Heliyon 10 (2024) e35738

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Exploration of trace elements in groundwater and associated human health risk in Chattogram City of Bangladesh

Md. Muzamamel Hoque [a,b], Md. Arif Hossen [c,*], Mst. Farzana Rahman Zuthi [a,c,**], Md. Reaz Akter Mullick [a], S.M. Farzin Hasan [a], Farjana Khan [a], Trisa Das [d]

[a] *Department of Civil Engineering, Chittagong University of Engineering and Technology (CUET), Chattogram, 4349, Bangladesh*
[b] *Southern University Bangladesh, Chattogram, 4000, Bangladesh*
[c] *Institute of River, Harbor and Environmental Science (IRHES), Chittagong University of Engineering and Technology (CUET), Chattogram, 4349, Bangladesh*
[d] *Department of Urban and Regional Planning, Chittagong University of Engineering and Technology (CUET), Chattogram, 4349, Bangladesh*

ARTICLE INFO

Keywords:
Groundwater
Trace metals
Health risk
Spatial analysis
Pollution sources

ABSTRACT

The study aimed to evaluate trace metals in the groundwater of Chattogram City located on the southeastern coast of Bangladesh and assess their potential health risks. Given the city's unique characteristics as both a coastal and industrial hub in Bangladesh, a knowledge gap persists particularly in the assessment of trace metals. A random sampling technique was applied to collect one hundred and seventeen groundwater samples from different wards of the city to analyze some trace metals (Cr, Cd, Fe, Cu, Mn, Pb, and Zn) and the quality of the collected water samples was evaluated using different indices, such as Heavy Metal Evaluation Index (HEI), Groundwater Quality Index (GWQI), Heavy Metal Pollution Index (HPI), and Degree of Contamination (C_d). The average concentration of all the studied metals except Fe, Mn, and Cd satisfied the Bangladesh drinking water standards. The Fe, Mn, and Cd content were observed higher in shallow wells (depth 10–150 ft) followed by intermediate (151–300 ft) and deep wells (>300 ft). However, the Cr, Cu, and Zn content did not significantly change with aquifer depth. The spatial distribution map showed that the highest values of Mn and Cu were observed in the west-northern region of the city. Metal As was only found in shallow and intermediate aquifers. The HEI suggested that about 9 % of samples fall into the higher degree of pollution category similar to the GWQI, while 37 % and 42 % of samples exhibited a higher degree of pollution in the case of HPI and C_d, respectively. The positive correlations and loadings found in the statistical analysis indicated that Fe, Mn, and Cu originated from the same sources. A variety of industrial activities might be ascribed to this type of pollution. However, an average Hazard Quotient (HQ) through ingestion was found to be greater than 1 for Cd, and the Carcinogenic Risk (C_R) values for children were identified as two-fold higher than that of adults. Raising social awareness, avoiding the usage of groundwater without proper treatment, and strict regulations and monitoring by the concerned authority are recommended in the study.

---

* Corresponding author.
** Corresponding author. Department of Civil Engineering, Chittagong University of Engineering and Technology (CUET), Chattogram, 4349, Bangladesh.
E-mail addresses: arifhossen0101@cuet.ac.bd (Md.A. Hossen), farzana@cuet.ac.bd (Mst.F.R. Zuthi).

https://doi.org/10.1016/j.heliyon.2024.e35738
Received 20 November 2023; Received in revised form 8 July 2024; Accepted 2 August 2024

1. Introduction

Providing adequate and safe water for human beings is crucial in the era of sustainable development and global climate change. To date, approximately two billion people worldwide still face a shortage of safe drinking water [1], posing a significant challenge for policymakers striving to achieve Sustainable Development Goal 6 (SDG-6) of securing safe water for all by 2030. In many developing countries, most surface water sources have become polluted by untreated domestic waste, potentially toxic industrial effluents, and hazardous agrochemicals, rendering them unsuitable for use without proper treatment. As a result, groundwater has emerged as a major and primary source for drinking, agriculture, and industrial demand in numerous countries due to its ready availability and natural protection against microbial contamination [2,3]. However, the quality and quantity of groundwater are progressively deteriorating worldwide due to excessive extraction, uncontrolled urbanization, rapid industrialization, intensive agricultural activities, and other factors [4–6]. Various inorganic elements, particularly trace or heavy metals, have been identified as significant sources of groundwater pollution [7,8]. While some heavy metals are essential for human nutrition and health, excessive intake of these potentially toxic metals can pose both non-carcinogenic and carcinogenic risks to human health [9,10]. Therefore, the utilization of contaminated groundwater aquifers and the associated health risks have become critical environmental issues worldwide, particularly in developing countries.

Natural processes like evaporation, secondary mineral precipitation, mineral dissolution, redox reactions, cation and anion exchange, microbial processes, etc., significantly influence the water-rock interactions that regulate groundwater quality [11,12]. Along with these natural processes, various anthropogenic activities like mining, smelting, leaching of industrial and municipal wastewater, and agricultural activities speed up the intrusion of heavy metals into the groundwater [12,13]. Several studies have shown that the metals Pb, As, Zn, Mn, Cd, Cr, Cu, Fe, etc., are the most frequently found in groundwater worldwide [5,6,14]. According to Mahapatra et al. [14], most of the groundwater samples taken in Chennai contained heavy metals (Cu, Cr, Mn, and Pb) and were subsequently unsuitable for human consumption. In contrast, Rushydi et al. [15] verified in a study on Indonesian groundwater that the salinity content of the water significantly affects the dissolution of Fe and Mn.

Numerous studies indicated that the consumption of trace metal-contaminated drinking water can lead to various health complications, such as hypertension, vascular disease, gastrointestinal bleeding, cancer, restrictive lung disease, neurological disorders, and reproductive consequences [16,17]. The scientific community has dedicated significant efforts to investigating and assessing the health risks associated with exposure to trace elements in groundwater, focusing on various related topics [6,7,18]. Elevated Cu levels in drinking water can lead to serious health issues, including kidney and liver diseases [19]. Similarly, excess Fe, while necessary for bodily functions, can harm organs like the liver, pancreas, and heart and contribute to conditions such as anaemia [19]. Long-term exposure to high Mn concentrations in drinking water may result in neurological and reproductive disorders [20,21]. Additionally, Fe and Mn-rich water may entertain bacteria, leading to the formation of reddish-brown or brownish-black slime and clogging water systems. The adverse health effects of Cd include intestinal mucosal necrosis, liver, heart, and kidney damage, and carcinogenic effects [21]. The degree and nature of these risks may vary depending on factors such as age, metabolism, and the specific metals present in groundwater. For instance, in a region of Ghana, non-carcinogenic risks of Fe and Mn were identified for both adults and children, while the carcinogenic hazard index for Pb was less than 1 [6]. Comprehensive monitoring and evaluation measures are, therefore, highly recommended to ensure the safety of groundwater, thereby safeguarding individuals' health and well-being.

Bangladesh, being a country prone to natural disasters and highly vulnerable to climate change, is already experiencing water scarcity to some extent. Without a proper and sustainable water management plan, this situation may worsen significantly in the near future. Furthermore, the country's groundwater quality has emerged as a major concern, like many other developing countries, due to the presence of trace metals and other contaminants in the water. The presence of heavy metals in the country's groundwater is particularly alarming due to their potential toxicity, persistence, and bioaccumulation capacity. Several studies have investigated the contamination of groundwater by trace metals and the associated health risks in different regions of Bangladesh, covering the central west, southern, northern, and central parts of the country [16,22,23]. In the southern part of the Bengal Basin, the scarcity of Fe and As-free drinking water has become an imminent threat [18,24]. Choudhury et al. [25] identified the presence of heavy metals such as Mn, Fe, Zn, and Sr in the groundwater near the Rooppur nuclear power plant and predicted As metal as the only metal posing health risks to adults and children. In another study conducted in Dhaka City, Sharmin et al. [26] reported higher concentrations of Pb and As in the groundwater, while Bodrud-Doza et al. [27] found that Fe and Mn concentrations exceeded national standards for drinking water. Hence, the presence of Mn-rich groundwater, along with As and Fe, has added extra challenges to groundwater management in the country. Another study on the groundwater of the southwest coastal zone of Bangladesh by Choudhury et al. [18] found a moderate non-carcinogenic health risk for adults and that for children was high in the study. However, there was a high cancer risk of As for both the adults and children observed in the study. Rakib et al. [8] observed a higher carcinogenic risk of Cr than that in the case of As and Cd in the water of coastal and floodplain areas of Bangladesh. Although studies have been conducted on trace metals and associated health risks in various parts of Bangladesh, comprehensive research on the groundwater of the southeastern region is still lacking. However, the region is densely populated due to its commercial importance.

In this backdrop, this study represents a comprehensive assessment of selected trace metals occurrence in the groundwater of Chattogram City, located in the southeastern coastal region of Bangladesh. The assessment of groundwater is deemed important considering that a large number of the city's population still relies on groundwater despite the provision of water supply by the Chittagong Water Supply and Sewerage Authority (CWASA). As the country's second-largest city and home to a bustling seaport on the Bay of Bengal, Chattogram serves as an important case study for assessing groundwater contamination. This study has two primary objectives. The first one is to evaluate the extent of trace metal contamination in the groundwater. The second objective is to assess the potential health risks associated with the consumption of trace metal-contaminated groundwater. Moreover, statistical techniques such as correlation analysis, Factor Analysis (FA), and Cluster Analysis (CA) were employed to identify probable sources of pollutants. By undertaking this comprehensive assessment, the study contributes novel insights into the state of groundwater quality and the associated health risks in the city, making it the first of its kind in this region. The findings of this study will greatly benefit water management authorities and public health professionals to gain valuable insights into the occurrence of trace metals in the city's groundwater and potential health risks.

2. Materials and methods

2.1. *Study area and sample analysis*

Chattogram is well-recognized as the commercial hub and the busiest maritime city in the country. The Bay of Bengal, the Halda River, and the Karnaphuli River border the city on its western, north-eastern, and south-eastern sides, respectively. As a coastal city, the present study area is sensitive to climate change. This city experiences tropical monsoon weather similar to other parts of Bangladesh. The average daily temperature of Chattogram City is 25.3 °C, with a yearly rainfall of 2777 mm [28,29]. Around 70–80 % of rainfall occurred during the months of June to September because of which the city experienced severe water logging problems due to the poor drainage network of the city during the rainy season [30]. Fig. 1a shows the drainage density of the study area. Regarding groundwater occurrences, the elevated drainage density corresponds to less water seeping into the ground and subsequently a higher rate of runoff [31]. CWASA is currently supplying 340 MLD of water to its city dwellers through its water distribution network after treating water at its surface and groundwater treatment plants. Around 80 % of the water supplied is from surface water, with the remaining 20 % coming from groundwater drawn from 41 deep tube wells positioned throughout the city, and CWASA supplies water for only 3.2 million city residents with a total population of around 6.0 million [32].

One hundred and seventeen groundwater samples were collected from 41 wards of Chattogram City from May 2021 to September 2021 using a stratified random sampling technique, as portrayed in Fig. 1b. A detailed description of the sampling sites is provided in Table S1. Ward number 10 (Pahartali), 11 (Halishahar), and 26 (North Halishahar) are situated in the western part of the city close to the Bay of Bengal, while ward number 36 (Gosaildanga), 37 (North Middle Halishahar), 38 (South Middle Halishahar), 39 (South Halishahar), 40 (North Patenga) and 41 (South Patenga) are surrounded by the Bay of Bengal in western side and the Karnaphuli river in eastern side. The east-northern part of the city is also near to Karnaphuli River where ward number 18 (East Bakalia), 19 (South Bakalia), 33 (Firinghee Bazar), 34 (Patharghata), and 35 (Boxirhat) are situated. From most of the wards, at least three groundwater samples were collected taking into consideration the depth of local tube wells to categorize as shallow, intermediate, and deep wells. Tube wells were classified into three categories, namely shallow wells (10–140 ft), intermediate wells (140–300 ft), and deep wells (>300 ft) [34]. The depth of the aquifer was identified from the consultation with the tube well's owners. Groundwater samples were mostly collected from wells installed in private residential buildings, small shops, and low-income settlements as well as from the wells of the CWASA. The sampling process involved the extraction of samples from these tube wells. To ensure the quality of the collected samples, a systematic approach was employed. Each well underwent a thorough pumping lasting 2 min before collection. This approach was implemented to secure samples that accurately capture the groundwater composition specific to each well. The well water examined in this study serves various purposes, playing a vital role in drinking, dish cleaning, and handwashing activities.

A flame Atomic Absorption Spectrophotometer (AAS) (Model: AA-7000, SHIMADZU, Japan) with a hollow-cathode lamp as a source of light was employed to measure the concentration of trace metals (Fe, Mn, Cu, Zn, Cr, As, Cd, and Pb). The Minimum Detection Limit (MDL) for Fe, Mn, Cu, Zn, and Cr was 0.01–0.004 mg/L, and for As, Cd, and Pb was 0.002, 0.001, and 0.001 mg/L, respectively.

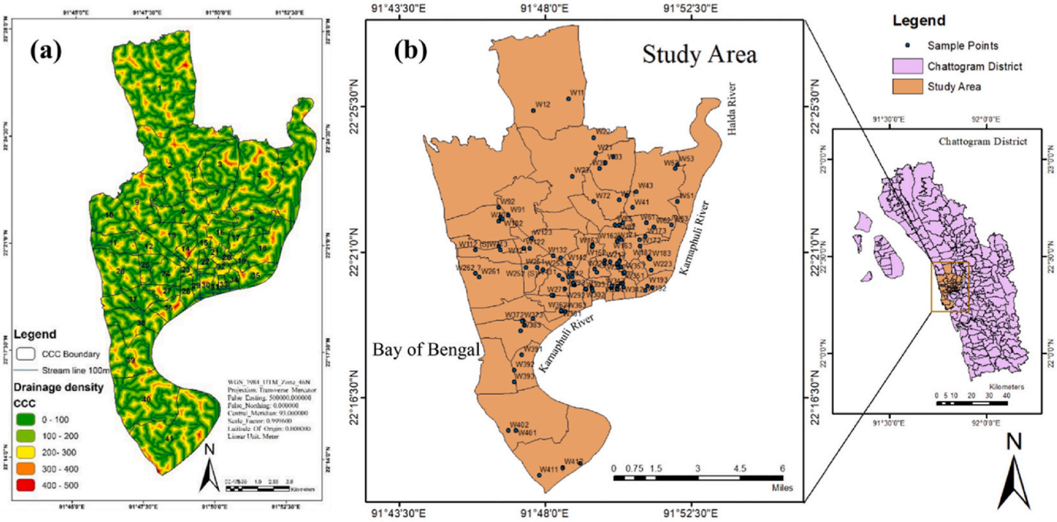

Fig. 1. Study area map of Chattogram City showing (a) Drainage density, adapted from Ref. [33]. (b) Sampling locations.

Calibration of the AAS was done by different concentrations of standard solution. Besides the metals, some basic physicochemical parameters such as pH, Total Dissolved Solids (TDS), and Electrical Conductivity (EC) were measured onsite with a calibrated portable digital pH meter and multi-meter (Model: HACH HQ2100). Three buffer solutions were used to calibrate the pH reading initially, and three water samples were used to determine accuracy. For checking the accuracy of the multi-meter, TDS and EC of the different known solutions were tested before starting actual experiments. The study adhered to rigorous Quality Assurance/Quality Control (QA/QC) protocols to uphold scientific integrity during the sampling and analysis phases. Key procedures encompassed meticulous calibration of instruments, systematic blank and duplicate analyses, and strict adherence to standard operating procedures. These comprehensive protocols were diligently followed to ensure transparency, accuracy, and methodological clarity, bolstering the robustness and reliability of our study's findings.

The data obtained from the trace metal analysis were utilized to calculate various indices such as the Ground Water Quality Index (GWQI), Heavy Metal Pollution Index (HPI), Heavy Metal Evaluation Index (HEI), and Degree of Contamination (C_d) (Table 1). Based on the calculated indices the pollution level of the groundwater was quantified.

2.2. *Statistical and spatial approach*

Multivariate statistical analysis is found to be very effective in extracting meaningful facts from the hydro-chemical database in the groundwater system. In this study, multivariate statistical approaches, including the Pearson correlation matrix, Factor Analysis (FA), and Cluster Analysis (CA), were performed. The Principal Component Analysis (PCA) was carried out using an orthogonal Kaiser's Varimax rotation to make the factors more understandable without altering the primary mathematical database. The varimax rotation can effectively reduce the influence of less crucial attributes on the groundwater quality determined by the PCA. All the statistical analyses were done using the SPSS software (version 26.0). The spatial distribution maps of the groundwater quality dataset were created using the Inverse Distance Weighted (IDW) approach.

2.3. *Risk assessment approach*

Both the carcinogenic and non-carcinogenic risks were carried out following USEPA guidelines [20]. Also, the oral and dermal exposure pathways were considered in the present study. The Chronic Daily Intake (CDI) of different elements via oral and dermal pathways has been estimated by following USEPA [39] and Karim [40] expressed as equations (1) and (2).

$$CDI_{oral} = \frac{(CW \times IR \times EF \times ED)}{(BW \times AT)} \tag{1}$$

$$CDI_{Dermal} = \frac{(CW \times SA \times Kp \times ET \times CF \times EF \times ED)}{(BW \times AT)} \tag{2}$$

where, CDI_{Oral} and CDI_{Dermal} indicate the exposure dose (mg/kg/day), through the oral and dermal pathways, respectively. The corresponding values used in this study to calculate CDI are tabulated in Table 2. However, the non-carcinogenic risks were evaluated by comparing CDI for every exposure pathway to the Reference Dose (R_fD) which is denoted as Hazard Quotient (HQ), defined by equation (3) [40]. A value of $HQ < 1$ indicates a standard level, whereas a value of $HQ > 1$ indicates potential adverse health effects [41].

$$HQ = \frac{CDI}{RfD} \tag{3}$$

Table 1
Equations and parameters for quantification of pollution level.

Index	Equations	Parameters	References
Groundwater Quality Index (GWQI)	$GWQI = \sum_{i=1}^{n} SI_i = \sum_{i=1}^{n} (W_i \times Q_i)$ $W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$ $Q_i = \frac{C_i}{S_i} \times 100$	S_i= Water quality standard value Wi = Assigned weightage C_i = Observed resulted in value "i" indicates the ith parameter	Vasanthavigar et al. [35]
Degree of Contamination (C_d)	$C_d = \sum_{i=1}^{n} C_{fi}$ $C_{fi} = \left(\frac{C_{ai}}{C_{ni}}\right) - 1$	C_{fi} = Contamination factor C_{ai} = Analytical value C_{ni} = Upper permissible concentration	Bhuiyan et al. [36]; Kabir et al. [12]
Heavy Metal Pollution Index (HPI)	$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i}$ $Q_i = \sum_{i=1}^{n} \frac{\lvert M_i - I_i \rvert}{S_i - I_i} \times 100$	Qi = Sub-index Wi = Unit weight n = Number of parameters Mi = Monitored heavy metal Ii and Si = Ideal and Standard values $M_i - I_i$ = The difference between Mi and Ii, and ignored the negative algebraic sign	Mohan et al. [37]
Heavy Metal Evaluation Index (HEI)	$HEI = \sum_{i=1}^{n} \frac{M_c}{M_{mac}}$	M_c = Metal concentration M_{mac} = Maximum allowable concentration	Edet and Offiong [38]

Table 2
Reference Doses (R_fd), slope factor of cancer-causing contaminants (CS_F), and dermal permeability coefficient (Kp) of trace metals used for risk assessment.

Parameters	R_fD (μg/kg/day)		S_F (μg/kg/day)$^{-1}$	Kp (cm/hr.)	References
	Oral	Dermal	Oral		
Fe	300	140	–	1×10^{-3}	USEPA [20]; USEPA [41]; Bortey-Sam et al. [42]
Mn	20	0.8	–	1×10^{-3}	
As	0.3	0.123	0.0015	1×10^{-3}	
Cr	3	0.075	0.0005	2×10^{-3}	
Cu	40	12	–	1×10^{-3}	
Zn	300	60	–	6×10^{-3}	
Cd	0.5	0.005	0.015	1×10^{-3}	
Pb	1.4	0.42	0.0085	1×10^{-3}	

The total non-carcinogenic risk caused by more than one element is estimated by equation (4) which is the summation of HQs for every responsible element, and it is expressed as Hazard Index (HI) [39].

$$HI = HQ_1 + HQ_2 + \ldots \ldots + HQ_n \tag{4}$$

There is no chronic risk assumed to occur at the site with the HI value less than one while $HI > 1$ indicates a non-carcinogenic risk of health [39]. On the other hand, carcinogenic risks are generally calculated as the gradual possibility of a person developing cancer over a lifetime due to exposure to a specific carcinogen [43]. The following carcinogenic risk equation (5) is used to estimate Cancer Risk (C_R) for every exposure route following USEPA guidelines [39].

$$C_R = CDI \times CS_F \tag{5}$$

where CS_F is named as the slope factor of a specific carcinogen which may vary for various routes for specific metals (Table 3). The acceptable value of C_R is in the range of 10^{-6} to 10^{-4} as per USEPA [44] and a $C_R > 10^{-4}$ indicates an increased probability of cancer risk [45].

3. Results and discussions

3.1. *Groundwater quality with varying depths of the study area*

In the study area of Chattogram City, geological records from the Bangladesh Bureau of Statistics (BBS) reveal a prevalent composition of clayey soil mixed with fine brown sand in shallow depth segments, exerting a significant influence on groundwater quality. Groundwater quality is inherently shaped by a region's geographical and geological characteristics, impacting various natural processes such as precipitation, mineral dissolution, groundwater flow, direction, residence time, and intra/inter-aquifer interactions [46]. The observed findings align with these geological influences, demonstrating that water samples from shallow (10–150 ft) and intermediate wells (151–300 ft) exhibited higher metal concentrations than deep wells, except Zn. Additionally, near the Karnafully River, groundwater locations (W391, W13, W14) are significantly affected by the leakage of contaminated surface water. During tidal waves, the water from the Karnafully River may infiltrate groundwater, potentially disseminating trace metals to other regions. In industrial zones such as locations W52 and W53, where garment industries engage in various dyeing activities, elevated levels of Cr are observed in shallow aquifers. Furthermore, contamination from industrial and sewage wastes affects other water bodies in the area, exacerbating aquifer pollution. Sewage line leakages, as highlighted by Bodrud-Doza et al. [27], may also contribute to groundwater contamination in the Chattogram City area. Moreover, sampling locations adjacent to the port (W361, W362, W363) may serve as sources of heavy metals due to various human activities and anthropogenic sources, ultimately affecting other sampling points through pocket flows.

Table 3
Input parameters used for risk assessment according to USEPA [20].

Parameters		Oral		Dermal		Unit
		Children	Adult	Children	Adult	
Exposure time	ET	–	–	1	0.58	h/day
Ingestion rate	IR	1	2	–	–	L/day
Skin area	SA	–	–	6600	18000	cm^2
Exposure duration	ED	10 (18[a])	30 (70[a])	6	30	years
Exposure frequency	EF	365	365	350	350	days/year
Average time	AT	3650 (6570[a])	10950 (25550[a])	2190	10950	days
Body weight	BW	15	70	15	70	kg
Dermal permeability factor	CF	–	–	1×10^{-3}	1×10^{-3}	L/cm^3

[a] Values for carcinogenic risk assessment.

The statistical summary of studied physicochemical water quality parameters and trace metals present in the groundwater samples at different depths along with the respective guideline values and national standards, are shown in Figs. 2 and 3. Moreover, the percentage of water samples exceeded the standard values in case of the studied quality parameters have been shown in Table 4. The pH values of the water samples were in the range of 5.14–7.56 (see Fig. 2a) with an average value of 6.70 ± 0.42 (as shown in Table 4) implying that the studied water is acidic to some degree. The average TDS content of water samples (791 mg/L) satisfies the drinking water quality standards for Bangladesh [47,48]. However, the TDS value of almost 29 % of the total samples was found to be higher than the national standard. The concentration of TDS was found to be higher in shallow tube wells followed by intermediate and deep tube wells. The EC of that water was found in the range of 157–8400 μS/cm having an average value of 1753 μS/cm. In a study conducted by Hoque et al. [49] in some areas of Chattogram City, the EC and TDS content were observed as approximately 1000–11000 μS/cm and 1000–7000 mg/L, respectively. This variation between the two studies might be due to the varying study periods and sampling sites as the sites of the later study were close to the sea areas of the city. However, EC is very important in the case of drinking water quality, and a higher value of EC indicates increased ionic strength and high TDS content in groundwater [10,16,50].

The difference in trace element concentrations in groundwater is influenced by the activities and types of adjacent areas as well as the characteristics of the aquifer. In trace elements analysis, the Fe content ranged from 0.01 to 13.54 mg/L with a mean value of 2.03 mg/L. Among 117 groundwater samples, the Fe concentration was found to be beyond the acceptable value of Bangladesh drinking water quality standard in 59 samples. A relatively higher value of Fe was found in the water of the southern and east-northern parts of the city for both the shallow and intermediate aquifer and of southeastern sites in the case of the deep aquifer. However, low-to-medium concentrations of Fe were found elsewhere in shallow aquifers. The metal Fe is a rising metal in the form of magnetite hematite, naturally. It comes into contact with water during the extraction of metal from its ore [52,53]. In the case of Mn, the highest concentration was found to be 2.56 mg/L, with an average value of 0.35 ± 0.41 mg/L and about 63 % of all the groundwater samples exceeded the Bangladesh water quality standard for drinking purposes (Table 4). However, the presence of Mn in shallow tube wells was found to be significantly higher than in intermediate and deep tube wells. The most common sources of Mn in groundwater are naturally occurring, for example from weathering of Mn-bearing minerals and rocks [54]. Industrial effluent, acid-mine drainage, sewage, and landfill leachate may also contribute Mn to penetrate into groundwater. The average value of As was found to be 0.003 ± 0.008 mg/L, and the majority of the samples satisfy the national drinking water quality for As contamination. The maximum As concentration (06 mg/L) was recorded at an intermediate depth in North Patenga, which is consistent with the previous study conducted by Hossen and Hoque [55]. There is a natural geological source of As in the groundwater of Bangladesh, which could be caused by water abstraction from quaternary, confined, and semi-confined alluvial or deltaic formations [45,56]. The average value of Cu and Zn were within the permissible level except for two sites in the case of Cu. In every sampling site, the As content was found below the detection limit. The average value of Cr was found to be 0.025 ± 0.017 mg/L, ranging from 0.001 to 0.091 mg/L, while only 8.55 % of samples exceeded the permissible value in this case. The highest concentration of Cd was 0.15 mg/L having an average value of 0.011

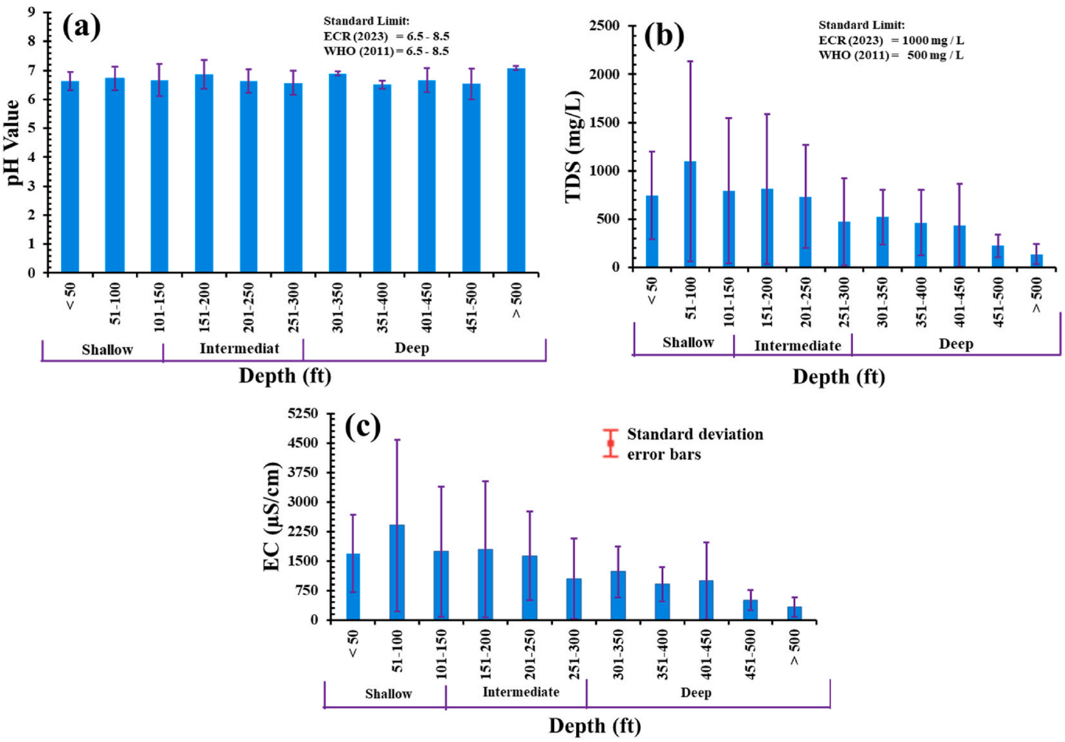

Fig. 2. Physicochemical parameters in groundwater at different depths of Chattogram City (a) pH, (b) TDS, and (c) EC.

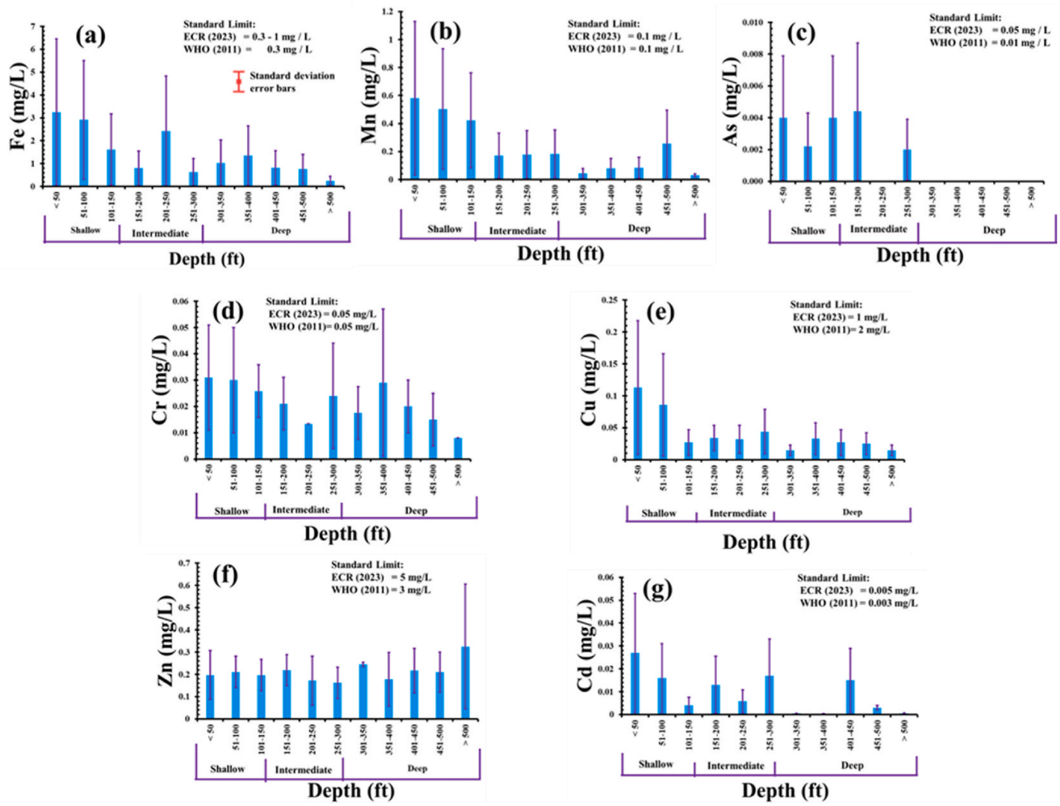

Fig. 3. Trace metals in groundwater at different depths of Chattogram City (a) Fe, (b) Mn, (c) As, (d) Cr, (e) Cu, (f) Zn, and (g) Cd.

± 0.019 mg/L. However, about 38 % of the samples had a Cd concentration higher than the acceptable limits. Both geogenic and anthropogenic sources can elevate Cd concentrations in groundwater. Important anthropogenic Cd sources include mining, atmospheric deposition of combustion emissions, and the use of Cd-containing fertilizers [57]. The concentration of Pb in all the analyzed samples was found below the detection limit (Table 4).

3.2. Comparison of groundwater quality in major districts of Bangladesh

The physicochemical quality of the groundwater of Chattogram City has been compared to studies on that of other districts in Bangladesh which have been shown in Table 5. Except for Khulna, the TDS and EC concentrations were found to be significantly higher in this study than other studies conducted in other parts of Bangladesh which might be ascribed to the possible climate change-induced salinity intrusion into the groundwater of this study area as it is one of the coastal areas of the country. Moreover, the studied groundwater bears a mean concentration higher than the other cities although the water of Chuadanga and Rajshahi districts contain higher Cu and Cd concentrations, and that of Rajshahi, Sylhet, and Khulna districts showed higher Fe concentrations than Chattogram City. Compared to the other studies performed in other districts of the country, the mean concentrations of Mn in major districts of Bangladesh were followed as the order of Rajshahi > Jamalpur > Dinajpur > This study > Sylhet > Chuadanga > Noakhali > Khulna > Dhaka. This variation in metal contents might be because of the variation in underlying rock layer characteristics, human activities surrounding the areas, varying industrial activities, and so on.

The variations in physicochemical quality observed among different districts in Bangladesh, as shown in Table 5, may be attributed to geological differences. The groundwater quality of Chattogram City, being a coastal area, exhibits higher TDS and EC concentrations compared to other districts, potentially due to climate change-induced salinity intrusion. Additionally, the mean concentrations of certain metals in Chattogram City's groundwater are higher compared to other cities, despite variations in Cu, Cd, and Fe concentrations in districts like Chuadanga, Rajshahi, Sylhet, and Khulna. These variations could be influenced by differences in underlying rock layer characteristics, local human activities, industrial operations, and other environmental factors.

3.3. Evaluation of groundwater quality using various indices

There are several indices, such as GWQI, Cd, HPI, and HEI, which have been used to evaluate the overall quality of groundwater, and the calculated evaluation indices are shown in Table 6. The GWQI indicates the overall quality of groundwater while the other

Table 4

The percentage of samples exceeded the standard values.

Parameters	Shallow (10–150 ft) well		Samples exceed BD std. at shallow depth	Intermediate (151–300 ft) well		Samples exceed BD std at Intermediate depth	Deep (>300 ft) well		Samples exceed BD std. at deep	Standard value/guidelines for drinking water quality			Total Samples exceed BD std.
	Mean	SD		Mean	SD		Mean	SD		*ECR* (2023)[a]	*BIS* (2012)[b]	*WHO* (2011)[c]	
pH	6.68	0.41	20 (29 %)	6.79	0.46	6 (27 %)	6.68	0.39	10 (40 %)	6.5–8.5	6.5–8.5	6.5–8.5	36 (31 %)
TDS	901	761	21 (30 %)	706	567	7 (32 %)	452	675	1 (4 %)	1000	–	500	29 (25 %)
EC	1990	1602	–	1688	1539	–	1024	1504	–	–	–	–	–
Fe	2.68	2.67	46 (66 %)	1.14	1.84	5 (23 %)	0.98	1.21	8 (32 %)	0.30–1	0.30	0.30	59 (50 %)
Mn	0.49	0.46	57 (81 %)	0.17	0.21	10 (45 %)	0.13	0.17	7 (28 %)	0.10	0.10–0.30	0.10	74 (63 %)
As	0.003	0.008	0	0.003	0.013	1 (4.5 %)	0.001	0.002	0	0.05	0.01–0.05	0.01	1 (0.85 %)
Cr	0.028	0.017	9 (13 %)	0.02	0.01	0	0.02	0.018	1 (4 %)	0.05	0.05	0.05	10 (8.55 %)
Cu	0.08	0.19	2 (3 %)	0.03	0.02	0	0.028	0.02	0	1	0.05–1.50	2	2 (1.71 %)
Zn	0.20	0.08	0	0.20	0.08	0	0.20	0.11	0	5	5–15	3	0
Cd	0.01	0.02	18 (26 %)	0.01	0.01	4 (18 %)	0.01	0.01	3 (12 %)	0.005	0.003	0.003	25 (37.9 %)
Pb	BDL		0	BDL		0	BDL			0.05	0.01	0.01	0

Note: All units are in mg/L except pH and EC (μS/cm); BDL stands for Below Detection Limit.

[a] Environmental Conservation Rules [48].

[b] Bureau of Indian Standards [51].

[c] World Health Organization [21].

Table 5

Comparison of groundwater quality of Chattogram with major districts of Bangladesh.

Parameters	This study	Other major cities of Bangladesh								
		Noakhali[a]	Dhaka[b]	Chuadanga[c]	Rajshahi[d]	Narayanganj[e]	Jamalpur[f]	Dinajpur[g]	Sylhet[h]	Khulna[i]
pH	6.70 ± 0.42	7.19	7.32	6.47	6.96	8.07	6.87	6.82	6.64	6.88
EC	1753 ± 1724	–	121	686	450	1350	271	–	303	2462
TDS	791 ± 810	398	72.2	–	270	555	162	–	–	1625
Fe	2.033 ± 2.413	1.95	0.21	1.30	2.67	–	0.36	0.35	5.91	2.96
Mn	0.352 ± 0.409	0.130	0.058	0.284	1.835	–	1.075	0.407	0.301	0.091
Cu	0.062 ± 0.155	0.002	–	0.335	0.235	–	0.008	0.038	–	–
Zn	0.204 ± 0.090	0.087	0.002	0.081	0.185	–	0.002	0.016	–	–
As	0.003 ± 0.008	0.039	–	–	0.015	–	–	–	0.022	0.051
Cr	0.025 ± 0.017	–	–	–	–	0.071	0.006	0.011	–	–
Cd	0.011 ± 0.019	0.002	–	0.033	0.015	0.007	0.008	–	–	–

*All units are in mg/L except pH, EC (μS/cm).

[a] Islam et al. [45].

[b] Bodrud-Doza et al. [27].

[c] Bodrud-Doza et al. [16].

[d] Mostafa et al. [22].

[e] Rahman et al. [58].

[f] Zakir et al. [52].

[g] Hossain et al. [23].

[h] Ahmed et al. [10].

[i] Choudhury et al. [18].

indices define the extent of pollution by selected quality parameters. Many researchers have used these indices for the evaluation of groundwater pollution levels [8,12,16,36,46]. The estimated GWQI was found in the range of 17.88–699.15, having a mean value of 151.18. Among all the studied water samples, 18.18 % were rated as excellent, while the remaining 24.24 %, 37.88 %, 10.61 %, and 9.09 % sampling sites were rated as good, poor, very poor, and unsuitable for drinking, respectively.

The extent of metal pollution in the sample sites was identified by the C_d value which gives an integrated effect of various water quality parameters. The obtained C_d values varied from <1 to 48.91, with an average value of 3.51. In this study, the pollution category findings for C_d indicated that 43.94 % of sampling sites were classified as having a low level of contamination, while the remaining 42.42 % and 13.64 % had high and medium levels of pollution, respectively. The water of studied sites contains few heavy metals exceeding standards for drinking purposes, and therefore the HPI was calculated to reflect the composite influence of heavy metals on groundwater quality by assigning appropriate weightage on selected parameters. The range of HPI for the groundwater samples varied from 1.56 to 2440.89, with a mean value of 241.74. It was revealed that 34.54 % of sample locations had low levels of pollution, while the remaining 28.64 % and 36.82 % had high and medium levels of pollution, respectively. The HEI has also been applied in the study to assess the overall water quality concerning heavy metals, and to harmonize the basis for different pollution indices. It was found in the range of 0.34–57.71. Overall, 66.67 % of the sample locations were classified as low-pollution, whereas 24.24 % and 9.09 % were classified as medium-pollution and high-pollution, respectively. The findings of the study are more or less compatible with the studies done in other parts of the country such as in Lakhipur district [36], and Dhaka City [16]. However, the opposite results were obtained in the central west part of the country by Bodrud-Doza et al. [27]. The C_d value indicated in the later study that 95 % of the water

Table 6

Classification of the groundwater quality based on indices value.

Index method	Category	Water class/Pollution level	% of sample
GWQI[a]	<50	Excellent	18.18
	50–100	Good	24.24
	101–200	Poor	37.88
	201–300	Very poor	10.61
	>300	Unsuitable for drinking	9.09
HEI[b]	<10	Low	66.67
	10–20	Medium	24.24
	>20	High	9.09
HPI[c]	<15	Low	34.54
	15–30	Medium	28.64
	>30	High	36.82
C_d[b]	<1	Low	43.94
	1–3	Medium	13.64
	>3	High	42.42

[a] Vasanthavigar et al. [35].

[b] Edet and Offiong [38].

[c] Bodrud-Doza et al. [16].

samples showed a higher degree of pollution. The variation in the results might be due to the differences in the geochemistry of the sample sites, river recharge to the aquifers, depth of aquifers, and others.

However, it is crucial to take an integrated assessment strategy when dealing with conflicting results from various water quality indices. For instance, if one index suggests moderate quality while others indicate significant contamination, it is important to prioritize efforts to address the specific pollutants causing the issues, while also working to improve overall water quality as indicated by the index showing moderate quality. To address conflicting evaluations, policymakers should focus on better monitoring and carefully selecting appropriate parameters, as the selection of water quality parameters is critical in such assessments. By using a multi-faceted approach, including contextual analysis and adaptive management, policymakers can make informed and balanced decisions.

3.4. Spatial distribution of the metals

The spatial distribution maps of the studied metals (Fe, Mn, As, Cr, Cu, Zn, and Cd*)* in groundwater for three types of depth have also been developed using the IDW method which is shown in Figs. 4–6. The spatial distribution maps revealed a significant variance of trace metals distribution in sampling sites of groundwater at different depths. Generally, the dispersion and mobility of trace metals in groundwater are controlled by the presence of metal in particular aquifers and the intrinsic environmental characteristics [45]. The spatial maps indicated an increased level of As, Cr, Cd, and Pb in the southwestern part of the study area, while that of the east-northern part showed low levels for shallow aquifers (Fig. 4). The west-northern (Kattali and Pahartali), northwestern (Bayejid Bostami), and central part (Sholakbahar) of the city have high value in the studied groundwater samples irrespective of aquifer depth while the other parts of the city contain low-to-medium Mn concentration. The central part of the study area showed a lower concentration of metals at intermediate depth, except Mn and Zn (Fig. 5). Most of the metals were concentrated in areas with poor drainage density, which may be related to a higher rate of infiltration. This finding is consistent with the recent study conducted in Scotland by Eschenfelder et al. [59]. Although the overall Zn content was within the permissible limit, a comparatively higher value was observed in the deep aquifer (Fig. 6). The presence of As was noticed only in shallow and intermediate aquifers. Deeper depths often had lower concentrations of As than shallow depths due to the geochemical sorption [60]. There is no specific distribution of trace elements has been observed in the study area which might be ascribed to the complex groundwater chemistry controlled by various factors such as weathering of underlying rock, depth and quality of aquifer, peripheral pollution sources, and others [23].

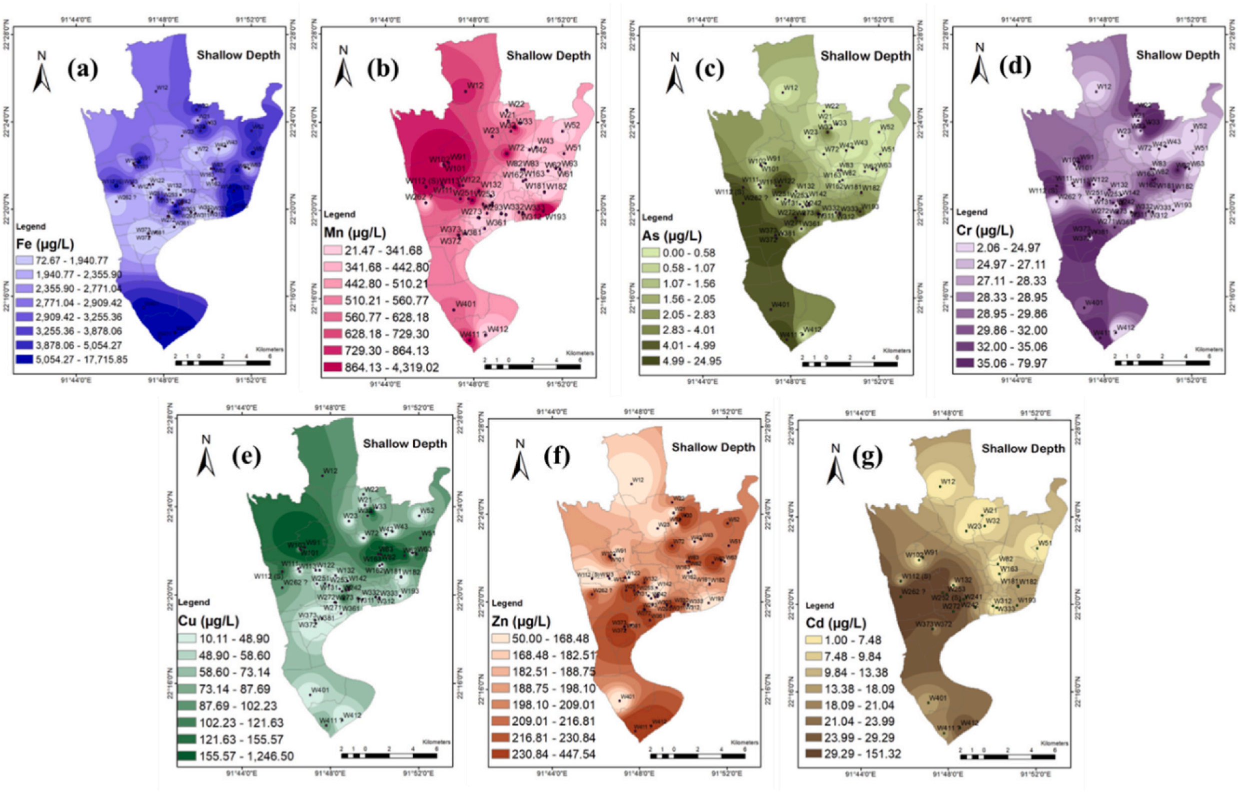

Fig. 4. Spatial distribution of heavy metals at shallow depth in the study area.

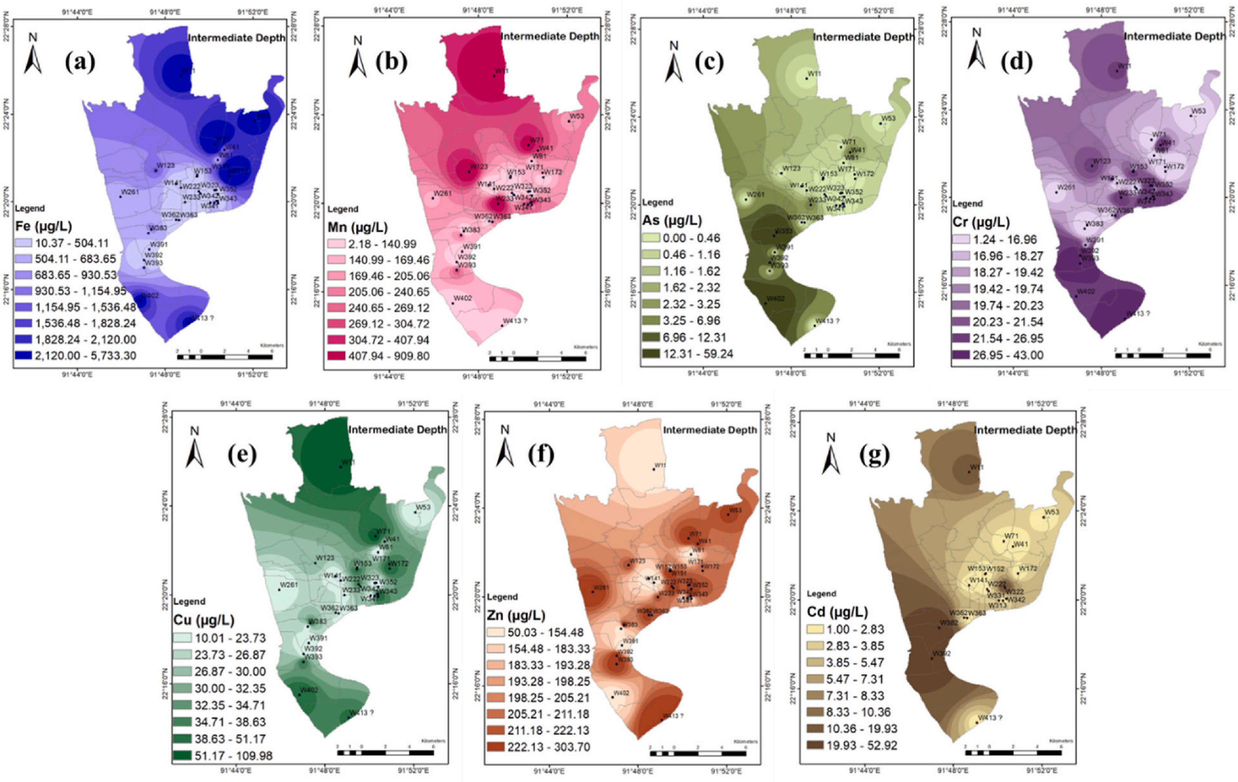

Fig. 5. Spatial distribution of heavy metals at intermediate depth in the study area.

3.5. Statistical analysis for possible sources of pollution identification

Pearson's correlation matrix as well as FA and CA have been used to evaluate the association between the trace metals and physicochemical parameters of groundwater and to find out the probable sources of the metals. A negative correlation has been observed between depth and physicochemical parameters as well as trace metal parameters, except pH which indicates that the quality of groundwater improves with the increase of depth of aquifer, as presented in Table 7. There is a moderate correlation among TDS, EC, and pH ($r = 0.631$, $p < 0.01$) and a weak relation with As ($r = 0.308$, $p < 0.01$). There is no significant relationship between physicochemical parameters and trace metals in the study. The correlation matrix showed a positively weak relationship between Fe and Mn ($r = 0.40$, $p < 0.01$), and between As and Cd ($r = 0.305$, $p < 0.05$) and a moderate relation Mn and Cu ($r = 0.612$, $p < 0.01$). The positive correlation indicates the metals are from the same origin while the negative significant co-relationship means the sources of metals are different [61]. The observed correlation indicating that Fe and Mn, as well as Mn and Cu, have similar sources, while As and Cd share common sources, could be attributed to several factors. The findings of strong relationships between various trace metals in terms of their occurrence align with the concept of homogeneity and coherence of deposition, as discussed by Rakib et al. [8]. The possible sources of these metal contaminants in the present study area can be attributed to both natural processes and human activities such as industrial disposal and agricultural activities. Natural geological formations and processes can contribute to the presence of trace metals in groundwater. Weathering and leaching of mineral-rich rocks and soils may contribute to the release of Fe, Mn, and As into the groundwater. Additionally, geological faults and fractures may serve as conduits for the movement of these metals. Human activities are significant contributors to trace metal contamination in groundwater. Industrial activities, including manufacturing, and waste disposal, can introduce As and Cd into the environment, which can eventually find their way into groundwater through various pathways. Agricultural practices, such as the use of fertilizers and pesticides, can also lead to the presence of Mn and Zn in groundwater. Urbanization and improper waste management can further contribute to metal contamination. Identifying the specific sources and pathways of these trace metals considering seasonal variations would require more detailed investigations, including source apportionment studies, analysis of groundwater flow patterns, and monitoring of industrial and agricultural activities. Such studies can provide valuable insights into the dominant sources of metal contamination in groundwater.

The PCA has been used to identify the potential sources of contaminants in the groundwater of the study area. This method of analysis has been used by many researchers to explain the possible sources of contamination e.g., Bhuiyan et al. [36] and Bodrud-Doza et al. [16]. The KMO value (0.638) and Bartlett's sphericity test values ($p < 0.01$) of this study suggested the suitability of FA analysis. In this study, four components have been extracted having eigenvalues more than 1 which exhibited 70.12 % of total variance (Table 8). In this study, PC1, PC2, PC3, and PC4 were explained by 24.86 %, 21.11 %, 12.54 %, and 11.61 % of the variance

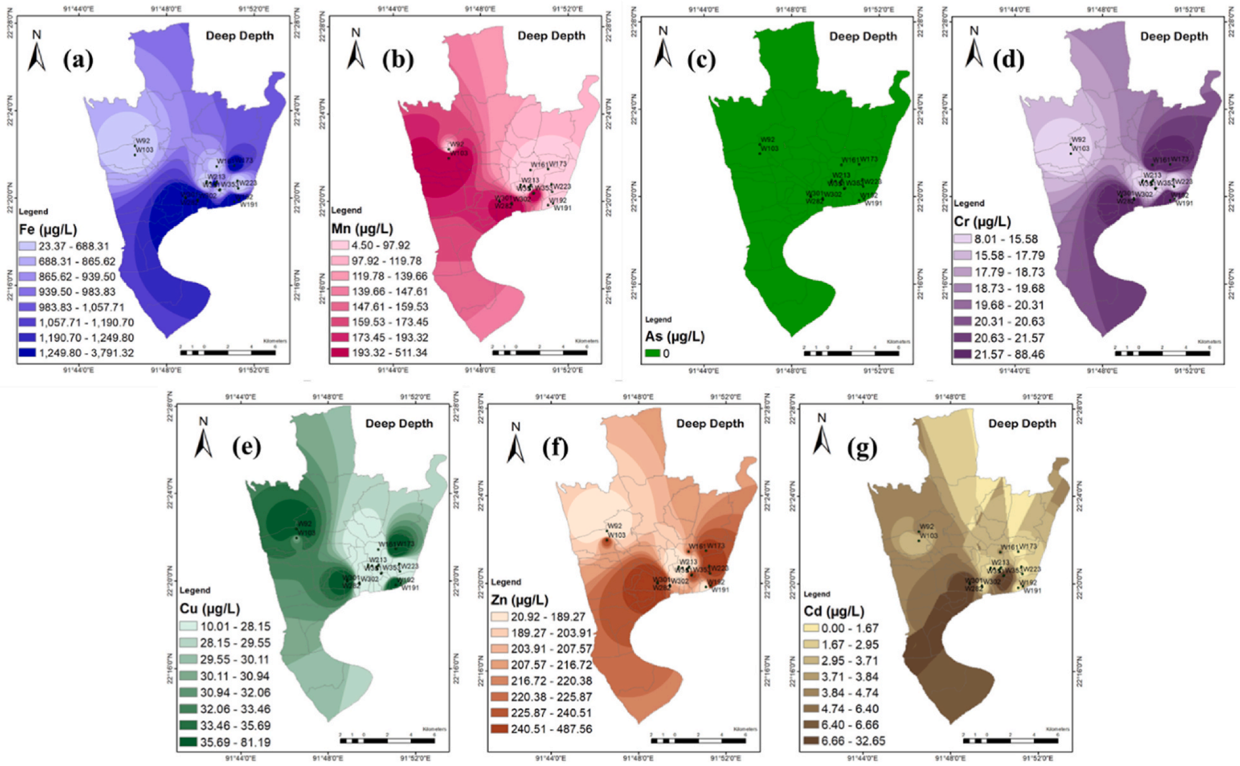

Fig. 6. Spatial distribution of heavy metals at deep depth in the study area.

Table 7
Correlation matrix of the studied parameters (Pearson correlation coefficients).

Parameters	Depth	pH	TDS	EC	Fe	Mn	As	Cr	Cu	Zn	Cd
Depth	1										
pH	0.118	1									
TDS	−0.296[b]	0.631[a]	1								
EC	−0.303[b]	0.631[a]	0.999[a]	1							
Fe	−0.386[a]	0.007	0.187	0.192	1						
Mn	−0.310[b]	−0.226	−0.022	−0.022	0.400[a]	1					
As	−0.152	0.308[b]	0.390[a]	0.391[a]	0.027	−0.013	1				
Cr	−0.372[a]	0.095	0.286[b]	0.278[b]	0.145	0.187	−0.079	1			
Cu	−0.223	−0.164	−0.023	−0.024	0.259[b]	0.612[a]	−0.071	0.115	1		
Zn	−0.099	0.092	0.127	0.122	−0.028	−0.178	−0.055	0.184	0.029	1	
Cd	−0.229[b]	0.100	0.306[b]	0.308[b]	0.143	0.095	0.305[b]	0.135	0.030	0.274[b]	1

[a] Correlation is significant at the 0.01 level (2-tailed).

[b] Correlation is significant at the 0.05 level (2-tailed).

respectively (Table 8). Moreover, the scree plot is also used to find out the number of PCs to be retained to recognize the underlying parameter structure (Fig. 7a), and about 70.12 % of the total variance is revealed in the rotated loading plots of the first four components extracted in the study (Fig. 7b). The first component explains that 24.86 % of total variances is positively loaded with pH, TDS, and EC. Bodrud-doza et al. [16] reported in a study that this type of loading might indicate the geogenic hydro-geochemical evolution of groundwater by rock-water interaction with ions exchange. However, being a coastal city, the study area experiences seawater intrusion to some extent, and a higher amount of TDS and EC might be considered as a consequence of the saline intrusion into the groundwater. The PC2 has high loadings in the case of four variables which are Fe (0.658), Mn (0.849), Cu (0.715), and depth (−0.619). The metal Fe is one of those metals that are abundant in nature, and the occurrence of Mn in groundwater is natural from rocks and sediment as a mineral [62]. The presence of Cu in the groundwater has been attributed to the open dumping of municipal waste, agricultural activities, and the erosion and leaching of minerals [63]. Therefore, the PC2 indicates a non-point source of pollution which is being occurred by leaching from underlying rock layers to the aquifer because of both the natural weathering process as well as anthropogenic activities. The PC3 exhibits high loadings with Zn (0.847), and Cd (0.524). The presence of Zn and Cd may occur in groundwater by geogenic processes which is increased by human activities such as unplanned industrial activities, the use of various

Table 8
Varimax rotated principal component matrix of the studied factors.

Parameters	Principal components			
	PC1	PC2	PC3	PC4
Depth	−0.189	−0.619	−0.350	−0.089
pH	0.807	−0.241	−0.063	0.070
TDS	0.931	0.125	0.131	0.155
EC	0.929	0.128	0.128	0.159
Fe	0.177	0.658	−0.003	−0.043
Mn	−0.134	0.849	−0.145	0.028
As	0.332	−0.010	−0.078	0.788
Cr	0.351	0.372	0.447	−0.422
Cu	−0.156	0.715	−0.035	0.007
Zn	0.016	−0.142	0.847	0.020
Cd	0.093	0.160	0.524	0.643
Eigenvalues	2.734	2.321	1.381	1.277
% of Variance	24.86	21.11	12.54	11.61
Cumulative %	24.86	45.97	58.51	70.12

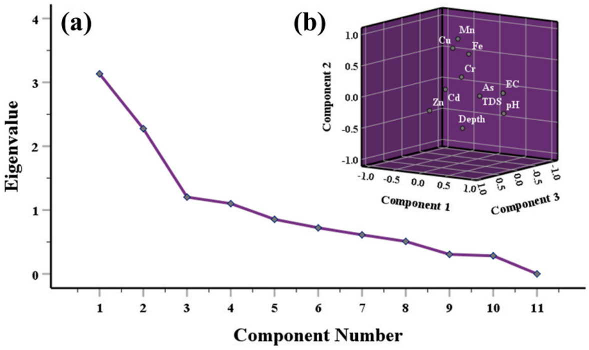

Fig. 7. PCA of the study by (a) scree plot of the characteristic roots (eigenvalues), and (b) **c**omponent plot in rotated space.

chemical fertilizers in agriculture, and others [36]. Moreover, the higher loading of Zn may be ascribed to the cation exchange behavior of the underlying aquifer [64]. The last component PC4 comprises 11.61 % of the total variance and is positively loaded with Cr and As implying that these two elements are from the same sources. These metals mainly are assumed to be originated from anthropogenic sources although there is an abundance of As in groundwater due to the geological formation of the country. Besides, there are many industries such as steel re-rolling mills, pharmaceuticals, textiles, shipbreaking, and oil refineries located in Chattogram City which may be attributed to these types of metals in groundwater. Bodrud-doza et al. [16] also reported that various industries situated in Dhaka City might be responsible for the pollution from different metals.

In this study, the hierarchical CA was also performed, and the PCA and CA results almost complemented each other. In general, parameters from the same cluster were probably originated from the same source [8,36]. The studied physicochemical and heavy metal parameters were grouped into three (03) major clusters (Fig. 8). It showed that cluster 1 includes TDS and EC. These parameters are related to the intrusions of seawater [8]. These three identical parameters were grouped with depth in cluster 2. In cluster 3, all the trace metals are grouped with pH and depth of aquifer. The existence of pH and all trace metals in the same group reflects the influence of geogenic interaction [16]. All the trace metals in cluster 3 are mainly dominated in aquifers of industrial zones [8,36]. The depth of aquifers and trace metals grouped which represents the variability of metals concentration at various depths of the aquifer. Referring to the CA findings, groundwater quality parameters have been categorized based on their potential sources and distributions.

3.6. Human health risk assessment

The estimated HQ and HI to assess the human chronic health risk because of exposure to the groundwater through oral and dermal routes have been shown in Table 9. The HQ_{oral} values of the studied trace metals ranged from 0 to 8.687 for adults while that for the children was found to be 0 to 20.267. However, the average HQ_{oral} values among the sampling sites for Mn and Cd were found to be greater than 1 for children which indicates that the individual appearance of these elements could create a significant hazard to the children of the study area [16,65]. The HQ values via oral routes of trace elements follow the order of Cd > Mn > As > Cr > Fe > Cu > Zn for adults and Cd > Mn > As > Cr > Fe > Cu > Zn (for children). In the case of the dermal pathway, the HQ values of all the trace metals were found to be less than 1 for both the adult and children which shows that the studied trace elements might pose a low level of hazard through dermal routes to the community of the area. However, the HQ_{dermal} of the trace metals values varied from 0 to 1.863

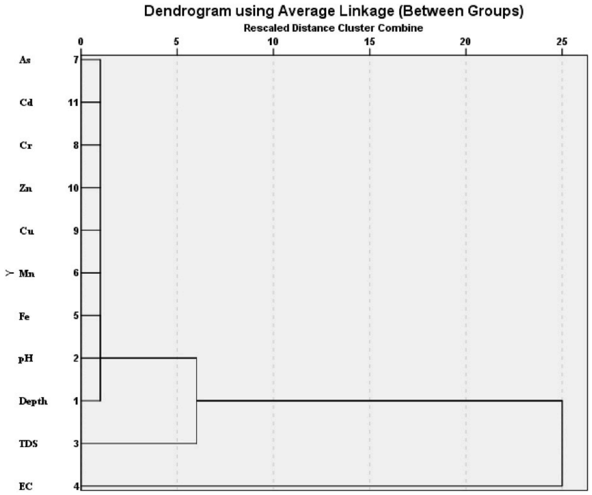

Fig. 8. Dendrogram showing the hierarchical clusters of analyzed parameters.

Table 9
Non-carcinogenic risk (N_{CR}) based on the hazard quotient (HQ) and hazard index (HI) of each analyzed trace metal.

Trace Metals		HQ_{oral}		HQ_{dermal}		HI	
		Adult	Children	Adult	Children	Adult	Children
Fe	Min	1×10^{-3}	2.2×10^{-3}	0	0	1×10^{-3}	2.3×10^{-3}
	Max	1.688	3.938	1.8×10^{-2}	0.053	1.706	3.991
	Mean	0.197	0.459	2.1×10^{-3}	6.2×10^{-3}	0.199	0.466
	SD	0.248	0.579	2.7×10^{-3}	7.9×10^{-3}	0.251	0.587
Mn	Min	1.4×10^{-3}	3.3×10^{-3}	2×10^{-4}	5×10^{-4}	1.6×10^{-3}	3.9×10^{-3}
	Max	6.186	14.433	0.774	2.284	6.959	16.717
	Mean	0.524	1.223	0.066	0.193	0.589	1.416
	SD	0.730	1.704	0.091	0.269	0.822	1.974
As	Min	0	0	0	0	0	0
	Max	5.714	13.333	6.9×10^{-2}	0.206	5.784	13.539
	Mean	0.244	0.571	2.9×10^{-3}	8.8×10^{-3}	0.247	0.579
	SD	0.790	1.843	9.6×10^{-3}	0.029	0.799	1.872
Cr	Min	9.5×10^{-3}	0.022	1.9×10^{-3}	5.6×10^{-3}	0.012	0.028
	Max	0.867	2.022	0.174	0.512	1.042	2.534
	Mean	0.241	0.563	0.048	0.143	0.289	0.706
	SD	0.161	0.375	0.032	0.095	0.193	0.471
Cu	Min	7.1×10^{-3}	0.017	1×10^{-4}	4×10^{-4}	7.3×10^{-3}	0.017
	Max	0.893	2.083	1.5×10^{-2}	0.044	0.908	2.127
	Mean	0.044	0.103	7×10^{-4}	2.2×10^{-3}	0.045	0.105
	SD	0.111	0.259	1.9×10^{-3}	5.5×10^{-3}	0.113	0.265
Zn	Min	1.9×10^{-3}	4.4×10^{-3}	0	1×10^{-4}	2×10^{-3}	4.6×10^{-3}
	Max	0.053	0.124	1.3×10^{-3}	3.9×10^{-3}	0.055	0.128
	Mean	0.0195	0.045	5×10^{-4}	1.4×10^{-3}	0.021	0.047
	SD	0.009	0.020	2.1×10^{-4}	6×10^{-4}	8.8×10^{-3}	0.021
Cd	Min	0	0.133	0	0	0	0
	Max	8.687	20.267	4.348	12.826	13.033	33.093
	Mean	0.797	1.861	0.225	0.664	0.675	1.714
	SD	1.302	3.039	0.531	1.565	1.592	4.037
Average		0.295	0.689	0.049	0.146	0.295	0.719

for adults and 0 to 7.696 for children following the order of Cd > Cr > Mn > Cu > As > Fe > Zn (for adults) and Cd > Mn > As > Cr > Fe > Cu > Zn (for children) (Table 9). The metal Cd had the highest HQ value of all the trace metals for both adults and children. Dermal exposure showed a lower non-carcinogenic health risk than oral exposure, and the HQ values of children were two to three times and four to five times greater than those of adults for oral and dermal exposure, respectively. The same finding has been observed in the case of HI as well, and the average HI values for Mn, and Cd for children were found to be greater than one which is of utmost concern. However, children are more vulnerable to any kind of pollutant ingestion particularly to the acute, sub-acute, and chronic effects of various chemical contaminants as they uptake more than adults per unit of their body weight [27]. The higher HQ or HI values for children indicate that they are more susceptible to the chronic non-carcinogenic effect of trace metals from drinking water on human health, which is similar to recent findings of studies conducted in other parts of Bangladesh [10,45].

In the case of carcinogenic health risk, the typically acceptable value of C_R is reported as 1×10^{-6} to 1×10^{-4} while a value higher than 1×10^{-4} is assumed to pose a high risk for cancer [45,65]. The estimated carcinogenic risk of As, Cr, and Cd via oral exposure to the groundwater in both adults and children has been shown in Table 10. The C_R value of the trace metals (As, Cr, and Cd) varied from 0 to 0.065 for adults and 0 to 0.152 for children. The average values of C_R for all trace metals (As, Cr, and Cd) through the oral exposure pathway were found to be higher than 1×10^{-4} in the case of both the children and adults. However, the C_R of children is found two-fold higher than adults in the study which supports other similar studies in Bangladesh [27,45]. In a study by Bodrud-Doza et al. [27] on the central part of Bangladesh, it was found that almost all the studied groundwater samples fall at high carcinogenic risk via the oral route due to the presence of Cd in the water. Moreover, numerous studies have been conducted worldwide regarding the risk due to the presence of trace metals in groundwater showing different findings. This variation in the results is ascribed to the different groundwater characteristics and geochemistry, human consumption behaviour, life expectancy, and others [27,62].

4. Conclusion

This study has been conducted to evaluate the occurrence of trace metals in the groundwater of Chattogram City as well as to assess the probable health risks due to exposure to these trace metals. The average concentrations of all the trace elements except Fe, Mn, and Cd were found to be within the allowable limits for drinking water quality standards of Bangladesh. The average concentrations of Mn, Fe, and Cd in 63 %, 50 %, and 38 % of the samples, respectively, exceeded the standard limits. The water samples from shallow and intermediate wells had higher values than deep wells for all the metals except in the case of Zn. The HEI suggested that 24 % of samples fall into the medium degree of pollution category, while 89 % and 42 % of samples exhibited a higher degree of pollution in the case of the HPI and C_d respectively.

The spatial distribution map of trace metals showed that Kattali, Pahartali, and Bayejid Bostami areas had higher values of Fe and Mn irrespective of their aquifer depth, while higher values of As, Cr, and Cd in Bandar and Double Mooring areas exhibited at shallow aquifer. The presence of As metal was noticed only in shallow and intermediate aquifers. The complicated groundwater chemistry in the present study area, which is influenced by several variables including the weathering of the underlying rock, the depth and quality of the aquifer, nearby pollution sources, and others, may account for the lack of a precise distribution of heavy metals. Statistical analysis indicates the same sources of pollution in the case of Fe, Mn, and Cu, and the same for As and Cd. The possible sources might be steel re-rolling mills, textiles, shipbreaking, pharmaceuticals, and oil refineries located around Chattogram City.

The average HQ values via the oral route for Cd were obtained to be more than 1 in the study areas, stipulating both the chronic and carcinogenic health risks. The C_R values estimated in the study were identified two-fold more in children than adults, implying that the children of the study area are more susceptible to these metals. It is recommended from this study to investigate the groundwater quality considering seasonal variations. The concerned authority could utilize this study to develop a comprehensive plan to reduce the discharge of these metals into the groundwater as well as to ensure healthy living in the city. However, similar to many other developing countries, social awareness campaigns, strict monitoring and regulations, and avoiding groundwater usage without proper treatment, as well as safe recharge of groundwater could help minimize the health hazards to the city dwellers.

Data availability

The data pertaining to this study have not been deposited in a publicly accessible repository, given that all data collected and/or analyzed during this study will be made available on request to the corresponding author.

CRediT authorship contribution statement

Md. Muzamamel Hoque: Writing – original draft, Software, Methodology, Investigation. **Md. Arif Hossen:** Writing – review &

Table 10
Carcinogenic risk (C_R) of As, Cr, and Cd metals.

Trace Metals		$C_{R\ oral}$	
		Adult	Children
As	Min	0	0
	Max	2.6×10^{-3}	6×10^{-3}
	Mean	1.2×10^{-4}	3×10^{-4}
	SD	3.6×10^{-4}	8.3×10^{-4}
Cr	Min	0	0
	Max	1.3×10^{-3}	3×10^{-3}
	Mean	4×10^{-4}	8×10^{-4}
	SD	2.4×10^{-4}	5.6×10^{-4}
Cd	Min	0	0
	Max	0.065	0.152
	Mean	3.4×10^{-3}	7.9×10^{-3}
	SD	7.8×10^{-3}	0.019
Average		1.3×10^{-3}	3×10^{-3}

editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mst. Farzana Rahman Zuthi:** Writing – review & editing, Supervision, Conceptualization. **Md. Reaz Akter Mullick:** Writing – review & editing, Conceptualization. **S.M. Farzin Hasan:** Visualization, Software. **Farjana Khan:** Writing – review & editing, Formal analysis. **Trisa Das:** Writing – 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.

Acknowledgments

The authors are grateful to the Institute of River, Harbor and Environmental Science (IRHES) (previous: Center for Environmental Science and Engineering Research) and the Department of Civil Engineering, Chittagong University of Engineering and Technology (CUET) for the laboratory support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e35738.

References

[1] S. Selvam, A. Antony Ravindran, S. Venkatramanan, et al., Assessment of heavy metal and bacterial pollution in coastal aquifers from SIPCOT industrial zones, Gulf of Mannar, South Coast of Tamil Nadu, India, Appl. Water Sci. 7 (2) (2017) 897–913.
[2] J. Xiao, L. Wang, N. Chai, T. Liu, et al., Groundwater hydrochemistry, source identification and pollution assessment in intensive industrial areas, eastern Chinese loess plateau, Environ. Pollut. 278 (2021) 116930.
[3] F. Liu, X. Song, L. Yang, et al., The role of anthropogenic and natural factors in shaping the geochemical evolution of groundwater in the Subei Lake basin, Ordos energy base, Northwestern China, Sci. Total Environ. 538 (2015) 327–340.
[4] R. Sharma, R. Kumar, P.R. Agrawal, et al., Groundwater extractions and climate change, in: Water Conservation in the Era of Global Climate Change, Elsevier, 2021, pp. 23–45.
[5] M.G. Uddin, M. Moniruzzaman, M.A. Quader, et al., Spatial variability in the distribution of trace metals in groundwater around the Rooppur nuclear power plant in Ishwardi, Bangladesh, Groundw. Sustain. Dev. 7 (2018) 220–231.
[6] P.A. Opoku, G.K. Anornu, A. Gibrilla, et al., Spatial distributions and probabilistic risk assessment of exposure to heavy metals in groundwater in a peri-urban settlement: case study of Atonsu-Kumasi, Ghana, Groundw. Sustain. Dev. 10 (2020) 100327.
[7] E. Vetrimurugan, K. Brindha, L. Elango, et al., Human exposure risk to heavy metals through groundwater used for drinking in an intensively irrigated river delta, Appl. Water Sci. 7 (6) (2017) 3267–3280.
[8] M.A. Rakib, S.B. Quraishi, M.A. Newaz, et al., Groundwater quality and human health risk assessment in selected coastal and floodplain areas of Bangladesh, J. Contam. Hydrol. 249 (2022) 104041.
[9] J. Morán-Ramírez, R. Ledesma-Ruiz, J. Mahlknecht, et al., Rock–water interactions and pollution processes in the volcanic aquifer system of Guadalajara, Mexico, using inverse geochemical modeling, Appl. Geochem. 68 (2016) 79–94.
[10] N. Ahmed, M. Bodrud-Doza, S.M.D.U. Islam, et al., Hydrogeochemical evaluation and statistical analysis of groundwater of Sylhet, north-eastern Bangladesh, Acta Geochim 38 (3) (2019) 440–455.
[11] N. Saha, M.S. Rahman, M.S., Groundwater hydrogeochemistry and probabilistic health risk assessment through exposure to arsenic-contaminated groundwater of Meghna floodplain, central-east Bangladesh, Ecotoxicol. Environ. Saf. 206 (2020) 111349.
[12] M.M. Kabir, N. Hossain, A.R.M.T. Islam, et al., Characterization of groundwater hydrogeochemistry, quality, and associated health hazards to the residents of southwestern Bangladesh, Environ. Sci. Pollut. Res. 28 (48) (2021) 68745–68761.
[13] A.B. Hasan, A.H.M.S. Reza, M.A.B. Siddique, et al., Spatial distribution, water quality, human health risk assessment, and origin of heavy metals in groundwater and seawater around the ship-breaking area of Bangladesh, Environ. Sci. Pollut. Res. 30 (6) (2022) 16210–16235.
[14] B. Mahapatra, N.K. Dhal, A. Pradhan, et al., Application of bacterial extracellular polymeric substances for detoxification of heavy metals from contaminated environment: a mini-review, Mater. Today: Proc. 30 (2020) 283–288.
[15] I. Rusydy, B. Setiawan, M. Zainal, et al., Integration of borehole and vertical electrical sounding data to characterise the sedimentation process and groundwater in Krueng Aceh basin, Indonesia, Groundw. Sustain. Dev. 10 (2020) 100372.
[16] M. Bodrud-Doza, S.M.D.U. Islam, M.T. Hasan, et al., Groundwater pollution by trace metals and human health risk assessment in central west part of Bangladesh, Groundw. Sustain. Dev. 9 (2019) 100219.
[17] M. Fida, P. Li, S.M. Alam, et al., Review of groundwater nitrate pollution from municipal landfill leachates: implications for environmental and human health and leachate treatment technologies, Expos. Health (2024) 1–25.
[18] M. Choudhury, M. Alomgir, M.A. Rahman, et al., Appraisal of groundwater quality and human health risk for water security and health safety assurance in southwest coastal zone of Bangladesh, Groundw. Sustain. Dev. 21 (2023) 100919.
[19] R. Tadiboyina, P.R. Ptsrk, Trace analysis of heavy metals in ground waters of Vijayawada industrial area, Int. J. Environ. Sci. Educ. 11 (10) (2016) 3215–3229.
[20] USEPA, Risk Assessment Guidance for Superfund Vol. 1 Human Health Evaluation Manual, Part E, Supplemental Guidance from Dermal Risk Assessment, Office of Emergency and Remedial Response, 2004. Washington, DC (USA).
[21] WHO, Environmental Health Criteria 216: Disinfectants and Disinfectant By-Products, 2011. Geneva, Switzerland.
[22] M.G. Mostafa, S.H. Uddin, A.B.M.H. Haque, Assessment of hydro-geochemistry and groundwater quality of Rajshahi City in Bangladesh, Appl. Water Sci. 7 (8) (2017) 4663–4671.
[23] S.M.S. Hossain, M.E. Haque, M.A.H. Pramanik, et al., Assessing the groundwater quality and health risk: a case study on Setabganj sugar mills limited, Dinajpur, Bangladesh, Water Sci 34 (1) (2020) 110–123.
[24] M.T. Ahmed, M.U. Monir, A.A. Aziz, et al., Hydrochemical investigations of coastal aquifers and saltwater intrusion in severely affected areas of Satkhira and Bagerhat districts, Bangladesh, Arabian J. Geosci. 15 (8) (2022) 1–22.
[25] T.R. Choudhury, J. Ferdous, M.M. Haque, et al., Assessment of heavy metals and radionuclides in groundwater and associated human health risk appraisal in the vicinity of Rooppur nuclear power plant, Bangladesh, J. Contam. Hydrol. 251 (2022) 104072.

[26] S. Sharmin, J. Mia, M.S. Miah, et al., Hydrogeochemistry and heavy metal contamination in groundwaters of Dhaka metropolitan city, Bangladesh: assessment of human health impact, HydroResearch 3 (2020) 106–117.

[27] M. Bodrud-Doza, S.M.D.U. Islam, T. Rume, et al., Groundwater quality and human health risk assessment for safe and sustainable water supply of Dhaka City dwellers in Bangladesh, Groundw. Sustain. Dev. 10 (2020) 100374.

[28] M.A. Hossen, A. Hoque, M. Salauddin, et al., Evaluation of physicochemical and trace metal qualities of rainwater in the south-eastern region of Bangladesh, AQUA—water Infrastruct, Ecosyst. Soc. 70 (5) (2021) 757–772.

[29] M.H. Masum, R. Islam, M.A. Hossen, et al., Time series prediction of rainfall and temperature trend using ARIMA model, J. Sci. Res. 14 (1) (2022) 215–227.

[30] S.K. Pal, M.M.H. Masum, M. Salauddin, et al., Appraisal of stormwater-induced runoff quality influenced by site-specific land use patterns in the south-eastern region of Bangladesh, Environ. Sci. Pollut. Res. 30 (13) (2023) 36112–36126.

[31] A. Akter, A.M.H. Uddin, K.B. Wahid, et al., Predicting groundwater recharge potential zones using geospatial technique, Sustain. Water Resources Manag. 6 (2020) 1–13.

[32] N. Ahmed, M.A. Choudhry, M. Khaliquzzaman, et al., An assessment of aquifer potential in and around a proposed well field area near Madunaghat, Chattogram using isotopic techniques, J. Water Resour. Protect. 13 (6) (2021) 395–418.

[33] S. Das, D.R. Raja, Susceptibility analysis of landslide in Chittagong city corporation area. Bangladesh, Int. J. Environ. 4 (2015) 157–181.

[34] J. Wu, M. Yunus, P.K. Streatfield, et al., Impact of tubewell access and tubewell depth on childhood diarrhea in Matlab, Bangladesh, Environ. Health 10 (1) (2011) 1–12.

[35] M. Vasanthavigar, K. Srinivasamoorthy, K. Vijayaragavan, et al., Application of water quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamilnadu, India, Environ. Monit. Assess. 171 (1) (2010) 595–609.

[36] M.A.H. Bhuiyan, M. Bodrud-Doza, A.R.M.T. Islam, et al., Assessment of groundwater quality of Lakshimpur district of Bangladesh using water quality indices, geostatistical methods, and multivariate analysis, Environ. Earth Sci. 75 (12) (2016) 1–23.

[37] S.V. Mohan, P. Nithila, S.J. Reddy, Estimation of heavy metals in drinking water and development of heavy metal pollution index, J. Environ. Sci. Health, Part A 31 (2) (1996) 283–289.

[38] A.E. Edet, O.E. Offiong, Evaluation of water quality pollution indices for heavy metal contamination monitoring. A study case from Akpabuyo-Odukpani area, Lower Cross River Basin (southeastern Nigeria), Geojournal 57 (4) (2002) 295–304.

[39] USEPA, Risk Assessment Guidance for Superfund Volume I Human Health Evaluation Manual (Part A), 1989.

[40] Z. Karim, Risk assessment of dissolved trace metals in drinking water of Karachi, Pakistan, Bull. Environ. Contam. Toxicol. 86 (6) (2011) 676–678.

[41] USEPA, Baseline Human Health Risk Assessment Vasquez Boulevard and I-70 Superfund Site, Denver CO, 2001.

[42] N. Bortey-Sam, S.M.M. Nakayama, Y. Ikenaka, et al., Health risk assessment of heavy metals and metalloid in drinking water from communities near gold mines in Tarkwa, Ghana, Environ. Monit. Assess. 187 (2015) 1–12.

[43] M.M. Rahman, M.A. Islam, M. Bodrud-Doza, et al., Spatio-temporal assessment of groundwater quality and human health risk: a case study in Gopalganj, Bangladesh, Expos Health 10 (3) (2018) 167–188.

[44] USEPA, National Primary Drinking Water Regulations, Drinking Water Contaminants, 2013, pp. 141–142.

[45] A.R.M.T. Islam, M.M. Kabir, S. Faruk, et al., Sustainable groundwater quality in southeast coastal Bangladesh: co-dispersions, sources, and probabilistic health risk assessment, Environ. Dev. Sustain. 23 (2021) 18394–18423.

[46] P. Tahmasebi, M.H. Mahmudy-Gharaie, F. Ghassemzadeh, et al., Assessment of groundwater suitability for irrigation in a gold mine surrounding area, NE Iran, Environ. Earth Sci. 77 (22) (2018) 1–12.

[47] S. Shukla, A. Saxena, Groundwater quality and associated human health risk assessment in parts of Raebareli district, Uttar Pradesh, India, Groundw. Sustain. Dev. 10 (2020) 100366.

[48] ECR, Environmental Conservation Rules, Department of Environment. Ministry of Environment and Forest.People's Republic of Bangladesh, 2023.

[49] A. Hoque, M.A. Hossen, M.F. Islam, et al., Seasonal variation of salinity of ground water at Patenga area of Chittagong district in Bangladesh, Progress. Agric. 30 (2019) 65–70.

[50] M.A. Hossen, A. Hoque, R.A. Jishan, et al., Water quality assessment in terms of water quality index: a case study of the Halda River, Chittagong, Appl. J. Environ. Eng. Sci. 4 (4) (2018) 447–455.

[51] BIS (Bureau of Indian Standards), Indian Standard Drinking Water-Specification, vol. 1, 2012, pp. 1–8.

[52] H.M. Zakir, A. Akter, A. Rahman, et al., Groundwater quality evaluation for irrigation and drinking utilities collected from Sadar Upazila of Jamalpur District, Bangladesh, Asian J. Appl. Chem. Res. 2 (1) (2018) 1–13.

[53] B.H. Jeon, B.A. Dempsey, W.D. Burgos, et al., Reactions of ferrous iron with hematite, Colloids Surf. A Physicochem. Eng. Asp. 191 (1–2) (2001) 41–55.

[54] E.C. Gillispie, R.E. Austin, N.A. Rivera, et al., Soil weathering as an engine for manganese contamination of well water, Environ. Sci. Technol. 50 (18) (2016) 9963–9971.

[55] M.A. Hossen, A. Hoque, Assessment of roof top rainwater harvesting system in saline prone area; A case study of muslimabad housing society, Chittagong. Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development (ICCESD 2018).

[56] M. Chakraborty, A. Mukherjee, K.M. Ahmed, Regional-scale hydrogeochemical evolution across the arsenic-enriched transboundary aquifers of the Ganges River Delta system, India and Bangladesh, Sci. Total Environ. 823 (2022) 153490.

[57] A. Kubier, R.T. Wilkin, T. Pichler, Cadmium in soils and groundwater: a review, Appl. Geochem. 108 (2019) 104388.

[58] M.A.T. Rahman, M. Paul, N. Bhoumik, et al., Heavy metal pollution assessment in the groundwater of the Meghna Ghat industrial area, Bangladesh, by using water pollution indices approach, Appl. Water Sci. 10 (8) (2020) 1–15.

[59] J. Eschenfelder, A.G. Lipp, G.G. Roberts, Quantifying excess heavy metal concentrations in drainage basins using conservative mixing models, J. Geochem. Explor. 248 (2023) 107178.

[60] A. Sarkar, B. Paul, G.K. Darbha, The groundwater arsenic contamination in the Bengal Basin-A review in brief, Chemosphere 299 (2022) 134369.

[61] S.D.U. Islam, R.K. Majumder, M.J. Uddin, et al., Hydrochemical characteristics and quality assessment of groundwater in Patuakhali district, southern coastal region of Bangladesh, Expos. Health 9 (1) (2017) 43–60.

[62] R. Bhutiani, D.B. Kulkarni, D.R. Khanna, et al., Water quality, pollution source apportionment and health risk assessment of heavy metals in groundwater of an industrial area in North India, Expos, Health 8 (1) (2016) 3–18.

[63] CDCP, Copper and Drinking Water from Private Wells, Center for disease control and prevention, Atlanta, USA, 2015.

[64] P.J.S. Kumar, Evolution of groundwater chemistry in and around Vaniyambadi Industrial Area: differentiating the natural and anthropogenic sources of contamination, Geochem. (Tokyo. 1967) 74 (4) (2014) 641–651.

[65] Y. Guo, P. Li, X. He, et al., Groundwater quality in and around a landfill in northwest China: characteristic pollutant identification, health risk assessment, and controlling factor analysis, Expos. Health 14 (4) (2022) 885–901.