

Assessing Coastal Groundwater Quality: Implications of Climate Change in Rangabali Upazila, Patuakhali, Bangladesh

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Abstract

The study investigates the impact of climate change on coastal groundwater systems in Rangabali Upazila, Patuakhali, Bangladesh. Groundwater quality is crucial for the livelihood and development of communities in these areas. Chemical parameters play a key role in assessing water quality. This research collected twenty-three groundwater samples from various locations in Rangabali Upazila to analyze hydrochemical facies and understand the evolution of groundwater quality. Major ion concentrations in the samples were found to be $\text{Na}^+ > \text{K}^+ > \text{Mg}^{2+} > \text{Ca}^{2+}$, while minor ion concentrations followed $\text{HCO}_3^- > \text{Cl}^- > \text{NO}_3^- > \text{SO}_4^{2-}$. Analysis using Piper trilinear diagrams, Sodium absorption ratio (SAR), Kelly's ratio (KR), and Sodium per cent (Na%) highlighted the dominance of alkalis (Sodium, Potassium) over alkaline earth metals (Calcium, Magnesium), and weak acidic anions (Carbonates and Bicarbonates) over strong acidic anions (Chlorides, Sulfates). The prevalence of sodium, potassium, and bicarbonate indicated primary alkalinity and NaHCO_3 type water facies, attributed to weathering processes and cation-exchange mechanisms. Results indicated that most groundwater samples met WHO standards for potable water, but 76% were classified as poor quality based on Water Quality Standards (WQI). Suitability for irrigation was assessed using SAR, KR, and Na%, with SAR suggesting 66% of samples were suitable. These findings underscore the complex interplay of climate change and hydrochemistry in coastal groundwater systems, necessitating careful management for sustainable use.

Keywords: Climate change, Physiochemical parameters, WQI, Piper Trilinear Diagram, SAR

1. Introduction

Bangladesh stands out as one of the world's most vulnerable countries, grappling with many challenges stemming from its geographical location, poverty levels, and the escalating impact of climate change-induced sea-level rise. Among the myriad issues faced by the nation, water scarcity looms largest, especially in its coastal regions. Covering nearly 29,000 sq. km, Bangladesh's coastal area is exceptionally susceptible due to factors like sea-level rise, saline water intrusion (SWI), erosion, accretion, recurring paleo-saline occurrences in aquifers, and periodic inundations by supercyclones like Sidr, Aila, and Mahasen (Haque et al., 2020; MoWR, 2005; Woobaidullah et al., 2006; Brammer, 2014; Islam et al., 2017; Khalil et al., 2016). The rise in sea levels, spurred by climate change, poses a monumental threat to both human communities and civilization at large. SWI has

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notably impacted groundwater quality and the overall sustainability of coastal aquifers in Bangladesh in recent decades (Ashrafuzzaman et al., 2022; Hasan et al., 2021; Sarwar and Woodroffe, 2013; World Bank, 2014; Mahmuduzzaman et al., 2014).

Given the scarcity of freshwater surface resources, reliance on groundwater has surged across various sectors. However, the spatial variance in groundwater quality, influenced by local geological structures and anthropogenic activities exacerbated by global climate change and sea-level rise, necessitates a thorough assessment of groundwater quality, including its suitability for human consumption. Commonly employed methods for assessing water quality encompass salinity (EC), Sodium adsorption ratio (SAR), magnesium adsorption ratio (MAR), permeability index (PI), Kelly's ratio (KR), and potential salinity (PS), particularly in evaluating water quality for irrigation purposes (Karakuş & Yıldız, 2020; Gautam et al., 2015; Palit et al., 2019). The groundwater quality index (GWQI) method, introduced by Horton in 1965, is an effective tool for tracking spatial and temporal changes in groundwater quality.

The coastal regions of Bangladesh grapple with salinity issues stemming from saltwater intrusion into shallow aquifers during storm surges, tides, and rising sea levels, pushing saline water upstream (BWDB, 2013). This predicament is further compounded by the presence of arsenic in shallow aquifers, exposing millions to varying degrees of risk from arsenic-contaminated groundwater (Rafiq et al., 2022; Shamsudduha et al., 2019). Saline water intrusion in coastal Bangladesh peaks during March-April and recedes during the monsoon, aligning with the ebb and flow of freshwater recharge into groundwater (Mahmuduzzaman et al., 2014; Hussain et al., 2019).

Public health in areas like Rangabali Upazila, Patuakhali, is imperiled by chemical contaminants in drinking water due to climate change and saline water intrusion, potentially leading to immediate health ramifications (Leveque et al., 2021; Skaland et al., 2022; Akter et al., 2016). The vulnerability of drinking water sources to pollutants, influenced by geological conditions, agricultural and industrial activities, and global climate change, underscores the urgent need for comprehensive studies on groundwater quality. While extensive research has been conducted globally on surface and groundwater quality, limited attention has been paid to the specific study area. Therefore, this study aims to evaluate the hydrogeochemistry of Rangabali Upazila, Patuakhali, shedding light on groundwater chemistry and its spatial and temporal variations.

2. Study Area

The study site encompasses the geographic coordinates of 21.86° to 22.02° latitude and 90.31° to 90.47° longitude within Rangabali Upazila (Fig. 1). Situated at the southernmost tip of the Patuakhali district, Rangabali Upazila is located on the fringes of the Bay of Bengal. It is bounded by the Chaulabunia and Agunmukha rivers, and Char Biswas to the north, the Ramnabad channel and Kalapara Upazila to the west, Char Kurri-Mukri of Char Fashion Upazila to the east, and the Bay of Bengal to the south. The population of this Upazila stands at 104,128 individuals.

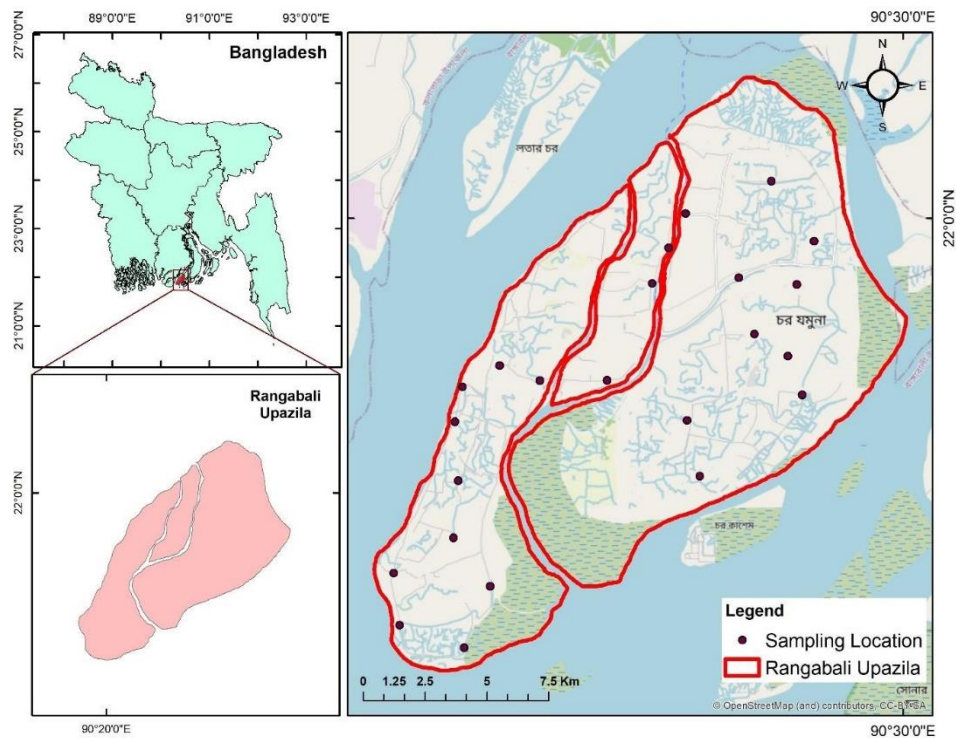


Fig. 1: Location map of the study area. The black dot shows the sampling points.

2.1. Geologic and Hydrogeological Settings

The Rangabali Upazila is south of Patuakhali, one of Bangladesh's coastal districts. The coastal region of Bangladesh is situated in the Bengal foredeep basin of the late Holocene, which had little or no tectonic movements (Adhikari et al., 2006; Saif et al., 2017). Very complex hydrogeological conditions and the distribution of aquifer sediments have been found in the coastal regions of Bangladesh (BWDB, 2013). Variations in aquifer-aquitard alteration and the presence of clay or silty clay aquitards have been found. At 350m, the aquifer seems to be hydraulically connected (BGS & DPHE, 2001). The aquifers in the study area are located within the shallow depth and are influenced by the rainfall pattern (Alam et al., 2017). Excessive abstraction of groundwater by heavy pumping at many places causes recharge during the monsoon (BGS & DPHE, 2001). The coastal areas have not been encouraged for extensive extraction due to the possibility of seawater intrusion (Aggarwal et al., 2000; Bonsor et al., 2017).

The recharge in the upper shallow aquifer of the coastal region is done chiefly by precipitation and complex river or channel networks (Bahar & Reza, 2010). Regional groundwater flow happens from north to south in the northwestern coastal regions during the dry season, suggesting that groundwater recharge occurs primarily from the northern part of the country (Fig. 2).

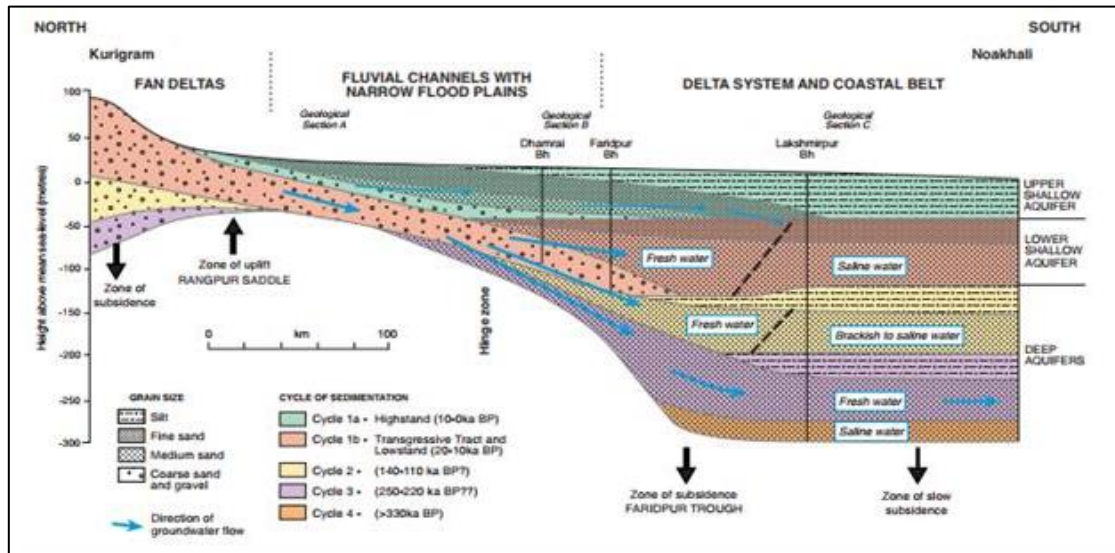


Fig. 2: Hydrological cross-section from north to south across Bangladesh shows geological structures and groundwater flow patterns (BGS & DPHE, 2001).

3. Methodology

This research was designed to assess the quality of the groundwater and the variation of physicochemical parameters due to climate change. Extensive fieldwork was conducted to collect 26 groundwater samples in the study area. All the samples were taken from the deep tube wells, and on-site physiochemical parameters such as EC, pH, Temperature, and Total Dissolved Solids (TDS) were measured in the field. During sampling, all relevant site information, including location details and type of pump depth, was recorded in a data sheet. Electrical Conductivity was measured in the fieldwork with a conductivity/TDS meter which can compensate for temperature automatically (HANNA instrument, model# DIST HI 198300/4). PH and Temperatures were measured using the same portable waterproof pH/°C (pHep® by HANNA, model# HI 98127). Then the collected samples were stabilized through acids, separated and labelled as filtered and unfiltered, and taken to the laboratory for analysis. Most of the study was carried out in the Geology and Mining Department. Some anions and cations (Mg^{2+} , Ca^{2+} , SO_4^{2-} , NO_3^-) were done later at the Patuakhali Science and Technology University (PSTU) central laboratory due to some difficulties in instrumentation at our laboratory.

3.1. Water Quality Index (WQI)

Water quality comprises the water's overall characteristics (physicochemical and biological) (Diersing and Nancy, 2009). Specific water quality indicators (parameters) must be monitored regularly to maintain the water bodies' health at optimum levels.

The water quality index is widely used to evaluate groundwater quality for drinking purposes. A formula is used to estimate the overall quality of the groundwater sample and present it with a single value. Calculation of WQI was performed by following the 'weighted arithmetic index method' (Brown et al. 1972), using the equation:

$$WQI = \frac{\sum Q_n W_n}{\sum W_n} \dots\dots\dots(1)$$

Q_n is the quality rating of n^{th} the water quality parameter, and n is the unit weight of n^{th} water quality parameter. The quality rating Q_n is calculated using the following equation

$$Q_n = 100 * \{(V_n - V_i)/(V_s - V_i)\} \dots \dots \dots (2)$$

V_n is the actual value of the parameter observed, V_i represents the ideal value of that parameter, and V_s stands for standard d permissible value for the n^{th} water quality parameter.

Unit weight (W_n) is calculated using the formula:

$$W_n = k/V_s \dots \dots \dots (3)$$

Where K is a constant of proportionality, and it is calculated using the equation:

$$k = \frac{1}{\sum_n^1 V_s=1,2,3,\dots} \dots \dots \dots (4)$$

Table 1. Water quality index classification ranges (Brown et al., 1972).

WQI Value	Water Class	Per cent of the sample
0-25	Excellent	0%
26-50	Good	0%
51-75	Poor	76%
76-100	Very Poor	24%
>100	Unsuitable for Drinking	0%

3.2. Sodium Percent (Na%):

A high concentration of Sodium in a water sample is a reference to poor water quality. The following formula is used to calculate Na% (Wilcox, 1955). All parameters concentration is in meq/l.

$$Na (\%) = \frac{(Na+K)}{(Ca+Mg+Na+K)} \times 100 \dots \dots \dots (5)$$

3.3. Kelly Ratio (KR)

This is a good indicator for evaluating groundwater quality for irrigation activities. The following formula calculates the value of the Kelly ratio (Kelly, 1951). All parameters concentration is in meq/l. If the estimated KR value exceeds one, the water is classified as unsuitable for irrigation.

$$KR = \frac{Na}{Ca+Mg} \dots \dots \dots (6)$$

3.4. Sodium Absorption Ratio

Sodium absorption ratio (SAR) is the most common method to evaluate the groundwater quality for irrigation purposes due to sodium hazards. It is a ratio between the sodium concentration concerning magnesium and calcium concentration in the water sample. Its calculated using the following equation (Patterson, 1994). The classification ranges of SAR are shown in Table 5.

$$SAR = \frac{Na}{\sqrt{\frac{(Ca+Mg)}{2}}} \dots \dots \dots (7)$$

4. Result and Discussion

4.1. Field Parameters

4.1.1. Electrical Conductivity (EC)

Water's electrical conductivity (EC) is a gauge of its ability to conduct electrical flow, attributed to the presence of conductive ions such as alkalis, chlorides, sulfides, and carbonate compounds. EC serves as an indicator of the total dissolved substances in water, as noted by Yilmaz and Koc in 2014. Although EC is directly linked to salinity and fluctuates with temperature, it does not provide insight into the specific composition of water samples, as highlighted by Hem in 1991. However, variations in EC offer crucial insights into groundwater chemistry, escalating with rising temperatures and increased levels of dissolved salts, as pointed out by Detay and Carpenter in 1997. Water with elevated EC levels can potentially lead to gastrointestinal irritation in humans, as indicated by Singh et al. in 2008. Therefore, maintaining EC within permissible limits is imperative, as it is influenced by rock-water interactions and the residence time of water in rocks, as outlined by Eaton (1950).

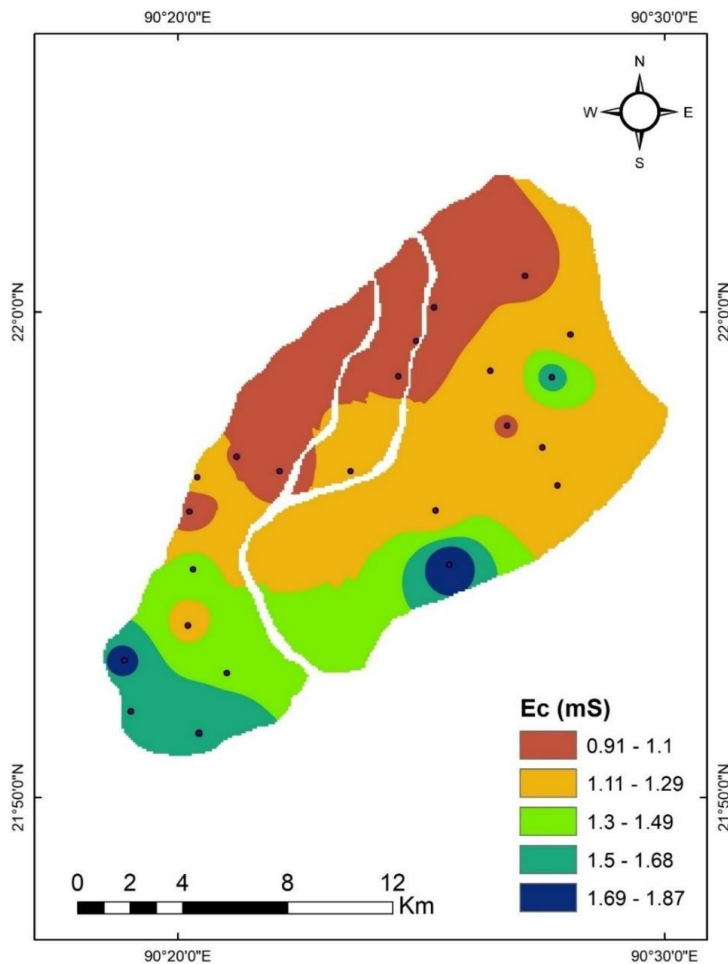


Fig. 3: EC distribution map of the Rangabali Upazila

In the study area, EC values range from 910 $\mu\text{S}/\text{m}$ to 1870 $\mu\text{S}/\text{cm}$, with higher values notably observed in the southern region proximate to the Bay of Bengal (refer to Fig. 3). Approximately 80% of the samples fall within permissible EC limits for drinking and agricultural purposes, in accordance with WHO guidelines from 2010. Conversely, the remaining groundwater samples are deemed unsuitable for use due to elevated EC levels.

4.1.2. pH Distribution

pH, an essential physio-chemical parameter, gauges the acidic or basic nature of water, providing comprehensive insights into its chemical composition. It plays a pivotal role in determining the taste and odor of substances, particularly by regulating the equilibrium concentration between a substance's neutral and ionized forms in solution. As pH levels rise from 5.0 to 9.0, the average threshold for substances increases from 0.075 to 0.450 mg/l, as outlined by WHO in 1984.

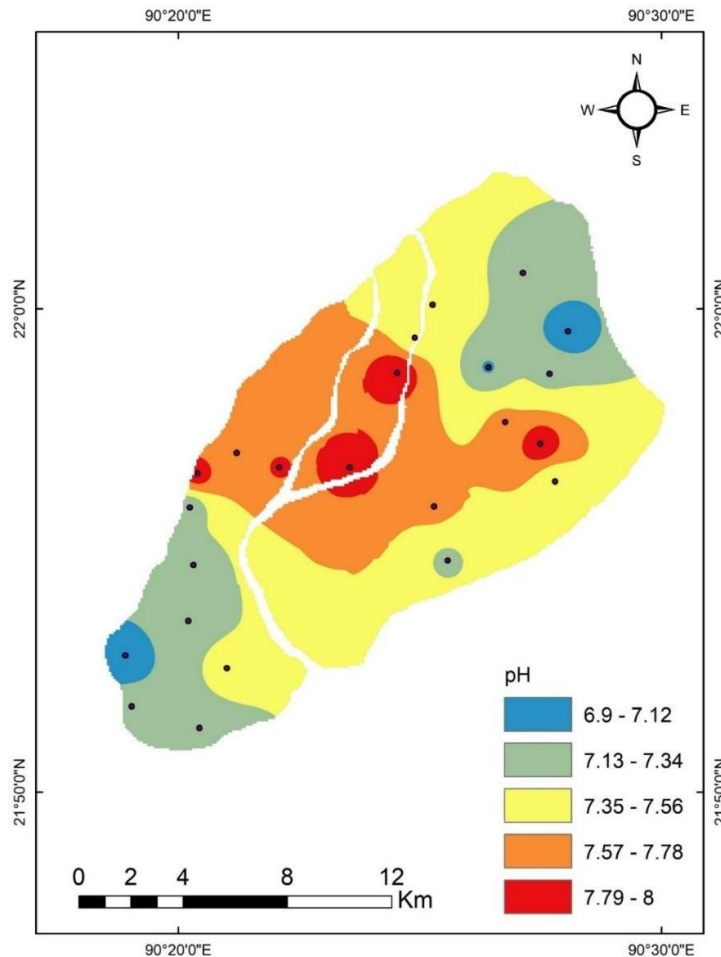


Fig. 4: pH distribution map of the Rangabali Upazila.

Typically, a slightly acidic to neutral pH environment favors the precipitation of mineral phases, while water with a low pH (< 6.5) can be acidic, soft, and corrosive, as indicated by studies like Preda and Cox in 2000 and WHO guidelines from 2010. Consequently, the aquifer could leach metal ions such as iron, manganese, copper, lead, zinc, plumbing fixtures, and piping. On the other hand, water with a pH > 8.5 could suggest that the water is hard. Though hardness of water does not pose any health risk but can cause aesthetic problems like the formation of a "scale" or precipitate on piping and fixtures, causing water pressures and interior diameter of piping to decrease, causing an alkali taste to the water, formation of a scale or deposit on dishes, utensils, and laundry basins, difficulty in getting soaps and detergents to foam and formation of insoluble precipitates on clothing, and decreases the efficiency of electric water heaters.

The study area showed pH values ranging from 6.9 to 8, indicating alkaline water in the Rangabali Upazila. Higher values were found in the central and northwestern parts of the study area (Fig. 4).

4.1.3. TDS Distribution

According to WHO specifications, TDS up to 500 mg/l is the most desirable, and 1,500 mg/l is the maximum permissible. Fig. 5 shows the spatial distribution map of TDS. The southern part has the higher TDS-like EC distribution. World Health Organization classified the water quality for drinking and irrigation according to the concentration of TDS in the water sample (WHO, 2018); the classification ranges, along with the per cent, are shown in Table 2.

Table 2. Classification of groundwater suitability based on TDS (WHO, 2018).

Range	Classification	Percentage
<500	Desirable for drinking water	7%
500-1000	Permissible for drinking water	93%
1000-3000	Useful for irrigation	0%
>3000	Unfit for drinking and irrigation	0%

4.2. Chemical Parameters

The average concentration of major cations in the groundwater shows a hierarchy of $\text{Na}^+ > \text{K}^+ > \text{Mg}^{2+} > \text{Ca}^{2+}$, while major anions follow $\text{HCO}_3^- > \text{Cl}^- > \text{NO}_3^- > \text{SO}_4^{2-}$. Among the cations, Na^+ stands out as the dominant ion, whereas Ca^{2+} is the least abundant. Similarly, HCO_3^- ranks as the most abundant anion, with SO_4^{2-} being the least prevalent. Specifically focusing on sodium (Na^+), it emerges as the most abundant alkali metal in the groundwater under study. Sodium concentrations in the groundwater samples range from 353 mg/l to 454 mg/l. Notably, areas closer to the Bay of Bengal in the southern part of the study area exhibit higher sodium values compared to the northern regions (Fig. 6). These higher values of sodium in groundwater might be due to dissolution of silicate minerals, cation exchange reaction or saltwater influence (Cerling et al., 1989; Taylor et al., 2014; Mostafa et al., 2017).

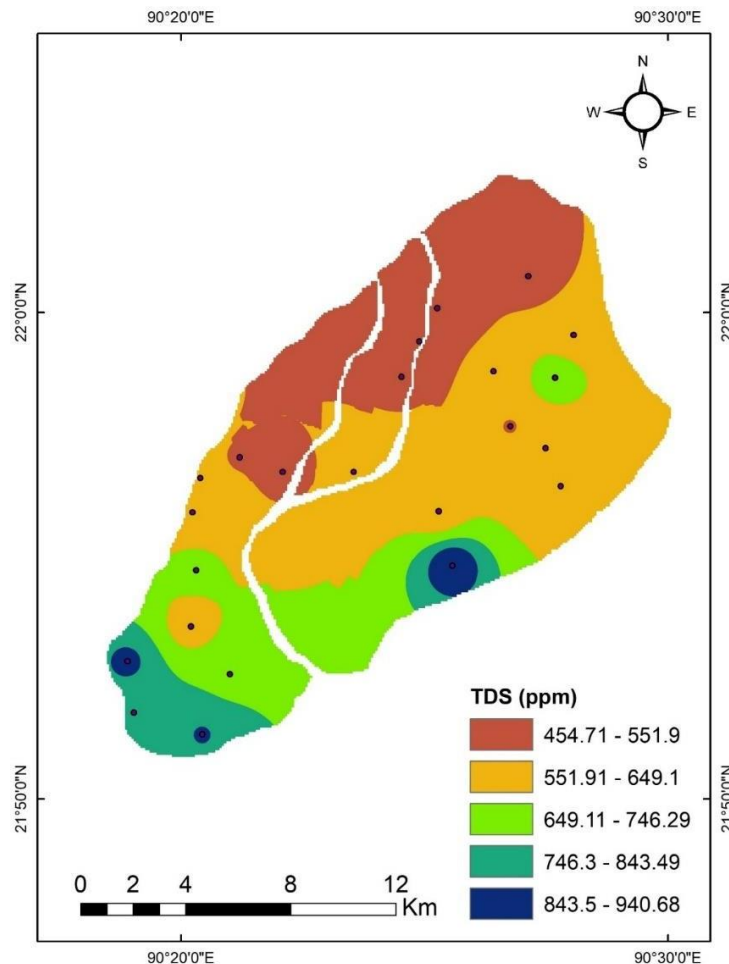


Fig. 5: TDS distribution map of the Rangabali Upazila

Calcium (Ca^{2+}): Calcium primarily originates from carbonate rocks like limestones and dolomites, which dissolve in groundwater due to carbonic acid. Chemical processes involving calcic-plagioclase feldspars and pyroxenes may also contribute to calcium in groundwater (Ganyaglo et al., 2010). Additionally, calcium can enter groundwater through lime used in agricultural fertilizers. The spatial distribution of calcium in Rangabali Upazila is depicted in Fig. 8, with higher concentrations noted in the eastern and southeastern parts of the study area.

Potassium (K^+): Potassium ranks as the second most abundant alkali metal in the groundwater samples analyzed. The lower concentrations of potassium compared to sodium are attributed to the slower weathering rate of potassium-bearing rocks. Areas with higher sodium concentrations were observed in the northeastern and southern parts of the study area, as shown in Fig. 6. Potassium is derived from the chemical breakdown of sylvite (KCl) and silicates, particularly clay minerals (Saha et al., 2019).

Magnesium (Mg^{2+}): The presence of magnesium in groundwater stems from the decomposition of minerals like dolomite, ferromagnesian minerals such as olivine, pyroxene, amphiboles, and dark-colored micas. Metamorphic rocks containing magnesium include chlorite, montmorillonite, and serpentine (Nag, 2009). The reaction involving magnesium dissolution is influenced by the level of CO_2 in groundwater. Higher magnesium levels were observed in the northeastern part of the study area (Fig. 7).

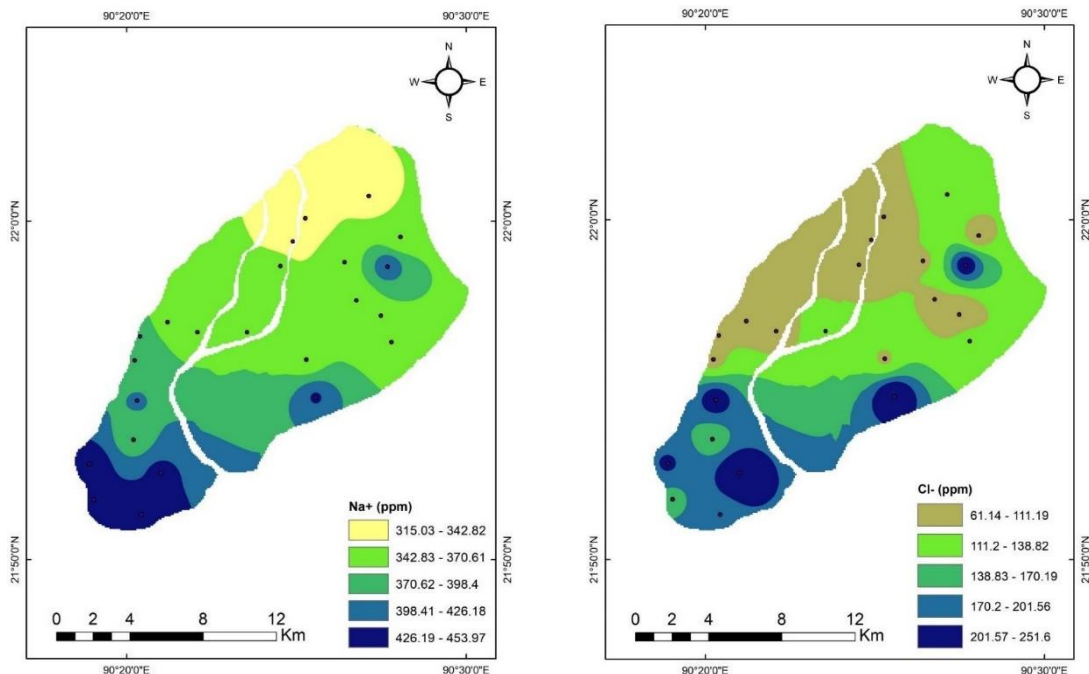
Chloride (Cl^-): Chloride concentrations in groundwater can be attributed to various sources such as

rocks, evaporates, seawater intrusion, connate and juvenile water, or pollution from industrial waste or domestic sewage. Concentrations ranged from 53 mg/l to 254 mg/l in the study area, with higher values in the southern strip compared to sodium distribution, as seen in Fig. 6. Chloride is derived from the dissolution of salt deposits or sediment deposition in the study area (Logeshkumaran et al., 2015).

Bicarbonate (HCO_3^-): Bicarbonate concentrations in the study area ranged from 610 mg/l to 778 mg/l, with an average of 694 mg/l, with higher values in the southern and northeastern part (Fig. 6). Possible sources include organic matter in the aquifer oxidizing to produce carbon dioxide, which promotes mineral dissolution (Khashogji and El Maghraby, 2013). Weathering of calcite and dolomite contributes to bicarbonate ions, enriching groundwater with calcium, magnesium, and bicarbonate ions. Bicarbonate ions may also result from the weathering of silicate minerals (Gastmans et al. 2010).

Nitrates (HNO_3^-): The concentration of nitrates in groundwater and surface water is low (Fig. 7), but it can reach high levels due to leaching of cultivated land or contamination by the waste of human or animal origin (WHO, 2003).

Sulfates (SO_4^{2-}): The occurrence of sulfate in groundwater resulted from the oxidation of sulfur of the igneous rocks, the dissolution of the other sulfur bearing minerals. Sedimentary rocks, such as organic shale, may play a key role in this connection by the oxidation of marcasite and pyrite (Matthess 1982; Rahman et al. 2013). Sulfate occurrence in groundwater is attributed to sulfur oxidation in igneous rocks, dissolution of sulfur-bearing minerals, and oxidation of marcasite and pyrite in sedimentary rocks such as organic shale (Matthess 1982; Rahman et al. 2013).



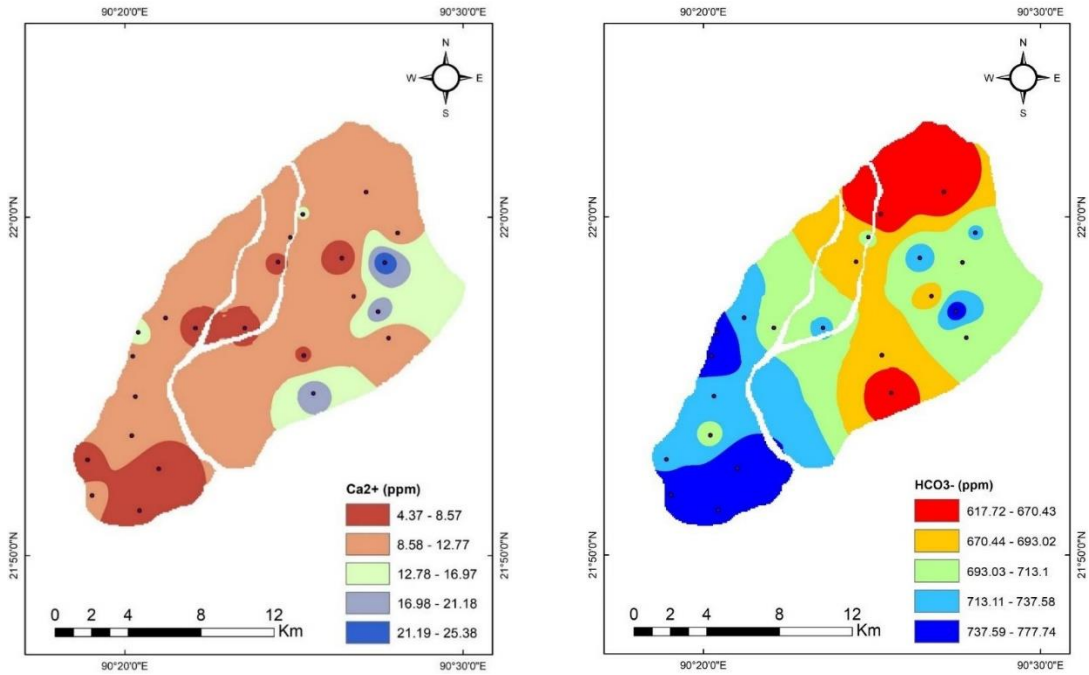
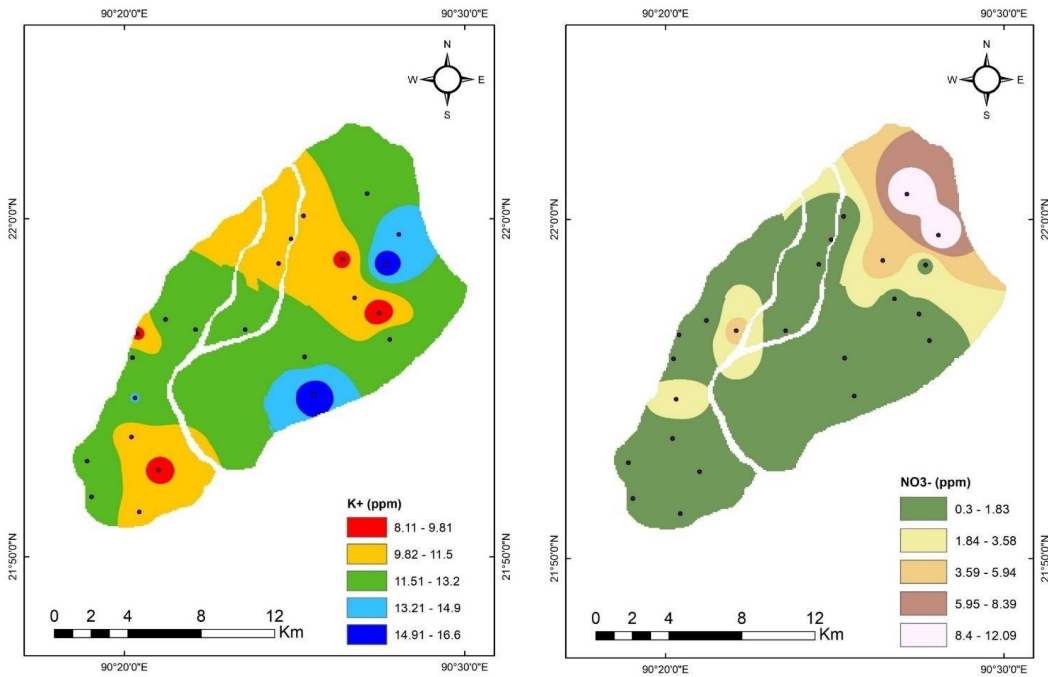


Fig. 6: Spatial distribution of Na⁺, Cl⁻, Ca²⁺ and HCO₃⁻. Each figure shows a similar pattern. Higher values dominate the southern part, close to the Bay of Bengal in the study area.



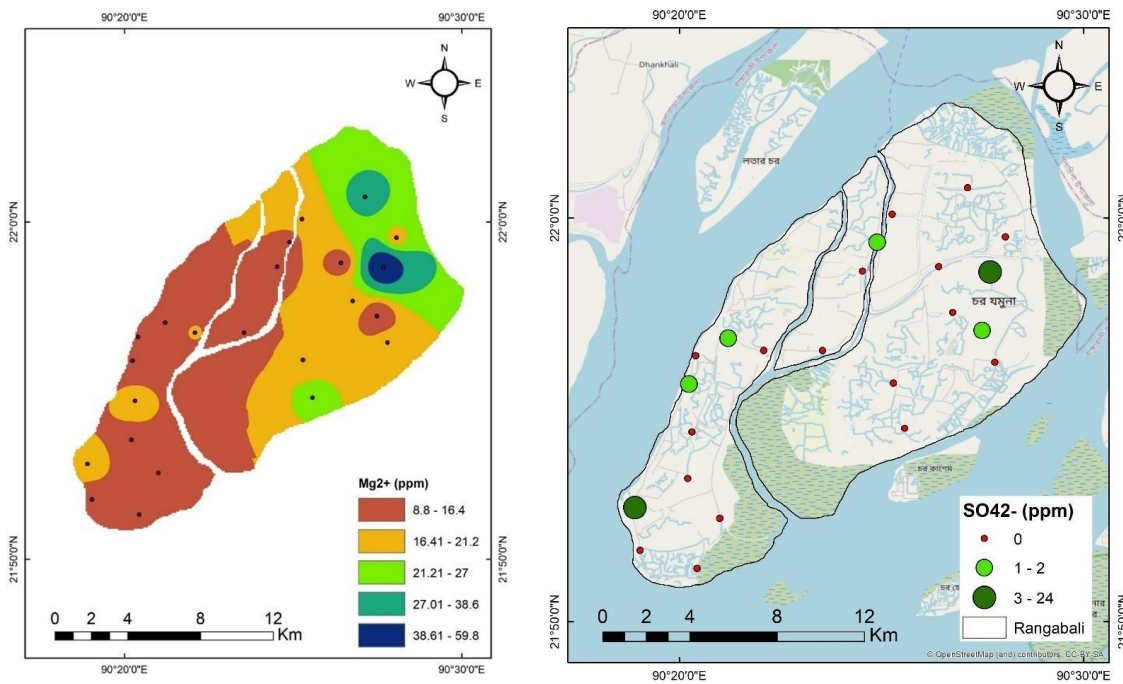


Fig. 7: The Spatial variation map of K^+ , HNO_3^- , Mg^{2+} and SO_4^{2-} in the study area. In contrast to the K^+ and Mg^{2+} , higher HNO_3^- and SO_4^{2-} prevail in the northern and western part of the study area.

4.3. Determination of Water Quality for Irrigation and Potable Purposes

The study area is, located in the vicinity of the Bay of Bengal, primarily an isolated strip of land from the mainland of Patuakhali district. Although the groundwater quality of the collected samples categorized as permissible for potable purposes (Table 1), but it was classified as mostly unsuitable irrigation and agricultural activities (Table 3 and 4). Most of the groundwater sample were unsuitable for agricultural purposes as indicated by the Na% and KR in Table 3 and Table 4 accordingly. Whereas, SAR revealed that around 66% of the sampled groundwater were suitable for the irrigation, and the other 34% could be used but with recommendations (Table 5).

Table 3. Results of Sodium Percent.

Range	Quality	percent
<20	Excellent	0%
20-40	Good	0%
40-60	Permissible	0%
60-80	Doubtful	4%
>80	Unsuitable	96%

Table 4. Suitability of groundwater for irrigation through Kelly’s Ratio (KR)

Parameter	Range	Degree of restriction of use	Percent of the sample
KR	<1	Suitable	0%
	>1	Unsuitable	100%

Table 5. SAR classification ranges along with the sample percentage in the study area.

Parameter	Range	Degree of restriction of use	Percent of the sample
SAR in meq/l	0-10	Excellent	6%
	10-18	Good	60%
	18-26	Doubtful	34%
	>26	Unsuitable	0%

4.4. Hydrogeochemical Analysis Box and Whisker Plot

Figure 8 illustrates the predominant major ions in the samples, with $Na^+ > K^+ > Mg^{2+} > Ca^{2+}$ among cations and $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-}$ among anions. A negative skewness is noticeable in most samples, as depicted in Fig. 8.

To comprehend the chemical composition of groundwater in the study area, samples were plotted on a Piper trilinear diagram (Piper, 1944) using Aqua CHEM software. The diagram analysis revealed that nearly all collected groundwater samples exhibited primary alkalinity, except for one sample showing a mixed type. Alkali metals were found to surpass alkaline earth metals, and weak acids dominated over strong acids (Fig. 9). The prevalence of $NaHCO_3$ facies in the analyzed groundwater samples may result from the weathering of sodium–potassium bearing minerals and/or various cation-exchange processes and rock-water interactions in the study area (Guo and Wang, 2004; Singh et al., 2006; Gopinath et al., 2019). The high concentrations of sodium and potassium could be attributed to sodium and potassium exchange facilitated by calcium and magnesium adsorbed on clay mineral surfaces (Cerling et al., 1989).

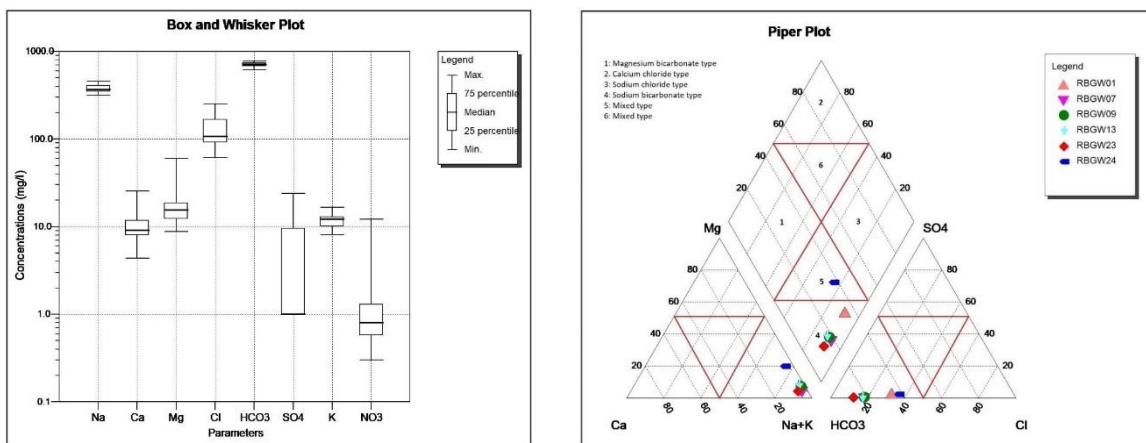


Fig. 8: Box and Whisker plot and Piper diagram assessing the groundwater chemistry

5. Climate Change and Groundwater Quality

Most research focused on climate variability and change's impact on groundwater has prioritized factors affecting water quantity, leaving few studies on how climate change influences groundwater quality. The chemical, physical, and biological aspects of groundwater significantly impact its quality, with changes in climate and human activities expected to influence groundwater quality due to factors like recharge, outflow, and land use. This holds significance for specific water-use criteria and drinking water health standards, making the preservation and enhancement of groundwater quality a key environmental objective (Levallois & Villanueva, 2019; Li & Wu, 2019; Alley, 1993). Other uses such as industrial, agricultural, or ecological demands may also be restricted by water quality, highlighting the importance of considering both groundwater quantity and quality in ensuring sustainable water supplies under future climate changes (Reilly *et al.*, 2008).

Global changes can impact groundwater quality in various ways, affecting contaminant transport through changes in recharge rates, processes, and locations. This can potentially lead to inaccurate interpretations of groundwater quality trends, particularly if limited samples are taken over time (Burri *et al.*, 2019; Gorelick & Zheng, 2015; Alley, 2001). Factors like precipitation patterns on interannual to multidecadal scales can influence groundwater quality, especially in semiarid and arid regions, where significant infiltration events can mobilize chloride and nitrate reservoirs in aquifer vadose zones (Filter *et al.*, 2024; Liu *et al.*, 2022); Gurdak *et al.*, 2007, 2008). Coastal regions, home to a significant population but limited water supply, are experiencing rapid population growth, sea-level rise, and changes in precipitation and evapotranspiration, which can increase groundwater salinization (Rakib *et al.*, 2020; Sarker *et al.*, 2021; Kundzewicz *et al.*, 2007). Predictions suggest increased recharge rates and alterations in groundwater flow due to rising sea levels, impacting both inland areas and coastal zones (Zahid *et al.*, 2018; Vandenbohede *et al.*, 2008).

Additional impacts on groundwater quality may arise from climate-induced increases in groundwater vulnerability to contaminants, changes in subsurface temperatures due to urbanization and global warming, and altered rates of nutrient and pesticide transport (Kovalevskii, 2007; Knorr *et al.*, 2005; Destouni and Darracq, 2009; Bloomfield *et al.*, 2006). These diverse effects underscore the complexity of understanding and predicting the multifaceted impacts of climate change on groundwater quality, highlighting the need for further research in this area.

5.1. Effects of Climate Change on Groundwater System

This section delves into the impact of climate change on the physico-chemical quality of water, noting that both direct and indirect effects play a role in altering this quality. Directly, climate warming accelerates chemical reactions in sediment and water due to higher temperatures, affecting processes like nitrification and denitrification which are temperature-sensitive (Barbieri *et al.*, 2023; Admiraal & Van der Vlugt, 1988). Indirectly, changes in hydrology due to climate change influence water quality. Predicted increases in precipitation intensity can lead to more nutrient runoff from agricultural areas into surface waters, while extreme rainfall events contribute to soil erosion, increasing water turbidity and contaminant loads (Gineyts & Niboyet, 2023; Kundzewicz *et al.*, 2007).

Mooij *et al.* (2009) highlight that eutrophication resulting from climate-induced hydrological changes will impact coastal regions in Bangladesh. They note that the pressure on ecosystems often follows a nonlinear pattern, with transitions between stable states known as "hysteresis." Global warming is projected to lower the

critical nutrient threshold at which an ecosystem shifts from clear to turbid states, affecting water transparency—a crucial factor in water management goals (Mooij et al., 2005).

Nevertheless, the physico-chemical state of groundwater in Bangladesh faces threats from climate change, leading to alterations in various water quality parameters. These include changes in (bio)chemical processes, acidification, salinization, nutrient and contaminant concentrations, stratification, light availability, and oxygen levels.

5.1.1. (Bio-) Chemical Reactions

The speed of (bio)-chemical reactions depends on the chemical properties of the molecules involved and the environmental conditions they encounter. Higher temperatures generally lead to faster chemical reactions, directly linking increased rates of (bio)-chemical processes to global warming, which elevates temperatures in the land surface, soil, and groundwater.

Microbial activity is intricately linked to sediment temperature and humidity. Van Dijk et al. (2009) predict that higher temperatures will result in overall increased microbial activity and rates of microbially mediated processes. This heightened microbial activity will lead to greater sediment respiration of organic material, causing soil concentrations of dissolved organic carbon (DOC) to increase. With anticipated higher and more intense precipitation, the elevated DOC levels will wash into surface waters and soils. Dissolved organic matter in the water absorbs light radiation, releasing heat into the water column. Water with higher DOC concentrations can absorb more light, further raising its temperature. Therefore, water columns with high DOC levels will experience a more significant temperature rise with increasing air temperatures compared to those with low DOC levels (Loeve et al., 2006).

Nitrogen is crucial for ecosystems as a primary nutrient alongside phosphorus. However, excess nitrogen can lead to eutrophication, negatively impacting water quality and habitats. The cycling of nitrate in water is governed by nitrification and denitrification processes. Nitrification (an aerobic process) converts ammonium (NH_4^+) into nitrate (NO_3^-), which is utilized by primary producers, acting as a 'nitrate' input for the water. Denitrification (an anaerobic process) transforms nitrate (NO_3^-) into nitrous oxide (N_2O) or nitrogen (N_2), releasing them from the water column into the atmosphere, thus removing nitrate from aquatic ecosystems. Nitric oxide, a primary greenhouse gas, is a byproduct of these processes, potentially impacting ecosystem health and water quality. The rates of nitrification and denitrification increase with rising temperatures due to global warming, upsetting the equilibrium between these processes. Moreover, increased concentrations of organic matter in the water column, often caused by erosion after heavy rainfall, can further disrupt this balance by raising nitrate concentrations. Human activities such as fertilization have also contributed to nitrogen cycle disruptions, leading to accumulations of ammonium and nitrate in the environment (Admiraal and Van der Vlugt, 1988; Admiraal and Botermans, 1989).

5.1.2. Acidification

Most scientists concur that the oceans become more acidic as a result of increasing CO_2 levels in the atmosphere (IPCC, 2007). Many freshwater environments get significant amounts of carbon from terrestrial ecosystems, unlike ocean waters (Van de Waal et al., 2009). Generally speaking, dissolved organic carbon (DOC) is how this happens. The DOC is mineralized by bacterial action into CO_2 . As a result, unlike oceans, lakes often do not have an equilibrium between their CO_2 content and the atmosphere; instead, it depends on the amount of

DOC present (Van de Waal et al., 2009). Most inland waters are supersaturated with CO₂. Therefore, an increase in the atmospheric CO₂ concentration is not expected to have a significant influence on the pH of freshwater systems.

Increasing warmth will result in more algal blooms, which does have an impact on the pH of freshwater systems but makes it more alkaline rather than acidic. Due to the rise in CO₂ that results from the water's increased uptake of CO₂, the water's (bi-) carbonate equilibria trigger the release of OH⁻ ions. Furthermore, increased erosion and the lengthening of the phytoplankton growing season can both cause pH to rise, raising the alkalinity of water systems and increasing cation deposition (Loeve et al., 2006). This suggests that the reduction of freshwater acidification is positively impacted by the indirect effects of climate change. Even though Parry (2000) contends that climate change may increase the acidification of freshwater bodies, this is unlikely to happen in Bangladesh because most freshwater systems are already CO₂-supersaturated and are less sensitive to acidification due to their high buffer capacity (personal communication, Wolf Mooij).

The acidification of soils and freshwaters results mainly from acid precipitation and acid deposition. Acid precipitation is caused by the emissions from SO₂, NO_x and NH₃, mainly from traffic, agriculture, and industry (Likens et al., 2007). The climate change KNMI '06 scenarios predict an increase in mean annual precipitation, which can lead to an increased input of acidifying components into the soil and surface water, depending on the amount of acidifying atmospheric compounds (Van Dijk et al., 2009).

5.1.3. Salinization

Salinization of freshwater can occur through saltwater intrusion or an increase in chloride content in surface waters. With rising sea levels, rivers flowing into the sea and groundwater in low-lying areas are prone to salinization. This is exacerbated during hot summers when river discharges decrease, leading to increased seawater intrusion due to higher sea levels. Coastal groundwater, particularly in polder areas, is significantly impacted by saltwater intrusion (Van Dijk et al., 2009). Freshwater aquifers near the coast are especially vulnerable to salinization from seawater intrusion (Van Dijk et al., 2009). This poses risks to drinking water sources, irrigation systems for agriculture, and the survival of freshwater aquatic organisms.

5.1.4. Nutrient and Contaminant Concentrations

Extreme weather conditions such as heat waves and heavy rainfall can significantly impact the nutrient and pollutant levels in surface water. In Bangladesh, intensified and more frequent precipitation events can lead to flooding, putting environments at risk. Floodwaters can carry contaminants that spread across the soil, causing soil contamination. Moreover, toxic substances from flooded landfills can leach into the water, along with leaked fertilizers, pesticides, and heavy metals, affecting both ground and surface waters (Claessens and Van der Wal, 2008).

On the other hand, extreme droughts can trigger dehydration episodes and reduce water releases, resulting in changes in pollutant and nutrient concentrations. Dehydration events halt microbial activity, leading to the accumulation of nutrients like nitrogen and phosphates. Furthermore, the breakdown of toxicants by biological processes can be hindered or halted. Low discharge periods may also lead to an increase in the concentration of harmful compounds, posing threats to aquatic life and water quality.

The bioavailability of heavy metals can also be influenced by extreme weather conditions. Claessens and Van der Wal (2008) highlight that factors such as pH, organic matter content, mineral composition, and redox potentials play a role in heavy metal behavior. Periodic shifts between wet and dry periods can enhance the

bioavailability of heavy metals by destabilizing metal deposits, making them more prone to release into the environment (Claessens and Van der Wal, 2008).

5.1.5. Stratification

Stratification refers to the layering phenomenon that occurs in a water column, especially in deep lakes, due to variations in density. While temperature differences are the primary cause of water stratification, changes in salinity or oxygen densities can also contribute to this process. Pure water reaches its maximum density at approximately 3.98°C, and this density is a quadratic function of water temperature. As a result, warmer water, with lower density, tends to float atop colder, denser water, creating distinct layers within the water column (epilimnion at the top and hypolimnion at the bottom).

According to Bates et al. (2008), stratification plays a significant role in shaping the physical, chemical, and biological characteristics of water bodies. Increased stratification time and higher epilimnion water temperatures can raise the likelihood of oxygen depletion below the thermocline, which is the transition zone between the epilimnion and hypolimnion (Alcamo et al., 2007). Strong winds have the potential to disrupt stratification by mixing the water column. However, it remains uncertain whether violent winds will become more frequent in the future (KNMI, 2008).

5.1.6. Light Conditions

Climate change can diminish the amount of light reaching surface waterways. This is primarily due to heightened turbidity caused by increased soil erosion resulting from more intense precipitation events. Mooij et al. (2009) suggest that global warming will reduce the critical nutrient threshold necessary for a water body to transition from clear to turbid states. This projection considers various factors such as the accelerated growth rate of phytoplankton and the greater availability of phosphorus due to increased mineralization and release (Mooij et al., 2007). Consequently, climate change affects water body transparency by escalating particulate matter and nutrient loads through soil erosion, while simultaneously lowering the critical nutrient threshold required for the system to shift from clear to turbid.

The heightened turbidity diminishes light penetration in the water column, negatively impacting aquatic organisms like phytoplankton and macrophytes. Moreover, water transparency is a significant aspect considered in the objectives outlined by the Water Framework Directive.

5.1.7. Oxygen Concentrations

Oxygen is a crucial element for sustaining life in aquatic ecosystems. Aquatic organisms rely on oxygen for respiration and decomposition processes. The primary sources of dissolved oxygen in water are the atmosphere and photosynthesis (Kalf, 2000). Generally, aquatic life requires dissolved oxygen levels of 5 mg/l or higher; levels below 2-3 mg/l are considered hypoxic and can lead to suffocation in most aquatic species (Ficke et al., 2007).

The concentration of oxygen in water is influenced by global warming in water systems. Temperature plays a significant role in determining the amount of oxygen that can dissolve in water (Kersting, 1983). Essentially, as water temperature rises, the concentration of dissolved oxygen decreases. This happens because warmer water has lower solubility for oxygen, and the metabolic rates of cold-blooded aquatic organisms and bacterial respiration increase with temperature. Consequently, the demand for oxygen rises while its supply decreases, leading to an "oxygen squeeze" for aquatic organisms exposed to warmer water temperatures. As noted by Bates et al. (2008), reduced oxygen levels often impact the composition of aquatic communities, biochemical processes, biodiversity,

and overall productivity of lakes and streams. Species that thrive in oxygen-depleted environments typically become more prevalent under these conditions.

6. Conclusion

Climate change and anthropogenic activities are affecting coastal groundwater systems throughout the world. The study reveals that the Rangabali Upazila, close to the Bay of Bengal, is vulnerable to water quality degradation due to the climate change. The mean major ion concentration in groundwater sample was $\text{Na}^+ > \text{K}^+ > \text{Mg}^{2+} > \text{Ca}^{2+}$, whereas the mean minor ion followed $\text{HCO}_3^- > \text{Cl}^- > \text{NO}_3^- > \text{SO}_4^{2-}$. Among the cations Na^+ was dominant and Ca^{2+} was the less dominant. On the other hand, HCO_3^- was the highest and SO_4^{2-} was the lowest in anions. Almost all the sampled groundwater were marked as permissible for potable purposes according to the WHO standard. The suitability of the groundwater for irrigation purposes was assessed by the SAR, Kelley ratio (KR) and Sodium percent (Na%). Almost all the sampled groundwater were categorized as unsuitable by KR and Na%. In contrast, SAR showed 66% of the sample was classified suitable for irrigation. Hydrogeochemical facies deciphered that the dominance of alkali metals and weak acids in the study area. The abundance of sodium, potassium and bicarbonate indicated the primary alkalinity, and NaHCO_3 type water facies. The weathering of sodium–potassium bearing minerals and/or some cation-exchange processes on clay mineral surface and dissolution of feldspar bearing minerals resulted in the dominance of Na and K.

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