Research Article DOI: https://doi.org/10.64862/ajeg.2026.301.04.305 Open Access

Fuzzy Overlay-Based Groundwater Quality Assessment for Drinking and Irrigation Purposes, Hydro geochemical Evaluation and Health Risk Assessment in the Coastal Aquifer of Lakshmipur District, Bangladesh

Md. Mahedi Hasan[1*], Khondaker Emamul Haque[1], Shamim Ahmed[2], and Md. Nazmul Islam Hasan[1]

[1]Department of Geology and Mining, University of Rajshahi, Rajshahi 6205, Bangladesh
[2]Institute of Environmental Science, University of Rajshahi ,Rajshahi 6205, Bangladesh

(*Corresponding E-mail: mdmahedihasan107190@gmail.com)

Received: December 18, 2025, Accepted: May 27, 2026

Abstract: In the coastal region of Bangladesh, groundwater is the main source of irrigation and drinking water; however, both natural and anthropogenic processes are progressively threatening groundwater quality. Using hydro geochemical analysis, the Water Quality Index (WQI), GIS-based fuzzy overlay modeling, Principal Component Analysis (PCA), the Na^+/Cl^- ratio, and the Chloro-Alkaline Index (CAI), this study assessed the hydro geochemistry and groundwater quality of the Lakshmipur coastal aquifer. The findings show that a number of groundwater samples were unfit for drinking without treatment because they had levels of arsenic, salinity, total dissolved solids, and some heavy metals that were higher than those allowed by the Department of Environment (DoE) and the World Health Organization (WHO). The Na^+/Cl^- ratios and CAI value further supported the roles of ion exchange, water–rock interaction, and localized saline water influence in groundwater evolution. PCA showed that salinity enrichment, mineralization, and geogenic processes dominate groundwater chemistry. A non-carcinogenic health risk assessment revealed that 70% of samples exceeded the Hazard Index (HI > 1) for adults and 75% for children, indicating significant health threats, particularly from arsenic and iron contamination through oral ingestion. While irrigation appropriateness varied throughout the study area, the WQI and fuzzy overlay analyses revealed a number of places with low water quality for drinking. In addition to highlighting the necessity of ongoing monitoring and sustainable groundwater management to guarantee safe drinking water and agricultural viability, these findings offer an integrated picture of groundwater evolution and quality in the Lakshmipur Coastal Aquifer.

Keywords: ***Hydro geochemistry, Rock-water interaction, Water quality index, Fuzzy overlay, Coastal aquifers.***

Introduction

Groundwater is a vital resource for agriculture, industry, and human use, particularly in areas where surface water is scarce. In recent years, growing population pressure, intensive agricultural methods, urbanization, and industrial expansion have caused serious issues with groundwater supply and quality. Understanding the physicochemical parameters of groundwater is essential for evaluating its quality, identifying potential contamination sources, and ensuring sustainable management. To fully explain the chemical properties and determine the main elements affecting water quality, this study focused on the groundwater quality evaluation of Lakshmipur.

To protect this important resource, it is necessary to study the chemical properties of groundwater. This helps us understand whether the water is safe to use and what factors might be polluting it. This study examined the groundwater in Lakshmipur to determine its quality and understand the natural and human-made factors that affect it. The goal is to use this knowledge to manage groundwater safely and sustainably in the future. According to the United Nations, approximately two-thirds of the world's population may be living in water-stressed conditions by 2025 (United Nations, 2016).

Bhuiyan et al. (2016) conducted a comprehensive study on the assessment of water quality in Lakshmipur district of Bangladesh using water quality indices, geo statistical methods, and multivariate analysis. Their research indicated that groundwater evaluation indices, multivariate statistical techniques, and geo statistical models were applied to assess the source apportionment and spatial variability of groundwater pollutants in the Lakshmipur district of Bangladesh. A total of 60 groundwater samples were collected from wells (shallow to deep wells, i.e., 10–375 m) in the study area. This study has multiple implications for the quality assessment and spatial variability of groundwater as an effort toward more effective water quality management.

Tens of millions of Bangladesh is who consume groundwater contaminated with as are at risk of developing serious health issues. A detailed geochemical study of groundwater was conducted to understand the role of various elements in groundwater aquifers, including all major ions such as Na, K, Ca, Mg,

Zn, Cu, Pb, As, Cd, NO^{3-}, SO_4^{2-}, PO_4^{3-},CO_3^{2-}, HCO_3^{-}, F^{-}, Br^{-}, I^{-}, Cl^{-}, Fe^{2+}, Mn^{2+}, B^{+}, Si^{+}, Al^{3+}, Cu^{2+}, and Cr^{3+}, and how the elemental fluxes are exchanged through atmospheric, terrestrial, and aquatic interactions. Groundwater geochemical studies help identify potential quality changes as development advances (Gupta et al., 2009). Geochemistry is the science that uses the tools and principles of chemistry to explain the mechanisms behind major geological systems, such as the Earth's crust and oceans. This study assessed the chemical characteristics and major influencing factors of water quality in the Lakshmipur area.

Study area

This is a location map (Figure 1) of the Lakshmipur District in southeastern Bangladesh. The district is bordered by the Meghna River to the west and south, which influences its coastal geography. It is geographically positioned between 90°40'E and 91°10'E longitude and 22°45'N and 23°10'N latitude. The region is bounded by Ramganj to the north, Kamalnagar and Ramgati to the south, Roypur to the west, and Meghna River to the southwest.

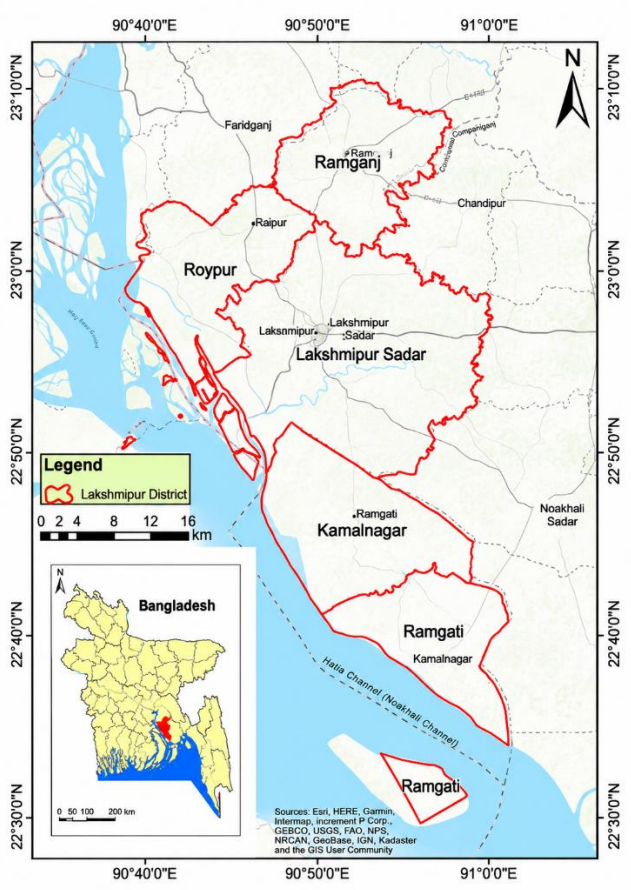


Figure 1, Location map of the study area.

Lakshmipur includes flat alluvial plains formed by sediments deposited by the Meghna River and its tributaries. This makes the region agriculturally fertile and heavily reliant on groundwater for irrigation, domestic use, and small-scale industry. The climate is typically tropical, with high humidity, significant rainfall during the monsoon season, and mild winter.

Methodology

Twenty groundwater (GW) samples were collected in 2021 from the Bangladesh Water Development Board in five Upazilas in the district of Lakshmipur, as depicted in Figure 2. The given chart was used for the research (Figure 3).

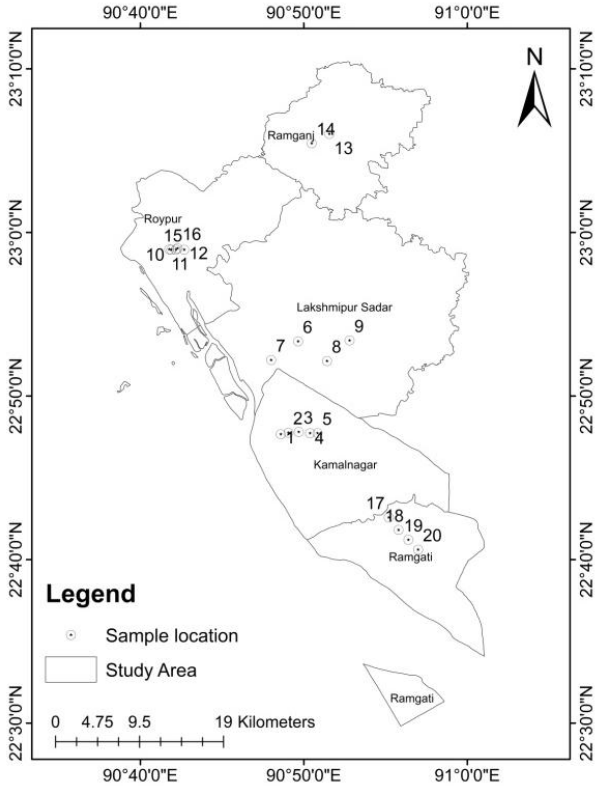


Figure 2, Shows the locations of the groundwater samples.

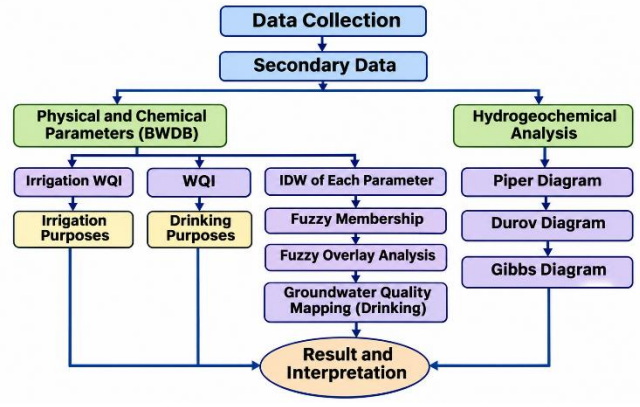


Figure 3, Methodology flow-chart.

WQI for drinking water

The WQI is an effective method for providing exact and comprehensive information about the overall quality of water for human consumption/drinking (Su et al., 2018). This method was first developed from thermodynamics to information systems (Shannon, 2001). The base of the entropy weight method is the volume of information used to calculate the index's weight, which is similar to the main objective of fixed-weight methods (Li et al., 2011). The WQI was measured

using the weighted arithmetic water quality index, which was first proposed by Horton (1965) and improved by Brown et al. (1972). Table 1 presents the Water Quality Index (WQI) classification categories based on the criteria adopted in this study.

The WQI is calculated as Eq. 1.

$$WQI = \frac{\sum_{i=1}^{n} w_i q_i}{\sum_{i=1}^{n} w_i} \qquad (1)$$

Where n is the number of parameters, w_i is the relative weight of the i^{th} parameter, and q_i is the water quality rating of the i^{th} parameter.

Here, the q_i value can be calculated by the following Equation 2 (Brown et al., 1972):

$$q_i = \left(\frac{v_i - v_{id}}{s_i - v_{id}}\right) \times 100 \qquad (2)$$

Where, v_i = Observed value of i^{th} parameter, s_i = Standard permissible limit of i^{th} parameter, v_{id} = Ideal value of i^{th} parameter in pure water.

The unit weight (w_i) of the i^{th} parameters is inversely proportional to the values of the recommended standards (s_i) and it can be calculated as Equation 3:

$$w_i = \frac{K}{S_i} \qquad (3)$$

Where, $K = \frac{1}{\sum_{i=1}^{n} \frac{1}{s_i}}$

Here, K is the constant and S_i is the sstandard permissible limit of i^{th}parameter.

Table 1, Classification categories of WQI (Sahu and Sikdar, 2008; Ketata-Rokbani et al., 2011) are given as follows:

WQI	Category
< 50	Excellent water
50–100	Good water
100–200	Poor water
200–300	Very poor water
> 300	Water unsuitable for drinking

WQI for irrigation

Sodium percentage (Na %)

The percentage of sodium water determines the presence of sodium in water as a soluble form. It is expressed as Na% and measured using the following Equation (4) (Wilcox, 1955):

$$Na\% = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100 \qquad (4)$$

All the concentration are measured in meq/L.

Sodium Absorption Ratio (SAR):

SAR is the most significant parameter for determining the acceptability of groundwater for irrigation purposes. The SAR can be calculated as following Eq. 5 (Richards, 1954).

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \qquad (5)$$

Where all ionic concentrations are expressed in meq/L

Residual Sodium Carbonate (RSC):

The equation for RSC calculation was proposed by Eaton (1950). The Equation 6 is as follows:

$$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}) \qquad (6)$$

Where all ionic concentrations are expressed in meq/L.

Magnesium Hazard (MH):

MH for irrigation water can be determined with the following Equation 7 (Szabolcs and Darab, 1964):

$$MH = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100 \qquad (7)$$

Where the concentrations are expressed in meq/L.

Kelly's ratio:

Kelly's ratio is determined by (Eq.8) dividing concentrations of sodium ions by the sum of calcium and magnesium ions (Kelly, 1940).

$$KR = \frac{Na^{2+}}{Ca^{2+} + Mg^{2+}} \qquad (8)$$

Where, concentrations of all ions were expressed in meq/l.

Permeability Index:

The permeability index is calculated by the following Equation 9:

$$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100 \qquad (9)$$

Here, concentrations of all ions were expressed in meq/l.

Total Dissolved Solids (TDS):

TDS is calculated with the following Equation (10):

$$TDS = (\sum Cations) + (\sum Anions) \qquad (10)$$

Where the concentrations are expressed in mg/L.

Statistical and hydro geochemical analyses

Principal Component Analysis, Na/Cl ratio analysis, and the Chloro-Alkaline Index were carried out to improve the understanding of groundwater evolution. Standardized data were used to perform PCA to determine the primary factors influencing groundwater composition. Scree and PCA biplots were used to evaluate the data (Cloutier et al., 2008). The Kaiser criterion (Kaiser, 1960) was used to retain components with eigenvalues greater than 1.0. The relative contributions of silicate weathering, evaporation, and salty water effect were assessed using the Na/Cl molar ratio, while the cation exchange processes between

groundwater and aquifer materials were evaluated using the Chloro-Alkaline Index (CAI).

Na/Cl ratio

To assess the origins of salinity and differentiate between seawater intrusion, mineral weathering, and ion exchange processes, the Na/Cl molar ratio was calculated (Appelo and Postma, 2005) using Equation 11:

$$\mathrm{Na/Cl} = \frac{\mathrm{Na^+}}{\mathrm{Cl^-}} \qquad (11)$$

where Na^+ and Cl^- represent the molar concentrations (meq/L) of sodium and chloride, respectively. Na/Cl >1 generally indicates silicate weathering or cation exchange, whereas Na/Cl <1 suggests chloride enrichment due to evaporation or saline water influence (Appelo and Postma, 2005).

Chloro Alkaline Index (CAI)

It is crucial to understand how the chemical composition of groundwater and subsurface flow channels varies over time (Jamal et al., 2024). To comprehend how the chemical composition of groundwater varies depending on its flow, chloro alkaline indicators were examined (Schoeller, 1977). To understand the ion exchange mechanisms between shallow aquifers and their surrounding environment, he proposed using the chloro-alkaline indices (Equation12):

$$\mathrm{CAI} = \frac{\mathrm{Cl-(Na+K)}}{\mathrm{Cl}} \qquad (12)$$

Where all ionic concentrations are expressed in meq/L. Positive CAI values indicate reverse ion exchange, whereas negative values indicate direct ion exchange between groundwater and aquifer materials.

Health risk assessment

An essential part of a thorough groundwater investigation is the evaluation of health concerns. Specifically, evaluating the possible impacts on human health is a crucial way to find harmful consequences in both adults and children (Takeya et al., 2025). Standard equations for calculating the overall health risk indices were suggested by USEPA (2021). The potential health risks associated with both ingestion and cutaneous exposure were estimated in this study using the United States Environmental Protection Agency (USEPA, 1989), which has been widely utilized in hydro-environmental risk assessments. The chronic daily intake through ingestion (CDI_{oral}) and dermal absorption (CDI_{dermal}) was determined using the following Equation (13),(14):

$$CDI_{oral} = (CW \times IR \times EF \times ED) / (BW \times AT) \qquad (13)$$

$$CDI_{dermal} = (CW \times SA \times ED \times EF \times ET \times CF \times KP \times 10\text{-}3)/(BW \times AT) \qquad (14)$$

The exposure parameters used in the human health risk assessment for adults and children are summarized in Table 2. The accepted values, which were based on established risk assessment standards, were used to determine both carcinogenic and non-carcinogenic health dangers. USEPA (1989) provided all of the parameters. According to NCR, the hazard quotient (HQ) assesses non-carcinogenic risk (USEPA, 1989). The total potential for non-carcinogenic consequences resulting from exposure to various pollutants is shown by the hazard index, which is calculated by adding the HQs. Equation 15 used to calculate HQ:

$$HQ = CDI / RfD \qquad (15)$$

Table 2, Exposure parameters used for human health risk assessment

Parameter	Description	Adult	Child	Unit
CW	Concentration of contaminants in groundwater	Measured value	Measured value	µg/L
IR	Ingestion rate	2.2	1.0	L/day
EF	Exposure frequency	365	365	days/year
ED (NCR)	Exposure duration (non-carcinogenic risk)	70	10	years
ED (CR)	Exposure duration (Carcinogenic risk)	70	70	years
BW	Body weight	70	25	kg
AT (NCR)	Averaging time (non-carcinogenic risk)	25,550	3,650	days
AT (CR)	Averaging time (Carcinogenic risk)	25,550	25,550	days
SA	Exposed skin surface area	18,000	6,600	cm^2
Kp	Skin permeability coefficient	0.001	0.001	cm/h
CF	Conversion factor	0.001	0.001	L/cm^3

The maximum acceptable level of exposure to an element through oral or dermal routes is indicated by the reference dose (RfD). The hazard index (HI), which is computed as the sum of all individual hazard quotients (HQs) and is determined by Equation 16, was used to evaluate the cumulative non-carcinogenic risk from these elements.

$$HI = HQ_1 + HQ_2 + HQ_3 + \ldots\ldots\ldots + HQ_n \qquad (16)$$

Human health is considered to be safeguarded when both HQ and HI levels are less than 1. When the hazard index (HI) is greater than 1, residents are at risk of non-carcinogenic health effects. Trace metals including as, Cr, Ni, and Pb may also increase the risk of cancer in addition to these non-carcinogenic problems. The carcinogenic risks related to skin contact and oral ingestion are calculated using the following Equation 17, 18:

$$CR_{oral} = CDI_{oral} \times SF_{oral} \quad (17)$$

$$CR_{dermal} = CDI_{dermal} \times SF_{dermal} \quad (18)$$

$$CR = CR_{oral} + CR_{dermal} \quad (19)$$

The term "carcinogenic risk" (CR) in Equation 19. According to USEPA, the acceptable limit for CR is 1.0×10-4. The slope factor (SF), expressed in $(mg/kg/day)^{-1}$, indicates the degree of a carcinogenic contamination. The related dermal slope factors (SF_{dermal}) are 3.66, 20, and 42 for as, Cr, Ni, and Pb, whereas the corresponding oral slope factors (SF_{oral}) are 1.50, 0.5, 1.7, and 0.0085. Five. CR readings above this cutoff point suggest a lifelong cancer risk for the affected group.

Water quality index development using fuzzy-GIS

It is challenging to make accurate estimations because the evaluation of the earth system is prone to ambiguity and uncertainty (Jha et al., 2020). In these situations, the researcher and other interested parties could employ Fuzzy Operation (FO) to convince people that human knowledge and expertise are sufficient for the accurate evaluation of the natural system (Zadeh, 1965). The Inverse Distance Weighting (IDW) interpolation technique in ArcGIS 10.8 was used to create spatial distribution maps of the water quality metrics. IDW is a deterministic interpolation method that uses the weighted influence of adjacent observations to estimate values at unsampled locations, with closer sampling points having a greater impact than those farther away. This approach was chosen because of its ease of use, computational effectiveness, and applicability for spatial interpolation of water quality parameters from a comparatively small number of sampling locations. However, prediction uncertainty may increase in regions with reduced sample density, similar to other deterministic interpolation techniques, and the interpolated maps should be interpreted appropriately.

Fuzzification of water quality parameter

It is challenging to make accurate estimations because the evaluation of the earth system is prone to ambiguity and uncertainty (Jha et al., 2020). In these situations, the researcher and other interested parties could employ Fuzzy Operation (FO) to convince people that human knowledge and expertise are sufficient for the accurate evaluation of the natural system (Zadeh, 1965). The Inverse Distance Weighting (IDW) interpolation technique in ArcGIS 10.8 was used to create spatial distribution maps of the water quality metrics. IDW is a deterministic interpolation method that uses the weighted influence of adjacent observations to estimate values at unsampled locations, with closer sampling points having a greater impact than those farther away. This approach was chosen because of its ease of use, computational effectiveness, and applicability for spatial interpolation of water quality parameters from a comparatively small number of sampling locations. However, prediction uncertainty may increase in regions with reduced sample density, similar to other deterministic interpolation techniques, and the interpolated maps should be interpreted appropriately.

Fuzzy overlay and fuzzy-GIS based water quality index map:

Every raster that was fuzzified was superimposed using fuzzy overlay techniques. Fuzzy AND, fuzzy OR, fuzzy SUM, fuzzy PRODUCT, and fuzzy GAMMA are the five fuzzy overlay choices accessible in ArcGIS. Using the fuzzy AND overlay function, the fuzzy raster returns the minimum value of the sets contained. When all input conditions are met, the least common denominator is determined using this method. The fuzzy OR overlay function returns the largest value of the sets in the fuzzified raster, in contrast to the fuzzy AND overlay function. For any input criterion, this is helpful in determining the highest membership values (Tiwari et al., 2023). A fuzzy overlay operation was used to identify the strictly suitable water quality zones in the study area.

Validation of the fuzzy-GIS groundwater quality map

The anticipated and actual WQI classes at 20 sampling locations were compared in order to validate the fuzzy-GIS groundwater quality map. To assess the categorization performance, a confusion matrix was created. The agreement between the observed and predicted groundwater quality classes was evaluated using Cohen's Kappa coefficient (κ) and Overall Accuracy (OA) (Wan et al., 2015).

The validation results give a clear measure of how reliable and accurate the fuzzy GIS map is in predicting groundwater quality. Comparing the actual results with the expected water quality index categories helped determine how well the different groundwater quality groups matched each other. The confusion matrix shows how well different sampling locations were correctly identified, while the Overall Accuracy (OA) tells us the general percentage of all samples that were correctly classified. Cohen's kappa coefficient (κ) shows how much agreement there is between the actual classifications and the predicted ones, taking into account the agreement that might happen just by chance. When OA and κ are higher, it means the classification is better and there is more agreement between the predicted groundwater quality map and the actual water quality index measurements. So, these validation metrics helped figure out how well and how

dependable the fuzzy-GIS method was for classifying groundwater quality in the study area.

Results and discussion

Physico-chemical assessment of groundwater

Results of physical parameters

The physical properties of groundwater in the research area indicate low water quality. Although the measured pH ranged from 5.5 to 7.2, indicating slightly acidic to nearly neutral conditions, several samples fell below the WHO-recommended range (6.5–8.5), rendering the water unsafe for drinking and agriculture. The usual shallow aquifer conditions are reflected in the groundwater temperature range of 25.8–29.4 °C. Elevated ionic concentrations were indicated by electrical conductivity (EC) values between 516 and 2130 µS/cm, with many samples surpassing the WHO limit of 1000 µS/cm.

Hem's (1970) categorization and WHO recommendations state that most samples with total dissolved solids (TDS) between 331 and 13,320 mg/L are unfit for irrigation or drinking. The WHO limit of 5 NTU was significantly exceeded by turbidity values (4.7–271 NTU), suggesting a high load of suspended particles and the need for treatment before home use. The extremely low dissolved oxygen (DO) content (0.044–1.03 mg/L), which may imply lowering circumstances linked with elevated levels of iron, manganese, or arsenic, further restricts drinking acceptability. Salinity ranges from 0.21 to 12.18 ppt, and higher values significantly exceed the allowable limits for drinking and irrigation, endangering both agricultural productivity and human health. As further shown by the regional distribution maps (Figure 4), the evaluation of field-based physical factors indicates that groundwater in the research area is typically unsuitable for residential, drinking, and irrigation use.

The overall physical parameters indicate high spatial variability of groundwater quality in the study area. High EC, TDS, turbidity, salinity and low DO together indicate significant hydrochemical stress on the aquifer system. These conditions may restrict the use of groundwater for drinking and irrigation purposes without proper treatment. Therefore, ongoing surveillance and proper water management practices are necessary to mitigate the potential risks to human health and agricultural productivity.

Results of chemical parameters

The principal ions and trace elements in the groundwater of the studied area exhibited a general deterioration in water quality and were indicative of complex anthropogenic and geogenic processes. Among the trace metals with high quantities that present serious health risks are iron (0.14–14.3 mg/L), manganese (0.07–3.09 mg/L), and arsenic (0–0.161mg/L), particularly when aquifer conditions deteriorate. Overall, the hydro chemical composition and spatial distribution patterns (Figure 5) demonstrate that groundwater in the study area is largely unsuitable for drinking and irrigation without appropriate treatment.

Comparison with drinking water quality standards

Water quality is widely above allowable limits throughout the research region when compared to WHO (2011) and DoE (2016) drinking water regulations. High hardness and salinity are indicated by increasing concentrations of major ions such calcium, magnesium, sodium, and potassium in a considerable number of samples (Table 3).

Arsenic, iron, manganese, and aluminum are among the trace and dangerous elements that, in the majority of samples, surpass both WHO (2011) and DoE (2016) criteria, raising grave implications for public health. Arsenic and Iron concentrations are far above permissible limits exceeding in all (16) samples. pH, electrical conductivity, total dissolved solids, and turbidity are examples of physical characteristics that routinely surpass recommended values, especially EC, TDS, and turbidity. Chloride and Salinity values are slightly above standard limits in some cases. Rather than direct human inputs, natural geochemical processes are probably in charge of the high arsenic contents found in several groundwater samples. Arsenic is frequently mobilized in coastal aquifers by the reductive breakdown of iron oxyhydroxides in reducing circumstances, which releases adsorbed arsenic into groundwater.

Furthermore, prolonged water-rock contact and competitive desorption by phosphate ions may increase arsenic mobility. The current study's finding of a correlation between iron and arsenic concentrations lends credence to iron mineral dissolution as a possible mechanism regulating arsenic release in the aquifer. Bangladesh’s sedimentary aquifers have significantly higher trace-element concentrations than crystalline basement aquifers (Ahmed et al., 2004; Bhattacharya et al., 2002; Nwankwo et al., 2020).

Elevated levels of arsenic, iron, manganese, aluminum, salinity, EC, and TDS all point to the necessity of routine groundwater monitoring and efficient water-treatment techniques. These findings highlight how crucial it is to find safe substitute water sources, especially for areas who rely significantly on groundwater for household and drinking needs.

Water Quality Index (WQI)

WQI readings and associated water quality status for groundwater samples taken from various sites in Bangladesh's Lakhsmipur district are displayed in Table 4. The study area's WQI values, which vary greatly throughout the district, range from 63.51 to 1922.51.

Table 3, Comparison of the groundwater quality in the study area with WHO, DoE standards.

Parameters	Units	WHO standards (2011)	DoE Standard (2016)	Concentration in the study area		Number of samples Exceeding	
				Max.	Min.	WHO	DoE
Calcium	mg/L	200	75	858.9	24.4	7	14
Magnesium	mg/L	150	35	362.5	23.0	5	18
Sodium	mg/L	200	200	2149.9	48.1	13	13
Potassium	mg/L	1.2	12	157.2	8.1	20	20
Arsenic	µg/mL	0.01	0.005	0.2	0	16	16
Iron	mg/L	0.3	0.3-1	14.3	0.1	16	16
Manganese	mg/L	0.4	0.1	3.1	0.07	6	18
Aluminium	mg/L	0.2	0.2	0.98	0.02	16	16
Chloride	mg/L	500	600	5900	135	13	13
Salinity	ppt	-	1	12.2	0.2	0	12
P^H		6.5-9.2	6.5-8.5	7.2	5.4	12	12
Temperature	°C	25	20-30	29.5	25.8	20	20
EC	µs/cm	1400	-	20200	509	14	0
TDS	mg/L	1500	1000	13260	326	13	14
Turbidity	NTU	5	10	273	4.1	19	14

The majority of the samples are classified as "unsuitable" by WQI, indicating significant deterioration of water quality in numerous areas. Samples with exceptionally high WQI values, such as Roypur (GQHS51580010), where the WQI is 1922.508, Roypur (GQHS5158004), where the WQI is 1252.774, and others, indicate that these water sources are highly contaminated and unfit for human consumption.

A small number of groundwater samples, meanwhile, exhibit somewhat higher quality. Sample GQHS5158002 (Roypur), for example, has a WQI score of 63.51, which is in the "Good" category and indicates that the drinking water quality is adequate there. In a similar vein, samples GQHS5133005 from Kamalnagar and GQHS5158001 from Ramganj are classified as "Good" and "Poor," respectively.

These results imply that although the majority of the Lakhsmipur district's groundwater is extremely unfit for human consumption, there are a few isolated areas with comparatively higher water quality.

The district-wide spatial variance in WQI indicates localized sources of contamination, which could be brought on by anthropogenic activity, inadequate sanitation, geogenic causes, and agricultural runoff. The findings show that in order to increase groundwater safety in the area, routine monitoring and focused mitigation measures are desperately needed.

Irrigation water quality

Groundwater's appropriateness for irrigation is important because of the impact that water's mineral components have on soil and plants. Since this mineral component (impurities) of water can affect osmotic pressures and produce metabolic reactions due to toxic elements, they can also impact on plant growth. Additionally, they might alter the permeability, aeration and structure of the soil.

Sodium percentage (Na%)

The Na% of the groundwater of the study area ranges from 31.71 to 88.12 (Table 11), which concluded that the groundwater is “Permissible” to the maximum station and “Unsuitable” (Table 5) in two sample. Most samples fall in the “Permissible” and “Doubtful” categories suggesting moderate to high sodium hazards for irrigation. The two “Unsuitable” samples show high sodium hazard and should not be used for irrigation without appropriate management.

Table 4, WQI values with pre-determined categories.

Sample ID	Location	WQI	Water quality Status
GQHS5133001	Kamalnagar	330.9	unsuitable
GQHS5133002	Kamalnagar	310.3	unsuitable
GQHS5133003	Kamalnagar	298.3	Very poor
GQHS5133004	Kamalnagar	275.6	Very poor
GQHS5133005	Kamalnagar	78.5	Good
GQHS5143001	Lakshmipur Sadar	581.8	unsuitable
GQHS5143002	Lakshmipur Sadar	670.9	unsuitable
GQHS5143003	Lakshmipur Sadar	704.1	unsuitable
GQHS5143004	Lakshmipur Sadar	864.7	unsuitable
GQHS5158001	Ramganj	122.1	poor
GQHS5158002	Ramganj	63.5	Good
GQHS5158003	Raipur	449	unsuitable
GQHS5158004	Raipur	1252.8	unsuitable
GQHS5158005	Raipur	538	unsuitable
GQHS5158007	Raipur	651.1	unsuitable
GQHS5158010	Raipur	1922	unsuitable
GQHS5165001	Ramgati	338.8	unsuitable
GQHS5165002	Ramgati	210.9	Very poor
GQHS5165003	Ramgati	313.8	unsuitable
GQHS5165004	Ramgati	428.9	unsuitable

Sodium percentage (Na%)

The Na% of the groundwater of the study area ranges from 31.71 to 88.12 (Table 11), which concluded that the groundwater is "Permissible" to the maximum station and "Unsuitable" (Table 5) in two sample. Most samples fall in the "Permissible" and "Doubtful" categories suggesting moderate to high sodium hazards for irrigation. The two "Unsuitable" samples show high sodium hazard and should not be used for irrigation without appropriate management.

Table 5, Classification of Sodium Percentage for Groundwater (Deshmukh and Pawar, 2001)

Water Class	Na%	Number of Samples
Excellent	<20	Nil
Good	20-40	4
Permissible	40-60	9
Doubtful	60-80	5
Unsuitable	>80	2

Sodium Absorption Ration (SAR)

The SAR values in the groundwater of the study area ranges from 1.33 to 28.5. In dry season (Table 11), which stands the groundwater is "Excellent" to "Good" for irrigation and GQHS5133003 station is "Bad" for irrigation. The quality of the Groundwater for irrigation purpose depends upon SAR (Raghunath, 1987) is given below (Table 6).

Table 6, Classification of groundwater depending upon SAR.

Water Class	SAR	Number of Samples
Excellent	<10	11
Good	10-18	8
Medium	18-26	Nil
Bad	>26	1

Residual Sodium Carbonate (RSC)

The RSC values in the groundwater of the study area ranges from (-10.12 to 48.70) meq/L (Table 11), which stands the groundwater is "Good" for irrigation and Nine samples is "Unsuitable" for irrigation (Table 7)

Table 7, Residual Sodium Carbonate (RSC) classification of the groundwater samples in the study area according to Eaton, 1950.

Water Class	RSC (meq/L)	Number of Samples
Good	<1.25	11
Doubtful	1.25-2.5	Nil
Unsuitable	>2.5	9

Magnesium Hazard (MH)

The MH values in the groundwater of the study area ranges from (23.61 to 75.46) % (Table 11), which stands most of the groundwater sample is "Suitable for irrigation" and Seven samples is "Unsuitable for irrigation" (Table 8).

Table 8, Magnesium hazard classification of the groundwater samples in the study area according to Szabolcs and Darab (1964).

Water Class	MH%	Number of Samples
Suitable for Irrigation	<50	13
Unsuitable for Irrigation	>50	7

Kelly's Ratio (KR)

The KR values in the groundwater of the study area ranges from (0.42 to 7.19) (Table 11), which stands most of the groundwater sample is "Unsuitable" for irrigation and nine samples is "suitable" for irrigation (Table 9).

Table 9, Kelly's Ratio (KR) classification of the groundwater samples in the study area according to Kelly, 1940.

Water Class	KR	Number of Samples
Suitable	<1	9
Unsuitable	>1	11

Permeability Index (PI)

The PI values in the groundwater of the study area ranges from (42 to 89.8) (Table 11), which stands most

of the groundwater sample is “Good” for irrigation and two samples is “Excellent” for irrigation (Table 10).

Table 10, Permeability index (PI) classification of the groundwater samples in the study area according to (Raghunath, 1987).

Water Class	PI	Number of Samples
Unsuitable	<25	Nil
Good	25-75	18
Excellent	>75	2

The evaluation of irrigation water quality has significant effects on the sustainability of agriculture in the research region. Reduced soil permeability, deterioration of soil structure, and limited water infiltration might occur from groundwater with high salinity and poor irrigation indices gradually raising soil salinity and sodicity. These modifications may restrict the availability of nutrients, hinder the uptake of water by plants, and eventually lower crop output. Therefore, continuous use of low-quality groundwater for irrigation may hasten soil degradation and jeopardize long-term agricultural sustainability, especially in Bangladesh's coastal agricultural districts. To reduce these negative effects and maintain agricultural output, appropriate irrigation management techniques, regular soil monitoring, and the concurrent use of alternate water sources are advised.

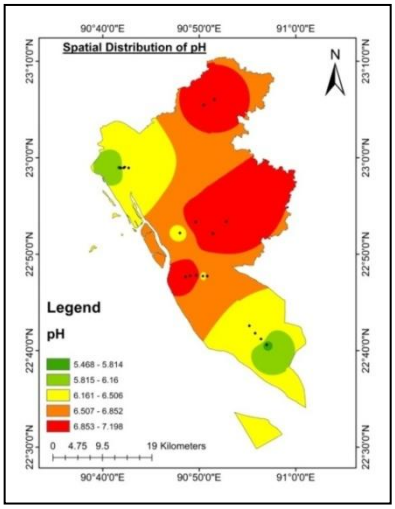
Fuzzy-GIS based groundwater quality index mapping

As stated in the methodology section, the coefficient of correlation approach was used to determine the optimal fuzzy overlay technique for creating the Fuzzy-GIS based Groundwater Quality Index (FGWQI) map.

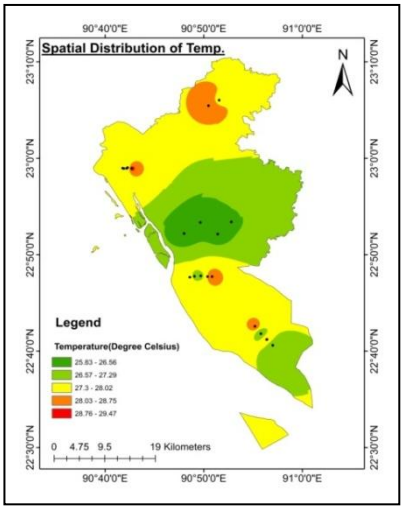
The most successful technique for this was the Fuzzy-AND overlay method. Each technique's fuzzy membership maps are shown in Figure 6. The FGWQI map of the study area is shown in Figure 7.

Table 11, Statistical results of groundwater for irrigation purposes.

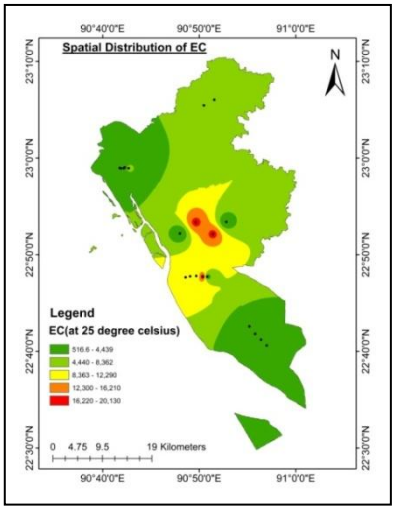
Sample ID	SAR	MH	RSC (meq/L)	Na%	PI	KR
GQHS5133001	10.1	52.4	-3.1	50.4	49.9	0.9
GQHS5133002	10.2	41.0	-10.1	47.2	47.1	0.9
GQHS5133003	28.5	67.8	48.7	88.1	89.8	7.2
GQHS5133004	16.4	37.7	28.3	59.8	59.8	1.4
GQHS5133005	2	66.7	-3.8	34.9	51.2	0.5
GQHS5143001	17.4	38.4	35.7	62.4	62.5	1.6
GQHS5143002	1.3	75.5	-2.9	32.7	51.1	0.4
GQHS5143003	12.7	38.1	10.7	54.7	55.3	1.2
GQHS5143004	2.7	70.3	-1.5	46.0	64.5	0.7
GQHS5158001	2.6	46.6	-1.0	45.7	66.1	0.8
GQHS5158002	2.3	48.2	-0.6	47.0	73.9	0.8
GQHS5158003	12.7	28.0	20.2	68.7	68.9	2.1
GQHS5158004	11.1	23.6	14.7	62.7	65.1	1.6
GQHS5158005	17.3	53.6	28.0	80.3	86.6	4
GQHS5158007	2.3	33.5	-7.7	31.7	42.0	0.4
GQHS5158010	8.5	30.7	8	60.4	65.8	1.5
GQHS5165001	4.6	50.7	1.1	53.8	54.9	1.1
GQHS5165002	6.0	45.7	3.8	60.1	65.5	1.4
GQHS5165003	4.4	48.4	0.5	52.4	61.7	1.1
GQHS5165004	1.9	41.7	-3.9	35.0	48	0.5
Maximum	**28.5**	**75.5**	**48.7**	**88.1**	**89.8**	**7.2**
Minimum	**1.3**	**23.6**	**-10.1**	**31.7**	**42.0**	**0.4**
Average	**8.75**	**46.93**	**8.2**	**53.7**	**61.5**	**1.5**
Standard Deviation	**7.02**	**14.0**	**15.6**	**16.0**	**12.1**	**1.52**



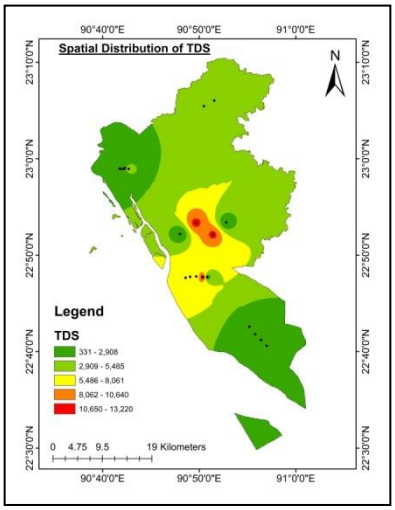
a)



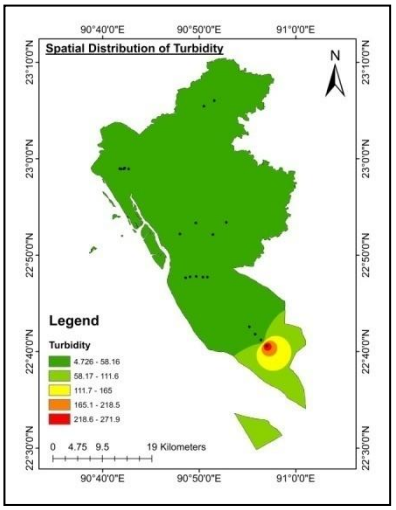
b)



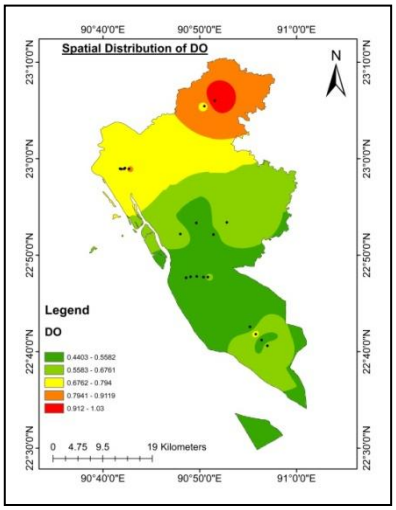
c)



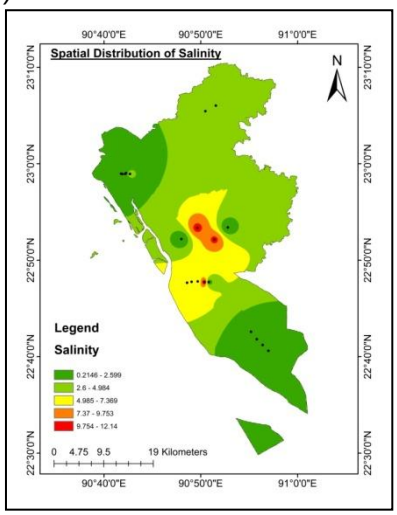
d)



e)

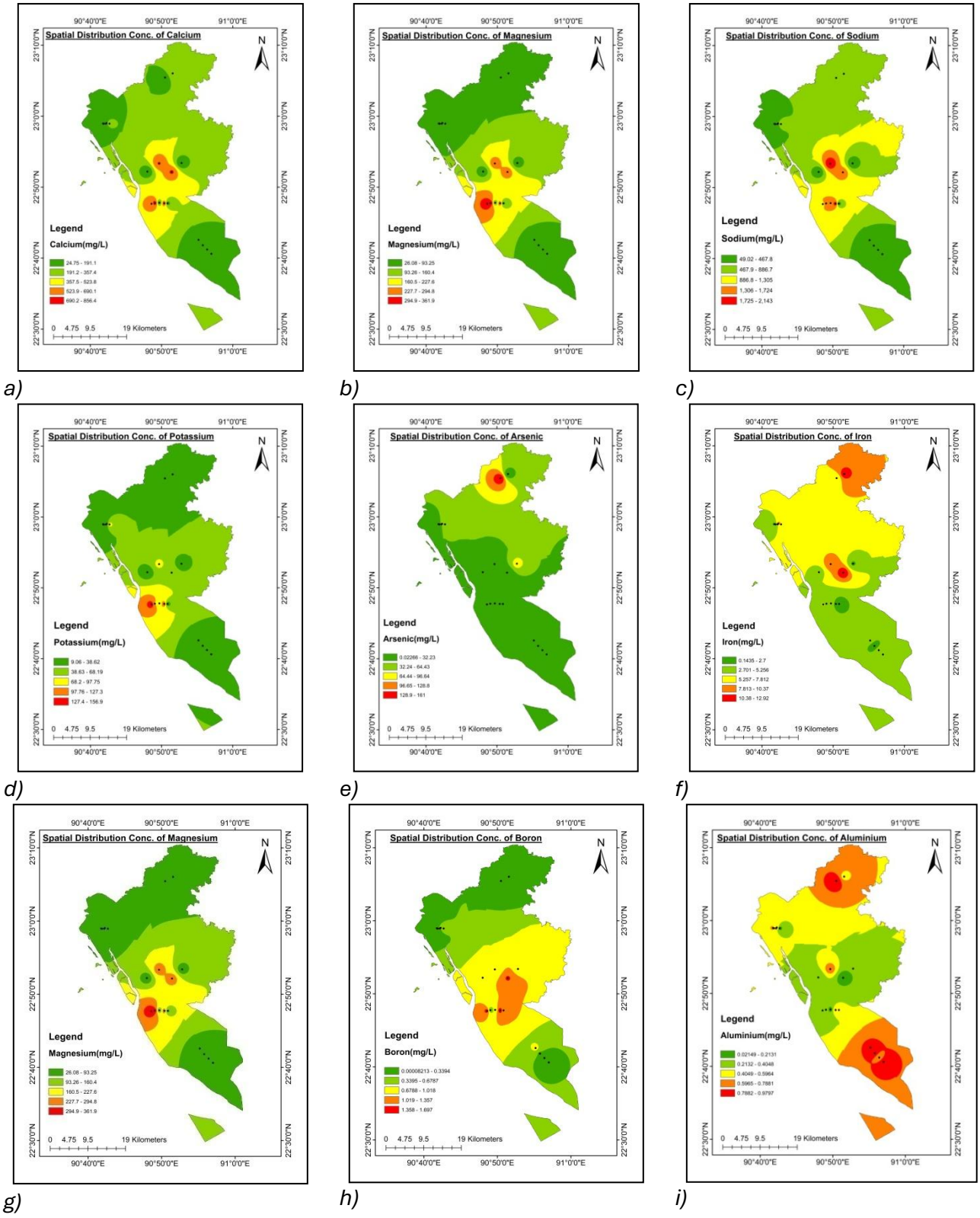


f)



g)

Figure 4, Spatial distribution map of (a) pH (b) Temperature (°C) (c) EC (µS/cm) (d) TDS (mg/L) (e) Turbidity (NTU) (f) DO (mg/L) (g) Salinity (ppt).

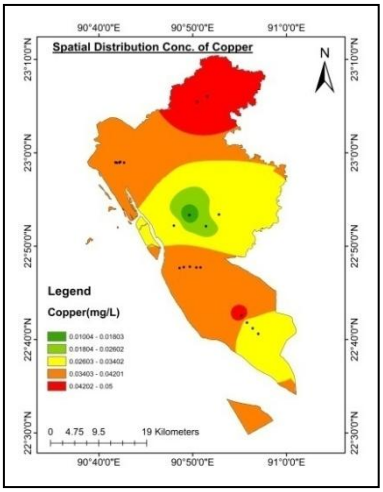


a) b) c)

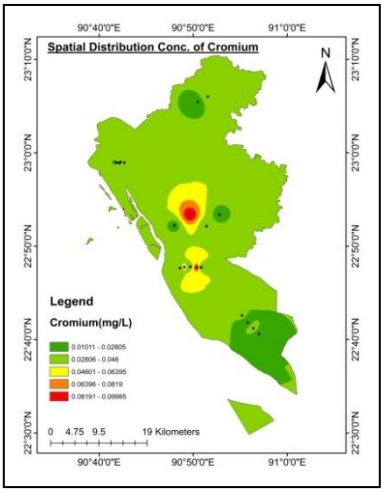
d) e) f)

g) h) i)

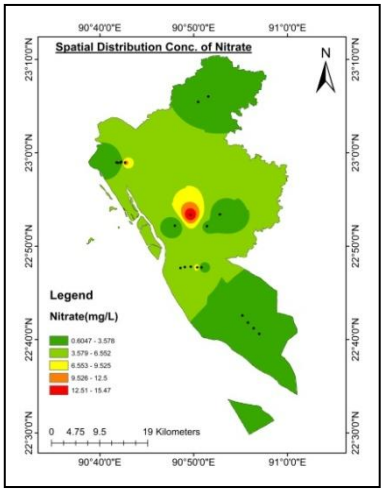
Figure 5, Spatial distribution map of (a) Calcium (mg/L) (b) Magnesium (mg/L) (c) Sodium(mg/L) (d) Potassium (mg/L) (e) Arsenic (µg/L) (f) Iron (mg/L) (g) Manganese (mg/L) (h) Boron (mg/L) (i) Aluminum(mg/L).



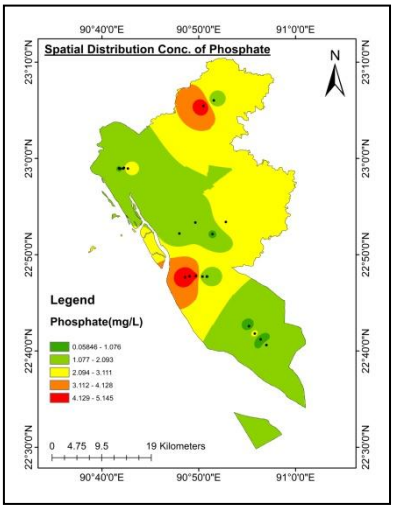
j)



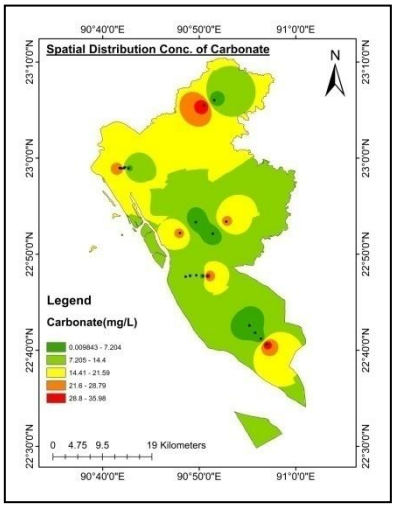
k)



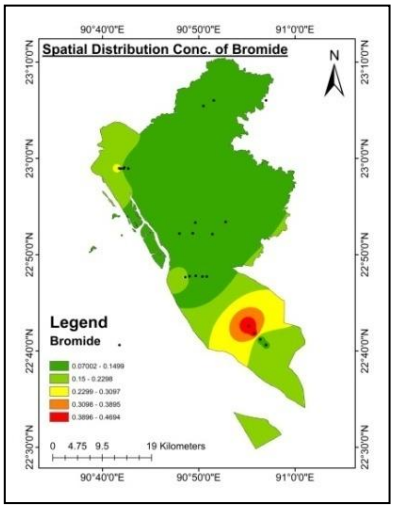
l)



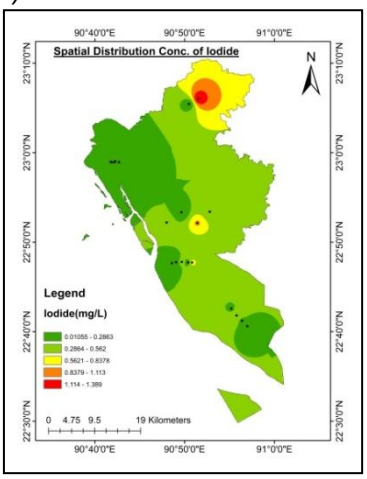
m)



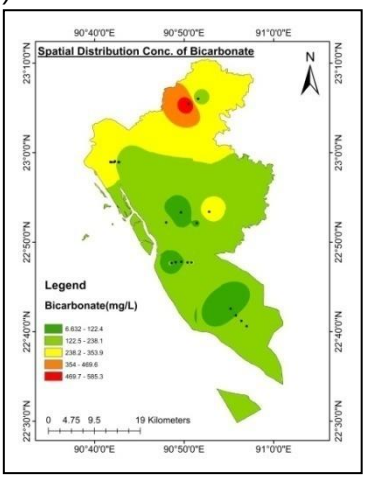
n)



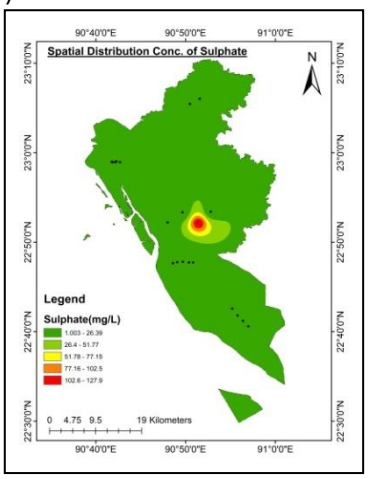
o)



p)



q)



r)

Figure 5 contd., Spatial distribution map of (j) Copper (mg/L) (k) Chromium (mg/L) (l) Nitrate (mg/L) (m) Phosphate (mg/L) (n) Carbonate (mg/L) (o) Bromide (mg/L) (p) Iodide (mg/L) (q) Bicarbonate (mg/L) (r) Sulphate (mg/L).

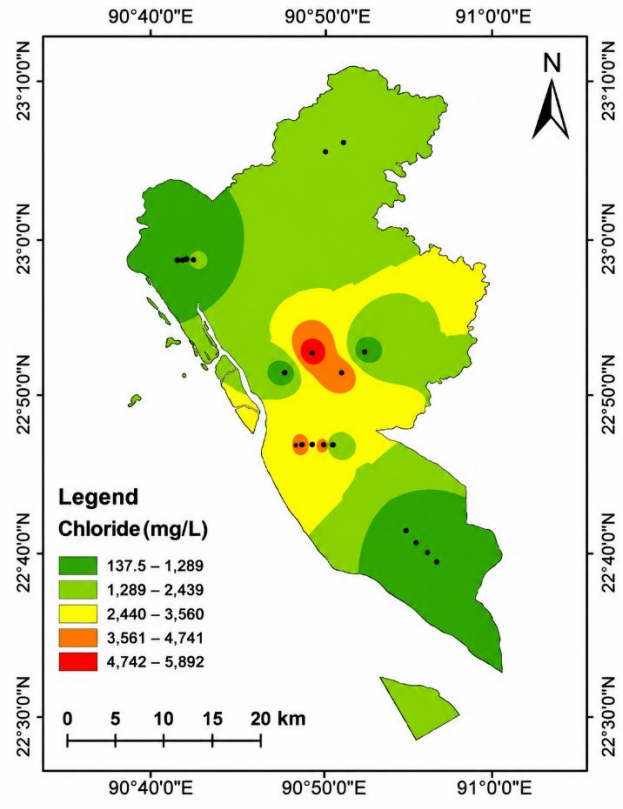


Figure 5 contd., Spatial distribution map of (s) Chloride(mg/L).

The research area's southern and western regions, which are closer to the Meghna estuary and more vulnerable to the effects of saline water, are where the highest concentrations of EC, TDS, salinity, Na^+, and Cl^- are found, according to the geographical distribution maps. While localized NO_3^- and PO_4^{3-} enrichment may be a result of domestic inputs and agricultural activity, higher Fe and as concentrations are probably linked to geogenic release from alluvial sediments under decreasing aquifer conditions. These geographical differences show that the combined effects of regional geology, coastal processes, and land-use practices regulate water quality.

Groundwater quality index mapping

Water Quality Map by Fuzzy Overlay represents the spatial variation in water quality across different upazilas (sub-districts) of the Lakshmipur district in Bangladesh (Figure7). The map uses a fuzzy overlay analysis, a GIS-based technique for integrating multiple water quality parameters to assess overall quality levels. The analysis categorizes water quality into five classes: Very Poor, Poor, Moderate, High, and Very High, each indicated by a specific color ranging from red (very poor) to bright green (very high).

The majority of the red-marked (Very Poor, 0–0.00357) areas are located in the district's western (Roypur) and southern (Ramgati) regions. These areas show serious problems with water quality, which could be brought on by pollution, saline intrusion, or heavy metal contamination. Water quality conditions in the orange zones (Poor, 0.00358 – 0.00912), which include portions of Ramganj and Kamalnagar, are marginally better but still cause for worry.

Particularly in central Lakshmipur Sadar and portions of Kamalnagar, yellow (Moderate, 0.00913 – 0.0129) and light green (High, 0.013 – 0.0159) areas indicate intermediate water quality, which is neither optimal nor significantly deteriorated. These areas can be undergoing mild anthropogenic influences or seasonal variations. Bright green (Very High, 0.016 – 0.0202), which is mostly seen in the central and northeastern zones, indicates the best water quality and is thought to be comparatively unpolluted and safe water resources.

Graphical representation of chemical analysis

Graphical representation of chemical analysis is very effective to understand the result of analysis and to provide means for comparing the analysis with each other, or to emphasize differences and similarities. To make the interpretation and description of the water quality variation and geochemical character of groundwater the results of chemical analysis of ground samples are represented in various graphical forms-

Piper diagram

For crucial investigations into the origins of the dissolved elements in water, the Piper Trilinear Diagram (Piper, 1944) is a useful tool for sorting hydro chemical analysis results. For critical investigations concerning the sources of dissolved constituents (major cations, Ca, Mg, Na, K and major anions, HCO_3^{2-}, Cl^-, SO_4^{2-}) in waters, changes in the character of water as it moves through an area, and associated geochemical issues, it is a useful tool for separating hydro-chemical analysis data. The areas make up the trilinear diagram's central plotting field (diamond shape), and water is categorized into nine types based on which area the analysis results fall into. The alkali cations (Na and K) are referred to as primary constituents, while the alkaline earth cations (Ca^{2+} and Mg^{2+}) are referred to as secondary constituents. $CO_3^{2-}$and HCO_3^{2-} are regarded as weak anions, while the strong anions (SO_4^{2-}, Cl^-) are regarded as saline components. The chemical makeup of water is determined by the approximate balance of these cations and anions (Figure 8).

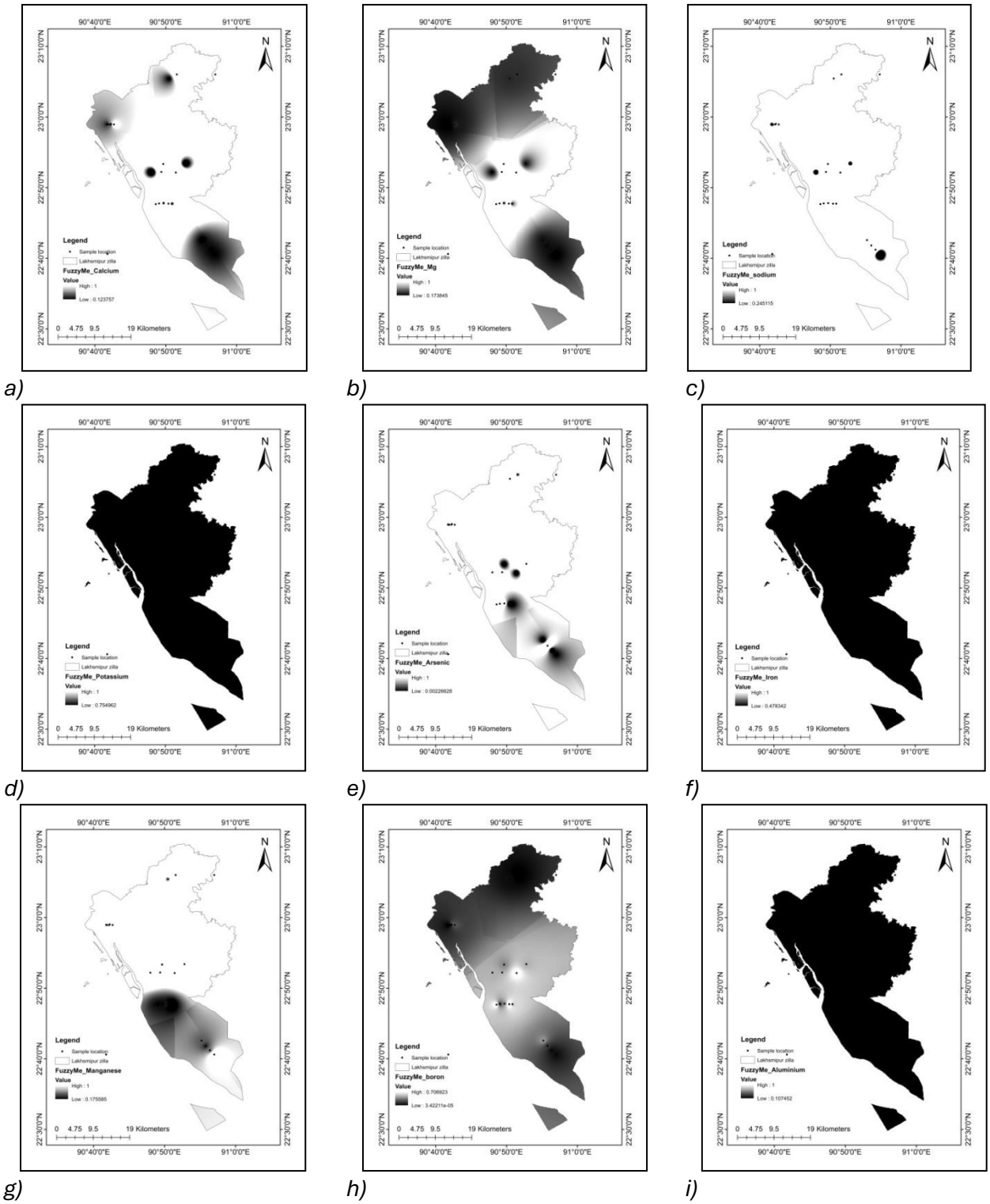
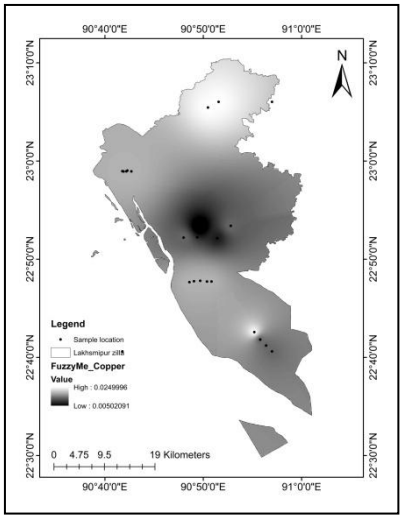
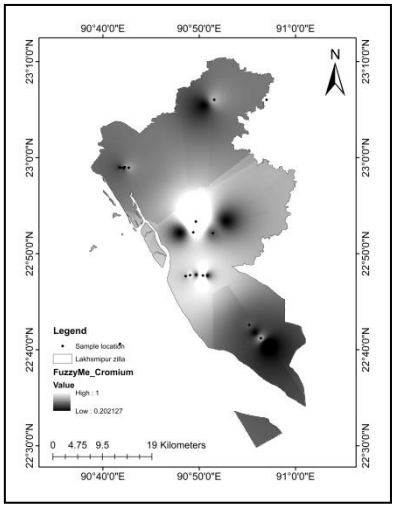


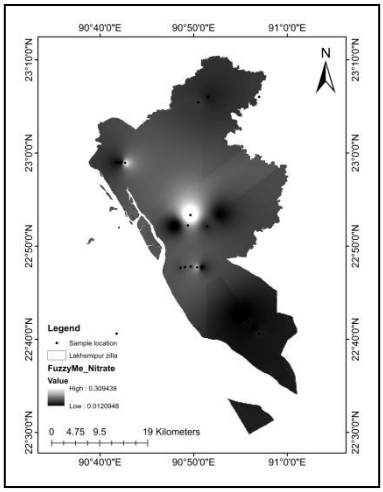
Figure 6, Fuzzy linear membership map of (a) Calcium (mg/L) (b) Magnesium (mg/L) (c) Sodium(mg/L) (d) Potassium (mg/L) (e) Arsenic (mg/L) (f) Iron (mg/L) (g) Manganese (mg/L) (h) Boron (mg/L) (i) Aluminum (mg/L).



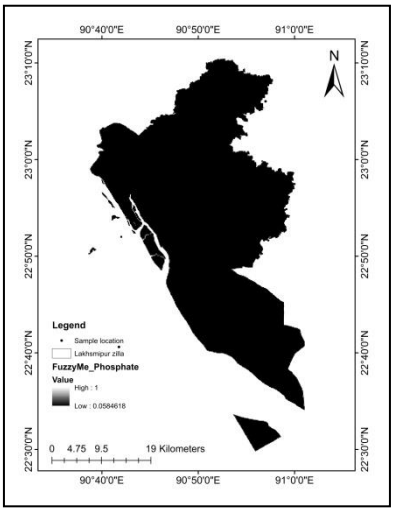
j)



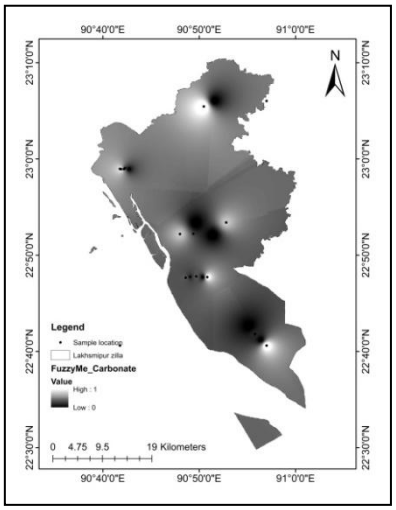
k)



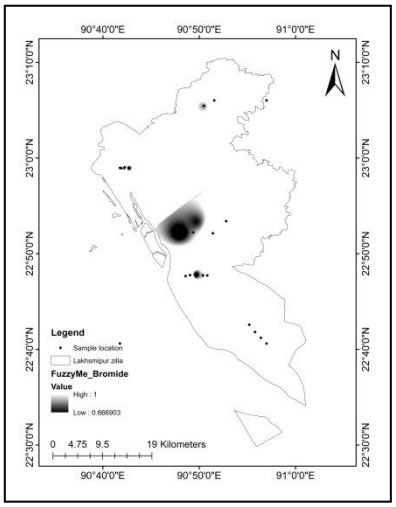
l)



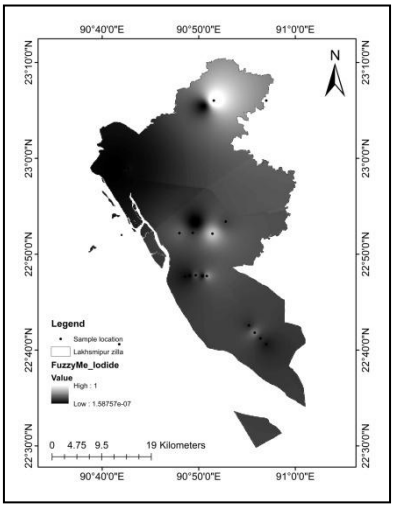
m)



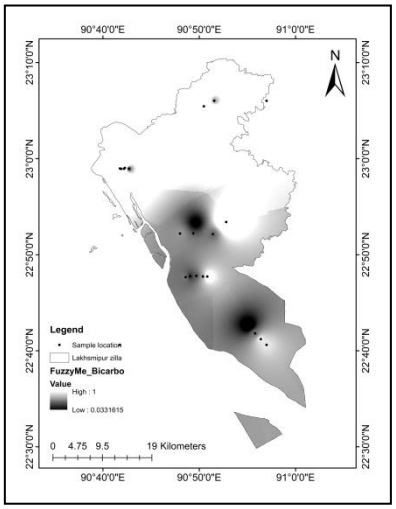
n)



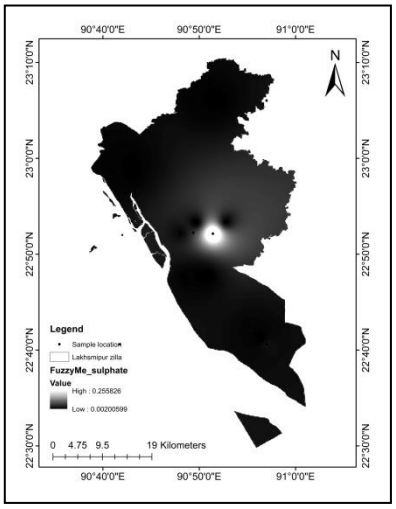
o)



p)



q)



r)

Figure 6 contd., Fuzzy linear membership map of (j) Copper (mg/L) (k) Chromium (mg/L) (l) Nitrate (mg/L) (m) Phosphate (mg/L) (n) Carbonate (mg/L) (o) Bromide (mg/L) (p) Iodide (mg/L) (q) Bicarbonate (mg/L) (r) Sulphate (mg/L).

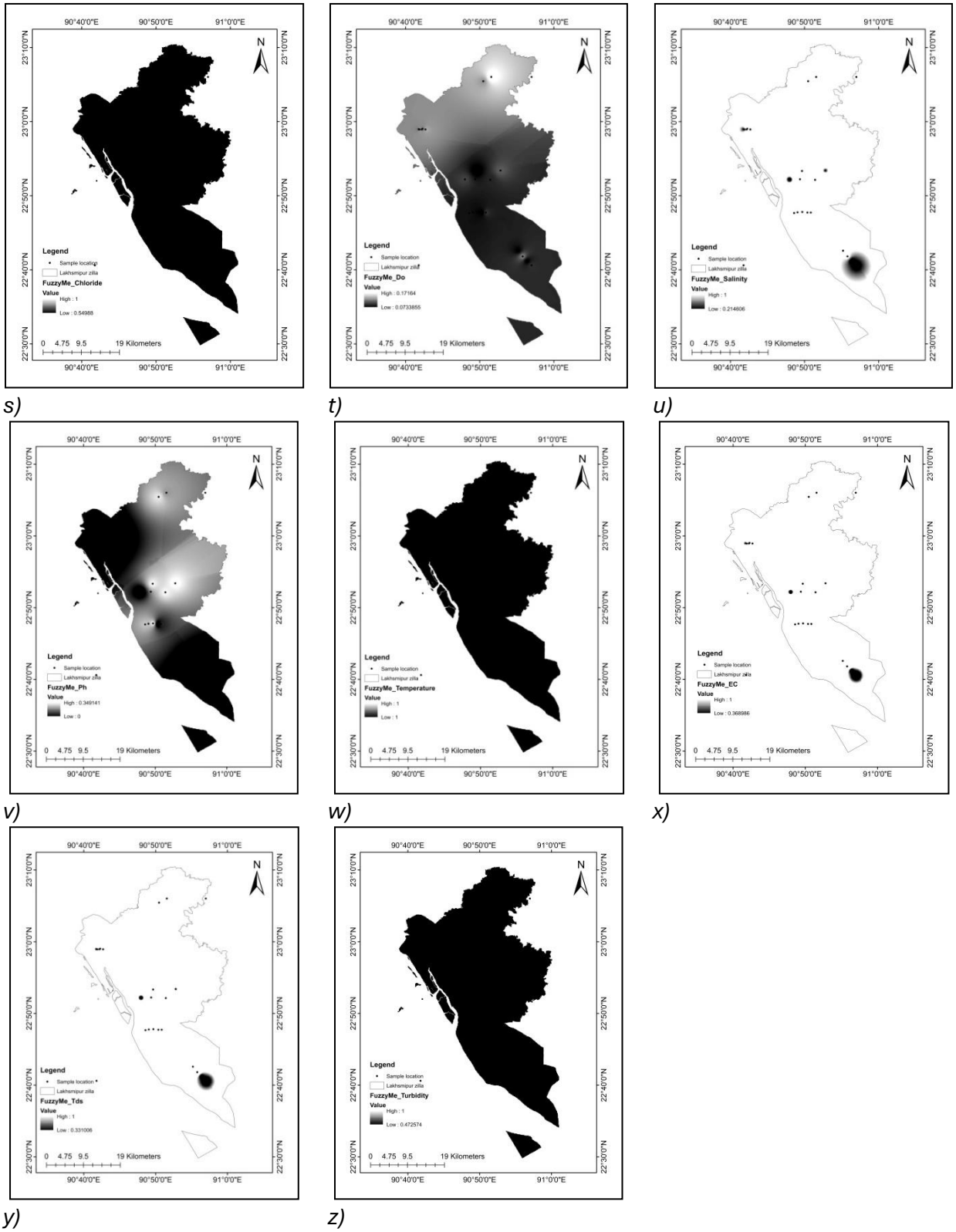


Figure 6 contd., Fuzzy linear membership map of (s) Chloride (mg/L) (t) DO (mg/L) (u) Salinity (ppt) (v) Lead (mg/L) (w) Temperature (°C) (x) EC (µs/cm) (y) TDS (mg/L) (z) Turbidity (NTU).

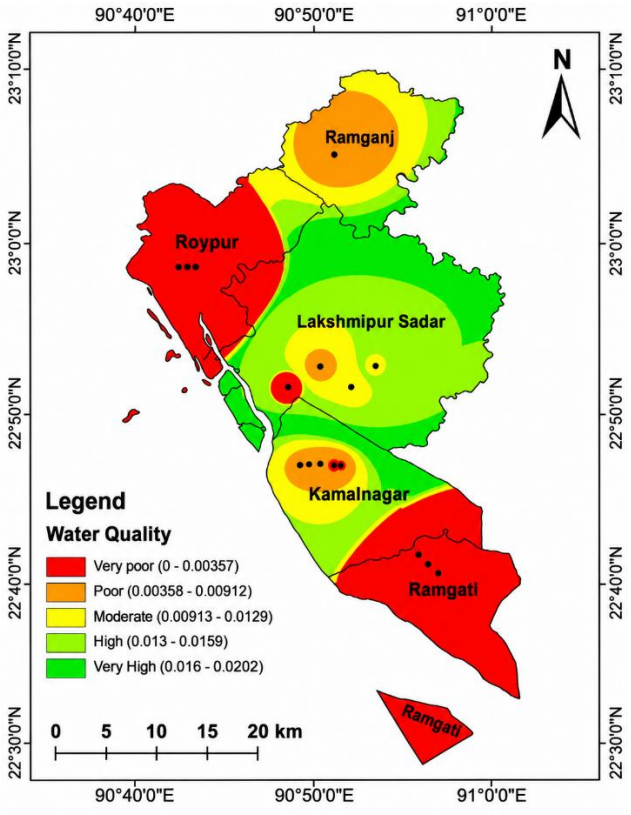


Figure 7, Groundwater Quality Index map by fuzzy overlay of the study area.

In this diagram, samples from Kamalnagar, Lakshmipur Sadar, Ranganj, Raipur, and Ramgati are plotted using different symbols. Most samples cluster in the $Na^{+}+K^{+}$-$Cl^{-}+SO_4^{2-}$ dominant zone, indicating a saline or marine-influenced water type, common in coastal regions. This suggests ion exchange or seawater intrusion may influence groundwater chemistry, especially near the coast. Such analysis is crucial for understanding water quality and planning for drinking and irrigation suitability.

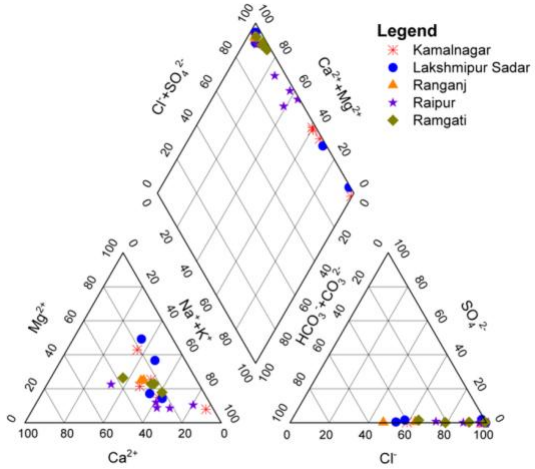


Figure 8, Piper's Trilinear Diagram of groundwater of the study area.

Durov diagram

The Durov diagram is used to reveal hydro geochemical processes associated with the chemical composition of water, such as cation exchange, reverse cation exchange, mixing, and simple dissolution (Durov, 1948; Ravikumar et al., 2015). It consists of a central square figure bounded on the left by a cation triangle, on the top by an anion triangle, on the right by a TDS (Total Dissolved Solids) rectangle, and on the bottom by a pH rectangle (Durov, 1948; Chen et al., 2020, Yu et al., 2021). The milliequivalent per liter concentrations of the total cations and anions are transformed into percentages and scaled on the diagram. According to the classification of Lloyd and Heathcote (1985), the central rectangular figure is subdivided into nine zones representing different hydro geochemical processes, including mixing and reverse cation exchange waters (Ca-Cl type water), mixing and reverse cation exchange reactions, mixing with seawater or halite, calcite and gypsum dissolution, mixing reactions from various origins, mixing and cation exchange waters, infiltration (Ca-HCO_3 type water), cation exchange reactions, and cation exchange waters (Na-HCO_3 type water).

In this plot (Figure 9), groundwater samples from Kamalnagar, Lakshmipur Sadar, Ranganj, Raipur, and Ramgati are color-coded and symbolized. Most samples plot toward the $Na^{+}+K^{+}$ and Cl^{-} dominant zones, indicating saline water influence or ion exchange processes, which are typical in coastal aquifers. The dominance of Mg^{2+} over Ca^{2+} in many samples also suggests cation exchange reactions. The clustering in the lower-right central square indicates Cl^{-}-Na^{+} water type, often linked with seawater intrusion or anthropogenic contamination. This type of analysis helps in understanding the groundwater evolution and suitability for drinking and agricultural use.

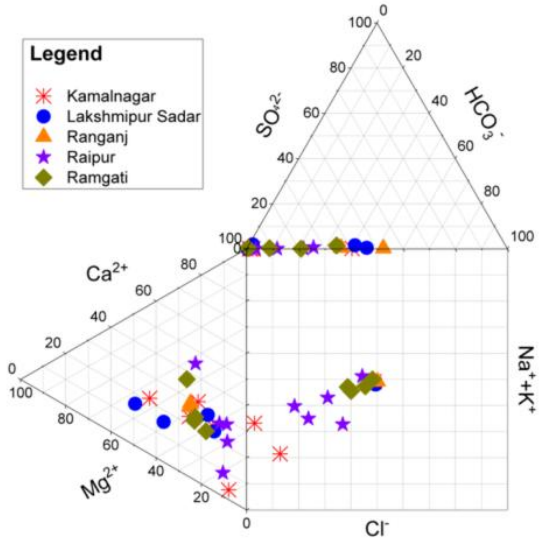


Figure 9, Durov diagram for hydrogeochemical types of the study area.

Gibbs diagram

For evaluating dominant hydro geochemical processes, such as hydrochemistry formation interactions, compositional change trends, and the hydro geochemical evolution of analyzed groundwater based on its chemical composition, the Gibbs diagram is

another useful tool (Liu et al., 2021; Lyu et al., 2019; Nazzal et al., 2014, Gibbs, 1970). Additionally, it shows how aquifer lithology characteristics and groundwater composition are related (Gibbs, 1970). The Gibs diagram was first used to assess the hydro-chemical processes that predominate in surface water, but it is also used to assess the hydro-chemical processes in groundwater (Palmer and Cherry, 1984; Barica, 1972).

Evaporation is less significant in groundwater chemistry (Marandi et al., 2018), and the dominance of the rock is more significant than other components in the Gibs diagram (Palmer and Cherry, 1984). Anthropogenic activities can occasionally affect how rocks weather (Pradhan et al., 2022). The plot of Total Dissolved Solids (TDS) against ($Na^+/Na^+ + Ca^{2+}$) and TDS against ($Cl^-/Cl^- + HCO_3^-$) is depicted in Figure 10 by the Gibbs diagram. The Na/Cl ratio, CAI, and PCA results provide additional support for the hydro chemical facies found in the Piper and Durov diagrams. The prevalence of Na–Cl facies, along with Na/Cl ratios that show chloride enrichment and positive CAI values, demonstrate that ion exchange, rock–water interaction, and salinity enrichment, rather than seawater intrusion alone, have an impact on groundwater evolution.

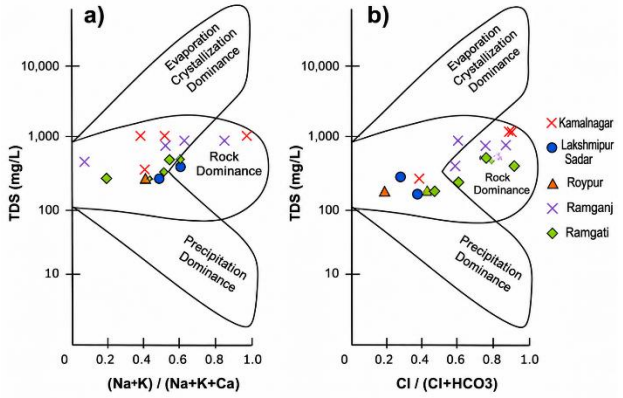


Figure 10, Gibbs diagram for representation of Hydogeochemical evolution of the study area.

Additionally, salinity-related variables (EC, TDS, salinity, Na^+, Ca^{2+}, and Mg^{2+}) were found to be the primary contributors to groundwater chemistry by PCA, which quantitatively supported the hydro chemical processes deduced from the facies study.

In both plots, most groundwater samples cluster within the "Rock Dominance" field, indicating that rock-water interactions, such as mineral weathering and dissolution, are the primary processes influencing groundwater chemistry. A few samples trend toward the Evaporation-Crystallization dominance field, suggesting possible salinization from evaporation effects, especially in coastal areas. These interpretations are crucial for understanding geochemical processes and ensuring sustainable groundwater management in the Lakshmipur region.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was applied to identify the major processes controlling groundwater chemistry in the study area. Three principal components with eigenvalues greater than one were extracted, explaining 79.09% of the total variance (Table 12). The scree plot also indicates that the first three principal components account for most of the variability in the dataset. PC1 explained 52.54% of the total variance and showed strong positive loadings for EC, TDS, salinity, Na^+, Ca^{2+}, and Mg^{2+}, indicating that groundwater chemistry is mainly controlled by salinity enrichment and mineralization processes. PC2 accounted for 16.56% of the total variance and was primarily associated with HCO_3^-, As, Fe, and Mn, suggesting the influence of geogenic processes on water quality. PC3 explained 10.00% of the total variance and was mainly related to NO_3^- and SO_4^{2-}, indicating a comparatively minor contribution from anthropogenic activities (Figure 11a). The PCA biplot (Figure 11b) further illustrates the relationships among the hydro chemical parameters and confirms the dominant influence of salinity-related variables on water quality. Overall, the PCA results are consistent with the interpretations derived from the Piper, Durov, and Gibbs diagrams, providing additional evidence for the hydro geochemical evolution of groundwater in the coastal aquifer.

The comprehensive hydro geochemical analyses show that geogenic processes dominate groundwater chemistry in the studied area. According to the PCA, hydro chemical facies, Na^+/Cl^- ratio, and CAI-I analyses, the main processes controlling the evolution of groundwater chemistry are water–rock interaction, mineral dissolution, ion exchange, and localized saline water effect. Natural geochemical processes, such as mineral weathering and the reductive dissolution of iron-bearing minerals, are primarily responsible for elevated concentrations of Fe, Mn, and As. On the other hand, nitrate enrichment, which is probably related to home wastewater, agricultural fertilizer application, and other human activities, is the main indicator of localized anthropogenic impacts. Overall, the findings imply that while anthropogenic inputs locally contribute to groundwater degradation, geogenic processes are the primary regulators of water quality.

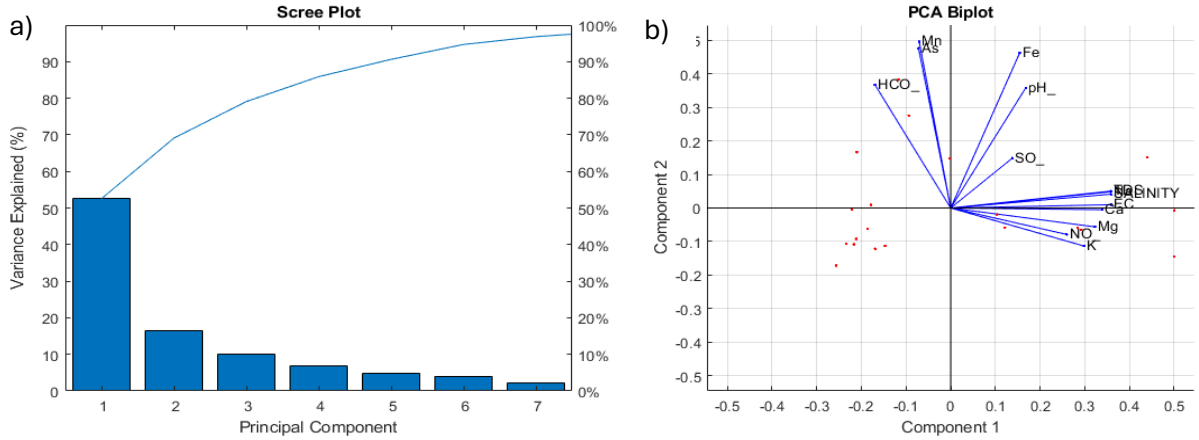


Figure 11, (a) Standard Scree Plot (b) PCA Biplot

Table 12, PCA Loading (PC1-PC3)

	PC1	PC2	PC3
pH	0.17	0.36	-0.05
EC	0.36	0.01	-0.004
TDS	0.36	0.05	-0.005
SALINITY	0.36	0.04	-0.002
Na	0.36	0.05	-0.108
K	0.30	-0.11	-0.305
Ca	0.34	-0.005	0.069
Mg	0.32	-0.06	-0.015
NO	0.26	-0.08	-0.31
SO	0.14	0.15	0.58
HCO_3^-	-0.17	0.37	-0.34
As	-0.07	0.48	-0.467
Fe	0.15	0.46	0.298
Mn	-0.07	0.50	0.177

Na/Cl ratio

The Na/Cl ratio increased marginally from 0.35 to 1.03 due to ongoing cation exchange and water-rock interaction through monsoonal recharge (Figure 12), demonstrating partial dilution of chloride through recharge. All other ratios that are less than unity (Na/Cl < 1) exhibit persistent chloride enrichment. Salinity has an impact on groundwater, and the Na/Cl ratios guarantee this. Additionally, the Na/Cl ratios show how groundwater salinity is affected by the combined actions of groundwater mineralization, cation exchange, evaporation, and localized saline groundwater mixing.

Numerous hydro geochemical processes, such as weathering, evaporation, and localized saline water mixing, contribute to groundwater salinity. This has been documented using Na/Cl ratio measurements in coastal aquifers on Hatiya Island and Bhola (Tajwar et al., 2023; Shaibur et al., 2023).

Chloro-Alkaline Index (CAI)

The evolution of groundwater is influenced by both concomitant cation exchange and mineral weathering, according to geochemical data from the CAI. Na^+ and K^+ in groundwater are exchanged with Ca^{2+} and Mg^{2+} adsorbed on aquifer materials, according to the consistently CAI values, which range from -0.05 to 0.63 (Table 13).

Table 13, Chloro-Alkaline Index (CAI) values of groundwater samples during the pre-monsoon and post-monsoon seasons.

Sample ID	CAI	Sample ID	CAI
GQHS5133001	0.39	GQHS5158002	0.16
GQHS5133002	0.47	GQHS5158003	0.22
GQHS5133003	0.23	GQHS5158004	0.43
GQHS5133004	0.36	GQHS5158005	-0.05
GQHS5133005	0.41	GQHS5158007	0.63
GQHS5143001	0.43	GQHS5158010	0.43
GQHS5143002	0.37	GQHS5165001	0.57
GQHS5143003	0.47	GQHS5165002	0.4
GQHS5143004	0.23	GQHS5165003	0.22
GQHS5158001	0.45	GQHS5165004	0.42
Average	0.36		
Standard Deviation	0.15		

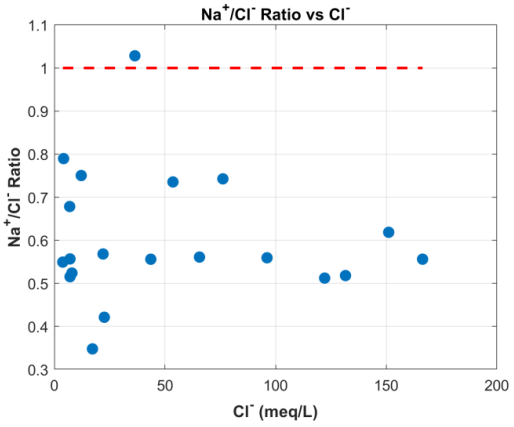


Figure 12, Seasonal variation of Na/Cl ratios

Because ion-exchange activities also significantly contribute to Na enrichment in the groundwater, elevated sodium concentrations should not be taken only as proof of seawater incursion.

Multiple hydro geochemical processes, as opposed to only exceeding drinking water requirements, regulate the degradation of groundwater quality. The main

processes controlling groundwater chemistry are rock–water contact, mineral dissolution, ion exchange, and salinity enrichment, according to the combined interpretation of the Piper, Durov, Gibbs diagrams, and PCA. Furthermore, the enrichment of Fe and As is probably linked to geogenic processes under decreasing aquifer conditions, but the higher amounts of Na^+, Cl^-, EC, and TDS indicate the influence of saline water. The observed decline in groundwater quality in the coastal aquifer is better explained by these findings.

Aquifer features and groundwater depth also affect groundwater chemistry in coastal aquifers. While deeper aquifers are frequently regulated by long-term water-rock interaction and geogenic processes, shallow aquifers are generally more vulnerable to surface contamination and salinity intrusion. The observed regional variability in groundwater chemistry may partially reflect variations in aquifer conditions and groundwater flow, even though groundwater depth measurements were not available for this investigation. A more thorough knowledge of the changes in groundwater quality in the study area might be possible with future research that incorporates comprehensive data and aquifer features. The hydro geochemical features found in the coastal aquifer of Lakshmipur are mostly in line with earlier research done in other coastal areas of Bangladesh, such as Bhola, Noakhali, Satkhira, and Hatiya. According to similar research, the main mechanisms governing groundwater chemistry in these coastal aquifers are increased salinity, Na^+–Cl^- dominant water types, ion exchange, and rock–water interaction (Bhuiyan et al., 2016; Shaibur et al., 2023; Tajwar et al., 2023). However, the comparatively greater concentrations of Fe and as found in this study suggest that geogenic processes contribute significantly to the degradation of groundwater quality in addition to salinity enrichment (Bhuiyan et al., 2016). These parallels show that geogenic pollution and salinity enrichment are prevalent hydro geochemical traits in Bangladesh's coastal aquifers.

Health risk assessment

The Hazard Index (HI) for groundwater drinking and cutaneous exposure ranged from 0.22 to 4.21 for adults and from 0.24 to 4.60 for children, according to the health risk assessment (Table 14). Oral intake is the main exposure channel, as demonstrated by the fact that HQ_{Total} (ingestion) consistently exceeded HQ_{dermal} across all samples. 14 out of 20 samples (70%) and 15 out of 20 samples (75%) surpassed the threshold for adults and children, respectively, according to USEPA recommendations (HI > 1 indicates potential non-carcinogenic risk), suggesting significant health concerns in the research area.

Sample No. 6 had the highest health hazards (HI: 4.21 adult, 4.60 child), followed by Samples No. 12 and 16. Sample No. 5 had the lowest risk. Due to their lower body weight and higher relative water intake, children showed noticeably greater sensitivity than adults in every location.

Table 14, Health risk of groundwater samples collected from Lakhsmipur district

Sample No	HQ_{oral}		HQ_{dermal}		HI	
	Adult	Children	Adult	Children	Adult	Children
1	0.97	1.24	0.56	0.44	1.54	1.68
2	1.06	1.35	0.62	0.48	1.68	1.83
3	1.09	1.39	0.63	0.50	1.73	1.89
4	1.19	1.51	0.69	0.54	1.88	2.05
5	0.14	0.18	0.08	0.06	0.22	0.24
6	2.66	3.39	1.55	1.21	4.21	4.60
7	0.59	0.75	0.34	0.27	0.93	1.02
8	1.68	2.14	0.98	0.76	2.66	2.90
9	0.54	0.69	0.32	0.25	0.86	0.94
10	0.24	0.30	0.14	0.11	0.38	0.41
11	0.18	0.23	0.10	0.08	0.28	0.31
12	2.16	2.75	1.26	0.98	3.42	3.74
13	1.71	2.18	0.99	0.78	2.70	2.95
14	1.05	1.33	0.61	0.48	1.66	1.81
15	0.94	1.20	0.55	0.43	1.49	1.63
16	2.00	2.54	1.16	0.91	3.16	3.45
17	0.72	0.92	0.42	0.33	1.14	1.24
18	0.30	0.38	0.18	0.14	0.48	0.52
19	0.71	0.90	0.41	0.32	1.12	1.22
20	0.76	0.97	0.44	0.34	1.20	1.31

The "Very Poor" groundwater quality zones found in Raipur and Ramgati are spatially correlated with the elevated HI values, highlighting the critical need for targeted arsenic/iron removal technologies and alternate safe water sources in these high-risk areas.

Validation of the fuzzy-GIS groundwater quality map

Table 15 and Figure 13 provide the validation results. An Overall Accuracy (OA) of 45.0% and a Kappa coefficient (κ) of 0.056 were found when the observed and projected WQI classes were compared, suggesting a small degree of agreement between the two classifications. The Very Poor group accounted for the majority of correctly identified samples, although misclassification mostly happened between adjacent quality classes. Uncertainties related to the fuzzy categorization approach and regional variability in groundwater quality could be the cause of these discrepancies.

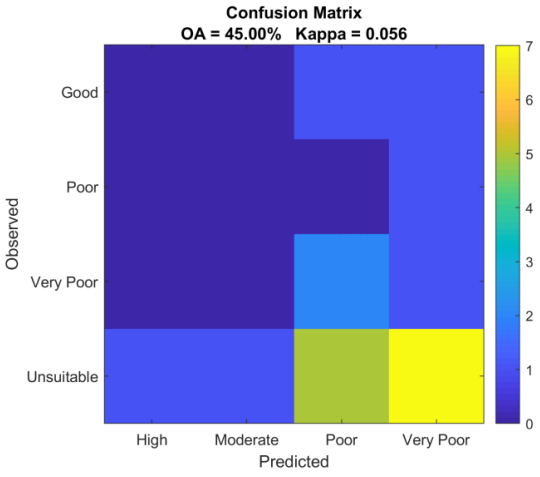


Figure 13. Confusion matrix showing the validation of the fuzzy-GIS groundwater quality map based on observed and predicted WQI classes.

Table 15, Observed and predicted WQI classes used for validation of the fuzzy-GIS groundwater quality map.

Sample ID	Sample No	Location	WQI Status	Fuzzy WQI
GQHS5133001	1	Kamalnagar	unsuitable	Poor
GQHS5133002	2	Kamalnagar	unsuitable	Poor
GQHS5133003	3	Kamalnagar	Very poor	Poor
GQHS5133004	4	Kamalnagar	Very poor	Poor
GQHS5133005	5	Kamalnagar	Good	Poor
GQHS5143001	6	Lakshmipur Sadar	unsuitable	Poor
GQHS5143002	7	Lakshmipur Sadar	unsuitable	Very Poor
GQHS5143003	8	Lakshmipur Sadar	unsuitable	moderate
GQHS5143004	9	Lakshmipur Sadar	unsuitable	High
GQHS5158001	10	Ramganj	poor	Very Poor
GQHS5158002	11	Ramganj	Good	Very Poor
GQHS5158003	12	Raipur	unsuitable	Very Poor
GQHS5158004	13	Raipur	unsuitable	Poor
GQHS5158005	14	Raipur	unsuitable	Poor
GQHS5158007	15	Raipur	unsuitable	Very Poor
GQHS5158010	16	Raipur	unsuitable	Very Poor
GQHS5165001	17	Ramgati	unsuitable	Very Poor
GQHS5165002	18	Ramgati	Very poor	Very Poor
GQHS5165003	19	Ramgati	unsuitable	Very Poor
GQHS5165004	20	Ramgati	unsuitable	Very Poor
FWQI (Predicted)	**WQI (Observed)**	-	-	-
Very High	Excellent water	-	-	-
High	Good water	-	-	-
moderate	Poor water	-	-	-
Poor	Very poor water	-	-	-
Very Poor	Water unsuitable for drinking	-	-	-

Study limitations and future research

Several limitations should be noted, despite the fact that the current study offers insightful information about the hydro geochemistry and groundwater quality of the Lakshmipur coastal aquifer. The groundwater data used for the analysis came from 20 BWDB monitoring sites, which might not accurately reflect the spatial diversity of groundwater quality throughout the district. Additionally, seasonal fluctuations in groundwater chemistry could not be assessed because the study was carried out using data from a single monitoring period. Furthermore, prediction uncertainty affects the spatial distribution maps produced by the IDW interpolation technique, especially in regions with comparatively low sampling density.

One disadvantage is the lack of a thorough conceptual hydro geological model that incorporates salinity patterns, chemical properties, and quality classifications. The existing dataset lacks the aquifer geometry, hydraulic gradient, and seasonal water-level data needed for development, which restricts interpretation to descriptive geographical analysis. To create such a model for the Lakshmipur coastal aquifer, future studies including hydro geophysical surveys, multi-level piezometric monitoring, and stable isotopes ($\delta^{1}{}_{2}O$, $\delta^{2}H$) are advised. To enhance the spatial and temporal representation of groundwater quality, future research should combine multi-season groundwater sampling with a bigger and denser monitoring network. The comprehension of groundwater evolution, contaminant transport, and groundwater quality prediction in coastal aquifers would be further improved by integrating hydro geochemical modeling, geochemical speciation, groundwater flow and solute transport modeling, isotope techniques, and machine learning approaches.

Conclusion

Some groundwater samples exceeded permissible limits (WHO, 2011; DoE, 2016) for parameters such as arsenic, TDS, salinity, and certain heavy metals, making them unsuitable for drinking without treatment. The results of Water Quality Index (WQI) and fuzzy-overlay map indicate that a significant portion of the groundwater in Lakshmipur district falls unsuitable for drinking purposes. The health risk assessment further revealed that 70% of the samples posed non-carcinogenic risks for adults (HI > 1) and 75% for children, with children being more vulnerable due to higher relative water intake. Oral ingestion was identified as the primary exposure pathway, with the highest risks concentrated in the western and southern regions (Raipur and Ramgati), correlating with the "Very Poor" groundwater quality zones. The irrigation water quality indices, including Na%, SAR, RSC, MH, KR, and PI, show varying suitability across the district. While some areas are excellent for irrigation, others are unsuitable. The findings highlight the urgent need for continuous monitoring, appropriate treatment, and sustainable groundwater management practices to ensure safe water for drinking and irrigation. It should be mentioned that these conclusions should not be applied to the entire Lakshmipur District because they are based on groundwater samples that were taken from the places under investigation throughout the research period. In order to enhance the geographical and temporal representation of groundwater quality and to support more comprehensive groundwater management methods, future research with a greater

number of sampling points and multi-season monitoring is advised.

Acknowledgements

Special thanks to two anonymous reviewers for their comments and suggestions, which helped to rectify the manuscript. The author also expresses sincere gratitude to University of Rajshahi for its continuous support.

Author contributions

Md. Mahedi Hasan contributed to data analysis and drafted the main manuscript, Khondaker Emamul Haque was responsible for visualization, supervision, and conceptualization of the study, Shamim Ahmed handled the software-related tasks and Md. Nazmul Islam Hasan revised the article. All authors also reviewed it.

Data availability

The data will be available upon request to the corresponding author.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Article note

This article is a full-length paper developed from **Extended Abstract #091**, entitled "**Assessment of Hydro Geochemistry and Groundwater Quality for Drinking and Irrigation purposes in Coastal Aquifer of Lakshmipur district, Bangladesh: Using Fuzzy Overlay**" which was presented at the 15th Asian Regional Conference of the International Association for Engineering Geology and the Environment (ARC-15 of **IAEG**), held in Kathmandu, Nepal, from 27 to 29 November 2025.

References

Ahmed, K. M., Bhattacharya, P., Hasan, M. A., Akhter, S. H., Alam, S. M., Bhuyian, M. H., Imam, M. B., Khan, A. A., and Sracek, O. (2004). Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: An overview. Applied Geochemistry, 19(2), 181–200. https://doi.org/10.1016/j.apgeochem.2003.09.006

Appelo, C. A. J., and Postma, D. (2005). Geochemistry, groundwater and pollution (2nd ed.). Balkema, Rotterdam. https://doi.org/10.1201/9781439833544

Barica, J. (1972). Salinization of groundwater in arid zones. Water Research, 6(8), 925–933. https://doi.org/10.1016/0043-1354(72)90044-9

Bhattacharya, P., Jacks, G., Ahmed, K. M., Routh, J., and Khan, A. A. (2002). Arsenic in groundwater of the Bengal Delta Plain aquifers in Bangladesh. Bulletin of Environmental Contamination and Toxicology, 69(4), 538–545. https://doi.org/10.1007/s00128-002-0095-5

Bhuiyan, M. A. H., Bodrud-Doza, M., Islam, A. R. M. T., Rakib, M. A., Rahman, M. S., and Ramanathan, A. L. (2016). Assessment of groundwater quality of Lakshmipur District of Bangladesh using water quality indices, geostatistical methods, and multivariate analysis. Environmental Earth Sciences, 75, 1020. https://doi.org/10.1007/s12665-016-5823-y

Brown, R. M., McClelland, N. I., Deininger, R. A., and Tozer, R. G. (1972). A water quality index: Do we dare? Water and Sewage Works, 117(10), 339–343.

Chen, G., Sun, Z., Nie, F., Li, C., Zhen, Y., and Zhou, Z. (2020). Hydrogeochemical characteristics of the sandstone-hosted uranium mineralization in northern Ordos Basin, China. Ore Geology Reviews, 126, 103769. https://doi.org/10.1016/j.oregeorev.2020.103769

Cloutier, V., Lefebvre, R., Therrien, R., and Savard, M. M. (2008). Multivariate statistical analysis of geochemical data as indicative of the hydrogeochemical evolution of groundwater in a sedimentary rock aquifer system. Journal of Hydrology, 353(3–4), 294–313. https://doi.org/10.1016/j.jhydrol.2008.02.015

Department of Environment. (2016). Surface and ground water quality report. Available at: https://doe.gov.bd/site/publications/5132a8d7-68e9-469d-a9af-8981306b3b9f/Surface-and-Ground-Water-Quality-Report-2016

Deshmukh, K. K., and Pawar, N. J. (2001). Impact of irrigation on the chemistry of the soils and groundwater from Sangamner area, Ahmednagar District (M.S.) Ph.D. Thesis. University of Pune, India.

Durov, S. A. (1948). Classification of natural waters and graphical representation of their composition. Doklady Akademii Nauk SSSR, 59(1), 87–90.

Eaton, F. M. (1950). Significance of carbonates in irrigated waters. Soil Science, 69, 127–128.

Gibbs, R. J. (1970). Mechanisms controlling world water chemistry. Science, 170(3962), 1088–1090. https://doi.org/10.1126/science.170.3962.1088

Gupta, S., Rao, K. S., Ranganathan, K., Padma, T. V., Kumar, R., and Krishnamurthy, V. (2009). Geochemical assessment of groundwater around Macherla-Karempudi area, Guntur District, Andhra Pradesh. Journal of the Geological Society of India, 73(2), 202–212. https://doi.org/10.1007/s12594-009-0076-y

Hem, J. D. (1970). Study and interpretation of the chemical characteristics of natural water (Water-

Supply Paper No. 1473). U.S. Government Printing Office.

Horton, R. K. (1965). An index number system for rating water quality. Journal of the Water Pollution Control Federation, 37(3), 300–306.

Jamal, A. S. I. M., Jhumur, N. T., Shaikh, M. A. A., Moniruzzaman, M., Uddin, M. R., Siddique, M. A. B., Al-Mansur, M. A., Akbor, M. A., Tajnin, J., Ahmed, S., and Mahmud, R. (2024). Spatial distribution and hydrogeochemical evaluations of groundwater and its suitability for drinking and irrigation purposes in Kaligonj Upazila of Satkhira District of Bangladesh. Heliyon, 10(7), e27857. https://doi.org/10.1016/j.heliyon.2024.e27857

Jha, M. K., Shekhar, A., and Jenifer, M. A. (2020). Assessing groundwater quality for drinking water supply using hybrid fuzzy-GIS-based water quality index. Water Research, 179, 115867. https://doi.org/10.1016/j.watres.2020.115867

Kaiser, H. F. (1960). The application of electronic computers to factor analysis. Educational and Psychological Measurement, 20(1), 141–151. https://doi.org/10.1177/001316446002000116

Kelly, W. P. (1940). Permissible composition and concentration of irrigated waters. Proceedings of the American Society of Civil Engineers, 66, 607–613.

Ketata-Rokbani, M., Gueddari, M., and Bouhlila, R. (2011). Use of geographical information system and water quality index to assess groundwater quality in El Khairat Deep Aquifer (Enfidha, Tunisian Sahel). Iranian Journal of Energy and Environment, 2, 133–144.

Li, P., Qian, H., Wu, J., Zhang, Y., and Zhang, H. (2011). Major ion chemistry of shallow groundwater in the Dongsheng coalfield, Ordos Basin, China. Environmental Earth Sciences, 64, 563–574. https://doi.org/10.1007/s12665-010-0863-9

Liu, H., Tang, J., Zhang, X., Wang, R., Zhu, B., Li, N., and Zhao, P. (2021). Seasonal variations of groundwater recharge in a small subtropical agro-forestry watershed with horizontal sedimentary bedrock. Journal of Hydrology, 596, 125703. https://doi.org/10.1016/j.jhydrol.2020.125703

Lloyd, J. W., and Heathcote, J. A. A. (1985). Natural inorganic hydrochemistry in relation to groundwater. Clarendon Press.

Lyu, M., Pang, Z., Yin, L., Zhang, J., Huang, T., Yang, S., and Gulbostan, T. (2019). The control of groundwater flow systems and geochemical processes on groundwater chemistry: A case study in Wushenzhao Basin, NW China. Water, 11(4), 790. https://doi.org/10.3390/w11040790

Marandi, A., and Shand, P. (2018). Groundwater chemistry and the Gibbs Diagram. Applied Geochemistry, 97, 209–212. https://doi.org/10.1016/j.apgeochem.2018.07.009

USEPA (1989). Risk assessment guidance for Superfund: Volume I, human health evaluation manual (Part A). U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC, EPA/540/1-89/002. https://www.epa.gov/sites/default/files/2015-09/documents/rags_a.pdf

Nazzal, Y., Ahmed, I., Al-Arifi, N. S., Ghrefat, H., Zaidi, F. K., El-Waheidi, M. M., and Zumlot, T. (2014). A pragmatic approach to study the groundwater quality suitability for domestic and agricultural usage, Saq Aquifer, northwest of Saudi Arabia. Environmental Monitoring and Assessment, 186, 4655–4667. https://doi.org/10.1007/s10661-014-3728-3

Nwankwo, C. B., Hoque, M. A., Islam, M. A., and Dewan, A. (2020). Groundwater constituents and trace elements in the basement aquifers of Africa and sedimentary aquifers of Asia: Medical hydrogeology of drinking water minerals and toxicants. Earth Systems and Environment, 4(2), 369–384. https://doi.org/10.1007/s41748-020-00151-z

Palmer, C. D., and Cherry, J. A. (1984). Geochemical evolution of groundwater in sequences of sedimentary rocks. Journal of Hydrology, 75(1–4), 27–65. https://doi.org/10.1016/0022-1694(84)90045-3

Piper, A. M. (1944). A graphic procedure in the geochemical interpretation of water-analyses. Transactions, American Geophysical Union, 25(6), 914–928. https://doi.org/10.1029/TR025i006p00914

Pradhan, R. M., Behera, A. K., Kumar, S., Kumar, P., and Biswal, T. K. (2022). Recharge and geochemical evolution of groundwater in fractured basement aquifers (NW India): Insights from environmental isotopes (δ18O, δ2H, and 3H) and hydrogeochemical studies. Water, 14(3), 315. https://doi.org/10.3390/w14030315

Raghunath, H. M. (1987). Groundwater (2nd ed.). Eastern Limited, New Delhi.

Ravikumar, P., Somashekar, R. K., and Prakash, K. L. (2015). A comparative study on usage of Durov and Piper diagrams to interpret hydrochemical processes in groundwater from SRLIS River Basin, Karnataka, India. Elixir Earth Science, 80, 31073–31077.

Richards, L. A. (1954). Diagnosis and improvement of saline and alkali soils (Agriculture Handbook No. 60). U.S. Government Printing Office.

Sahu, P., and Sikdar, P. K. (2008). Hydrochemical framework of the aquifer in and around East Kolkata wetlands, West Bengal, India. Environmental Geology, 55, 823–835. https://doi.org/10.1007/s00254-007-1034-x

Schoeller, H. (1977). Geochemistry of groundwater. In Groundwater studies: An international guide for research and practice, UNESCO, Paris, pp. 1–18.

Shaibur, M. R., Ahmmed, I., Sarwar, S., Karim, R., Hossain, M. M., Islam, M. S., Shah, M. S., Khan, A. S., Akhtar, F., Uddin, M. G., and Rahman, M. M. (2023). Groundwater quality of some parts of coastal Bhola District, Bangladesh: Exceptional evidence. Urban Science, 7(3), 71. https://doi.org/10.3390/urbansci7030071

Shannon, C. E. (2001). A mathematical theory of communication. ACM SIGMOBILE Mobile Computing and Communications Review, 5(1), 3–55.

Su, L., Xiao, M., Zhou, M., Wang, F., and Zhang, Y. (2018). Assessment of groundwater quality using water quality index (WQI) and GIS in a rural area of China. Ecological Indicators, 87, 22–29. https://doi.org/10.1016/j.ecolind.2017.12.001

Szabolcs, I., and Darab, C. (1964). The influence of irrigation water of high sodium carbonate content on soils. In I. Szabolics (Ed.), Proceedings of the 8th International Congress of Soil Science: Sodic soils. Research Institute of Soil Science and Agricultural Chemistry, Hungarian Academy of Sciences, pp. 802–812.

Tajwar, M., Uddin, A., Lee, M. K., Nelson, J., Zahid, A., and Sakib, N. (2023). Hydrochemical characterization and quality assessment of groundwater in Hatiya Island, southeastern coastal region of Bangladesh. Water, 15(5), 905. https://doi.org/10.3390/w15050905

Takeya, L. A., Haque, K. E., Ahmed, S., Siddique, M. A. B., Moniruzzaman, M., Uddin, M. R., and Rahman, M. S. (2025). Hydrochemistry, quality, and potential health risk appraisal of arsenic-enriched groundwater in central-west Bangladesh using the integrated water quality index and Monte Carlo simulation. Science of the Total Environment, 1003, 180707. https://doi.org/10.1016/j.scitotenv.2025.180707

Tiwari, A., Kumar, M., Thakur, S., Singh, P., Yadav, A., and Mehra, R. (2023). Groundwater quality assessment for drinking purpose using traditional and fuzzy-GIS-based water quality index in Gurugram District of Haryana, India. Environmental Geochemistry and Health. https://doi.org/10.1007/s10653-023-01783-6

United Nations Department of Economic and Social Affairs. (2016). The sustainable development goals report 2016. United Nations.

U.S. Environmental Protection Agency. (2021). Regional screening levels (RSLs): Equations. https://www.epa.gov/risk/regional-screening-levels-rsls-equations

Wan, T., Jun, H., Pan, W., and Hua, H. (2015). Kappa coefficient: A popular measure of rater agreement. Shanghai Archives of Psychiatry, 27(1), 62. https://doi.org/10.11919/j.issn.1002-0829.215010

World Health Organization. (2011). Guidelines for drinking-water quality (4th ed.). World Health Organization, Geneva, Switzerland. https://apps.who.int/iris/bitstream/10665/44584/1/9789241548151_eng

Wilcox, L.V. (1955). Classification and Use of Irrigation Water. US Department of Agriculture, Circular 969, Washington DC.

Yu, J., Jiao, Y., Yang, W., Yang, J., and Liu, L. (2021). Hydrogeochemical characterization of a possible carbon sink from shallow saline-alkaline groundwater in the eastern Hetao Basin of Inner Mongolia in China. Environmental Science: Processes and Impacts, 23(2), 344–356. https://doi.org/10.1039/d0em00415d

Zadeh, L. A. (1965). Fuzzy sets. Information and Control, 8(3), 338–353.