



Heavy metal pollution in water and soil and associated health risks in a tin mining region of Hunan Province, Central China

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ABSTRACT

To assess the effect of mining activity on heavy metal pollution and associated health risks in tin mining regions, water and soil sampling was conducted near a tin mining site in Hunan Province. The content and distribution of heavy metals were determined. Pollution, ecological risks, and potential health hazards were evaluated using the ground accumulation index, potential ecological risk index, and health risk assessment models, respectively. The results indicated elevated levels of heavy metals in water and soil samples compared to acceptable background values. Ground accumulation index assessment revealed extreme pollution of soil with As and Cd and moderate pollution with Cu, Pb, and Zn. Cr and Hg were categorized as non-pollutants. Water samples exhibited extreme pollution levels of Hg, Cr, Cd, and As; moderate pollution levels of Pb; and moderate to high pollution levels of Cu and Zn. The tin mining area demonstrated a significantly high level of potential ecological risk, where As and Cd were the primary risk elements in soil, whereas Cr, Cd, and As contributed predominantly to water ecological risk. The human health risk assessment highlighted As, Cd, Cr, Hg, Pb, and Cu in water and As and Pb in soil as the principal non-carcinogenic factors. The primary carcinogenic factors were As, Cr, and Cd in water and As in soil, with As posing the greatest risk for non-carcinogenic and carcinogenic effects. Furthermore, oral intake was the primary exposure route, with children being particularly vulnerable to the adverse effects of heavy metal pollution.

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1. Introduction

Heavy metals such as Cu and Zn are inherent constituents of the Earth's crust and play essential roles in human metabolism. Normally, these metals exist in low concentrations in the environment, posing minimal harm to ecosystems. However, industrial expansion and the subsequent heightened demand for mineral resources have led to the activation of heavy metals, resulting in their release into surface water, groundwater, and soil during mining activities. This influx of heavy metals near mining regions poses potential health hazards to nearby residents (Lu J et al., 2019; Zhang JD et al., 2021). Although some studies have investigated soil pollution in mining zones (Yu X et al., 2016;

Jiang CY, 2020; Yu JY et al., 2020), research specifically focusing on tin mining areas remains scarce. Hunan Province, renowned for its abundant mineral wealth, has experienced heavy metal pollution spanning approximately 2.8×10^4 km², which constitutes 13% of the total area of the province (Guo ZH et al., 2004). Despite this, research on heavy metal pollution in mining regions, particularly tin mining areas, is lacking. Given the vital role of natural water and soil in ecosystems, an in-depth understanding of the characteristics and patterns of heavy metal pollution in water and soil in ecosystems within tin mining areas is imperative (Chen ZY et al., 2023; Li Q et al., 2023; He Y et al., 2024; Tan HW et al., 2023; Wu YH et al., 2022).

Driven by concerns regarding ecological preservation and the wellbeing of local inhabitants, this study concentrated on a representative medium-sized tin mining region in Hunan Province. The study area accommodates extensive tin mining operations and encompasses industrial and agricultural activities, which, in daily operations, potentially jeopardize the surrounding water and soil environments. Despite the significance of the issue, investigations into heavy metal

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pollution and subsequent health risk assessments in this region, is relatively scant. Therefore, this study employed a diverse evaluation framework to comprehensively analyze the heavy metal content and distribution characteristics in both water and soil within the tin mining area. The objective was to assess the extent of heavy metal pollution and determine the associated ecological risks, ultimately facilitating initiatives aimed at environmental conservation and restoration in the local ecosystem.

2. Samples and methods

2.1. Geological background of the mining area

The geological strata in the region predominantly consist of the Nanhua, Devonian, and Carboniferous systems (Fig. 1a). The Nanhua System comprises shallow metamorphic clastic rocks with carbonate formations and is primarily situated on the backslope of the Sizhu Mountain. In contrast, the Carboniferous System is characterized by shallow marine carbonate rocks with coastal clastic rock formations surrounding the Dayishan rock body, with a minor Quaternary presence along the riverbanks, characterized by flood, alluvial, and residual slope deposits. Regional basement folds generally trend NNE and influence the overarching tectonic framework. Cover folds, however, predominantly trend near-SN to NNW and are distributed around the rock body. The backslopes typically exhibit tight linear features, whereas the obliques are more open. Regional fracture structures mainly trend at 325° with a northeast orientation and a dip angle

exceeding 65°. These structures are categorized into the following four groups based on their orientations: NE, NW-NNW, NW, and NNW-near-SN (Zhang ZZ et al., 2022).

Regarding magmatic formations, the region primarily comprises Dayishan rocks, featuring fine- to medium-grained porphyritic hornblende diorite granite ($\eta\gamma J_3^a$), medium to fine-grained porphyritic black mica diorite granite ($\eta\gamma J_3^c$), less fine-grained porphyritic black mica diorite granite ($\eta\gamma J_3^d$), and fine-grained porphyritic black mica diorite granite with tourmaline ($\eta\gamma J_3^e$) (Li JF et al., 2023). Among these, the fine to medium-grained porphyritic angular mafic diorite serves as the host rock for samples collected within this area.

Dayi Mountain stands as a significant tin-forming rock body within the Nanling region. Since 2000, the identification of seven large and medium-sized mines, including Wanjinwo, Catzai Mountain, Vine Mountain Pass, Baishazi Ridge, Dashuncong, Taizi Shang, and Shishang Ridge, along with over 40 small deposits, has underscored the importance of this area (Li JF et al., 2023). Presently, over 10⁵ tons of tin resources have been confirmed.

This study focuses on a medium-sized tin polymetallic mining area located in the southeast region of the rock mass. The deposit boasts accumulated proven resources totaling 90000, 17000, 110000, and 50000 t of Cu, Sn, As, and Zn, respectively. It comprises of skarn-type and quartz vein-dolomite type tin deposits. The former predominantly occurs in the contact zone between the Dayishan granite and the Carboniferous Permo-carbonate rocks. It features an average thickness of 2.08 m and an average grade of 1.07% Cu, 0.23%

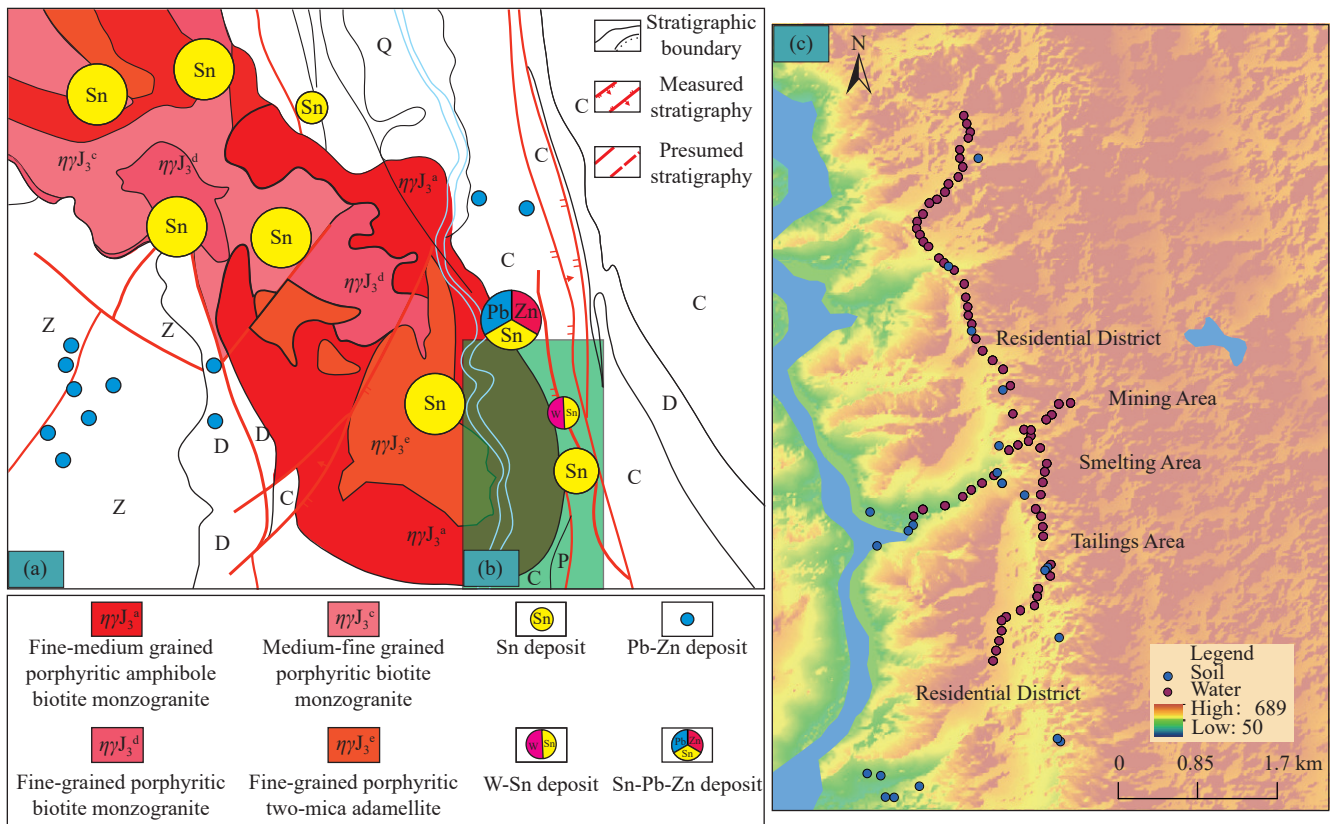


Fig. 1. Overview of the study area (a) and sampling site locations (b).

tin, and 0.31% Zn. The ore exhibits a hemidiomorphic structure, characterized by granular, massive, disseminated, and banded structures, with cassiterite, chalcopyrite, galena, and magnetite as the main ore minerals. Conversely, the latter primarily occurs within the Dayishan granite, controlled by the joint fracture system. It spans 220 m in length and 2–5 m in thickness, with most of the ore exhibiting massive and disseminated structures. The primary ore minerals include cassiterite, wolframite, chalcopyrite, and molybdenite.

Mining activities in this area primarily involve physical and mechanical methods, resulting in minimal environmental impact. However, the presence of a concentrator within the mining area raises concerns about potential heavy metal pollution stemming from chemical usage, tailings deposition, and wastewater discharge, constituting the focal point of this study.

2.2. Sample collection and analytical determination

Numerous studies have indicated significant heavy metal anomalies or contamination in the soil and water of most mining areas. In this study, Cu, Pb, Zn, Cr, Cd, As, and Hg were chosen for analysis based on existing analytical precedents and the compositional characteristics of mineralized elements in the study area. A total of 70 surface soil and 30 water samples were collected from the mine and its surrounding areas. Among these, 55 soil samples were collected from the N–S direction and 15 from the E–W direction at sampling depths of 0–20 cm, as illustrated in Fig. 1b. Two water samples (500 g each) were collected in bottles that underwent three washes before bottling. The bottles were tightly capped underwater and dispatched to the laboratory for subsequent analysis and testing.

Soil samples were acquired using a multipoint sampling method. Impurities such as plant roots and debris were removed, leaving 1 kg of material in the sample bag. Following drying, the samples were ground and passed through a 100-mesh nylon sieve, with 150 g of each sample collected from the lower sieve level. Sample testing was conducted at the Wuhan Geological Survey Center of the China Geological Survey.

The levels of Cu, Pb, Zn, and Cr were determined using an atomic absorption spectrophotometer (AAS nos300-ZEEnit600), whereas Cd, As, and Hg levels were determined using an automatic atomic fluorescence spectrophotometer (AFS-230E). Accuracy and precision were confirmed using national-level standard substances, and all samples were tested and analyzed within acceptable limits. Two detection limits, 1 mg/kg and 0.001 mg/kg, with analytical accuracy exceeding 0.8% were obtained for Cu, Pb, Cr, As, Cd, and Hg.

2.3. Evaluation of heavy metal pollution

2.3.1. Geoaccumulation index

The geoaccumulation index is a quantitative measure used to assess the extent of heavy metal pollution in the environment. It can delineate the distribution characteristics of soil heavy metal pollution while considering anthropogenic

pollution factors, environmental geochemical background values, and natural rock formation. The calculation formula is as follows:

$$I_{geo} = \log_2 \left(\frac{C_i}{K \cdot B_i} \right) \quad (1)$$

where, C_i is the measured value of the i th heavy metal, B_i is the geochemical background value of the element in the soil, and K is the coefficient of variation of the background value owing to diagenesis (usually taken as $K = 1.5$). According to the criteria proposed by Förstner U et al. (1993), heavy metals can be classified into seven categories, as listed in Table 1.

2.3.2. Potential ecological risk index

The ecological risk posed by soil heavy metals was evaluated using the Hakanson L (1980) potential ecological risk index method, which integrates ecological, toxicological, and environmental effects (Table 2). This method enables a systematic and comprehensive assessment of soil heavy metal pollution status (He DM et al., 2014; Gao RZ et al., 2019). The calculation formula is as follows:

$$RI = \sum_{i=1}^n E_r^i = \sum_{i=1}^n T_r^i \cdot P_i = \sum_{i=1}^n T_r^i \cdot \frac{C_i}{C_n^i} \quad (2)$$

where, RI is the integrated potential ecological risk index; E_r^i is the individual RI of the i th heavy metal; T_r^i is the corresponding toxicity coefficient of the i th heavy metal (toxicity response coefficients for each metal are Cu = 5, Pb = 5, Zn = 1, Cr = 2, Cd = 30, As = 10, and Hg = 40) (Hakanson L, 1980; Xu ZQ et al., 2008); P_i is the pollution index of heavy metal i ; C_i is the measured value of heavy metal i ; C_n^i is the background value of heavy metal elements.

2.3.3. Human health risk evaluation

According to the U.S. Environmental Protection Agency risk assessment methodology, humans are typically exposed to heavy metals through three pathways: Oral intake, dermal contact, and soil particle inhalation. The calculation formulae are as follows:

$$ADD_{ing} = \frac{C_i \times IR \times CF \times EF \times ED}{BW \times AT} \quad (3)$$

$$ADD_{derm} = \frac{C_i \times SA \times SF \times ABS \times CF \times EF \times ED}{BW \times AT} \quad (4)$$

Table 1. Classification of pollution levels according to the geoaccumulation index.

Geoaccumulation index I_{geo}	Level	Pollution level
$I_{geo} < 0$	0	Non-polluting
$0 \leq I_{geo} < 1$	1	Light pollution
$1 \leq I_{geo} < 2$	2	Medium pollution
$2 \leq I_{geo} < 3$	3	Medium - Heavy pollution
$3 \leq I_{geo} < 4$	4	Heavy pollution
$4 \leq I_{geo} < 5$	5	Heavy - very heavy pollution
$5 \leq I_{geo}$	6	Very heavy pollution

$$ADD_{inh} = \frac{C_i \times PM_{10} \times DAIR \times PLAF \times FSPO \times CF \times EF \times ED}{BW \times AT} \quad (5)$$

where, ADD_{ing} , ADD_{derm} , and ADD_{inh} represent the exposure dose by oral ingestion, dermal contact, and respiratory inhalation, respectively, and C_i is the heavy metal content i in the sample. The exposed skin surface area was obtained from Liu T et al. (2022), and the other parameter values (Table 3) were based on the recommended values in the Soil Environment Quality Risk Control Standards for Soil Contamination of Agriculture Land (GB15618-2018) and the EPA exposure factor manual.

The analysis of health risk effects was divided into carcinogenic and non-carcinogenic effects. The non-carcinogenic effects were expressed through the non-carcinogenic risk index (HQ) and the total non-carcinogenic risk index (HI). Carcinogenic effects were expressed using the carcinogenic risk index (CR) and total carcinogenic risk index (TCR).

Here, ADD is the average daily exposure level via ingestion, dermal, or respiratory exposure routes, RfD is the reference dose, and SF is the slope factor. Specific reference values are listed in Table 4 (Wang CY et al., 2021; Liu T et al., 2022). When $HI \leq 1$, the non-carcinogenic risk is within the acceptable range. Values of $HI > 1$ indicate a potential non-carcinogenic risk due to exposure to specific toxic

elements. Values of $TCR < 1.0 \times 10^{-6}$ do not indicate carcinogenic risk to humans. When $1.0 \times 10^{-6} \leq TCR \leq 1.0 \times 10^{-4}$, the carcinogenic risk is within the acceptable range. When $TCR > 1.0 \times 10^{-4}$, the carcinogenic risk is considered unacceptable and poses a threat to human health (Rehman et al., 2018).

3. Results and discussion

3.1. Characterization of heavy metal content

The concentrations of heavy metals are presented in Table 5. The average values of certain heavy metals surpassed the screening values outlined in the Soil Environmental Quality Risk Control Standards for Agricultural Land Pollution (GB15618-2018). Specifically, Cu, Pb, Zn, Cd, and As levels exceeded the soil environmental background limits, with As and Cd exceeding this limit by 88.04 and 49.38 times, respectively. Cu, Pb, and Zn exceeded the acceptable soil environmental background limits by 3.65, 6.34, and 4.57 times, respectively. Among the total samples, 34, 56, 46, 4, 57, and 70 samples for Cu, Pb, Zn, Cr, Cd, and As, respectively, exceeded the screening values, accounting for 49%, 80%, 66%, 6%, 81%, and 100%, respectively, of the total samples. These findings suggest varying degrees of enrichment of all heavy metals in the surface soil of the study area. Notably, Cd and As exhibited the most significant enrichment, followed by Pb, Zn, and Cu; Cr and Hg levels were also elevated. The coefficients of variation indicate the spatial dispersion and variability of heavy metals; higher coefficients suggest greater possible anthropogenic influence. Spatial differences in the distribution and anthropogenic pollution of these heavy metals were evident.

The average concentrations of heavy metals in water were assessed against the Sanitary Standard for Drinking Water (GB5749-2022). All heavy metals tested exceeded the limit values for drinking water. Specifically, the average concentrations of As, Cd, Hg, Zn, Cr, Pb, and Cu exceeded the acceptable background limits by 4140.4, 1352, 130, 45.88, 58.2, 4.8, and 3.54 times, respectively. Number of samples exceeding the standard values were 24, 30, 19, 30, 30, 30, and 30 for Cu, Pb, Zn, Cr, Cd, As, and Hg, respectively, accounting for 80%, 100%, 63%, 100%, 100%, 100%, and 100% of the total samples. Levels of Pb, Cr, Cd, As, and Hg

Table 2. Graded classification of potential ecological risk.

E_r^i	Ecological risk level	RI	Ecological risk level
≤ 40	Minor	≤ 150	Minor
40–80	Moderate	150–300	Moderate
80–160	Severe	300–600	Severe
160–320	Very heavy	> 600	Extremely heavy
> 320	Extremely heavy		

Table 3. Exposure parameters of the health risk assessment model.

Symbols	Meaning	Unit	Adults	Children
IR	Soil intake rate	mg/kg	100	200
CF	Conversion Factor	kg/mg	10^{-6}	10^{-6}
EF	Exposure frequency	d/a	350	350
ED	Years of exposure	a	24	6
BW	Average weight	kg	61.8	19.2
SA	Exposed skin surface area	cm ²	5075	2448
SF	Skin adhesion coefficient	mg/cm ²	0.07	0.2
ABS	Skin absorption factor	–	.001	0.001
PM ₁₀	Levels of respirable suspended particulates in the air	mg/cm ³	0.15	0.15
DAIR	Daily air breathing volume	m ³ /d	14.5	7.5
PIAF	Retention rate of inhaled particulate matter in the human body	–	0.75	0.75
FSPO	Proportion of airborne particulate matter from soil	–	0.5	0.5
AT	Average exposure time (carcinogenic)	d	27740	27740
AT	Average exposure time (non-carcinogenic)	d	ED×365	ED×365

Table 4. Reference dose (RfD) and slope factor (SF) of various exposure routes.

Heavy Metals	Respiratory inhalation		Skin contact		Oral intake	
	RfD	SF	RfD	SF	RfD	SF
Cu	1.20×10^{-2}	–	4.00×10^{-2}	–	4.00×10^{-2}	–
Pb	3.52×10^{-3}	4.20×10^{-2}	5.25×10^{-4}	1.70×10^{-2}	3.50×10^{-3}	8.50×10^{-3}
Zn	3.00×10^{-1}	–	6.00×10^{-2}	–	3.00×10^{-1}	–
Cr	2.86×10^{-5}	42	6.00×10^{-5}	20	3.00×10^{-3}	5.01×10^{-1}
Cd	2.40×10^{-6}	6.3	1.00×10^{-5}	6.1	1.00×10^{-3}	6.1
As	3.01×10^{-4}	15.1	1.23×10^{-4}	3.66	3.00×10^{-4}	1.5
Hg	7.66×10^{-5}	–	2.10×10^{-5}	–	3.00×10^{-4}	–

exceeded the acceptable limit standards. The order of the coefficients of variation was as follows: Cd > Zn > As > Hg > Cu > Pb > Cr. Specifically, the coefficients of variation for Cd, Zn, As, and Hg were 3.71, 2.62, 2.17, and 1.23, respectively.

3.2. Analysis of the geoaccumulation index

Seven heavy metals were assessed in the surface soil and water of the study area based on the geoaccumulation index. The average values of soil *I*_{geo}, in descending order, were As (3.58) > Cd (2.00) > Pb (0.99) > Zn (0.34) > Cu (-0.09) > Cr (-2.44) > Hg (-4.88); the average values of water *I*_{geo}, in descending order, were As (7.69) > Hg (5.97) > Cd (5.92) > Cr (5.13) > Pb (1.51) > Cu (0.66) > Zn (0.18). As illustrated in Fig. 2, the percentage of samples with different contamination levels indicated the most severe contamination of As in the surface soil, with 27% of samples classified as extremely contaminated and 86% as contaminated moderately and above. Similarly, 16% of samples were extremely contaminated with Cd, and 58% were contaminated moderately and above. For Cu, Pb, and Zn, 24%, 26%, and 30% of samples, respectively, were contaminated moderately and above. However, Hg and Cr were not identified in the heavily polluted samples.

The geoaccumulation index revealed significant accumulation of Cd, As, and Pb in the soil of the study area, followed by Zn and Cu, whereas Hg and Cr showed lower levels of accumulation. These findings align with those of previous studies (Mo J et al., 2015; Zhang JD et al., 2021), indicating Cd and As as the most prominent pollutants in tin mining areas, followed by Pb, Zn, and Cu, with Cr and Hg showing relatively low pollution levels. Therefore, heavy metal pollution management in the soil surrounding tin mining areas should prioritize addressing Cd, As, Pb, Zn, and Cu pollution.

In water, Hg pollution was the most severe, accounting for 93% of extremely polluted samples and 100% of moderately and above polluted samples. Additionally, Cr, Cd, and As accounted for 60%, 53%, and 77% of extremely polluted samples and 100%, 100%, and 97% of moderately and above polluted samples, respectively. Zn accounted for 13% of extremely polluted samples and 53% of moderately and above polluted samples. Cu and Pb accounted for 43% and 87% of moderately and above polluted samples, respectively.

3.3. Analysis of potential ecological risk index

The mean values of potential ecological risk factors (*E*_rⁱ) for Cu, Pb, Zn, Cr, Cd, As, and Hg in the surface soils of the

Table 5. Heavy metal contents in the soil and water of a mining area in Hunan Province.

Characteristic parameters		Cu		Pb		Zn		Cr		Cd		As		Hg	
Samples		soil	water	soil	water	soil	water	soil	water	soil	water	soil	water	soil	water
Experimental data	Minimum value	13.7	0.16	48.8	0.08	103	0.01	4.28	0.96	0.1	0.04	29.8	0.27	0.02	0.04
	Maximum value	2600	9.48	5080	0.58	10800	1040	284	5.6	707	137	19500	3660	1.37	0.94
	Average value	362.02	3.54	1077.87	0.24	1371.41	91.76	108.03	2.91	29.625	6.76	2201.08	414.04	0.23	0.13
Calculated data	Standard deviation	571.04	2.81	1432.31	0.12	2299.61	240.55	78.41	1.27	92.32	25.1	3992.77	897.01	0.22	0.16
	Coefficient of variation/%	1.58	0.79	1.33	0.50	1.68	2.62	0.73	0.44	3.12	3.71	1.81	2.17	0.96	1.23
	Skewness	2.19	0.68	1.8	1.47	2.56	3.12	0.39	0.46	6.07	5.16	2.39	2.73	3.28	4.71
	Kurtosis	4.36	-0.8	1.96	2.04	6.03	9.3	-0.85	-0.4	42.97	27.44	5.84	7.3	13.47	24.01
	Background value	100	1	170	0.05	300	2	250	0.05	0.6	0.005	25	0.1	3.4	0.001
	Exceedance times	3.62	3.54	6.34	4.8	4.57	45.88	0.43	58.2	49.38	1352	88.04	4140.4	0.07	130
	Number of samples Exceeding the standard	34	24	56	30	46	19	4	30	57	30	70	30	0	30
Exceedance rate/%	0.49	0.8	0.8	1	0.66	0.63	0.06	1	0.81	1	1	1	0	1	

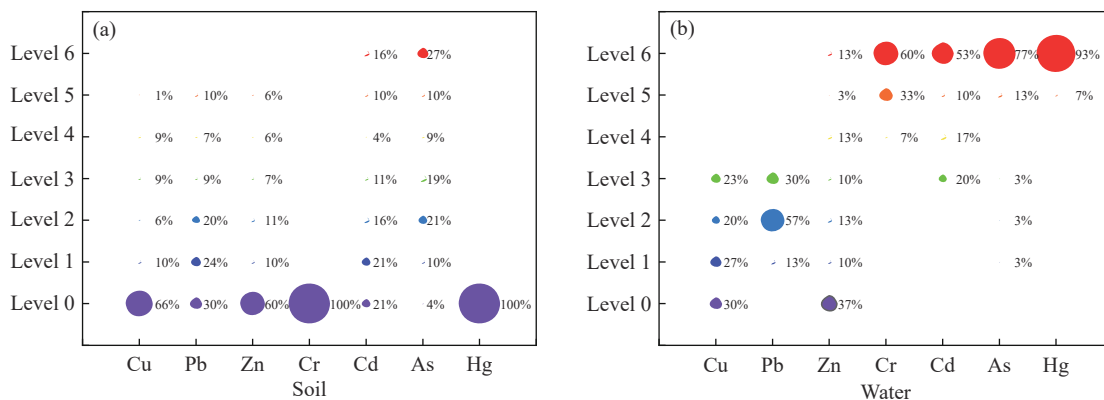


Fig. 2. Classification of the heavy metal pollution geoaccumulation index in a mining region of Hunan Province.

study area were 18.10, 31.70, 4.57, 0.86, 1481.25, 880.43, and 2.73, respectively (Fig. 3a). Ecological risk indices indicated slight ecological risk for Zn, Cr, and Hg pollution in most samples, with less than 40, whereas Cu and Pb showed slight pollution, with fewer than 20% of samples above medium risk level. Cd posed the highest ecological risk, with 79% of samples being at moderate risk and above levels, making it the primary potential ecological risk factor in the study area. Soil ecological risk index values ranged from 31.34 to 41599.71, with a mean value of 2419.65. The ecological risk varied from slight to very severe, with 66% of samples showing moderate risk and above levels and 34% exhibiting extremely severe risk levels. Fig. 3c depicts significant positive correlations among various elements, indicating similar sources or influencing factors.

In water, the mean values of potential ecological risk factors (E_i^j) for Cu, Pb, Zn, Cr, Cd, As, and Hg were 17.71, 23.74, 45.88, 116.41, 40536.60, 41403.5, and 5009.33, respectively (Fig. 3b). Most samples of Cu, Pb, and Zn showed slight pollution levels, with fewer than 20% being at moderate risk or above levels. However, 93% and 97% of samples exhibited moderate risk or above levels for Cr and As, respectively. Cd posed high to very high risk, with 100% of samples being at moderate risk and above levels, alongside 100% of samples showing a very high risk of Hg pollution,

making Cd the predominant potential ecological risk factor in water. The ecological risk index values ranged from 758.14 to 118844.55, with a mean value of 82143.88. Ecological risk fell within the extremely heavy risk interval. Fig. 3d illustrates the significant positive correlations for Cu-As, Zn-Cd, Zn-As, and Cd-As and significant negative correlations for Cu-Cr, Zn-Cr, and Cr-As, suggesting potential interactions or common sources among these heavy metals, warranting further investigation.

Overall, the study area exhibited a high ecological risk, with Cr, Cd, and As being the main contributors in both soil and water. Hg, as a specific influencing factor in water, is likely influenced primarily by topography and the water–land relationship.

The spatial distribution pattern of the ecological risk index revealed that the overall ecological pollution index of several water environment samples in the southwest of the mining area was low, along with that of several water and soil environment samples in the northern periphery of the mining area (Fig. 4). The river flow, precipitation, and self-purification effects caused the heavy metal content to decrease along the direction of water flow from the mining area. Within the mining area, surface water and groundwater exhibited higher pollution levels than those in the upstream and downstream areas, whereas the degree of heavy metal

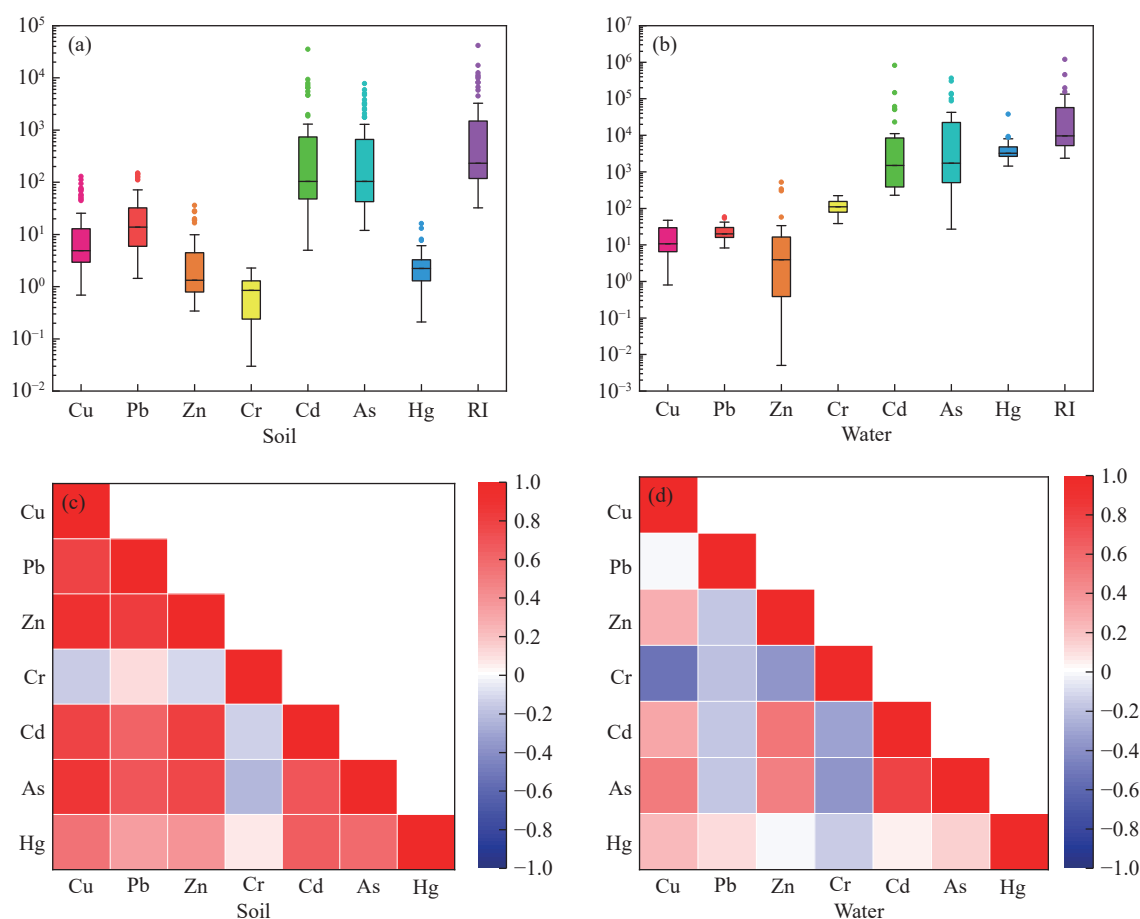


Fig. 3. Heat map depicting statistics and correlation analysis of potential ecological risk indices of heavy metals in soil and water of mining region in Hunan Province.

accumulation in soil and associated risk decreased downstream of the mining area. Soil contamination inside the mine area was more severe, with contamination levels matching those of the water samples.

The surface elevation characteristics of the mining area indicated different pooling systems, influencing the ecological risk of water pollution primarily through natural weathering processes, representing the natural pollution level. Within the mining area, high levels of water and soil pollution correspond to high ecological pollution indices, likely owing to substantial backfill accumulation during production processes and the physical input of accumulated waste,

thereby increasing heavy metal content in the water body. These findings underscore the potential risks associated with mining activities in the ecosystem.

3.4. Analysis of human health risk

3.4.1. Exposure risk assessment

Based on the exposure parameters of the health risk assessment model, the daily exposure to heavy metals in the water and soil of the study area was calculated. As indicated in Tables 6 and 7, the average daily intake of carcinogenic and non-carcinogenic compounds through the soil for both

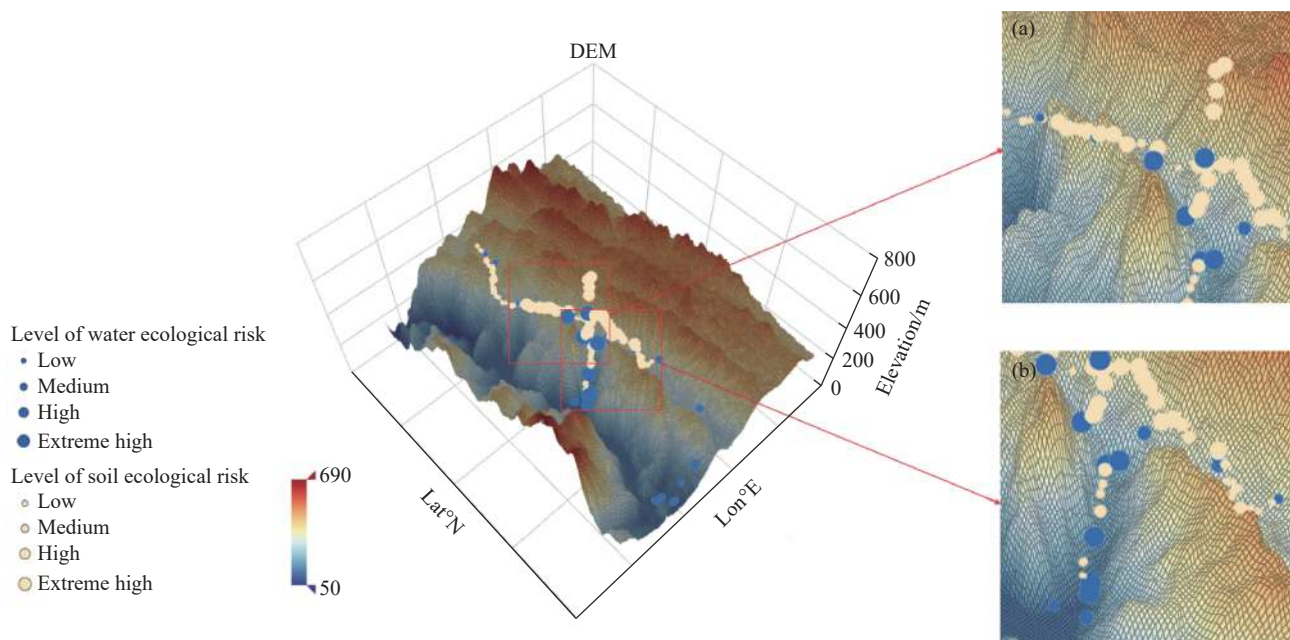


Fig. 4. Evaluation of heavy metal pollution in the water and soil and the risk of human health in a tin mining region of Hunan Province.

Table 6. Average daily exposure to non-carcinogenic heavy metals in a mining region of Hunan Province (mg/(kg·d)).

Heavy Metals	ADDing Non-carcinogenic		ADDderm Non-carcinogenic		ADDinh Non-carcinogenic		ADD	
	Adults	Children	Adults	Children	Adults	Children	Adults	Children
soil								
Cu	5.62×10^{-4}	3.62×10^{-3}	2.00×10^{-6}	8.85×10^{-6}	4.58×10^{-6}	1.46×10^{-4}	5.68×10^{-4}	3.77×10^{-3}
Pb	1.67×10^{-3}	1.08×10^{-2}	5.94×10^{-6}	2.64×10^{-5}	1.36×10^{-5}	4.36×10^{-4}	1.69×10^{-3}	1.12×10^{-2}
Zn	2.13×10^{-3}	1.37×10^{-2}	7.56×10^{-6}	3.35×10^{-5}	1.74×10^{-5}	5.55×10^{-4}	2.15×10^{-3}	1.43×10^{-2}
Cr	1.68×10^{-4}	1.08×10^{-3}	5.95×10^{-7}	2.64×10^{-6}	1.37×10^{-6}	4.37×10^{-5}	1.70×10^{-4}	1.13×10^{-3}
Cd	4.60×10^{-5}	2.96×10^{-4}	1.63×10^{-7}	7.24×10^{-7}	3.75×10^{-7}	1.20×10^{-5}	4.65×10^{-5}	3.09×10^{-4}
As	3.42×10^{-3}	2.20×10^{-2}	1.21×10^{-5}	5.38×10^{-5}	2.79×10^{-5}	8.90×10^{-4}	3.46×10^{-3}	2.09×10^{-2}
Hg	3.60×10^{-7}	2.32×10^{-6}	1.28×10^{-9}	5.67×10^{-9}	2.94×10^{-9}	9.39×10^{-8}	3.64×10^{-7}	2.42×10^{-6}
ADD	7.99×10^{-3}	5.14×10^{-2}	2.84×10^{-5}	1.26×10^{-4}	6.52×10^{-5}	2.08×10^{-3}	8.08×10^{-3}	5.37×10^{-2}
water								
Cu	5.50×10^{-2}	1.24×10^{-1}	1.95×10^{-5}	8.66×10^{-5}			5.50×10^{-2}	1.24×10^{-1}
Pb	3.68×10^{-3}	8.30×10^{-3}	1.31×10^{-6}	5.80×10^{-6}			3.68×10^{-3}	8.31×10^{-3}
Zn	1.42×10	3.21×10	5.06×10^{-4}	2.24×10^{-3}			1.42×10	3.21×10
Cr	4.52×10^{-2}	1.02×10^{-1}	1.60×10^{-5}	7.12×10^{-5}			4.52×10^{-2}	1.02×10^{-1}
Cd	1.05×10^{-1}	2.36×10^{-1}	3.72×10^{-5}	1.65×10^{-4}			1.05×10^{-1}	2.36×10^{-1}
As	6.42×10^0	1.45×10^1	2.28×10^{-3}	1.01×10^{-2}			6.43×10^0	1.45×10^1
Hg	1.94×10^{-3}	4.38×10^{-3}	6.90×10^{-7}	3.06×10^{-6}			1.94×10^{-3}	4.38×10^{-3}
ADD	8.06×10^0	1.82×10^1	2.86×10^{-3}	1.27×10^{-2}			8.06×10^0	1.82×10^1

Table 7. Average daily exposure to carcinogenic heavy metals in a mining region of Hunan Province (mg/(kg·d)).

Heavy Metals	ADD _{ing}		ADD _{derm}		ADD _{inh}		ADD	
	Adults	Children	Adults	Children	Adults	Children	Adults	Children
Soil								
Pb	5.28×10^{-4}	8.50×10^{-4}	1.88×10^{-6}	2.08×10^{-6}	4.31×10^{-6}	3.44×10^{-5}	5.34×10^{-4}	8.86×10^{-4}
Cr	5.29×10^{-5}	8.52×10^{-5}	1.88×10^{-7}	2.09×10^{-7}	4.32×10^{-7}	3.45×10^{-6}	5.36×10^{-5}	8.88×10^{-5}
Cd	1.45×10^{-5}	2.34×10^{-5}	5.16×10^{-8}	5.72×10^{-8}	1.18×10^{-7}	9.46×10^{-7}	1.47×10^{-5}	2.44×10^{-5}
As	1.08×10^{-3}	1.74×10^{-3}	3.83×10^{-6}	4.25×10^{-6}	8.80×10^{-6}	7.03×10^{-5}	1.09×10^{-3}	1.81×10^{-3}
ADD	1.67×10^{-3}	2.69×10^{-3}	5.95×10^{-6}	6.60×10^{-6}	1.37×10^{-5}	1.09×10^{-4}	1.69×10^{-3}	2.81×10^{-3}
water								
Pb	1.16×10^{-3}	6.55×10^{-4}	5.90×10^{-6}	2.29×10^{-7}			1.17×10^{-3}	6.55×10^{-4}
Cr	1.43×10^{-2}	8.03×10^{-3}	3.62×10^{-5}	1.40×10^{-5}			1.43×10^{-2}	8.05×10^{-3}
Cd	3.31×10^{-2}	1.86×10^{-2}	4.20×10^{-5}	1.63×10^{-5}			3.31×10^{-2}	1.87×10^{-2}
As	2.03×10^0	1.14×10^0	2.57×10^{-3}	9.99×10^{-4}			2.03×10^0	1.14×10^0
ADD	2.08×10^0	1.17×10^0	2.66×10^{-3}	1.03×10^{-3}			2.08×10^0	1.17×10^0

adults and children followed the order $ADD_{ing} > ADD_{inh} > ADD_{derm}$. Similarly, the average daily intake of carcinogenic and non-carcinogenic compounds through the water for both adults and children followed the order $ADD_{ing} > ADD_{derm}$. Oral intake emerged as the primary route for both carcinogenic and non-carcinogenic risks.

Children exhibited higher exposure levels than did adults in terms of both non-carcinogenic and carcinogenic routes of exposure to soil heavy metals. This difference may stem from the physiological and behavioral characteristics of children, such as sucking behavior and diminished detoxification abilities, which heighten their susceptibility to certain health risks. Conversely, the greater exposure of adults to carcinogenic heavy metals through water may be attributed to the accumulation of toxic elements in their bodies over years of water source utilization in the area.

3.4.2. Health risk evaluation

The non-carcinogenic and carcinogenic health risk indices of heavy metals in the study area were calculated based on daily exposure and reference doses (Tables 8 and 9).

The non-carcinogenic health risk index revealed that for both adults and children in the study area, $HQ_{ing} > HQ_{derm}$ for the non-carcinogenic risk via different exposure routes (Table 8), indicating oral intake as the primary route of non-carcinogenic risk (Fig. 5). The ranking of non-carcinogenic risk for adults and children concerning heavy metals was in the order $As > Cd > Cr > Zn > Cu > Pb$. For both adults and children, the number of oral intake pathways for As, Cr, Cd, Pb, and Cu exceeded one, suggesting potential adverse health effects through drinking water ingestion. Moreover, the number of intake pathways for As, Cd, and Cr, including dermal contact, also exceeded one, indicating potential health risks via this exposure route. The order of different exposure pathways for non-carcinogenic risk in the study area was $HQ_{ing} > HQ_{inh} > HQ_{derm}$ for adults and $HQ_{ing} > HQ_{derm} > HQ_{inh}$ for children, emphasizing oral intake as the primary pathway contributing to non-carcinogenic risk. The non-carcinogenic risk posed by heavy metals was ranked as follows: $As > Pb > Cd > Cr > Cu > Zn > Hg$ for adults and As

$> Cd > Pb > Cr > Cu > Zn > Hg$ for children, with As, Cd, and Pb posing high risks.

For children, the mean value of the respiratory inhalation route exceeded one for Cd, indicating a potential non-carcinogenic risk via inhalation. Additionally, the mean value of the oral intake route for children exceeded one for Pb, suggesting potential health impacts through oral ingestion. Furthermore, the mean value of the respiratory inhalation pathway for children for Cr in the study area soil exceeded one, indicating a potential health risk. Therefore, managing and controlling the contamination status of As, Pb, Cd, and Cr in the study area is crucial to prevent adverse effects on local residents, particularly children.

The carcinogenic health risk index (Table 9) indicated $CR_{ing} > CR_{derm}$ for both children and adults for heavy metals in water, highlighting the oral intake route as the primary exposure pathway. The total carcinogenic risk of the four heavy metals to human health was in the order $As > Cr > Cd > Pb$ for both adults and children. According to U.S. Environmental Protection Agency guidelines, carcinogenic risk levels of As, Cr, and Cd exceeding 10^{-4} indicate a significant carcinogenic risk to human health. The order of carcinogenic risk for both adults and children in the study area across different exposure routes was $CR_{ing} > CR_{inh} > CR_{derm}$, underscoring oral intake as the major route for both groups, with inhalation being a minor route.

The mean values of CR_{ing} for As were 1.19×10^{-3} for adults and 1.91×10^{-3} for children, with CR_{inh} values of 9.74×10^{-5} and 4.05×10^{-5} and CR_{derm} values of 1.03×10^{-5} and 1.14×10^{-5} , respectively. Oral intake posed a carcinogenic risk to human health, whereas the levels associated with respiratory inhalation and dermal contact were within acceptable ranges. Mean values of oral intake for Cd fell between 10^{-6} and 10^{-4} , indicating an acceptable range, whereas those for respiratory inhalation and dermal contact were below 10^{-6} , posing no carcinogenic risk. The maximum values for oral intake for Cd were 5.56×10^{-4} and 8.95×10^{-4} for adults and children, respectively, indicating the presence of Cd at some sites. Values for all exposure routes for Cr fell within a range of 10^{-6} to 10^{-4} , i.e., within acceptable ranges;

Table 8. Non-carcinogenic health risk index of heavy metals in a mining region of Hunan Province.

Heavy Metals		HQing		HQderm		HQinh		HI	
		Adults	Children	Adults	Children	Adults	Children	Adults	Children
Soil									
Cu	Average value	1.40×10^{-2}	9.04×10^{-2}	4.99×10^{-5}	2.21×10^{-4}	3.82×10^{-4}	1.22×10^{-2}	1.45×10^{-2}	1.03×10^{-1}
	Maximum value	1.01×10^{-1}	6.49×10^{-1}	3.58×10^{-4}	1.59×10^{-3}	2.74×10^{-3}	8.76×10^{-2}	1.04×10^{-1}	7.38×10^{-1}
Pb	Average value	4.78×10^{-1}	3.08×100	1.13×10^{-2}	5.02×10^{-2}	3.88×10^{-3}	1.24×10^{-1}	4.93×10^{-1}	3.25×100
	Maximum value	2.25×100	1.45×101	5.33×10^{-2}	2.37×10^{-1}	1.83×10^{-2}	5.84×10^{-1}	2.32×100	1.53×101
Zn	Average value	7.09×10^{-3}	4.57×10^{-2}	1.26×10^{-4}	5.59×10^{-4}	5.79×10^{-5}	1.85×10^{-3}	7.28×10^{-3}	4.81×10^{-2}
	Maximum value	5.59×10^{-2}	3.60×10^{-1}	9.92×10^{-4}	4.40×10^{-3}	4.56×10^{-4}	1.46×10^{-2}	5.73×10^{-2}	3.79×10^{-1}
Cr	Average value	5.59×10^{-2}	3.60×10^{-1}	9.92×10^{-3}	4.40×10^{-2}	4.78×10^{-2}	1.53×100	1.14×10^{-1}	1.93×100
	Maximum value	1.47×10^{-1}	9.46×10^{-1}	2.61×10^{-2}	1.16×10^{-1}	1.26×10^{-1}	4.02×100	2.99×10^{-1}	5.08×100
Ni	Average value	4.48×10^{-3}	2.89×10^{-2}	5.90×10^{-5}	2.62×10^{-4}	3.55×10^{-5}	1.13×10^{-3}	4.58×10^{-3}	3.02×10^{-2}
	Maximum value	1.55×10^{-2}	9.99×10^{-2}	2.04×10^{-4}	9.06×10^{-4}	1.23×10^{-4}	3.93×10^{-3}	1.58×10^{-2}	1.05×10^{-1}
Cd	Average value	4.60×10^{-2}	2.96×10^{-1}	1.63×10^{-2}	7.24×10^{-2}	1.56×10^{-1}	4.99×100	2.19×10^{-1}	5.36×100
	Maximum value	1.10×100	7.06×100	3.90×10^{-1}	1.73×100	3.73×100	1.19×102	5.21×100	1.28×102
As	Average value	1.14×101	7.33×101	9.86×10^{-2}	4.38×10^{-1}	9.25×10^{-2}	2.96×100	1.16×101	7.67×101
	Maximum value	1.01×102	6.49×102	8.74×10^{-1}	3.88×100	8.20×10^{-1}	2.62×101	1.03×102	6.79×102
Hg	Average value	1.20×10^{-3}	7.73×10^{-3}	6.09×10^{-5}	2.70×10^{-4}	3.83×10^{-5}	1.23×10^{-3}	1.30×10^{-3}	9.22×10^{-3}
	Maximum value	7.09×10^{-3}	4.56×10^{-2}	3.60×10^{-4}	1.60×10^{-3}	2.26×10^{-4}	7.24×10^{-3}	7.67×10^{-3}	5.44×10^{-2}
Water									
Cu	Average value	1.37×10^0	3.10×10^0	1.74×10^{-3}	2.71×10^{-3}			1.38×10^0	3.10×10^0
	Maximum value	3.68×10^0	8.29×10^0	4.67×10^{-3}	7.24×10^{-3}			3.68×10^0	8.29×10^0
Pb	Average value	1.05×10^0	2.37×10^0	3.56×10^{-2}	5.53×10^{-2}			1.09×10^0	2.43×10^0
	Maximum value	2.57×10^0	5.79×10^0	8.70×10^{-2}	1.35×10^{-1}			2.66×10^0	5.93×10^0
Zn	Average value	4.75×10^0	1.07×10	1.81×10^{-2}	2.80×10^{-2}			4.76×10^0	1.07×10
	Maximum value	5.38×10	1.21×10^2	2.05×10^{-1}	3.18×10^{-1}			5.40×10	1.22×10^2
Cr	Average value	1.51×10	3.39×10	1.91×10^0	2.97×10^0			1.70×10	3.69×10
	Maximum value	2.90×10	6.53×10	3.67×10^0	5.71×10^0			3.26×10	7.10×10
Cd	Average value	1.05×10^2	2.36×10^2	1.33×10	2.07×10			1.18×10^2	2.57×10^2
	Maximum value	2.13×10^3	4.79×10^3	2.70×10^2	4.19×10^2			2.40×10^3	5.21×10^3
As	Average value	2.14×10^4	4.82×10^4	6.63×10	1.03×10^2			2.15×10^4	4.84×10^4
	Maximum value	1.89×10^5	4.27×10^5	5.86×10^2	9.09×10^2			1.90×10^5	4.27×10^5
Hg	Average value	1.94×10^{-3}	4.38×10^{-3}	3.29×10^{-2}	1.46×10^{-1}			3.48×10^{-2}	1.50×10^{-1}
	Maximum value	1.46×10^{-2}	3.29×10^{-2}	2.47×10^{-1}	1.09×10^0			2.61×10^{-1}	1.13×10^0

oral intake of Pb was acceptable, whereas inhalation and dermal exposure posed no carcinogenic risks.

Considering the TCR and the above-described analysis, soil As was identified as posing a potential carcinogenic risk to human health in the study area and Cd posing a risk at select sites. However, Cr and Pb levels were within acceptable ranges, thus posing a low carcinogenic risk to humans.

4. Conclusions

(i) Analysis of the investigated soil and water samples revealed that the average heavy metal content exceeded pollution risk control standards, with a notable accumulation of As, Cd, and Zn. Additionally, Hg exhibited significant accumulation in the samples.

(ii) The study area exhibited high ecological risk, which is primarily attributed to elevated levels of As and Cd in the soil as well as As, Cd, Hg, and Zn levels in water bodies, serving as the main contributors to ecological risk.

(iii) Carcinogenic risks were mainly associated with As, Cd, and Pb intake through the soil, whereas non-carcinogenic risks were primarily linked to As, Cd, and Cr intake through water. Efforts for investigating and controlling heavy metal pollution must be intensified in this area to mitigate potential adverse health effects on the residents.

CRediT authorship contribution statement

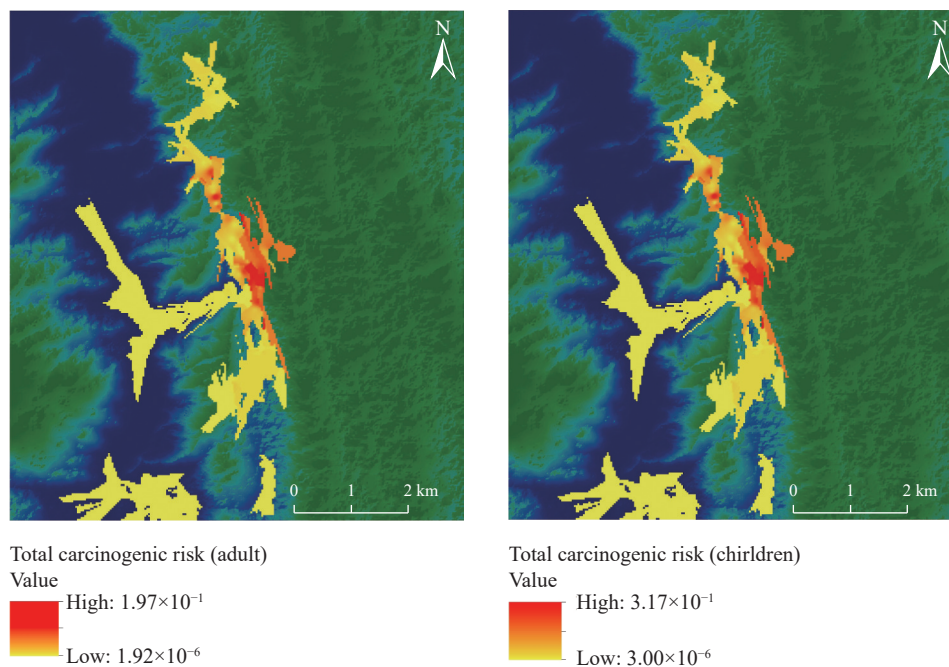
Lan Wang: Conceptualization, methodology, data curation, writing- original draft preparation. Jian-feng Li: Field data collection, thesis supervision, writing-reviewing and editing; Xiu-wen Liu: Data collation and analysis; Li-xiao Feng: Data collation; All authors read and approved the final manuscript. All authors contributed to the study conception and design.

Declaration of competing Interest

The authors declare no conflict of interest.

Table 9. Carcinogenic health risk index of heavy metals in a mining region of Hunan Province.

Heavy Metals		CRing		CRderm		CRinh		TCR	
		Adults	Children	Adults	Children	Adults	Children	Adults	Children
Soil									
Pb	Average value	4.49×10^{-6}	7.22×10^{-6}	3.19×10^{-8}	3.54×10^{-8}	1.81×10^{-7}	1.45×10^{-6}	4.70×10^{-6}	8.71×10^{-6}
	Maximum value	2.12×10^{-5}	3.41×10^{-5}	1.50×10^{-7}	1.67×10^{-7}	8.53×10^{-7}	6.81×10^{-6}	2.22×10^{-5}	4.10×10^{-5}
Cr	Average value	2.65×10^{-5}	4.27×10^{-5}	3.76×10^{-6}	4.17×10^{-6}	1.81×10^{-5}	1.45×10^{-4}	4.84×10^{-5}	1.92×10^{-4}
	Maximum value	6.97×10^{-5}	1.12×10^{-4}	9.89×10^{-6}	1.10×10^{-5}	4.77×10^{-5}	3.81×10^{-4}	1.27×10^{-4}	5.04×10^{-4}
Cd	Average value	8.85×10^{-5}	1.43×10^{-4}	3.15×10^{-7}	3.49×10^{-7}	7.46×10^{-7}	5.96×10^{-6}	8.96×10^{-5}	1.49×10^{-4}
	Maximum value	2.11×10^{-3}	3.40×10^{-3}	7.51×10^{-6}	8.33×10^{-6}	1.78×10^{-5}	1.42×10^{-4}	2.14×10^{-3}	3.55×10^{-3}
As	Average value	1.62×10^{-3}	2.60×10^{-3}	1.40×10^{-5}	1.56×10^{-5}	1.33×10^{-4}	1.06×10^{-3}	1.76×10^{-3}	3.68×10^{-3}
	Maximum value	1.43×10^{-2}	2.31×10^{-2}	1.24×10^{-4}	1.38×10^{-4}	1.18×10^{-3}	9.40×10^{-3}	1.56×10^{-2}	3.26×10^{-2}
water									
Pb	Average value	9.89×10^{-6}	5.57×10^{-6}	1.00×10^{-7}	3.90×10^{-9}			9.99×10^{-6}	5.57×10^{-6}
	Maximum value	2.42×10^{-5}	1.36×10^{-5}	2.45×10^{-7}	9.52×10^{-9}			2.44×10^{-5}	1.36×10^{-5}
Cr	Average value	7.14×10^{-3}	4.02×10^{-3}	7.24×10^{-4}	2.81×10^{-4}			7.87×10^{-3}	4.31×10^{-3}
	Maximum value	1.37×10^{-2}	7.74×10^{-3}	1.39×10^{-3}	5.41×10^{-4}			1.51×10^{-2}	8.28×10^{-3}
Cd	Average value	2.02×10^{-1}	1.14×10^{-1}	2.56×10^{-4}	9.94×10^{-5}			2.02×10^{-1}	1.14×10^{-1}
	Maximum value	4.09×10	2.31×10^0	5.20×10^{-3}	2.02×10^{-3}			4.10×10^0	2.31×10^0
As	Average value	3.04×10	1.71×10	9.42×10^{-3}	3.66×10^{-3}			3.05×10^0	1.72×10^0
	Maximum value	2.69×10	1.52×10	8.33×10^{-2}	3.23×10^{-2}			2.70×10	1.52×10

**Fig. 5.** Average daily exposure to cancer-causing heavy metals in soil (mg/(kg·d)).

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Data Availability Statement

The primary data used to support the findings of this study are available from the corresponding author upon request.

References

- Chen ZY, Zhao YY, Chen DL, Huang HT, Zhao Y, Wu YJ. 2023. Ecological risk assessment and early warning of heavy metal cumulation in the soils near the Luanchuan molybdenum polymetallic mine concentration area, Henan Province, Central China. *China Geology*, 6(1), 15–26. doi: [10.31035/cg2023003](https://doi.org/10.31035/cg2023003).

- Förstner U, Ahlf W, Calmano W. 1993. Sediment quality objectives and criteria development in Germany. *Water Science and Technology*, 28(8-9), 307–316. doi: [10.2166/wst.1993.0629](https://doi.org/10.2166/wst.1993.0629).
- Gao RZ, Zhang AL, Zhang S, Jia DB, Du DD, Qin ZY, Wang XX. 2019. Spatial distribution characteristics and potential ecological risk assessment of Cr, Hg and As in soils of the Salt Lake Basin in northwest China. *Acta Ecologica Sinica*, 39(7), 2532–2544 (in Chinese with English abstract). doi: [10.5846/stxb201711292142](https://doi.org/10.5846/stxb201711292142).
- Guo ZH, Zhu YG. 2004. Contamination and available contents of heavy metals in soils in the typical mining and smelting circumjacent districts. *Ecology and Environmental Sciences*, 13(4), 553–555 (in Chinese with English abstract). doi: [10.16258/j.cnki.1674-5906.2004.04.025](https://doi.org/10.16258/j.cnki.1674-5906.2004.04.025).
- Hakanson L. 1980. An ecological risk index for aquatic pollution control. A sedimentological approach. *Water Research*, 14(8), 975–1001. doi: [10.1016/0043-1354\(80\)90143-8](https://doi.org/10.1016/0043-1354(80)90143-8).
- He DM, Wang XF, Chen LJ, Su R. 2014. Assessment on heavy metals contaminations of Sugarcane soil in Guangxi Province by the geo-accumulation index and potential ecological risk index. *Journal of Agricultural Resources and Environment*, 31(02), 126–131(in Chinese with English abstract). doi: [10.13254/j.jare.2014.0008](https://doi.org/10.13254/j.jare.2014.0008).
- He Y, Zhang Q, Li H, Wang W, Hua J. 2024. Heavy metal pollution characteristics and systemic risk assessment of the environment around the tailings site. *Journal of Soils and Sediments*, 24(1), 217–229. doi: [10.1007/s11368-023-03588-7](https://doi.org/10.1007/s11368-023-03588-7).
- Jiang CY. 2020. Heavy metal pollution in farmland soil and crops in a mining area in Hunan province and its health risk assessment. Changsha, Hunan Agricultural University, Master thesis, 1–61 (in Chinese with English abstract).
- Li Q, Li X, Bu C, Wu P. 2023. Distribution, risk assessment, and source apportionment of heavy metal pollution in cultivated soil of a typical mining area in Southwest China. *Environmental Toxicology and Chemistry*, 42(4), 888–900. doi: [10.1002/etc.5586](https://doi.org/10.1002/etc.5586).
- Li JF, Lu YY, Zhang ZZ, Fu JM, Qin ZW. 2023. Research and prospecting progress of dayishan pluton in Nanling range. *Earth Science*, 48(10), 3707–3724 (in Chinese with English abstract). doi: [10.3799/dqkx.2021.242](https://doi.org/10.3799/dqkx.2021.242).
- Liu T, Liu CP, Deng J, Kang PY, Wang KK, Zhao YY. 2022. Ecological health risk assessment of soil heavy metals in eastern Yinan County, Shandong Province. *Geology in China*, 49(5), 1497–1508 (in Chinese with English abstract). doi: [10.12029/gc20220509](https://doi.org/10.12029/gc20220509).
- Lu J, Lu H, Lei K, Wang W, Guan Y. 2019. Trace metal element pollution of soil and water resources caused by small-scale metallic ore mining activities: A case study from a sphalerite mine in North China. *Environmental Science and Pollution Research*, 26(24), 24630–24644. doi: [10.1007/s11356-019-05703-z](https://doi.org/10.1007/s11356-019-05703-z).
- Mo J, Lei LQ, Shi ZH, Mo BJ. 2015. Heavy metal pollution comprehensive evaluation of oxide tailings in Shanhu tungsten-tin mine area of Guangxi. *Nonferrous Metals Engineering*, 5(4), 79–84 (in Chinese with English abstract). doi: [10.3969/j.issn.2095-1744.2015.04.019](https://doi.org/10.3969/j.issn.2095-1744.2015.04.019).
- Rehman IU, Ishaq M, Ali L, Khan S, Ahmad I, Din IU, Ullah H. 2018. Enrichment, spatial distribution of potential ecological and human health risk assessment via toxic metals in soil and surface water ingestion in the vicinity of Sewakht mines, district Chitral, Northern Pakistan. *Ecotoxicology and Environmental Safety*, 154, 127–136. doi: [10.1016/j.ecoenv.2018.02.033](https://doi.org/10.1016/j.ecoenv.2018.02.033).
- Tan HW, Zhang G, Luo QJ, Miao Y, Chu JL, Chu LJ. 2023. Investigation and comprehensive treatment of heavy metal pollution in a nonferrous metal mining area. *Mine Engineering*, 11(3), 403–408 (in Chinese with English abstract). doi: [10.12677/me.2023.113050](https://doi.org/10.12677/me.2023.113050).
- Xu ZQ, Ni SJ, Tuo XG, Zhang CJ. 2008. Calculation of heavy metals' toxicity coefficient in the evaluation of potential ecological risk index. *Environmental Science & Technology*, 31(2), 112–115 (in Chinese with English abstract). doi: [10.19672/j.cnki.1003-6504.2008.02.030](https://doi.org/10.19672/j.cnki.1003-6504.2008.02.030).
- Yu X, Song LT, Teng YG. 2016. Pollution analysis and ecological environment risk assessment of heavy metals in soils of a Pb-Zn mine in Hunan Province. *Journal of Huazhong Agricultural University*, 35(5), 27–32 (in Chinese with English abstract). doi: [10.13300/j.cnki.hnlkxb.2016.05.004](https://doi.org/10.13300/j.cnki.hnlkxb.2016.05.004).
- Yu JY, Li BY, Zhou YM, Li YJ, Lei M. 2020. Pollution and risk assessment of heavy metal in agricultural soil around an abandon mine site in Hunan Province. *Environmental Chemistry*, 39(4), 1024–1030 (in Chinese with English abstract). doi: [10.7524/j.issn.0254-6108.2019040201](https://doi.org/10.7524/j.issn.0254-6108.2019040201).
- Wu YH, Zhou NQ, Wu ZJ, Lu SS, Cai Y. 2022. Carbon, nitrogen and phosphorus coupling relationships and their influencing factors in the critical zone of Dongting Lake wetlands, China. *Journal of Groundwater Science and Engineering*, 10(3), 250–266(in Chinese with English abstract). doi: [10.19637/j.cnki.2305-7068.2022.03.004](https://doi.org/10.19637/j.cnki.2305-7068.2022.03.004).
- Wang CY, Zhang SR, Liu JH, Xing Y, Li MZ, Liu QX. 2021. Pollution level and risk assessment of heavy metals in a metal smelting area of Xiong'an New District. *Geology in China*, 48(06), 1697–1709(in Chinese with English abstract).
- Zhang JD, Tian L, Pei SL. 2021. A discussion of soil and water pollution and control countermeasures in mining area of China. *Hydrogeology & Engineering Geology*, 48(2), 157–163 (in Chinese with English abstract). doi: [10.16030/j.cnki.issn.1000-3665.202003031](https://doi.org/10.16030/j.cnki.issn.1000-3665.202003031).
- Zhang ZZ, Lin DY, Yu YS, Lu YY, Fu JM, Li JF, Qin ZW, Ma LY, Ning YY, Zhang JT. 2022. Implications to the Petrogenesis and Sn Mineralization of the Granite in the Tengshan' ao Sn deposit, the Nanling Metallogenic Belt. *South China Geology*, 38(3), 441–458 (in Chinese with English abstract). doi: [10.3969/j.issn.2097-0013.2022.03.007](https://doi.org/10.3969/j.issn.2097-0013.2022.03.007).