Journal of Water & Health

 Journal of Water and Health Vol 22 No 1, 52 doi: 10.2166/wh.2023.072

A chemometric and ingestion hazard prediction study of groundwater in proximity to the Bandhwari landfill site, Gurugram, India

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ABSTRACT

Groundwater contamination due to the leaching of harmful pollutants such as heavy metals, xenobiotic compounds, and other inorganic compounds from solid waste dumping sites has become a major health concern in recent times. Therefore, to assess the effects of the Bandhwari landfill site, groundwater samples from the surrounding region of the dumping site were collected and analyzed for heavy metals and physicochemical properties. The total dissolved solids (TDS) of 67% of samples exceeded the Bureau of Indian Standards (BIS) permissible limits which makes it unfit for drinking purposes. The groundwater samples were also analyzed for iron (Fe), lead (Pb), zinc (Zn), nickel (Ni), copper (Cu), cadmium (Cd), and chromium (Cr) concentrations and results of heavy metal concentration in the groundwater around the Bandhwari landfill follow the concentration trend of Pb > Cd > Ni > Cu > Zn > Fe > Cr. Risk assessment of consumers' health was done using target hazard quotient calculations which were less than unity (threshold value of <1), indicating that heavy metal concentrations do not pose any serious health effect according to total hazard quotient values. The results of the study made it evident that groundwater is not suitable for drinking purposes due to excess values of water quality parameters but poses no risk due to studied metal concentrations.

Key words: groundwater contamination, heavy metals, landfill, leachate, solid waste

HIGHLIGHTS

- Landfill sites are becoming a problem instead of a solution.
- The Bandhwari landfill site is close to the Aravalli forest area.
- The Bandhwari landfill site leads to groundwater contamination in nearby areas.
- Most of the physicochemical parameters exceed the permissible limit.
- Residents of the nearby area of the Bhandwari landfill site were not at risk due to the heavy metals concentration in groundwater.

GRAPHICAL ABSTRACT

Landfill site   Groundwater Sampling Location   Heavy metals hazard

INTRODUCTION

Water is the most valuable resource on the planet and is regarded as an essential requirement for life and the country's economic progress (Malik *et al.* 2024). The health of the population of an area is significantly determined by the quality of water. Groundwater is the most crucial water source for any nation and has a critical role in the community's health especially in countries like India, where groundwater supplies 90% of the country's water demands (Khyalia *et al.* 2023). India's 60% demand for agriculture is fulfilled by groundwater (Bhattarai *et al.* 2021). Despite the significant reliance on subsurface water supplies, groundwater contamination has resulted from a variety of sources, viz. irrigation water percolation, septic tank spillages, industrial effluent disposal, and toxic chemical leaching from dumpsites, all of which have degraded the quality of groundwater resources and rendered them unfit for use (Sarvajayakesavalu *et al.* 2018; Przydatek & Kanownik 2019; Siwila & Buumba 2021). India with its 1.39 billion people is the second most populated country in the world, preceding China (1.44 billion), and with the current rate of population growth, India has been predicted to have more than 1.53 billion people by the end of 2030 (Omolola *et al.* 2023). Rapid growth in urbanization, industrialization, and economic development coupled with an ever-increasing population and a changing lifestyle has resulted in the amplified generation of municipal solid waste. Currently, the disposal and management of municipal solid waste are one of the major environmental concerns faced by both developed and developing countries. The most common methods of waste disposal in India are open dumping and landfills because they do not require skilled workers and sophisticated technology (Narayana 2009). Though landfills provide a quick and easy solution, according to Lee & Jones (1993), the disposal of municipal solid waste by landfilling has proven to be one of the main culprits behind groundwater pollution as the waste in landfills undergoes various chemical, physical, and biochemical reactions and generates leachate as a by-product. Various studies have been conducted at different landfill sites to understand their role in groundwater contamination (Acharya *et al.* 2018; Abiriga *et al.* 2020; Amano *et al.* 2021; Podlasek *et al.* 2021).

The area near the landfill site is usually more vulnerable to groundwater pollution (Singh *et al.* 2008; Njoku *et al.* 2019). The leachate produced by landfills is composed of concentrated complex effluents containing waste products such as humic acids, NH_3, Ca, Fe, Na, Mg, K, SO_4^{2-}, Cl^- with heavy metals, viz. Cd, Cu, Pb, Cr, Zn, and anthropogenic xenobiotic compounds (Kjeldsen *et al.* 2002; Boateng *et al.* 2019). These pollutants have detrimental impacts on aquatic life, the ecology, and the food chain, leading to various health problems like carcinogenic effects, acute toxicity, and genotoxicity (Gajski *et al.* 2011). Therefore, the improper and unscientific disposal of this municipal solid waste has an adverse impact on all the components of the environment (Sharma *et al.* 2018). The study documented here was carried out to measure the impact of the Bandhwari landfill on the groundwater quality of surrounding areas. Groundwater quality in the landfill region was checked for several physicochemical parameters of collected samples, with a concentration of selected heavy metals including Fe, Cd, Pb, Zn, Cu, Ni, and Cr. The health risk from consumption of the studied groundwater samples was also calculated to develop clarity about the risk from groundwater use.

MATERIALS AND METHODS

Study area

The Bandhwari landfill site is one of the largest landfill sites in Northern India and it is situated in Bandhwari village of Gurugram on Gurugram-Faridabad National Highway-48. Bandhwari village has a population of 3,624 people living in around 557 households. Bandhwari landfill site is an open dumping site which was established in 2009 and since then, the site has been accommodating waste from Gurugram and Faridabad. This landfill is 37.2 m high and is spread across an area of nearly 30 acres on the Faridabad-Gurugram road. According to a report submitted by the Municipal Corporation of Gurugram (MCG) to the National Green Tribunal (NGT), the landfill receives around 1,800 tonnes of fresh municipal waste every day (TOI 2021). As per NGT's latest order, the quantity of untreated waste at the landfill has increased to 40 lakh tonnes now. The landfill was built on an old mining pit with a depth of 250 feet in the proximity of groundwater aquifers and the site is also very close to the last remaining area of the Aravalli forest, a sacred groove for the natives. So, landfill is extremely harmful to biodiversity and human health as it is not only causing a substantial amount of pollution but also disturbing the ecologically vulnerable Aravalli range.

Sampling and water quality analysis

To study the contamination of the aquifer, groundwater samples were collected during March, 2021 from the nearby areas of the landfill site. Global Positioning System (GPS), i.e., Garmin GPS-etrex-10 was used to identify coordinates of accurate sampling locations (Table 1 and Figures 1 and 2). The groundwater samples were collected in triplicate from 18 different sampling sites. Pre-treated polyethylene bottles (soaked with 10% HNO_3 acid overnight and rinsed with distilled water multiple times to remove the impurities clinging to the interior wall of the bottle) were used for the collection of groundwater samples. The bottles were properly labelled with information such as sample code, date of sampling and the details of sampling locations. The samples for heavy metal analysis were preserved by acidifying them with concentrated nitric acid (1.5 ml of conc. HNO_3/L sample) in the glass bottles. The water sources (tube well, hand pump and submersible) were run initially for 2–3 min and bottles were cleaned well to reduce the chances of error during sample collection.

The analysis and measurement of physicochemical parameters along with heavy metals in collected groundwater samples were carried out as per the standard methods described using standard methodology (APHA 2017).

The pH with electrical conductivity (EC) was assessed in situ, using a digital pH meter (HM Digital, pH-200) and a digital EC meter (HM Digital, aquapro), respectively. Total dissolved solids (TDS) content was measured using the gravimetric method, and total alkalinity (TA) was analyzed using acid–base titrimetric methods (APHA 2017). Total hardness (TH), calcium (Ca^{2+}), magnesium (Mg^{2+}), and chloride (Cl^{-}) were also analyzed by the titrimetric method. Alkali metals such as sodium and potassium contents were analyzed using a Digital Flame Photometer (Esico, Model-381). A UV-visible spectrophotometer was used to determine sulphate (APHA 2017). Heavy metals like lead, iron, nickel, copper, and zinc were estimated by using an atomic absorption spectrophotometer (Shimadzu, AA-6880).

Health risk assessment

A hazard quotient is a process of evaluating the adverse health effects of human exposure to environmental hazards. In the present study, it was done by calculating the target hazard quotient using the United States Environmental Protection Agency (USEPA) methodology. The total hazard quotient (THQ) is the ratio of exposure to toxic elements to the reference dose prescribed, which is the maximum concentration at which no adverse health effects are expected (Johann *et al.* 2017). The value of THQ was calculated using methodology prescribed by USEPA (2012) and Singh & Garg (2022).

THQ = Concentration of exposure/Concentration prescribed as reference

Concentration of exposure = EFr × ED × WI × MCW × 0.001

Table 1 | Locations of the sampling sites

Sampling sites	Latitude	Longitude
1	28 °24′17″N	77°10′27″E
2	28°24′16″N	77°10′27″ E
3	28°24′16″N	77°10′29″ E
4	28°24′25″N	77°11′32″ E
5	28°25′17″N	77°11′25″ E
6	28°25′02″N	77°11′32″ E
7	28°23′38″N	77°11′09″ E
8	28°23′36″N	77°11′08″ E
9	28°24′34″N	77°10′09″ E
10	28°24′41″N	77°09′22″ E
11	28°25′31″N	77°08′45″ E
12	28°22′55″N	77°10′36″E
13	28°22′51″N	77°10′11″E
14	28°23′37″N	77° 09′8″E
15	28°23′14″N	77° 09′27″E
16	28°24′11″N	77° 09′18″E
17	28°25′34 ′N	77°10′8″E
18	28°25′32″N	77°10′32″E

Figure 1 | Bandhwari landfill site.

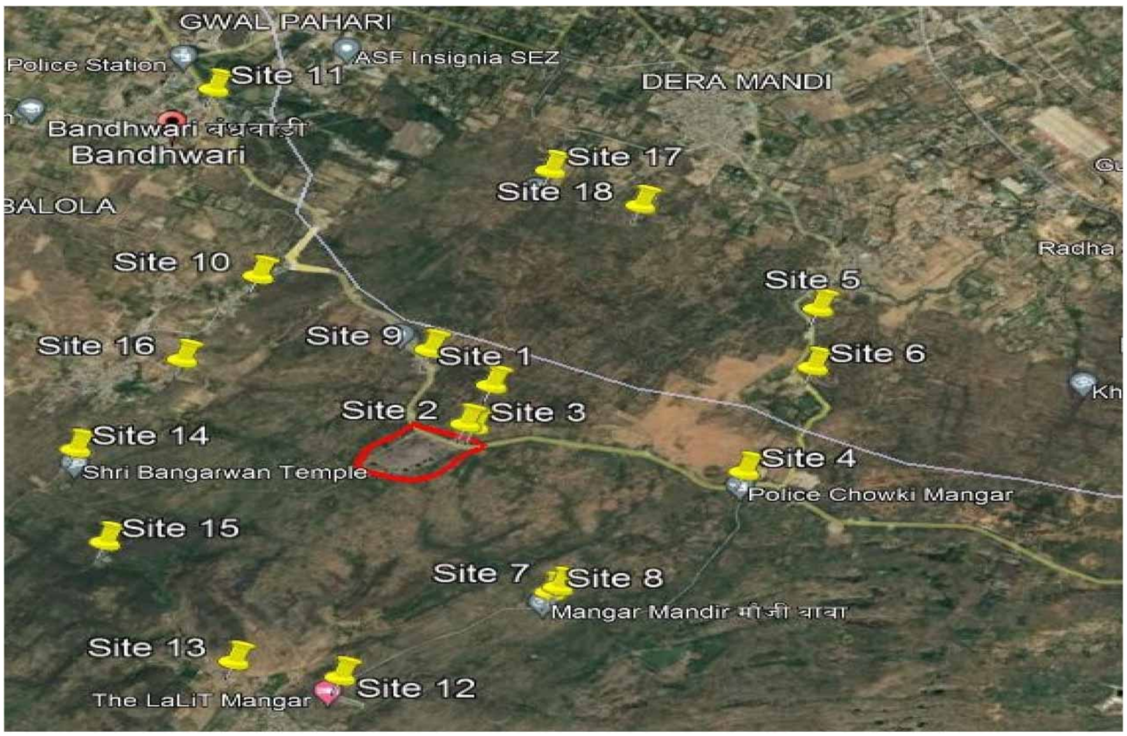

Figure 2 | Location map of sampling sites.

Concentration prescribed as reference (RfC) = RfDo × BW × AT

$$THQ = \frac{EFr \times ED \times WI \times Cm \times 0.001}{RfDo \times BW \times AT}$$

where EFr is the frequency of exposure (365 days/year), ED is the duration of exposure (65 years), WI is the water ingestion rate in litres per day (4.05 L/day), Cm is the metal concentration in water, RfDo means oral reference metal dose in mg/kg/day which are 9×10^{-3}, 4×10^{-3}, 4×10^{-2}, 2×10^{-2}, 4×10^{-2}, 3×10^{-3} and 9×10^{-3} for Fe, Pb, Zn, Ni, Cu, Cr and Cd, respectively. BW is the average body weight, i.e., 56 kg for the Indian adult (Shukla *et al.* 2002) and AT is the average exposure time (365 days × 65years).

The THQ is basically the evaluation of the non-carcinogenic health risk presented by exposure to a particular toxic element. If THQ is less than 1, then non-carcinogenic health effects are not seen. However, if THQ is more than 1, it indicates the possibility of adverse non-carcinogenic health effects (Akande *et al.* 2019).

RESULTS AND DISCUSSION

A comprehensive investigation of groundwater quality was done for 18 groundwater sampling locations from the surroundings of the landfill area to evaluate the degree of contamination caused by downward infiltration and horizontal migration of leachate from the landfill site.

Physicochemical analysis

The pH of the groundwater samples was from 6.7 to 7.7, which demonstrates that the groundwater is slightly acidic to alkaline in nature and for all the samples were within the permissible limit prescribed by Bureau of India Standards (BIS 2012), i.e., 6.5–8.5. The EC of the groundwater samples ranged from 1.15 to 6.69 mS/cm, which is beyond the BIS permissible limit of 2.5 mS/cm. EC was reported at its maximum at sampling site S1, followed by site S2, which were proximal to the Bandhwari landfill site. This could be due to the percolation of salts and minerals into the groundwater from the leachate. Similar results were reported by Kuriakose *et al.* (2016), who reported a high value of EC (>2.6 mS/cm) in groundwater samples collected from the vicinity of the Okhla landfill site, Delhi. According to WHO (2008), TDS is generally used to determine the salinity and overall quality of water. The concentration of TDS in all the samples ranged from 231 to 2,240 mg/L and the highest concentration of TDS was found at site no. 18. The TDS of around 67% of the samples exceeded the BIS permissible limit of 500 mg/L. Furthermore, the high TDS content in groundwater which is present around the landfill site renders it unsafe for drinking and may induce gastrointestinal irritation (Kuriakose *et al.* 2016). The TA was reported to occur between 216 and 852 mg/L. The highest alkalinity values were reported at sampling site S2 and the lowest was at S10. All the assessed groundwater samples were found to have values exceeding the BIS permissible limits of 200 mg/L. The results of the present study were supported by the study conducted by Alam *et al.* (2020), who reported a very high range of alkalinity (2,123–3,256 mg/L) in the groundwater samples collected from the vicinity of the Ghazipur landfill site, Delhi. The degree of hardness in water depends on the concentration of calcium and magnesium ions (Tanwer *et al.* 2023a). The TH values ranged between 168 and 1,220 mg/L, with the highest being at S1 and the lowest at S4. Almost all the samples were very hard and exceeded the BIS permissible limit, i.e., 200 mg/L. The Ca^{2+} values were in the range of 46.49–184.36 mg/L with an average of 99.47 mg/L; more than 50% of the samples were found to exhibit calcium values exceeding the BIS permissible limit of 75 mg/L. Excess Ca^{2+} in the body creates health issues in the body such as kidney stones or calculi, as well as inflammation in the urinary tract. Calcium may enter groundwater aquifers via limestone, marble, calcite, and gypsum (Bozdağ 2016). Magnesium is the second-most abundant cation in the cells (Fawcett *et al.* 1999). The minimum concentration of Mg^{2+} found in groundwater samples was 10.65 mg/L whereas the maximum concentration was 252.6 mg/L, with a mean value of 59.52 mg/L. 15 out of 18 groundwater samples were found to exhibit Mg^{2+} values exceeding the BIS permissible limit (30 mg/L) of drinking water standards. Excessive intake of Mg^{2+} salts may cause diarrhoea also (Sengupta 2013). Similarly, a high value of Mg concentration (329.3–369.26 mg/L) in the leachate from Bhalswa landfill was also reported by Ahamad *et al.* (2019). The sodium salt is found in almost every food item and drinking water and, as per the BIS acceptable limit, the sodium content should not exceed 200 mg/L. In the present study, all the groundwater samples were lower than the highest permissible limit of Na as they ranged between 19 and 162 mg/L; all the samples showed acceptable conditions. The amount of K in the groundwater samples varied from 1.5 to 9.2 mg/L, with an average of 3.8 mg/L. So, all the groundwater samples were within the acceptable range regarding K content. Along with geological composition, Cl^- concentration in groundwater is influenced by anthropogenic activities consisting of improper management of septic tanks, sewage disposal, and animal waste (Tanwer *et al.* 2023b). Its concentration in the groundwater samples ranged from 34 to 474 mg/L (an average of 116.09 mg/L). Cl^- in all the samples, except from site S1 (474 mg/L), which was adjacent to the landfill, were below the BIS desirable limit, i.e., 250 mg/L. Sudha *et al.* (2021) studied the hydro-chemical characterization of groundwater quality near the municipal solid waste dumping site at Vellalore in Coimbatore and found that a Cl^- plume (854 mg/L) was affecting the water resources. Rocks, fertilizers, and the burning of fossil fuels are the main sources of SO_4^{2-} groundwater. It can be found in almost all natural waters. A higher level of SO_4^{2-} present in drinking water can have laxative effects if present alongside Ca^{2+} and Mg^{2+} (Tanwer *et al.* 2023b). In the present study, the SO_4^{2-} concentration in almost all the groundwater samples except for S11 (273 mg/L) was significantly lower than the BIS (2012) permissible limit of 200 mg/L.

The results of the samples analyzed for the site under study revealed that the samples closest to the landfill site are the most affected by the leachate produced by the landfill. Other affected samples located far from the landfill site could be the result of an unlined wastewater drain, quaternary aquifer over-extraction or other anthropogenic influences in the research area. Table 2 shows the detailed measured values of various physicochemical parameters of chosen groundwater samples as well as their comparison with BIS (2012), EU (2020) and WHO (2017) permissible criteria.

Heavy metal analysis

The results of heavy metal concentration in the groundwater around the Bandhwari landfill follow the trend of Pb > Cd > Ni > Cu > Zn > Fe > Cr. The details of the concentrations of metals analyzed are given in Table 3 and distribution in the

Table 2 | Physicochemical analysis of groundwater samples from the Bandhwari landfill site area

S.No.	pH	EC (ms)/cm	TDS (mg/L)	TH (mg/L)	TA (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	SO_4^{2-} (mg/L)	Cl^- (mg/L)
1	7.1	6.59	1,318	1,200	532	65.73	252.6	112	5.1	79.3	474
2	6.8	6.38	1,276	800	852	184.36	82.7	162	9.2	18.6	125
3	7.6	5.25	1,050	332	564	83.36	30.14	141	8.4	273	202
4	7.2	1.53	307	168	324	48.09	11.65	47	2.6	18.6	46
5	7.1	3.7	740	324	576	78.55	31.12	77	2.4	15.3	98
6	7.4	2.15	1,430	296	452	62.52	34.07	61	1.8	28.3	56
7	7	1.56	313	196	256	60.92	10.65	28	2.3	74.1	36
8	7.7	1.39	280	208	300	54.5	39.93	29	2.0	37.6	52
9	7.5	2.44	488	320	508	46.49	49.7	62	3.2	16.3	102
10	6.9	1.15	231	244	216	51.3	28.23	19	1.5	35.2	34
11	7.6	1.91	382	224	588	81.76	41.78	41	2.7	26.3	52
12	7.5	2.62	1,120	980	352	144.12	67.96	46	3.2	25.6	45
13	7.3	2.14	1,436	1,046	456	153.82	72.54	58	4.6	48.7	49
14	6.7	3.4	1,640	1,220	321	179.41	84.60	24	2.1	56.4	56
15	7.1	1.98	968	456	364	67.06	31.62	38	1.8	19.8	46
16	7.3	2.35	1,376	780	412	114.71	54.09	98	4.6	28.6	84
17	7	4.18	1,630	964	256	141.76	66.85	74	7.1	45.3	74
18	7.4	5.7	2,240	1,170	532	172.06	81.14	80	3.2	47.5	62
IS-10500 (BIS 2012)	6.5–8.5	2,250 at 25 °C	500	200 (600)[a]	200 (as $CaCO_3$)	75	30	–	–	200	250
WHO (2017)	6.5–8.5	–	600	300 (500)[a]	–	75–200	–	200	–	250	200–300
EU (2020)	6.5–8.5 (up to 9.5)	2,500 at 20 °C	500	150–500[a]	–	100	–	200	–	250	250

[a]In the absence of a substitute source.

Table 3 | Heavy metal concentration in groundwater samples

S. No.	Fe (mg/L)	Pb (mg/L)	Zn (mg/L)	Ni (mg/L)	Cu (mg/L)	Cr (mg/L)	Cd (mg/L)
1	0.36	1.65	0.08	0.72	0.64	0	1.05
2	0.5	1.19	0.17	0.76	0.54	0	1.07
3	0.35	0.96	0.19	0.63	0.48	0	1.05
4	0.33	1.44	0.0007	0.64	0.64	0	1.06
5	0.33	0.92	0.21	0.64	0.48	0	1.06
6	0.36	0.95	0.05	0.63	0.49	0	1.06
7	0.38	3.55	4.18	2.41	3.22	0	0.95
8	0.35	2.55	1.4	0.77	1.66	0.26	0.98
9	0.27	0.94	1.02	0.62	0.48	0.2	1.07
10	0.41	1.28	0.01	0.65	0.67	0	1.06
11	0.37	1.03	0.19	0.61	0.49	0.21	0.56
12	0.36	0.26	0.28	0.54	0.74	0	1.05
13	0.25	0.58	0.56	0.23	0.58	0	0.98
14	0.49	0.84	0.78	0.48	0.26	0	0.87
15	0.87	1.08	0.45	0.51	0.23	0.25	0.52
16	0.86	1.24	0.13	1.25	0.21	0	1.45
17	0.58	0.89	1.04	0.75	0.74	0	1.27
18	0.74	0.92	0.87	0.63	0.36	0	1.39
IS-10500 (BIS 2012)	0.3	0.003	5	0.02	0.05	0.05	0.003

form of box-plots is given in Figure 3. A box-plot is a diverse family of statistical techniques called exploratory data analysis, used to visually identify patterns and compare the data (Khyalia *et al.* 2022). Box-plots in Figure 3 show the distribution of different metals within the samples analyzed. None of the metals showed a normal distribution and each metal has some

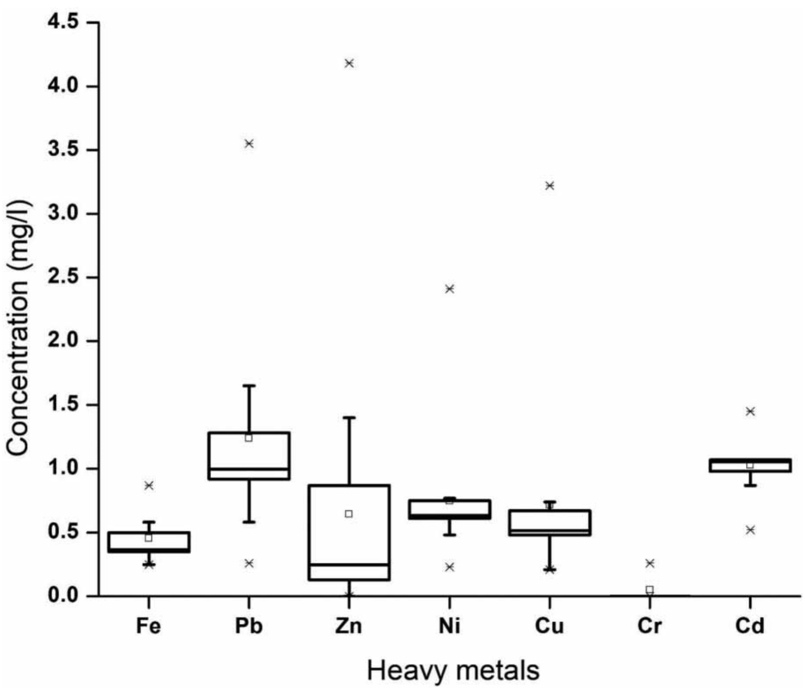

Figure 3 | Box-plots depicting the distribution of the analyzed heavy metals.

outlier concentration value. Lead was the most abundant metal found in the groundwater samples, with the highest concentration of 3.55 mg/L (at site S7). The disposal of lead-based paints, pipes, and batteries may be the main reason for the high lead content in the groundwater around the landfill (Boateng *et al.* 2019). The concentration of Cd was in the range of 0.52–1.45 mg/L with a mean value of 1.03 mg/L, which is above the BIS permissible limit of 0.003 mg/L. High levels of Pb and Cd are a cause of great concern as these heavy metals have been recognized as toxic metals for drinking and household use (WHO 2008). The concentration of Ni and Cu in each studied groundwater sample exceeded the BIS permissible limit of 0.02 and 0.05 mg/L, respectively. The highest concentration of Cu (3.22 mg/L) was observed at sampling site S7; excessive Cu concentration in drinking water can induce renal damage, diarrhoea, nausea, vomiting, stomach cramps, and death (Mathew & Krishnamurthy 2015). The Zn concentration of all the samples was reported to be within the standard permissible limit of 5 mg/L. The BIS permissible limit for Fe is 0.3 mg/L. However, in the present study, it was found in the range of 0.25–0.87 mg/L in phreatic water samples; 89% of samples exceeded the standard permissible limit. The heavy metal concentration in the existing study is more in comparison to the landfill impact observations in Lagos metropolis, southwest Nigeria (Aboyeji & Eigbokhan 2016). The presence of the above heavy metals in detectable concentrations in groundwater is a sign of toxicity posing a serious environmental risk to soil, animals, and even humans (Ismanto *et al.* 2023). Despite the high concentration of analyzed metals, the groundwater is rarely affected by the presence of chromium, which was found below the instrumental detection limit in 78% of the samples. Kumari *et al.* (2018) detected a very small concentration of Cr in groundwater in the vicinity of the Ghazipur landfill site in Delhi, similar to the current study. This could be because the greater adsorption of Cr^{6+} to a zone of waste material that is unsaturated with water or soil results in only a small amount that can solubilize in water and penetrate deeper into the soil (Alam *et al.* 2012).

The correlation among the metals analyzed was also studied using IBM SPSS Statistics 22 and significant positive correlations were observed between Pb and Zn ($r = 0.758$, $p \leq 0.01$), Pb and Ni ($r = 0.814$, $p \leq 0.01$), Pb and Cu ($r = 0.872$, $p \leq 0.01$), Zn and Ni ($r = 0.798$, $p \leq 0.01$), Ni and Cu ($r = 0.813$, $p \leq 0.01$) and Zn with Cu ($r = 0.891$, $p \leq 0.01$); while a significant negative correlation was found between Cr and Cd ($r = -0.594$, $p \leq 0.01$). It shows that Pb coexisted in water with Zn, Ni and Cu while Zn also exhibited coexistence with Ni and Cu (Supplementary material, Table S1). Further studies with controlled natural attenuation processes have been recommended by various authors for the coexistence and migration of these metals in groundwater. The major reasons provided in the literature are pH, dissolution and solubility of metals in groundwater (Xu *et al.* 2015; Shrestha *et al.* 2016; Mahapatra & Nimmy 2021).

Health risk from metal consumption through groundwater

Human health risk from consumption of the studied groundwater samples was calculated using THQ, a methodology developed by USEPA (USEPA 2012). The calculated THQ values were found to be in the order of Cd > Pb > Fe > Ni > Cu > Zn > Cr with respective values as 6.9E-02, 2.1E-02, 3.4E-03, 2.5E-03, 1.2E-03, 1.5E-04, and 2.3E-06. The values for THQ depicted a somewhat consistent distribution trend for all heavy metals in Figure 4. Apart from Pb and Cd, the values for THQ were

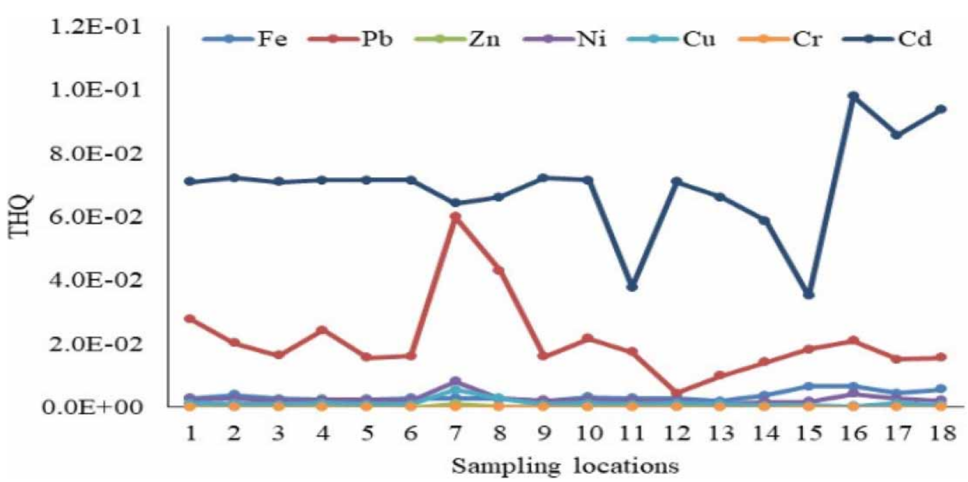

Figure 4 | Total hazard quotient for different heavy metals.

observed in a very low magnitude in an order of 10^{-3} to 10^{-6}. None of the THQ values were found to be equal to or higher than unity which indicated that these values are not a risk to the people consuming the water. The details of the THQ values observed are encapsulated in Supplementary material (Table S2) and Figure 4.

The major pathways which can introduce metals into the human body are ingestion through food and water, inhalation (through smoke, fumes or dust), radiation exposure and dermal contact with metals (Duhan *et al.* 2022; Sharma *et al.* 2023; Tanwer *et al.* 2023c). Different metals can cause different types of risks to the human body including neurotoxicity, nephrotoxicity, hepatotoxicity etc. (USEPA 2005; Tanwer *et al.* 2022; Duhan *et al.* 2023). Various studies have been conducted globally to estimate heavy metals in groundwater (Kana 2022; Mawari *et al.* 2022; Ullah *et al.* 2022). Tong *et al.* (2021) also studied and reported THQ values for As, Co, Cd, Fe, Pb, Ni, Zn and Cu in groundwater from different areas of China and documented it to be safe except for arsenic content. Negligible health risk from consumption of Zn, As and Fe in groundwater was reported by Anim-Gyampo *et al.* (2019) from the Atankwidi basin of Ghana due to their very low concentration while it was reported to pose a significant risk from greater concentration of Pb in the same water. Maigari *et al.* (2016) documented significant risk for children and adults due to ingestion of Fe, Ni, Mn, and Co via drinking groundwater. There have been some other studies including Vetrimurugan *et al.* (2017) from the Cauvery river basin, Tamil Nadu, India in context to Mn, Pb, Ag, Cd and Ni; Islam *et al.* (2017) reporting arsenic risk from groundwater consumption in Chapai-Nawabganj district, Bangladesh; Hossain *et al.* (2020) documenting the risk from various metals present in groundwater from Dinajpur, Bangladesh. In comparison to these referenced studies, the values of THQ in the presented study imply that the region of Bandhwari landfill site is not a risk in consideration with Cd, Pb, Fe, Ni, Cu, Zn, and Cr content in the groundwater.

CONCLUSIONS

Water quality assessed for the Bandhwari landfill site region indicated that groundwater from the study area depicted some of the physicochemical characteristics in the greater concentration as compared to the prescribed limits by the World Health Organization and Indian Standards. The presence of metals, viz. Pb with Zn, Ni and Cu; Zn with Ni and Cu were found to be in positive correlation. The values of Pb were found to be in correlation with other metals hence showing no inhibition in migration and diffusion of metals. No significant health risk was observed due to the presence of analyzed metals in groundwater as per THQ values calculated although the THQ values were significantly higher for Pb and Cd in comparison to other studied metals. This study may be useful for future studies for the analysis of trends in metal concentration and groundwater parameters in the vicinity of Bandwari landfill site.

ETHICAL APPROVAL

No ethical approval is required as no living organism/plant or human was subjected to research.

AUTHORS' CONTRIBUTION

V.W. and L.B. were involved in the execution of the sampling/analysis work; V.M. was involved in conception and design of the work; M.S. was involved in data analysis, interpretation writing, and proofreading; P.K. was involved in statistical analysis and proof reading.

FUNDING

No funding was received for the research work.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abiriga, D., Live, S., Vestgarden, T. & Harald, K. 2020 Groundwater contamination from a municipal landfill: Effect of age, landfill closure, and season on groundwater chemistry. *Science of The Total Environment* **737**, 140307. https://doi.org/10.1016/j.scitotenv.2020.140307.

Aboyeji, O. S. & Eigbokhan, S. F. 2016 Evaluations of groundwater contamination by leachates around Olusosun open dumpsite in Lagos metropolis, southwest Nigeria. *Journal of Environment Management* **1** (183), 333–341.

Acharya, S., Sharma, S. K. & Khandegar, V. 2018 Assessment of groundwater quality by water quality indices for irrigation and drinking in South West Delhi, India. *Data in Brief* **18**, 2019–2028.

Ahamad, A., Raju, N. J., Madhav, S., Gossel, W. & Wycisk, P. 2019 Impact of non-engineered Bhalswa landfill on groundwater from Quaternary alluvium in Yamuna flood plain and potential human health risk, New Delhi, India. *Quaternary International* **507**, 352–369. https://doi.org/10.1016/j.quaint.2018.06.011.

Akande, M. G., Sanni, F. S. & Enefe, N. G. 2019 Assessment of the concentrations and health risk of some heavy metals in cowpea (Vignus unguiculata) in Gwagwalada, Nigeria. *Drug and Chemical Toxicology* **44** (5), 518–523. doi: 10.1080/01480545.2019.1621334.

Alam, M., Rais, S. & Aslam, M. 2012 Hydrochemical investigation and quality assessment of ground water in rural areas of Delhi, India. *Environmental Earth Sciences* **66** (1), 97–110.

Alam, P., Sharholy, M. & Ahmad, K. 2020 A study on the landfill leachate and its impact on groundwater quality of Ghazipur area, New Delhi, India. In: *Recent Developments in Waste Management* (Kalamdhad, A. S., ed.). Springer, Singapore, pp. 345–358.

Amano, K. O. A., Danso-Boateng, E., Adom, E., Kwame Nkansah, D., Amoamah, E. S. & Appiah-Danquah, E. 2021 Effect of waste landfill site on surface and ground water drinking quality. *Water and Environment Journal* **35** (2), 715–729.

Anim-Gyampo, M., Anornu, G. K., Appiah-Adjei, E. K. & Agodzo, S. K. 2019 Quality and health risk assessment of shallow groundwater aquifers within the Atankwidi basin of Ghana. *Groundwater for Sustainable Development* **9**, 100217.

APHA 2017 Standard methods for the Examination of water and Wastewater. In: *Standard Methods for the Examination of Water and Wastewater*, 23rd edn (Rice, E. W., Baird, R. B. & Eaton, A. D., eds). American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC. ISBN: 9780875532875.

Bhattarai, N., Pollack, A., Lobell, D. B., Fishman, R., Singh, B., Dar, A. & Jain, M. 2021 The impact of groundwater depletion on agricultural production in India. *Environmental Research Letters* **16** (8), 085003.

BIS 2012 Indian standard drinking water – Specification (Second Revision). ICS 13.060.20. Bureau of Indian Standards (IS 10500: 2012). Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Delhi-110002.

Boateng, T. K., Opoku, F. & Akoto, O. 2019 Heavy metal contamination assessment of groundwater quality: A case study of Oti landfill site, Kumasi. *Applied Water Science* **9** (2), 1–15.

Bozdağ, A. 2016 Assessment of the hydrogeochemical characteristics of groundwater in two aquifer systems in Çumra Plain, Central Anatolia. *Environmental Earth Sciences* **75**, 1–15.

Duhan, S. S., Khyalia, P. & Laura, J. S. 2022 A comprehensive analysis of health risk due to natural outdoor gamma radiation in southeast Haryana, India. *Current Science (00113891)* **123** (2), 169–176.

Duhan, S. S., Khyalia, P., Solanki, P. & Laura, J. S. 2023 Uranium sources, uptake, translocation in the soil-plant system and its toxicity in plants and humans: A critical review. *Oriental Journal of Chemistry* **39** (2), 303–319.

EU 2020 DIRECTIVE (EU) 2020/2184 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2020 on the quality of water intended for human consumption. Official Journal of the European Union. (23.12.2020).

Fawcett, W. J., Haxby, E. J. & Male, D. A. 1999 Magnesium: Physiology and pharmacology. *British Journal of Anaesthesia* **83** (2), 302–320. doi: 10.1093/bja/83.2.302.

Gajski, G., Orescanin, V. & Garaj-Vrhovac, V. 2011 Cytogeno toxicity of sewage sludge leachate before and after calcium oxide-based solidification in human lymphocytes. *Ecotoxicology and Environmental Safety* **74**, 1408–1141. https://doi.org/10.1016/j.dib.2018.04.120.

Hossain, S. M. S., Haque, M. E., Pramanik, M. A. H., Uddin, M. J. & Al Harun, M. A. Y. 2020 Assessing the groundwater quality and health risk: A case study on Setabganj sugar mills limited, Dinajpur, Bangladesh. *Water Science* **34** (1), 110–123.

Islam, A. R. M., Shen, S. H. & Bodrud-Doza, M. 2017 Assessment of arsenic health risk and source apportionment of groundwater pollutants using multivariate statistical techniques in Chapai-Nawabganj district, Bangladesh. *Journal of the Geological Society of India* **90** (2), 239–248.

Ismanto, A., Hadibarata, T., Widada, S., Indrayanti, E., Ismunarti, D. H., Safinatunnajah, N., Kusumastuti, W., Dwiningsih, Y. & Alkahtani, J. 2023 Groundwater contamination status in Malaysia: Level of heavy metal, source, health impact, and remediation technologies. *Bioprocess and Biosystems Engineering* **46** (3), 467–482.

Johann, M. R., Antoine, L., Hoo, A., Charles, F. & G, N. 2017 Assessment of the potential health risks associated with the aluminium, arsenic, cadmium and lead content in selected fruits and vegetables grown in Jamaica. *Toxicology Reports* **4**, 181–187. doi: 10.1016/j.toxrep.2017.03.006.

Kana, A. A. 2022 Heavy metal assessment of groundwater quality in part of Karu, Central Nigeria. *Water Practice & Technology* **17** (9), 1802–1817.

Khyalia, P., Laura, J. S., Khosla, B., Sahoo, S. K., Tiwari, S. N. & Nandal, M. 2022 Analysis of effective equivalent dose to the organs and cancer risk assessment due to natural outdoor gamma radiation in Eastern Thar Desert, India. *International Journal of Environmental Analytical Chemistry* 1–13. https://doi.org/10.13005/ojc/390505.

Khyalia, P., Duhan, S. S., Laura, J. S. & Nandal, M. 2023 A comprehensive analysis of fluoride contamination in groundwater of rural area with special focus on India. In: *Water Resources Management for Rural Development* (Madhav, S., Srivastav, A.L., Izah, S.C & Hullebusch, E.V., eds.). Elsevier, Amsterdam, pp. 201–212.

Kjeldsen, P., Barlaz, A. M., Rooker, P. A., Baun, A., Ledin, A. & Christensen, T. H. 2002 Present and long-term composition of MSW landfill leachate: A review. *Critical Reviews in Environmental Science and Technology* **32** (4), 297–336.

Kumari, P., Kaur, A. & Gupta, N. C. 2018 Extent of groundwater contamination Due to leachate migration adjacent to unlined landfill site of Delhi. *Environmental Claims Journal* **31**, 1–16. doi:10.1080/10406026.2018.1543825.

Kuriakose, T., Ramanathan, S., Sankar, K., Rawat, M. & Sahoo, M. 2016 Characterizing waste dump effects on ground water through electrical resistivity sounding around okhla landfill site, New Delhi, India. *Journal of Applied Geochemistry* **18** (4), 457–463.

Lee, G. F. & Jones-Lee, A. 1993 Groundwater Quality Monitoring at Lined Landfills: Adequacy of Subtitle D Approaches. El Macero, CA, USA.

Mahapatra, S. R. & Nimmy, P. M. 2021 Groundwater contamination with heavy metals in Chennai city, India – A threat to the human population. *IOP Conference Series: Earth and Environmental Science* **889**, 012037. doi:10.1088/1755-1315/889/1/012037.

Maigari, A. U., Ekanem, E. O., Garba, I. H., Harami, A. & Akan, J. C. 2016 Health risk assessment for exposure to some selected heavy metals via drinking water from Dadinkowa dam and river gombe abba in Gombe state, Northeast Nigeria. *World J. Anal. Chem.* **4** (1), 1–5.

Malik, S., Khyalia, P. & Laura, J. S. 2024 Conventional methods and materials used for water treatment in rural areas. In: *Water Resources Management for Rural Development* (Madhav, S., Srivastav, A.L., Izah, S.C & Hullebusch, E.V., eds.). Elsevier, Amsterdam, pp. 79–90.

Mathew, B. & Krishnamurthy, N. B. 2015 Health effects caused by metal contaminated ground water. *International Journal of Advances in Scientific Research* **1** (2), 60–64.

Mawari, G., Kumar, N., Sarkar, S., Frank, A. L., Daga, M. K., Singh, M. M., Joshi, T. K. & Singh, I. 2022 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. *Environmental Health Insights* **16**, 11786302221146020.

Narayana, T. 2009 Municipal solid waste management in India: from waste disposal to recovery of resources. *Waste Management* **29** (3), 1163–1166.

Njoku, P. O., Edokpayi, J. N. & Odiyo, J. O. 2019 Health and environmental risks of residents living close to a landfill: A case study of thohoyandou landfill, Limpopo Province, South Africa. *International Journal of Environmental Research and Public Health* **16** (12), 2125.

Omolola, O. E., Elijah, O. A. & Ede, O. J. 2023 Effects of population dynamics on economic growth among the world most populous countries. *African Journal of Economic Review* **11** (3), 69–90.

Podlasek, A., Jakimiuk, A., Vaverková, M. D. & Koda, E. 2021 Monitoring and assessment of groundwater quality at landfill sites: Selected case studies of Poland and the Czech republic. *Sustainability* **13** (14), 7769.

Przydatek, G. & Kanownik, W. 2019 Impact of small municipal solid waste landfill on groundwater quality. *Environmental Monitoring and Assessment* **191** (3), 1–14.

Sarvajayakesavalu, S., Lakshminarayanan, D., George, J., Magesh, S. B., Anilkumar, K. M., Brammanandhan, G. M. & Ravikumar, M. 2018 Geographic information system mapping of gross alpha/beta activity concentrations in ground water samples from Karnataka, India: A preliminary study. *Groundwater for Sustainable Development* **6**, 164–168.

Sengupta, P. 2013 Potential impacts of hard water. *International Journal of Preventive Medicine* **4** (8), 866–875.

Sharma, A., Gupta, A. K. & Ganguly, R. 2018 Impact of open dumping of municipal solid waste on soil properties in mountainous region. *Journal of Rock Mechanics and Geotechnical Engineering* **10**, 725–739.

Sharma, J., Kumar, S., Kumar, V., Singh, P., Khyalia, P., Verma, S., Saini, S. & Sharma, A. 2023 Foliar application of glycine betaine to ameliorate lead toxicity in barley plants by modulating antioxidant enzyme activity and biochemical parameters. *Environmental Research Communications*. https://doi.org/10.1088/2515-7620/acde38.

Shrestha, S. M., Rijal, K. & Pokhrel, M. R. 2016 Assessment of Heavy Metals in Deep Groundwater Resources of the Kathmandu Valley, Nepal J. Environ. Prot. (Irvine,. Calif). 07 516–31.

Shukla, H. C., Gupta, P., Mehta, H. C. & Hebert, J. 2002 Descriptive epidemiology of body mass index of an urban adult population in western India. *Journal of Epidemiology Community Health* **56**, 876–880.

Singh, M. & Garg, V. K. 2022 A comprehensive physico-chemical quality and heavy metal health risk assessment study for phreatic water sources in Narora Atomic Power Station region, Narora, India. *Environmental Monitoring and Assessment* **194** (2), 69. https://doi.org/10.1007/s10661-021-09694-8.

Singh, U. K., Kumar, M., Chauhan, R., Jha, P. K., Ramanathan, A. L. & Subramanian, V. 2008 Assessment of the impact of landfill on groundwater quality: A case study of the Pirana site in western India. *Environmental Monitoring and Assessment* **141**, 309–321.

Siwila, S. & Buumba, C. 2021 Investigation of groundwater contamination in relation to septic systems in Kitwe West Township, Kitwe, Zambia. *Water Science and Technology* **84** (10–11), 3277–3285.

Sudha, P. R., Uma, R. N. & Murali, K. 2021 Hydro chemical characterization of groundwater quality due to municipal solid waste dumping at Vellalore in Coimbatore, Tamil Nadu, India. *International Journal of Earth Sciences and Engineering* **8** (4), 1791–1798.

Tanwer, N., Khyalia, P., Deswal, M., Laura, L. S. & Khosla, B. 2022 Spatial Distribution of Uranium in Groundwater and its Health Risk Assessment in Haryana, India. *Rasayan Journal of Chemistry* **15** (1), 343–349.

Tanwer, N., Deswal, M., Khyalia, P., Laura, J. S. & Khosla, B. 2023a Fluoride and nitrate in groundwater: a comprehensive analysis of health risk and potability of groundwater of Jhunjhunu district of Rajasthan, India. *Environmental Monitoring and Assessment* **195** (2), 267.

Tanwer, N., Deswal, M., Khyalia, P., Laura, J. S. & Khosla, B. 2023b Assessment of groundwater potability and health risk due to fluoride and nitrate in groundwater of Churu District of Rajasthan, India. *Environmental Geochemistry and Health* **45**, 4219–4241.

Tanwer, N., Deswal, M., Khyalia, P., Laura, J. S., Gautam, Y. P. & Khosla, B. 2023c Mapping of outdoor gamma radiation and consequential health risk assessment in north-eastern regions of Rajasthan. *India. Environmental Forensics* 1–9.

TOI 2021 Bandhwari landfill site is 37 m tall now & 1,800 tonnes being added daily. Times of India. Available from: https://timesofindia.indiatimes.com/city/gurgaon/bandhwari-landfill-site-is-37m-tall-now-1800-tonnes-being-added-daily/articleshow/81540397.cms.

Tong, S., Li, H., Tudi, M., Yuan, X. & Yang, L. 2021 *Ecotoxicology and Environmental Safety*, 219, 112283. https://doi.org/10.1016/j.ecoenv.2021.112283.

Ullah, Z., Rashid, A., Ghani, J., Nawab, J., Zeng, X. C., Shah, M., Alrefaei, A. F., Kamel, M., Aleya, L., Abdel-Daim, M. M. & Iqbal, J. 2022 Groundwater contamination through potentially harmful metals and its implications in groundwater management. *Frontiers in Environmental Science* **10**, 1021596.

USEPA 2005 Human Health Risk Assessment Protocol. Characterizing Risk and Hazard: Chapter 7. September 2005. USEPA, Office of Solid Waste, pp. 1–15. Available from: https://archive.epa.gov/epawaste/hazard/tsd/td/web/pdf/05hhrap7.pdf (accessed April 2022).

USEPA 2012 Integrated Risk Information System – Database. Philadelphia PA; Washington, DC. Available from: https://iris.epa.gov/AtoZ/?list_type=alpha.

Vetrimurugan, E., Brindha, K., Elango, L. & Ndwandwe, O. M. 2017 Human exposure risk to heavy metals through groundwater used for drinking in an intensively irrigated river delta. *Applied Water Science* **7** (6), 3267–3280.

World Health Organization 2017 *Guidelines for Drinking-Water Quality, Fourth Edition, Incorporating the First Addendum*. World health Organization, Geneva, pp. 219–230.

World Health Organization (WHO) 2008 *Guideline for Drinking Water Quality, 2nd ed., Health Criteria and Other Supporting Information*, Vol. 2. World Health organization, Geneva, pp. 940–949.

Xu, B., Xu, Q., Liang, C., Li, L. & Jiang, L. 2015 Occurrence and health risk assessment of trace heavymetals via groundwater in shizhuyuan polymetallic mine in Chenzhou City, China Front. *Environmental Science & Engineering* **9**, 482–493.

First received 30 March 2023; accepted in revised form 4 December 2023. Available online 14 December 2023