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Research article

Arsenic, manganese, and iron concentration in groundwater of northwestern part of Bangladesh using self-organizing maps: Implication for health risk assessment

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A B S T R A C T

Quantification of the non-linear relationship between arsenic (As) and physico-chemical parameters in groundwater through a Self-Organizing Map (SOM) was performed for the first time in Chapai-Nawabganj, Bangladesh. Due to the continuous assessment of groundwater quality, the spatial distribution of As with associated elements was observed for the aerial extent of contaminated groundwater. The results exhibited that 57 % and 31 % of groundwater samples (n = 35) exceeded the allowable limit of As according to the WHO recommended drinking water standard (10 μg/L) and Bangladesh Drinking Water Standard (BDWS) (50 μg/L), respectively. The spatial distribution map of As demonstrated that a higher concentration of As in groundwater was found in the central portion of the study area and less amount was observed in the eastern part. Whereas 83 % of the samples for iron (Fe) concentration in groundwater surpassed the WHO guideline limit (0.3 mg/L) and were distributed all over the area except in the central part. Moreover, manganese (Mn) concentration varied from place to place within the allowable limit of WHO. The SOM analysis elucidated the non-linear relationship of As with other elements in two-dimensional planes of having 49 nodes (7 × 7), which incorporated with Spearman's correlation coefficient quantified the positive correlation among As, Mn and Ca, and negative correlation among As, Fe, EC and pH. In accordance with human health risk was also explained in terms of non-carcinogenic and carcinogenic risk. Health risk assessment demonstrated that higher health hazard (HQ) values in 57 % of the samples exceeded the threshold value for adults through the oral route, which implied the potential non-carcinogenic health risk, while 63 % of the samples for cancer risk (CR) was higher than the allowable limit indicating the considerable cancer risk zone for the residents of the area. This analysis provides information to the planners for formulating effective groundwater resources management and minimizing health sustainably.

1. Introduction

Groundwater is the most important source of freshwater, which is tremendously utilized for drinking, agriculture, and industrial sectors in Bangladesh. Arsenic contamination in groundwater from sedimentary aquifers poses a significant health risk. High concentrations of naturally occurring arsenic have been found in groundwater across various regions, including Bangladesh, China, India, Nepal, Thailand, Taiwan, and Vietnam [1–3]. However, arsenic (As) enrichment in groundwater causes serious environmental

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Abbreviations

ANN	Artificial Neural Network
As	Arsenic
ASS	Atomic Absorption Spectrophotometer
BDWS	Bangladesh Drinking Water Standard
BGS	British Geological Survey
Ca	Calcium
CDI	Chronic Daily Intake
CR	Cancer Risk
DPHE	Department of Public Health Organization
EC	Electrical Conductivity
EPA	Environmental Protection Agency
Fe	Iron
HI	Hazard Index
HQ	Hazard Quotient
HRA	Health Risk Assessment
IDW	Inverse Distance Weighted
ML:	Machine Learning
Mn	Manganese
SOM	Self-Organizing Map
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

disasters in the world like Bangladesh [4–6]. However, elevated As in groundwater with different contaminants deteriorates the groundwater quality, making the water unsuitable for consumption in Bangladesh [7–11]. Lack of awareness about the adverse health effects due to intake of As-contaminated groundwater, most of the people of this region are at significant threat of health risks [12,13]. Elevated level of As in the human body causes long-term health effects such as skin cancers, muscle fatigue and digestive system disturbance [14–16]. In Bangladesh, the geogenic process under natural reducing conditions is the main reason to release of As in groundwater, which deteriorates the groundwater quality [17–21]. Further, several studies stated that the processes of mobilization were also involved with groundwater abstraction [22–24]. So, it is necessary to identify the mechanism of As releasing in groundwater for As risk management. Similar to As, the presence of higher levels of iron (Fe) and manganese (Mn) in groundwater for a long time can also cause severe health problems in human [25]. So, several research works demonstrated the existence and mobilization of As in groundwater of Bangladesh [1,26–28]. Some areas of this region exhibit higher levels of As in groundwater, which may have on hostile health effects due to prolonged consumption of this water. Therefore, regular monitoring and continuous assessment of hydrochemical characteristics are needed to understand the dynamic nature of As contamination with other toxic elements.

The study area is under the Chapai-Nawabganj district, considered an arsenic hotspot region in Bangladesh. Most of the people of this region consume As contaminated groundwater for drinking purposes. For this reason, human health issues are the most concerning for drinking this contaminated water. Several pollution indices are used to evaluate the degree of groundwater contamination, and this contamination level depicts the nature of human health risk potentiality in terms of carcinogenic and non-carcinogenic effects [29,30]. Clarifying the connection between As and other physico-chemical properties helps to comprehend the mobilization of As in groundwater and depict the carcinogenic scenario for this region.

Gradually, machine learning (ML) is a powerful data analysis technique for water quality classification and assessment [31–33]. Self-organizing map (SOM) is an unsupervised method among other algorithms used in ML techniques. This technique is also applied to recognize the geochemical processes by mapping high-dimensional hydrogeochemical data in two-dimensional component planes [34–39]. Previously, linear correlation is mainly used to exhibit the correlation of As with other physio-chemical data in groundwater [40,41]. However, SOM has a visual interpretation feature, which determines the nonlinear relationship between As and others in groundwater [42,43]. In this study, SOM is applying hydrogeological data to decipher the nonlinear relationship of As with other elements and statistical methods to delineate the releasing mechanism of As. Along with this releasing mechanism, it is also important to find out the health risks of As contaminated groundwater, which will conduce to understand the specific aerial extent of As pollution, the chronic daily intake (CDI), hazard quotient (HQ), and carcinogenic risk (CR).

SOM is a powerful technique for non-linear relationships, visualizing complex patterns, and dimensionality reduction rather than more conventional methods like regression and principal component analysis (PCA), or clustering techniques [44]. This holistic approach is applied for the first time in this region to examine the relationship of As with other elements, and this result will provide new insights and enhance understanding about water quality monitoring and decision-making in resource management. Till to date, literature has yet to decipher the self-organizing map (SOM) of As and other physio-chemical elements for analyzing the mobilization of As in the study area. The objectives of this research work are to delineate the nonlinear relationship between As and other physio-chemical data for the assessment of As-enrichment in groundwater, identify the spatial distribution of elevated levels of As and elements, and evaluate the health risk assessment of As to the inhabitants in Chapai-Nawabganj, Bangladesh. For these purposes, self-organizing map (SOM), multivariate statistical methods, and spatial distribution models are applied to elucidate As, Fe and Mn distribution, the nonlinear relationship between As and other elements, and the As-releasing mechanisms in groundwater. In addition, health risk assessment approaches evaluate the As, Fe and Mn-induced potential health risks in the study area. The outcomes of this research can help identify sustainable management strategies for groundwater quality in this region.

2. Location of the study area

The study area covers the Chapai-Nawabganj Sadar upazila, which is in the northwestern part of Bangladesh. It is located between 24° 26′ and 24° 42′ N latitude and 88^0 06′ and 88° 26’ E longitude (Fig. 1). The area exhibits the Ganges-Mahananda floodplain with gentle topographic features, which ranges from 20 to 25 m elevation above mean sea level. The Mahananda River is the major river which flows north to south direction and meets with the Ganges River downstream. Whereas the Ganges River flows from west to southeast direction in the southwestern part of the area. These two prominent river systems may control the quality of groundwater. People of this area are fully dependent on groundwater resources for drinking, domestic, and agricultural purposes.

3. Materials and methods

3.1. Sample collection and analysis

Water samples (35 samples) from aquifers have been collected through tube wells (Fig. 1). Before groundwater sampling, each well should be pumped at least for 10 min. A multi-parameter waterproof portable instrument (HANNA, HI-98194) was used to measure in-situ parameters such as pH, Temperature and electrical conductivity (EC). For each location, two sets of water samples were stored in polypropylene bottles. However, non-acidified groundwater samples were preserved for other water quality parameter analyses, whereas acidified samples were used only for As measurements. All samples were stored safely and transported to the laboratory within five days for further study. An Atomic Absorption Spectrophotometer (AAS; Shimadzu AA-7000) was used to analyze the trace element (As, Fe, Mn, Pb, Cr, Cd and Ni). The level of accuracy and precision of these analyses were examined very carefully.

3.2. Self-organizing map (SOM)

SOM is one kind of an artificial neural network (ANN) which is known as Kohonen map [45]. Having an unsupervised learning algorithm, SOM exhibits an excellent visualization capability and provides an informative pictorial view of the data set. Competitive learning techniques between neighboring nodes are imposed for the training of SOM processes. Basically, the original topology of assigned data is maintained by these neighborhood functions. The input and output layers regulate the structure of the SOM process. The input layer indicates an n-dimensional vector ($X = [x_1, x_2, \ldots, x_m]$), which means the m-variables of data [31,46,47]. Whereas the competitive layer (output layer) is a two-dimensional of having n-nodes (neurons), which is connected in a hexagonal lattice.

The self-organizing map technique was used to examine the relation of As with other elements in the groundwater of Chapai-Nawabganj. The number of nodes in SOM procedures regulates the capability and accuracy of the data set. In this case, no

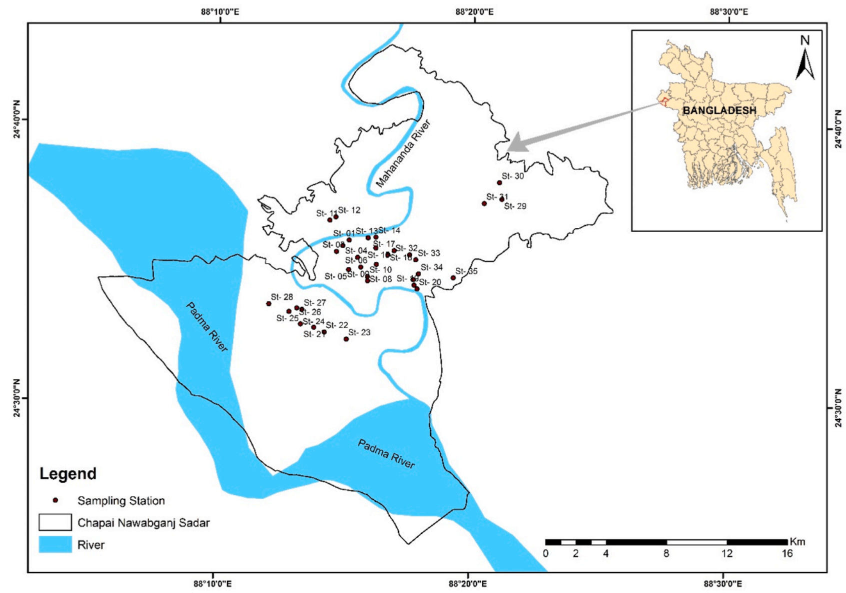

Fig. 1. Sampling location map of the study area.

mandatory rules exist to determine the number of nodes [48]. However, the heuristic formula ($m = 5\sqrt{n}$) was applied to define the number of nodes for a reasonable optimum solution and accuracy. In this formula, m and n represent the number of nodes and input data, respectively [49–51]. In accordance with the SOM architecture (7 × 7), it was selected for the output neurons. SOM was mainly used for correlation hunting. Therefore, the two-dimensional component plane having the original topology was used to recognize the correlation between As and other elements in groundwater.

The color patterns of the component planes represent the level of variables. The color of each node was assigned according to the relative value of the respective variables. High values exhibit in light color whereas low values are in dark color. Similar color gradients of two maps indicate the possibility of positive correlation between the corresponding components, while the opposite gradient represents the correlation in negative order [52]. In this study, self-organizing map was performed using SOM Toolbox in Matlab software.

3.3. Health risk assessment (HRA)

These HRA procedures evaluated the impacts of elevated levels of elements in groundwater on human health due to drinking this groundwater. The chronic daily intake (CDI) was determined for oral and dermal pathways through the following equations (1) and (2) recommended by USEPA [53–56]:

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

$$CDI_{dermal} = (CW \times SA \times EF \times ED \times CF \times ET \times K_p)/(BW \times AT) \quad (2)$$

Where CW is the elemental concentration in groundwater, IR defines the ingestion rate (L/day), EF means the exposure frequency (day/year), BW indicates the body weight (kg), AT means average time (days), ED is the exposure duration (year), CF means the conversion factor (L/cm^3), SA stands for the skin area (cm^2), K_p is the permeability coefficient (cm/hr) and ET indicates the exposure time (h/event). Generally, the hazard quotient (HQ) was determined by the following equations (3) and (4):

$$HQ_{oral} = CDI_{oral}/RfD_{oral} \quad (3)$$

$$HQ_{dermal} = CDI_{dermal}/RfD_{dermal} \quad (4)$$

Where HQ represents the quantitative carcinogenic effects. The reference dose (RfD) of As for oral and dermal is 0.3 μg/kg/day and 0.123 μg/kg/day, respectively. The RfD of Fe and Mn for oral is 700 and 24 μg/kg/day, respectively, while for dermal 140 and 0.96 μg/kg/day, respectively. However, the hazard quotient (HQ) value is less than one, which indicates the negative impact of elements in groundwater on human health. Whereas if the value is greater than one, which signifies the possibility of adverse health effects. The Hazard Index (HI) was calculated by the summation of HQ values for the elements of As, Fe and Mn, and to estimate the overall potential non-carcinogenic effect. The HI is expressed in equation (5) as follows:

$$HI = HQ_{As} + HQ_{Fe} + HQ_{Mn} \quad (5)$$

For carcinogenic risk assessment, the cancer risk (CR) was estimated using the following equation (6):

$$CR = CDI \times SF \quad (6)$$

Where SF denotes the cancer slope factor of contaminants. The threshold value for cancer risk was 1×10^{-4} [57,58].

3.4. Statistical and spatial analysis

The descriptive statistical analyses were conducted through SPSS software. This software was also used to analyze the Spearman's coefficient. Inverse Distance Weighted (IDW) is a simple interpolation and intuitive deterministic method, which was applied to define the spatial variation of groundwater elements. The spatial distribution map of the selected groundwater parameters was prepared using the IDW interpolation method in ArcGIS 10.2.

Table 1
Summary of physico-chemical properties of groundwater samples (n = 35).

Parameters	Minimum	Maximum	Mean ± SD
pH	6.1	7.5	6.8 ± 0.3
EC (μS/cm)	533	2000	1082 ± 405
As (μg/L)	0.2	253	47 ± 66.4
Mn (mg/L)	0.0056	0.36	0.08 ± 0.07
Fe (mg/L)	0.15	0.58	0.43 ± 0.11
Cr (mg/L)	0.0001	0.0091	0.004 ± 0.003
Cd (mg/L)	0	0.0063	0.0006 ± 0.001
Ni (mg/L)	0	0.029	0.012 ± 0.007
Ca (mg/L)	0.18	4.93	3.36 ± 0.9
Pb (mg/L)	0	0.06	0.0059 ± 0.01

4. Results and discussions

4.1. Physico-chemical and trace elements concentration in groundwater

The physico-chemical and trace elements of groundwater samples of Chapai-Nawabganj are shown in Table 1. The pH value ranged from 6.1 to 7.5 (mean 6.8 ± 0.3), indicating the neutral nature of water for this region. This data was compared with previous studies of having the pH value of 7.53 in the northwestern part of Bangladesh [59]. It is also reported that As mobilization in groundwater is very sensitive to the pH value under oxidizing and reducing environments [3]. The EC values ranged from 533 to >2000 μS/cm with a mean value of 1082 ± 405 μS/cm. Among the 35 groundwater samples, only one sample exceeded the range 2000 μS/cm. Another five samples also indicated a high range of EC values (1612, 1742, 1810, 1812, and 1866 μS/cm). The lower EC value indicates the groundwater is fresh, while the higher EC value exhibits the groundwater is saline. According to the EC values of groundwater samples

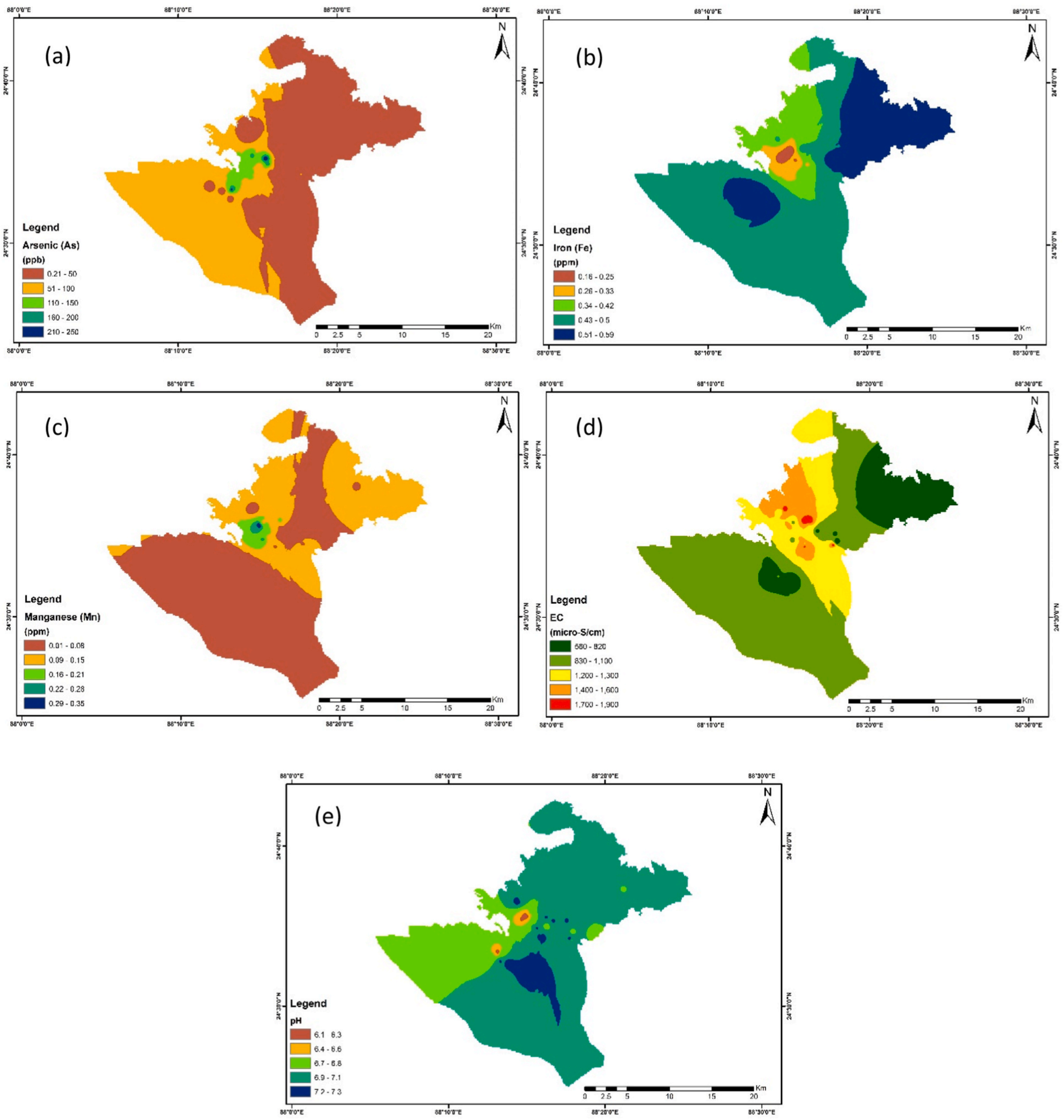

Fig. 2. Spatial distribution of As (a), Fe (b), Mn (c), EC (d) and pH (e) concentration in groundwater.

of this region, 82 % of the sample shows the freshwater category.

As concentration was investigated and presented a wide range of concentration (0.2–253 μg/L) with a mean concentration of 47 ± 66.4 μg/L, where 57 % of the samples exceeded the World Health Organization (WHO) permissible limit (10 μg/L) and 31 % of the total samples surpassed the Bangladesh drinking water standard (BDWS) limits (50 μg/L). Mn value was found to be ranged from 0.006 to 0.36 mg/L with a mean concentration of 0.08 ± 0.07 mg/L. All values for Mn concentration in this study were below the WHO's permissible limit. These values were compared with other reports on Mn concentration in groundwater from different regions of Bangladesh [60–62]. The concentration of Fe ranged from 0.15 to 0.58 mg/L, with the mean value of 0.43 ± 0.11 mg/L. Approximately 83 % of Fe concentration in the groundwater sample exceeded the WHO's limit (0.3 mg/L). The trace elements like as Ca, Cd, Cr, Pb and Ni concentration were found and varied from 0.18 to 4.93 mg/L, 0–0.0063 mg/L, 0.0001–0.0091 mg/L, 0–0.067 mg/L and 0–0.029 mg/L, respectively.

4.2. Spatial distribution of As, Fe, Mn, pH and EC

Spatial distribution of As concentration in groundwater was investigated for this region (Fig. 2a). The higher levels of As were found in the central region of the study area, while the lower As value was observed in the northeastern and eastern parts of the study area. The highest value (112–253 μg/L) of As was noticed at sampling site st-3, st-4, st-6, st-26 and st-27 among 35 sampling stations. These sampling stations are situated near the Mahanada River and this low-lying area is under the floodplain deposit.

The spatial distribution map of iron (Fe) concentration in groundwater of the study area is shown in Fig. 2b. The elevated levels of Fe in groundwater (>0.3 mg/L) were mainly distributed all over the study area except in the central part of the area. These levels of Fe concentration in this area are mainly due to the weathering of bedrock, which is mainly aluminosilicate, and the interaction of water and carbonate rock [63].

The distribution of Mn exhibits spatial variation (Fig. 2c) and the highest values were distributed in the central part of the area, while in other parts of this region Mn varies from place to place, but all values are below the WHO's permissible limit. EC and pH of groundwater were observed throughout the study area (Fig. 2d and e). The higher EC values were observed in the central portion of the area. The highest value (>2000 μS/cm) was pointed at the hot spot which is located at Rajarampur in the central zone, where the depth of the tube-well is about 297 m. Whereas, the north-eastern and south-western regions of the area exhibited lower values of EC. This information provides the fresh and saline zone of groundwater. On the other hand, the pH of groundwater was distributed with the ranges from 6.1 to 7.5 overall in the study area.

4.3. Self-organizing map (SOM) for deciphering the nonlinear relationship

Due to the ability to analyze complex and high-dimensional data, SOM is effective in identifying and providing intuitive visualizations of patterns of water quality or clusters of similar geological or hydrogeological features for long-term environmental monitoring [64–67]. The physical and chemical elements such as EC, pH, As, Fe, Mn and Ca were used for self-organizing map analysis and

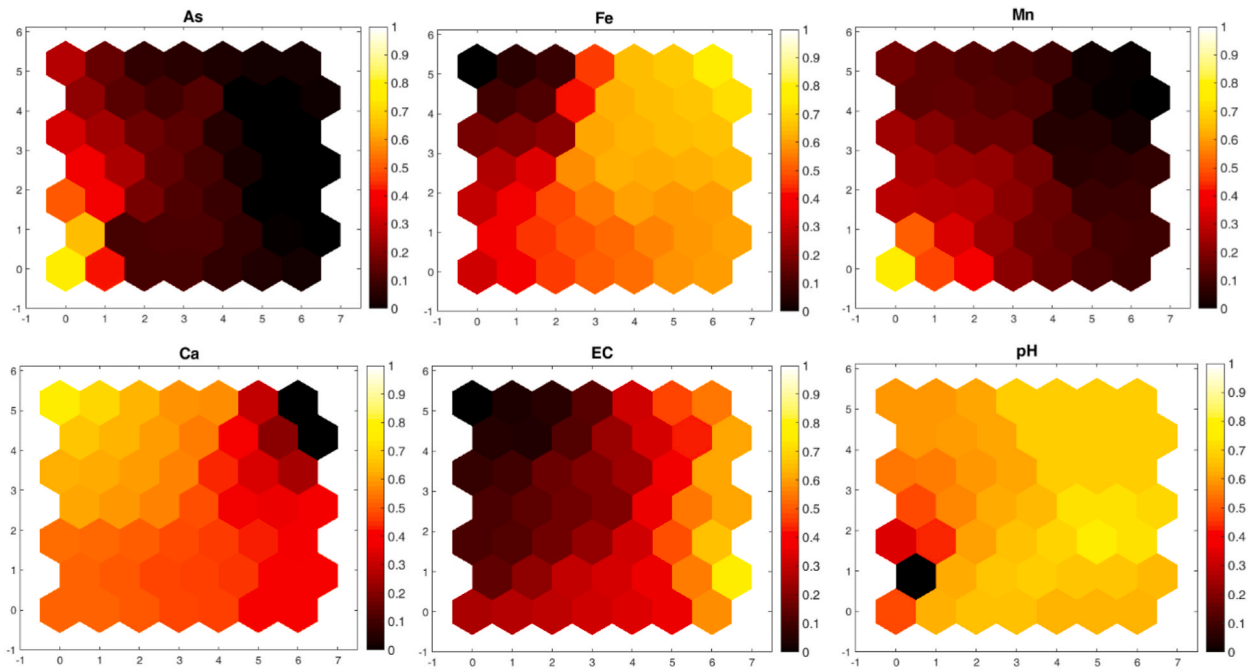

Fig. 3. Component planes for As, Fe, Mn, Ca, EC and pH using self-organizing map (SOM).

presented in the two-dimensional planes (Fig. 3). The number of nodes used for SOM was considered as 49, and the number of rows and column were 7 and 7, respectively. This analysis was used to decipher the nonlinear relationship among the elements in the groundwater of Chapai-Nawabganj. After completion of the training process, each map exhibits the component value of the reference vectors ranging from 0 to 1 with the shades of color. The high value of the nodes indicated light color, while low values were dark color. Comparing the similar topological distribution with color gradients between the components SOM map can point out the qualitative relations among the parameters.

The SOM map of As revealed that the higher values of arsenic existed in the lower left corner of the toroidal map. Lower values of As were observed in the upper right corner of the map. In accordance with As toroidal map, Mn and Ca showed the lowest values in the upper right corner of the map, while the highest values of Mn and Ca were exhibited in the lower and upper left corner of the map, respectively. However, Fe and EC showed the lowest values in the upper left corner of the map. The highest values of Fe and EC are pointed at the upper and lower right corner of the map, respectively. The minimum value of the pH component plane was located in the lower-left corner of the map, while the maximum value was in the upper right corner of the map.

In this process, As, Mn and Ca had similar color gradients through visual investigation of SOM maps, which indicated the possibility of positive correlation among these parameters. In contrast, Fe, EC and pH showed the possibility of negative correlation among these parameters with the reverse color gradient with As of the SOM maps. The non-linear relationship between As and other elements was quantified based on this SOM analysis and the Spearman's correlation coefficient (Fig. 4) was used to define the influence of other parameters on As concentration in groundwater in this region.

4.4. Health risk assessment

The probability of carcinogenic and non-carcinogenic effects of As, Fe and Mn in groundwater for this region is presented in Table 2. Due to long periods of groundwater consumption, the probable health risk assessment is necessary to calculate the potential health concerns of the local residents. These analyses focused on non-carcinogenic and carcinogenic health risks for adults with the consideration of ingestion pathway for As, Fe and Mn, whereas the dermal pathway was considered for only As. Chronic daily intake of As through drinking water varied from 0.0062 to 7.95 μg/kg/day for adults. The mean HQ value remained >1 for oral and it remained <1 for dermal exposure for adults. The HQ value ranged from 0.02 to 26.5, with an average value of 4.95 for oral, while for dermal exposure the HQ value ranged from 0.0002 to 0.29 with the average value of 0.05. Considering the non-carcinogenic risk perspective, 57 % of the samples surpassed the maximum tolerable limit of HQ value for oral, which indicated that As concentration in groundwater may create possible non-carcinogenic risk for adults. HQ values of Fe and Mn varied from 0.0069 to 0.02 and 0.007 to 0.47, respectively. These values may not pose a non-carcinogenic risk for this region. It is evident that HQ values were declined in the following order As > Mn > Fe via oral routes for adults. This analysis exhibited that HQ values for Fe and Mn were less than the threshold value of HQ for adults, suggesting that these two elements may not pose toxic impacts on adults over a longer period of exposure.

However, HQ values of As indicate a significant level of health risk for adults due to drinking groundwater over time. It is also demonstrated that the spatial distribution of HQ values for As was found higher in the central and western part of the region and HQ values for Fe and Mn were distributed all over the area in the allowable limit (Fig. 5). In this study, hazard index (HI) was calculated to assess jointly the non-carcinogenic effects of As, Fe, and Mn. HI results indicated that 21 sampling sites surpassed the allowable limit of USEPA (HI > 1), where HI value ranged from 0.06 to 26.7 with an average value of 5.08, owing to the HQ elevated level of As, which suggested a significant non-carcinogenic health hazard due to continuous drinking of groundwater for the people of this region.

In the case of carcinogenic risk assessment, the cancer risk (CR) values ranged from 9.42×10^{-6} to 0.01, with the mean value of 0.002. It is evident that the mean value of CR was greater than the allowable limit (1×10^{-4}) of USEPA [68] for oral. On the other hand, the CR values ranged from 1.04×10^{-7} to 0.0001 with the mean of 2.4×10^{-5} for dermal. The results of CR showed that 63 % of the groundwater sample was greater than the threshold value, which indicated a considerable cancer risk zone of As-contaminated water for this region. Spatial distribution of carcinogenic risk for adults exhibited that the northeastern and eastern parts of the study area were less cancer risk zones whereas the central part, western part and southwestern part were more vulnerable to cancer risk zone (Fig. 6).

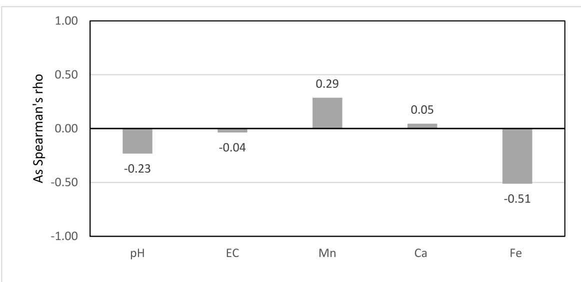

Fig. 4. Spearman's coefficient for selected variables with As.

Table 2
Risk assessment of potential elements in groundwater.

	As				Fe	Mn
	(Oral)		(Dermal)		(Oral)	(Oral)
Station	HQ	CR	HQ	CR	HQ	HQ
1	9.53	0.00429	0.1058	4.763E-05	0.007	0.159
2	9.95	0.0044785	0.1104	4.972E-05	0.009	0.472
3	17.81	0.0080142	0.1976	8.898E-05	0.009	0.306
4	26.50	0.01	0.2941	0.000132	0.010	0.215
5	7.86	0.0035357	0.0872	3.925E-05	0.012	0.305
6	18.33	0.00825	0.2034	9.160E-05	0.013	0.102
7	0.03	1.414E-05	0.0003	1.570E-07	0.014	0.020
8	0.04	1.885E-05	0.0004	2.093E-07	0.014	0.114
9	3.88	0.001744	0.0430	1.936E-05	0.017	0.054
10	5.76	0.002592	0.0639	2.878E-05	0.018	0.188
11	1.57	0.000707	0.0174	7.851E-06	0.020	0.068
12	0.03	1.414E-05	0.0003	1.570E-07	0.017	0.050
13	0.03	1.178E-05	0.0002	1.308E-07	0.022	0.116
14	0.03	1.414E-05	0.0003	1.570E-07	0.020	0.223
15	0.94	0.000424	0.0104	4.710E-06	0.019	0.092
16	4.61	0.002074	0.0511	2.303E-05	0.019	0.015
17	4.19	0.001885	0.0465	2.093E-05	0.021	0.085
18	0.03	1.414E-05	0.0003	1.570E-07	0.021	0.074
19	6.70	0.003017	0.0744	3.349E-05	0.021	0.189
20	0.03	1.414E-05	0.0003	1.570E-07	0.022	0.154
21	5.76	0.002592	0.0639	2.878E-05	0.023	0.028
22	4.30	0.001932	0.0476	2.146E-05	0.023	0.011
23	1.36	0.000612	0.0151	6.804E-06	0.022	0.049
24	2.62	0.001178	0.0290	1.308E-05	0.024	0.039
25	1.15	0.000518	0.0127	5.757E-06	0.024	0.065
26	11.73	0.00528	0.1302	5.862E-05	0.023	0.007
27	23.36	0.01	0.2592	0.000116	0.023	0.012
28	4.09	0.001838	0.0453	2.041E-05	0.024	0.069
29	0.03	1.414E-05	0.0003	1.570E-07	0.024	0.118
30	0.02	9.428E-06	0.0002	1.046E-07	0.023	0.095
31	0.03	1.178E-05	0.0002	1.308E-07	0.025	0.127
32	0.94	0.000424	0.0104	4.710E-06	0.024	0.016
33	0.03	1.414E-05	0.0003	1.570E-07	0.026	0.028
34	0.03	1.178E-05	0.0002	1.308E-07	0.023	0.123
35	0.03	1.272E-05	0.0003	1.413E-07	0.026	0.088

5. Conclusions

In this study, comprehensive physico-chemical analyses of groundwater were performed, and further self-organizing map (SOM) and spatial distribution of chemical elements in groundwater were to delineate the non-linear relationship among the other parameters with As and their zonal concentration in the study area. In addition, the health hazard risk assessment was applied to calculate the potential non-carcinogenic and carcinogenic effects on adults due to the consumption of groundwater for a longer time.

The detailed physico-chemical analyses revealed that a higher concentration of As in groundwater (As >10 μg/L) was found in the study area, demonstrating that 57 % and 31 % of collected groundwater samples exceeded the allowable limit of WHO and BDWS, respectively. For Fe concentration in groundwater, it was also observed that 83 % of samples surpassed the permissible level of WHO. Meanwhile, Mn concentration in groundwater samples was found within the allowable limit of WHO for this region.

The spatial distribution of trace elements pointed out the aerial extent of the As, Fe and Mn in the study area. These analyses exhibited that the elevated level of As in groundwater was spatially distributed in the central portion of the area, while lower concentration was found in the northeastern to eastern part of the area. Elevated levels of Fe were found all over the study area except in the middle portion. Although the Mn concentration in groundwater was found within the allowable limit of WHO, the higher value of this analysis was found in the central portion of the area.

The self-organizing map (SOM) analysis elucidated the non-linear correlation between As and other physico-chemical parameters, and the results revealed in 2-D component planes that As was positively correlated with Mn and Ca, whereas negatively correlated with Fe. These non-linear relationships among the elements in groundwater decipher the positive or negative relation of As with others, which may focus on the possibility of As mobilization in groundwater. However, more variable parameters of water samples will enhance the effectiveness of visualizing and clustering in SOM, and this will provide a more comprehensive non-linear relationship of As with other elements in the study area.

The health hazard risk assessment demonstrated that 57 % of the samples exceeded the threshold value of HQ for adults through the oral route and indicated the potential non-carcinogenic health risk for the inhabitants of the study area. While the HQ values of Fe and Mn may not pose non-carcinogenic health risks. HI values also indicated that 21 sampling sites among 35 data surpassed the threshold

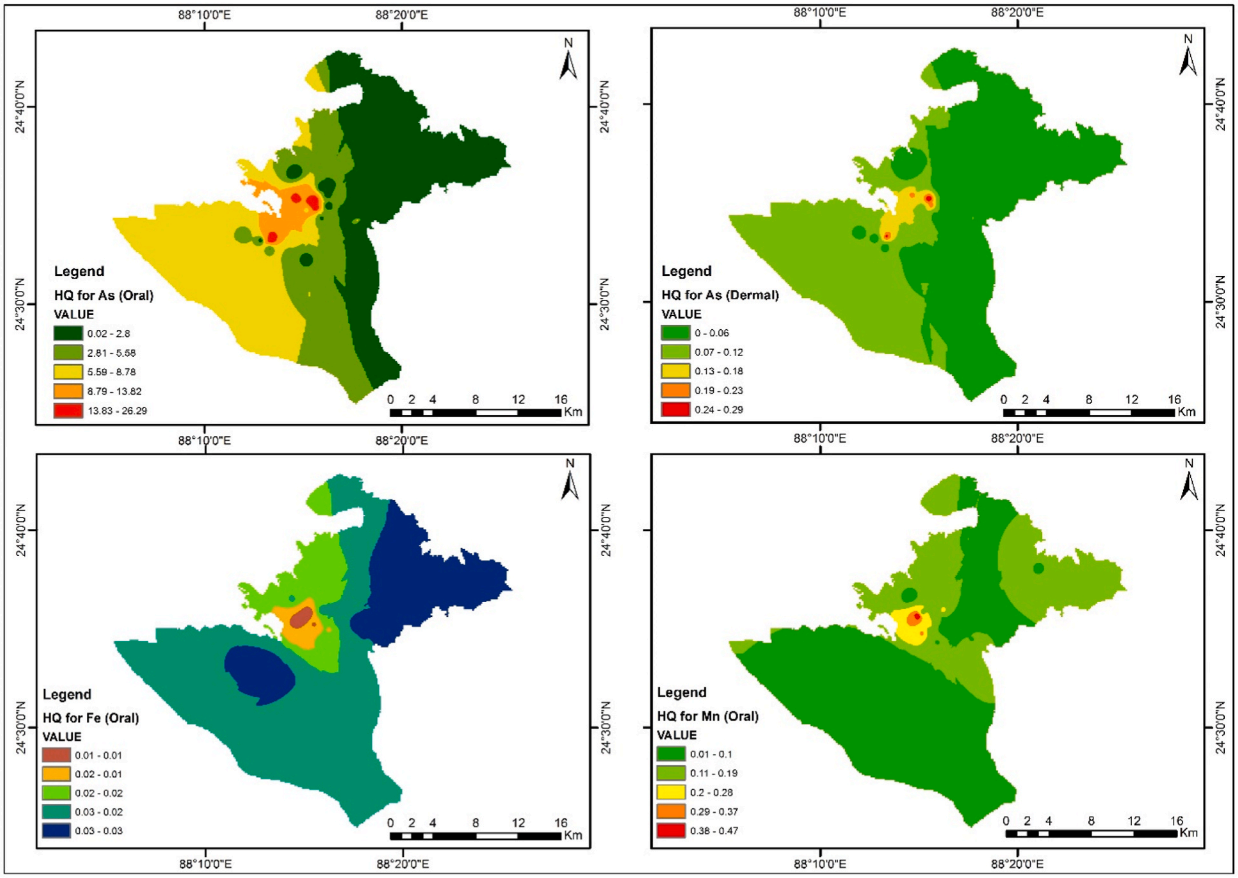

Fig. 5. Spatial distribution of HQ for As, Fe and Mn for adults.

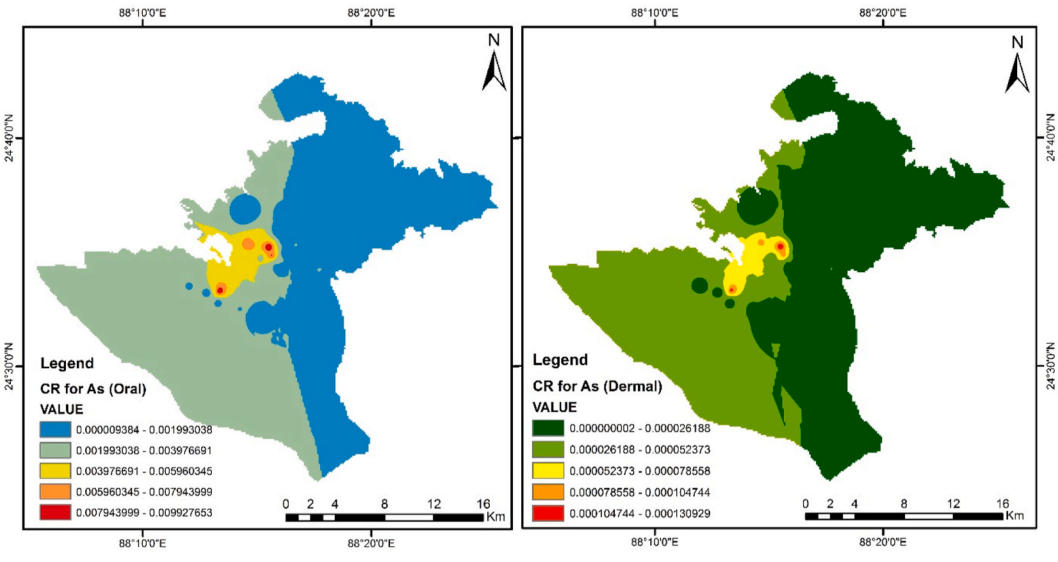

Fig. 6. Spatial variation of CR for As through oral and dermal routes in study area.

value, which signified the non-carcinogenic health hazard due to drinking As contaminated groundwater. For carcinogenic risk assessment, it was evident that CR value of 63 % samples was higher than the thresholds, which indicated the considerable cancer risk zone by drinking As contaminated groundwater. These analyses deliver a comprehensive understanding of the non-linear relationship among other parameters with As, spatial variations of groundwater contaminations, and their health risk of drinking water. Knowing this information, it will help the plans formulate for effective groundwater resources management and minimizing human health risks in this region.

CRediT authorship contribution statement

Obaida Urme: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **AHM Selim Reza:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Data curation, Conceptualization. **Md Ibrahim Adham:** Writing – review & editing, Supervision, Resources, Data curation, Conceptualization. **Golam Sabbir Sattar:** Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Ethics approval

All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors. They are also aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Data availability statement

Data will be made available on request.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:AHM Selim Reza reports a relationship with University of Rajshahi that includes: non-financial support. If there are other authors, they 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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