Pollution and health risk assessment of heavy metals in soils of Guizhou, China

Gao Yu\textsuperscript{a,b}, Fen Chen\textsuperscript{a,b}, Hongli Zhang\textsuperscript{c} and Zuhua Wang\textsuperscript{a}

\textsuperscript{a}College of Agroforestry Engineering and Planning, Tongren University, Tongren, People’s Republic of China; \textsuperscript{b}Key Laboratory of Original Agro-Environmental Pollution Prevention and Control, Ministry of Agriculture and Rural Affairs/Tianjin Key Laboratory of Agro-environment and Safe-product, Tianjin, People’s Republic of China; \textsuperscript{c}Remote Sensing Monitoring Department, Geo-Cosmos Information Technology Company, LTD, Beijing, People’s Republic of China

**ABSTRACT**
Mining of minerals in Guizhou, China, where it is enriched with reserves, may lead to soil contamination with heavy metals. We assessed the risk of eight typical heavy metals in Guizhou soils by collecting province-wide data available in the literature and using the geo-accumulation index method, the ecological risk assessment method, and the USEPA health risk assessment model. The concentrations of eight heavy metals, except for Pb and Cr, were above the background levels. Soil heavy metal pollution evaluation results showed that As, Cu, Zn, Pb, Cr, Cd, and Ni reached the pollution levels, while Hg fell into the category of moderate contamination. As, Cu, Zn, Pb, Cr, and Ni posed low potential ecological risk, while Cd and Hg demonstrated a considerable or a very high potential ecological risk. Totally, the integrated potential ecological risk was ranked “very high”. Regarding to health risk, the non-carcinogenic risks caused by heavy metals were insignificant, but the carcinogenic risk caused by As was significant. Consequently, there appeared serious soil contamination of Hg and As, with the latter also being the greatest potential risk to human health. Both Hg and As should stay at the highest priority for remediation efforts in Guizhou soils.

**Introduction**

The term “heavy metals” refers to a group of metallic elements with densities greater than 5 g/cm\(^3\), including mercury (Hg), copper (Cu), zinc (Zn), lead (Pb), chromium (Cr), cadmium (Cd), and nickel (Ni), among others. Because of similarities in chemical properties and environmental behavior, metalloid arsenic (As) is often grouped with heavy metals (Leong and Chang 2020). Although naturally ubiquitous in the soil environment (Jin et al. 2019), excessive amounts of heavy metals in soils, resulted from human activities such as mining, smelting, electroplating and other industrial processes, can be harmful to the environment (Jamal et al. 2019).

High levels of heavy metals present in soils in either ionic or organometallic form can have serious adverse health implications for human beings and animals (Baltas et al. 2020). For example, chronic exposure to Cd through soil ingestion can lead to prostatic proliferative lesions, hypertension, bone fractures, pulmonary adenocarcinomas, kidney dysfunction, and lung cancer (James et al. 2020). Long-term exposure to Hg is associated with damages to central and autonomic nervous systems, heart, kidneys, and the digestive tract (Harry et al. 2018; Yin et al. 2018). Because of their ability to cause long-term irreversible damages to human being and animal health, many heavy metal elements, e.g., Hg, As, Cu, Zn, Pb, Cr, Cd, and Ni, have been listed as priory control pollutants by the State Environmental Protection Administration of China, State Land and Resources Administration of China (National soil pollution survey bulletin 2014), and the United States Environmental Protection Agency (USEPA 1998). Issues associated with heavy metal pollution are receiving greater attention in many parts of the world (Anna et al. 2006; Fan, Ding, and Ziad 2013; Rodrigues et al. 2013; Sodango et al. 2018; Mishra et al. 2019).

Guizhou is a mountainous province in the Southwest region of China, with a land mass of ~176,000 km\(^2\). Guizhou is the home for 36 million people (Chen et al. 2018). It has a humid subtropical monsoon climate with an average annual temperature of 15°C and average annual rainfall of 687–1480 mm (Chen et al. 2016). The province is rich in mineral resources, with more than 3,000 confirmed mineral deposits and a large number of active mines of all sorts to match. These collectively make Guizhou Province one of the predominant mineral producers in China. Meanwhile, mineral mining and
associated industries have also contributed to the concern of heavy metal pollution that may endanger environment and human being health (Mishra et al. 2019). For example, a recent study found that residents living near a mercury mine in Guizhou Province have higher rates of cancer at younger age less than 30 years old (Chen et al. 2020). It is understood that such studies are very preliminary. A great deal more information with regard to heavy metal levels in the environment and in human beings and animals, as well as their association with potential sources, are needed before any definitive or even tentative conclusion that could be drawn.

Proper use of the geo-accumulation index \( I_{geo} \) to gauge pollution levels of heavy metals in soils and sediments needs to take into account the natural variation of background values. The choice of coefficient \( k \) is important in this regard (He et al. 2019). It is selected because of possible variations in background values for a given metal in the environment, as well as very small anthropogenic influences (Zhao and Li 2013). During the weathering process, the main crystal structure of some rock minerals is completely destroyed, and the related chemical elements are predominately absorbed by the soil (Solitito et al. 2010). In areas with different types of lithology, the content of heavy metals in the soil varies greatly due to different parent materials and soil properties (Mico et al. 2006). Given the influence of geochemical backgrounds, such as sedimentary diagenesis, choosing different geochemical backgrounds has a significant influence on the geoaccumulation index (Wang et al. 2017). At the same time, the \( k \) value should be adjusted appropriately by considering that there are certain differences between the physical and chemical properties of the soil, and the later would alter the migration ability of such heavy metals (Guo et al. 2011). Therefore, when using this method to evaluate soil heavy metal pollution risk, the choice of \( k \) value should be based on local conditions. The potential ecological hazard index method is to evaluate the heavy metals in soil or sediment from the perspective of sedimentology based on the nature of heavy metals and their behavioral characteristics, such as their migration and transformation in the environment (Håkanson 1980). Although it is based on solid principles, the weighing factors and the interactions among multiple heavy metal elements are not fully understood (He et al. 2019). At the same time, the toxicity response coefficient proposed by the US Environmental Protection Agency is mainly applicable to the environmental assessment of the atmosphere (Guo et al. 2011). If it is applied to the environmental assessment of heavy metals in soil, it needs to be calibrated according to the actual situation (Guo et al. 2011). It can be based on the heavy metal elements in various environmental substances, such as rocks, freshwater, soil, terrestrial animals, and plants, for accurate calculation (Xu et al. 2008). Consequently, combining geo-accumulation index and ecological risk index can produce informative results with regard to risks associated with heavy metal pollutions, with a few caveats (He et al. 2019). USEPA Human health risk assessment method (USEPA 1998) is a quantitative risk-based health risk assessment method. It is simple to calculate, easy to use, and the output can better represent the basic level of the research area.

Currently, these methods have been broadly used to assess the contamination status and human health risk of heavy metals in soil (e.g., Ahmed et al., 2015; Chen et al. 2015; Josè et al., 2017; Do Shahab et al. 2018; Tong et al. 2020). For example, Ahmed and Abdelhafez (2015) determined that the soils of industrial areas along the Jinxing River and surrounding Lake Qingshan were contaminated with Cr, Cu, As, Se, Cd, Pb, and Zn. Calculation of the hazard index (HI) revealed that humans, especially children, have potential health risks. Moreover, As was found to contribute to greater magnitude of cancer risks than other heavy metals. Chen et al. (2015) estimated that Cd and Hg were the priority control metals due to their high concentrations in soils or high health risks posed to the public in China. José, José, and Sergi (2017) determined that the average concentrations of Cu, Ni, Pb, Cd, Hg, and Zn were 1149, 661, 0.071, 0.040, 0.159, and 1365 mg/kg, respectively, which exceeded the world normal averages, with the exception of Pb and Cd. According to geo-accumulation index, contamination factor (CF), enrichment factor (EF), and a risk assessment code (RAC) indexes, the soils show a high degree of pollution of Ni and a moderate to high contamination of Zn and Cu; whereas, Pb, Cd, and Hg present moderate pollution. Do Shahab et al. (2018) determined that the pollution levels were in the order of Ni>Cu>Cr>Zn for agricultural soils. The main exposure pathway of heavy metals to both children and adults is ingestion. And the carcinogenic risk values for Ni and Cr were higher than the safe value (1 × 10⁻⁴). Tong et al. (2020) found that Hg and Cd were at moderate contamination levels, while As, Cr, Pb, Cu, Zn, and Ni did not appear contamination. As a result, the integral urban soils ranked high contamination levels and moderate ecological risk degree, respectively. The human health risk assessments for the heavy metals indicated that Hazard index values of eight heavy metals all showed that adverse effects on human health were unlikely, and the mean carcinogenic values of As, Cr, and Ni for children and adults all suggested an acceptable carcinogenic risk to human beings. In addition, children exposed to these heavy metals faced more serious non-carcinogenic and carcinogenic health threats compared to adults, throughout 71 cities of China, based on data from online literature, during the period 2003–2019.

We used the geo-accumulation index method, the ecological risk assessment method, and the USEPA
health risk assessment model to assess the pollution status and the human health risk of heavy metals in soils of Guizhou, China. Specifically, the objectives of this study were (1) to broadly collect and holistically analyze the data on concentrations of major heavy metal elements, including Hg, As, Cu, Zn, Pb, Cr, Cd, and Ni in soils of Guizhou; (2) to assess eco-environmental pollution risks of these heavy metals in soils; and (3) to evaluate the potential risks of the heavy metals to human health.

Data sources and research methods

Data sources

Data on levels of heavy metals in soils of Guizhou Province were collected and summarized in Table 1.

All data are geographically identified at the County level, with the intention to represent the predominant areas of mining along with the post-mining transportation paths and processing across the province. Sampling areas for risk assessment of heavy metals in Guizhou are shown in.

Assessment methods

Assessment of contamination and ecological risk

Levels of soil contamination by heavy metal elements were assessed using the geo-accumulation index ($I_{geo}$) method (Sulaiman, Salawu, and Barambu 2019).

$$I_{geo} = \log_2 \left( \frac{C_i}{k_B} \right)$$

Table 1. Heavy metal concentrations in soils of Guizhou, mg/kg.

| City   | County   | Sampling time | No. of samples | Hg   | As   | Cu   | Zn   | Pb   | Cr   | Cd   | Ni   | References              |
|--------|----------|---------------|----------------|------|------|------|------|------|------|------|------|--------------------------|
| Guiyang | Baiyi    | 2016.09       | 125            | 33.53| 116.50| 55.76| 73.11| 0.45 | 45.69|      | Xiong et al. 2018        |
|        | Xiwu     | 2017.09       | 25             | 0.69 | 11.77| 51.60| 66.84| 25.20| 49.99| 0.17 | 45.69| Du et al. 2019           |
|        | Xifeng   | 2017.10       | 31             | 0.25 | 19.19| 67.50| 60.82| 0.49 |      | Deng et al. 2006         |
| Anshun  | Qianjiao  | 2015.10       | 30             | 0.12 | 1.51 | 112.79| 22.15| 19.35|      | Zhang et al. 2018        |
|        | Ninggu   | 2015.10       | 30             | 0.21 | 1.20 | 89.49| 23.84| 9.08 |      | Zhang et al. 2018        |
|        | Guanling | 2017.07       | 20             | 0.08 | 15.14|      |      | 32.24| 93.11| 1.12 | Chai et al. 2018         |
| Zunyi   | Zunyi    | 2017.07       | 29             | 0.21 | 12.88|      |      | 53.20| 55.87| 0.43 | Chen et al., 2008        |
|        | Fenggang | 2017.07       | 22             | 0.27 | 25.28|      |      | 29.33| 39.71| 0.32 | Chen et al., 2008        |
|        | Xiazhi   | 2015.08       | 19             | 0.10 | 14.09| 53.00| 101.00| 34.00| 90.00| 0.33 | 443.00| Zhang et al. 2017        |
| Liupanshui | Liupanshui | 2013       | 11             | 115.7 | 364.9 | 47.22 | 207.1 | 45.90 | Hu et al. 2014          |
| Bijie   | Weining  | 2017.07       | 72             | 25.19| 29.48| 144.75| 45.33| 93.03| 45.08|      | Zhao et al. 2018         |
|        | Zhijin   | 2013.10       | 47             | 0.76 | 12.70| 58.90| 134.22| 10.83| 33.98| 0.53 | 59.79 | Geng 2015                |
| Tongren | Gaoluping | 2016.03      | 12             | 4.29 | 117.6| 43.77| 29.13| 48.99| 59.06| 0.43 | 18.80 | Zhao et al., 2018        |
|        | Wanshan  | 2015.06       | 30             | 14.15| 14.24| 41.45| 95.30| 353.22| 0.87 | 33.58|      | Hu et al. 2015           |
|        | QNBM     | Duyun         | 279            | 0.31 | 18.50| 27.5 | 74.50| 52.80| 0.214|      | Zhang et al. 2012        |
|        | Guiding  |              | 400            | 0.26 | 12.60| 18.60| 64.90| 44.50| 0.23 |      | Zhang et al. 2012        |
|        | MMD      | Huangping     | 2016.08       | 112  | 0.26 | 8.55 | 25.10| 54.80| 0.29 |      | Zhai et al. 2018         |
|        | Jianhe   |              | 92             | 0.23 | 3.32 | 10.95| 21.18| 38.72| 0.29 |      | Zhang et al. 2016        |
|        | Majiang  |              | 18             | 0.28 | 38.00| 26.00| 97.00| 50.00| 65.00| 0.30 | 30.00 | Gou et Zhang 2019        |
| QYBM   | Wangmo   | 2017.07       | 31             | 0.05 | 9.71 |      |      | 22.26| 64.60| 0.09 | Chai et al. 2018         |

Figure 1. Sampling areas for risk assessment of heavy metals in Guizhou.
where $I_{\text{geo}}$ is a geochemical index used to evaluate pollution levels in soils or sediments and has been used since 1960s (Muller 1969; Pathak et al. 2015); $C_i$ (mg/kg) is the measured concentration of a heavy metal element in the soil; $B_i$ (mg/kg) is the background concentration of the same element in soils of Guizhou province (Background value of soil environment in China, 1990); the coefficient $k = 1.5$, which is used to detect very small anthropogenic influences (Doabi, Karami, and Afyuni 2019). The resulting values are listed in Table 2.

Ecological risk assessment of heavy metals was performed using the modified method of Håkanson (1980) (Zhao and Li 2013):

$$ADD_{\text{inhala}} = C \times \frac{\text{Inh} \times EF \times ED}{AT \times BW \times PEF} \quad \text{(2)}$$

where $I_i$ is the toxic-response factor, the values for each heavy metal are in the order of Zn(1.0)<Cr(2.0)<Cu=Pb= Ni(5.0)<As(10.0)<Cd(30.0)<Hg(40.0) (He et al. 2019); $C_i$ and $B_i$ are the same as the definition in Eq. (1); $E_i$ is the ecological risk factors for heavy metal $i$; $RI$ is the potential ecological risk index, which represents the overall ecological risk of multiple heavy metals in the soil (Håkanson 1980). The classification values of $E_i$ and $RI$ are listed in Table 2.

**Human health risk assessment method**

Human health risks can be resulted from the intake of heavy metals through ingestion, inhalation, and dermal contact (US EPA, 1998; Mirzaei et al. 2020; Kaur et al. 2020). Human health risks are classified into non-carcinogenic and carcinogenic risks (Adimalla et al., 2020). In this study, Cu, Pb, Ni, Zn, Cd, Cr, As and Hg are considered to have chronic non-carcinogenic health risks, while Ni, Cd, Cr and As are considered to have carcinogenic risks (Ferreira-Baptista and De Miguel 2005). The average daily intake of carcinogenic (adult) and non-carcinogenic (adults and children) heavy metal, caused by the three exposure pathways, was calculated as follows Eq.(3)- Eq.(5) (Fan et al. 2019):

$$ADD_{\text{ingest}} = C \times \frac{\text{Inh} \times CF \times EF \times ED}{AT \times BW} \quad \text{(3)}$$

$$ADD_{\text{inhala}} = C \times \frac{\text{Inh} \times EF \times ED}{AT \times BW \times PEF} \quad \text{(4)}$$

$$ADD_{\text{dermal}} = C \times \frac{\text{SA} \times SL \times ABS \times CF \times EF \times ED}{AT \times BW} \quad \text{(5)}$$

where $C$ is the concentration of heavy metal in soil (mg/kg); $\text{Inh}$ is the ingestion rate of soil (mg/d); $CF$ is a conversion factor (m$^3$/kg); $EF$ is the exposure frequency (d/a); $ED$ is the exposure duration (a); $AT$ is the time period over which the dose is averaged (d), and it is derived by using pathway-specific period of exposure for non-carcinogenic effects (ED × 365 days/year) and 74.8-year life-time for carcinogenic effects (74.8 years × 365 days/year) averaging time; $BW$ is the average body weight (kg); $\text{Inh}$ is the inhalation rate (m$^3$/d); $PEF$ is the particle emission factor (m$^3$/kg); $SA$ is the skin surface area (cm$^2$); $SL$ is the soil adsorption coefficient to skin (mg/cm$^2$/d); and $ABS$ is the dermal absorption factor. The values used in these equations are listed in Table 3.

The average lifetime daily intake of carcinogenic (children) heavy metal, caused by the three exposure pathways, was calculated as follows Eq.(6)- Eq.(8) (Fan et al. 2019):

**Table 2. The classification of heavy metal indexes (Muller 1969; Håkanson 1980).**

| Geo-accumulation index ($I_{\text{geo}}$) | Potential ecological risk ($E_i$) | Ecological risk index (RI) |
|-----------------------------------------|----------------------------------|---------------------------|
| Practically uncontaminated              | $E_i<40$                         | Low                       |
| 0< $I_{\text{geo}}<1$                  | $40< E_i<80$                     | Moderate                  |
| 1< $I_{\text{geo}}<2$                  | $80< E_i<160$                    | Considerable              |
| 2< $I_{\text{geo}}<3$                  | $160< E_i<320$                   | High                      |
| 3< $I_{\text{geo}}<4$                  | $E_i \geq 320$                   | Very high                 |
| 4< $I_{\text{geo}}<5$                  |                                  |                           |
| 5< $I_{\text{geo}}$                    |                                  |                           |

**Table 3. Health risk parameters for heavy metals in soil (HJ 25.3–2014., 2014; Ministry of Environmental Protection., 2013(a, b), 2016; Li et al. (2018); Fan et al. (2019); Cao et al. (2020)).**

| Exposure pathway | Parameter | Age | CF | EF | ED | AT | Carcinogenic | Non-carcinogenic | BW | PEF | Ing | Inh | SA | SL | ABS |
|------------------|-----------|-----|----|----|----|----|--------------|-----------------|-----|-----|-----|-----|----|----|-----|
| Ingestion        | Child     | 0–5 | 10$^{-6}$ | 350 | 6  | 74.8 × 365 | ED ×365 | 6.4 | 1.36 × 10$^9$ | 73  |      |    |    |    |
|                   | Adult     | 6–17 | 10$^{-6}$ | 350 | 6  | 74.8 × 365 | ED ×365 | 26.5 | 1.36 × 10$^9$ | 103 |      |    |    |    |
|                   |           | 18–75 | 10$^{-6}$ | 350 | 6  | 74.8 × 365 | ED ×365 | 60.6 | 1.36 × 10$^9$ | 100 |      |    |    |    |
| Inhalation        | Child     | 0–5  | 10$^{-6}$ | 350 | 6  | 74.8 × 365 | ED ×365 | 6.4 | 1.36 × 10$^9$ | 3.7 |      |    |    |    |
|                   | Adult     | 6–17 | 10$^{-6}$ | 350 | 6  | 74.8 × 365 | ED ×365 | 26.5 | 1.36 × 10$^9$ | 10.1|      |    |    |    |
|                   |           | 18–75 | 10$^{-6}$ | 350 | 6  | 74.8 × 365 | ED ×365 | 60.6 | 1.36 × 10$^9$ | 15.7|      |    |    |    |
| Dermal            | Child     | 0–5  | 10$^{-6}$ | 350 | 6  | 74.8 × 365 | ED ×365 | 6.4 | 1.36 × 10$^9$ | 1224| 0.2 | 10$^{-3}$ |    |    |
|                   | Adult     | 6–17 | 10$^{-6}$ | 350 | 6  | 74.8 × 365 | ED ×365 | 26.5 | 1.36 × 10$^9$ | 3564| 0.2 | 10$^{-3}$ |    |    |
|                   |           | 18–75 | 10$^{-6}$ | 350 | 6  | 74.8 × 365 | ED ×365 | 60.6 | 1.36 × 10$^9$ | 5120| 0.07| 10$^{-3}$ |    |    |


\[ LADD_{\text{ingest}} = \frac{C \times CF \times EF}{AT} \times \left( \frac{\ln_{\text{child}} \times ED_{\text{child}}}{BW_{\text{child}}} + \frac{\ln_{\text{adult}} \times ED_{\text{adult}}}{BW_{\text{adult}}} \right) \]  

(6)

\[ LADD_{\text{inha}} = \frac{C \times EF}{AT} \times \left( \frac{\ln_{\text{child}} \times ED_{\text{child}}}{BW_{\text{child}}} + \frac{\ln_{\text{adult}} \times ED_{\text{adult}}}{BW_{\text{adult}}} \right) \]  

(7)

\[ LADD_{\text{dermal}} = \frac{C \times CF \times EF \times SL \times ABS}{AT} \times \left( \frac{SA_{\text{child}} \times ED_{\text{child}}}{BW_{\text{child}}} + \frac{SA_{\text{adult}} \times ED_{\text{adult}}}{BW_{\text{adult}}} \right) \]  

(8)

where \( C, CF, EF, AT, \ln_{\text{ing}}, ED, BW, PEF, SL, ABS, \) and \( SA \) are the same as the definitions in Eq.(3)-Eq.(5).

The assessment of carcinogenic risk was conducted using the following formula (Cui et al. 2018; Fan et al. 2019; Md et al. 2020):

\[ CR = ADD \times SF \]  

(9)

The assessment of non-carcinogenic risk was performed using the following formula (Cui et al. 2018; Fan et al. 2019; Md et al. 2020):

\[ HQ = \frac{ADD}{RFD} \]  

(10)

where \( ADD \) is the average daily intake (mg/(kg-day)); \( SF \) (dimensionless) is the carcinogenic slope factor (per mg/kg-day); \( CR \) is the carcinogenic risk index (Li et al. 2018); \( RFD \) is the reference does of (mg/kg-day) (Table 4); and \( HQ \) is the non-carcinogenic risk index (Li et al. 2018).

**Results and discussion**

**Heavy metal concentration in soils**

Heavy metal concentrations in Guizhou soils are shown in Table 5. Compared to the reference background values for Guizhou Province (China National Environmental Monitoring Centre 1990), the average concentrations of Hg, As, Cu, Zn, Cd, and Ni were in the order of 13.91, 1.05, 1.59, 1.32, 2.94, and 2.31 folds, respectively. This is likely related to the direct emissions generated during the mining and post-mining processing (Zhan et al. 2017). Compared to risk screening values of Soil Environmental Quality Risk Control Standard for Soil Contamination of Agricultural Land (GB 15618–2018 (2018)), Cd was significantly higher, 6.47 times, than the risk screening value. The other seven elements were lower than their respective risk screening values. However, all eight heavy metal elements were lower than the risk intervention values (GB

| Element | Ingestion | Inhalation | Dermal |
|---------|-----------|------------|--------|
| Hg      | 3.00 × 10^{-4} | 8.57 × 10^{-5} | 2.10 × 10^{-3} |
| As      | 3.00 × 10^{-4} | 3.00 × 10^{-4} | 1.23 × 10^{-4} |
| Cu      | 4.00 × 10^{-3} | 4.02 × 10^{-3} | 1.20 × 10^{-2} |
| Zn      | 3.00 × 10^{-3} | 3.00 × 10^{-3} | 6.00 × 10^{-2} |
| Pb      | 3.50 × 10^{-3} | 3.52 × 10^{-3} | 5.25 × 10^{-4} |
| Cr      | 3.00 × 10^{-3} | 2.86 × 10^{-3} | 6.00 × 10^{-5} |
| Cd      | 1.00 × 10^{-3} | 1.00 × 10^{-3} | 1.00 × 10^{-5} |
| Ni      | 2.00 × 10^{-3} | 2.06 × 10^{-3} | 5.40 × 10^{-3} |

| Background values (mg/kg) | Ingestion | Inhalation | Dermal |
|---------------------------|-----------|------------|--------|
| 0.11                      | 20        | 32         | 99.50  |
| 0.05                      | 10.95     | 29.13      | 10.83  |
| 1.50                      | 15.1      | 3.66       |        |

**Table 4. RFD and SFH of heavy metals in soils with different exposures (Li et al. 2018; Fan et al. 2019; Cao et al. 2020).**

| Reference areas | Hg | As | Cu | Zn | Pb | Cr | Cd | Ni | Reference |
|-----------------|----|----|----|----|----|----|----|----|-----------|
| Chongqing, China| 1.18 | 18.8 | 36.3 | 112.6 | 41.8 | 82.3 | 0.59 | 36.1 | Bao et al. 2020 |
| Shenzhen, China | 12.59 | 73.14 | 211.49 | 83.47 | 40.39 | 0.59 | 17.03 | Chang et al. 2019 |
| Shanxi, China   | 0.067 | 7.75 | 9.68 | 57.1 | 0.15 | 5.35 | 0.22 | 8.13 | Meng et al. 1997 |
| Inner Mongolia, China | 32.48 | 107.17 | 12.31 | 53.35 | 0.22 | 7.13 | 0.14 | 53.07 | Zhu et al. 2020 |
| Dhaka, Bangladesh | 39.14 | 115.43 | 49.71 | 53.70 | 11.42 | 58.16 | Jasm and Md 2010 |
| Mediterranean, Greece | 7.1 | 65.23 | 72.15 | 20.1 | 72.3 | 0.45 | 120.3 | Keleperitzis 2014 |
| Mojo, Ethiopia   | 24.50 | 25.96 | 98.86 | 37.93 | 36.23 | 5.30 | 35.58 | Gebeeyehu, Bayissa, and Bhatnagar 2020 |

*Local soil background values (China National Environmental Monitoring Centre 1990)  
GB 15618–2018  
This paper
A pollutant concentration falling into the range between the risk screening value and the risk intervention value is interpreted as that there is a risk that the edible agricultural products do not meet the agricultural product quality and safety standards. The risk is determined by taking both the quality of the agricultural products and the monitoring results into consideration. It is thus suggested that a vigilant Cd monitoring program for food crops of Guizhou is desirable.

Compared with other cities in China and other countries in the world, the concentrations of most metals in Guizhou were higher than those in Chongqing, Shenzhen, Shanxi, Inner Mongolia, Dhaka (Bangladesh), Mediterranean (Greece), and Mojo (Ethiopia) (Bao et al. 2020; Chang et al. 2019; Meng et al. 2019; Zhu et al. 2020; Jasim and Md 2010; Kelepertzis 2014; Gebeyehu and Bayissa 2020 (Table 5)). Moreover, the concentrations of Zn and Pb were lower than those in Shenzhen, Dhaka (Bangladesh) (Chang et al. 2019; Jasim and Md 2010), while the concentrations of Hg, Cu, Zn, Pb, Cr, and Ni were higher than those in Shanxi, Inner Mongolia, Mediterranean (Greece), and Mojo (Ethiopia) (Meng et al. 2019; Zhu et al. 2020; Kelepertzis 2014; Gebeyehu, Bayissa, and Bhatnagar 2020).

The non-dimensionalized coefficient of variation (CV) can reflect the fluctuation of heavy metal content. Larger CV values suggest higher in dispersion and less uniform spatial distribution of the element (Li et al. 2018). According to the criterion suggested by Phil-Eze (2010), there were small variations for Ni with a CV value of 3.83% (i.e., <20%); moderate variations for Pb with a CV value of 45.03% ranging from 20% to 50%, and large variations for Hg, As, Cu, Zn, Cr, and Cd, with CV values of 226.14%, 121.74%, 65.13%, 76.77%, 91.02%, and 247.94% (i.e., >50%), respectively. The high CV values indicate that Hg, As, Cu, Zn, Cr, and Cd had wide concentration ranges. This was resulted from local mining activities, industrial activities, and traffic flow (Ran et al. 2016). For example, in the long-term mercury mining process, waste residues, waste gas, and wastewater containing mercury element were almost directly discharged into the natural environment. This would have led to the accumulation of Hg in the soils, with a gradual decline in concentration when leaving the mining spot (Hu et al. 2015; Zhai et al. 2018). Similar to Hg, spatial variation in concentrations of the accompanying elements, As, Cu, Zn, Cr, and Cd, are often found. In addition, automobile circulation also releases certain heavy metal elements such as As, Cu, Zn, Cr, and Cd into the environment (Foti et al. 2017), which leads to the accumulation of heavy metals in the surrounding soil environment.

**Pollution assessment**

The $I_{geo}$ index values for eight heavy metals in soils of Guizhou are shown in Figure 2(a). The enrichment levels were in the order Hg>Ni(Cu)>Pb>Zn>Cr>Cd>As. Averaged $I_{geo}$ index values for As, Cu, Zn, Pb, Cr, Cd, and Ni were less than zero, suggesting that there had not been widespread pollution in soils of Guizhou with these elements. The average value of $I_{geo}$ index for Hg, 1.21, was within the range between 1 and 2, which is generally considered moderate to heavy pollution. There are no supervises with this. There are a large number of mercury mines in Guizhou, with the Wanshan mercury mine once known as the “Mercury Capital” of China, ranked first in Asia and third in the world. The site had been mined for mercury for more than 600 years by the time when it was closed in 2002 (Hu et al. 2015; Zhai et al. 2018). It was estimated that the Wanshan mercury mine generated 20.24 billion m$^3$ of mercury-containing waste gas, 5.192 million m$^3$ of mercury-containing wastewater, and 4.26 million m$^3$ of mercury-containing waste residue into the environment (Yin et al. 2014).

The $E_{i}$ index values are shown in Figure 2(b). The average $E_{i}$ values were in the order of $Hg>Cd>Ni>As>Cu>Cr>Pb>Zn$. Average $E_{i}$ index values for As, Cu, Zn, Pb, Cr, and Ni were less than 40. According to the criteria listed in Table 2, the $E_{i}$ index values presented suggest there were low potential

![](image.png)

**Figure 2.** $I_{geo}$ (a) and $E_{i}$ (b) of heavy metals in soils of Guizhou.
ecological risks posed by these elements in Guizhou soils. The average $E_i$ index value for Cd, 88.34, was within the range of 80–160, indicating considerable potential ecological risk. The average $E_i$ index value for Hg, 555.35, was higher than 320, representing very high potential ecological risk. The higher $E_i$ index values for Cd and Hg were mainly due to higher toxicity values assigned, Cd ($T_1 = 30$) and Hg ($T_1 = 40$), despite the negative $I_{geo}$ index value for Cd and a modest $I_{geo}$ index value for Hg (Table 2). The integrated index RI was 678.45, suggesting a very high ecological risk (>600) according to the criteria listed in Table 2. Hg accounted for 81.86% and played predominant roles contributing to RI.

The $I_{geo}$ and $E_i$ values of the eight heavy metal elements did not follow the same order. For example, Cd was assessed to be a lower-risk contaminant with $I_{geo}$, but $E_i$ assessment indicated a higher risk. Pb was assessed to be a higher-risk contaminant by $I_{geo}$, but a lower risk with $E_i$ assessment. This was resulted from the differences in toxicity values assigned to each element (Kusin et al. 2016; Diami et al. 2016; Zhuang et al. 2018). For example, Men et al. (2018) found that Cu was assessed to be a high-risk contaminant with $I_{geo}$, but a low risk with $E_i$. And Hg was considered a low-risk contaminant, but indicated moderate to considerable risks in road dust in Beijing due to the differences in toxicities of heavy metals. He et al. (2019) estimated that Cd was assessed to be a lower risk with $E_i$ assessment, but fell into the category of practically uncontaminated by $I_{geo}$, because of the differences in toxicities of heavy metals. All these results indicated that toxicity coefficient is one of the important factors affecting $E_i$ values.

Both $I_{geo}$ and $E_i$ of Hg were the highest among all eight elements assessed. Consequently, judged from either the content and the degree of contamination discussed previously or the potential ecological hazards of toxicity, Hg appears clearly a predominant pollutant to the soils of Guizhou. Necessary measures must be adopted for efficient remediation to safeguard food production safety and human health.

**Health risk assessment**

**Exposure dose analysis**

As shown in Table 6, regardless of age, the non-carcinogenic average daily exposure doses through three commonly identified pathways followed the order of ingestion > dermal > inhalation, consistent with the findings of Fan (2019). Heavy metals enter into the human body primarily through ingestion. Rigorous washing can thus go a long way in reducing risks posed by heavy metal pollution in soils. The exposure doses in human body followed the order of 0–5 years old > 6–17 years old > 18–85 years old for each of the three exposure pathways (Table 6). This means that the exposure doses decrease with age. This is due to 1) the lower body weight and weaker immune system of children compared to adults, and 2) the fact that children have higher intake rate of pollutants than adults (Schachter et al., 2020). This explains the fact that children are more sensitive to pollutants than adults, even if all live in the same environment. The average daily exposure doses of soil heavy metals followed the order: Zn>Ni>Cr>Cu>Pb>As>Cd>Hg (Table 6). However, this needs to be validated with biological studies.

**Health risk analysis**

Due to the high toxicity of heavy metals, their accumulation in the human body can not only cause damage to the nervous system (Chang et al. 2015), but also damage the accumulated organs or cells, and even cause cancer (Cai et al. 2014). Therefore, a study on human health risk assessment of heavy metals has a great significance to the public. According to USEPA (1998), USEPA. (2001), the HQ had a threshold of 1 in three exposure pathways. If HQ<1, there is a small or negligible risk; if HQ>1, there is a non-carcinogenic risk. We calculated human health risk index for children and adults under the three exposure pathways according to the exposure doses in Table 6 using the formulas (9) and (10). HQ was less than 1 (Table 7), suggesting that heavy metal elements in soils of Guizhou pose no or little non-carcinogenic health risk for humans. Compared with adults, the HQ and CR for children were significantly higher than those for adults. Similar trends were reported by other scholars (Chabukdhara et al. 2017; Xiao et al. 2017).

In the case of the ingestion pathway, the HQ for children was in the order of Pb>As>Hg>Cr>Cu>Ni>Zn>Cd; and the HQ for adults was in the order of As>Pb>Cr>Hg>Ni>Cu>Cd>Zn. Regarding to the

| Table 6. Children and adult exposure of soil heavy metals in three pathways in Guizhou. |
| --- |
| **Ingestion** | **Inhalation** | **Dermal** |
| **Child** | **Adult** | **Child** | **Adult** | **Child** | **Adult** |
| 0–5 | 6–17 | 18–75 | 0–5 | 6–17 | 18–75 | 0–5 | 6–17 | 18–75 |
| **Element** | Years old | Years old | Years old | Years old | Years old | Years old | Years old | Years old | Years old |
| Hg | 1.67E-05 | 5.70E-06 | 2.42E-06 | 6.24E-10 | 4.11E-10 | 2.64E-10 | 5.61E-08 | 3.95E-08 | 8.68E-09 |
| As | 2.29E-04 | 7.80E-05 | 3.31E-05 | 8.53E-09 | 5.62E-09 | 3.82E-09 | 7.68E-07 | 5.40E-07 | 1.19E-07 |
| Cu | 5.57E-04 | 1.90E-04 | 8.06E-05 | 2.08E-08 | 1.37E-08 | 8.77E-09 | 1.87E-06 | 1.31E-06 | 2.89E-07 |
| Zn | 1.44E-03 | 4.91E-04 | 2.09E-04 | 5.37E-08 | 3.54E-08 | 2.27E-08 | 4.83E-06 | 3.40E-06 | 7.47E-07 |
| Pb | 4.45E-04 | 1.51E-04 | 6.43E-05 | 1.66E-08 | 1.09E-08 | 7.00E-09 | 1.49E-06 | 1.05E-06 | 2.30E-07 |
| Cr | 9.29E-04 | 3.17E-04 | 1.34E-04 | 3.46E-08 | 2.28E-08 | 1.55E-08 | 3.12E-06 | 2.19E-06 | 4.82E-07 |
| Cd | 2.12E-05 | 7.23E-06 | 3.07E-06 | 7.91E-10 | 5.21E-10 | 3.54E-10 | 7.12E-08 | 5.00E-08 | 1.10E-08 |
| Ni | 9.87E-04 | 3.36E-04 | 1.43E-04 | 3.68E-08 | 2.42E-08 | 1.65E-08 | 3.31E-06 | 2.33E-06 | 5.12E-07 |
inhalation pathway, the HQ for children was in the order of \( \text{Cr} > \text{As} > \text{Pb} > \text{Ni} > \text{Cu} > \text{Cd} > \text{Zn} \), and the HQ for adults was in the order of \( \text{Cr} > \text{As} > \text{Hg} > \text{Pb} > \text{Ni} > \text{Cu} > \text{Cd} > \text{Zn} \). For the dermal pathway, the HQ for both children and adults was in the order of \( \text{Cr} > \text{Pb} > \text{Hg} > \text{Cd} > \text{As} > \text{Ni} > \text{Cu} > \text{Zn} \). HQ of different elements was in the order of ingestion >dermal >inhalation. This indicates that ingestion was the most important pathway that soil-born heavy metals takes to enter the human body for both children and adults. Risks through ingestion and dermal contacts were higher than inhalation, and the risk to children was higher than adults. Similar trends were reported by Xiao et al. (2017) and Kaur et al. (2018) and (2020). It is reasonable to conclude that the higher ingestion rate of soil and lower body weight of children were the two reasons for the higher values of risks through ingestion and dermal contact (Chen et al. 2016). Encouraging proper hygienic habits can be effective in helping to reduce the ingestion rate and protect children from health risks.

Because of lack of the carcinogenic slope factors for Hg, Cu, Zn, and Pb, only the carcinogenic risks for As, Cr, Cd, and Ni were estimated (Sah et al. 2017). According to Fryer et al. (2006), risks surpassing \( 1 \times 10^{-4} \) are viewed as unacceptable, whereas risks below \( 1 \times 10^{-6} \) are not considered to pose significant health effects, and risks lying in the range of \( 10^{-6} \sim 10^{-4} \) are generally regarded as tolerable to some degree. As shown in Table 7, the CR values for children were higher than adults. For both children and adults, the CR values followed the order of \( \text{As} > \text{Cr} > \text{Ni} > \text{Cd} \). Of the four heavy metals, Cr, Ni, and Cd were less than \( 10^{-6} \). But the CR of As for children and adults was \( 5.37 \times 10^{-5} \) and \( 1.61 \times 10^{-5} \), respectively, which were between \( 10^{-5} \sim 10^{-4} \). Thus, there was a large carcinogenic risk of As in Guizhou soils. The result clearly suggests that As was the most important risk factor causing cancer for human beings in the study area.

It is important to note that human health risk of heavy metals can vary depending on their bioavailability, which can differ with soil type and environmental factors, such as precipitation. Chemical behaviors of heavy metals in soils, as well as further in eco-systems, must be taken into consideration to precisely evaluate their risks for various age groups.

### Conclusions

Guizhou is one of the major producers of China’s mineral resources. Mining of minerals has led to serious environmental pollution. Except for Pb and Cr, the other six heavy metals were elevated in the soils in Guizhou, with the average concentration of Hg being 13.91 times of the background value. The results of \( I_{GES} \) showed that the pollution levels ranged from no pollution (As, Cu, Zn, Pb, Cr, Cd, and Ni) to moderate contamination (Hg). While most heavy metals posed low potential ecological risk, Cd and Hg presented considerable or very high potential ecological risk. In general, the integrated potential ecological risk of the eight heavy metals was very high, with Hg accounting for 81.86%. The non-carcinogenic risks associated with the eight heavy metals were neglectable, but the carcinogenic risk caused by As was significant. Heavy metals posed greater stress to children than to adults for both non-carcinogenic and carcinogenic risks. It needs to point out that the details on the spatial distribution of heavy metal risks across the province are not available using the approach adopted in the current study, which, however, is needed to pinpoint the remediation practices in a mostly efficient manner. In addition, future research needs to explore the chemical behaviors of Hg and As in soils of the study region, based on which beneficial management practices can be developed for effective remediation.

### Highlights

- Risk assessment of eight heavy metals was systematically studied in soils of Guizhou, China.
- Pollution levels were ranked from none (As, Cu, Zn, Pb, Cr, Cd, and Ni) to moderate (Hg).
- Eight heavy metals posed a very high ecological risk.
- Human carcinogenic risk caused by As was significant.

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Decloration of conflict interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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