge events, as suggested by Singh and Kumar (2015).

**Table 3.** Pearson's correlation coefficient between IWQI and other water quality parameters.

| | pH | EC | TDS | TH | SAR | MAR | RSC | PI | SSP | KR | PS | IWQI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1 | | | | | | | | | | | |
| EC | 0.78 | 1 | | | | | | | | | | |
| TDS | 0.43 | 0.57 | 1 | | | | | | | | | |
| TH | 0.00 | -0.07 | -0.13 | 1 | | | | | | | | |
| SAR | -0.12 | -0.11 | -0.19 | 0.67 | 1 | | | | | | | |
| MAR | 0.16 | 0.08 | -0.18 | 0.39 | 0.32 | 1 | | | | | | |
| RSC | 0.25 | 0.47 | 0.09 | -0.79 | -0.40 | -0.17 | 1 | | | | | |
| PI | -0.03 | 0.15 | 0.01 | -0.81 | -0.46 | -0.15 | 0.87 | 1 | | | | |
| SSP | -0.24 | -0.04 | -0.07 | -0.11 | 0.64 | 0.02 | 0.30 | 0.27 | 1 | | | |
| KR | -0.25 | -0.26 | 0.03 | -0.30 | -0.11 | -0.89 | 0.10 | 0.08 | 0.15 | 1 | | |
| PS | 0.11 | 0.40 | 0.07 | -0.56 | -0.20 | -0.04 | 0.87 | 0.88 | 0.38 | 0.03 | 1 | |
| IWQI | 0.40 | 0.67 | 0.55 | 0.00 | -0.07 | 0.01 | 0.19 | 0.04 | -0.06 | -0.15 | 0.17 | 1 |

**Gibbs diagram:** The Gibbs diagram, renowned for its utility in correlating water composition and aquifer attributes, is central to assessing the relationship between cationic concentrations ($Na^+$, $Ca^{2+}$) and anionic concentrations ($Cl^-$, $HCO_3^-$), along with TDS, in order to trace the origin of ions within groundwater. The diagram reveals three discernible zones: precipitation dominance, evaporation dominance, and rock dominance, as illustrated in Figure 4b. After graphing the analytical findings obtained from this investigation, it became evident that the groundwater samples had congregated within the rock dominance sector. This phenomenon could be attributed to the chemical alteration of rock-forming minerals, which had primarily determined the groundwater composition in the area under examination.

## Conclusion

This investigation centers on evaluating the suitability of groundwater quality for agricultural irrigation in the Paikara Union, which is situated in the Tangail District of Bangladesh, specifically in the Kalihati Upazila region. Key parameters such as pH, EC, and TDS consistently remained well within permissible limits for irrigation; notably, TDS levels spanned from 48 to 182 ppm, indicating low salinity and excellent water quality. SAR values consistently remained low, suggesting excellent suitability for irrigation with minimal risk of sodium-induced soil issues. However, a significant portion, comprising 60% of the study area, exceeded the recommended thresholds for RSC due to elevated concentrations of carbonate and bicarbonate ions. Additionally, 40% surpassed the limits for MAR as defined in irrigation water standards. Groundwater quality in the study area displayed varying degrees of hardness, with certain samples classified as 'moderate' or 'hard,' which could potentially impact irrigation practices. Furthermore, the utilization of the PI, PS, and KR indices for assessing the appropriateness of groundwater for irrigation yielded highly favorable results. The calculated IWQI values indicated that all samples fell within the 'permissible' range, signifying excellent water quality for irrigation. Moreover, the correlation analysis unveiled connections among various water quality parameters, contributing to a more comprehensive understanding of groundwater quality within the study area. The graphical representations employing Piper and Gibbs diagrams demonstrated that the groundwater predominantly falls under the Ca-$HCO_3$ classification and is influenced by rock-forming minerals. In summary, this study emphasizes the favorable quality of groundwater for irrigation in the Kalihati Upazila of Bangladesh, with the need for caution in specific areas characterized by elevated hardness and carbonate levels. These findings serve as valuable input for informed decision-making in water resource management, promoting sustainable agricultural practices and safeguarding the welfare of local communities.

## Conflict of interest

The authors declare that there are no conflicts of interest related to the publication of this paper.



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