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PERCEPTIONS IN GROUNDWATER CONTAMINATION, RISK ASSESSMENT, AND MANAGEMENT STRATEGIES

Potential toxic element contamination and non-carcinogenic risk assessment of groundwater from rapidly growing urban areas in Telangana, India

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Abstract
Groundwater is a critical resource for drinking purposes that is under pressure and polluted with multiple inorganic contaminants. Among various contaminants, potentially toxic element contamination in groundwater has significant public health concerns due to their toxicity at a low level of exposure. This investigation aimed to assess the toxic element contamination and associated non-carcinogenic human health risk at rapidly growing urban centers in Telangana to ensure potable water and to generate baseline data in the study province. Thirteen potential toxic trace elements (Al, As, B, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Se, and Zn) were determined in 35 groundwater samples collected from the Karimnagar and Siddipet smart cities in lower Manair River basin using inductively coupled plasma mass spectrometry (ICP-MS). The trace element concentration is found in the range for Al (1–112 µg/L), As (2–8 µg/L), B (34–438 µg/L), Cd (bdl–2 µg/L), Co (bdl–17 µg/L), Cr (bdl–4 µg/L), Cu (bdl–216 µg/L), Fe (4–420 µg/L), Mn (bdl–3311 µg/L), Ni (5–31 µg/L), Pb (bdl–62 µg/L), Se (1–18 µg/L), and Zn (3–1858 µg/L). Analytical data of groundwater revealed the occurrence of toxic elements observed as above the acceptable limits of Bureau of Indian Standards for drinking purposes found in the order of Al > Ni ≥ Mn > Se ≥ Cu ≥ Pb > Fe with 26% > 14% ≥ 14% > 9% ≥ 9% ≥ 9% > 6% of samples, respectively. The non-carcinogenic health risk to humans upon groundwater ingestion has been evaluated and found to be non-hazardous for all the individual elements studied except for aresenic. However, cumulative hazard quotient observed as > 1 in the category of infants and children might be a major potential health concern. This study provided baseline data and suggested implementing preventive measures to protect human health around the urban areas of lower Manair river basin, Telangana, India.

Keywords Groundwater · Heavy metal pollution · Health risk assessment · Urban regions · Telangana

Introduction

Groundwater is a natural resource for drinking purposes in urban and rural areas that is under pressure and polluted with multiple inorganic contaminants. Groundwater contamination has become a challenge task for survival of human beings (Akhtar et al. 2020). Many regions worldwide are overburdened due to releasing of pesticides, fertilizers, and toxic metals from agricultural activities as well as hazardous waste containing inorganic and organic substances from industrial processes is vulnerable to pollute the soil further contaminating groundwater resources through leaching into the sub-surface system (Doyi et al. 2018; Akhtar and Rai 2019; Ahmad et al. 2022). Rapid industrialization and urbanization are the major sources that led to groundwater contamination, thereby deteriorating the quality that is unfit for consumption (Bhutiani et al. 2016). Study of potential toxic element contamination of groundwater is needed because their amalgamation in the food chain causes serious health disorders in human beings.

Groundwater pollution risk assessment is an important part of environmental assessment. Literature reivew showed that different types of methods adopted for groundwater contamination assessment and sources and hazards of

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potentially toxic elements have been reported. For instance, groundwater vulnerability assessment using bivariate and multi-criteria decision-making approach coupled with metaheuristic algorithm has been reported by Lakshminaryanan et al. (2022). Besides, an integrated variable weight model and improved DRASTIC model has been reported in shallow aquifer (Yu et al. 2022). Characterization of groundwater pollutant identification, health risk assessment, and controlling factor analysis have been reported at a landfill site (Guo et al. 2022) and intensive agricultural area (Varol and Tokatli 2022). Xu et al. (2023) reported a multi-dimensional method by combining the advantages of remote sensing cloud computing, long-term groundwater modeling simulation, and GIS technology. Huang et al. (2023) have reported non-carcinogenic health risk comprehensive assessment based on DLAFVRT model in an island city. Recently, groundwater pollution risk assessment was reported based on groundwater vulnerability and pollution load in an isolated island (Zhao et al. 2022).

Potential toxic element contamination is a substantial environmental concern worldwide due to their persistence, bioaccumulation, and toxic nature that lead to a cumulative impact on the ecosystem (Ali et al. 2019; Papazotos 2021). Consequently, determination of trace elemental concentrations in groundwater resources and its health risk assessment plays a vital role in reducing the health hazards of human beings. Trace elements of toxic nature can influence the water resources either by natural sources or anthropogenic sources. Natural sources of trace elements are expected due to weathering of rocks and the degradation of living matter (Jaishankar et al. 2014). Water–rock interaction processes are a significant natural source for the transfer of toxic elements to soil and then to water resources at high concentrations. Trace elements are persistent in the environment and can be accumulated in soils and waters through geochemical processes. Nevertheless, different geochemical behaviors of elements can lead to water geochemistry variations during water–rock interaction processes such as weathering and dissolution, ion exchange, competitive adsorption, oxidation, and reduction (Chen et al. 2021; Xiao et al. 2023).

The major routes of the anthropogenic sources in which heavy metals contaminate the groundwater are agricultural, industrial waste, solid waste disposal, biomedical wastes, and mining (Patel et al. 2018; Sharma et al. 2022). However, because of their high toxicity, elements present in trace levels also have a tendency to bioaccumulate in the food chain (Rezaei et al. 2019; Alfaifi et al. 2021). Heavy metals can intrude the food chain through groundwater, leading to many human health problems (Krishna and Mohan 2014; Qasemi et al. 2019; Karunanidhi et al. 2022). Literature search showed that heavy metal contamination in urban areas along the river basin found a high rate of anthropogenic discharge that depletes the quality of water resources (Patel et al. 2016; Ahamad et al. 2021; Vaiphei and Kurakalva 2021; Parween et al. 2021). Most of the people in India use groundwater resource for drinking purposes, irrespective of their place of living. However, urbanized localities are more exposed as the population density is higher than that in rural communities. Therefore, the present study proposed fast-growing urbanized areas that fall under the Lower Manair River Basin (LMRB) in Telangana state, India. No data are available at Manir river basin on heavy metal pollution in groundwater resources, and this is the first study of its kind. The objective of this investigation is to evaluate potential toxic element contamination and its associated health risk of groundwater of the urban vicinities of the lower Manair river basin, Telangana, India.

Study area

The study province has a geographical location that falls in the latitude of 78°47′6″N to 79°18′18″N and longitude of 17°49′51″E to 18°41′14″E covering significant urban regions, namely, Karimnagar and Siddipet of Telangana under the LMRB. The extent of the study area occupies an area of 3325 km^2. The two cities, viz., Karimnagar and Siddipet, had rapid growth in the development of various sectors for the last 7 years after forming a new state in June 2014 (GoI 2014). Furthermore, these two cities of Telangana state were designated as Smart Cities Mission (SCM) and Atal Mission for Rejuvenation and Urban Transformation (AMRUT) programs for infrastructure development. In addition, the Government of Telangana also initiated the construction of water storage structures like Mallana Sagar Reservoir in the study region.

Karimnagar is one of the major urban agglomerations with a population of 1,005,711 and the fifth largest city in Telangana state, and is the third largest and fastest growing urban settlement. Siddipet is a central urban hub and an education center with a population of 1,012,065, according to the census report (Census 2011). The area under investigation experiences dry inland climatic conditions with hot summer and cool winter. Most of its rainfall is from the Southwest monsoon, with an average rainfall of 907 mm and 779 mm in Karimnagar and Siddipet, respectively. Rapid urbanization and associated demand, as well as newly constructed water conservation structures and annual weather conditions, motivated a selection of the study region on a river basin scale. The geographical location map and land use and land cover (LULC) map of the study area are presented in Figs. 1 and 2, respectively.

Hydrogeological setting of the study area

The major aquifers in the study area is weathered and fractured granites, as well as basalts. Groundwater is designed in the study area under the conditions of consolidated formation or semi-consolidated formation and unconsolidated formation. Since the study area is composed of hard rock terrain

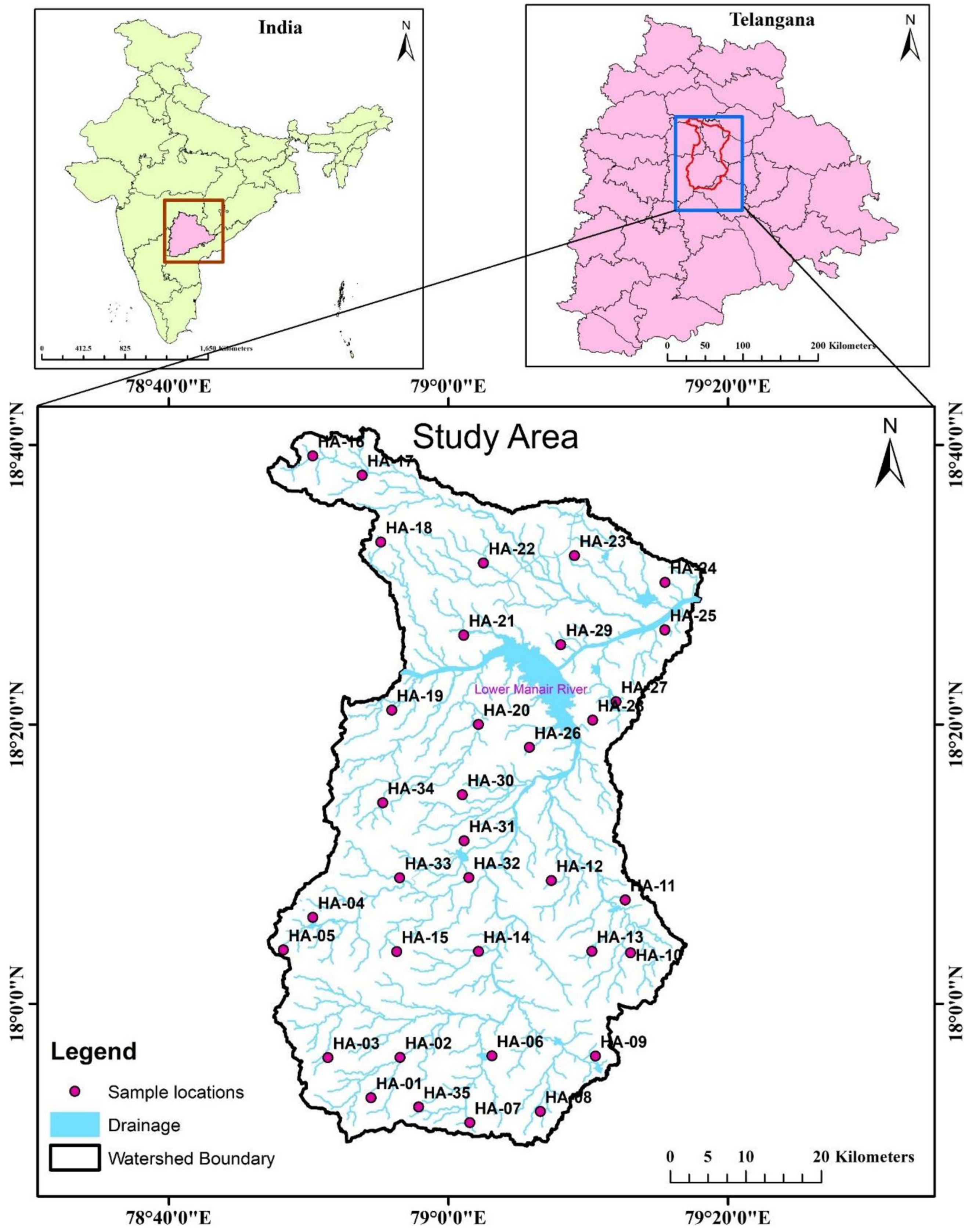


Fig. 1 Geographical location map of the study region with sampling locations and drainage

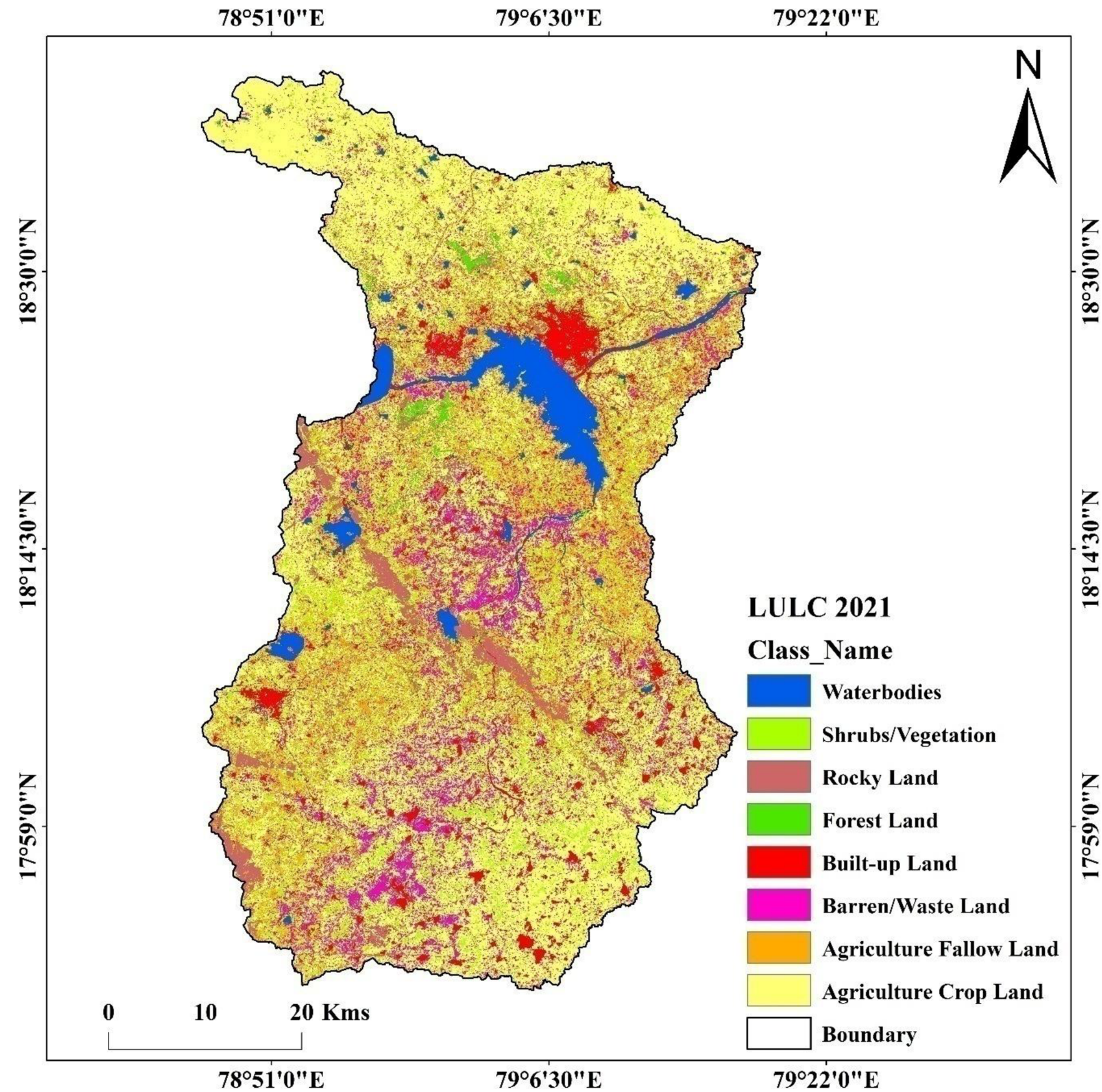


Fig. 2 LULC map lower Manair River basin for the year 2021

(granitoid), groundwater is found either in contact zone or in the fractured zone, which directly connects to the aquifer or itself acts as an aquifer (consolidated formation). The study area has been declared as overexploited with reference to the groundwater development (CGWB 2007; Kurakalva et al. 2021). The maximum depth of the weathered zone goes up to 29 m bgl (meters below ground level), while the deepest fracture is recorded up to 124.5 m bgl (CGWB 2019). Groundwater occurs under phreatic conditions in weathered zones and under semiconfined to confined conditions in the fractured zones. Ground water used to be exploited through shallow, large-diameter dug wells until 1970 to meet domestic and irrigation requirements. Presently, groundwater is principally exploited through shallow and deep bore wells with a depth ranging from 100 to 300 m (CGWB 2013).

Groundwater yield in the study area varies from 0.01 to 10 lps (liters per second) as probability of striking a fracture decreases with depth and away from the lineaments/topographic lows and found that majority of fractures (90%) occur within 100-m depth in the study region. Aquifer tests have shown that the aquifers have limited porosity due to compactness and secondary porosity is developed due to weathering and fracturing. A third- or fourth-order basin can have distinct aquifers defined by adjacent catchments. The pattern of drainage is generally dendritic with wide valleys in western pediplain. Most of the smaller streams feed innumerable tanks (CGWB 2017 and CGWB 2021). The annual extractable groundwater resources is 15.03 bcm and extraction is 8.01 bcm that accounts for 53.32% of resources (CGWB 2021).

Groundwater sample collection and analysis

Groundwater samples were collected from borewells including handpumps and submersible pumps from the LMRB at 35 locations during March 2021. Sampling points were designed to collect on a grid wise (10×10 km^2) to cover the entire study region with the goal of one sample at least from one grid. However, the sampling was much preferred near the agricultural, industrial, and municipal solid waste disposal sites in the urban regions, namely, Karimnagar and Siddipet in the study region. Groundwater samples were collected in clean polyethene bottles (60 mL) that were treated with dilute HNO_3 for 24 h, followed by rinsing several times with deionized water and dried. Prior to sampling of groundwater, the borewells are pumped out for 5–10 min to discard the stagnant water. Later, the samples were collected in 60-mL bottles, and a few drops of concentrated HNO_3 were added as a preservative to prevent precipitation and then sealed carefully and sent to Environmental Geochemistry laboratory of CSIR-NGRI for further analysis. After receipt at the laboratory, the water samples were filtered through a 0.22-µm membrane filter. The filtered water samples were used to determine the potential toxic element (Al, As, B, Cd, Co, Cr, Cu Fe, Mn, Ni, Pb, Se, and Zn) concentrations using Agilent 7800 quadrupole inductively coupled plasma mass spectrometry (ICP-MS) adopting the EPA 6020A method (USEPA 1994).

Assessment and mobility of toxic element contamination

The study of toxic elements in groundwater is a prerequisite as their amalgamation in the food chain causes potential health hazards to human beings. Suitability of groundwater for drinking purposes was evaluated using the concentrations of elements obtained by comparing the international standard values, e.g., WHO (2011) permissible values and Indian standards 10500 prescribed by the BIS (2012). These findings would help ascertain its suitability for drinking and heavy metal pollution load. Also, the spatial distribution of all 13 elements measured at each sampling location also helps identify the hotspots of groundwater resource contamination.

The mobility of toxic elements can be assessed using Ficklin–Caboi diagram (Ficklin et al. 1992; Caboi et al. 1999) and can also differentiate the various geological aspects of water chemistry (Herojeet et al. 2015). The metal load of each groundwater sample was computed using the following equation:

$$Metal\ load\ (mg/L) = \sum_{i=1}^{n} Concn.\ metal \tag{1}$$

Caboi plot shows the degree of mobility of heavy metals, which is proportional to any change in pH (Khan et al. 2022).

Health risk assessment

Health risk assessment has a vital and easy evaluation methodology with the existing data that devoids in situ toxicological dose assessment. Non-carcinogenic health risk of toxic metals is assessed using average daily dose (ADD) and hazard quotient (HQ) values as per the given Eqs. (2) and (3) (USEPA 2001; Bhardwaj et al. 2017; Kurakalva et al. 2021; Rostami et al. 2021; Sharma et al. 2022). The present investigation includes potential toxic metals such as As, Co, Cr, Cu, Mn, Ni, Pb, and Zn that are largely non-carcinogenic except Co, Cr, and Ni. Most of the metals entered the human body majorly through the ingestion of water.

$$\mathrm{ADD_{Oral}} = \frac{(C \times IR \times EF \times ED)}{(ABW \times AET)} \tag{2}$$

where.

ADD_{oral} = oral average daily dose (mg/kg/day).

C = average concentration of each trace metal in groundwater (mg/L).

IR = ingestion rate of groundwater (L/day).

EF = frequency of exposure (days/year).

ED = exposure duration (years).

BW = body weight per kilogram and.

AT = average time which can be calculated by multiplying EF and ED.

The standard health risk factor values (USEPA 2014; Kurakalva et al. 2021) assigned for different age groups (i.e., adults, children, and infants) of human beings are presented in Table 1.

$$\mathrm{HQ_{Oral}} = \frac{ADD}{RfD} \tag{3}$$

RfD signifies toxicity reference dose (mg/kg/day) oral.

Non-carcinogenic risk posed due to potential toxic metals is evaluated through the hazard index (HI) as per the following Eq. (4):

$$\mathrm{HI} = HQ\mathrm{metal1} + HQ\mathrm{metal2} + HQ\mathrm{metal3} + HQ\mathrm{metaln} \tag{4}$$

The average daily dose (ADD_{oral}) is exclusively for non-carcinogenic pollutants and is calculated using Eq. (4).

Table 1 Standard health risk factor values assigned for different ages groups (Qasemi et al. 2018)

Standard values for different age groups				
Health risk factors	Adults	Children	Infants	Units
C	Measured concentration value of trace element in groundwater sample			mg/L
IR	2	1.5	0.8	L/day
EF	365	365	365	Days/year
ED	40	10	1	Years
BW	70	20	10	Weight
AT	14,600	3650	365	Days

Results and discussion

Heavy metal contamination

Table 2 shows descriptive statistics of the trace elemental concentration and their comparison with BIS- and WHO-recommended values for drinking purposes. BIS has two different guideline values for drinking purposes—one is acceptable limits and the other one is maximum permissible limits that are designated in case no other alternative water resource is available in a particular area. The pH is observed in the range of 6.67–7.46 with an average of 6.95 showing that groundwater is neutral. TDS values of groundwater samples range from 400 to 1630 mg/L with an average value of 750 mg/L. Data indicate that 77% of samples exceed the BIS (2012) drinking water acceptable limit of 500 mg/L of TDS content in groundwater. On the other hand, most of the samples are within maximum permissible limit of 2000 mg/L if no other alternative source is available for drinking pruposes. The high TDS concentrations above the BIS acceptable limit of 500 mg/L were found in the regions where the percolation of degraded waste generated from dump yards and industries (i.e., agrobased, brick and granite quarrying) might contribute (Aduojo et al. 2020). Besides, geochemical process occurring in the study area that consists of peninsular gneissic complex also contributed to the high TDS in groundwater (Selvakumar et al. 2017; Vasu et al. 2017).

Analytical data showed that the occurrence of toxic elements among the groundwater samples collected was observed above the acceptable limits of BIS for drinking purposes in the order Al > Ni ≥ Mn > Se ≥ Cu ≥ Pb > Fe with 26% > 14% ≥ 14% > 9% ≥ 9% ≥ 9% > 6% of samples studied, respectively. Besides, BIS (2012) prescribed maximum permissible limits for the elements under investigation, included (Table 2) to utilize in case there is no other water resource available for drinking use in the region, were also evaluated. These data demonstrated that maximum permissible limit for elements like Al, As, B, Cd, Co, Cr, Cu, Fe, and Zn found within the limits except for Mn at the location HA17 (Kodimial) might be due to anthropogenic activities such as waste dumpsites, cement brick, and agro-based industries, which are potential sources of attributed variations. In addition, the trace elements found in groundwater is compared with WHO. (2011) drinking water guidelines with maximum permissible values to decipher the extent of contamination and suitability for drinking purposes. According to WHO guideline values, carcinogenic elements such as Mn, Pb, and Se were found beyond the permissible limits for drinking use as 11%, 9%, and ≥ 9% of samples, respectively. In conclusion, most toxic elements like Mn, Pb, and Se exceed the maximum permissible limits of BIS in case no other water resource is available in the region, as well as WHO guideline values.

To determine the effect of natural and anthropogenic activities on these elements and to distinguish sources of contamination, background levels (BGV) of heavy metals are adopted from our previous work (Govil et al. 2008) which has a similar granitic formation of the present study area. It is well known that the background levels of heavy metals in soils were usually determined by the levels that existed in the parent materials and by redistribution in the profile due to pedogenesis during the process of soil formation. Pb background values in soils are reported to be in the range of 35–94 mg/kg in granitic soils of Hyderabad. The present study reported Pb concentrations in groundwater as bdl–62 μg/L (Table 1), indicating that there might be leaching of Pb from soils as well as anthropogenic inputs from agricultural drainage wastewater, granite quarries, and urban waste dumping. On the other hand, average background values in soils for Mn and Se are reported as 600 mg/kg and 0.3 mg/kg, respectively (Lindsay 1979). It is observed that the concentration of Mn (bdl–3311 μg/L) and Se (1–18 μg/L) found in groundwater of the study area might be due to leaching from soil and anthropogenic input from agricultural-based waste water. It clearly indicates that there might be contribution from the leaching from soils (geogenic source); however, above all there is a suggestion that there is an anthropogenic (human) source that caused the heavy metal contamination as concentrations are above BGV of heavy metals in soils. These findings demonstrate that groundwater of LMRB region is unsuitable for drinking and poses health hazards to humans.

Table 2 Trace elemental concentration and their comparison with WHO/BIS permissible limit for drinking purposes ($n = 35$)

Trace metal	Units	Range		Average	Median	SD	BIS (2012) Guideline values for DRINKING WATER			WHO (2011) recommended safe limits for DRINKING WATER	
		Min	Max				Acceptable limit (requirement)	% of samples exceeded acceptable limits	Permissible limit (in the absence of an alternate source)	Max permissible limits	% of samples exceed permissible limits
pH	–	6.67	7.46	6.97	6.95	0.16	6.5–8.5	Nil	No relaxation	6.5–8.5	Nil
TDS	mg/L	400	1630	786	750	287	500	77	2000	500–1500	3
Al	µg/L	1	112	27.8	17	29	30	26	200	900	Nil
As	µg/L	2	8	5	6	1	10	nil	50	10	Nil
B	µg/L	34	438	139	114	92	500	nil	1000	2400	Nil
Cd	µg/L	bdl	2	0	bdl	0	3	nil	No relaxation	5	Nil
Co	µg/L	bdl	17	1	1	3	n/a	n/a	n/a	n/a	n/a
Cr	µg/L	bdl	4	1	bdl	1	50	nil	No relaxation	50	Nil
Cu	µg/L	bdl	216	14	3	38	50	9	1500	< 2000	Nil
Fe	µg/L	4	420	53	16	97	300	6	No relaxation	n/a	n/a
Mn	µg/L	bdl	3311	119	4	557	100	14	300	120	11
Ni	µg/L	5	31	15	14	6	20	14	No relaxation	70	Nil
Pb	µg/L	bdl	62	6	1	15	10	9	No relaxation	10	9
Se	µg/L	1	18	5	4	4	10	9	No relaxation	10	9
Zn	µg/L	3	1858	204	18	472	5000	nil	15,000	3000	Nil

bdl below detection limit, *n/a* not available

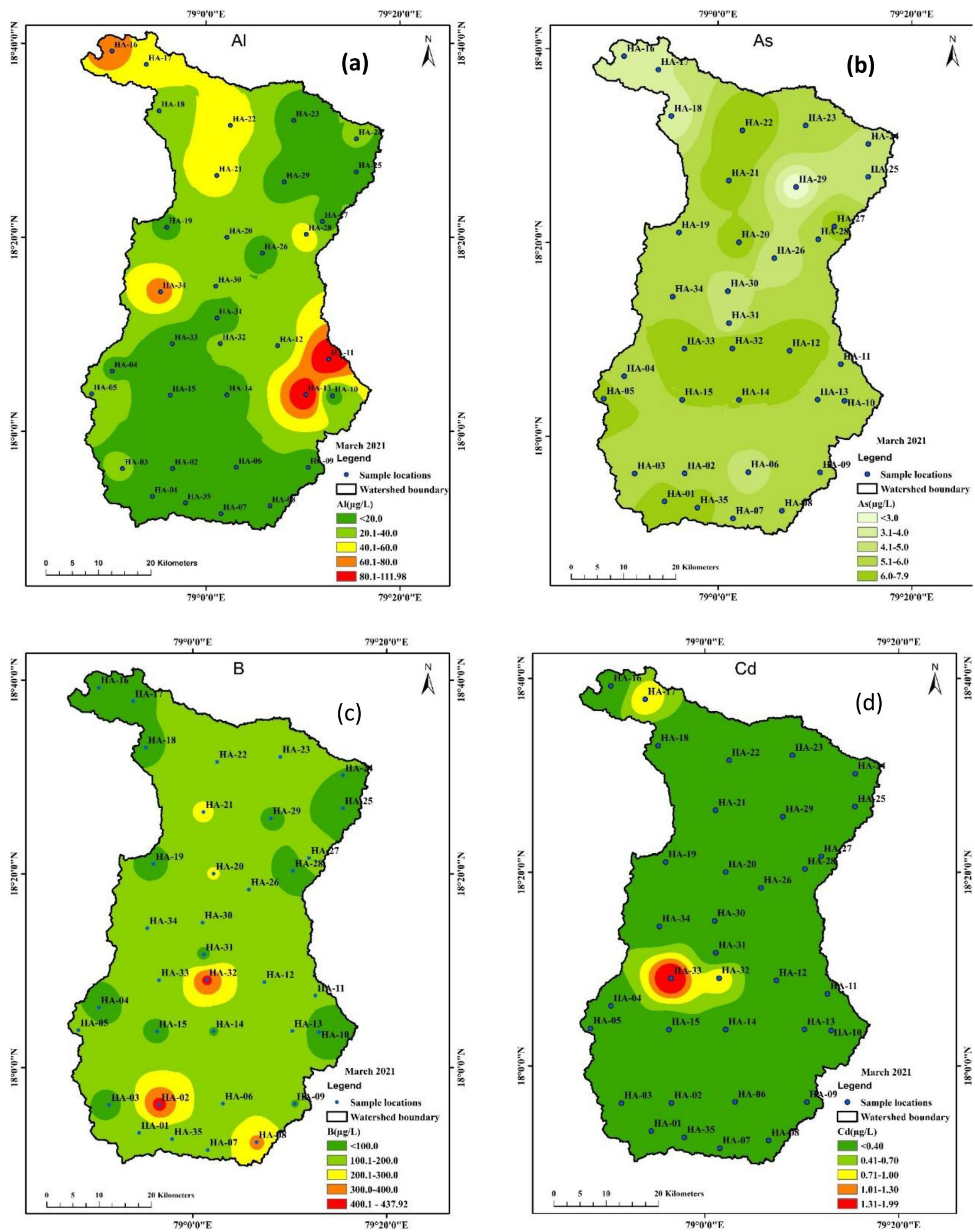
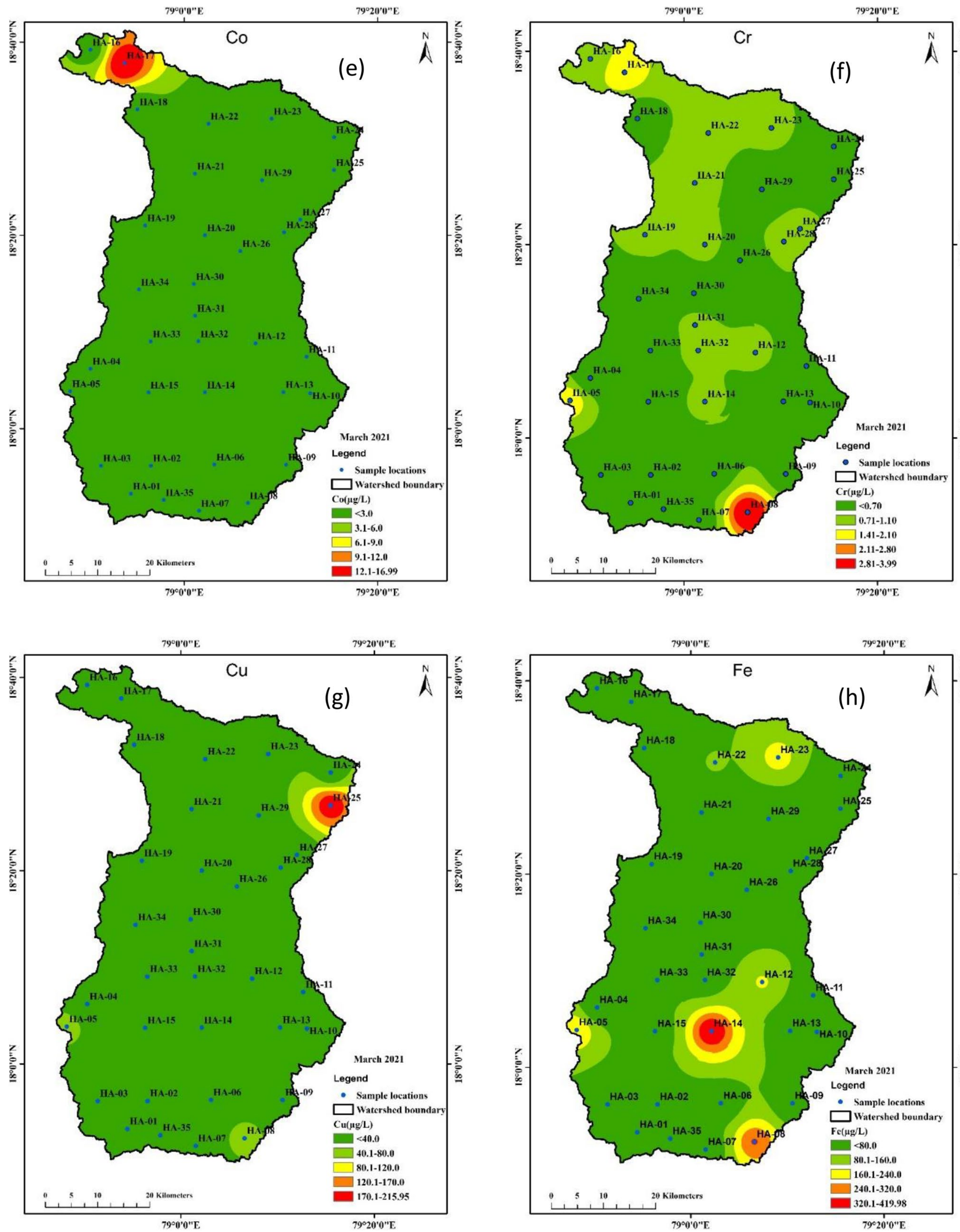


Fig. 3 **a**–**m** Spatial distribution of potential toxic elements load showing hotspots of contamination in the study region



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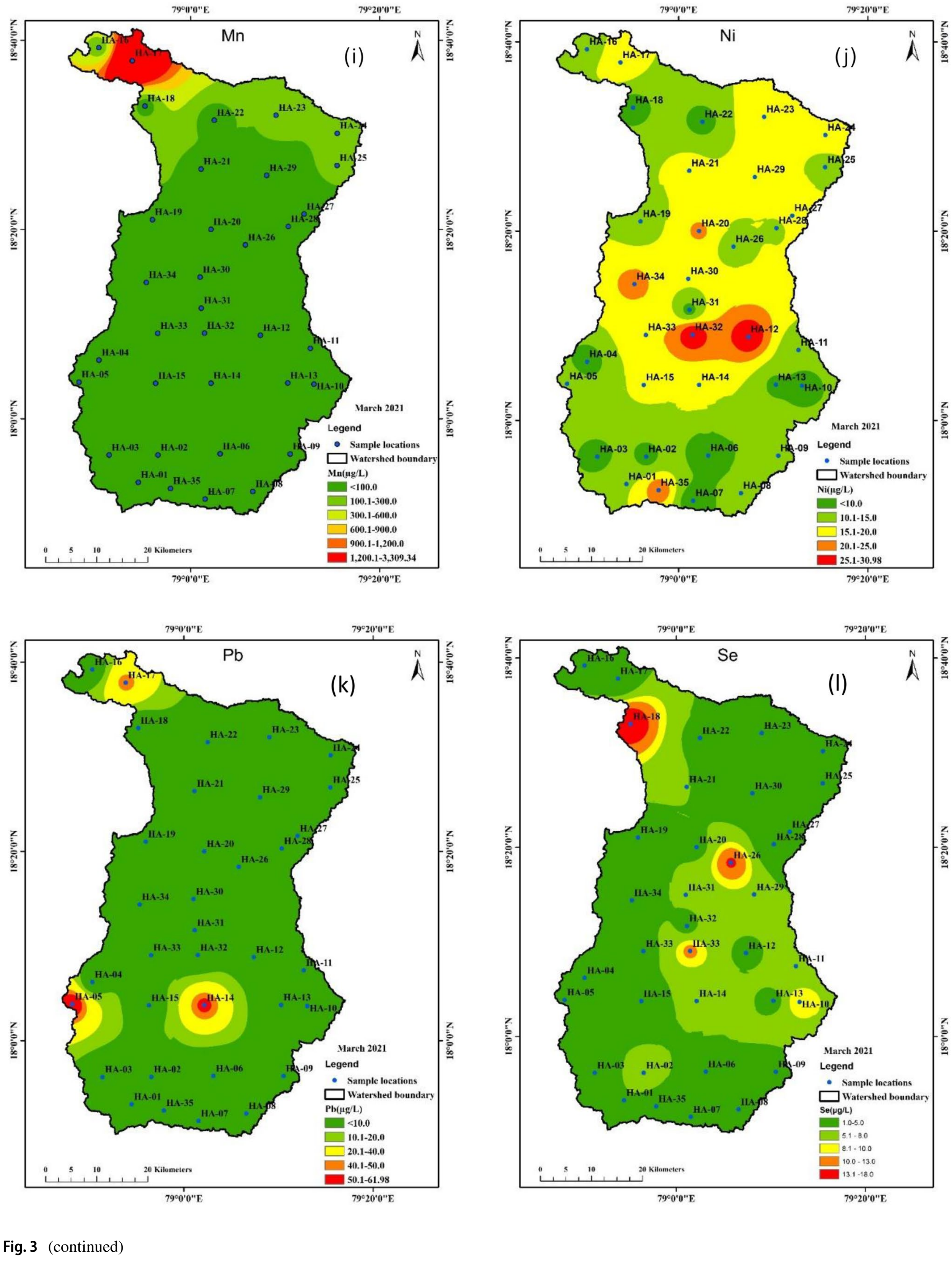

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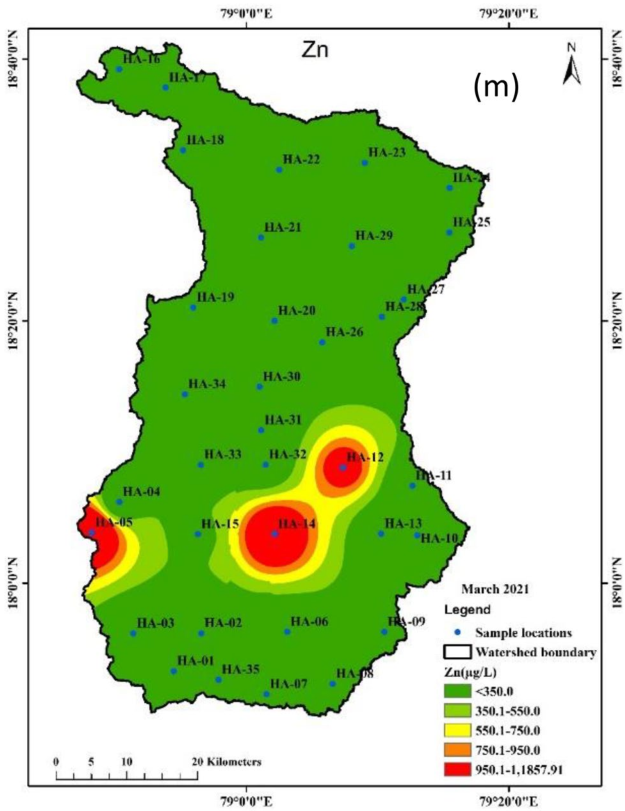

Fig. 3 (continued)

Spatial distribution of potential toxic elements

The presence of heavy metals and their distribution in groundwater depends on the local geology, hydrogeology, and geochemical characteristics of the aquifer (Wang and Mulligan 2006). Spatial variations of various potential toxic elements (Al, As, B, Cd, Co, Cr, Cu Fe, Mn, Ni, Pb, Se, and Zn) in groundwater of lower Manair river basin are presented in Fig. 3a–m. Most of the elements studied were distributed in the eastern part of the study area might be due to anthropogenic activity such as granite mining and waste dump sites. Furthermore, Pb, Se, and Zn found to have more variations with an elevated concentration of 62 µg/L, 18 µg/L, and 1858 µg/L, respectively, are beyond the regulatory limits for drinking purposes as shown in Fig. 3k to m. In particular, Pb is found high in the north-western part of the study area, the major urban aggolmoration (Karimnagar) generating huge amounts of solid waste, while Se and Zn were found in the southeastern part where the major urban area Siddipet is located. This might be due to improper municipal and domestic solid waste dumping on open lands causing toxic trace elemental concentrations to the groundwater through leaching into the sub-surface system. Spatial distribution of potential toxic element load at each sampling site was also assessed, and their spatial variations are presented in Fig. 4. These evaluations ascertain that at sampling sites HA17 (Kodimial), HA-23 (Choppadandi), HA-14 (Nanganur), HA-8 (Veldanda), HA-12 (CC Pally), and HA-05 (Tadkapally), there is potential of contamination with toxic metals, and in the future, these become hotspots of contamination. Arsenic found in the study area is below the permissible level, i.e., 10 µg/L, for drinking purposes. However, Se concentrations in groundwater were found beyond the permissible limit at locations HA-10 (Anthakapet), HA-32 (Shanigaram), HA-26 (Gundlapalli), and HA-18 (Ananthapalli), as these locations are surrounded by agricultural waste/drainage water. Literature reveals that Devi et al. (2021) reported that similar sources are contributing to Se concentration in groundwater reso urces.

Mobility of potential toxic elements

The mobility of potential toxic metals can be understood by Ficklin–Caboi methods that help differentiate several geological aspects of water chemistry. The data obtained on pH and metal load of each groundwater sample from the LMRB were plotted in Ficklin–Caboi diagram and classified as shown in Fig. 5. The diagram shows that most of the groundwater in the study area (91.4% of samples) is classified as "near neutral low metal class," while the remaining 8.6% of the samples are classified as near neutral high metal class. From these classifications, it can inferred that toxic metals present in the groundwaters of urban areas of LMRB are relatively low and less mobile in the aqueous phase.

Evaluation of health risk

Non-carcinogenic health risk was considered for the 13 elements such as Al, As, B, Cd, Co, Cr, Cu Fe, Mn, Ni, Pb, Se, and Zn, which are presented in Table 3 and evaluated according to USEPA guideline values (USEPA 2015). The mean values of ADD ingestion and HQ values for three different categories, such as adults, children, and infants, in the study region (Table 3) are evaluated to understand their associated human health risk due to ingestion of contaminated groundwater with potential toxic elements. If HQ value > 1 is observed, it poses a non-carcinogenic adverse health impact and the groundwater is unsuitable for drinking purposes (USEPA 2015; Kurakalva et al. 2021; Jooybari et al. 2022). Besides, the hazard index (HI) is calculated using Eq. (4) that is a summation of all the hazard quotient (HQ) values of target elements studied for non-carcinogenic health risk assessment (Table3).

The mean HQ values are < 1 for various toxic elements for the adult group, indicating no significant health risk. However,

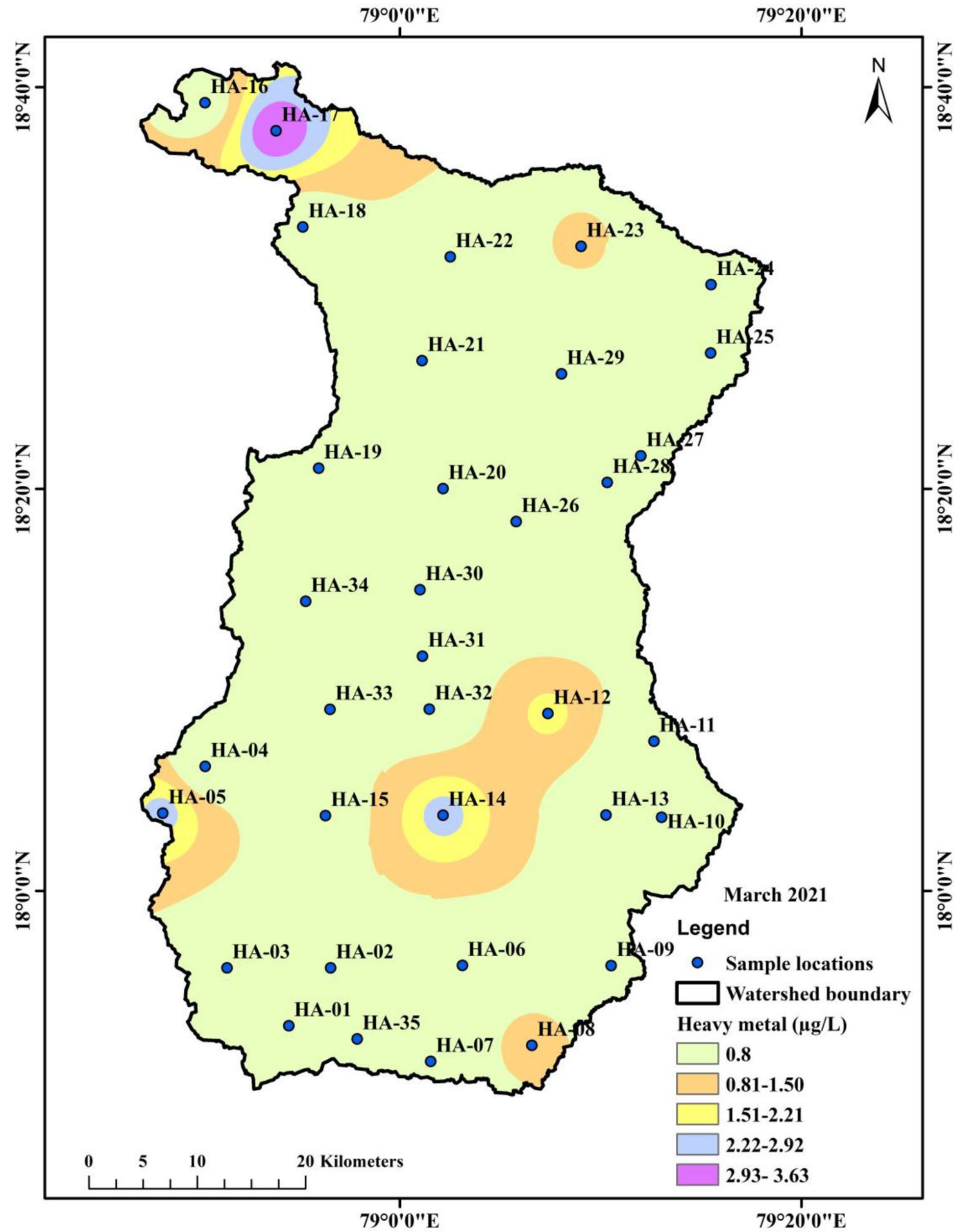

Fig. 4 Spatial distribution of sum of all elements' load at each sampling site in the study region

the HQ values for the children and infants group showed > 1; there is a potential health hazard to these groups, particularly with elements like As and Se (Fig. 6). On the other hand, HI values obtained were greater than one demonstrating that the potential health risk is in the order of infants (2.822) > children (2.646) > adults (1.008), as shown in Table 3.

Conclusion

Heavy metal pollution of groundwater and associated health risk assessment around urban regions in lower Manair river basin is the first study of its kind, hence providing a baseline data. This study revealed that the groundwater of lower Manair river basin contains toxic elements such as Al, As, B, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Se, and Zn. However, the potential toxic elements, namely, Mn, Pb, and Se, are predominant in groundwater samples of the lower Manair river basin of Telangana. Presence of toxic elements in groundwater indicated that 11% of samples with Mn and 9% of samples with Pb and Se are beyond the maximum permissible limits of WHO-recommended guidelines for drinking purposes. Therefore, groundwater is unsuitable for consumption as drinking water and is hazardous to human health in the study region. The contamination hotspots found at sampling sites HA17 (Kodimial), HA-23 (Choppadandi), HA-14 (Nanganur), HA-8

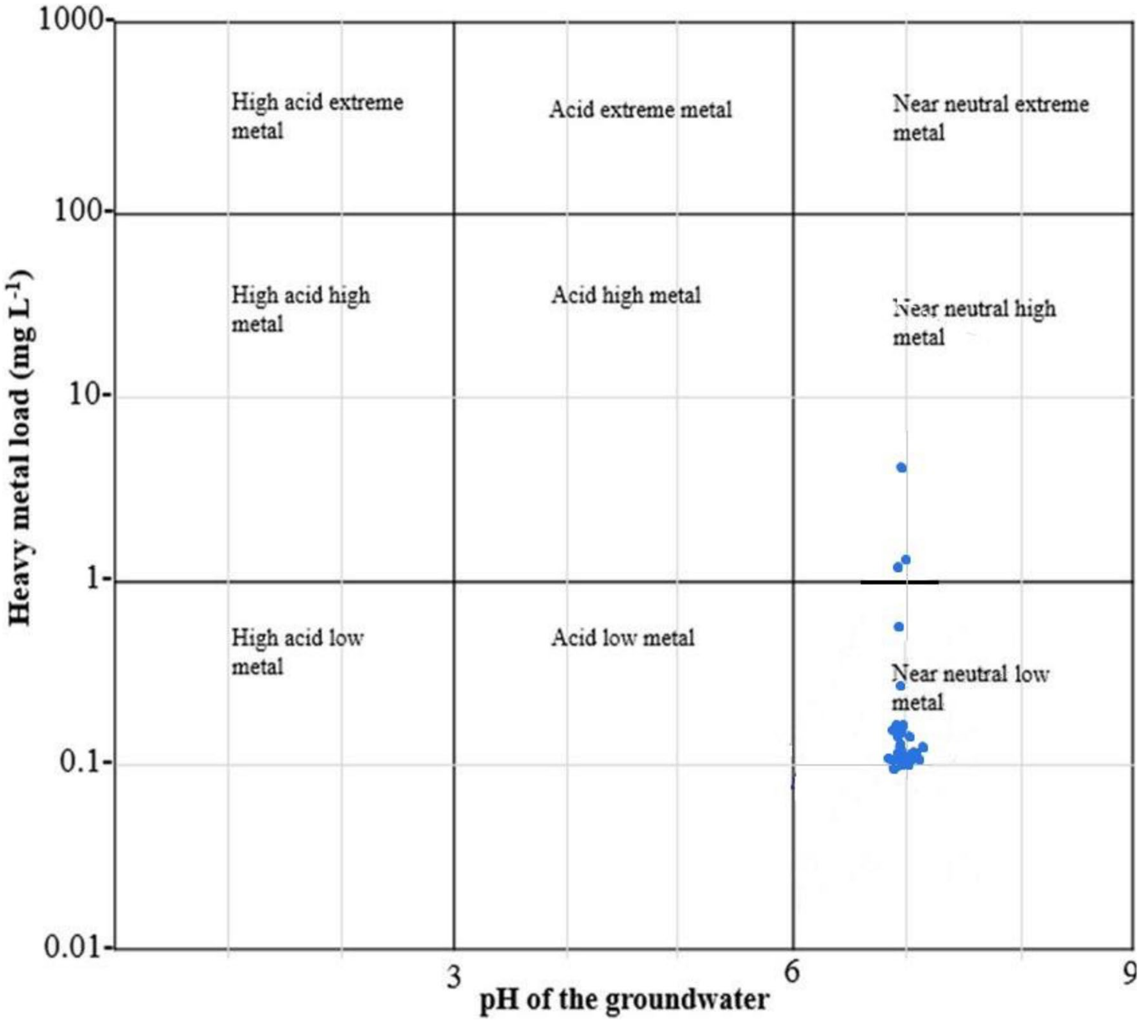

Fig. 5 Ficklin–Caboi diagram shows the groundwater classification based on total heavy metal load vs. pH of the study area

(Veldanda), HA-12 (CC Pally), and HA-05 (Tadkapally) are located around urbanized areas and near municipal solid waste dumpsites indicating influence of anthropogenic activities on groundwater contamination. The hazard quotient (HQ) was found > 1 significantly in the children and infant group for arsenic only. However, hazard index (HI) values > 1 found in the order of infants (2.822) > children (2.646) > adults (1.008) infer that there is a potential health risk. The findings of this study will help to plan and design the protective measures to supply potable water to the inhabitants. The following recommendations and future perspectives are arrived at from this study:

1. The present investigation found the presence of the toxic elements such as Mn (11% of samples) and Pb (9% of samples) that are beyond the maximum permissible limits of WHO-recommended guidelines for drinking purposes. Hence, people in the study area are advised to treat the water to remove the reported toxic metals prior to use for drinking purpose.
2. The most promising methods suggested are ion exchange, adsorption, membrane filteration, and reverse osmosis for removal of toxic elements from contaminated groundwater.
3. The specific alert should be given to the public about the hotspots of contamination of groundwater with potential toxic elements to adopt the said remedial measures.
4. The data generated on groundwater quality will be shared with policy makers to adopt suitable mitigation measures to supply potable water in the study region.
5. This study indicates the need to identify the sources of these pollutants using isotopic studies that, in turn, will help prevent spread and enrichment of the contamination.
6. Contaminant transport modeling of the pollutants to understand the fate and behavior in the groundwater environment is essential for its sustainable management.

Table 3 Risk assessment of potential toxic metals exposure in groundwater

Trace metal	C (mg/L) $n=35$	Adults				Children				Infants			
		ADD	RfD	HQ	HI	ADD	RfD	HQ	HI	ADD	RfD	HQ	HI
Al	0.0278	0.0008	n/a	n/a		0.0021	n/a	n/a		0.0022	n/a	n/a	
As	0.0055	0.0002	0.0003	0.5224		0.0004	0.0003	1.3714		0.0004	0.0003	1.4629	
B	0.1386	0.0040	0.2000	0.0198		0.0104	0.2000	0.0520		0.0111	0.2000	0.0555	
Cd	0.0001	0.0000	0.0005	0.0067		0.0000	0.0005	0.0176		0.0000	0.0005	0.0188	
Co	0.0011	0.0000	n/a	n/a		0.0001	n/a	n/a		0.0001	n/a	n/a	
Cr	0.0009	0.0000	0.0030	0.0083		0.0001	0.0030	0.0217		0.0001	0.0030	0.0232	
Cu	0.0141	0.0004	0.0050	0.0805		0.0011	0.0050	0.2113		0.0011	0.0050	0.2254	
Fe	0.0527	0.0015	n/a	n/a		0.0040	n/a	n/a		0.0042	n/a	n/a	
Mn	0.1220	0.0035	0.1400	0.0249		0.0092	0.1400	0.0654		0.0098	0.1400	0.0697	
Ni	0.0145	0.0004	0.0200	0.0208		0.0011	0.0200	0.0545		0.0012	0.0200	0.0582	
Pb	0.0057	0.0002	0.0036	0.0455		0.0004	0.0036	0.1195		0.0005	0.0036	0.1275	
Se	0.0045	0.0001	0.0005	0.2596		0.0003	0.0005	0.6814		0.0004	0.0005	0.7269	
Zn	0.2038	0.0058	0.3000	0.0194	1.0080	0.0153	0.3000	0.0510	2.6460	0.0163	0.3000	0.0544	2.8220

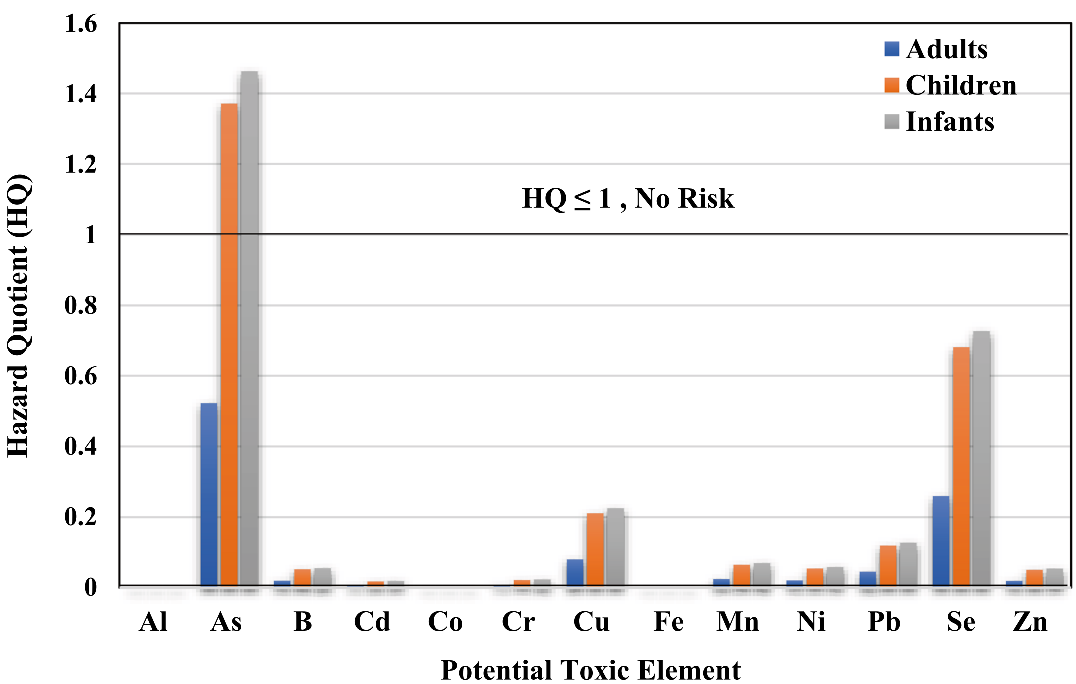

Fig. 6 Distribution of hazard quotient among the various groups (adults, children, and infants) across the potential toxic elements

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Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Consent for publication All the authors have consented to publish this manuscript.

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