Proceedings of the Indian National Science Academy (2024) 90:931–942
https://doi.org/10.1007/s43538-024-00273-2

RESEARCH PAPER

Heavy metal contamination and health risks in ground water at Byrnihat industrial area: urgent need for remediation and public health safeguards

Devashree Borgohain[1] · Shaneem Lanong[1] · Hari Prasad Jaishi[1]

Received: 21 October 2023 / Accepted: 29 February 2024 / Published online: 28 March 2024
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Abstract
This article focuses on heavy metal concentration and human health risk assessment in the Byrnihat Industrial area, situated near Guwahati-Shillong Highway. The heavy metals such as chromium (Cr), cadmium (Cd), lead (Pb), copper (Cu) and zinc (Zn) were monitored in the ground water of the Industrial area highlighting the environmental and health concerns associated with elevated levels of Cr, Cd and Pb in groundwater. The average concentrations of Cr, Cd, Pb, Cu and Zn (in mg/L) are reported to be 0.0601, 0.0104, 0.1372, 0.0680 and 2.5321 respectively. The reported average values of Cr, Cd and Pb are found to be higher than the permissible limit set by World Health Organization (WHO) and Bureau of Indian Standard (BIS). The study identifies the diverse sources of heavy metal pollution, including industrial activities, geological formations, and anthropogenic discharges. The health risk assessment reveals significant non-carcinogenic health risks, especially for children, due to exposure to Cr and Pb, as well as substantial carcinogenic risks associated with Cr and Cd. This study offers crucial insights to support well-informed decision-making and effective intervention strategies aimed at tackling the issue of heavy metal pollution in the Byrnihat Industrial area, which has seen limited prior efforts in this regard.

Keywords Heavy metal concentration · Human health risk assessment · Byrnihat industrial area · Groundwater pollution

Introduction

Water constitutes the most fundamental element for sustaining all kind of life on earth and access to the quality water is the most basic human need. But due to rapid urbanization and industrialization contamination of water is the utmost significant environmental problem and endangers human beings throughout the world. The United Nations General Assembly (UNGA) has also listed improvement of water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials for all as one of the sustainable development goals to be attained by 2030 (Cepal 2018). Heavy metal contamination of groundwater stands out as one of the most crucial environmental challenges faced today due to their toxicity and potential health risks (Vodela et al. 1997). There are natural and anthropogenic sources producing heavy metal contamination to the groundwater. Industrial wastewater from diverse sources such as mining, cement industries, metal plating, tanneries, painting, batteries, paper industries, printing and photographic industries, pesticides and fertilizer industries, as well as car radiator manufacturing is a primary contributor to ground water pollution (Nriagu and Pacyna 1988; Kadirvelu et al. 2001). Heavy metals pose significant health risks due to their persistence, potential for accumulation in the food chain, and harm to vital body systems, including the cardiovascular, gastrointestinal, nervous, endocrine, renal, hepatic, pulmonary, and skeletal systems (Badeenezhad et al. 2023). Therefore, the effective health risk assessment methods are critical for comprehending the potential health hazards tied to heavy metal concentrations. These methods enable us to evaluate and mitigate the health risks arising from exposure to heavy metals, thereby safeguarding public well-being and the environment.

The Byrnihat Industrial Cluster in Assam-Meghalaya border area has been identified by the Central Pollution Control Board (CPCB) as a critically polluted region due to its extremely high levels of pollution. This elevated

✉ Hari Prasad Jaishi
harijaishi.ustm@gmail.com

1 Department of Physics, University of Science & Technology Meghalaya, Baridua 9th Mile, Meghalaya 793 101, India

pollution poses significant threats to both human health and the environment. The primary composition of the Byrnihat Industrial Cluster consists of small-scale industrial units clustered together. Within this region, the CPCB has identified a total of 1,384 industrial units that are sources of pollution (CPCB 2020). Most of these units fall under the category of small and tiny enterprises. The area may pose a significant problem of heavy metals pollution. This issue has arisen due to various industrial activities and processes in the region, which have led to the release of heavy metals into the environment. The sources of heavy metals pollution in the Byrnihat area may include industrial operations, such as metallurgical processes, mining, and manufacturing, as well as improper disposal of industrial waste and effluents. These activities can result in the contamination of soil, water bodies, and even the air in the vicinity. In addition, vehicular exhaust emissions represent a substantial contributor to the prevailing pollution issue in this area. The area is located on the main Guwahati-Shillong highway, about 90 km from Shillong and 14 km from Guwahati. The CPCB has been actively collecting and compiling data regarding the pollution levels and sources within industrial clusters like Byrnihat to better understand and address the pollution concerns in this critically affected area. Recently, a study (Kshetriya et al. 2021) has reported heavy metal concentrations in the area. This study revealed that the average concentration of cadmium, copper, and chromium exceeds the national standard values. They recommended remedial actions to support a healthy aquatic ecosystem inhabited by aquatic organisms. Based on their findings, it is imperative to employ available techniques to assess environmental heavy metal concentrations and evaluate their potential risks to human health. The current study presents measurements of heavy metals, specifically chromium (Cr), cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn), in groundwater collected from the Byrnihat Industrial cluster. The objective is to assess the potential risks posed by these heavy metals to human health. Figure 1 shows the Byrnihat Industrial cluster with sampling locations of heavy metals.

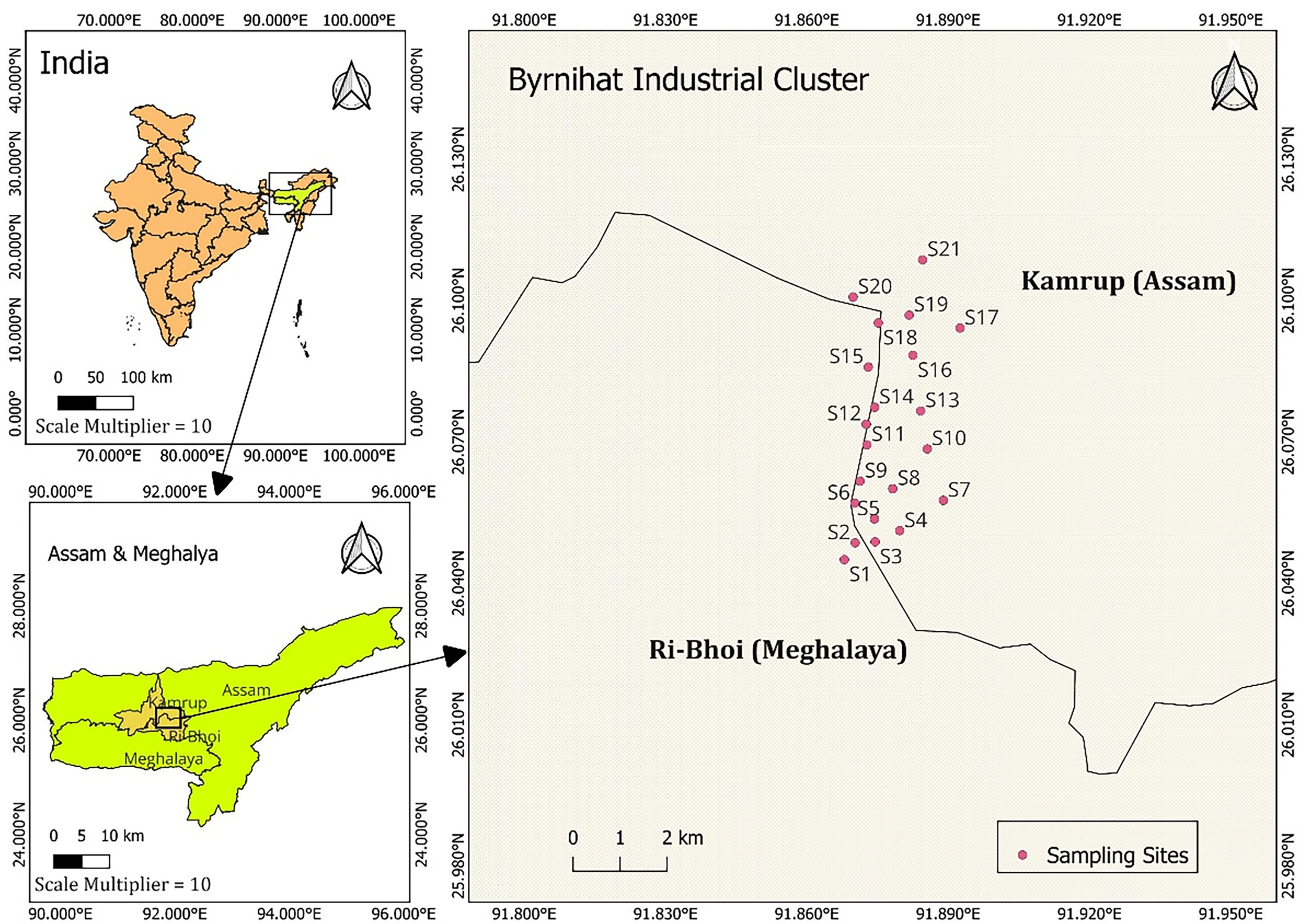


Fig. 1 Location map of study area showing the sampling points

Experimental technique and methodology

Data collection and analysis

Groundwater samples were collected from 21 distinct locations, approximately 500 m to 1 km apart from each other within the Byrnihat industrial area. High-quality, 1 L capacity polypropylene bottles with secure screw caps were used for the collection of samples. These containers were pre-sterilized and appropriately labeled before being subjected to laboratory analysis for trace metals using an Atomic Absorption Spectrometer (Badeenezhad et al. 2023). Approximately 50 mL of each sample was carefully transferred into a conical flask, followed by the precise addition of 5 mL of Nitric acid (HNO_3), ensuring thorough mixing within the flask. The mixture was allowed to dissolve for a minimum of 12 h. Following this, the solution underwent a slow boil and evaporation process on a hot plate until its volume reduced to 10–20 mL. The solution was then left to cool. Once cooled, it was filtered through Whatman-41 filter paper into a volumetric flask, with the final volume adjusted to 250 mL.

The resulting filtered sample was subjected to analysis using Flame type Atomic Absorption Spectroscopy (AAS) equipment, specifically Model: iCE 3000 AA05192103 v1.30, manufactured by Thermofisher Scientific. The Atomic Absorption Spectroscopy (AAS) is a technique to detecting the concentration of metal ions in water samples. During this procedure, as a sample solution is drawn into a flame; the elements within the sample undergo a conversion into atomic vapor within the fiery environment. The flame encompasses atoms of the specific element under investigation, with some of these atoms experiencing thermal excitation due to the flame's heat, while the majority remains in their original ground state. Subsequently, the ground-state atoms have the capacity to absorb radiation of a specific wavelength emitted by a source, typically a hollow cathode lamp specific to the metal being analyzed. This emitted wavelength corresponds to the same wavelength absorbed by the atoms in the flame, allowing for precise and accurate measurement of the metal ion concentration in the sample (Lagalante 2004). The concentration of the target element in the sample is assessed through the creation of a calibration curve, utilizing standard solutions with known element concentrations. This curve establishes a direct connection between the absorbance of light and the element's concentration. To accurately determine the concentration of the target element in the sample, one measures the absorbance of the sample and refers to the calibration curve (Van Loon 1980; García and Báez 2012).

Human health risk assessment

The heavy metals contained in ground water may cause severe health risks to the human body if consumed. Using this method, the harm of heavy metals to human body can be evaluated. An evaluation of non-carcinogenic human health risks was conducted for Pb, Cd, Zn, Cu, and Cr in water and a separate assessment focusing on the carcinogenic health risks associated with Pb, Cd, and Cr was also evaluated. The main purpose was to quantify the health risks associated with heavy metals in groundwater, considering two distinct exposure routes: oral (ingestion) and skin contact (dermal). The chronic daily intakes (mg/kg/day) due to ingestion (CDI_{ing}) and dermal contact (CDI_{der}) are calculated by the following equations (Mawari et al. 2022).

$$CDI_{ing} = \left(C \times IR_{ing} \times EF \times ED\right)/(BW \times AT), \tag{1}$$

$$CDI_{der} = (C \times SA \times KP \times EF \times ED \times ET \times CF)/(BW \times AT), \tag{2}$$

where C is the concentration of heavy metal in water sample (mg/L), IR_{ing} is the ingestion rate (L/day), EF is the exposure frequency (days/yr.), ED is the exposure duration (yr.), BW is the body weight (kg), AT is the average time (days), SA is Skin surface area parameter (cm^2), KP is the Dermal Permeability Coefficient (cm/h), ET is the Exposure time (h/day), CF is the Conversion factor (L/cm^3). The values of the parameters utilized are outlined in the Table 1.

The Hazard Quotient (HQ) is formulated to assess the non-carcinogenic human health risk associated with a hazardous substance. Additionally, the Hazard Index (HI) has been established to assess the potential risk to human health when multiple metals or pathways are considered. If the Hazard Index (HI) is less than or equal to 1, it indicates that there is no adverse impact on human health whereas if their values exceed 1 then there may be significant non-carcinogenic risk to human body (USEPA 2001). Both HQs and HIs are dimensionless probabilities, and are calculated as follows:

$$HQ_{ing} = CDI_{ing}/RfD_{ing}, \tag{3}$$

$$HQ_{der} = CDI_{der}/RfD_{der}, \tag{4}$$

$$HI = HQ_{ing} + HQ_{der}, \tag{5}$$

where RfD_{ing} and RfD_{der} are the oral and dermal reference dose respectively. The Cancer Risk (CR) signifies the estimated exposure to carcinogenic elements, while TCR (Total Cancer Risk) serves as the cumulative cancer risk index for

Table 1 Risk parameters utilized in this study (USEPA 1989, 2004, 2007; Saha et al. 2017; Prasad et al. 2020; Zakir et al. 2020; Seleem et al. 2021)

Parameter	Unit	Adult	Child
Ingestion rate (IR_{ing})	L/day	2.5	0.78
Exposure duration (ED)	yr.	30	6
Exposure frequency (EF)	days/yr.	350	350
Body weight (BW)	kg	52	15
Skin surface area parameter (SA)	cm^2	18,000	6600
Average time (AT)	days	ED×365	ED×365
Exposure time (ET)	h/day	0.58	0.58
Conversion factor (CF)	L/cm^3	10^{-3}	10^{-3}
Dermal permeability coefficient (KP)	cm/h	0.001 (Cd, Cr, Cu), 0.0001 (Pb), 0.0006 (Zn)	0.001 (Cd, Cr, Cu), 0.0001 (Pb), 0.0006 (Zn)

multiple heavy metals or various exposure routes. Specifically, if CR/TCR is less than 10^{-6}, it indicates a negligible carcinogenic risk. If the CR/TCR falls within the range of 10^{-4} to 10^{-6}, there exists a moderate level of risk. On the other hand, when CR/TCR exceeds 10^{-4}, it signifies a significantly elevated risk of cancer (USEPA 2012; Arisekar et al. 2020). The values of CR and TCR are calculated as follows.

$$CR_{ing} = CDI_{ing} \times CPF, \tag{6}$$

$$CR_{der} = CDI_{der} \times CPF, \tag{7}$$

$$TCR = CR_{ing} + CR_{der}, \tag{8}$$

where, CR_{ing}, CR_{der} and CPF represent the cancer risk through ingestion pathway, cancer risk through dermal pathways and cancer potency factor respectively. The values of RfDs and CPFs for various heavy metals used in this study are highlighted in Table 2.

Results and discussion

Analysis of heavy metals

Initially, calibration for all the heavy metals investigated in this study was performed which involved the use of a blank and three distinct standards. The principles governing AAS measurements are based on Beer's law, which establishes proportionality between concentration and absorbance (Williams 1972). It is notable that as the concentration of heavy metals in the standards increases, a greater amount of light is absorbed by the atoms of the target elements. After calibrating the instrumentation, the collected water samples were tested for the presence of five different heavy metals: chromium (Cr), cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn). The concentrations of these heavy metals in all the collected samples are presented in Table 3, while Table 4 provides descriptive statistics and permissible limits for these heavy metals.

In the study area, the average concentrations of chromium (Cr), cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn) were observed as follows: 0.0601, 0.0104, 0.1372, 0.0680, and 2.5321 mg/L, respectively. The concentration of chromium (Cr) varies between 0.0111 and 0.1129 mg/L, with a mean and standard deviation (SD) of 0.0601 ± 0.0370 mg/L. It is noteworthy that the average chromium (Cr) concentration in the study area, which is 0.0601 mg/L, exceeds the maximum permissible limits set by both the World Health Organization (WHO 2017) and the Bureau of Indian Standards (BIS 2012). Chromium (Cr) is classified as one of the 129 priority pollutants by the Environmental Protection Agency and is considered one of the 14 most hazardous heavy metals (Sharma et al. 2012). This elevated level of Cr in the current study area is likely attributed to the rapid industrial growth in the region over the past few decades. The waste generated by these industries has been illicitly disposed of in deep boreholes, open land areas, and rivers.

Table 2 References doses (RfDs) and the cancer potency factors (CPFs) of the heavy metals adopted in this study (Kolo et al. 2018; Ahmad et al. 2021; Wang et al. 2022)

Elements	RfD_{ing} (mg/kg/day)	Rfd_{der} (mg/kg/day)	CPF_{ing}	CPF_{der}
Zn	3.00E-01	6.00E-02	–	–
Cu	4.00E-02	1.20E-02	–	–
Cr	3.00E-03	6.00E-05	5.00E-01	2.00E+01
Cd	1.00E-03	1.00E-05	6.10E+00	3.80E-01
Pb	3.50E-03	5.25E-04	8.50E-03	4.20E-02

Table 3 The measured concentrations of the heavy metals in the study area along with sampling locations

Sampling locations	Sample ID	Lat. (°N)	Long. (°E)	Concentrations (mg/L)				
				Cr	Cd	Pb	Cu	Zn
Near Bajaj Parivahan Pvt. Limited (Assam)	S1	26.0450	91.8680	0.1033	0.0102	0.3182	0.0127	1.5320
Near Ri-Bhoi Filling Station (Meghalaya)	S2	26.0486	91.8703	0.0532	0.0032	0.0370	0.1832	0.5509
Near Umtru River (Assam)	S3	26.0488	91.8745	0.1129	0.0023	0.0352	0.2320	5.6002
Near Sonapur-Byrnihat road (Assam)	S4	26.0512	91.8797	0.0152	0.0205	0.0421	0.0433	3.6600
Near Sarutari Health Sub Centre (Assam)	S5	26.0537	91.8744	0.1007	0.0113	0.1292	0.0226	2.1101
Near LS Furniture (Meghalaya)	S6	26.0570	91.8702	0.0776	0.0122	0.0292	0.0056	1.5293
Near Super Lite AAC Block Industry (Assam)	S7	26.0576	91.8890	0.0912	0.0013	0.0788	0.0110	4.3232
Near SBM Cement Factory (Assam)	S8	26.0601	91.8783	0.0238	0.0027	0.2010	0.0320	3.4021
Near 14th Mile Petrol Pump (Meghalaya)	S9	26.0617	91.8713	0.0521	0.0012	0.1580	0.0046	1.4883
Near New Rajdhani Motors (Assam)	S10	26.0685	91.8856	0.0152	0.0112	0.2276	0.2450	3.2963
Near Byrnihat Post Office (Meghalaya)	S11	26.0694	91.8728	0.0138	0.0233	0.1343	0.0165	4.8321
Near Jantia Ferro Alloys Pvt. Ltd. (Meghalaya)	S12	26.0738	91.8726	0.1077	0.0148	0.0173	0.0154	1.5001
Near Om Shiv Ashram (Assam)	S13	26.0766	91.8842	0.0211	0.0123	0.2033	0.0428	3.2382
Near MSR Motors (Meghalaya)	S14	26.0774	91.8744	0.0464	0.0124	0.0859	0.2379	1.5201
Near Conservation Training Institute (Meghalaya)	S15	26.0859	91.8731	0.1021	0.0117	0.3362	0.0482	0.4901
Near RSH Agro Products Ltd. (Assam)	S16	26.0884	91.8825	0.1054	0.0023	0.0883	0.0012	3.5150
Near Ganga Tea Manufacturing Unit (Assam)	S17	26.0942	91.8925	0.0521	0.0200	0.2094	0.0375	0.4901
Near Astha Clinic (Meghalaya)	S18	26.0953	91.8752	0.0321	0.0025	0.2139	0.0354	2.7436
Near Concrete Manufacturing Industry (Assam)	S19	26.0969	91.8818	0.0382	0.0202	0.1191	0.0287	0.5421
Near SM Cement Industries (Assam)	S20	26.1008	91.8698	0.0111	0.0108	0.0784	0.0146	2.3101
Near JP Polymer (Assam)	S21	26.1087	91.8846	0.0871	0.0120	0.1395	0.1584	4.5002

Table 4 Descriptive statistics of the measured heavy metals concentration

Elements	Descriptive statistics of the measured heavy metals concentration (mg/L)					Maximum permissible limit (mg/L)	
	Mean	SD	Minimum	Median	Maximum	(WHO 2017)	(BIS 2012)
Cr	0.0601	0.0370	0.0111	0.0521	0.1129	0.05	0.05
Cd	0.0104	0.0070	0.0012	0.0113	0.0233	0.003	0.003
Pb	0.1372	0.0917	0.0173	0.1292	0.3362	0.01	0.01
Cu	0.0680	0.0849	0.0012	0.0320	0.2450	2.00	1.50
Zn	2.5321	1.5418	0.4901	2.3101	5.6002	na	15.0

The maximum permissible limit is also shown

na not available

The concentration of cadmium (Cd) in the groundwater within the study area exhibits a range between 0.0012 mg/L and 0.0233 mg/L, with a calculated mean and standard deviation of 0.0104 ± 0.0070 mg/L. Notably, the mean concentration of Cd exceeds the permissible limits established by both the World Health Organization (WHO) and the Bureau of Indian Standards (BIS), as outlined in Table 4. Several factors may contribute to the heightened levels of Cd in the groundwater. These potential sources encompass natural phenomena, industrial activities, mining operations, and agricultural practices. Notably, the district of Ri-Bhoi, Meghalaya, near Byrnihat, is known for the presence of sulphide minerals, dimensional stones, road metal, masonry sand, and minor sillimanite. Furthermore, mining of boulder stone stands out as a prominent industrial activity in this district. It is conceivable that mining and related industrial activities represent a significant source of the observed elevated Cd levels in the groundwater. This situation raises concerns regarding potential hazards to the health and well-being of both employees and the general public. The concentration of lead (Pb) ranges from 0.0173 to 0.3362 mg/L, with an average value of 0.1372 mg/L and a standard deviation of 0.0917 mg/L. The average lead concentration surpasses the permissible limits established by both the World Health Organization (WHO) and the Bureau of Indian Standards (BIS). It is crucial to highlight that all samples collected from the study area exceeded these permissible limits, raising concerns about the presence of this element in elevated level. The potential sources of elevated lead levels in groundwater are multifaceted. Firstly, underground water sources may contain naturally occurring ore deposits rich in toxic metals, which can leach into water bodies, thereby causing pollution (Ukaogo et al. 2020). Instances of significant lead contamination in groundwater have been associated with such geological phenomena. Additionally, the geological formations in different areas play a substantial role in determining the elemental composition of water bodies, potentially contributing to heightened concentrations of elements responsible for water pollution (Ewuzie et al. 2020). Furthermore, anthropogenic sources, including various industrial waste discharges within the study area, may also contribute to lead contamination. The average concentrations of copper (Cu) and zinc (Zn) fall within the permissible limits established by the World Health Organization (WHO) and the Bureau of Indian Standards (BIS). The concentrations of Cu and Zn (measured in mg/L) range from 0.0012 to 0.2450 and from 0.4901 to 5.6002, respectively. These values have corresponding average values and standard deviations of 0.0680 ± 0.0849 mg/L for Cu and 2.5321 ± 1.5418 mg/L for Zn. Among the five heavy metals measured in the groundwater samples from the study area, chromium (Cr), cadmium (Cd), and lead (Pb) are found to be present at elevated levels. These elevated concentrations have the potential to negatively impact human health, potentially leading to various health-related issues. A comparison of the average values of these heavy metals in the groundwater samples obtained in this investigation with values from different regions around the world is presented in Table 5.

The relationship between different heavy metals and their sources were analyzed using Pearson's correlation coefficient, which assesses their interdependence and origins. Correlation measures the association between quantitative variables, assuming a linear relationship. A correlation coefficient of $+1$ indicates a perfect positive linear relationship, -1 a perfect negative linear relationship, and 0 signifies no linear relationship (Gogtay and Thatte 2017). The Pearson's correlation coefficients were computed using an Excel spreadsheet to examine the interdependencies between the heavy metals. Furthermore, the Hypothesis test was used to evaluate the significance of these correlations (Jaishi et al. 2023). The Null Hypothesis suggest no significant relationship (correlation coefficient not significantly different from zero), while the Alternative Hypothesis suggests a significant relationship (correlation coefficient significantly different from zero). By calculating the t-value and its corresponding p-value, the determination of whether to accept or reject the Null Hypothesis was made, using a significance level of $\alpha = 0.05$. If $p < \alpha$ ($\alpha = 0.05$), the Null Hypothesis is rejected; otherwise, it is not rejected. The Pearson's correlation coefficients, along with the t-values and p-values between various heavy metals, are presented in Table 6. From the table it can be observed that the p-value (highlighted by bold numbers) between all the heavy metals were found to be greater than the α-value. Hence, the Null Hypothesis cannot be rejected, indicating that there is no significant relation between the heavy metals in the ground water samples. Such kind of non-significant relationship between the heavy metals in ground water was also reported elsewhere (Bazrafshan et al. 2016; Egbueri 2020). The absence of correlation indicates that the presence or concentration of one heavy metal does

Table 5 Comparison of the mean concentration of heavy metals in groundwater from current investigation to various regions within the country and globally

Location	Average Concentrations of heavy metals (in mg/L)					References
	Cr	Cd	Pb	Cu	Zn	
Byrnihat Industrial Cluster, India	0.0601	0.0104	0.1372	0.0680	2.5321	Present study
Tamil Nadu, India	0.08	0.04	0.47	0.03	0.23	Raja et al. 2021
Ropar wetland, Punjab, India	0.075	0.003	0.022	0.03	0.42	Sharma et al. 2019
Nashik, India	1.588	0.027	0.998	0.037	0.065	Wagh et al. 2018
Toledo, Brazil	0.015	na	0.02	0.017	0.065	Monte Blanco et al. 2018
Cameroon, West Africa	0.9225	0.0275	0.3075	na	na	Defo et al. 2015
Vado Carranza dump, Mexico	na	0.0362	0.0425	0.2783	0.0488	Gómez-Puentes et al. 2014
Radiowo landfill, Poland	0.01	0.0004	0.005	na	0.065	Podlasek et al. 2021
Zdounky landfill, Czech Republic	0.045	0.0031	0.009	na	0.018	Podlasek et al. 2021
Guanzhong Plain, China	0.00554	0.00002	0.00009	0.00056	0.0921	Qiao et al. 2020
Industrial area, Lagos, Nigeria	0.0321	0.0005	0.0017	0.5464	0.7185	Ukah et al. 2019
Agricultural area, Northwestern Turkey	0.00026	0.000007	0.000114	0.00041	0.0051	Varol and Tokatlı 2022
Arkhangelsk Agglomeration, Northwest Russia	0.01595	0.00005	0.00092	0.00297	0.02516	Yakovlev et al. 2022

na not available

Table 6 Correlation coefficients between the heavy metals with t-value and p-value

		Cr	Cd	Pb	Cu	Zn
Cr	Pearson Correlation	1.00	− 0.31	− 0.06	− 0.04	− 0.04
	Coefficient (b)		− 1.64	− 0.02	− 0.02	− 0.001
	Standard Error (SE)		1.16	0.09	0.10	0.0055
	t-value (b/SE)		− 1.41	− 0.22	− 0.20	− 0.18
	Sig. (p-value)		**0.17**	**0.81**	**0.86**	**0.86**
Cd	Pearson Correlation	− 0.31	1.00	0.02	− 0.12	− 0.18
	Coefficient (b)	− 1.64		0.002	− 0.009	− 0.0008
	Standard Error (SE)	1.16		0.017	0.018	0.001
	t-value (b/SE)	− 1.41		0.11	− 0.50	− 0.80
	Sig. (p-value)	**0.17**		**0.93**	**0.60**	**0.44**
Pb	Pearson Correlation	− 0.06	0.02	1.00	− 0.12	− 0.22
	Coefficient (b)	− 0.02	0.002		− 0.127	− 0.0128
	Standard Error (SE)	0.09	0.017		0.246	0.0133
	t-value (b/SE)	− 0.22	0.11		0.52	0.96
	Sig. (p-value)	**0.81**	**0.93**		**0.61**	**0.35**
Cu	Pearson Correlation	− 0.04	− 0.12	− 0.12	1.00	0.19
	Coefficient (b)	− 0.02	− 0.009	− 0.127		0.010
	Standard Error (SE)	0.10	0.018	0.246		0.012
	t-value (b/SE)	− 0.20	− 0.50	0.52		0.83
	Sig. (p-value)	**0.86**	**0.60**	**0.61**		**0.41**

Bold values indicates that the p-vale is greater than the α-value

not provide meaningful information about the presence or concentration of another. This suggests that these heavy metals may originate from diverse sources or undergo different geochemical processes in the groundwater.

They could be influenced by various environmental factors or human activities, resulting in their independent occurrence. Additionally, these metals may have distinct anthropogenic and natural sources in sediment reservoirs, reflecting the primary anthropogenic discharges for several heavy metals. While most large-scale industries have treatment facilities for industrial effluents, small-scale industries are often unable to invest heavily in pollution control equipment due to slim profit margins. It is interesting to note that such kind of tiny and small scale industries are prevalent in the Byrnihat Industrial Cluster (CPCB 2020). This situation has led to evidence of industrial waste mismanagement in the study area.

Health risk assessment

To evaluate the potential health risks associated with the measured heavy metals, various health risk parameters were computed in accordance with the guidelines established by the United States Environmental Protection Agency (USEPA). These parameters offer valuable insights into the toxicity and safe exposure levels for heavy metals, encompassing both carcinogenic and non-carcinogenic health risks. In this study, non-carcinogenic health effects were assessed for all heavy metals examined. Carcinogenic effects, on the other hand, were evaluated specifically for chromium (Cr), lead (Pb), and cadmium (Cd). Exposure to heavy metals in groundwater primarily occurs through two pathways: ingestion (oral) and dermal (skin contact). Chronic daily intake (CDI) was computed for both adults and children using Eqs. (1) and (2). CDI represents the estimated daily intake of a specific heavy metal over an extended period from a particular exposure source. The CDIs were calculated based on the average values of heavy metals obtained from all samples, and the parameters used for these calculations can be found in Table 1. The average CDI values for both adults and children are presented in Table 7.

The calculated value of CDI through ingestion pathway is found to be higher than the dermal pathway for all the heavy metals indicating that individuals who consume the contaminated groundwater are at a greater risk of exposure and potential health problems. Ingesting heavy metals can lead to a more significant health risk compared to skin contact. This information is essential for understanding the relative risk of exposure through different routes, informing public health measures, and may necessitate actions to improve the quality of groundwater sources or implement water treatment processes to reduce heavy metal concentrations to safe levels.

The CDI computed for each pathway is subsequently employed to assess the non-carcinogenic risk through the calculation of hazard quotient (HQ) and hazard index (HI). Non-carcinogenic pertains to substances or agents that lack

Table 7 Average computed values of CDI, HQ and HI for both adults and children

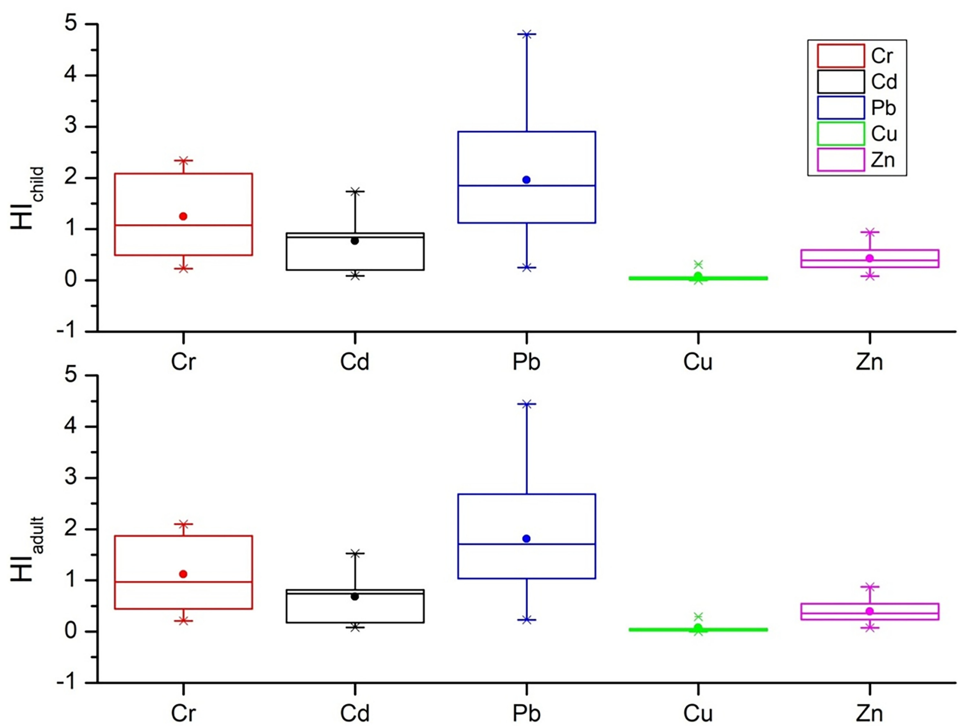
	ADULT					CHILD				
	CDI_{ing}	CDI_{der}	HQ_{ing}	HQ_{der}	HI	CDI_{ing}	CDI_{der}	HQ_{ing}	HQ_{der}	HI
Cr	2.77E-03	1.16E-05	0.924	0.193	**1.116**	3.00E-03	1.47E-05	0.999	0.245	**1.244**
Cd	4.79E-04	2.00E-06	0.479	0.200	0.680	5.19E-04	2.55E-06	0.519	0.255	0.773
Pb	6.33E-03	2.64E-06	**1.807**	0.005	**1.812**	6.84E-03	3.36E-06	**1.955**	0.006	**1.961**
Cu	3.13E-03	1.31E-05	0.078	0.001	0.079	3.39E-03	1.66E-05	0.085	0.001	0.086
Zn	1.17E-01	2.92E-04	0.389	0.005	0.394	1.26E-01	3.72E-04	0.421	0.006	0.427

Bold values indicates the value higher than the permissible limit of 1

the capacity to induce or facilitate the development of cancer in living organisms (Kolo et al. 2018; Wang et al. 2022). The values of HQ and HI are calculated using Eqs. (3) and (4). The references doses used for the calculation of HQ are highlighted in Table 2. The average calculated values of HQ and HI are highlighted in Table 7. The value of HQ and HI that exceeds the limit set by USEPA (2001) is highlighted by bold numbers in Table 7. The average value of HQ through ingestion pathway for lead (Pb) is found to be 1.807 and 1.961 for adult and children respectively. The value of HQ (Pb) for children is found to be slightly higher than that for adults. The observed values of HQ are much higher than the permissible limit of 1 set by USEPA (USEPA 2001). The values of HQ through ingestion pathways for Cr (both adult and children) are found to be slightly less than 1. High HQ for lead through ingestion indicates an increased risk of non-carcinogenic health effects due to lead exposure. These health effects may include neurological and developmental issues, especially in children, and can also affect adults, potentially leading to cardiovascular, kidney, and other health problems (Sanders et al. 2009). It is a clear indicator that measures need to be taken to mitigate lead exposure through ingestion pathways in the ground water of the study area. This may involve improving the quality of drinking water by reducing lead levels and implementing public health interventions to protect vulnerable populations, particularly infants and children (Wani et al. 2016).

The HQ for ingestion and dermal pathways are added together to get the value of hazard index (HI). The Hazard Index assesses the cumulative or combined effects of exposure to multiple pathways, rather than looking at each pathway in isolation. From Table 7 it is clear that the HI values for both Cr and Pb are higher than the permissible limits set by USEPA for both adults and children. Additionally, it notes that the HI values are higher for Pb compared to Cr and that the values are higher for children than for adults.

Fig. 2 Box plot showing the variation of the hazard index for adult and children in the investigation area



The variation of hazard index (HI) for individual heavy metals for all the samples is shown in Fig. 2.

From the box plot of HI, it is evident that, in case of children, more than 50% of the samples collected had hazard index values exceeding the recommended limiting value of 1. For adults, approximately 40% of the samples exceeded the limiting value. On average, the hazard index for Cr was calculated to be 1.117 for adults and 1.244 for children (refer Table 7). The highest observed values of hazard index for Cr were found to be 2.097 for adults and 2.337 for children. For Cd, only about 19% of the samples collected exceeded the limiting value of 1 for adult, while approximately 23% of the samples exceeded the limit for children. The average hazard index for Cd was lower than the limiting value, measuring at 0.680 for adults and 0.773 for children. The hazard index for Pb exhibited significant variation for both adults and children. The average hazard index for Pb was notably higher, measuring 1.813 for adults and 1.962 for children, surpassing the recommended upper limit of 1. Approximately 76% of the samples collected had hazard index values that exceeded the limiting value (for both adults and children). The highest recorded values of hazard index for Pb were found to be 4.203 for adults and 4.805 for children. Based on the box plot in Fig. 2, the hazard index values for both adults and children due to Cu and Zn were significantly lower than the recommended limits in all the samples, indicating no significant health risks associated with Cu and Zn exposure. The findings indicate that exposure to Cr and Pb, especially for children, poses significant non-carcinogenic health risks as their hazard index values frequently exceeded the recommended limits. The hazard index for Cd, on the other hand, generally remained below the specified limit, indicating lower health risks associated with cadmium exposure in the studied samples. The elevated hazard index values for Cr and Pb suggest the need for further investigation and potential remediation measures to mitigate the associated health risks. This is a cause for concern because it implies that the levels of these heavy metals in the environment, possibly in groundwater, are exceeding what is considered safe for human health. It suggests that lead contamination poses a more significant risk to human health in this specific context. The comparative toxicity of heavy metals varies, with lead known for its severe health implications, particularly in children. These findings emphasize the importance of addressing lead contamination promptly in the investigation area. Another critical observation is that the HI values are higher for children as compared to adults. This is consistent with existing knowledge that children are often more vulnerable to the harmful effects of heavy metal exposure (Zeng et al. 2016; Bair 2022).

To assess the carcinogenic health risks linked to heavy metals, calculations were performed for cancer risks (CR) and total cancer risks (TCR) associated with three specific heavy metals: chromium (Cr), lead (Pb), and cadmium (Cd). CR values for both oral and dermal exposure routes were computed using Eqs. (6) and (7), and subsequently the TCR was determined using Eq. (8). The cancer potency factors (CPF) required for TCR calculations were referenced from Table 2. TCR represents the cumulative cancer risks over a lifetime of exposure to these heavy metals. The average CR and TCR values are presented in Table 8.

For chromium, the CR due to oral ingestion for both adults and children was 1.39E-03 and 1.50E-03, respectively, both exceeding the recommended value of 1.0E-04 (USEPA 2012). This indicates a significant cancer risk associated with consuming contaminated water. CR values for dermal exposure were 2.31E-04 for adults and 2.94E-04 for children, slightly above the recommended limit. However, the ingestion pathway posed a more substantial cancer risk than the dermal pathway. The lifetime cancer risks for chromium were 1.62E-03 for adults and 1.79E-03 for children, both considerably higher than the recommended value of 1.0E-04. Moreover, TCR values were slightly higher for children than for adults, suggesting increased susceptibility in children due to exposure to chromium. In the case of cadmium, CR from oral ingestion was 2.92E-03 for adults and 3.16E-03 for children, both exceeding the recommended limit. However, CR from dermal exposure remained within permissible limits for both adults and children, indicating no significant risks from dermal contact (USEPA 2012). Total cancer risks due to cadmium exposure were 2.93E-03 for adults and 3.16E-03 for children, both higher than the recommended values, indicating a substantial risk from cadmium exposure. Similar to chromium, TCR was higher for children compared to adults. In contrast, the CR and TCR values for lead exposure in both adults and children were within the recommended limits set by USEPA, suggesting a

Table 8 Average calculated values of CR and TCR

	ADULT			CHILD		
	CR_{ing}	CR_{der}	TCR	CR_{ing}	CR_{der}	TCR
Cr	**1.39E-03**	**2.31E-04**	**1.62E-03**	**1.50E-03**	**2.94E-04**	**1.79E-03**
Cd	**2.92E-03**	7.61E-07	**2.93E-03**	**3.16E-03**	9.67E-07	**3.16E-03**
Pb	5.38E-05	1.11E-07	5.39E-05	5.82E-05	1.41E-07	5.83E-05

Bold values indicates the values exceeding the upper recommended value of 1.0E-04

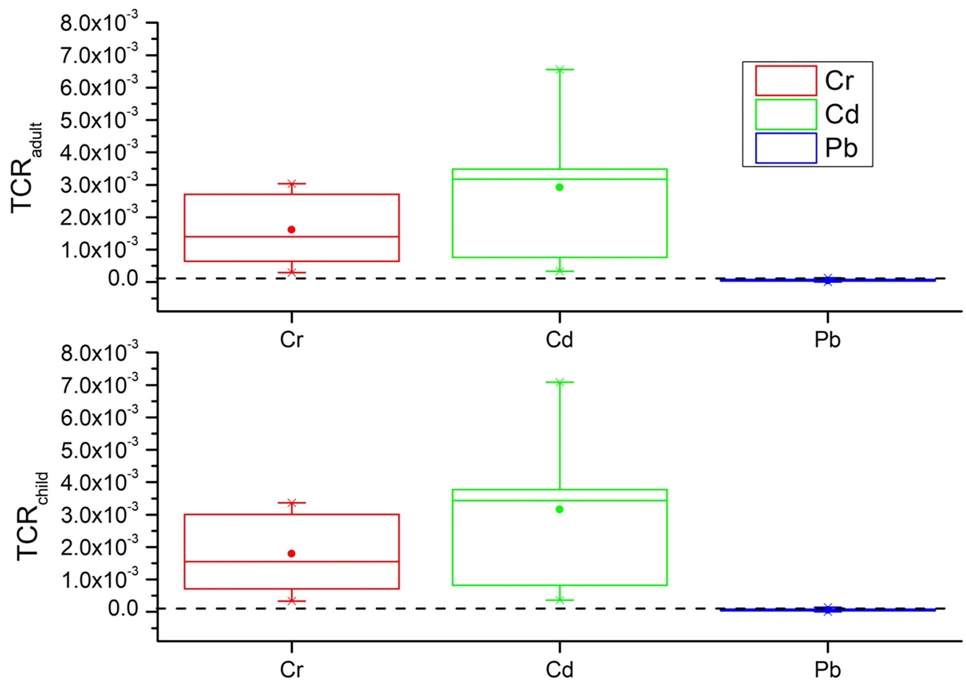


Fig. 3 Box plot showing the variation of TCR for adult and children in all the samples collected in the investigation area. The dash line represents the maximum permissible limit of 1.0E-04

negligible carcinogenic risk associated with lead exposure through both ingestion and dermal pathways. The variation in TCR values for all samples is represented in Fig. 3.

The figure showed that TCR values for chromium and cadmium consistently exceeded the upper limit in all samples collected during the investigation, highlighting the widespread and significant cancer risks associated with these heavy metals. On the other hand, the contribution of lead to the total cancer risk was relatively minor, with values remaining within the range of 1.0E-06 to 1.0E-04. High TCR values for chromium (Cr) and cadmium (Cd) in the present investigation indicate a significant cancer risk associated with exposure to these heavy metals over a lifetime. TCR values for Cr and Cd are elevated, it means that the potential cancer risk from these metals is substantial, and the exposure levels in the study or investigation are a cause for concern. The International Agency for Research on Cancer (IARC) has classified cadmium (Cd) and chromium (Cr) as Group 1 carcinogens for humans (Hossain et al. 2018). Prolonged exposure to these heavy metals can lead to detrimental health effects in humans. High TCR values suggest that individuals exposed to Cr and Cd, especially children who are often more vulnerable, face an increased risk of developing cancer due to the long-term accumulation of these heavy metals in their bodies. There should be efforts from the government agency to reduce exposure to Cr and Cd and measures should be taken to mitigate the effect of heavy metals in ground water. This may involve improving water quality, regulating industrial processes, or implementing other strategies to limit heavy metal contamination.

Conclusion

In conclusion, the results of this study have revealed concerning levels of heavy metal contamination in the groundwater of the Byrnihat Industrial Area. The elevated concentrations of chromium (Cr), cadmium (Cd), and lead (Pb) in the water samples exceed the permissible limits set by both the World Health Organization (WHO) and the Bureau of Indian Standards (BIS), raising significant health and environmental concerns. The sources of these heavy metals are diverse, including industrial activities, geological formations, and potential anthropogenic discharges, indicating a complex interplay of factors contributing to water pollution. The health risk assessment further underscores the seriousness of the situation. The hazard index (HI) values for Cr and Pb, especially for children, exceed recommended limits, indicating significant non-carcinogenic health risks associated with exposure to these heavy metals. The elevated hazard index values emphasize the need for immediate attention and potential remediation measures to safeguard public health. Moreover, the assessment of carcinogenic health risks reveals that both chromium (Cr) and cadmium (Cd) pose substantial cancer risks, with CR and TCR values consistently exceeding recommended limits. The classification of these heavy metals as Group 1 carcinogens for humans by the International Agency for Research on Cancer underscores the urgency of addressing their presence in the groundwater. In light of these findings, it is imperative to take immediate action to mitigate heavy metal contamination in the groundwater. This may involve improving water quality, regulating industrial processes, and implementing measures to reduce heavy metal concentrations. Safeguarding the health and well-being of the affected communities, particularly children, should be a top priority, and this study provides a crucial foundation for informed decision-making and intervention strategies.

Acknowledgements Authors would like to thank the Advanced Research Centre, University of Science and Technology Meghalaya (USTM) for granting access to Atomic Absorption Spectrometer for heavy metal analysis. The authors would also like to express their gratitude to the Department of Chemistry at USTM for their invaluable assistance in conducting the sample preparation.

Author contributions All authors contributed to the study conception and design; SL: Data collection & Investigation; DB: Formal analysis & original draft preparation; HPJ: Writing, review, editing & overall supervision. All authors read and approved the final manuscript.

Funding No funding was received for conducting this study.

Data availability The data used/analyzed in the paper are available in tabular form within the manuscript.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interest.

References

Ahmad, W., Alharthy, R.D., Zubair, M., Ahmed, M., Hameed, A., Rafique, S.: Toxic and heavy metals contamination assessment in soil and water to evaluate human health risk. Sci. Rep. **11**(1), 17006 (2021). https://doi.org/10.1038/s41598-021-94616-4

Arisekar, U., Shakila, R.J., Shalini, R., Jeyasekaran, G.: Human health risk assessment of heavy metals in aquatic sediments and freshwater fish caught from Thamirabarani River, the western ghats of South Tamil Nadu. Mar. Pollut. Bull. **159**, 111496 (2020). https://doi.org/10.1016/j.marpolbul.2020.111496

Badeenezhad, A., Soleimani, H., Shahsavani, S., Parseh, I., Mohammadpour, A., Azadbakht, O., Javanmardi, P., Faraji, H., Babakrpur Nalosi, K.: Comprehensive health risk analysis of heavy metal pollution using water quality indices and Monte Carlo simulation in R software. Sci. Rep. **13**(1), 15817 (2023). https://doi.org/10.1038/s41598-023-43161-3

Bair, E.C.: A narrative review of toxic heavy metal content of infant and toddler foods and evaluation of United States policy. Front. Nutr. **9**, 919913 (2022). https://doi.org/10.3389/fnut.2022.919913

Bazrafshan, E., Mostafapour, F.K., Esmaelnejad, M., Ebrahimzadeh, G.R., Mahvi, A.H.: Concentration of heavy metals in surface water and sediments of Chah Nimeh water reservoir in Sistan and Baluchestan Province, Iran. Desalination Water Treat. **57**(20), 9332–9342 (2016). https://doi.org/10.1080/19443994.2015.1027958

BIS Bureau of Indian Standards 10500 Indian Standard Drinking Water Specification (2012). https://www.indiawaterportal.org/articles/indian-standard-drinking-water-bis-specifications-10500-2012-secondrevision

Cepal, N.U.: The 2030 agenda and the sustainable development goals: an opportunity for Latin America and the Caribbean. (2018). https://hdl.handle.net/11362/40156

CPCB Central Pollution Control Board. Comprehensive Environmental Pollution Abatement Action Plan Byrnihat Industrial Cluster-Assam. Pollution Control Board, Assam 2020 (2020). https://cpcb.nic.in/industrial_pollution/New_Action_Plans/CEPI_Action%20Plan_Byrnihat.pdf

Defo, C., Yerima, B.P.K., Noumsi, I.M.K., Bemmo, N.: Assessment of heavy metals in soils and groundwater in an urban watershed of Yaoundé (Cameroon-West Africa). Environ. Monit. Assess. **187**, 1–17 (2015). https://doi.org/10.1007/s10661-015-4292-1

Egbueri, J.C.: Heavy metals pollution source identification and probabilistic health risk assessment of shallow groundwater in Onitsha. Nigeria Anal. Lett. **53**(10), 1620–1638 (2020). https://doi.org/10.1080/00032719.2020.1712606

Ewuzie, U., Nnorom, I.C., Eze, S.O.: Lithium in drinking water sources in rural and urban communities in Southeastern Nigeria. Chemosphere. **245**, 125593 (2020). https://doi.org/10.1016/j.chemosphere.2019.125593

García, R., Báez, A.P.: Atomic absorption spectrometry (AAS). In: Farrukh MA(ed) Atomic absorption spectroscopy. IntechOpen Limited, London, UNITED KINGDOM, pp 1–12 (2012). https://doi.org/10.5772/25925

Gogtay, N.J., Thatte, U.M.: Principles of correlation analysis. J. Assoc. Phys. India **65**(3), 78–81 (2017)

Gómez-Puentes, F.J., Reyes-López, J.A., López, D.L., Carreón-Diazconti, C., Belmonte- Jiménez, S.: Geochemical processes controlling the groundwater transport of contaminants released by a dump in an arid region of México. Environ. Earth Sci. **71**, 609–621 (2014). https://doi.org/10.1007/s12665-013-2456-2

Hossain, M.T., Hassi, U., Imamul Huq, S.M.: Assessment of concentration and toxicological (Cancer) risk of lead, cadmium and chromium in tobacco products commonly available in Bangladesh. Toxicol. Rep. **5**, 897–902 (2018). https://doi.org/10.1016/j.toxrep.2018.08.019

Jaishi, H.P., Singh, S., Tiwari, R.P., Tiwari, R.C.: Analysis of subsurface soil radon with the environmental parameters and its relation with seismic events. J. Geol. Soc. India **99**(6), 847–858 (2023). https://doi.org/10.1007/s12594-023-2392-z

Kadirvelu, K., Thamaraiselvi, K., Namasivayam, C.: Removal of heavy metals from industrial wastewaters by adsorption onto activated carbon prepared from an agricultural solid waste. Bioresour. Technol. **76**(1), 63–65 (2001)

Kolo, M.T., Khandaker, M.U., Amin, Y.M., Abdullah, W.H., Bradley, D.A., Alzimami, K.S.: Assessment of health risk due to the exposure of heavy metals in soil around mega coal-fired cement factory in Nigeria. Results Phys. **11**, 755–762 (2018). https://doi.org/10.1016/j.rinp.2018.10.003

Kshetriya, D., Warjri, C.D., Chakrabarty, T.K., Ghosh, S.: Assessment of heavy metals in some natural water bodies in Meghalaya, India. Environmental nanotechnology. Monit. Manage. **16**, 100512 (2021). https://doi.org/10.1016/j.enmm.2021.100512

Lagalante, A.F.: Atomic absorption spectroscopy: a tutorial review. Appl. Spectrosc. Rev. **34**(3), 173–189 (2004). https://doi.org/10.1081/ASR-100100844

Mawari, G., Kumar, N., Sarkar, S., Frank, A.L., Daga, M.K., Singh, M.M., Joshi, T.K., Singh, I.: Human health risk assessment due to heavy metals in ground and surface water and association of diseases with drinking water sources: a study from Maharashtra, India. Environ. Health Insights **16**, 11786302221146020 (2022)

Monte Blanco, S.P.D., Módenes, A.N., Scheufele, F.B., Marin, P., Schneider, K., Espinoza-Quiñones, F.R., Paraíso, P.R., Bergamasco, R.: Groundwater quality monitoring of the Serra Geral aquifer in Toledo, Brazil. J. Environ. Sci. Health Part. A. **53**(14), 1243–1252 (2018). https://doi.org/10.1080/10934529.2018.1528038

Nriagu, J.O., Pacyna, J.M.: Quantitative assessment of worldwide contamination of air, water and soils by trace metals. Nature. **333**(6169), 134–139 (1988). https://doi.org/10.1038/333134a0

Podlasek, A., Jakimiuk, A., Vaverkov, M.D., Koda, E.: Monitoring and assessment of groundwater quality at landfill sites: Selected case studies of Poland and the Czech Republic. Sustainability. **13**(14), 7769 (2021). https://doi.org/10.3390/su13147769

Prasad, S., Saluja, R., Joshi, V., Garg, J.K.: Heavy metal pollution in surface water of the Upper Ganga River, India: human health risk assessment. Environ. Monit. Assess. **192**(11), 742 (2020). https://doi.org/10.1007/s10661-020-08701-8

Qiao, J., Zhu, Y., Jia, X., Niu, X., Liu, J.: Distributions of arsenic and other heavy metals, and health risk assessments for groundwater in the Guanzhong Plain region of China. Environ. Res. **181**, 108957 (2020). https://doi.org/10.1016/j.envres.2019.108957

Raja, V., Lakshmi, R.V., Sekar, C.P., Chidambaram, S., Neelakantan, M.A.: Health risk assessment of heavy metals in groundwater of industrial township Virudhunagar, Tamil Nadu, India. Arch. Environ. Contam. Toxicol. **80**, 144–163 (2021). https://doi.org/10.1007/s00244-020-00795-y

Saha, N., Rahman, M.S., Ahmed, M.B., Zhou, J.L., Ngo, H.H., Guo, W.: Industrial metal pollution in water and probabilistic assessment of human health risk. J. Environ. **85**, 70–78 (2017). https://doi.org/10.1016/j.jenvman.2016.10.023

Sanders, T., Liu, Y., Buchner, V., Tchounwou, P.B.: Neurotoxic effects and biomarkers of lead exposure: a review. Rev. Environ. Health **24**(1), 15–45 (2009). https://doi.org/10.1515/reveh.2009.24.1.15

Seleem, E.M., Mostafa, A., Mokhtar, M., Salman, S.A.: Risk assessment of heavy metals in drinking water on the human health, Assiut City, and its environs, Egypt. Arab. J. Geosci. **14**, 1–1 (2021). https://doi.org/10.1007/s12517-021-06784-2

Sharma, P., Bihari, V., Agarwal, S.K., Verma, V., Kesavachandran, C.N., Pangtey, B.S., Mathur, N., Singh, K.P., Srivastava, M., Goel, S.K.: Groundwater contaminated with hexavalent chromium [Cr (VI)]: A health survey and clinical examination of community inhabitants (Kanpur, India). PloS One. **7**(10), e47877 (2012). https://doi.org/10.1371/journal.pone.0047877

Sharma, S., Nagpal, A.K., Kaur, I.: Appraisal of heavy metal contents in groundwater and associated health hazards posed to human population of Ropar Wetland, Punjab, India and its environs. Chemosphere **227**, 179–190 (2019). https://doi.org/10.1016/j.chemosphere.2019.04.009

Ukah, B.U., Egbueri, J.C., Unigwe, C.O., Ubido, O.E.: Extent of heavy metals pollution and health risk assessment of groundwater in a densely populated industrial area, Lagos, Nigeria. Int. J. Energy Water Resour. **3**, 291–303 (2019). https://doi.org/10.1007/s42108-019-00039-3

Ukaogo, P.O., Ewuzie, U., Onwuka, C.V.: 21-Environmental pollution: causes, effects, and the remedies. In: Chowdhary, P., Raj, A., Verma, D., Yusuf Akhter, Y. (eds.) Microorganisms for sustainable environment and health. Elsevier, Amsterdam (2020)

USEPA: Risk assessment guidance for superfund. Volume I: human health evaluation manual (Part A). Office of Superfund Remediation and Technology Innovation, U.S. Environmental Protection Agency. EPA/540/1–89/002. (1989)

USEPA (2001) Risk Assessment Guidance for Superfund. Volume III: Process for Conducting Probabilistic Risk Assessment (part A). Office of Emergency and Remedial USEPA, Response: U.S. Environmental Protection Agency, Washington DC. EPA 540-R-02-002, OSWER 9285.7–45 (2001)

USEPA: Risk assessment guidance for superfund. Volume I: human health evaluation manual (Part E, supplemental guidance for dermal risk assessment). Office of Superfund Remediation and Technology Innovation, U.S. Environmental Protection Agency. 5, EPA/540/R/99. (2004)

USEPA: Guidance for evaluating the oral bioavailability of metals in soils for use in human health risk assessment. U.S. Environmental Protection Agency, OSWER. 9285.7–80. (2007)

USEPA: EPA region III risk-based concentration (RBC) Table 2008 region III, United States Environmental Protection Agency, (2012). 1650 Arch Street.

Van Loon, J.C.: Analytical atomic absorption spectroscopy: selected methods. Elsevier, Amsterdam (1980)

Varol, M., Tokatlı, C.: Seasonal variations of toxic metal (loid) s in groundwater collected from an intensive agricultural area in northwestern Turkey and associated health risk assessment. Environ. Res. **204**, 111922 (2022). https://doi.org/10.1016/j.envres.2021.111922

Vodela, J.K., Renden, J.A., Lenz, S.D., McElhenney, W.H., Kemppainen, B.W.: Drinking water contaminants (arsenic, cadmium, lead, benzene, and trichloroethylene). 1. Interaction of contaminants with nutritional status on general performance and immune function in broiler chickens. Poult. Sci. **76**(11), 1474–1492 (1997). https://doi.org/10.1093/ps/76.11.1474

Wagh, V.M., Panaskar, D.B., Mukate, S.V., Gaikwad, S.K., Muley, A.A., Varade, A.M.: Health risk assessment of heavy metal contamination in groundwater of Kadava River Basin, Nashik, India. Model. Earth Syst. Environ. **4**, 969–980 (2018). https://doi.org/10.1007/s40808-018-0496-z

Wang, C.Q., Liu, K., Huang, D.M., Chen, Q., Tu, M.J., Wu, K., Shui, Z.H.: Utilization of fly ash as building material admixture: basic properties and heavy metal leaching. Case Stud. Constr. Mater. **17**, e01422 (2022). https://doi.org/10.1016/j.cscm.2022.e01422

Wani, A., Ara, A., Usmani, J.: Lead toxicity: A review. Interdiscip. Toxicol. **8**(2), 55–64 (2016). https://doi.org/10.1515/intox-2015-0009

WHO: Guidelines for drinking-water Quality: Fourth Edition Incorporating First Addendum. World Health Organization 541p, Geneva (2017) https://apps.who.int/iris/handle/10665/254637

Williams, T.R.: Analytical methods for atomic absorption spectrophotometry (Perkin-Elmer Corp). J. Chem. Educ. **49**(4), A250 (1972). https://doi.org/10.1021/ed049pa250.2

Yakovlev, E., Zykova, E., Zykov, S., Druzhinina, A., Ivanchenko, N.: Evaluation of heavy metal pollution of snow and groundwater on the territory of suburban community garden plots of the Arkhangelsk Agglomeration (Northwest Russia). Pollution **8**(4), 1448–1473 (2022). https://doi.org/10.22059/poll.2022.342253.1456

Zakir, H.M., Sharmin, S., Akter, A., Rahman, M.S.: Assessment of health risk of heavy metals and water quality indices for irrigation and drinking suitability of waters: A case study of Jamalpur Sadar area, Bangladesh. Environ. Adv. **2**, 100005 (2020). https://doi.org/10.1016/j.envadv.2020.100005

Zeng, X., Xu, X., Boezen, H.M., Huo, X.: Children with health impairments by heavy metals in an e-waste recycling area. Chemosphere. **148**, 408–415 (2016). https://doi.org/10.1016/j.chemosphere.2015.10.078

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