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## Article

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# Potential Environmental, Health risk assessment and source identification of Heavy metals in Groundwater in a major agricultural hub in southwestern Bangladesh

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32 **Abstract**

33 Groundwater quality has serious implications for human health and ecosystem sustainability due  
34 to heavy metal contamination, specifically in populated and intensively cultivated areas. This  
35 study characterized the hydro chemical and heavy metals contamination status in groundwater in  
36 the region using several indices and multivariate statistical methods. Over 63% of samples are  
37 above the critical value of 90 thresholds, which indicates that the majority of the groundwater  
38 samples are severely polluted. The groundwater quality index (GWQI) and entropy weighted  
39 water quality index (EWQI) results reflect poor quality for over 70% of the analyzed samples  
40 indicating that the samples were unsuitable for human consumption directly. The mean degree of  
41 contamination (15.57) indicates moderate contamination in the study area. Multivariate analyses,  
42 including spearman correlation and principal component analysis (PCA), identified geogenic and  
43 anthropogenic influences and clusters revealed a mixture of industrial, agricultural, and  
44 lithogenic influences. Although human health risk assessment indicated exposure to dermal risks  
45 is low; the ingestion risk posed significant effects, with Hazard Quotients (HQ) greater than one  
46 for Zr, Pb, and Mn, particularly for children. The results indicate that groundwater in the study  
47 area is moderate to heavily contaminated, deem mostly inappropriate for drinking without a  
48 treatment process. This study emphasizes the ongoing monitoring and follow-up treatments that  
49 may need to be established to protect groundwater resource and future generations.

50 **Key words:** Groundwater, Heavy metals, Health risk, Water quality, Source analysis

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## 1. Introduction:

Groundwater is the major source of drinking water, irrigation, and industry in Bangladesh, satisfying almost 97% of the drinking water requirement (Islam and Mostafa, 2021; Islam et al., 2025). Areas like Jashore Sadar are increasingly reliant on groundwater for water supply due to intensive agricultural practices, rapid population growth and industrial development (Rahman & Habiba, 2023). However, increasing dependence on groundwater has raised questions about water quality, as groundwater systems are under increasing threat from both natural and anthropogenic pollution.

Industrial effluents, agricultural chemicals, and poor waste disposal are the main causes of groundwater contamination in the area (Lamma, 2021). Often contaminated with toxic trace metals, such as arsenic, cadmium, and lead, and with poorly treated or untreated wastewater discharged into the area, one of the most severe health risks is the infiltration of trace metals into aquifers (Ehsan et al., 2025). At low concentrations, trace metals can bioaccumulate and activate chronic illnesses, including cancer, hypertension, renal failure, and neurological problems (Ghosh et al., 2025). Excessive use of agrochemicals also exacerbates the leaching of toxic substances into groundwater; salinity intrusion due to sea-level rise has become an additional stressor to coastal aquifers (Islam & Mostafa, 2021; Islam et al., 2025).

Although concern is growing, research on groundwater quality has not been extensive in Jashore Sadar. Much research in Bangladesh relates to arsenic contamination (Ghosh et al., 2023), and not many studies have researched trace metals and the interaction of metal contamination with physicochemical parameters, such as pH, EC, salinity, and TDS (Rahman et al., 2022; Shuvo and Rashidul Alam, 2026). Recently, about 73% of groundwater sources in Jashore Sadar exceeded allowable levels of arsenic (Chakraborty et al., 2022), which presents an urgent public health problem. Research on the spatial distribution, sources, and interactions of heavy metals leading to pollution in groundwater water in Jashore has not been reported (Habib et al., 2024).

The geology of the western Bengal Basin, which is part of the Ganges-Brahmaputra delta, also complicates groundwater chemistry. The sediments that form from the Himalayas contain a

range of lithology that may add release various trace elements into the aquifer (Dar et al., 2026). These metals along with anthropogenic discharges, such as untreated wastewater and industrial releases, add to the risk of groundwater degradation (Akhtar et al., 2021). Hence, we hypothesize that anthropogenic sources dominate over geogenic inputs in controlling metal contamination in shallow aquifers.

To fill these gaps in knowledge, this research evaluates Jashore Sadar's groundwater quality through a paradigmatic calculation that includes evaluation of physicochemical parameters, heavy metal pollution indices and water quality indices. The multivariate statistical analyses applied to evaluate potential contamination sources and short-range spatial variability include Principal Component Analysis (PCA), with Cluster Analysis (CA), as well as human health risks posed by potential toxic metals in ground water using USEPA health risk models (Saha & Rahman, 2016, Shajib et.al, 2019, Shajib et.al, 2020). By integrating geospatial and statistical methods, an enhanced assessment of groundwater and pollution is more comprehensive and better understand priority areas for interventions. Findings from the study are anticipated to assist local authorities and decision makers with targeted interventions for sustainable groundwater, protection of public health. To the best of our knowledge, this is the first study to comprehensively evaluate 13 heavy metals in groundwater and assess the water quality by integrating level of heavy metal pollution and water quality pollution by using different indices, source identification and human health risk assessment.

## **2. Materials and Methods**

### **2.1 Study area**

The Jashore district is bordered on the north by Jhenaidah district, on the west by Narail and Magura districts, on the south by Khulna and Sathkhira districts, and on the west by India. The district has a total area of 2606.94 square kilometers (1006 square miles), with 23.39 square kilometers (9.03 square miles) reserved for riverine (Hashim et al., 2022) with the total population is about 3,076,849 (BBS, 2022). The district is located between the latitudes of 22°48' and 23°22' north, and the longitudes of 88°51' and 89°34' east. In between November and December 2024, 30 surface water samples (**Fig. 1**) were collected from different locations in

Jashore, Bangladesh following the guidelines provided by the Bangladesh Standards and Testing Institution (BSTI).

**Fig. 1. Study area map showing the sampling locations.**

## **2.2 Sample preparation and analysis**

Seventy milliliters (mL) of each water sample were taken and heated to evaporate and concentrate. Each sample was acidified with 0.1 M HNO<sub>3</sub> to break down organic matter and release metals held in suspension prior to heating. Twelve water samples and one blank were processed in a batch. During the heating, additional 30 mL aliquots were taken of the same sample to ensure consistency. After heating, samples were left overnight for equilibration, diluted with distilled water to 50 mL, filtered to remove any particulates, and preserved for analysis. Calibration and Quality Control Calibration involved multiple element standard solutions, reagent blanks, duplicates, and certified reference material (for example, NIST 1643e). Precision was evaluated through triplicate analyses of three replicate bottles for each site, yielding coefficient of variability (CV) < 10% (Saha et al., 2017). For NIST 1643e, recovery was within limits of 91.7% to 109.2% for metals, showing good contract to certified values. Instrumental Setup and Analysis Water samples were calculated on an Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES 5800, Agilent, USA) in the Water Quality Research Laboratory, Chemistry Division, Atomic Energy Centre, Dhaka.

## **2.2 Geostatistical Modelling**

Ordinary kriging (OK) was used to evaluation the spatial distribution of groundwater parameters related to hydrological studies. This method, well-documented in latest studies (e.g., Islam et al., 2017; Bodrud-Doza et al., 2016), applies least squares-based interpolation, using a variogram as a weighting function. The spatial estimate is given by Eq (1):

$$Z(x_0) = \sum_{i=1}^n \lambda_i z(x_i) \dots \dots \dots (1)$$

Here,  $z(x_0)$  is the predicted value of an attribute at the point of interest  $x_0$ ,  $z$  is the observed value at the sampled point  $x_i$ ,  $\lambda_i$  is the kriging weight assigned to a sampled point, and  $n$  is the number of sampled points used in the estimation. The weights minimize estimation variance and sum to 1 to avoid bias (Guisande et al., 2019). Among geostatistical methods, OK is suitable for mapping heavy metals in the surface water in Jashore Sadar.

## 2.3 Metal Pollution Indices

### 2.3.1 Heavy Metal Pollution Index (HPI) and Heavy Metal Evaluation Index (HEI)

HPI and HEI are effective tools for assessing groundwater pollution. HPI uses a weighted arithmetic mean to evaluate the combined impact of heavy metal concentrations which is given in Eq. (2) (Sharma et al., 2025).

$$HPI = \frac{\sum_{i=1}^n \left( \frac{MC_i}{SC_i} \times 100 \right) \times \frac{1}{SC_i}}{\sum_{i=1}^n \frac{1}{SC_i}} \dots \dots \dots (2)$$

Water quality was then assessed using the Heavy Metal Evaluation Index (HEI), which classifies pollution levels in an environment. HEI provides an overall measure of heavy metal pollution, calculated by the equation (3) assigned to each site (Mukherjee et al., 2020).

$$HEI = \sum_{i=1}^n \frac{MC_i}{Hmac} \dots \dots \dots (3)$$

Where, Hmac is maximum admissible concentration of metal.

### 2.3.2 Contaminated Degree

Contaminated Degree is indicated landscape water reveals describe harmful agents (Abolli et al., 2024). The CD value for each site was calculated using the equation (4) below.

$$CD = \sum_{i=1}^n \frac{MC_i}{SC_i} \dots \dots \dots (4)$$

### 2.3.3 Pollution Index (PI)

To evaluate the pollution level in groundwater, the pollution index (Pi) method (see equation (5)) was utilized (Yan et al., 2015).

$$P_i = \frac{C_i}{S_i} \dots \dots \dots (5)$$

In this equation, Pi represents the pollution index of the i'th pollutant, Ci indicates the concentration of the pollutant, and Si refers to the ground water quality standard for that pollutant (WHO, 2011). We adopted five categories to characterize the pollution status of the surface water: unpolluted (Pi < 0.4), slightly polluted (Pi = 0.4 to 1.0), moderately polluted (Pi = 1.0 to 2.0), and heavily polluted (Pi = 2.0 to 5.0).

Ultimately, the integrated pollution load index (IPI) serves to encompass all pollutants are given in equation (6):

$$IPI = \frac{1}{n} \sum P_i \dots \dots \dots (6)$$

Where the summation runs from i=1 to n. According to Yan et al. (2015), the IPI is categorized into six distinct levels ranging from no pollution to serious pollution, indicating the level of pollution: unpolluted (0 to IPI 0.2), sub-clean (0.2 to 0.4), slightly polluted (0.4 to 0.7), moderately polluted (0.7 to 1.0), heavily polluted (1.0 to 2.0), and seriously polluted (>2.0), as noted in equation (6) (Yan et al., 2015; Shajib et al., 2019).

## 2.4 Water Quality Assessment indices

### 2.4.1 Ground Water Quality Assessment

The Water Quality Index (WQI) evaluates water quality against WHO drinking water standards based on physicochemical and chemical parameters (Din et al., 2023). It is calculated using equation (7):

$$GWQI = \frac{\sum_i W_i \times Q_i}{\sum_i W_i} \dots \dots \dots (7)$$

Where  $i$  is the parameter,  $W_i$  is the weight assigned to each parameter based on its toxic effect on primary health and suitability for drinking and  $Q_i$  is the quality rating rate of the  $i^{\text{th}}$  parameter calculated using equation (8) (Ramakrishnaiah et al., 2009).

$$Q_i = 100 \times \frac{MC_i}{SC_i} \dots \dots \dots (8)$$

Where  $MC_i$  values is the measured value of each parameter and  $SC_i$  values of the metals used in this study are taken from Turkish Groundwater Quality Regulation (TSWQR, 2016), which maximum standard concentrations of metals for coastal and transitional waters.

#### 2.4.2 Entropy water quality index

Information entropy, defined by Shannon (1948), quantifies uncertainty and is useful for water quality assessment by capturing relevant information and addressing limitations in current methods. Studies (Wu et al., 2020) applied Entropy-Weighted Water Quality Indices (EWQIs) to evaluate water quality effectively. EWQI is favored for its simplicity, accuracy, and reliability. The entropy weight method calculates parameter weights through a three-step process to compute the EWQI (Wu et al., 2020).

The first step is to find the eigenvalue matrix ( $X$ ), which is organized with respect to the water samples ( $m$ ) and the parameters ( $n$ ). This matrix is calculated using Equation (1).

$$X = \begin{bmatrix} x_{11} & x_{12} & x_{1n} \\ x_{21} & x_{22} & x_{2n} \\ x_{m1} & x_{m2} & x_{mn} \end{bmatrix} \dots \dots \dots (1)$$

The eigenvalue matrix ( $X$ ) is standardized into matrix ( $Y$ ) to eliminate unit and scale differences, ensuring consistent evaluation using Equation (2).

$$Y = \begin{bmatrix} x_{11} & x_{12} & x_{1n} \\ x_{21} & x_{22} & x_{2n} \\ x_{m1} & x_{m2} & x_{mn} \end{bmatrix} \dots \dots \dots (2)$$

Subsequently, the ratio of the parameter index value  $j$  in the  $i^{\text{th}}$  sample is calculated using Equation (3).

$$P_{ij} = Y_{ij} / \sum_{i=1}^m Y_{ij} \dots \dots \dots (3)$$

Hence, the information entropy can be determined using Equation (4).

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m P_{ij} \ln P_{ij} \dots \dots \dots (4)$$

The usefulness of entropy parameter j is inversely related to the entropic value it carries; e.g., smaller entropy equals greater value. After that the entropy weight (wj) estimate for parameter j can be calculated using equation (5).

$$w_j = \frac{1-e_j}{\sum_{j=1}^n (1-e_j)} \dots \dots \dots (5)$$

The second step in the process of EWQI calculations is to establish or define the qualitative rating scale (qj) for each variable, which is computed using Equation (6).

$$q_j = \frac{c_j}{s_j} \times 100 \dots \dots \dots (6)$$

Where cj is the concentration of the chemical parameter, depending on the parameter, Sj is the allowable concentration (µg/L) based on drinking water quality (guidelines). In this study, standards from Bangladesh were used. The third step of the EWQI calculations utilizes Eq. (7).

$$EWQI = \sum_{j=1}^n w_j q_j \dots \dots \dots (7)$$

## 2.5 Ecological Risk Index (ERI)

The ecological risk index (ERI) was developed for assessing the ecological risks of metals in sediment, but it has recently been used for assessing the ecological risks of metals in water. In this study, the ERI values for each site were calculated using the following formula (Wen et al., 2019).

$$ERI = \sum_{i=0}^n Ti \times \frac{MCI}{SCI} \dots \dots \dots (8)$$

The Ti (toxicity factor) values for ERI calculations were 2 for Cr, 5 for Ni, Cu and Pb, 1 for Mn and Zn, and 30 for Cd (Hakanson, 1980). The classification for the ERI is provided in **Table S1**.

## **2.6 Source Identification**

The dataset's suitability for multivariate analysis was evaluated using the Kaiser-Meyer-Olkin (KMO) test, which yielded a value below 0.4, indicating it was unsuitable for Principal Component Analysis (PCA). Spearman correlation analysis explored relationships among metal contaminants, revealing potential common sources. IBM SPSS Statistics 22 and Origin Pro were used to analyze the data.

## **2.7 Human Health Risk Assessment**

Human health risk assessment considers the potential harm to human health from exposure to hazardous materials or actions (Rahman et al., 2019). Humans are exposed to contaminants through multiple pathways, primarily ingestion (drinking contaminated water) and dermal contact (skin exposure during cleaning or washing) (Rashid et al., 2021). Trace metals in groundwater mainly influence health via drinking water consumption and skin contact. The risks are categorized into carcinogenic and non-carcinogenic, depending on the metal involved. Several models are used to evaluate health risks posed by metallic essentials (Rahman et al., 2019). This study evaluated both non-carcinogenic (NCR) and carcinogenic risks (CR) from metal exposure at each sampling site, considering ingestion and dermal contact (Varol et al., 2021).

Following IARC (1987) guidelines, cadmium (Cd) and lead (Pb) are classified as carcinogenic, while other trace metals are considered non-carcinogenic. The non-carcinogenic risk assessment incorporates several key parameters: contaminant concentration in water ( $C_w$ ), ingestion rate ( $IR_{wrec}$ ), exposure frequency ( $EF_{rec}$ ), exposure duration (ED), event frequency (EV), body weight (BW), and averaging time ( $AT_{rec}$ ), calculated as  $ED \times 365$  days for non-carcinogens. The dermal permeability coefficient ( $K_p$ ) estimates skin absorption, and the reference dose ( $RfD$ ) indicates the safe exposure level (mg/kg/day). The gastrointestinal absorption factor (GIABS) is assumed to be one (USEPA, 2009).

Risk is expressed as a hazard quotient (HQ) or hazard index (HI). Values below 1 suggest safe exposure, while values above 1 indicate potential non-carcinogenic health risks (Haghnazar et al., 2022). Carcinogenic risk uses models to calculate long-term cancer risk probabilities based on exposure to carcinogenic contaminants.

### 2.7.1 Non carcinogenic risks

$$HQ_{ingestion} = \frac{Cw \times IRW_{rec} \times EF_{rec} \times ED \times EV \times ET_{rec}}{Bw \times AT_{rec} \times RfDo \times 10^3} \dots\dots\dots(9)$$

$$HQ_{dermal} = \frac{Cw \times SA \times Kp \times ET_{rec} \times EV \times EF_{rec} \times ED}{Bw \times AT_{rec} \times RfDo \times GIABS \times 10^6} \dots\dots\dots(10)$$

Additionally, the hazard index (HI) was used to determine the total NCR from exposure to all metals in each exposure pathway. The computed HIs for the ingestion and dermal contact pathways were added up to determine the total HI (THI). There is no discernible risk of non-carcinogenic consequences when the HQ and HI values are less than 1, and as the HQ and HI values rise, so does the danger of non-carcinogenic effects.

$$HI = \sum HQs \dots\dots\dots(11)$$

$$THI = HI_{ingestion} + HI_{dermal} \dots\dots\dots(12)$$

### 2.7.2. Carcinogenic risks

$$CR_{ingestion} = \frac{Cw \times IFW_{rec} \times CSFo}{AT \times 10^3} \dots\dots\dots(13)$$

$$IFW_{rec} = \frac{EV_a \times ET_{rec-a} \times EF_{rec} \times ED_a \times IRW_{rec-a}}{BW_a} + \frac{EV_c \times ET_{rec-c} \times EF_{rec} \times ED_c \times IRW_{rec-c}}{BW_c} \dots\dots\dots(14)$$

$$CR_{dermal} = \frac{Cw \times Kp \times 0.001 \times ET_{event-rec} \times DFW_{rec} \times CSFo}{AT \times GIABS \times 10^3} \dots\dots\dots(15)$$

$$ET_{event-rec} = \frac{ET_{rec-a} \times ED_a + ET_{rec-c} \times ED_c}{ED} \dots\dots\dots(16)$$

$$DFW_{rec} = \frac{EV_a \times EF_{rec} \times ED_a \times Saa}{BW_a} + \frac{EV_c \times EF_{rec} \times ED_c \times Sac}{BW_c} \dots\dots\dots(17)$$

Total carcinogenic risk (TCR) was found by summing CR ingestion and CR dermal values.

$$TCR = CR_{ingestion} + CR_{dermal}$$

### 3. Results and Discussion:

#### 3.1 Metal concentrations in groundwater samples in intensively cultivated regions in Bangladesh

The analysis of the heavy metals through descriptive statistics indicates a high variability in concentration across the study area (**Table 1, Fig. 2**). Out of all the metals, Fe had drastically high variability, with concentrations ranging from a low of 43.71 to a high of 3021.50 µg/L (mean 409.97 µg/L, SD 746.65), which likely indicates local hotspots impacted by both geogenic leaching and anthropogenic discharges. Al had also high variability (127.45-720.05 µg/L, mean 234.70 µg/L, SD 159.37) but was positively skewed (skewness =1.97), indicating that most values were in the lower range, with some extreme outlier values in heavier concentrations. Cd and Cr exhibited high coefficients of variation of 70.88% and 75.06%, respectively, also indicating a variety of conditions, heterogeneous distributions, and/or localized contamination. High variability was observed in the metals Ba, Cu, and Zn, which are also substantially positively skewed and exhibited leptokurtic distributions indicating localized but high-frequency enrichment events. Pb, in comparison to all other metals, exhibited the least variability (33.92-68.35 µg/L, mean 51.65 µg/L), resulting in the lowest coefficient of variation (14.87%). Collectively, Pb was negatively skewed- indicating a very uniform distribution of values across the study area, likely because of anthropogenic contributions, such as from traffic emissions or industrial activities. Sr and Ti exhibited moderate variability and near-symmetric distributions. In contrast, Ni and Zr displayed lower skewness values, indicating a potential for more homogeneity. Using statistical descriptors, the relatively high kurtosis values for Ba (10.48), Cr (13.47), and Cu (12.22) further validated the

presence of sharp peaks and extreme values, which increase localized ecological and health risks. Inclusively, the results demonstrate that while metals are classified as fairly uniform (Pb, Sr, Ti), metals like Fe, Al, Cd, Cr, Cu, or Ba exhibited clear spatial heterogeneity, and while the absolute risk due to concentrations of Pb, Sr, and Ti was expected to be lower, some metals (Fe, Al, Cd, Cr, Cu, Ba) presented a higher probability or risk and therefore require a hotspot management response.

#### **Fig. 2:** Distribution of Total Heavy Metal Load in Groundwater Samples

The ground water samples were also classified using the relation between the load of heavy metals and pH (Ficklin et al., 1992; Islam et al., 2025). The Change in pH and mobility of heavy metals are explained by Caboi plot (Sharma et al., 2025). The scatter plots of sample pH and trace metal loadings (**Fig. 3**) illustrate that the ground water samples all fall in the near-neutral extreme-metal zones.

#### **Fig 3:** Scatter diagram of the total concentration of metals and pH

### **3.2 Evaluation of water quality**

#### **3.2.1 Heavy metal pollution Assessment**

##### ***Contaminated Degree***

A key measure for determining the degree of groundwater contamination was the Contamination Degree (Cd). The average Cd value in this study was 15.57, with a range of 12.01 to 25.94 (**Fig. 4**). According to Edet and Offiong's classification (2002), 10% of the samples had calculated Cd values above the critical limit of 20. The majority of the study area's groundwater sampling locations are classified as moderately contaminated.

**Fig 4:** Degree of contamination ( $C_d$ ) of heavy metals in different drinking water samples based on Edet and Offiong's classification (2002).

In groundwater, dissolution of minerals which contain metals, mechanisms of ion exchange, and redox-controlled transport of metals into that water through the reduction of those metals through redox reactions, are among the dominant controls of the presence of the concentration of trace metals (Wen et al., 2019). Additionally, anthropogenic activities such as agricultural runoff, use of fertilizers and pesticides, disposal of domestic waste, or localized industrial activities can increase the Cd levels in the study area (Affandi et al., 2019). Similar findings were observed in Nigeria where contamination degree (Cd) usually falls within a very good category, which is suitable for drinking purposes (Musa et al., 2026). While the groundwater quality of Meghna Ghat had relatively low pollution levels, the water was still considered unsafe for drinking. It indicates that even low Cd values do not guarantee safety when certain contaminants exceed permissible limits (Rahman et al., 2020). Additionally, groundwater quality in Lakshmipur district was found to be severely degraded (Bhuiyan et al., 2016). Seasonal variation also significantly influenced Cd values. Higher contamination levels occurred during the dry season because of reduced dilution and increased concentration of trace metals. Lower Cd values during the wet season resulted from dilution effects from rainfall (Saleem, Iqbal, and Shah, 2019). The findings from other regions revealed herein support the findings of this present study that both natural geochemical processes and anthropogenic forces are significant drivers of groundwater contamination.

### **3.2.2 Heavy Metal Pollution Index**

The Indian groundwater quality standards (2012) were used to assess the concentrations of Ba, Cd, Cu, Fe, Mn, Ni, Pb, Sn, Sr, Ti, Zn, and Zr in order to calculate the Heavy Metal Pollution Index (HPI). Result showed that the average HPI value was 97.25, with a range of 61.47 to 172.83 (**Fig. 5-A**). Interestingly, there were differences between the two indices, with some areas being categorized as more polluted based on Cd values even though their HPI levels were comparatively lower. A significant percentage of the groundwater sources may be in danger, as evidenced by the fact that 63.33% of the samples were above the critical HPI threshold of 90.

**Fig 5:** Heavy metal Pollution index (Fig A) and Heavy Metal Evaluation Index (Fig. B) based on Prosad and Bose, 2001.

This finding is similar to the studies conducted in few developing countries in South Asia (specify the place e.g. Bangladesh or China or Myanmar), where many reports highlight the

decline in groundwater quality. This decline is largely due to human activities and various hydrogeochemical processes that increase metal levels (Alam et al., 2025; Maliqi, Jusufi & Singh, 2020). The deterioration of groundwater quality is largely due to natural sources, such as the release of Fe and Mn due to mineral weathering, and anthropogenic sources including waste disposal (landfill), agricultural runoff (fertilizers and pesticides used), and industrial leaks (Subba Rao, 2019).

The observed differences in the study area highlight the complicated nature of groundwater contaminated. For example, at Meghna Ghat, approximately 35% of the groundwater samples tested unfit due to contamination; however, some locations exhibited low environmental impacts (Rahman et al., 2020). Conversely, HPI values for groundwater in the Lakshmipur district indicate a much more serious level of contamination than at Meghna Ghat leading to higher health risks (Bhuiyan et al., 2016). Additionally, the Chuadanga district has also been classified as an unsafe source of drinking water (Rahman & Habiba, 2023).

Results of this study align with previous literature for Bangladesh indicating that shallow aquifers are generally more contaminated than deep aquifers due to greater proximity to the effects of human activity (Rahman et al., 2017). International comparisons further support these results; for example, research conducted in Taizhou, China indicates that approximately 50%-75% of groundwater samples have low HPI values indicating a declining water quality trend, though some areas continue to have major water quality challenges (Meng et al., 2023). The results of this study indicate that groundwater quality can be very different from one location to another based on a variety of environmental factors and anthropogenic influences on a location's environment. Some areas, such as Lakshmipur, have experienced significant negative impacts on groundwater quality; while other areas have experienced only modest improvements in groundwater quality (Bhuiyan et al., 2016).

### **3.2.3 Heavy Metal Evaluation Index**

The aggregated effects of heavy metal concentrations on the quality of the groundwater have been evaluated and is referenced as a Heavy Metal Evaluation Index (HEI), which is a scoring system. Using this index, we took into consideration anything below 10 as low, between 10-20 as moderate, and above 20 as high. The results are represented in Table 4. Most samples including, S02-S12, S15-S17, S19-S22, S25 are scored moderate meaning there are clear signs of

contamination, though not extensive. Samples S01 and S14 are classified as low meaning they were relatively safe for groundwater use. Other samples, S13, S18, S24, S26, and S30 scored high values meaning they should be considered as heavy metal pollution hotspots (**Fig. 5- B**).

These findings generally match previous research, in Meghna Ghat, groundwater had relatively low pollution levels but was still deemed unsafe for drinking due to certain contaminants exceeding limits (Rahman et al., 2020). In Taizhou, China, some areas had poorer HPI values, but overall, there has been a gradual improvement in water quality compared to other heavily impacted sites (Meng et al., 2023). In contrast, the Lakshmipur district faces a more serious situation, with severely degraded groundwater quality (Bhuiyan et al., 2016). These comparisons highlight that while some regions may experience slight improvements or moderate contamination, others remain very vulnerable, showing the combined effects of human activity and hydro geochemical changes on groundwater quality.

#### ***Pollution Index (PI) and Integrated Pollution Index (IPI)***

The single-factor pollution index (PI) values for Cd, Cu, Fe, Mn, Ni, and Pb across the examined sampling locations are presented in **Fig. 6-A**. The PI values showed significant variation between sites, indicating differences in metal pollution levels. Among the metals studied, Pb showed the highest Pi values at various locations, suggesting relatively high levels of pollution. The highest Pi value was observed at S24 (19.55), followed by S18 (16.11), S13 (15.67), and S30 (12.07). Notably high Pi values were also found at S11 (11.97), signaling considerable contamination at these locations. Conversely, lower PI values were noted at S16 (5.78), S2 (6.27), and S22 (6.66). Overall, the Pi values varied from 5.78 to 19.55, indicating a range from moderate to very high contamination throughout the study.

#### **Fig 6: Pollution Index (A) and integrated pollution index (IPI) (B) based on Yan et al., 2015**

The Integrated Pollution Index (IPI) number for each sampling location is indicated in **Fig. 6-B**. The range of IPI numbers (1.36 to 1.64) indicates that different amounts of total pollution are found among sampling locations. S24 has the highest IPI Value at 1.64, S18 follows next at 1.59, S13 at 1.58, and S30 with 1.51; all four of these sites had the highest cumulative amount of pollution accumulated over time. S6, S2, and S22 had the lowest IPI Integer Values ranging from 1.43 to 1.36, which suggested that these locations contained lower amounts of cumulative

pollution than other sampling locations. With only 3 exception sampling locations out of 12 sampled had IPI values below 1, it can be reasonably concluded that moderate levels of pollution existed in the sampled areas.

### **3.3 Water Quality Assessment**

#### ***3.3.1 Ground Water Quality Index***

The overall impact of different water quality parameters on the suitability of groundwater for human consumption is reflected in the Groundwater Quality Index (GWQI), a rating system. Using Equation (1), the World Health Organization (WHO, 2011) was used to evaluate the drinkability of groundwater. The average GWQI value was 136.15, with a range of 76.24 to 300.22. 13.33% of the samples (S8, S16, S22, and S27) were classified as having good water quality based on the analysis (**Fig. 7-A**). However, 13.33% of the samples (S13, S18, S24, and S30) were categorized as having very poor quality, while 73.33% of the samples (S1-S7, S9-S12, S14-S15, S17, S19-S21, S23, S25-S26, S28-S29) were found to have poor water quality.

These results are in contract with observations in other regions where the groundwater quality exhibits similar dominance of poor conditions. In the groundwater of Meghna ghat, a small percentage of ground water is considered to be of good quality while most is reported to be of poor quality (Rahman et al., 2020). In Chuadanga, the groundwater was found to be mostly unsuitable for drinking purpose indicating serious deterioration of water quality (Rahman & Habiba, 2023). On the other hand, studies from southern India report relatively better conditions with almost 53% of samples classified as excellent, 43% as good and only a small fraction as poor indicating comparatively healthier groundwater system (Subramaniyan, 2026). Similarly, in Lakshmipur, about 50% of water has been found to be acceptable, but quality problems still exist elsewhere (Bhuiyan et al., 2016).

**Fig 7:** Interpolation Map of Entropy Weighted Water Quality Index (Fig. A) and Groundwater Quality Index (Fig. B)

#### ***3.3.2 Entropy Weighted Water Quality Index***

The Entropy Weighted Water Quality Index (EWQI) was used to assess the overall usability for drinking water purposes of groundwater by combining multiple physicochemical parameters. The values of EWQI obtained from the analysis ranged between 78.91 and 184.64, with an average value of 132.95 (**Fig. 7-B**). Using the classification scheme, 6.67% of the samples (S16)

belonged to good water quality, while the remaining 93.33% of samples (S1-S15, S17-S30) encapsulated poor water quality. No sample was in the very good or very poor classes. This result shows that, the groundwater in the area is of poor quality and therefore should demonstrate some degree of treatment before drinking.

The overall patterns of results from this study closely matched those from earlier research; however, quality loss from sample to sample was found to vary across different regions. In some regions, positive results were shown in the form of an EWQI-based assessment, where more than 57% to 74% of groundwater samples were classified as being in the range of excellent to medium quality, depending on seasonal variability based on the standards used (Mohsin et al., 2026). In another region, Zhouzhi County, approximately 64.79% of groundwater samples had excellent to good quality and 35.21% had moderate quality; therefore, the quality of groundwater in Zhouzhi County is comparatively higher than that of other regions (Yan et al., 2023). One other study showed that across the study area, between 34.3% and 37.72% had good quality groundwater through dry and wet seasons; therefore, this area has well to moderate-quality groundwater but is experiencing seasonal variability (Krishna and Achari, 2023).

Comparatively, the groundwater quality of this study area was observed to be of much poorer quality than these other studies and suggest that the study area is experiencing increasing degradation of groundwater quality at a greater rate than other regions of the world, likely as a result of the interaction between the anthropogenic pressures present and the hydro geochemical conditions of the study area.

### **3.4 Ecological Risk Assessment**

#### ***3.4.1 Ecological Risk Index***

To analyze the ecological risk of heavy metals in groundwater, a potential ecological risk index (PERI) was used. The calculated values for ecological risk ranged from 7.79 to 38.23 with an average value of 17.15 (**Fig. 8**). Using the classification method (Hakason, 1980);  $RI < 40$ : low risk, 40-80: moderate risk, 80-160: considerable risk, 160-320: very high risk,  $>320$ : dangerous, 100% of samples (S1-S30) fell under the low-risk classification. In this scenario, the ecological risk of heavy metals in the study area is low and does not pose serious risk to surrounding environment. However, continued monitoring is required to confirm future sustainability in low-risk levels over time.

**Fig 8: Ecological Risk Index based on Hakanson, 1980**

These findings are consistent with, but also in contrast to, previous research. For example, in Jiangxi, China, about 17.24% of samples were determined to be at higher ecological risk levels, suggesting local contamination hotspots (Ke et al., 2026). The groundwater of North center Nigeria has been generally reported to be suitable for drinking with an increasing population density as one of the key factors influencing the gradual deterioration of water quality. This region shows a more stable ecological condition at the time of assessment when compared to the present study area (Musa et al., 2026). However, the possibility of subsequent deterioration cannot be overlooked, since natural geochemical processes and anthropogenic activities greatly influence the degree of ecological risk.

### **3.5 Source Identification**

#### **3.5.1 Spearman Correlation Matrix**

The Spearman correlation coefficients obtained from the analysis are depicted in the figure. Weak correlations are between 0.3 and 0.5, moderate correlations are between 0.5 and 0.75, and strong correlations are between 0.75 and 1, according to established thresholds (Ejegwa, et al., 2025). A correlation coefficient of less than 0.3 is regarded as insignificant. Whereas negative values show an inverse relationship between parameters, positive coefficients show that the variables rise or fall together. A significant positive correlation between two variables (Cu and Al) can indicate that these variables are related through a common source, whether anthropogenic or geogenic origin. An absence of correlation may indicate that the variables have different sources or processes impacting those (Zhang et al. 2025). For instance, Cu, Zn, and Al were positively correlated with each other in **Fig 9**; therefore, their respective sources are likely similar, as are their respective transport mechanisms. In addition, there were moderate correlations between pH, Sr, Ti, and Al; this suggests that these parameters will behave in similar fashion from a geochemical perspective it's believed that the geogenic influences of the groundwater system will have the biggest impact on the geochemical behavior of these parameters.

Fig 9: The Spearman correlation coefficients for analyzed parameters in drinking water samples.

#### **3.5.2 Principal Component Analysis**

Principal Component Analysis (PCA) was applied to lessen the dimensionality of the dataset and identify patterns among the variables. The Kaiser-Meyer-Olkin (KMO) value (**Table 2**) was found to be 0.3998, indicating a low level of sampling acceptability, which suggests that the dataset may not be strongly suited for PCA. However, Bartlett's Test of Sphericity was statistically significant ( $\chi^2 = 262.63$ ,  $df = 136$ ,  $p < 0.001$ ), confirming the presence of meaningful links among variables and justifying the use of PCA.

The analysis initially extracted six components with eigenvalues greater than one (**Fig A-2**). PC1 explained 21.27% of the total variance, followed by PC2 with 16.25%, PC3 with 12.15%, PC4 with 9.55%, PC5 with 8.70%, and PC6 with 7.97%. Cumulatively, these six principal components accounted for approximately 75.89% of the total variance in the dataset.

**Table 2.** KMO and Bartlett's Test

|                                                  |                    |         |
|--------------------------------------------------|--------------------|---------|
| Kaiser-Meyer-Olkin Measure of Sampling Adequacy. |                    | 0.400   |
| Bartlett's Test of Sphericity                    | Approx. Chi-Square | 262.627 |
|                                                  | df                 | 136     |
|                                                  | Sig.               | 0.000   |

After applying varimax rotation, the variance was more consistently distributed across the components, successful interpretability (**Table A1, Fig 10**). Each principal component likely represents a combination of variables (e.g., heavy metals) that exhibit similar behavior or are influenced by similar sources. These components can be further interpreted to understand potential pollution sources, such as geogenic, anthropogenic, or mixed influences in the study area.

**Fig 10.** Component plot for metals in drinking waters in south western part of Bangladesh

By using the correlation matrix and principal component analysis (PCA), essential information was found regarding controls of the concentrations of the physicochemical parameters and the trace metals identified in the analyzed water samples and potential sources for these parameters.

Several strong positive correlations were found between Al, Cd, Fe, Pb, Ti, and Zn (e.g. Al and Cd = 0.66; Al and Fe = 0.66; Al and Zn = 0.65; Pb and Ti = 0.64; Cd and Zn = 0.59), suggesting that these metals may share an anthropogenic source, such as industrial discharges and urban

runoff and that corrosion of construction materials is occurring as a result of corrosion. In addition, Al, Fe, and Pb showed strong correlations; which agrees with Shajib (2019). According to this research, the results of the present study support earlier works indicating that Al and Fe have strong correlations (Shajib, 2019; Sansalone et al., 2025). The significant positive correlations found between Al and Fe with other elements, such as Mn, Pb, Cr, Ni, and Zn may imply associations of these trace metals and Al and Fe hydroxide phases in runoff. This finding corroborates earlier research showing that metal cations have a known affinity to adsorb onto Fe and Al hydroxides (Shajib, 2019).

In the current study, there were similarly strong positive factor loadings for Cu (0.844) and Zn (0.784) and a moderate positive correlation between the two metals ( $r=0.68$ ). Industrial sources, including Cu, Zn and Mn, have been linked (Khan et al. 2025) to these three metals and Zn from agricultural production also has been shown to be coming from agricultural production sources, including fertilizers (Zhang et al., 2025). This indicates they originated from either common sources associated with industrial activities and agricultural activities. Conversely, PC2 had moderate negative loadings for Ni (-0.577) and Ti (-0.509), therefore the origin of these metals likely differs where, Ni is primarily considered lithogenic or geogenic in nature (Choudhury et al., 2024) and Ti serves as the main element in the Earth's crust, is extensively distributed in rocks and minerals (Zu et al., 2024).

PC3 had very large concentrations of Cr (0.894) and Sn (0.919), both of which were positively correlated with one another ( $\text{Cr-Sn} = 0.75$ ) as the highest correlation in the correlation matrix. However, PC4 had strong positive correlation loads for Mn (0.839), Zr (0.770) with moderate correlation ( $\text{Mn-Zr} = 0.46$ ), indicating the association with geologic processes such as mineral weathering, sediment dissolution, and lithogenically-derived materials. The associations of Mn and Zr probably indicate the presence of geogenic controls from the weathering of Mn-bearing minerals, sediment-water interactions that are affected by redox state, and inputs from stable lithogenic minerals, all of which demonstrate that the chemistry of groundwater in this instance will be controlled primarily by the weathering of natural minerals; detrital materials; and the geology of the underlying aquifer, as opposed to being affected by anthropogenic contamination (Jiang et. al., 2025).

PC5 was defined predominantly by pH (0.768), Ba (0.812), with an inverse relationship to Sr (-0.716), indicating hydro chemical influences brought about by mineral dissolution, ion exchange, and salinity processes. This composite of variables Sr and Ba is believed to represent geochemical characteristics that tracers of sedimentary and igneous rock weathering, that highlighting the importance of water rock interaction in regulating trace element mobility (Kaleem et al., 2021).

PC6 is closely associated with B (0.703), and to a lesser extent, with Pb (0.433), indicating areas where agricultural runoff, fertilizers, domestic sewage, or detergents may have contributed to their presence. Based on that B has been relatively weakly correlated to most heavy metals suggests its source is independent and likely related to agricultural or household activities rather than natural sediment derived heavy metal sources (Sharma et al., 2022).

### **3.6 Human Health Risk Assessment**

#### ***3.6.1 Non-Carcinogenic Risk***

In accordance with guidelines set by the U.S. Environmental Protection Agency (USEPA, 1989, 2001), non-carcinogenic health risks from oral ingestion and dermal contact with groundwater are evaluated using Hazard Quotient (HQ) values. An HQ less than 1 indicates an acceptable level of risk, meaning that non-carcinogenic effects are unlikely to occur. On the other hand, an HQ higher than 1 indicates a possible risk of negative health consequences. The HQ values for dermal absorption of trace metals were all less than 1 for both adults and children, suggesting that this exposure pathway poses little danger. However, HQ values from oral intake were consistently higher than those from cutaneous exposure, especially in youngsters, indicating that ingestion carries a larger risk.

#### **Fig 11. Distribution of HI values for adults and children**

The ingestion HQ values were ranked as follows: Zr > Pb > Mn > Cd > Sr > Ni > Fe > Cu > B > Ba > Al > Zn > Sn > Ti > Cr for adults, and Zr > Pb > Mn > Cd > Ni > Sr > Fe > Cu > B > Ba > Zn > Al > Ti > Sn > Cr for children. These findings indicate that the main factor contributing to the total non-carcinogenic risk is zirconium (Zr). Interestingly, children showed HQ ingestion values larger than 1 for Zr, Pb, and Mn, indicating an unacceptable level of non-carcinogenic risk

from eating groundwater contaminated with these metals, although adult HQ values remained below 1 for all trace metals (**Fig. 11**).

These results are in line with earlier studies that show children are more susceptible to groundwater contamination than adults because of increased consumption rates in relation to body weight and higher physiological sensitivity (Bodrud-Doza et al., 2020). Similarly, while many groundwater samples do not exceed reference limits from non-carcinogenic risk, a significant proportion of samples still exhibit elevated hazard index values, especially for children, according to comparative risk assessments using both deterministic and probabilistic approaches (Meng et al., 2023). Approximately 40.8% of adult samples and 69.7% of kid samples in some places have been shown to have HI values greater than unity, further supporting the idea that younger populations are more susceptible (Kaur, Rishi & Siddiqui, 2020).

### **3.6.2 Carcinogenic Risk**

Due to the lack of arsenic (As) data in the examined samples, a comprehensive carcinogenic health risk evaluation was not possible in this investigation. Although arsenic's well-defined slope factor makes it one of the most widely recognized heavy metals for calculating cancer risk, other carcinogenic metals including Cd, Ni, and Pb also have recognized slope factors and were thus included in the assessment. The total carcinogenic risk (TCR) values varied from  $8.27 \times 10^{-8}$  to  $5.59 \times 10^{-6}$  (**Table A6**), showing that most sampling locations displayed carcinogenic risk levels around the order of  $10^{-7}$ , whereas the highest carcinogenic risk was noted at S31, at the order of  $10^{-6}$ . The CR values were evaluated within the typical range of  $1 \times 10^{-6}$  to  $1 \times 10^{-4}$  (Wagh et al., 2018; Raja et al., 2021; Ghosh et al., 2024).

### **3.6.3 Monte Carlo Simulation**

The uncertainty and sensitivity of the total carcinogenic risk (TCR) associated with exposure to heavy metals through ingestion and cutaneous routes were evaluated using a Monte Carlo simulation with 1,000 iterations. A satisfactory fit between the fitted and expected results was shown by the resulting TCR values, which generally followed a gamma distribution. At the 95% confidence interval, the expected carcinogenic risk values mostly fell between  $1.0 \times 10^{-6}$  and  $1.0 \times 10^{-4}$ .

**Fig. 12.** Parameter sensitivity of CR<sub>total</sub>.

According to sensitivity analysis, lead (Pb) accounted for 88.8% of the total variance in carcinogenic risk, whereas nickel (Ni) contributed 10.7% (Fig. 12). The overall evaluation of carcinogenic risk was mostly unaffected by other metals and exposure characteristics. While negative sensitivity values suggested an inverse relationship with the risk outcome, positive sensitivity values demonstrated a direct association between the concentration of heavy metals and the carcinogenic risk. The findings emphasise the significance of continuous monitoring and efficient management strategies to reduce Pb contamination and associated health hazards since Pb exposure is the most important factor impacting carcinogenic health risk in the study area.

#### 4. Conclusion

Groundwater quality in the south-western part of Bangladesh reflects a system influenced by both natural processes and human activities, with clear signs of severely degraded conditions in several locations. Descriptive statistical analysis exposed substantial spatial variability in heavy metal concentrations, indicating heterogeneous distribution across the study area. Metals such as Fe and Al showed particularly high variability and skewness, suggesting localized enhancement from both geogenic and anthropogenic sources. Similarly, Cd, Cr, Cu, and Ba exhibited high coefficients of variation and kurtosis, highlighting the presence of unsafe values and contamination hotspots. In contrast, Pb showed relatively low variability and a more unfluctuating distribution, while Sr and Ti revealed moderate variation and Ni and Zr appeared moderately homogeneous. The pH-metal relationship placed groundwater samples within the near-neutral, extreme-metal zone, indicating unchanging pH conditions but higher metal concentrations.

The level of contamination is further determined using pollution indices. With an average of 15.57 and a range of 12.01 to 25.94, the Contamination Degree (Cd) classified the majority of samples as moderately contaminated, with 10% exceeding the critical threshold of value 20. With 63.33% of samples surpassing the threshold limit of 90, the Heavy Metal Pollution Index (HPI) ranged from 61.47 to 172.83 (mean 97.25). The majority of samples were moderately contaminated, according to the Heavy Metal Evaluation Index (HEI), with a few low-risk sites (S01, S14) and multiple high-risk hotspots (S13, S18, S24, S26, S30).

Indices of water quality showed that the water was not fit for human consumption. With an average of 136.15 and a range of 76.24 to 300.22, the Groundwater Quality Index (GWQI)

ranked 73.33% of samples as bad, 13.33% as good, and 13.33% as very poor. In a similar vein, 93.33% of samples fell into the poor category and just 6.67% indicated acceptable quality according to the Entropy Weighted Water Quality Index (EWQI), which ranged from 78.91 to 184.64 (mean 132.95). In spite of this, all samples fell into the low ecological risk category, with the Potential Ecological Risk Index (PERI) ranging from 7.79 to 38.23 (mean 17.15).

These results were corroborated by multivariate statistical studies, which also assisted in locating the sources of contamination. Strong positive correlations between Cu, Zn, and Al indicated shared origins, but modest correlations between pH, Sr, Ti, and Al indicated natural geochemical control, according to Spearman correlation. Six components that accounted for roughly 75.9% of the variance were identified by Principal Component Analysis (PCA), indicating a variety of sources, including home activities, industrial discharge, agricultural inputs, and natural mineral dissolution. While factors like pH, Sr, and EC were affected by natural processes, heavy metals including Cd, Pb, Cr, and Sn were primarily associated with human sources.

Non-carcinogenic hazards are generally minimal for adults but more concerning for youngsters, according to a human health risk assessment. Oral consumption presented greater risks, but dermal exposure pathways demonstrated less risk ( $HQ < 1$ ). All adult HQ values were less than 1. Zirconium (Zr) was the main contributor, but HQ values for Zr, Pb, and Mn were greater than 1 for children, suggesting possible health hazards. The majority of sampling locations had Total Carcinogenic Risk values within the acceptable to possible threat range, according to the carcinogenic risk assessment; however, a thorough examination was limited by the lack of arsenic (As) data. Sensitivity analysis revealed Pb as the primary cause of carcinogenic risk, followed by Ni, while Monte Carlo simulation verified the accuracy of the predicted hazards.

In conclusion, the findings unequivocally show that the study area's groundwater is moderately to severely contaminated and generally unfit for direct consumption. Even though there is currently little ecological risk, the decline in water quality and possible health hazards especially for children, highlight the critical need for routine monitoring, appropriate treatment, and efficient management techniques to guarantee the safe and sustainable use of groundwater resources going forward.

## ***Credit authorship contribution statement***

**Ayesha Aktar:** Writing original draft, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marzia Sultana Shefa:** Writing original draft, Investigation, Formal analysis, **M. Safiur Rahman:** Conceptualization, Investigation, Formal analysis. **Mehedi Hasan Ovi:** Visualization, Investigation, Formal analysis, **Ahmed Parvez:** Funding acquisition, editing **Md. Fuad Hasan:** Visualization, Investigation, **Mahmud Hasan Prince:** Visualization, Investigation, **Muhammad Arifur Rahman:** Visualization, Investigation, **Md. Rakibul Ahsan:** Visualization, Investigation **Md. Tariqul Islam Shajib:** Conceptualization and review & editing.

## ***Declaration of competing interest***

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 paper.

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## **Data Availability Statement**

The datasets analyzed during this study are available from the corresponding author upon reasonable request.

## **Appendix A: Supplementary Information**

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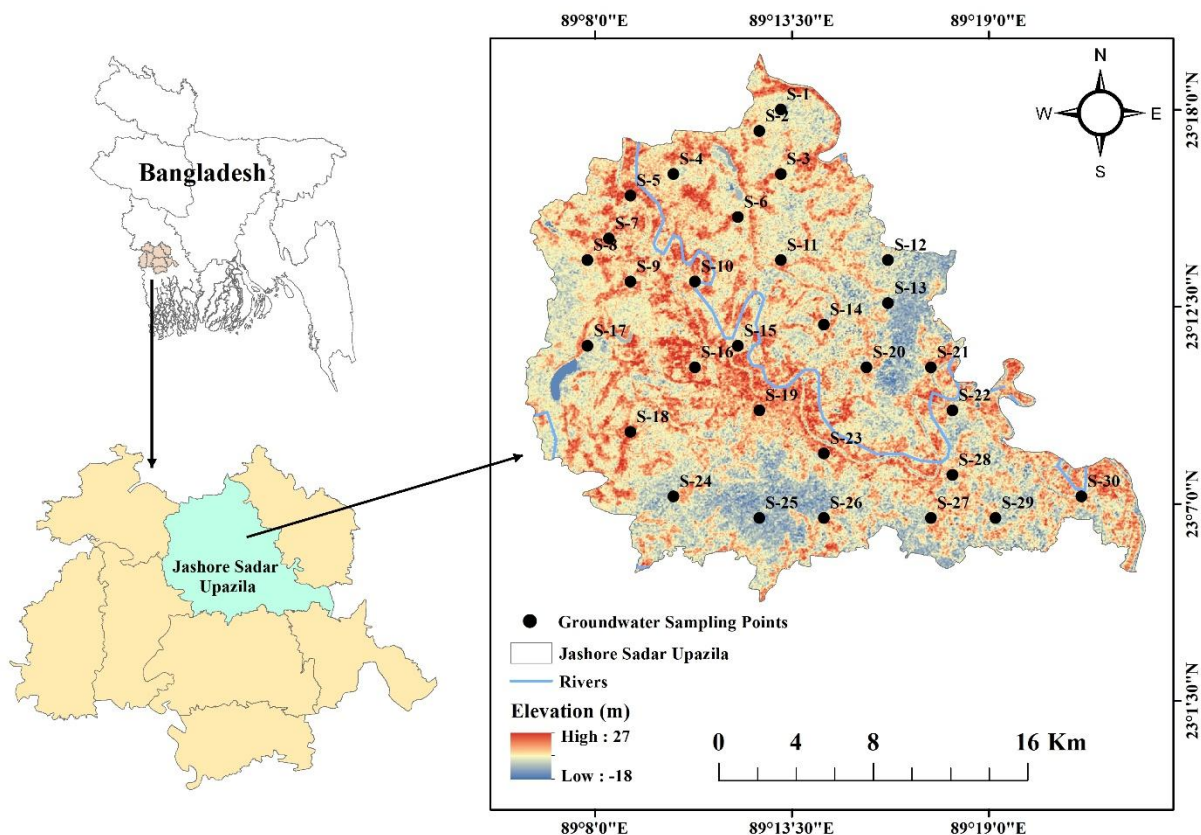
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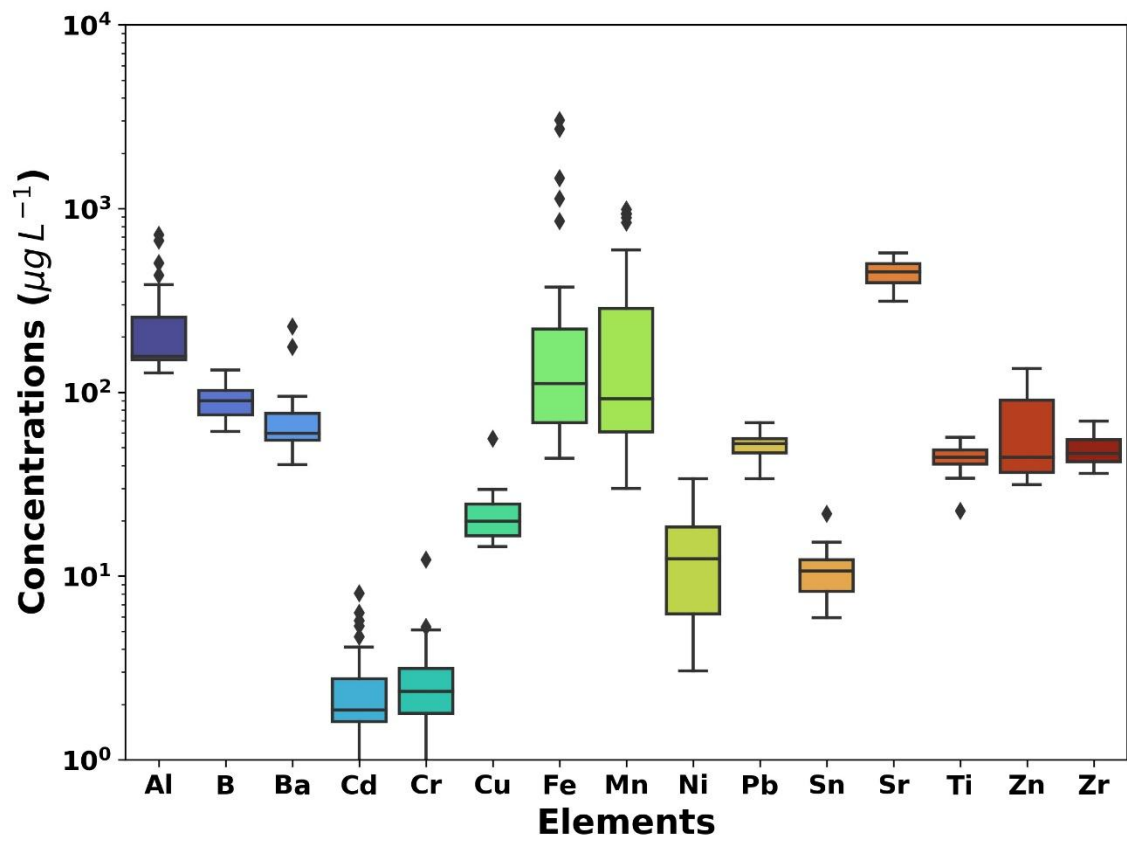
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Fig. 1. Study area map showing the sampling locations.



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Fig. 2: Distribution of Total Heavy Metal Load in Groundwater Samples

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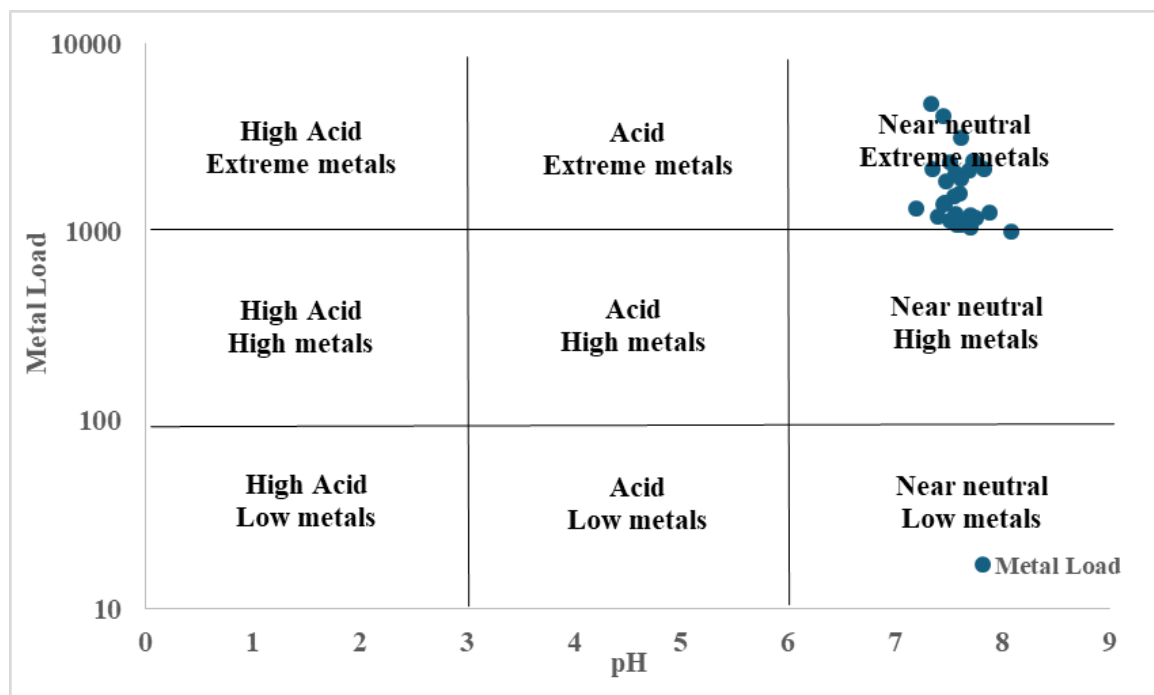


**Fig 3:** Scatter diagram of the total concentration of metals and pH

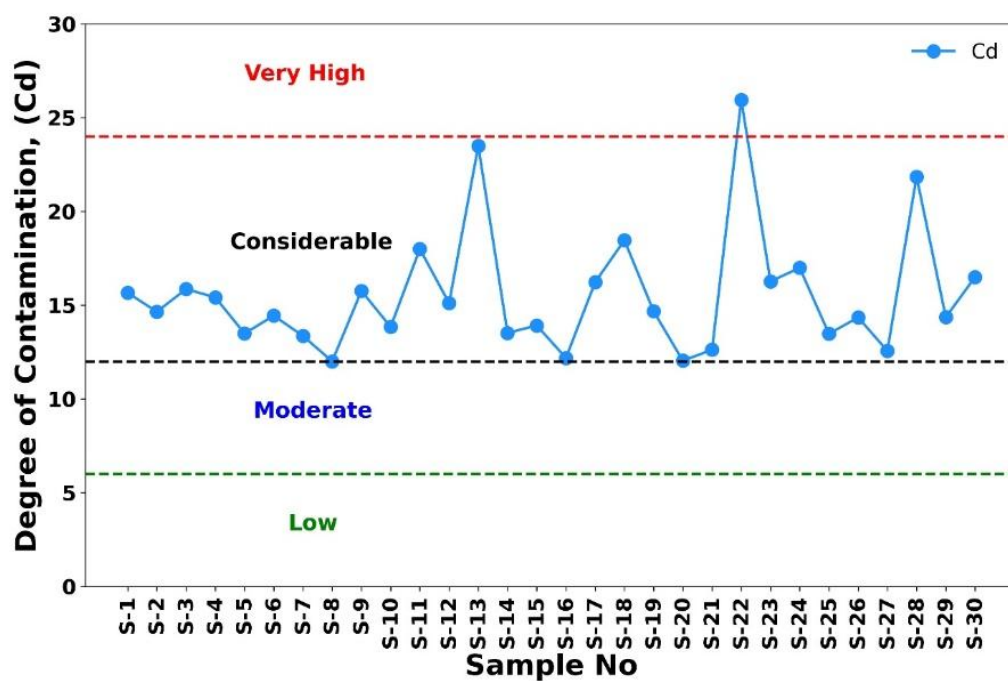
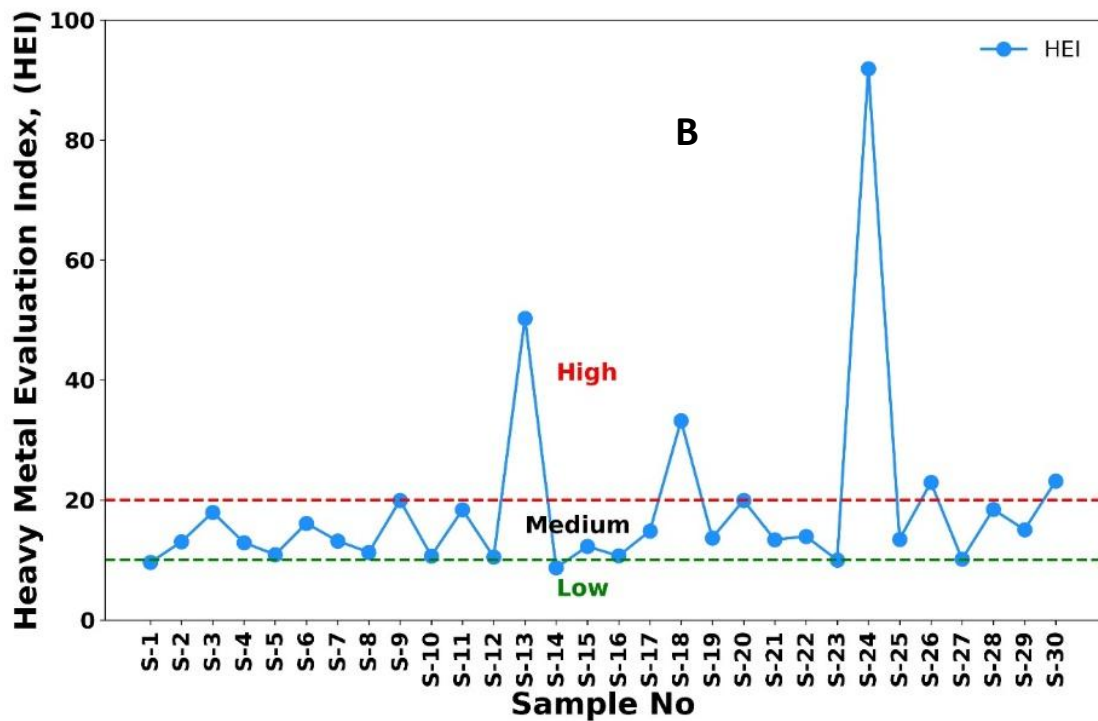
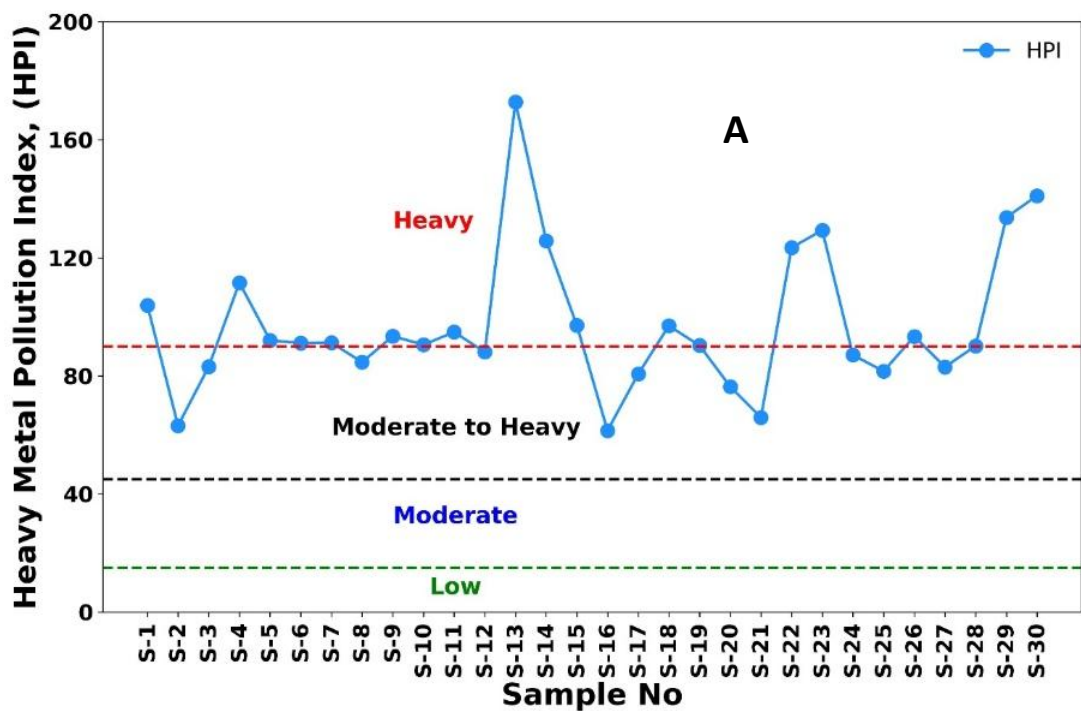


**Fig 4: Degree of contamination (Cd) of heavy metals in different drinking water samples based on Edet and Offiong's classification (2002)**

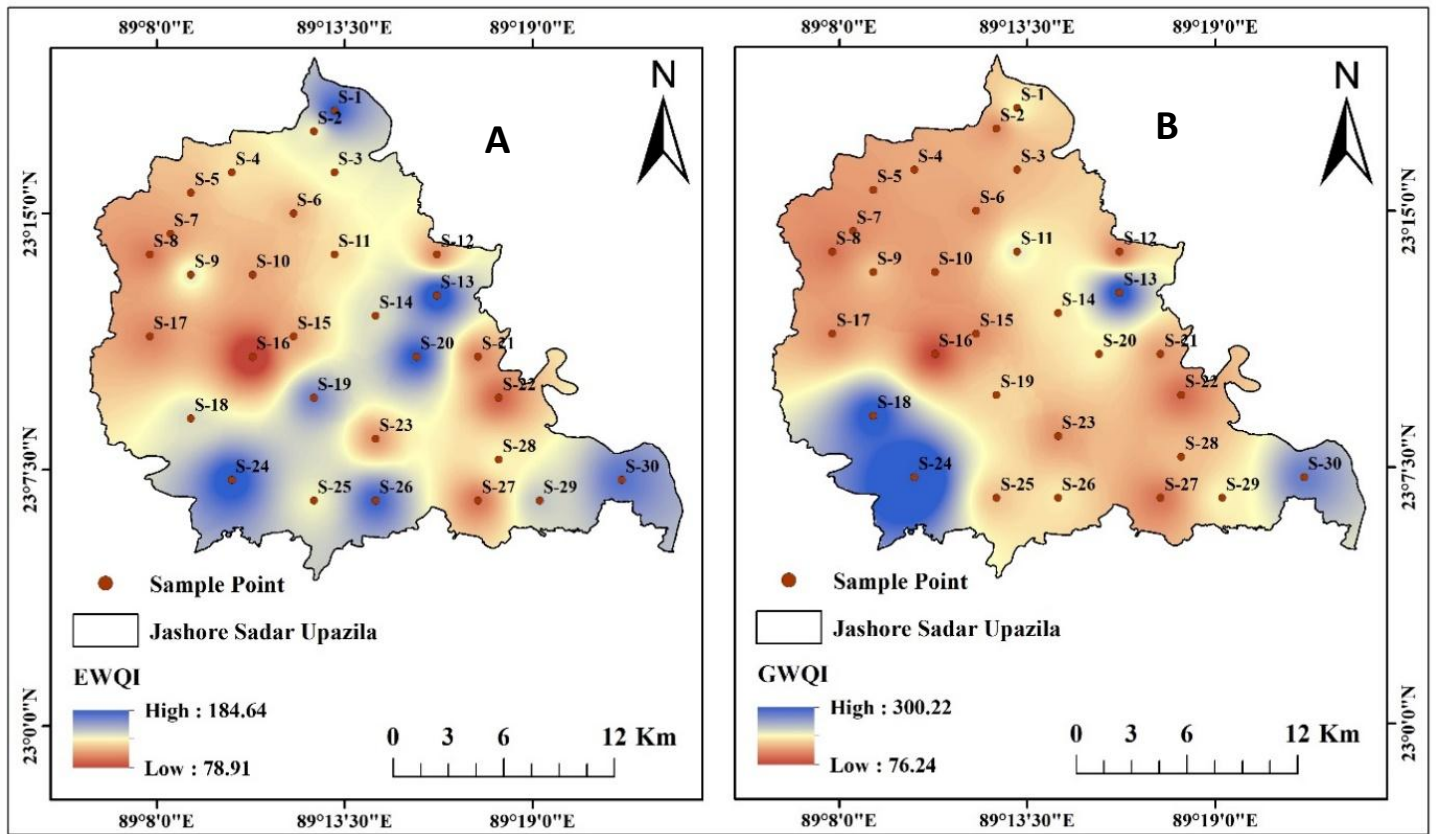


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994 **Fig 5:** Heavy metal Pollution index (Fig A) and Heavy Metal Evaluation Index (Fig. B) based on  
 995 Prosad and Bose, 2001

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998 **Fig 6:** Interpolation Map of Entropy Weighted Water Quality Index (Fig. A) and Groundwater  
 999 Quality Index (Fig. B)

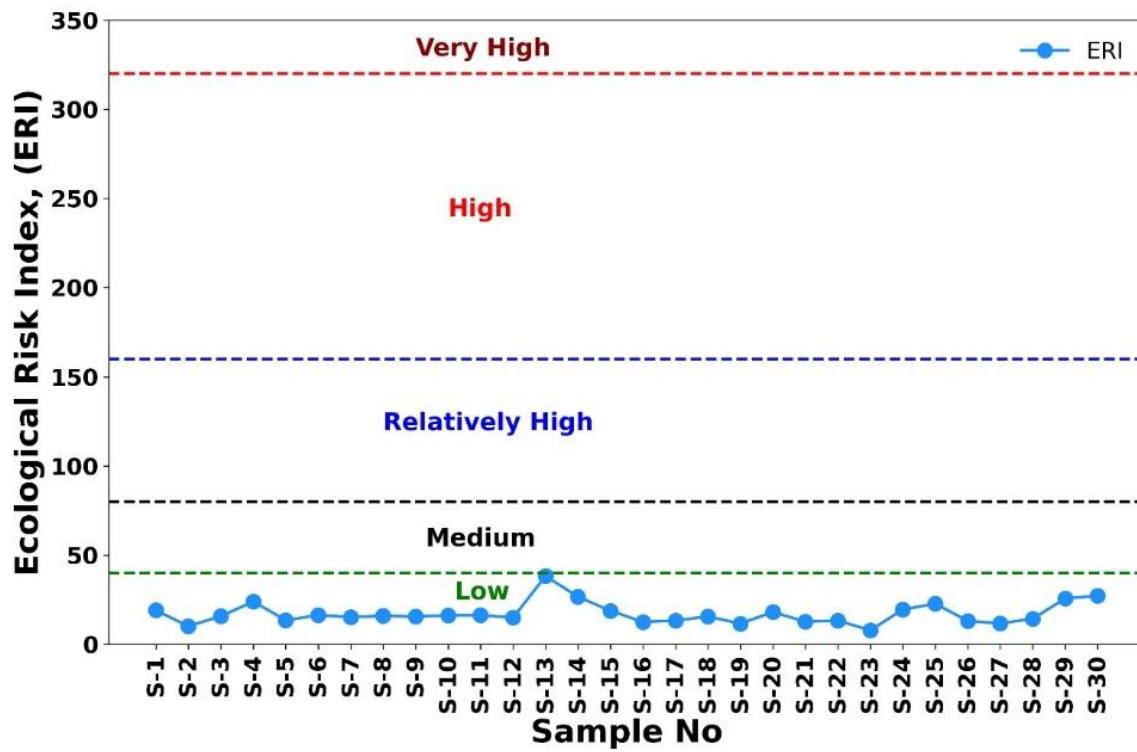


Fig 7: Ecological Risk Index based on Hakson, 1980

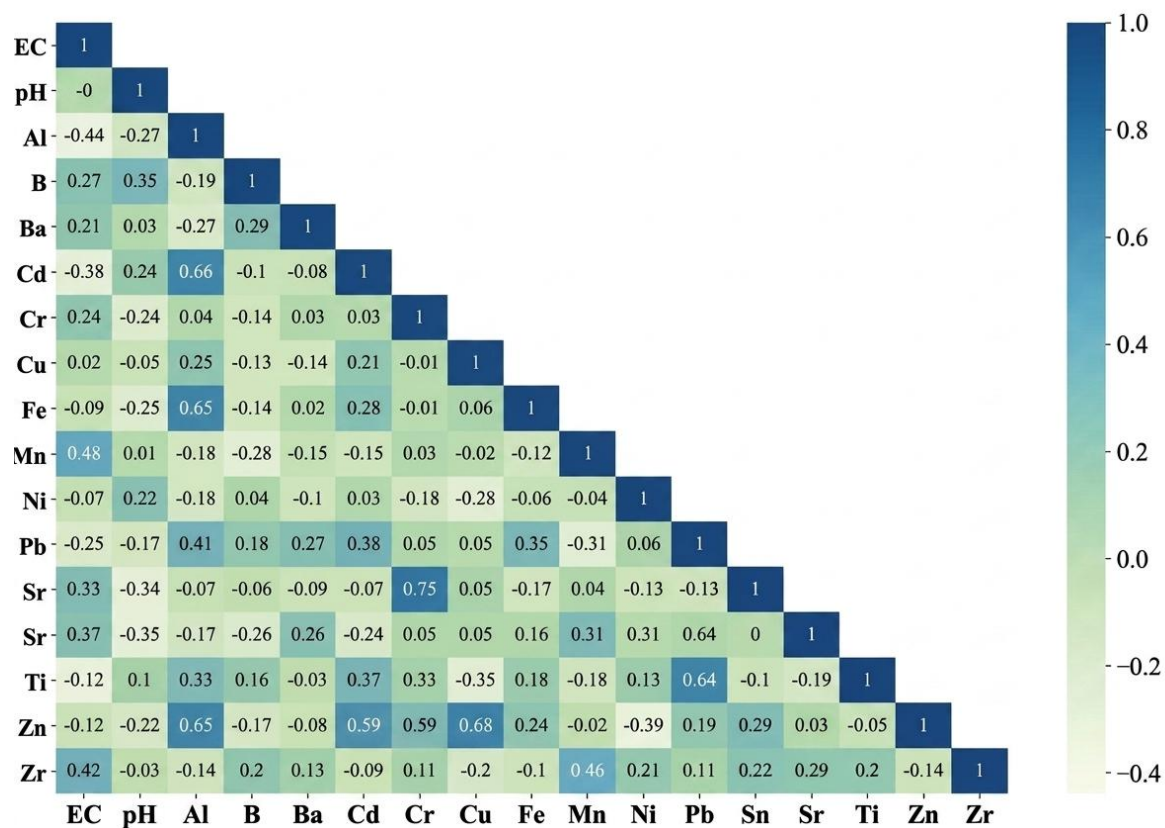
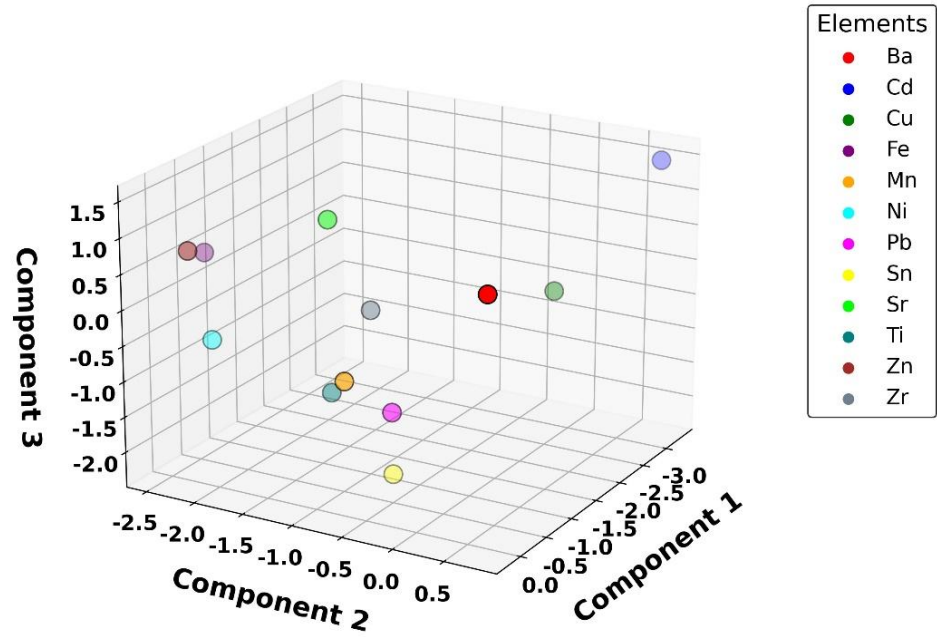


Fig 8: SpearHeat map of the parameters

### Component Plot in Rotated Space



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1005 **Fig 9.** Component plot for heavy metals in drinking waters in south western part of Bangladesh.

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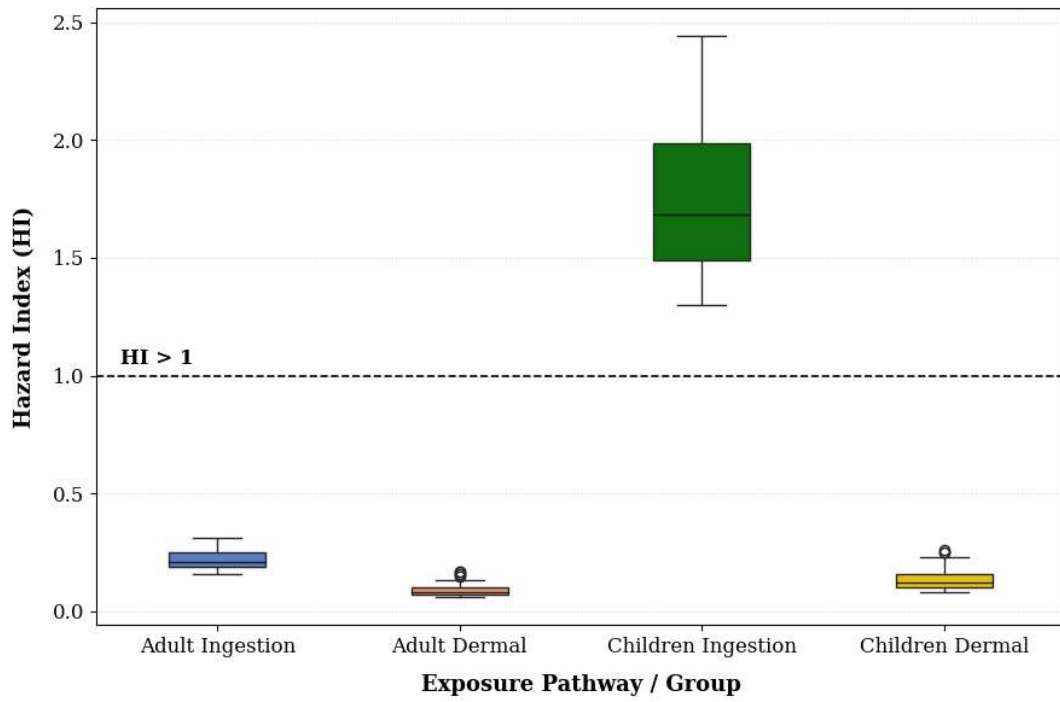


**Fig 10.** Distribution of HI values for adults and children

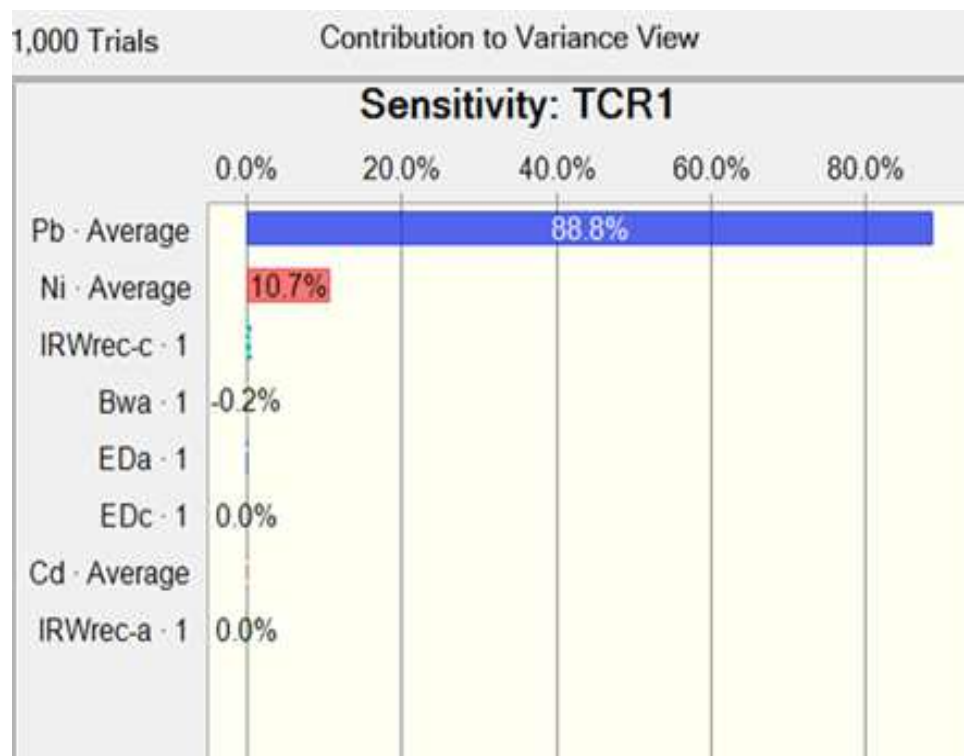


**Fig. 11.** Uncertainty simulation results and parameter sensitivity of CR<sub>total</sub>

**Table 1:** Heavy metal concentrations ( $\mu\text{g/l}$ ) in groundwater samples from Jashore Sadar including recommended values by WHO, BMAC and Indian Standards.

| Heavy Metals | Range          | Mean   | Standard Deviation | Reference Study                              |                                       | WHO (2011) | BMAC (1997) | Indian Standards (2012) |                   |
|--------------|----------------|--------|--------------------|----------------------------------------------|---------------------------------------|------------|-------------|-------------------------|-------------------|
|              |                |        |                    | Bangladesh                                   | International                         |            |             | Acceptable limit        | Permissible limit |
| <b>Al</b>    | 127.45- 720.05 | 234.70 | 159.37             | -                                            | 12.3 <sup>a</sup> -33.1 <sup>b</sup>  | ≤ 200      | -           | -                       | -                 |
| <b>B</b>     | 61.04-132.45   | 90.69  | 17.79              | -                                            | 67.1 <sup>a</sup>                     | -          | -           | -                       | -                 |
| <b>Ba</b>    | 40.37-228.13   | 71.70  | 38.59              | -                                            | 14.1 <sup>a</sup>                     | ≤ 700      | -           | -                       | -                 |
| <b>Cd</b>    | 0.09- 8.04     | 2.54   | 1.80               | -                                            | 0.4 <sup>b</sup> -2.14 <sup>a</sup>   | ≤ 3        | -           | -                       | -                 |
| <b>Cr</b>    | 0.42-12.27     | 2.83   | 2.13               | -                                            | 4.0 <sup>b</sup>                      | ≤ 50       | -           | -                       | -                 |
| <b>Cu</b>    | 14.47-56.00    | 21.51  | 7.91               | 30.0 <sup>c</sup>                            | 3.87 <sup>a</sup> -5.03 <sup>b</sup>  | ≤1000      | -           | -                       | -                 |
| <b>Fe</b>    | 43.71-3021.50  | 409.97 | 746.65             | 47 <sup>a</sup> - 5951 <sup>cdefghijk</sup>  | 29.7 <sup>a</sup> -77 <sup>b</sup>    | ≤300       | 300-1000    | 300                     | --                |
| <b>Mn</b>    | 29.98-986.41   | 253.74 | 323.15             | 0.64 <sup>d</sup> -1470 <sup>cdefghijk</sup> | 13.9 <sup>a</sup> -337 <sup>b</sup>   |            | 100         | 100                     | 300               |
| <b>Ni</b>    | 3.04-33.72     | 13.02  | 8.11               |                                              | 4.7 <sup>l</sup> -26.6 <sup>n</sup>   | 70         | 100         | 20                      | -                 |
| <b>Pb</b>    | 33.92-68.35    | 51.65  | 7.68               |                                              | 13.7 <sup>n</sup> -71.0 <sup>lm</sup> | ≤10        | 50          | 10                      | -                 |
| <b>Sn</b>    | 5.92-21.78     | 10.78  | 3.30               |                                              |                                       | -          | -           | -                       | -                 |
| <b>Sr</b>    | 313.85-573.36  | 448.77 | 71.30              |                                              |                                       | -          | -           | -                       | -                 |
| <b>Ti</b>    | 22.53-56.89    | 43.78  | 7.04               |                                              |                                       | -          | -           | -                       | -                 |
| <b>Zn</b>    | 31.42-134.55   | 62.06  | 33.40              | 6 <sup>g</sup> -180 <sup>cdefhijk</sup>      | 3.99 <sup>b</sup> -12.8 <sup>a</sup>  | -          | 5000        | 5000                    | 15000             |
| <b>Zr</b>    | 36.13-69.74    | 49.00  | 8.94               |                                              |                                       | -          | -           | -                       | -                 |

1050 WHO- World Health Organization; BMAC- Bangladesh Maximum Admissible Concentration; <sup>a</sup>Triassi et al., 2023, <sup>b</sup>Meng et al., 2023; <sup>c</sup>Rahman and Habiba et  
1051 al., 2023; <sup>d</sup>Bodruza et al, 2020; <sup>e</sup>Sarker and Zaman, 2003; <sup>f</sup>Islam et al, 2017a; <sup>g</sup>Islam et al, 2017b; <sup>h</sup>Mostafa et al, 2017; <sup>i</sup>Bhuiyan et al., 2016; <sup>j</sup>Bodruza et al., 2016;  
1052 <sup>k</sup>Rahman et al., 2017; <sup>l</sup>Wu et al., 1998; <sup>m</sup>Westerlund and Viklander, 2006; <sup>n</sup>Zhao et al., 2010;

**Table 2:** KMO and Bartlett's Test

|                                                  |                    |         |
|--------------------------------------------------|--------------------|---------|
| Kaiser-Meyer-Olkin Measure of Sampling Adequacy. |                    | 0.400   |
| Bartlett's Test of Sphericity                    | Approx. Chi-Square | 262.627 |
|                                                  | df                 | 136     |
|                                                  | Sig.               | 0.000   |

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1076 Table 3: Carcinogenic risk (CR) and total CR (TCR) values of Cd, Ni, Pb

| Sampling Site | CR ingestion | CR Dermal | TCR      |
|---------------|--------------|-----------|----------|
| S1            | 6.95E-08     | 1.94E-08  | 8.90E-08 |
| S2            | 1.24E-07     | 5.48E-08  | 1.79E-07 |
| S3            | 1.74E-07     | 8.06E-08  | 2.55E-07 |
| S4            | 2.72E-07     | 1.32E-07  | 4.04E-07 |
| S5            | 7.31E-08     | 1.38E-08  | 8.69E-08 |
| S6            | 1.84E-07     | 7.78E-08  | 2.62E-07 |
| S7            | 1.34E-07     | 5.11E-08  | 1.85E-07 |
| S8            | 1.36E-07     | 5.73E-08  | 1.94E-07 |
| S9            | 1.60E-07     | 6.28E-08  | 2.22E-07 |
| S10           | 1.62E-07     | 6.75E-08  | 2.29E-07 |
| S11           | 1.58E-07     | 6.19E-08  | 2.19E-07 |
| S12           | 1.75E-07     | 7.39E-08  | 2.49E-07 |
| S13           | 2.30E-07     | 1.07E-07  | 3.37E-07 |
| S14           | 1.60E-07     | 6.93E-08  | 2.29E-07 |
| S15           | 1.90E-07     | 8.57E-08  | 2.76E-07 |
| S16           | 1.82E-07     | 9.01E-08  | 2.72E-07 |
| S17           | 8.85E-08     | 2.59E-08  | 1.14E-07 |
| S18           | 1.10E-07     | 4.13E-08  | 1.51E-07 |
| S19           | 7.12E-08     | 1.62E-08  | 8.74E-08 |
| S20           | 2.20E-07     | 1.02E-07  | 3.21E-07 |
| S21           | 6.74E-08     | 1.53E-08  | 8.27E-08 |
| S22           | 1.18E-07     | 4.82E-08  | 1.66E-07 |
| S23           | 8.94E-08     | 2.50E-08  | 1.14E-07 |
| S24           | 1.12E-07     | 3.01E-08  | 1.42E-07 |
| S25           | 1.01E-07     | 2.85E-08  | 1.29E-07 |
| S26           | 9.04E-08     | 2.57E-08  | 1.16E-07 |
| S27           | 8.01E-08     | 2.16E-08  | 1.02E-07 |
| S28           | 9.05E-08     | 2.37E-08  | 1.14E-07 |
| S29           | 1.05E-07     | 3.60E-08  | 1.41E-07 |
| S30           | 9.51E-08     | 2.93E-08  | 1.24E-07 |
| S31           | 4.02E-06     | 1.57E-06  | 5.59E-06 |

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