




# Ecological security and health risk assessment of soil heavy metals on a village-level scale, based on different land use types

Shiqi Tian · Shijie Wang · Xiaoyong Bai  · Dequan Zhou · Guangjie Luo · Yujie Yang · Zeyin Hu · Chaojun Li · Yuanhong Deng · Qian Lu

Received: 27 September 2019 / Accepted: 17 April 2020 / Published online: 27 April 2020  
© Springer Nature B.V. 2020

**Abstract** Land use affects the accumulation of heavy metals in soil, which will endanger ecological safety and human health. Taking the village as an administrative unit, the ecological safety and health risks of heavy metals, namely, Cr, Cu, Zn, and Pb in soils in the Houzhai River Watershed of Guizhou Province, China, were evaluated based on land use types by the Hakanson potential ecological risk methods and human health risk model. Results showed that the spatial heterogeneity of Cu and Zn was greatly

affected by primary structural factors, and Cr and Pb were interfered by both structural factors and human activities. The geo-accumulation index of the heavy metals showed a light pollution in the study area. The comprehensive potential ecological risk of heavy metal in the area was divided into three levels: slight, moderate, and intense, and it is spatially high in the northwest and low in the southeast. Both non-carcinogenic risk and carcinogenic risk of the heavy metals to the human body are not significant and are

---

S. Tian · S. Wang · X. Bai (✉) · Y. Yang · Z. Hu · C. Li · Y. Deng · Q. Lu  
State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, Guizhou Province, China  
e-mail: baixiaoyong@vip.skleg.cn

S. Tian · D. Zhou · Y. Yang · C. Li  
School of Geography and Environmental Sciences, Guizhou Normal University, Guiyang 550001, China

S. Tian · S. Wang · Y. Yang · Z. Hu · C. Li · Y. Deng · Q. Lu  
Puding Karst Ecosystem Observation and Research Station, Chinese Academy of Sciences, Puding 562100, Guizhou Province, China

X. Bai  
CAS Center for Excellence in Quaternary Science and Global Change, Xi'an 710061, Shanxi Province, China

X. Bai · G. Luo  
Guizhou Provincial Key Laboratory of Geographic State Monitoring of Watershed, Guizhou Education University, Guiyang 550018, China

acceptable. The risks of children are higher than adults, and direct intake is the primary route of exposure in the area. The potential ecological risk and human health risk of soil heavy metals are relatively obviously affected by digital elevation data and normalized vegetation index. The study has certain reference value for the prevention and control of regional soil heavy metal risk.

**Keywords** Land use · Soil heavy metals · Ecological security · Health risk

## Introduction

Heavy metal pollution in soil has been widely recognized as a very serious environmental problem. The accumulation of excessive heavy metals in the soil may lead to a decline in soil quality and ultimately to the ecological safety of the affected areas. Studies have shown that excessive intake of heavy metals in the human body can cause neurological diseases, cardiovascular diseases, chronic kidney diseases, tumors, and even cancers (Khlifi and Hamza-Chaffai 2010; Yao 2011; Alissa and Ferns 2011; Kim et al. 2015; Wang et al. 2014). Heavy metals accumulated in the soil may enter the human body through different exposure routes, causing incalculable harm to human health. Therefore, it is important to assess the ecological and health risks of heavy metals in the region.

Many scholars have studied the ecological safety pattern and health risks of soil heavy metals and laid a solid foundation for soil remediation and pollution prevention measures. However, most of the relevant research focuses on the national (Li et al. 2014; Chen et al. 2015; Li et al. 2016; Gu and Gao 2017), regional (Olawoyin et al. 2012; Zong et al. 2017), provincial (Man et al. 2010; Pan and Pan 2015), municipal (Zhong et al. 2007; Chen et al. 2010; Luo et al. 2012), and county (Liu et al. 2008a, b; Liu et al. 2008b) scales. Research at the village scale is relatively limited.

Rural areas represent the main location for agricultural production activities. Excessive accumulation of heavy metals in the countryside directly affects the food security pattern, ecosystem, and human health. Therefore, research on heavy metals in rural soils is crucial. Many studies have confirmed that soil heavy metal accumulation can be inextricably linked to land

use patterns (Bai et al. 2010; Li et al. 2015; Zheng et al. 2016; Tian et al. 2019). Some scholars have carried out research on the accumulation characteristics of soil heavy metals at the village scale (F. Liu et al. 2015; Yang et al. 2016), but they do not consider the possible risk of soil heavy metal accumulation from the perspective of land use type. Other scholars have analyzed the risk of heavy metals in soil based on land use patterns, but most reports focus on single land use types, such as industrial areas (Jiao et al. 2015), mining areas (Cai et al. 2014; Zhang et al. 2014), and agricultural land (Wu et al. 2016; Mamattursun et al. 2017). Few risk studies on the combined effects of land use types have been published. Commonly used ecological safety and health risk assessment methods include Hakanson potential ecological risk assessment method (Hakanson 1980) and the human health exposure risk assessment model (US EPA 1996). Although these two models are very mature, many studies often overlook differences in the types of heavy metals studied, the geographical background of the study area, and the complexity of social development levels; hence, the model may not be applicable. In addition, the relevant parameters, indicators, and grading standards have not been adjusted and improved, leading to biased evaluation results and difficulties in objectively analyzing actual research.

This paper takes a typical karst watershed, the Houzhai River, as the research area and the village as the administrative unit. The ecological safety patterns and health risks of four heavy metals, namely Cr, Cu, Zn, and Pb, in soil are studied based on four different land use types, namely, cropland, forestland, grassland, and construction land. First, geo-accumulation indices ( $I_{geo}$ ) are used to analyze the characteristics of soil heavy metal pollution in the study area. Second, Hakanson potential ecological risk indices are used to evaluate the ecological safety pattern of heavy metals, and the potential ecological risk is classified according to the actual research. Finally, the USEPA health risk assessment model and common research practices are combined to assess the effect of heavy metals on the health of children and adults. This work aims to provide decision support for the formulation of soil remediation strategies and rational use and management of land resources. The results play an important role in promoting the construction of ecological civilization and practicing rural revitalization.

## Materials and methods

### Study area and data source

The Houzhai River Watershed is a typical karst watershed that located in Puding County, Guizhou Province, China, and has a total area of about 75 km<sup>2</sup>. The climate of the area is subtropical monsoon, and its average annual temperature and rainfall are 15.1 °C and 1378.2 mm, respectively. Land use types here include cropland, forestland, grassland, construction land, and water bodies. The cropland is mainly composed of paddy fields and dry land. The forestland is mainly composed of shrubland, forestland, and sparse forestland. The grassland is mainly composed of medium- and low-coverage grassland. Finally, the construction land mainly includes rural residential areas and other construction lands.

A total of 100 top soil samples were collected from different land use types in the study area, including 60 cropland, 20 forestland, 17 grassland, and 3 construction land samples (Fig. 1).

### Determination and analysis of soil heavy metal content

Each soil sample was pretreated by natural air drying, impurity removal, grinding, sieving, and microwave

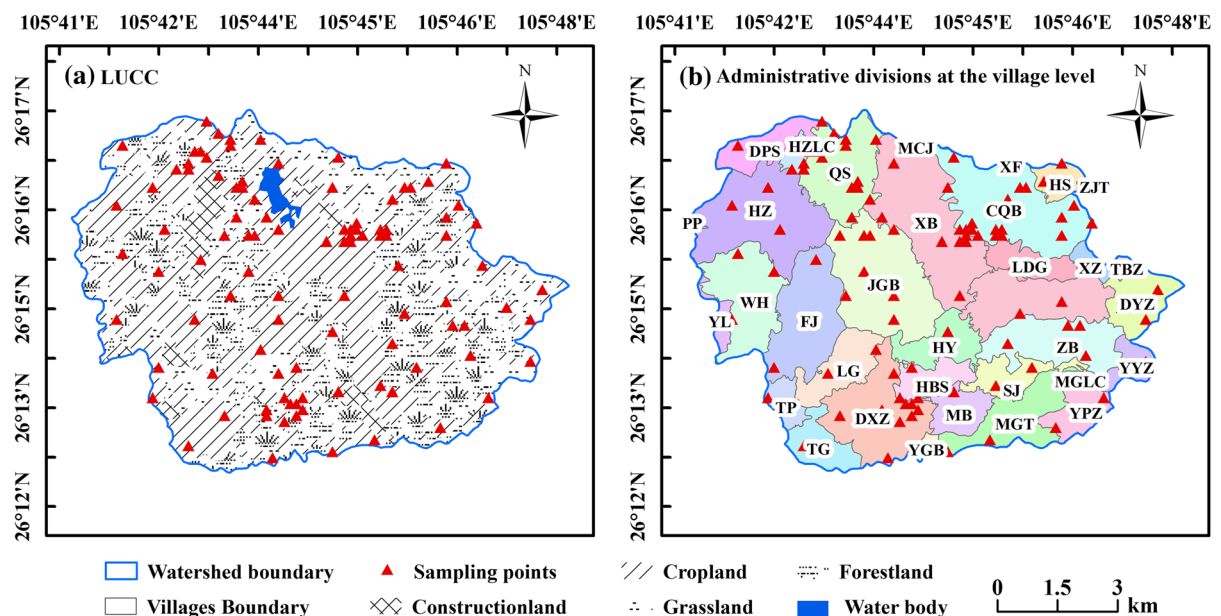
digestion. The contents of Cr, Cu, Zn, and Pb were determined by four-pole inductively coupled plasma mass spectrometry (Q-ICP-MS, PerkinElmer, Canada). To ensure the quality of the analysis, quality control was carried out using the national standard GSB04-1767–2004.

Descriptive statistical analysis of soil heavy metal content, including anomaly value, maximum value, average value, standard deviation, and coefficient of variation (CV), was completed in SPSS19.0 software. The semi-variogram function model used for spatially differentiated structure analysis was built based on the geo-statistical module of the ArcGIS platform.

### Geo-accumulation index

$I_{geo}$  is often used for environmental pollution assessments, mainly to evaluate trace metal contamination in sediments (Hasan et al. 2013; Al-Haidarey et al. 2010). Because this method considers not only the influence of human activities and soil natural background values but also the variation of background values that may be caused by rock differences, it has been widely used in soil pollution evaluation in recent years (Wei et al. 2011; Ma et al. 2014). It can be calculated as follows:

$$I_{geo} = \log_2 \left( \frac{c_n}{K \cdot B_n} \right) \tag{1}$$



**Fig. 1** Study area and the distribution of sampling points

where  $B_n$  is the background value of the element. This paper refers to the background value of soil element in the A layer of Guizhou Province (Center 1990).  $C_n$  is the heavy metal content measured in the laboratory.  $K$  is a variation conversion factor (usually taken as 1.5) that eliminates variations in background values that may be caused by rock differences. The degree and classification of metal contamination in the soil in this study are shown in Table 4.

#### Hakanson potential ecological risk assessment method

The Hakanson potential ecological risk assessment method was used to evaluate the single-factor and comprehensive potential ecological risk of heavy metals in the study area. It is calculated as follows:

$$E_i^j = T_i \times P_i^j = T_i \times \frac{C_i}{B_i} \quad (2)$$

$$RI_j = \sum_{i=1}^n E_i^j \quad (3)$$

where  $E_i^j$  is the single-factor potential ecological risk index of heavy metal  $i$  at sampling point  $j$ ;  $T_i$  is the toxicity response coefficient of heavy metals, the value of which can be referred from Hakanson's research;  $P_i^j$  is the single-factor pollution index of heavy metal  $i$  at sampling point  $j$ ;  $C_i$  is the background value of the element;  $B_i$  is the measured value of the element; and  $RI_j$  is the comprehensive ecological risk of heavy metals. While Hakanson studied the ecological risk of eight heavy metal elements, only four are studied in this paper. Using Hakanson's ecological risk grading may lead to research that is inconsistent with the actual situation. Therefore, previous studies (Fernandez and Carballeira 2001; Ma et al. 2011) must be combined to re-classify the potential ecological risks according to the actual situation. The grading of this paper is as follows: The first-level threshold of single-factor ecological risk grading is 5, and the first-level threshold of comprehensive ecological risk grading is 15, that is,  $E_i < 5$ ,  $RI_j < 15$ . The threshold value of the second level is twice the first level,  $5 \leq E_i < 10$ ,  $15 \leq RI_j < 30$ . By analogy, risk can be divided into five levels: slight, moderate, intense, very intense, and extremely intense.

#### Human health risk assessment model

The human body is exposed to heavy metals through direct intake, nose and mouth inhalation, and skin contact. Therefore, this paper calculates the exposure risk of these three pathways. Thus, the USEPA proposed health risk assessment model, the Guizhou Provincial National Fitness Monitoring Bulletin (Sport 2011), "Technical guidelines for risk assessment of contaminated sites" (MEPPRC 2014), and related research (Huang et al. 2016; Li et al. 2018) are combined, and the non-carcinogenic and carcinogenic human health risks of children and adults are evaluated separately. The calculation formulas are as follows:

##### (1) Exposure through different pathways:

Direct intake:

$$ADD_{ing} = \frac{C_i \times R_{ing} \times EF \times ED \times CF}{BW \times AT} \quad (4)$$

Nose and mouth inhalation:

$$ADD_{inh} = \frac{C_i \times R_{inh} \times EF \times ED}{PEF \times BW \times AT} \quad (5)$$

Skin contact:

$$ADD_{dermal} = \frac{C_i \times SA \times AF \times ABS \times EF \times ED \times CF}{BW \times AT} \quad (6)$$

where  $ADD_{ing}$ ,  $ADD_{inh}$ , and  $ADD_{dermal}$  are the daily average exposures of heavy metals in the soil under direct exposure, nose and mouth inhalation, and skin exposure, respectively.  $C_i$  is the measured content of heavy metals, and the remaining indicators and their related descriptions are shown in Table 1.

##### (2) Human health risk index:

Non-cancer risk index calculation:

$$HI = \sum_{i=1}^n HQ_i = \sum_{i=1, j=1}^n \frac{ADD_{ij}}{RfD_{ij}} \quad (7)$$

Carcinogenic risk index calculation:

$$TCR = \sum_{i=1}^n CR_i = \sum_{i=1, j=1}^n ADD_{ij} \times SF_{ij} \quad (8)$$

where HI is the total non-carcinogenic risk index for four heavy metals,  $HQ_i$  is the single risk index for heavy metals  $i$ ,  $ADD_{ij}$  is the daily average exposure of

**Table 1** Parameters related to soil heavy metal health risks

Parameters	Description	Adults	Child	References
$R_{ing}$ (mg/day)	Intake rate	100	200	MEPPRC (2014), US EPA (1996)
$R_{inh}$ (m <sup>3</sup> /day)	Nose and mouth inhalation	14.5	7.5	US EPA (1996), MEPPRC (2014)
EF (day/a)	Exposure frequency	365	365	Li et al. (2016)
ED (a)	Exposure period	24	6	US EPA (1996)
BW (kg)	body weight	57.9	23.97	Sport (2011)
AT-non-carcinogenic (days)	Total time of non-cancer risk exposure	24 × 365	6 × 365	US EPA (1996)
AT- carcinogenic (days)	Total time of cancer risk exposure	70 × 365	70 × 365	MEPPRC (2014)
PEF (m <sup>3</sup> /kg)	Particle emission factor	1.36E + 09	1.36E + 09	MEPPRC (2014)
SA (cm <sup>2</sup> )	Exposure of total skin area	5075	2448	MEPPRC (2014), US EPA (1996)
AF (mg/m <sup>2</sup> *day)	Skin adhesion factor	0.2	0.07	US EPA (1996)
ABS (dimensionless)	Skin absorption factor	0.001	0.001	MEPPRC (2014)
CF (dimensionless)	Conversion factor	10 <sup>-6</sup>	10 <sup>-6</sup>	Huang et al. (2016)

heavy metals  $i$  under the  $j$  exposure pathway,  $RfD_{ij}$  is the reference dose for heavy metals  $i$  under the  $j$  exposure pathway, TCR is the total carcinogenic risk index of the four heavy metals,  $CR_i$  is the single carcinogenic risk index of heavy metal  $i$ , and  $SF_{ij}$  is the carcinogenic risk slope coefficient of heavy metal  $i$  under the  $j$  exposure pathway. The values of  $RfD_{ij}$  and  $SF_{ij}$  may be referred from the study by Jiang et al. (2015).

When  $HI < 1$ , heavy metals have no significant effect on the non-carcinogenic risk of the human body. When  $HI > 1$ , heavy metals have a certain effect on the non-carcinogenic risk of the human body; when  $TCR < 1 \times 10^{-6}$ , the effect of carcinogenic heavy metals on human health in this area is negligible. When the TCR is between  $1 \times 10^{-6}$  and  $1 \times 10^{-4}$ , the effect of carcinogenic heavy metals is acceptable. When  $TCR > 1 \times 10^{-4}$ , carcinogenic heavy metals have a significant effect on human health (Wei et al. 2015). Among the four heavy metals studied in this paper, Pb and Cr are listed as carcinogenic substances by heavy metals in the Agency for Toxic Substances and Disease Registry (ATSDR 2003). Therefore, the effects of these two heavy metals on human carcinogenesis were considered.

### Geo-detector model

The geo-detector model was originally proposed by Wang et al. (2010). It can not only detect the influence of factor X on factor Y, but also detect the influence of factor X on factor Y after interacting with factor Z. This study is mainly based on the two parts of the factor detector and the interaction detector to calculate the explanatory power  $q$  value of different geographical elements on the potential ecological risk (RI), non-carcinogenic risk (HI), and carcinogenic risk (TCR) of soil heavy metals. See Wang and Xu (2017) for its inner principle and calculation formula of  $q$  value.

- a. *Factor detector* Judging the main controlling factor of heavy metal risk by comparing the explanatory power  $q$  of each factor to the heavy metal risk. The greater the value of  $q$ , the greater the explanatory power of the risk of heavy metals and the greater the impact;
- b. *Interaction detector* By comparing the value of the explanatory power  $q$  of a single factor to the risk of heavy metals and the magnitude of the explanatory power  $q$  after the interaction of the two factors, the change of the influence of the two factors on the risk of heavy metals after the interaction is determined.

## Results and analysis

### Analysis of soil heavy metal content and spatial heterogeneity

The data were first subjected to outlier processing to reduce calculation errors. Values outside the interval where the average is greater than or less than three times the standard deviation are considered to be outliers (Qian et al. 2013; Lingming, et al. 2014), and the abnormal value is replaced by the average value. The statistical characteristics of Cr, Cu, Zn, and Pb in the study area under the different land use types of cropland, grassland, forestland, and construction land were obtained (Table 2).

The over-standard rate can reflect the accumulation of heavy metals in the study area to a certain extent and is equal to the ratio of the sample size with a content greater than the soil background to the total sample size. Based on the soil background values of the A layer in Guizhou Province, Cr, Cu, Zn, and Pb were

accumulated to different degrees in the study area and showed concentration ranges of 53.29–184, 23.45–144, 60.73–400, and 19.88–171.54 mg/kg, respectively. The over-standard rates range from 51 to 89%, and the CV is between 28 and 55%, which indicates moderate variability. The degree of variation decreased in the order of Pb > Zn > Cu > Cr, which means the dispersion of Pb content is strong and the spatial differentiation of Cr is relatively small. From the perspective of individual land use types, the over-standard rates of Cr, Cu, Zn, and Pb in cropland are between 55 and 95%, and the accumulation of Cu in soil is the most serious. The degree of variation in cropland, which is between 28 and 57%, is not much different from the overall variation. The over-standard rates of Cr, Cu, Zn, and Pb in grassland are 47%, 76%, 71%, and 82%, respectively, and the degrees of variation decreased in the order of Pb (64%) > Zn (48%) > Cr (29%) > Cu (5%). The over-standard rate of Cr, Cu, Zn, and Pb in forestland is between 8 and 65%, and the CV is between 4 and 49%. In this land

**Table 2** Statistical characteristics of soil heavy metal content (mg/kg)

Land use	Heavy metals	Min	Max	Mean	SD	CV	Skewness	Kurtosis	Over-standard rate
Cropland ( <i>N</i> = 60)	Cr	53.29	184	110.99	31.24	0.28	0.72	− 0.36	0.55
	Cu	27.84	144	57.74	27.07	0.47	1.86	2.96	0.95
	Zn	69.21	400	144.1	81.85	0.57	1.85	2.82	0.65
	Pb	24.16	171.54	63.55	33	0.52	1.5	1.9	0.87
Grassland ( <i>N</i> = 17)	Cr	68.51	161	104.11	30.23	0.29	0.52	− 1.01	0.47
	Cu	26.86	101	51.48	25.74	0.5	1.08	− 0.4	0.76
	Zn	60.73	274	134.18	64.1	0.48	0.99	− 0.09	0.71
	Pb	19.88	164.43	73.67	47.03	0.64	0.93	− 0.27	0.82
Forestland ( <i>N</i> = 20)	Cr	63.91	157.7	95.92	23.2	0.24	1.07	1.29	0.45
	Cu	23.45	92.48	43.75	17.3	0.4	1.56	2.4	0.8
	Zn	65.91	223	106.9	41.71	0.39	1.65	2.33	0.45
Construction land ( <i>N</i> = 3)	Pb	26.12	109.62	48.94	23.76	0.49	1.63	2.05	0.65
	Cr	88.08	146	109.24	31.96	0.29	1.67	—	0.33
	Cu	38.99	74.5	51.36	20.05	0.39	1.72	—	1
Overall ( <i>N</i> = 100)	Zn	80.41	189	131.4	54.6	0.42	0.54	—	0.67
	Pb	37.06	88.71	62.93	25.82	0.41	− 0.02	—	1
	Cr	53.29	184	106.75	29.82	0.28	0.77	− 0.22	0.51
	Cu	23.45	144	53.69	25.3	0.47	1.77	3	0.89
	Zn	60.73	400	134.6	72.53	0.54	1.93	3.72	0.62
	Pb	19.88	171.54	62.33	34.46	0.55	1.46	1.66	0.82

*N* is the number of samples. The background values of the above heavy metals are: Cr = 95.9, Cu = 32, Zn = 99.5, Pb = 35.2; refer to the soil background value of the A layer in Guizhou Province (National Environmental Protection 1990.)

type, Pb shows the most serious accumulation and the widest dispersion; by contrast, Cu shows the mildest accumulation and the narrowest dispersion. Cu and Pb accumulate the most extensively in construction land, with an over-standard rate reaching 100%, followed by Zn, which shows an over-standard rate of 67%. Among the metals, Cr is the most lightly accumulated, with an over-standard rate of 33%. The degree of variation of the heavy metals in construction land is smaller than those of the three other types of land use, ranging from 29 to 42%.

To analyze the spatial heterogeneity characteristics of the four heavy metals, the geo-statistical module based on the ArcGIS platform is used to establish a semi-variogram function model (Liu et al. 2012). Before that, histogram distribution analysis was conducted based on the geo-statistical module, and distribution patterns of four heavy metals were obtained. Table 3 shows that, except for Cr, which follows a normal distribution, the three other heavy metals demonstrate a lognormal distribution. We thus conclude that the most suitable statistical models for the four heavy metal contents are the ordinary Kriging model for Cr and the logarithmically transformed Kriging model for Cu, Zn, and Pb. The nugget effect can be used to indicate the spatial correlation of variables in the system (Burgos et al. 2006; Xu et al. 2014). Table 3 lists the relevant parameters of several optimal fit models. Cr conforms to the exponential function model, and the nugget effect is 0.685, which is between 0.25 and 0.75. The spatial correlation of the heavy metals is moderately correlated, indicating that its spatial heterogeneity is influenced by both human and natural factors. Cu conforms to the rational quadratic equation model, and its nugget effect is

0.141, which is less than 0.25. The heavy metal is spatially significantly correlated, thereby indicating that its spatial heterogeneity is only slightly affected by human activities but remarkably affected by natural factors such as soil type, topography, lithology, and altitude. Zn conforms to the Gaussian function model, and its nugget effect is 0.042. Similar to Cu, the spatial correlation of Zn is significant, which means its accumulation is greatly affected by spatial and primary structural factors. Pb conforms to the trigonometric function model, and its nugget effect is equal to 0.46, which is also between 0.25 and 0.75. Accumulation of this metal is thus moderately related to space, and its spatial differentiation characteristics are affected by human and natural factors. The nugget effect of all four metals is less than 0.75, that is, they are not significantly affected by human factors.

### Heavy metal pollution characteristics

Table 4 shows the calculated  $I_{geo}$  of Cr, Cu, Zn, and Pb in the Houzhai River Watershed. Moderate or more than moderate pollution of the metals is not found, the overall pollution level is light, and most of the metals are non-polluting. Cr shows the lowest pollution degree and can be divided into two levels, namely non-polluting (83%) and mildly polluting (17%). Cu is divided into three pollution levels: non-polluting (58%), mildly polluting (35%), and mildly to moderately polluting (7%). Zn can also be divided into three pollution levels, but its pollution is slightly lighter than that of Cu: non-polluting (73%), mildly polluting (22%), and mildly to moderately polluting (5%). The pollution situation of Pb is the most serious among the four metals: non-polluting (55%), mildly polluting

**Table 3** Semi-variogram function model of soil heavy metals

Heavy metals	Distribution type	Fitting model	Nugget value	Sill value	Nugget effect	Prediction error		
						RMSE	SMS	RMSSE
Cr	Normality	Exponential function	404.888	590.713	0.685	21.541	0.037	0.79
Cu	Lognormal	Rational quadratic equation	0.02	0.144	0.141	18.363	0.042	0.863
Zn	Lognormal	Gaussian function	0.007	0.176	0.042	48.853	0.017	1.013
Pb	Lognormal	Trigonometric function	0.093	0.201	0.46	24.503	0.038	0.894

Nugget effect < 0.25, significant spatial correlation; 0.25 ≤ nugget effect ≤ 0.75, medium spatial correlation; nugget effect > 0.75 weak spatial correlation

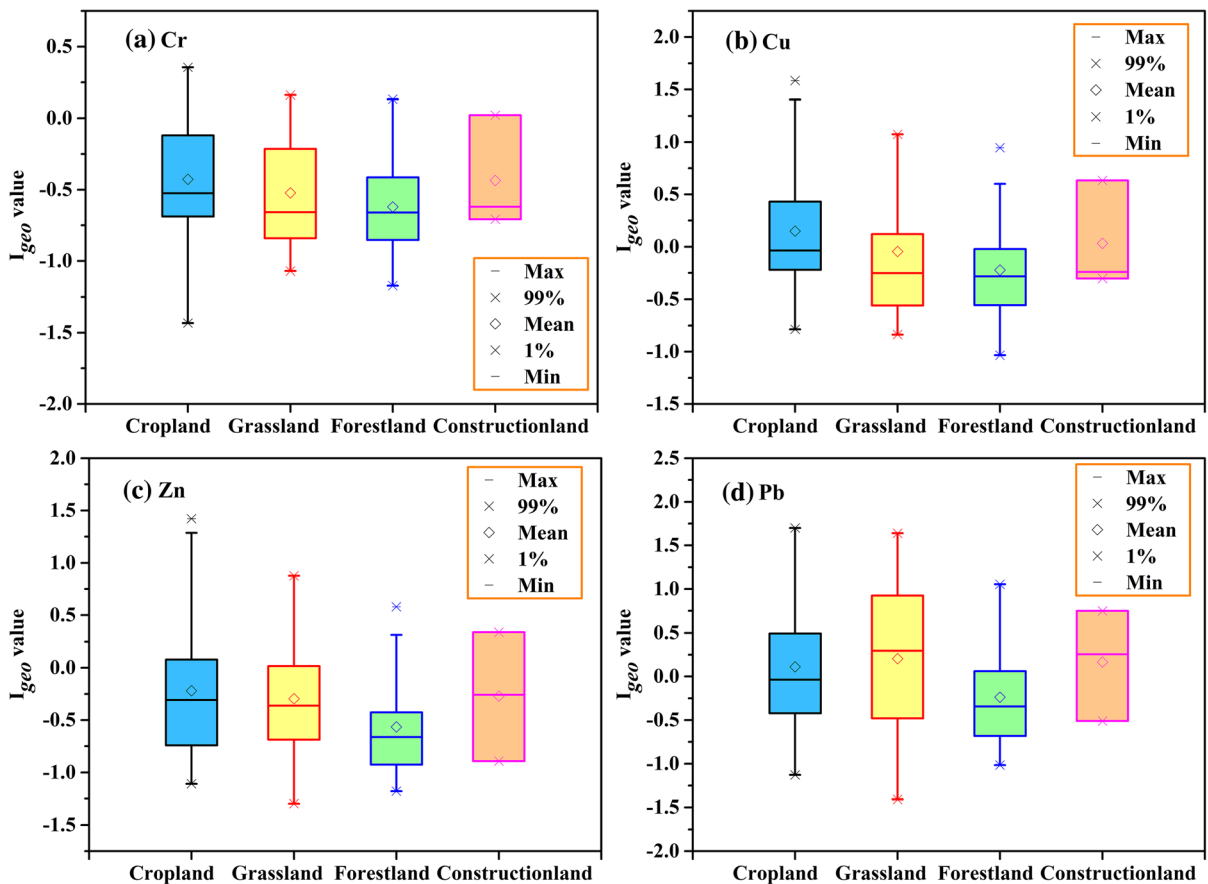
**Table 4** Classification of soil heavy metal pollution

Heavy metals	Non-polluting $I_{geo} \leq 0$	Mildly polluting $0 < I_{geo} \leq 1$	Mildly to moderate pollution $1 < I_{geo} \leq 2$	Moderate pollution $2 < I_{geo} \leq 3$	Moderate to heavy pollution $3 < I_{geo} \leq 4$	Heavy pollution $4 < I_{geo} \leq 5$	Extremely heavy pollution $I_{geo} > 5$
Cr	83%	17%	–	–	–	–	–
Cu	58%	35%	7%	–	–	–	–
Zn	73%	22%	5%	–	–	–	–
Pb	55%	33%	12%	–	–	–	–

(33%), and mildly to moderately polluting (12%). The degree of heavy metal pollution in the study area decreases in the order of  $Pb > Cu > Zn > Cr$ .

Figure 2 shows that different heavy metals present different degrees of pollution in different land use types. First, the pollution degree of Cr among the different land use types decreases in the order of cropland > construction

land > grassland > forestland, and the pollution of Cu and Zn is consistent with that of Cr. The pollution of cropland is the most serious, and the forestland is the least. The pollution levels of Pb among the different land use types decrease in the order of construction land > cropland > grassland = forestland. Thus, cropland and construction land are more polluted with the heavy metals than other types of



**Fig. 2** Box diagram of the geo-accumulation index of heavy metals under different land use types



land, and pollution in forestland is the least significant. Second, comparison of the pollution characteristics of different heavy metals under the same land use type reveals that, except for the pollution levels of the four heavy metals in cropland, which shows the order  $\text{Cu} > \text{Pb} > \text{Zn} > \text{Cr}$ , the pollution levels of these metals in the three other land types are similar and of the order  $\text{Pb} > \text{Cu} > \text{Zn} > \text{Cr}$ . Thus, the pollution degree of Pb and Cu under different land use types is relatively higher than that of the two other heavy metals. As well, the pollution degree of Cr is the lightest, consistent with the overall pollution characteristics.

### Potential ecological risk assessment

#### *Single-factor potential ecological risk assessment*

Based on the ArcGIS platform, the potential ecological risks of the four heavy metals were interpolated and analyzed, and the spatial distribution map of the single-factor potential ecological risk in the study area was obtained (Fig. 3). The proportion of the risk grade area distribution of each heavy metal under the different land use types was extracted (Table 5). Table 5 shows that the single-factor potential ecological risk in the study area can be divided into three levels: slight, moderate, and intense. Cr and Zn only show slight ecological risk. The ecological risks of Cu and Pb range from slight to moderate. From the perspective of land use type, the proportion of the potential ecological risk grades of Cr and Zn under different land use types is consistent; the proportion of the total area shows the order cropland (48.42%) > forestland (33.45%) > grassland (13.45%) > construction land (4.37%). Cu and Pb show similar moderate ecological risk in most of the land use types; the proportion of ecological risk area at each level reveals the order moderate > intensity > light, and the proportion. The proportion of slight risk of Cu follows the order grassland > cropland > forestland > construction land; the proportion of moderate risk shows the order cropland > forestland > grassland > construction land; and the proportion of intense risk decreases in the order of cropland > grassland > forestland > construction land. The proportion of slight risk of Pb shows the order forestland > grassland > cropland > construction land, and forestland accounts; and the proportion

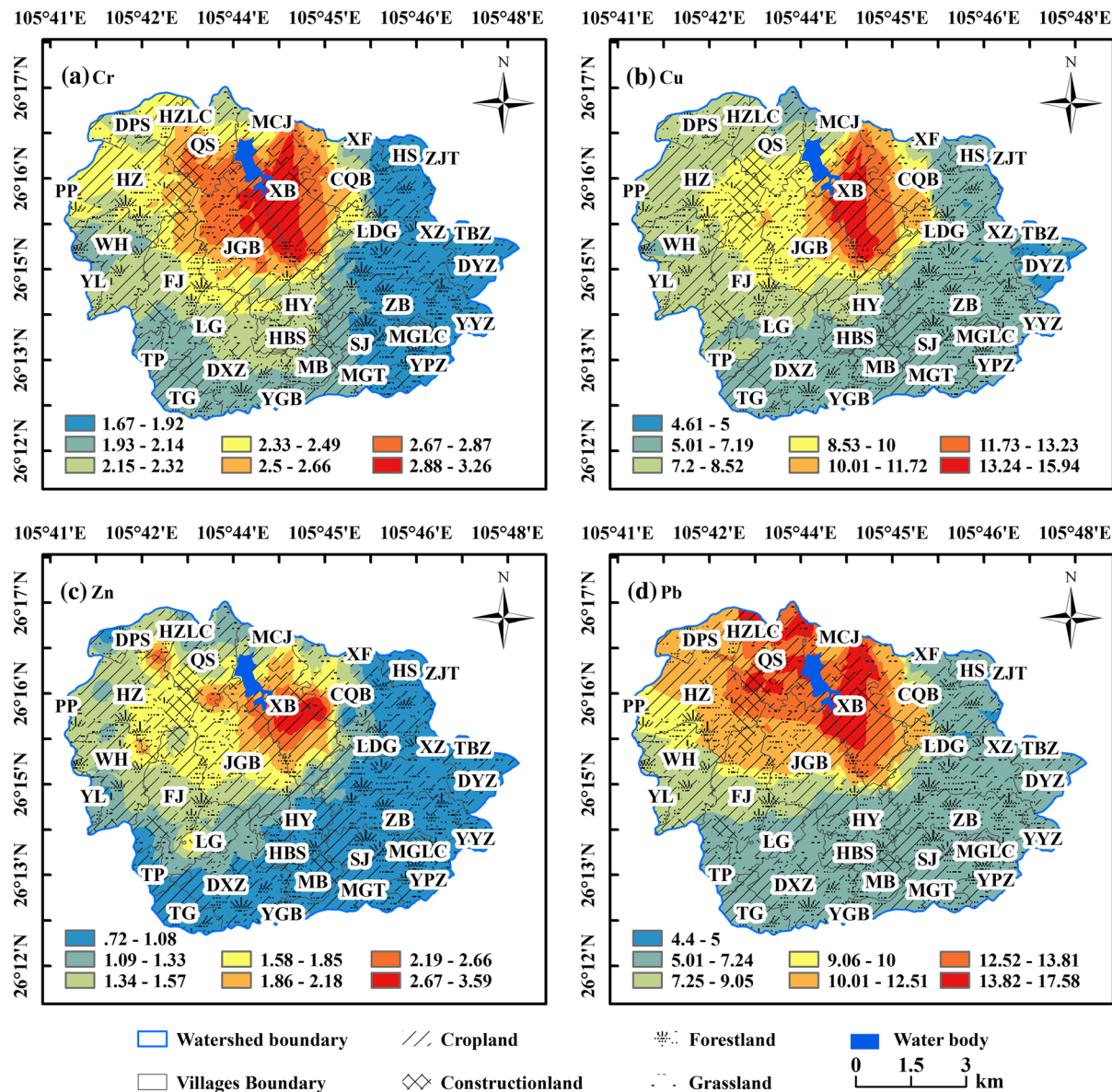
of moderate and intensity risks is cropland > forestland > grassland > construction land.

Figure 3 shows that the potential ecological risks of the four heavy metals show a similar distribution in space, with potential ecological risks relatively high in the northwest and relatively low in the southeast. The high-value area is concentrated near Xinbao Village, and the risk gradually decreases from the high-value center to both sides. The slight risks of Cu are mainly distributed in Dayouzhai Village in the east with sporadic distributions in Xiaba Village and Chenqibao Village. The intense risk is distributed in the east of Jiaguanbao Village, most areas of Xinbao Village, the west of Chenqibao Village, and the northwest of Lishang Arch Village. Moderate risk is distributed in the rest of the region. The slight risk distribution of Pb is relatively small, and it is distributed in the small area of Lidagong Village and Chenqibao Village. The intense-risk distribution area is relatively wide and mainly found in the central and northwestern parts of the watershed, with the highest risk in Xinbao Village and Qingshan Village. Moderate risk is widely distributed in the eastern and southwestern regions.

#### *Comprehensive potential ecological risk assessment*

Figure 4 shows a comprehensive potential risk-level distribution map of the study area under the combined action of the four soil heavy metals. The comprehensive ecological risk can be divided into three grades, and most areas show second-level moderate ecological risk. The total ecological risk area ratio is moderate > slight > intense. In terms of village-level administrative divisions, first-level risks (slight) are distributed in the eastern part of the study area and Daxinzhai Village and Tianguan Village in the southwest. Third-level risks (intense) are distributed in the northeast of Xinbao Village, the northeast of Jiaguanbao Village, and the west of Chenqibao Village. The rest of the area shows second-level risks (moderate).

Combined with Table 5, from the perspective of land use types, slight ecological risks are distributed in the forestland and cropland in the east. The proportion of different land use types at this level is forestland (13.1%) > cropland (8.85%) > grassland (4.4%) > construction land (0.01%). Forestland accounts for the largest proportion of its own area, and construction land accounts for the smallest



**Fig. 3** Soil heavy metal single-factor potential ecological risk

proportion of its own area, which are 38.87% and 0.27%, respectively; moderate ecological risks are widely distributed in various land use types in the study area. The proportion of land use at this level is cropland (34.91%) > forestland (20.17%) > grassland (8.42%) > construction land (3.84%). Construction land accounts for the largest proportion of its own area, which is 88.04%, and forestland accounts for the smallest proportion of its own area, which is 59.84%; intense risk is distributed in the cropland in the north.

The proportion of different land use types under this level is more than 5%, which is represented by cropland (4.61%) > grassland (0.61%) > construction land (0.51%) > forestland (0.44%). Construction land accounts for the largest area ratio of 11.6%, and the smallest is forestland, accounting for 1.29% of its own area ratio.

**Table 5** Area ratio of soil heavy metal ecological risk grades under different land use types (%)

Heavy metals	Land use	Level 1 (slight) $E_i < 5$ ; $Ri < 15$	Level 2 (moderate) $5 \leq E_i < 10$ ; $15 \leq Ri < 30$	Level 3 (intense) $10 \leq E_i < 20$ ; $30 \leq Ri < 60$			
		Own area ratio	Total area ratio	Own area ratio	Total area ratio	Own area ratio	Total area ratio
Cr	Cropland	100	48.42	–	–	–	–
	Grassland	100	13.45	–	–	–	–
	Forestland	100	33.76	–	–	–	–
	Construction land	100	4.37	–	–	–	–
Cu	Cropland	1.83	0.88	81.25	39.22	16.92	8.17
	Grassland	7.29	0.98	79.44	10.65	13.27	1.78
	Forestland	0.93	0.31	94.41	31.77	4.66	1.57
	Construction land	0.27	0.01	85.97	3.75	13.75	0.60
Zn	Cropland	100	48.42	–	–	–	–
	Grassland	100	13.45	–	–	–	–
	Forestland	100	33.76	–	–	–	–
	Construction land	100	4.37	–	–	–	–
Pb	Cropland	0.29	0.14	62.35	30.19	37.36	18.09
	Grassland	0.51	0.07	59.92	8.06	39.57	5.32
	Forestland	1.08	0.37	79.64	26.88	19.28	6.51
	Construction land	0.27	0.01	36.88	1.61	62.85	2.75
Total	Cropland	18.30	8.85	72.18	34.91	9.52	4.61
	Grassland	32.74	4.40	62.70	8.42	4.56	0.61
	Forestland	38.87	13.10	59.84	20.17	1.29	0.44
	Construction land	0.27	0.01	88.04	3.84	11.6	0.51

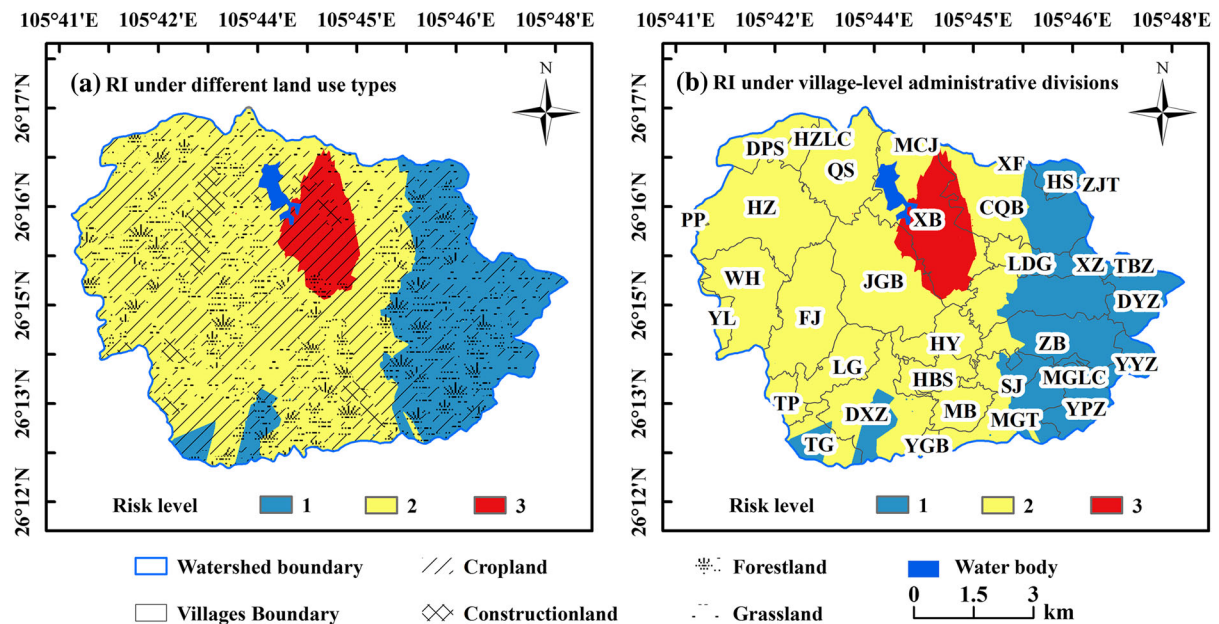
The ecological risk has no intensity above the level, so it is not listed; this paper mainly discusses the risk of soil heavy metals, so the area of the water body is not considered in the calculation

Human health risk assessment

*Non-carcinogenic risk assessment*

Table 6 shows the effects of heavy metals in soil on human health in adults and children under different exposure routes. Overall, the children’s non-carcinogenic risk index is higher than that of adults, at 0.475 and 0.128, respectively, but the total non-oncogenic index is less than 1, which means that the non-carcinogenic effects of the four heavy metals on the human body are not significant. In terms of the non-carcinogenic risk of adults, the effects of different exposure pathways on the overall non-carcinogenic

risk follow the order direct intake > skin contact > nose and mouth inhalation. The effect of different heavy metals on the comprehensive non-carcinogenic risk is ordered Cr > Pb > Cu > Zn. In terms of the non-carcinogenic risk of children, the risks of direct intake, nose and mouth inhalation, and skin contact are  $4.61 \times 10^{-1}$ ,  $8.64 \times 10^{-4}$ , and  $1.28 \times 10^{-2}$ , respectively. Similar to the effect on adults, the non-carcinogenic risk of children is dependent on direct intake, and the contribution of different heavy metals to the comprehensive non-carcinogenic risk is consistent with that of adults. Therefore, the non-carcinogenic risk in the study area



**Fig. 4** Distribution of soil heavy metal comprehensive ecological risk grades in the study area

depends on the direct intake of heavy metals, especially Cr.

The calculation results were also interpolated on ArcGIS to obtain the health risk distribution map of soil heavy metal comprehensive cancer in the study area (Fig. 5). From the spatial point of view, differences in the distribution characteristics of adults and children are small. Areas with high non-cancer risk are concentrated in and around Xinbao Village, which cropland is widely distributed and tends to gradually decrease from the high-value center to the surrounding area. Combining Fig. 6a, b, the comprehensive non-carcinogenic risk of different land use types shows the order cropland > grassland > construction land > forestland, and the single-factor non-carcinogenic risk is cropland > grassland > forestland > construction land.

#### Carcinogenic risk assessment

Table 6 shows that the total cancer risk of adults and children is  $3.22 \times 10^{-5}$  and  $3.87 \times 10^{-5}$ , respectively, that is, 322 adults may have cancer in every 10 million adults, and 387 children may have cancer in every 10 million children. Given that  $1 \times 10^{-6} < \text{total cancer risk} < 1 \times 10^{-4}$ , the carcinogenic heavy metals in the study area may pose certain risks to

human health, but the risk is acceptable. The risk of cancer in adults and children is very close, and the risk of cancer in children is slightly higher than that in adults, which is consistent with previous studies (Chen et al. 2014; Li et al. 2014), probably because children are exposed to heavy metals by the mouth and hand more frequently than are adults.

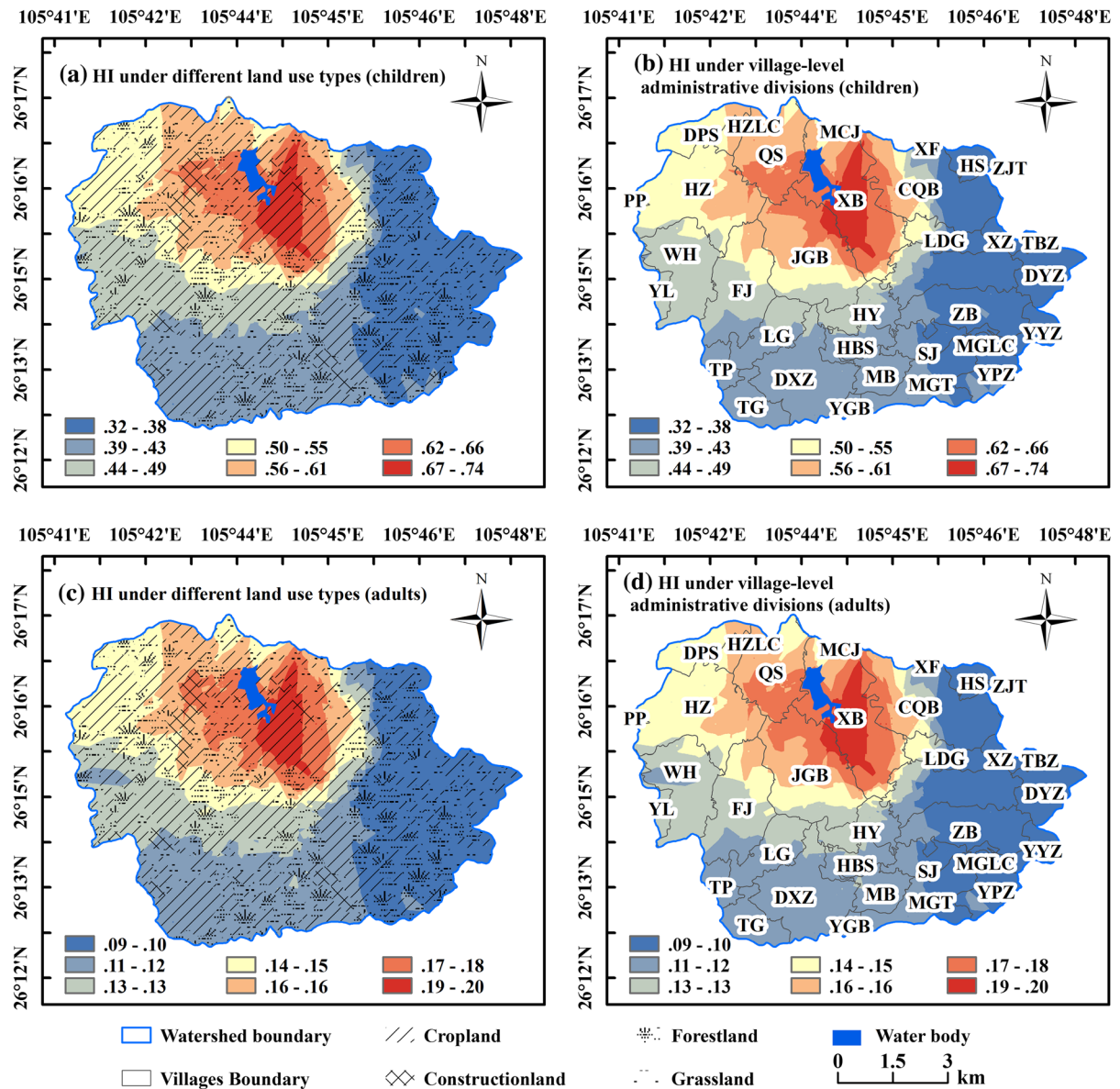
From the two routes of direct intake and nose and mouth inhalation, the risk index of direct intake of adults and children is  $3.19 \times 10^{-5}$  and  $3.86 \times 10^{-5}$ , respectively, and the contribution to total cancer risk reaches 99.12% and 99.77%, respectively, indicating that direct intake is the main route of exposure leading to cancer. From the spatial point of view (Fig. 7), no significant difference is observed in the distribution characteristics of children and adults. The high-risk areas are concentrated in Qingshan Village–Jiaguanbao Village–Xinbao Village–Chenqibao Village. Combined with Fig. 6c, d, the total cancer risk under each land use type shows the order cropland > grassland > forestland > construction land.

#### Factors affecting spatial distribution of risk

This article uses RI, HI, and TCR as dependent variables. Geo-detector was used to detect the effects of factors such as digital elevation data (DEM),

**Table 6** Health risk index under different exposure routes

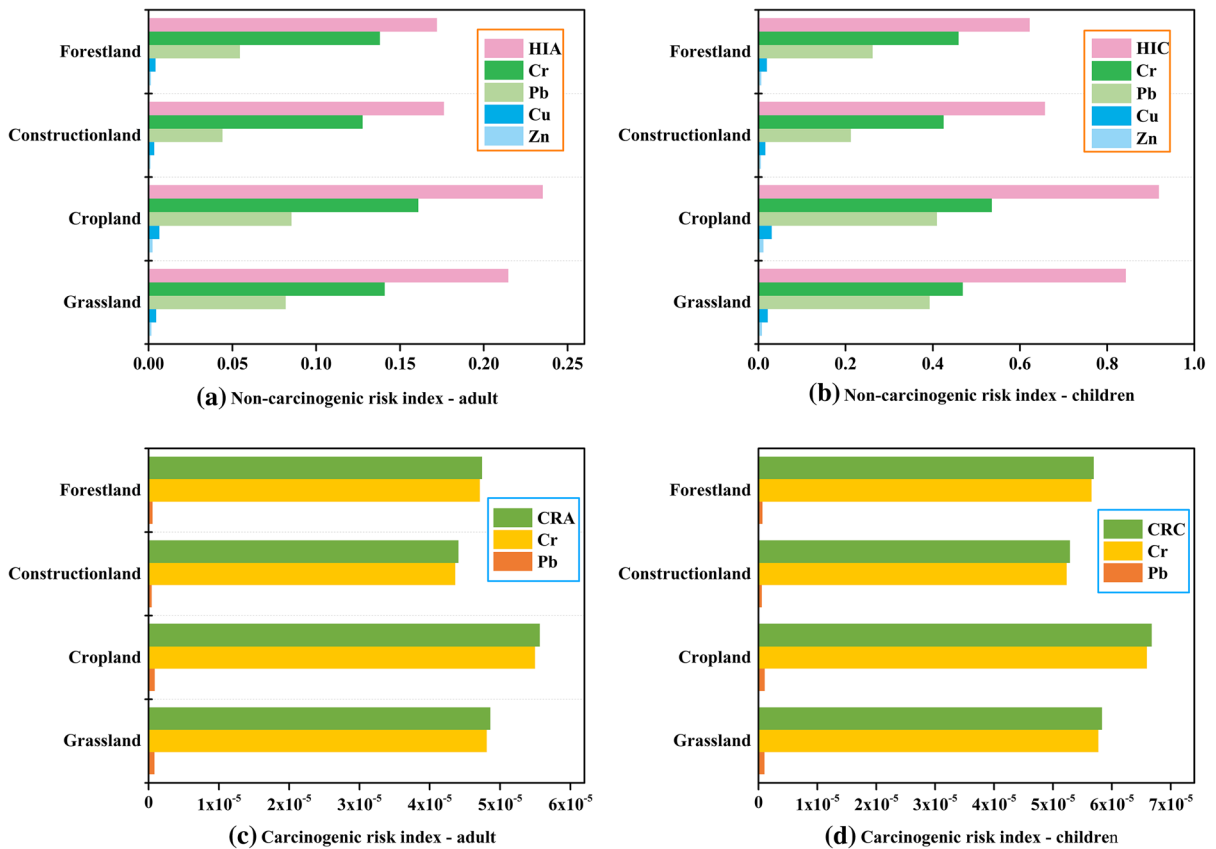
Risk types	Exposure routes	Heavy metals	Min	Max	Mean	Total
Non-carcinogenic	Direct intake—adult	Cr	3.07E−02	1.06E−01	6.15E−02	9.54E−02
		Cu	1.01E−03	6.22E−03	2.32E−03	
		Zn	3.50E−04	2.30E−03	7.75E−04	
		Pb	9.81E−03	8.46E−02	3.08E−02	
	Nose and mouth inhalation—adult	Cr	3.43E−04	1.18E−03	6.87E−04	6.91E−04
		Cu	1.07E−07	6.60E−07	2.46E−07	
		Zn	1.86E−07	1.23E−06	4.13E−07	
		Pb	1.04E−06	8.97E−06	3.26E−06	
	Skin contact—adult	Cr	1.56E−02	5.38E−02	3.12E−02	3.15E−02
		Cu	3.43E−05	2.10E−04	7.84E−05	
		Zn	3.55E−06	2.34E−05	7.86E−06	
		Pb	6.64E−05	5.73E−04	2.08E−04	
	Single factor risk—adult	Cr	4.66E−02	1.61E−01	9.34E−02	1.28E−01
		Cu	1.05E−03	6.43E−03	2.40E−03	
		Zn	3.53E−04	2.33E−03	7.83E−04	
		Pb	9.88E−03	8.52E−02	3.10E−02	
	Total risk—adult	HIA	6.87E−02	2.35E−01	1.28E−01	1.28E−01
	Direct intake—children	Cr	1.48E−01	5.12E−01	2.97E−01	4.61E−01
		Cu	4.89E−03	3.00E−02	1.12E−02	
		Zn	1.69E−03	1.11E−02	3.74E−03	
		Pb	4.74E−02	4.09E−01	1.49E−01	
	Nose and mouth inhalation—children	Cr	4.29E−04	1.48E−03	8.59E−04	8.64E−04
		Cu	1.34E−07	8.24E−07	3.07E−07	
		Zn	2.33E−07	1.53E−06	5.16E−07	
Pb		1.31E−06	1.13E−05	4.10E−06		
Skin contact—children	Cr	6.35E−03	2.19E−02	1.27E−02	1.28E−02	
	Cu	1.40E−05	8.58E−05	3.20E−05		
	Zn	1.45E−06	9.53E−06	3.21E−06		
	Pb	2.71E−05	2.34E−04	8.49E−05		
Single factor risk—children	Cr	1.55E−01	5.35E−01	3.11E−01	4.75E−01	
	Cu	4.91E−03	3.01E−02	1.12E−02		
	Zn	1.69E−03	1.11E−02	3.74E−03		
	Pb	4.74E−02	4.09E−01	1.49E−01		
Total risk—children	HIC	2.61E−01	9.18E−01	4.75E−01	4.75E−01	
Carcinogenic	Direct intake—adult	Cr	1.58E−05	5.45E−05	3.16E−05	3.19E−05
		Pb	1.00E−07	8.63E−07	3.14E−07	
	Nose and mouth inhalation—adult	Cr	1.41E−07	4.88E−07	2.83E−07	2.83E−07
		Total risk—adult	CRA	1.61E−05	5.56E−05	
	Direct intake—children	Cr	1.91E−05	6.58E−05	3.82E−05	3.86E−05
		Pb	1.21E−07	1.04E−06	3.79E−07	
	Nose and mouth inhalation—children	Cr	4.41E−08	1.52E−07	8.84E−08	8.84E−08
		Total risk—children	CRC	1.93E−05	6.68E−05	



**Fig. 5** Spatial distribution of non-carcinogenic risk of heavy metals in soil

normalized vegetation index (NDVI), fractional vegetation cover (FVC), land use type, slope, aspect, and soil types. The results of the factor detector and interaction detector are shown in Fig. 8. Figure 8a shows the calculated  $q$  values of all factors. The results show that among the factors selected in this paper, NDVI and FVC are the main environmental factors affecting ecological risk. They each explain the spatial pattern of ecological risk of 16%; the DEM and NDVI have the same effect on the spatial differentiation

characteristics of non-carcinogenic risk, with  $q$  values of 0.14; the factor that has the greatest effect on carcinogenic risk is DEM, which is explained by the 11% spatial heterogeneity. Figure 8b shows the result of the interaction detector. The value in the figure is the  $q$  value after the interaction of the two independent variables. It can be seen that the interaction of any two independent variables on the dependent variable is greater than the effect of a single independent variable. Among them, the interaction between aspect and FVC



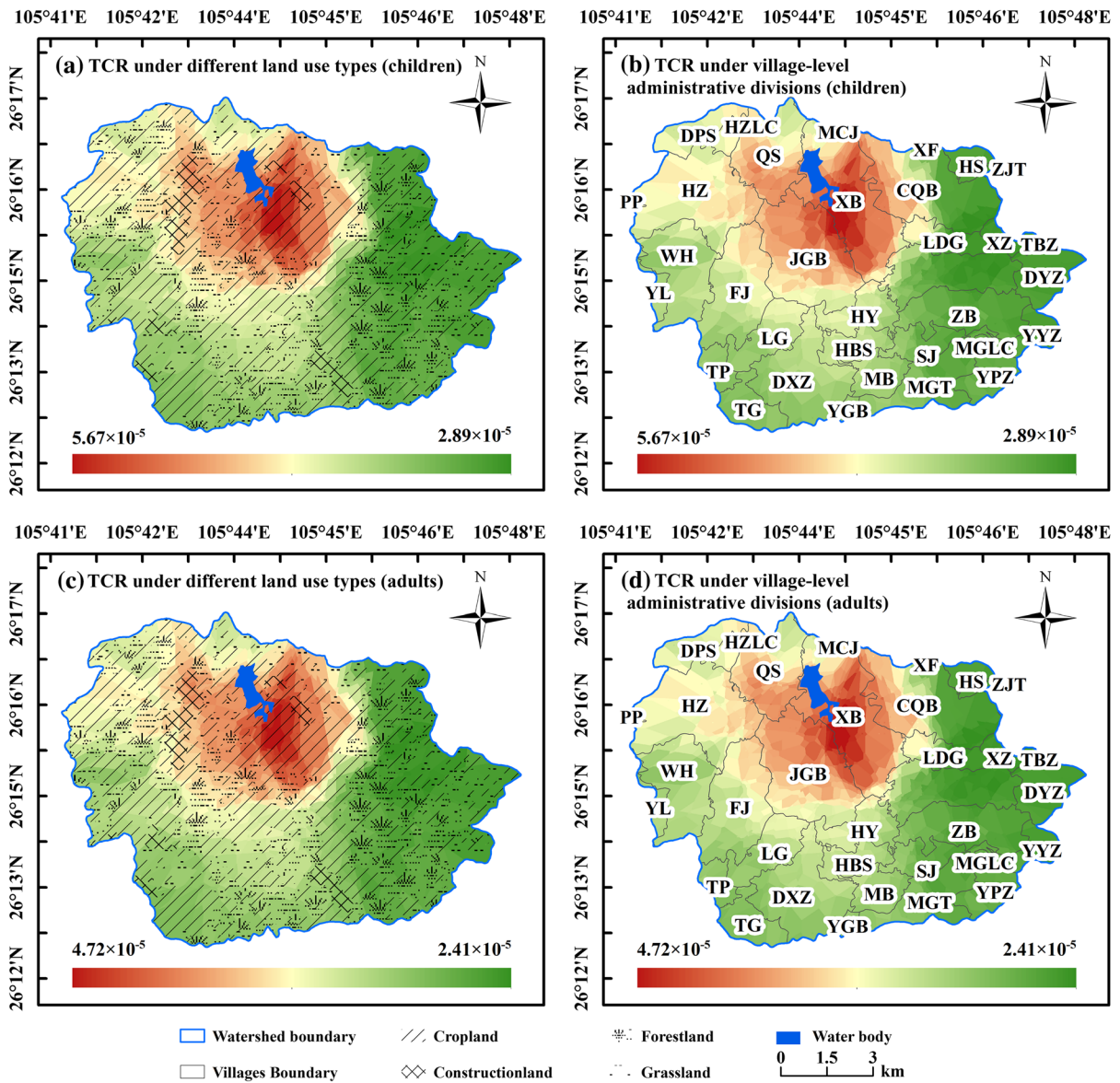
**Fig. 6** Health risks under different land use types

has the greatest impact on ecological risk ( $q = 41\%$ ); similar to ecological risk, the interaction between aspect and FVC also has the highest interpretation of the non-carcinogenic risk spatial distribution ( $q = 35\%$ ); the interaction between aspect and NDVI is equivalent to it; the interaction effect of aspect and slope on carcinogenic risk was much larger than that of other variables ( $q = 32\%$ ). It can be seen that DEM and NDVI are the main natural factors affecting ecological risk, non-carcinogenic risk, and carcinogenic risk. When aspect interacts with other factors, its effect is much greater than others.

### Discussion

#### Correlation analysis of potential ecological risks and health risks

To clarify the correlation between potential ecological risks and health risks, Pearson correlation analysis was performed using SPSS. Table 7 shows that potential ecological risks are significantly positively correlated with non-cancer and cancer risks in adults and children. Heavy metals with high ecological risks have a significant effect on human health. Overall, the correlation between ecological risk and non-cancer risk in children is highly significant with a correlation coefficient of 0.955. The correlation between ecological risk and carcinogenic risk is relatively slight, but the correlation coefficient is still 0.792. From the perspective of different land use types, the correlation coefficient between ecological risk and construction land is high, but this correlation is not significant,



**Fig. 7** Spatial distribution of carcinogenic risk of heavy metals in soil

probably due to the small sample size of construction land. Among the three other land use types, the correlation between potential ecological risk and carcinogenic risk is most significant in cropland. The effect of potential ecological risk on carcinogenic risk of adults and children is the same, with a correlation coefficient of 0.840. The correlation with non-carcinogenic risk was not much different between grassland and cultivated land, although that of grassland is slightly higher, and the correlation between adult and child non-cancer risk is 0.951 and 0.969,

respectively. The correlation coefficient between ecological risk and carcinogenic risk in forestland is less than 0.5.

#### Deficiencies and perspective

Although the findings of this article indicate that ecological and health risks are relatively low, we believe this research is still meaningful. This paper used the village as an administrative division to evaluate the effect of different land use types on soil



**(a) Factor detector**

RI	q statistic	p value
DEM	0.11	0.01
NDVI	0.16	0.01
FVC	0.16	0.01
Landuse type	0.05	0.58
Slope	0.07	0.23
Aspect	0.01	0.86
Soil type	0.00	0.87
HI	q statistic	p value
DEM	0.14	0.00
NDVI	0.14	0.04
FVC	0.13	0.06
Landuse type	0.05	0.81
Slope	0.05	0.40
Aspect	0.02	0.73
Soil type	0.01	0.84
TCR	q statistic	p value
DEM	0.11	0.02
NDVI	0.10	0.30
FVC	0.08	0.43
Landuse type	0.04	0.92
Slope	0.07	0.28
Aspect	0.05	0.42
Soil type	0.02	0.62

**(b) Interaction detector**

RI	DEM	NDVI	FVC	Landuse type	Slope	Aspect	Soil type
DEM	0.11						
NDVI	0.30	0.16					
FVC	0.30	0.17	0.16				
Landuse type	0.19	0.23	0.23	0.05			
Slope	0.18	0.30	0.30	0.13	0.07		
Aspect	0.19	0.40	0.41	0.16	0.27	0.01	
Soil type	0.15	0.19	0.19	0.15	0.10	0.06	0.00
HI	DEM	NDVI	FVC	Landuse type	Slope	Aspect	Soil type
DEM	0.14						
NDVI	0.32	0.14					
FVC	0.31	0.15	0.13				
Landuse type	0.19	0.22	0.21	0.05			
Slope	0.20	0.28	0.26	0.13	0.05		
Aspect	0.24	0.35	0.35	0.20	0.26	0.02	
Soil type	0.18	0.18	0.17	0.15	0.08	0.09	0.01
TCR	DEM	NDVI	FVC	Landuse type	Slope	Aspect	Soil type
DEM	0.11						
NDVI	0.27	0.10					
FVC	0.26	0.11	0.08				
Landuse type	0.14	0.18	0.15	0.04			
Slope	0.21	0.26	0.22	0.16	0.07		
Aspect	0.24	0.29	0.28	0.23	0.32	0.05	
Soil type	0.15	0.15	0.15	0.13	0.12	0.14	0.02

**Fig. 8** The results of geo-detector

**Table 7** Correlation analysis between potential ecological risks and health risks

Health risk	Land use				
	Cropland	Grassland	Forestland	Construction land	Total
Non-carcinogenic—adult	0.950**	0.951**	0.767**	0.999*	0.936**
Non-carcinogenic—children	0.965**	0.969**	0.825**	1.000*	0.955**
Carcinogenic—adult	0.840**	0.761**	0.489*	0.984	0.792**
Carcinogenic—children	0.840**	0.761**	0.489*	0.984	0.792**

\*\*Indicates a significant correlation at the 0.01 level (both sides); \*indicates a significant correlation at the 0.05 level

ecological safety patterns and human health risks. The ecological risk was re-classified according to the actual situation, and some parameters of the human health risk assessment model were improved to improve the accuracy of the evaluation results. It also confirms the applicability of Hakanson potential

ecological risk methods and human health risk model in karst areas. Most importantly, traditional views have shown that regions with prominent geological backgrounds have serious pollution of heavy metals. The research area of this paper is pure karst area, but we still get the result that pollution, ecological, and

health risks are low, which happens to refute this view. In addition, Guizhou, as a national experimental area of ecological civilization, bears heavy burdens for green development. The scientific record of this article is of certain significance to promote the export of agricultural products, the development of local green economy, and the construction of ecological civilization. However, the following limitations still exist:

This study considers the effect of land use types but does not guarantee the uniformity of the collected samples. Inconsistent soil samples of different land use types may result in inaccurate assessment results. As well, only four heavy metals, Cr, Cu, Zn, and Pb, are selected in this research, but the accumulation of heavy metals in soil may be more diverse and complex. Therefore, the ecological security and health risks of the study area may be more serious than the results offered in this paper.

In terms of human health risk assessment, although some parameters of the model have been improved by combination with China's "Technical guidelines for risk assessment of contaminated sites" and the human health status of Guizhou Province, some parameters are still recommended by USEPA. Whether these values are consistent with reality due to individual differences requires further exploration. Moreover, this study assumes that the exposure frequency of heavy metals in each land use type is the same; however, this assumption may not be entirely true. Thus, further consideration is needed in future research.

Due to data constraints, this paper only selects the above seven variables in the selection of impact factors, which lacks the analysis of socioeconomic factors. In addition, as the research results show that the pollution degree is relatively light, coupled with technical and time constraints, this article does not track and analyze the relatively high pollution areas. These are the directions that need to be breakthrough in the next research.

## Conclusion

Cr, Cu, Zn, and Pb accumulate in different degrees in the study area. The order of over-standard rate is  $Cu > Pb > Zn > Cr$ , and the degree of variation from strong to weak is  $Pb > Zn > Cu > Cr$ . The spatial heterogeneity of Cu and Zn is greatly affected by

spatial structural factors and primary structures. The spatial heterogeneity of Cr and Pb is the result of the interaction of human and natural factors.

Moderate or more than moderate pollution of heavy metals in the soil is not observed in the study area, and most of the metals are non-polluting. Among the metals, Cr shows the lightest pollution, while Pb shows the heaviest. The pollution characteristics of the four heavy metals in cropland and construction land are more significant than those in other land use types, and the pollution in forestland is relatively light.

Potential ecological risks can be divided into three levels: slight, moderate, and intense. The single-factor potential risks presented by the four heavy metals are relatively high in the northwest and low in the southeast. High-risk areas are concentrated near Xinbao Village, and risk gradually decreases from the center to the surrounding areas. Cr and Zn present slight ecological risks, the risk of Cu and Pb pollution is distributed in three grades, and the area distribution ratio is moderate > intense > slight. From the perspective of comprehensive potential ecological risks, most study areas reveal moderate ecological risks, and intense ecological risks are mainly distributed in and around Xinbao Village in the north. Potential ecological risks in cultivated land and construction land are more serious.

A significant positive correlation exists between human health risks and potential ecological risks in the study area, and the spatial distribution characteristics are similar. DEM and NDVI are the main factors affecting the risk of soil heavy metals, and the effect of each factor after interaction is obviously stronger than that of single factor. Cultivated land is a land use type with high health risks. Children's health risks are higher than those of adults in this land type. Direct intake is the most important exposure route in this area. From the perspective of risk type, the non-carcinogenic effects of soil heavy metals on the human body are not significant, and Cr contributed the most to comprehensive non-carcinogenic risks. Although the cancer risk presented by the metals is within an acceptable range, it should still be taken seriously due to beyond the safe value.

**Acknowledgements** This research work was supported jointly by national key research program of China (Nos. 2016YFC0502300 and 2016YFC0502102), Western Light Talent Program (Category A) (No. 2018- 99), United fund of karst science research center (No. U1612441), Science and

Technology Plan of Guizhou Province of China (2017–2966), Chinese academy of science and technology services network program (No. KFJ-STS-ZDTP-036) and international cooperation agency international partnership program (Nos. 132852KYSB20170029, 2014–3), International cooperation research projects of the national natural science fund committee (No. 41571130074 & 41571130042).

## References

- Al-Haidarey, M. J. S., Hassan, F. M., Al-Kubaisey, A. R. A., & Douabul, A. A. Z. (2010). The geoaccumulation index of some heavy metals in Al-Hawizeh Marsh, Iraq. *E-Journal of Chemistry*, 7, S157–S162. <https://doi.org/10.1155/2010/839178>.
- Alissa, E. M., & Ferns, G. A. (2011). Heavy metal poisoning and cardiovascular disease. *Journal of Toxicology*, 2011, 870125. <https://doi.org/10.1155/2011/870125>.
- ATSDR. (2003). Toxicological profile information sheet [EB / OL]. <http://www.atsdr.cdc.gov/toxprofiles>.
- Bai, J. H., Yang, Z. F., Cui, B. S., Gao, H. F., & Ding, Q. Y. (2010). Some heavy metals distribution in wetland soils under different land use types along a typical plateau lake China. *Soil and Tillage Research*, 106(2), 344–348. <https://doi.org/10.1016/j.still.2009.11.003>.
- Burgos, P., Madejon, E., Perez-De-Mora, A., & Cabrera, F. (2006). Spatial variability of the chemical characteristics of a trace-element-contaminated soil before and after remediation. *Geoderma*, 130(1–2), 157–175. <https://doi.org/10.1016/j.geoderma.2005.01.016>.
- Cai, G., Zhang, X., Liang, M., Ye, L., & Jiang, J. (2014). Health risk assessment of heavy metals pollution in farmland soil surrounding Dachang ore district in Nandan. *Journal of Guilin University of Technology*, 34, 554–559.
- Center, N. E. M. (1990). Background values of soil elements in China.
- Chen, H. Y., Teng, Y. G., Lu, S. J., Wang, Y. Y., & Wang, J. S. (2015). Contamination features and health risk of soil heavy metals in China. *Science of the Total Environment*, 512, 143–153. <https://doi.org/10.1016/j.scitotenv.2015.01.025>.
- Chen, J., Zhang, H., He, X., Cao, S., & Yang, G. (2010). Distribution and evaluation on potential ecological risk of heavy metals in soils of Huzhou. *Soils*, 42, 595–599.
- Chen, X., Ma, J., Li, X., Liu, D., & Li, Y. (2014). Health risk assessment of soil heavy metals in residential communities built on brownfields. *Environmental Science*, 35, 1068–1074.
- Fernandez, J. A., & Carballeira, A. (2001). Evaluation of contamination, by different elements, in terrestrial mosses. *Archives of Environmental Contamination and Toxicology*, 40(4), 461–468.
- Gu, Y., & Gao, F. (2017). Spatial distribution and health risk assessment of heavy metals in provincial capital cities, China. *Environmental Chemistry*, 36, 62–71.
- Hakanson, L. (1980). An ecological risk index for aquatic pollution control: A sedimentological approach. *Water Research*, 14, 975–1001.
- Hasan, A. B., Kabir, S., Reza, A. H. M. S., Zaman, M. N., Ahsan, A., & Rashid, M. (2013). Enrichment factor and geo-accumulation index of trace metals in sediments of the ship breaking area of Sitakund Upazilla (Bhatary-Kumira), Chittagong, Bangladesh. *Journal of Geochemical Exploration*, 125, 130–137. <https://doi.org/10.1016/j.gexplo.2012.12.002>.
- Huang, J. H., Liu, W. C., Zeng, G. M., Li, F., Huang, X. L., Gu, Y. L., et al. (2016). An exploration of spatial human health risk assessment of soil toxic metals under different land uses using sequential indicator simulation. *Ecotoxicology and Environmental Safety*, 129, 199–209. <https://doi.org/10.1016/j.ecoenv.2016.03.029>.
- Jiang, Y. X., Zeng, X. C., Fan, X. T., Chao, S. H., Zhu, M. L., & Cao, H. B. (2015). Levels of arsenic pollution in daily foodstuffs and soils and its associated human health risk in a town in Jiangsu Province, China. *Ecotoxicology and Environmental Safety*, 122, 198–204. <https://doi.org/10.1016/j.ecoenv.2015.07.018>.
- Jiao, X., Teng, Y., Zhan, Y., Wu, J., & Lin, X. (2015). Soil heavy metal pollution and risk assessment in Shenyang industrial district Northeast China. *PLoS One*, 10(5), e0127736. <https://doi.org/10.1371/journal.pone.0127736>.
- Khlifi, R., & Hamza-Chaffai, A. (2010). Head and neck cancer due to heavy metal exposure via tobacco smoking and professional exposure: A review. *Toxicology and Applied Pharmacology*, 248(2), 71–88. <https://doi.org/10.1016/j.taap.2010.08.003>.
- Kim, N. H., Hyun, Y. Y., Lee, K. B., Chang, Y., Rhu, S., Oh, K. H., et al. (2015). Environmental heavy metal exposure and chronic kidney disease in the general population. *Journal of Korean Medical Science*, 30(3), 272–277. <https://doi.org/10.3346/jkms.2015.30.3.272>.
- Li, C. F., Cao, J. F., Lu, J. S., Yao, L., & Wu, Q. Y. (2018). Ecological risk assessment of soil heavy metals for different types of land use and evaluation of human health. *Huan Jing Ke Xue*, 39(12), 5628–5638. <https://doi.org/10.13227/j.hjke.201804228>.
- Li, P., Zhang, B., Wang, W., & Gao, P. (2016). Contamination and risk assessment of heavy metal in urban soils of China. *China Population Resources & Environment*, 26, 88–90.
- Li, Q., Wu, Q., Gao, J., Ma, J., Xu, Q., & Yu, S. (2015). Distribution of heavy metals in topsoils affected by land use patterns at a small watershed scale: a case study in the Bantou Reservoir watershed in Xiamen, China. *Acta Ecologica Sinica*, 35, 5486–5494.
- Li, Z. Y., Ma, Z. W., van der Kuijp, T. J., Yuan, Z. W., & Huang, L. (2014). A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment. *Science of the Total Environment*, 468, 843–853. <https://doi.org/10.1016/j.scitotenv.2013.08.090>.
- Lingming, L., Yu, D., Chen, Y., Song, W., Liang, D., & Wang, Z. (2014). Spatial distribution and sources of heavy metals in soils of Jinghui Irrigated Area of Shaanxi, China. *Transactions of the Chinese Society of Agricultural Engineering*, 30, 88–96. <https://doi.org/10.3969/j.issn.1002-6819.2014.06.011>.
- Liu, F., Yu, L., Wu, H., & Xu, B. (2015). Survey of the content of cadmium and lead in rural soil, Ningxia. *Modern Preventive Medicine*, 42, 798–800.

- Liu, Q., Wang, J., Shi, X., Zhang, Y., & Wang, Q. (2008a). Health risk assessment on heavy metals in soil based on GIS-A case study in Cixi City of Zhejiang Province. *Chinese Journal of Soil Science*, 39, 634–640. <https://doi.org/10.19336/j.cnki.trtb.2008.03.035>.
- Liu, Q., Wang, J., Wang, Q., Zhang, J., & Zhang, Y. (2008b). Potential ecological risk assessment of heavy metal in soils based on GIS. *Science of Surveying & Mapping*, 33, 90–92. <https://doi.org/10.3771/j.issn.1009-2307.2008.03.031>.
- Liu, Y., Zhang, I., Han, X., Zhuang, T., Shi, Z., & Lu, X. (2012). Spatial variability and evaluation of soil heavy metal contamination in the urban-transect of Shanghai. *Environmental Science*, 33, 599–605.
- Luo, X. S., Ding, J., Xu, B., Wang, Y. J., Li, H. B., & Yu, S. (2012). Incorporating bioaccessibility into human health risk assessments of heavy metals in urban park soils. *Science of the Total Environment*, 424, 88–96. <https://doi.org/10.1016/j.scitotenv.2012.02.053>.
- Ma, J., Wang, X., Hou, Q., & Duan, H. (2011). Pollution and potential ecological risk of heavy metals in surface dust on urban kindergartens. *Geographical Research*, 30, 486–495.
- Ma, Z., Li, T., Qu, C., Bi, J., & Huang, L. (2014). Evaluation and source identification of trace element contamination of soils in the Qixia lead-zinc mining area, Jiangsu China. *Journal of Soils and Sediments*, 14(10), 1703–1712. <https://doi.org/10.1007/s11368-014-0900-x>.
- Mamattursun, E., Ajigul, M., Anwar, M., & Ma, G. (2017). Assessment of heavy metal pollution and its potential ecological risks of farmland soils of oasis in bosten lake basin. *Acta Geographica Sinica*, 72, 1680–1694. <https://doi.org/10.11821/dlxb201709012>.
- Man, Y. B., Sun, X. L., Zhao, Y. G., Lopez, B. N., Chung, S. S., Wu, S. C., et al. (2010). Health risk assessment of abandoned agricultural soils based on heavy metal contents in Hong Kong, the world's most populated city. *Environment International*, 36(6), 570–576. <https://doi.org/10.1016/j.envint.2010.04.014>.
- MEPPRC. (2014). Technical guidelines for risk assessment of contaminated sites. In *Ministry of environmental protection of the People's Republic of China, Beijing*.
- Olawoyin, R., Oyewole, S. A., & Grayson, R. L. (2012). Potential risk effect from elevated levels of soil heavy metals on human health in the Niger delta. *Ecotoxicology and Environmental Safety*, 85, 120–130. <https://doi.org/10.1016/j.ecoenv.2012.08.004>.
- Pan, Q., & Pan, F. (2015). Status and assessment of heavy metal pollution in soils of metallurgical cities in Hunan Province. *Jiangsu Agricultural Sciences*, 43, 405–410.
- Qian, Y., Yu, H., & Wang, L. (2013). Spatial distribution of heavy metal content in the farm lands from Midong district of Urumqi. *Arid Land Geography*, 30, 88–96. <https://doi.org/10.13826/j.cnki.cn65-1103/x.2013.02.012>.
- Sport, G. A. O. (2011). Guizhou Provincial People's Physical Fitness Monitoring Bulletin 2010. <https://www.sport.gov.cn/n316/n338/c213051/content.html>.
- Tian, S. Q., Wang, S. J., Bai, X. Y., Zhou, D. Q., Luo, G. J., Wang, J. F., et al. (2019). Hyperspectral prediction model of metal content in soil based on the genetic ant colony algorithm. *Sustainability*. <https://doi.org/10.3390/su11113197>.
- US EPA (1996). Soil screening guidance: technical background document.
- Wang, J., Li, X., Christakos, G., Liao, Y., Zhang, T., Gu, X., et al. (2010). Geographical detectors-based health risk assessment and its application in the neural tube defects study of the Heshun Region, China. *International Journal of Geographical Information Science*, 24, 107–127. <https://doi.org/10.1080/13658810802443457>.
- Wang, J., & Xu, C. (2017). Geodetector: Principle and prospective. *Acta Geographica Sinica*, 72, 116–134. <https://doi.org/10.11821/dlxb201701010>.
- Wang, Y., Liu, J., & Zhu, F. (2014). Study on the correlation of heavy metal exposure with Parkinson's disease. *Chinese Journal of Practical Nervous Diseases*, 17, 16–17.
- Wei, X., Gao, B., Wang, P., Zhou, H. D., & Lu, J. (2015). Pollution characteristics and health risk assessment of heavy metals in street dusts from different functional areas in Beijing, China. *Ecotoxicology and Environmental Safety*, 112, 186–192. <https://doi.org/10.1016/j.ecoenv.2014.11.005>.
- Wei, Z., Wang, D., Zhou, H., & Qi, Z. (2011). Assessment of soil heavy metal pollution with principal component analysis and geoaccumulation index. *Procedia Environmental Sciences*, 10, 1946–1952. <https://doi.org/10.1016/j.proenv.2011.09.305>.
- Wu, J., Song, J., Li, W., & Zheng, M. (2016). The accumulation of heavy metals in agricultural land and the associated potential ecological risks in Shenzhen China. *Environmental Science and Pollution Research*, 23(2), 1428–1440. <https://doi.org/10.1007/s11356-015-5303-z>.
- Xu, X. H., Zhao, Y. C., Zhao, X. Y., Wang, Y. D., & Deng, W. J. (2014). Sources of heavy metal pollution in agricultural soils of a rapidly industrializing area in the Yangtze Delta of China. *Ecotoxicology and Environmental Safety*, 108, 161–167. <https://doi.org/10.1016/j.ecoenv.2014.07.001>.
- Yang, Y., Shi, X., & Zhang, C. (2016). Spatial distribution and evaluation of heavy metal pollution of reclaiming village based on nemerow integrated pollution index method. *Research of Soil & Water Conservation*, 23, 338–343. <https://doi.org/10.13869/j.cnki.rswc.2016.04.043>.
- Yao, Z. (2011). The harm of lead to human health. *Studies of Trace Elements and Health*, 28, 67–68.
- Zhang, L., Mo, Z., Qin, J., Chen, Z., Xiong, Y., Wei, Y., et al. (2014). Contamination of heavy metals in soils and health risk assessment in children in a downstream village of Dachang mining area in Guangxi. *Journal of Environment & Health*, 31, 512–516. <https://doi.org/10.16241/j.cnki.1001-5914.2014.06.023>.
- Zheng, R., Zhao, J., Zhou, X., Ma, C., Wang, L., & Gao, X. (2016). Land use effects on the distribution and speciation of heavy metals and arsenic in coastal soils on chongming island in the Yangtze River Estuary China. *Pedosphere*, 26(1), 74–84. [https://doi.org/10.1016/S1002-0160\(15\)60024-8](https://doi.org/10.1016/S1002-0160(15)60024-8).
- Zhong, X., Zhou, S., & Zhao, Q. (2007). Spatial characteristics and potential ecological risk of soil heavy metals contamination in the Yangtze River delta—a case study of Taicang city, Jiangsu Province. *Scientia Geographica Sinica*, 27, 395–400.
- Zong, Q., Dou, L., Hou, Q., Yang, Z., You, Y., & Tang, Z. (2017). Regional ecological risk assessment of soil heavy

metals in pearl river delta economic zone based on different land uses. *Advances in Earth Science*, 32, 875–884.

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.