



Distribution characteristics and pollution assessment of soil heavy metals over a typical nonferrous metal mine area in Chifeng, Inner Mongolia, China

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Abstract

The spatial distribution characteristics of heavy metals (As, Cd, Cu, Pb, and Zn) in a typical lead–zinc mine located in Inner Mongolia were studied by applying mathematical statistics and the ArcGIS spatial interpolation analysis. The Nemerow index and potential ecological-risk index were applied to the pollution assessment of heavy metals from the soil in accordance with the Environmental Quality Standard for Soils of China (grade 2) and background value for heavy metals. Results indicated that the average concentrations of As, Cd, Cu, Pb, and Zn were 82.39, 1.01, 33.47, 96.47, and 254.64 mg kg⁻¹, respectively, and these values were higher than the regional background values in the studied scale. The average single-factor index (P_i) values of As, Cd, Cu, Pb, and Zn were 6.46, 6.61, 1.81, 3.93, and 4.02, respectively, when the regional background value was used as the assessment standard. Based on the Nemerow pollution index (P_N), all areas over the mine were in moderate or heavy pollution. The result of potential ecological-risk assessment showed that the mining-activity area and its surrounding areas were in the moderate risk level or above. Pollution was concentrated in the centre mining-activity area of tailing reservoir, concentrator, and waste dumps. The degree of heavy-metal pollution decreased with increased distance from the mining-activity area.

Keywords Inner Mongolia · Heavy-metal pollution · ArcGIS · Spatial distribution · Pollution assessment

Introduction

With the development of the society and economy, the exploitation of mineral resources is accelerating. This type of exploitation causes a series of serious ecological and environmental problems, among which the pollution of heavy metals in soil is one of the most crucial environmental problems and is also a global problem. This type of pollution in soils is serious and widely distributed in China (Guo et al.

2011; Zhou and Guo 2015; Cheng 2003; Li et al. 2014). A large number of heavy metals are enriched in the soil of mining areas (Zhao et al. 2012) due to the direct discharge of mining wastewater and mineral processing waste liquid and the piling and leaching of solid waste, such as waste rock and tailings.

Treating heavy-metal pollution with the characteristics of concealment, hysteresis, accumulation, and irreversibility in soil is difficult, and they can be directly or indirectly harmful to human health by polluting surface water or enriching crops (Zou et al. 2013; Mico et al. 2006; Zhang et al. 2016). At present, the research on heavy metals in mining areas mainly focuses on the assessment, characteristics, mechanism, ecological remediation, and biological effects of heavy-metal pollution. The study involves farmland, city, water area, grassland ecosystem, and other ecosystems around the mining area (Lei et al. 2010; Bermea et al. 2010; Escarre et al. 2009; Guo et al. 2011). Heavy-metal pollution caused by mining, processing, transportation, and storage of ore and the accumulation of tailings in the grassland landscape area will have a significant effect on the local

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grassland, residents, livestock, etc. (Kang and Bai 2005), and harm the grassland ecosystem. Therefore, studying the heavy-metal pollution in the grassland mining area and surrounding soil is significant.

The characteristics of heavy-metal pollution in the soil of a typical nonferrous metal mine in Inner Mongolia and its surrounding areas were investigated and analysed, and the Nemerow index and potential ecological-risk index (RI) methods were applied to assess the pollution. The aim of this paper is to provide a scientific theoretical basis for heavy-metal pollution control and ecological restoration in mining areas and reduce the harm of heavy metals to human health and the local grassland ecosystem in the process of mineral exploitation.

Materials and methods

The Laogenba lead–zinc mine is located in the southern section of the Da Hinggan Mountain in China, in the northern part of Chifeng, Inner Mongolia (Fig. 1). The mine is a skarn deposit, and the ore and mineral assemblage includes chalcopyrite, galena, sphalerite, and arsenopyrite. The mining area is a middle–low mountainous area with an altitude of

930–1240 m. The climate is dry with a semi-arid continental climate. The annual temperature difference is significant. The annual precipitation is 293–480 mm, with an average of 397.7 mm. The dominant wind direction is northwest, and the maximum wind speed is 18.70 m/s. The surface vegetation is mainly grassland and a small amount of woodland in the mine region, and the surrounding area is pasture, where the degraded grassland has formed to some extent within a certain range. A seasonal river is 500 m below the tailing reservoir. The soil type is brown and grey loam, with a few roots, and the pH value of the soil ranges from 6.2 to 7.4.

This study collected a total of 88 samples (Fig. 1), among which 82 samples from the surface soil and six samples from the deep layer (100–120 cm) were collected southeast of the reservoir at different distances (0, 20, 50, 100, 200, and 500 m) from the tailing reservoir dam. Thirty regional background samples were collected with equal intervals of approximately 2 km in the small watershed keeping away from the mining area; the rest of the samples were collected in and around the mining area. All samples were collected from July to August 2017.

The samples were naturally dried in a room without pollution. After air-drying, the samples were crushed with wood hammer to pass through a 20-mesh (aperture

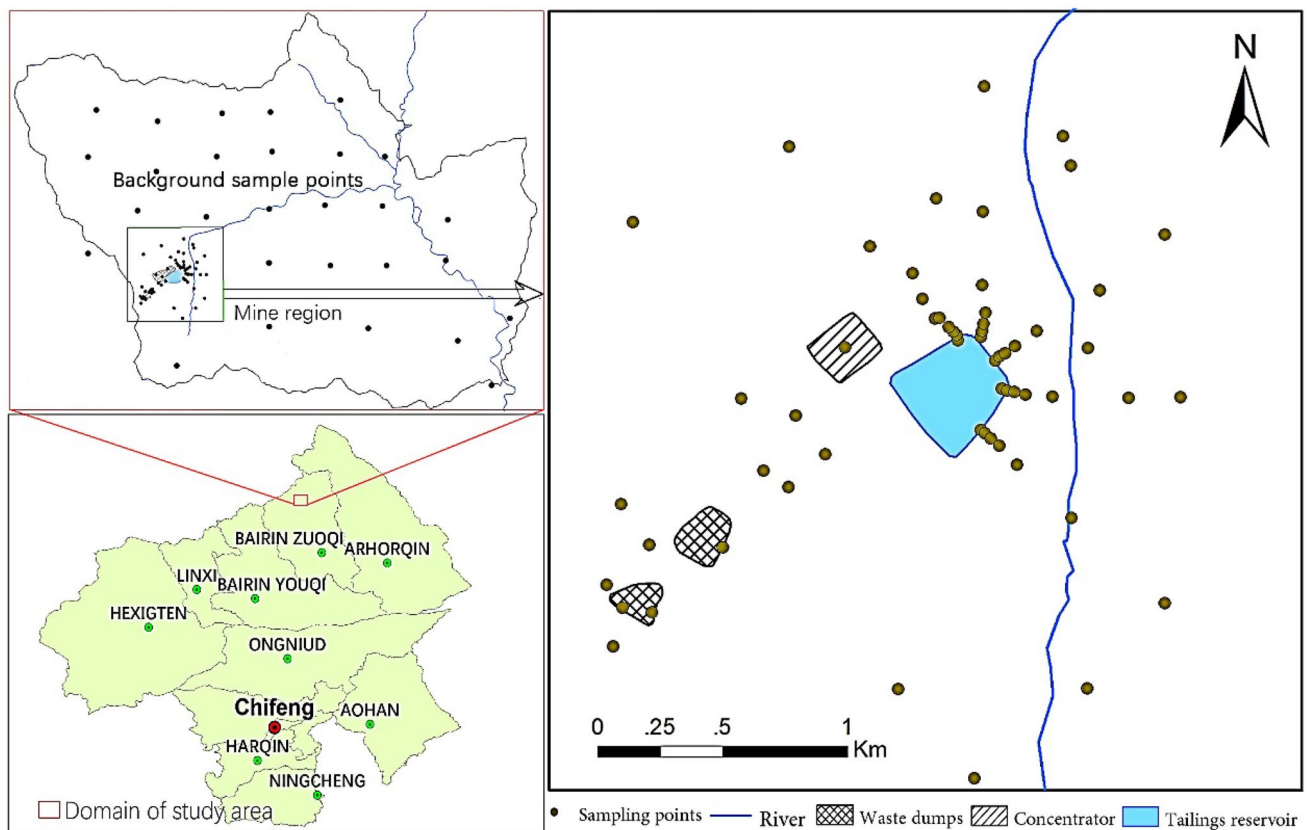


Fig. 1 Location map of the studied area indicating sampling points

of 0.25 mm) nylon sieve after removing stones and plant material and sealed in plastic bags for laboratory studies.

Each soil sample was digested with perchloric and nitric acids (HNO₃) at 140 °C for 8 h. The solution was evaporated at approximately 180 °C after cooling down completely. The sample was evaporated again when hydrofluoric acid (HF) was added just after the first evaporation. To dissolve the silicate minerals completely, the treatment with HF was repeated several times. Finally, the residual solution was diluted with HNO₃ and filtered through a syringe filter (Qin et al. 2016). The concentration of As was determined by atomic fluorescence spectrometry, and the rest of the heavy-metal elements were determined by inductively coupled plasma mass spectrometry.

The statistical analysis of all the data detected was completed using Excel 2016, and the Pearson correlation analysis was achieved using SPSS 18.0. The sampling point distribution map and spatial interpolation analysis were accomplished using ArcGIS 10.5.

The pollution assessment was based on the single-factor, Nemerow comprehensive pollution index, and potential ecological RI. The single-factor index can reflect the cumulative pollution degree of heavy-metal elements (Fan et al. 2010). The formula is as follows:

$$P_i = C_i/S_i, \tag{1}$$

where P_i is the environmental quality index of pollutant i in soil. P_i of each metal was classified as no pollution ($P_i \leq 1$), low level of pollution ($1 < P_i \leq 2$), moderate level of pollution ($2 < P_i \leq 3$), and high level of pollution ($P_i > 3$) (Rukeya et al. 2018). C_i (mg/kg) indicates the actual measured concentration of pollutant i ; S_i (mg/kg) represents the environmental standard for soils of heavy metal i . In this paper, the secondary environmental quality standard for soils and the background value ($X + 2S$) in the studied area were selected as the criteria for pollution assessment.

The Nemerow comprehensive index (Nemerow 1974) is an assessment method established on the basis of the single-factor index, which can comprehensively reflect the pollution degree of heavy metals to the region and can be used to evaluate the soil quality or combined pollution in the whole region. The formula is as follows:

$$P_N = \sqrt{\left(\overline{P_i}^2 + P_{i(max)}^2\right)} / 2, \tag{2}$$

where P_N is the soil comprehensive pollution index, $\overline{P_i}$ denotes the average index of each pollutant in the soil, and $P_{i(max)}$ refers to the maximum value of the single-pollutant index in soil.

On the basis of the Nemerow comprehensive pollution index, heavy-metal pollution in soil can be divided into five grades (Guo et al. 2011) (Table 1).

Table 1 Criteria for the classification of soil heavy-metal pollution

Grade division	Nemerow pollution index	Pollution degree
I	$P_N \leq 0.7$	Clean (safe)
II	$0.7 < P_N \leq 1$	Relatively clean (alert limit)
III	$1.0 < P_N \leq 2$	Mild concentration
IV	$2.0 < P_N \leq 3$	Moderate pollution
V	$P_N > 3$	Heavy pollution

The potential ecological RI assessment method (Hakanson 1980) not only considers the content of heavy metals in soil, but also contacts the ecological effects, environmental effects, and toxicology of heavy metals together and quantitatively divides the potential ecological-risk degree of heavy metals. The formula is as follows:

$$E_r^i = T_r^i \times \frac{C_s^i}{C_n^i}, \tag{3}$$

$$RI = \sum_{i=1}^m E_r^i, \tag{4}$$

where C_s^i is the measured concentration of heavy metal i in the soil sample and C_n^i indicates the background concentration of heavy metal i . In this work, $X + 2S$ was applied as the background concentration of each individual metal; E_r^i represents the potential ecological-risk factor of single heavy metal; and T_r^i denotes the biological toxicity factor provided by Hakanson (T_r^i for As, Cd, Cu, Pb, or Zn is 10, 30, 5, 5, or 1, respectively); RI signifies the potential ecological-risk index, which is the sum of E_r^i . Hakanson defined five categories of E_r^i and four categories of RI, as shown in Table 2 (Wu et al. 2010).

Results and discussion

Statistical analysis

The SPSS was applied to measure the data of heavy-metal elements in all soil samples by K–S test method. Results showed that all the heavy-metal data were in accordance with the normal distribution.

Table 3 shows the description statistics results of heavy metals in background soils. The contents of As, Cd, Cu, Pb, and Zn in all background soil samples were lower than the second environmental quality standard for soils (GB15618-1995). The coefficient of variation of each heavy-metal detection data was less than 0.5, which indicates that the content of the same heavy metal in background soil samples

Table 2 Risk grade indexes and grades of the potential ecological risk of heavy-metal pollution

E_r^i	Potential ecological-risk grade	RI	Potential ecological-risk grade
< 40	Low risk	< 150	Low risk
40–80	Moderate risk	150–300	Moderate risk
80–160	Considerable risk	300–600	High risk
160–320	High risk	≥ 600	Significantly high risk
≥ 320	Significantly high risk		

Table 3 Description statistics of heavy metals in background soils (30 samples)

Heavy metal	Maximum concentration/ mg kg ⁻¹	Minimum concentration/ mg kg ⁻¹	Mean concentration/ mg kg ⁻¹	Standard deviation	Coefficient of variation	Limit for grade 2 ^a / mg kg ⁻¹
As	18.63	3.65	8.19	3.08	0.38	30.00
Cd	0.24	0.04	0.09	0.04	0.49	0.30
Cu	21.57	5.96	12.02	3.78	0.31	100.00
Pb	25.68	15.33	21.18	2.74	0.13	300.00
Zn	71.90	21.51	46.69	11.34	0.24	250.00

^aEnvironmental quality standard for soils, Ministry of Environmental Protection of China (GB15618-1995)

Table 4 Description statistics of heavy metals over the mine region (52 samples)

Heavy metal	Maximum concentration/ mg kg ⁻¹	Minimum concentration/ mg kg ⁻¹	Mean concentration/mg kg ⁻¹	Standard deviation	Coefficient of variation	Limit for grade 2/ mg kg ⁻¹	Background in studied scale/ mg kg ⁻¹
As	562.61	7.41	82.39	106.57	1.29	30.00	14.34
Cd	8.35	0.08	1.01	1.58	1.56	0.30	0.17
Cu	219.39	9.45	33.47	34.75	1.04	100.00	19.57
Pb	1431.70	20.91	96.47	198.50	2.06	300.00	26.65
Zn	1909.50	40.38	254.64	372.66	1.46	250.00	69.37

was relatively stable, and the data reflected the actual content of heavy metals in the regional background soil. The $X + 2S$ (background average value plus double standard deviation of a heavy metal) was used as the assessment standard due to the high background value in the mining area. Zeng et al. (1999), Xing and Chen (2008), and Li et al. (2008) evaluated the soil heavy-metal pollution using $X + 2S$ as the standard.

Table 4 presents the results of the descriptive statistical analysis of heavy metals for the surface soil samples of the mining area and its surrounding areas. The average values of As, Cd, Cu, Pb, and Zn were 82.39, 1.01, 33.47, 96.47, and 254.64 mg kg⁻¹, respectively, in which As, Cd, and Zn values were higher than the second environmental quality standard for soils. In addition, the values of all the heavy metals studied were higher than the regional background values, which indicates that the mining activities have a significant effect on the contents of heavy metals in soil. With the second environmental quality standard for soils, the over-standard rates of As, Cd, Cu, Pb, and Zn were 58%, 56%, 5%, 5%, and 24%, respectively. The exceeding rates of

Table 5 Correlations among heavy-metal contents in soils over the mine region

Heavy metal	As	Cd	Cu	Pb	Zn
As	1				
Cd	0.757	1			
Cu	0.543	0.832	1		
Pb	0.644	0.889	0.803	1	
Zn	0.717	0.986	0.836	0.857	1

As, Cd, Cu, Pb, and Zn at 78%, 71%, 64%, 78%, and 71%, respectively, were high when the background value is the standard.

The correlation of 52 soil samples from the mining area was analysed with SPSS 18.0 to determine the extent of the relationships between heavy metals. The results (Table 5) show that As, Cd, Cu, Pb, and Zn were closely related to each other. Thus, As, Cd, Cu, Pb, and Zn in soil have similar sources or pollution degree (Liao 2005), which indirectly

suggests that mining activities have a significant effect on the contents of these heavy metals in soil.

Spatial distribution characteristics of heavy metals

ArcGIS provides several types of spatial interpolation method. The Kriging interpolation method is mostly used for the spatial interpolation analysis of soil heavy-metal content, but the fitting degree of the result obtained by natural neighbourhood interpolation is higher than that by Kriging interpolation when sample collection is scattered and considerably uneven. Therefore, by considering the spatial distribution of sample points, as shown in Fig. 1, this study applied the natural neighbourhood method (Sibson 1981) to complete the spatial interpolation analysis.

In accordance with the data of heavy-metal contents in soil samples from the mining area, the spatial distribution maps of heavy-metal elements were obtained (Fig. 2). The maps show that the distribution characteristics of As, Cd, Pb, Zn, and Cu were similar and that heavy metals were mainly distributed in the mining-activity area, especially

in the tailing reservoir and waste rock dumps areas, which indicates that mining activities were the main cause of heavy-metal pollution in soil. The contents of heavy metals in soils decreased with increased distance from the mining-activity area. At the same time, the contents of heavy metals were significantly high in the southeast of the tailing reservoir, compared with other directions.

In the field investigation, the sand in the tailing reservoir was found to be transported under the wind and settled on the ground, which resulted in considerable tailings sand accumulation in a certain range of the surface around the tailing reservoir. To analyse the heavy-metal pollution in two different depths at different distances caused by the dominant wind (northwest wind) on tailings sand transport, six samples from the deep layer (C layer or regolith, 100–120 cm) were collected at different distances (0, 20, 50, 100, 200, and 500 m from the tailing reservoir dam) in the southeast of the reservoir. Six other samples at the same location were collected from the surface layer (0–20 cm) of the soil.

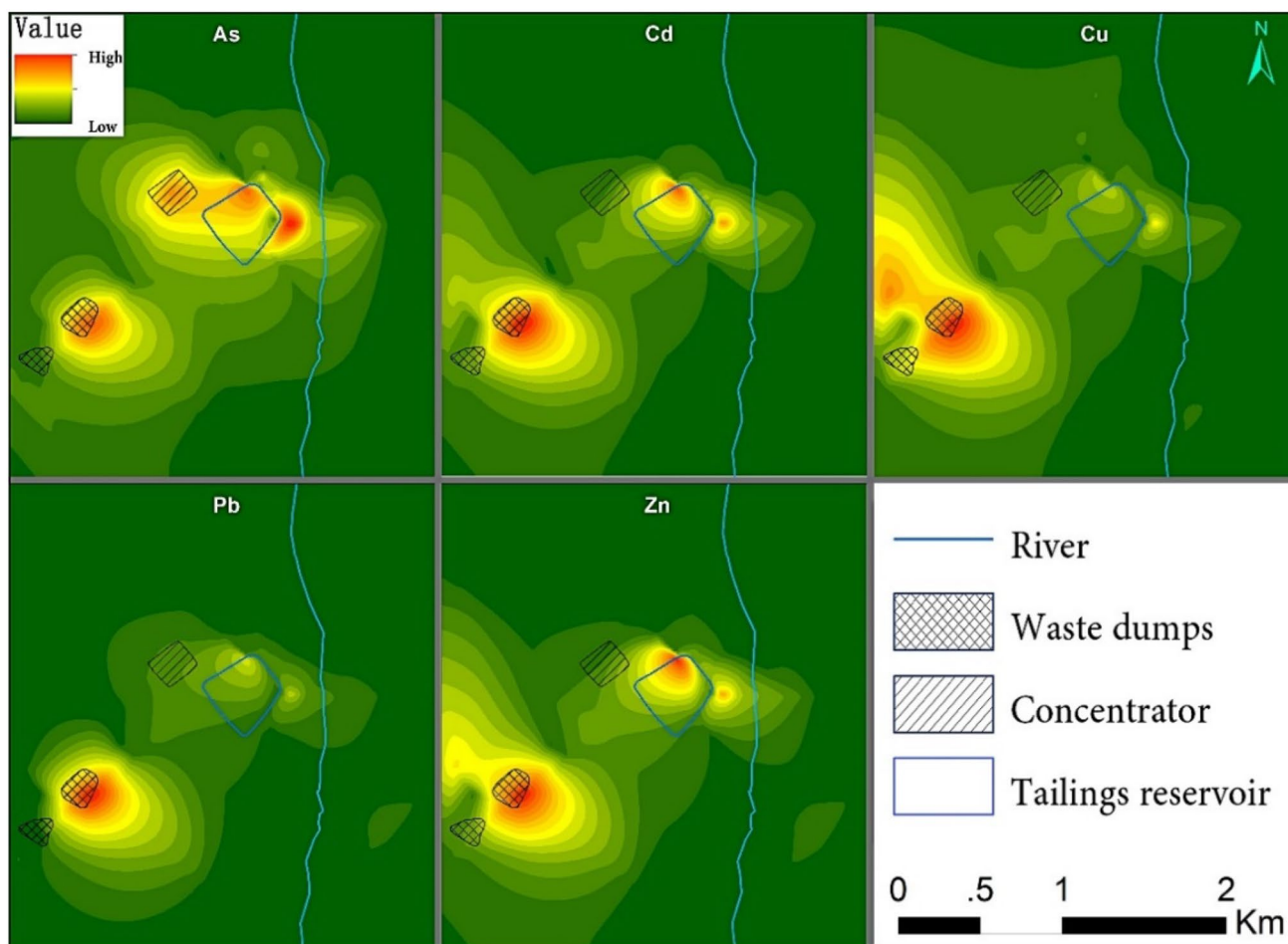


Fig. 2 Spatial distribution of soil heavy metal in the mine region

The contents of all heavy metals in deep soil are relatively stable compared with the contents in surface soil (Fig. 3). The contents of heavy metals with large changes in surface soil also change relatively obviously in deep soil. This means that the heavy metals in surface soil have affected the deep soil to some extent no matter how large the effect is. The results (Fig. 4) show that the contents of As, Cd, Cu, Pb, and Zn in all surface soil samples were higher than those in deep soil samples, which means that the tailing reservoir has a significant influence on the contents of heavy metals in the surfaces soil. Meanwhile, the contents of heavy metals in the deep soil remained relatively stable, which indicates that deep soils have not been affected significantly by mining activities temporarily, but the impact is likely to become larger as time goes by. With increased distance from the tailing reservoir, the contents of As, Cd, Cu, Pb, and Zn in the surface soil initially increased, then decreased continuously and remained close to the content in the deep soil at > 200 m distance. As the tailings dam has a certain height, the settlement of tailings gradually increases within 50 m from the tailings dam, but not the closer to the tailing reservoir, the more the settlement accumulation.

Assessment based on the single-factor and Nemerow indexes

The pollutions were assessed for eight areas (Table 6) in accordance with the second environmental quality standard for soils. The table shows that the average values of single pollution indexes of As, Cd, Cu, Pb, and Zn were 3.09, 3.74, 0.35, 0.35, and 1.12, respectively. The P_i values of Cu and Pb were below 1; thus, the area was not contaminated by these heavy metals. The P_i value of Zn was between 1 and 2, indicating a low level of pollution. The P_i values of As and Cd surpassed 3, indicating high levels of pollution. On the basis of the Nemerow index, the heavy-metal pollution around waste dumps was the most serious, followed by tailing reservoir and concentrator, and

the periphery regions were the safe and clean grade. The pollution degrees varied significantly in different directions of the tailing reservoir and were ranked in the following order: E > SE > NE > N > NW. As the mining area is dominated by northwest wind, the soil heavy-metal pollution in the southeast direction of the tailing reservoir was serious. The north and northwest (upwind direction) of the tailing reservoir were less polluted. At the same time, under the influence of topography, overland flow migration and leakage of tailings water resulted in a high level of pollution in the east and northeast of the tailing reservoir.

Table 7 shows the results of the pollution assessment based on the regional background values. The single and Nemerow pollution indexes were higher than those in accordance with the secondary environmental quality for soils. All P_i values for heavy metals were more than 1. The average values of single-factor indexes of As, Cd, Cu, Pb, and Zn were 6.46, 6.61, 1.81, 3.93, and 4.02, respectively; all heavy-metal elements polluted the soils in different levels. On the basis of the Nemerow index, the relative order of pollution degree in the eight regions was the same as that in Table 5. Except that the periphery regions were relatively clean, other areas were in moderate or heavy pollution levels.

Figure 5 presents the spatial distribution of P_N . Graph (a) is based on the second environmental quality for soils, and Graph (b) is based on the regional background value of heavy metals. The figure shows that moderate and heavy pollutions were mainly concentrated in the mining-activity area centred by the tailing reservoir, concentrator, and waste dumps, and the periphery area followed was mild pollution, relative cleanliness and cleanliness. In addition, the southeast direction of the tailing reservoir extends farther, which indicates the influence of the dominant wind. The distribution range of heavy pollution reached and crossed the river under the two assessment standards, so heavy metals in soil would pollute the river and possibly affect other areas with the migration of heavy metals along the river. The

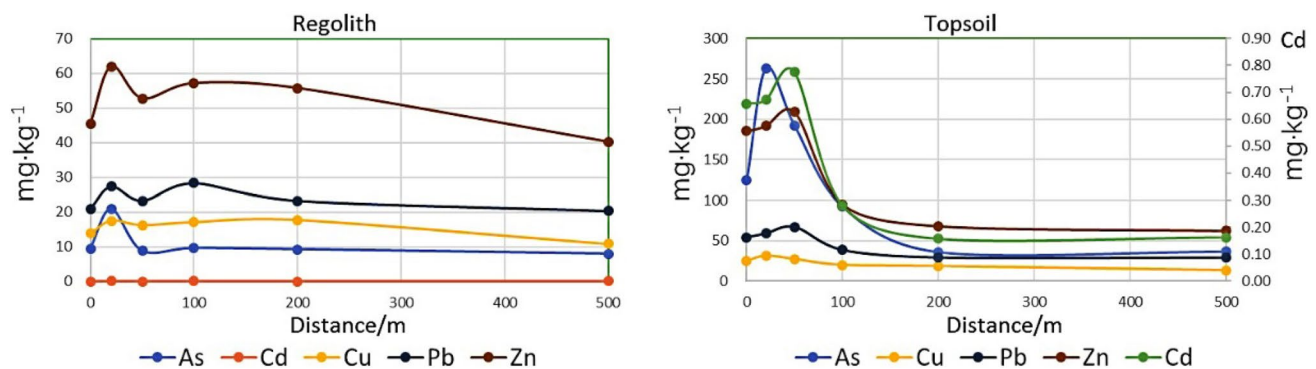


Fig. 3 Distribution of heavy metals in different depth in southeast of tailings reservoir

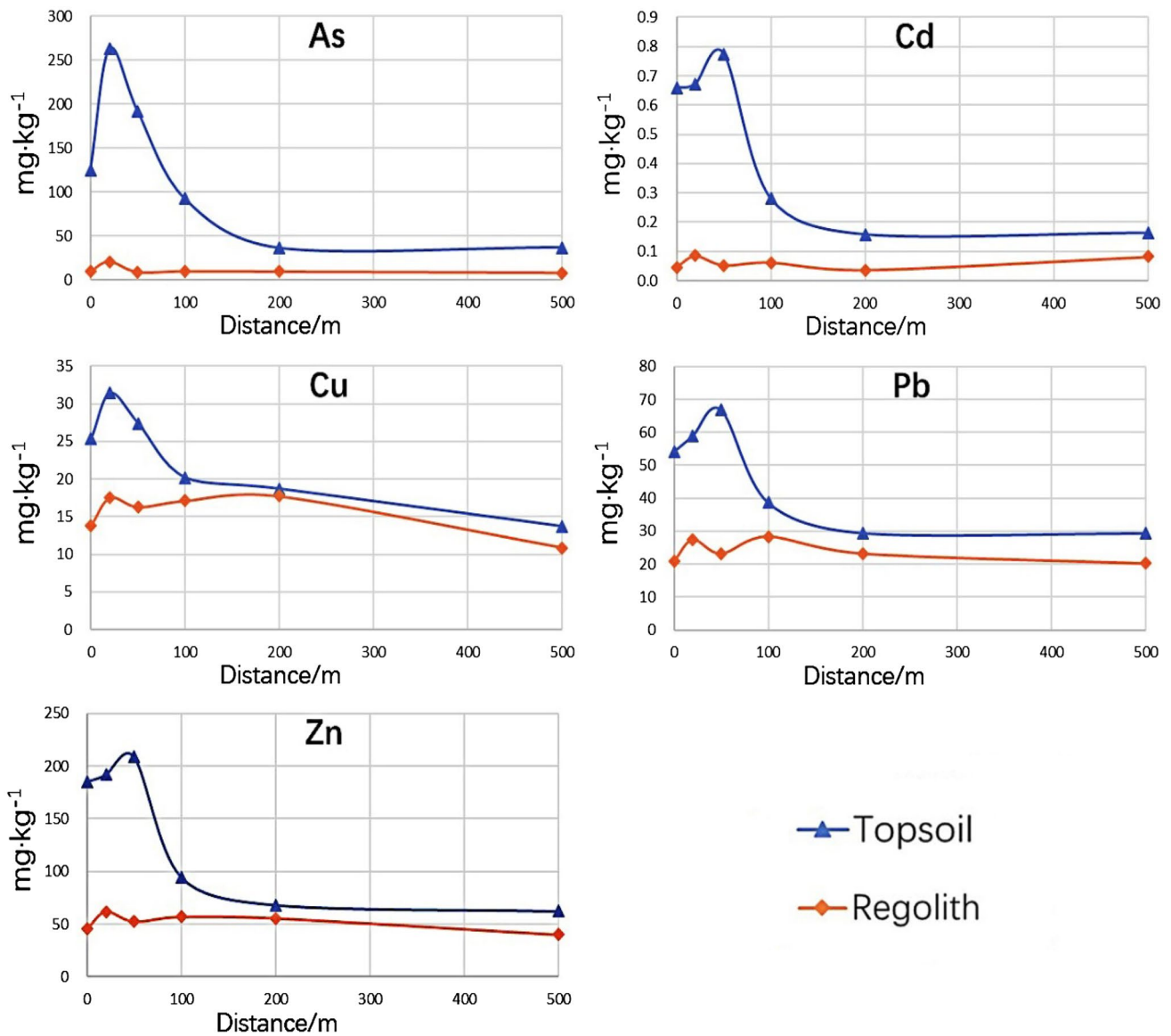


Fig. 4 Distribution of heavy metals in the southeast of the tailing reservoir

Table 6 Pollution appraisal indexes of soil heavy metal in the studied areas (1)

Sampling sites	Single-factor index (P_i)					P_N
	As	Cd	Cu	Pb	Zn	
Tailing reservoir (SE)	5.13	4.66	0.29	0.39	1.55	4.01
Tailing reservoir (E)	6.50	6.76	0.41	0.48	1.77	5.29
Tailing reservoir (NE)	3.83	4.10	0.29	0.34	1.14	3.20
Tailing reservoir (N)	2.67	2.40	0.26	0.25	0.71	2.09
Tailing reservoir (NW)	0.76	1.50	0.20	0.15	0.48	1.15
Waste dumps	2.56	7.12	0.87	0.79	2.14	5.38
Concentrator	2.86	2.89	0.35	0.30	0.88	2.29
Periphery regions	0.40	0.52	0.15	0.09	0.24	0.42
Mean	3.09	3.74	0.35	0.35	1.12	2.98

soil heavy-metal pollution grade was high and the pollution range was large when the background value was used as the assessment standard.

Assessment based on potential ecological RI

Table 8 presents the results of the E_r^i and RI calculations for the four regions. The results show that the E_r^i values for

Cu and Zn were less than 40 in all regions, which indicates that the two heavy metals had low potential ecological risk in the study area. E_r^i for Pb was less than 40 except in the waste dumps, and the average E_r^i for Pb was 21.24 in the four regions. Pb was also in the low-risk grade in the whole study area. The main heavy metals causing potential ecological hazards were As and Cd, especially Cd, the average value of which was 165.59, and the maximum value was 376.71,

Table 7 Pollution appraisal indexes of soil heavy metal in the studied areas (2)

Sampling sites	Single-factor index (P_i)					P_N
	As	Cd	Cu	Pb	Zn	
Tailing reservoir (SE)	10.74	8.22	1.50	4.39	5.60	8.13
Tailing reservoir (E)	13.61	11.93	2.11	5.42	6.39	10.31
Tailing reservoir (NE)	8.01	7.23	1.48	3.78	4.10	6.15
Tailing reservoir (N)	5.59	4.24	1.34	2.77	2.56	4.30
Tailing reservoir (NW)	1.58	2.66	1.03	1.74	1.73	2.12
Waste dumps	5.36	12.56	4.46	8.94	7.73	9.63
Concentrator	5.98	5.11	1.80	3.38	3.17	4.66
Periphery regions	0.84	0.92	0.78	1.02	0.88	0.95
Mean	6.46	6.61	1.81	3.93	4.02	5.78

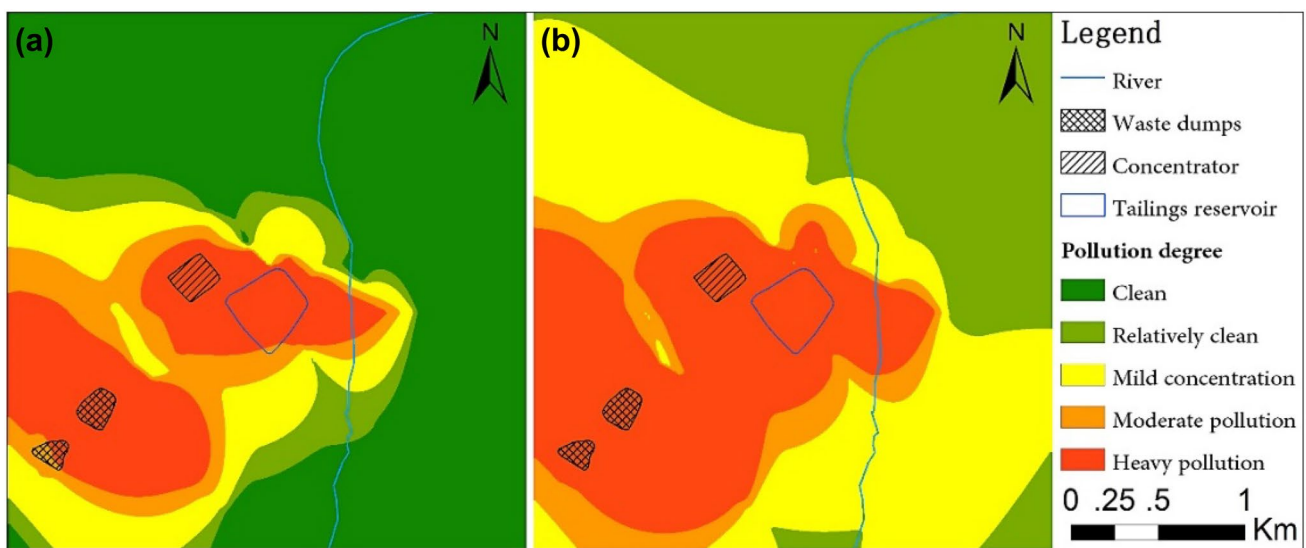


Fig. 5 Spatial distribution of the Nemerow pollution index in the mine region

Table 8 Potential ecological-risk factor of single metal and potential ecological RI

Station	Potential ecological-risk factor of single metal (E_r^i)					Potential ecological RI
	As	Cd	Cu	Pb	Zn	
Tailing reservoir	79.97	206.99	7.45	18.22	4.13	316.76
Waste dumps	53.57	376.71	22.32	44.70	7.73	505.04
Concentrator	59.77	51.08	9.00	16.90	3.17	139.91
Periphery regions	8.38	27.57	3.88	5.12	0.88	45.83
Mean	50.42	165.59	10.66	21.24	3.98	251.88

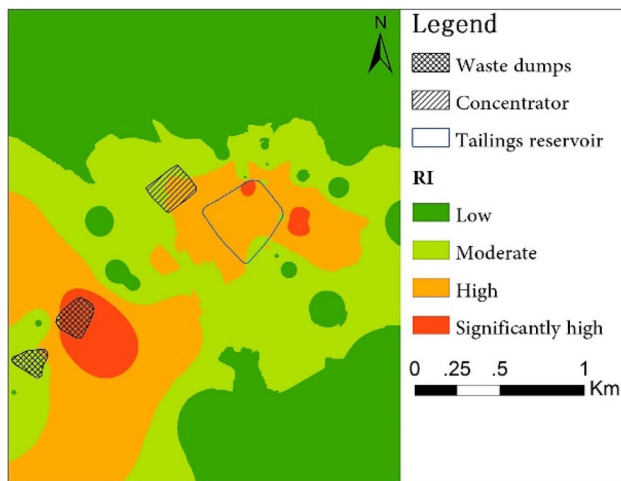


Fig. 6 Distribution of grades on potential ecological risk of heavy metals in soil

which appears in the waste rock dumps. All the E_r^i values for the heavy metals in the periphery regions were less than 40. At present, the periphery regions were in low risk, with the low RI value of 45.83. The RI values of waste dumps and the tailing reservoir were between 300 and 600, which indicated the high potential ecological-risk grade, and the RI values of the concentrator and periphery regions were lower than 150, which represented the low ecological-risk grade.

The spatial distribution figure of RI (Fig. 6) shows that the potential ecological risk of the waste dumps was the highest, followed by the tailing reservoir and concentrator. The mining-activity area and its surrounding areas were above the moderate risk level. The distribution of RI is consistent with the results in Table 8.

Conclusions

1. The surface soil in the mining area has been polluted by heavy metals (As, Cd, Cu, Pb, and Zn) in varying degrees. The heavy metals in the soils are mainly derived from the mining development activities, and the pollution has the characteristics of concentrated distribution and compound pollution. Heavy-metal pollution is mainly concentrated in the mining-activity area and its surrounding areas. At present, the deep-layer (C horizon) soils are almost free from heavy-metal pollution. The pollution degrees of heavy metals in different directions of the tailing reservoir are varied due to the influence of wind and topography and are ranked in the following order: E > SE > NE > N > NW.
2. With the regional background value as the assessment standard, the five heavy metals were all in the pollution state. With the average value of the Nemerow index

$P_N > 3$, the surface soil of this mine had been seriously polluted by heavy metals. The moderate and heavy pollution was mainly concentrated in the mining-activity area, which centred on the tailing reservoir, concentrators and waste dumps, whereas the periphery regions were in a clean, relatively clean, or slightly polluted state.

3. The main heavy metals causing potential ecological hazards were As and Cd. The waste dumps and tailing reservoir were the high potential ecological-risk grade. The potential ecological risk of the waste dumps was the highest, followed by the tailing reservoir and concentrator. The risk level of the mining-activity area and its surrounding areas was above the moderate risk, whereas the periphery regions was at the low-risk level.
4. The serious pollution of heavy metals in and around the mining area directly affects the health of livestock and the normal growth of vegetation in the surrounding pastures, and under the effects of wind and runoff migration, the contaminated range of heavy metals in the soil will expand. Therefore, conducting prevention and control work on pollution sources for the tailing reservoir, waste dumps and so on is urgent, to reduce the harm of pollution to the local ecosystem and the health of humans and animals.
5. The key to mitigating soil heavy-metal pollution is the efficient control of the pollution sources. In this study, the main pollution sources are the waste dumps and tailing reservoir. Biological method should be considered first due to its low cost, effectiveness and preferable ecological effect. The method of reclamation by planting hyperaccumulators after covering abandoned tailing reservoir with soils is suggested to control the pollution of the tailing reservoir. Planting trees around the tailing reservoir is also necessary especially in the southeast of the reservoir in case the pollution spreads farther, and the contaminated region should be fenced to keep the livestock out. Waste dumps can be used as building or filling materials for goaf stowing, for instance, waste rocks can be used in concrete production after being crushed. Moreover, biological reclamation after flattening and soil covering is also advisable.

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References

- Bermea OM, Alvarez EH, Lozano R (2010) Spatial distribution of heavy metals in top soils around the industrial facilities of

- Cromatosde Mexico, Tultitlan Mexico. *Bull Environ Contam Toxicol* 85:520–524
- Cheng S (2003) Heavy metal pollution in China: origin, pattern and control. *Environ Sci Pollut Res Int* 10:192–198
- Escarré J, Lefèbvre C, Raboyeau S (2009) Heavy metal concentration survey in soils and plants of the Les Malines mining district (Southern France): implications for soil restoration. *Water Air Soil Pollut* 201:485–504
- Fan S, Gan Z, Li M, Zhang Z, Zhou Q (2010) Progress of assessment methods of heavy metal pollution in soil. *Chin Agric Sci Bull* 26(17):310–315
- GB15618-1995 (1995) Environmental quality standard for soils (in China). Developed by Ministry of Ecology and Environment of the People's Republic of China
- Guo W, Zhao R, Zang J, Bao Y, Wang H, Yang M, Sun X, Jin F (2011) Distribution characteristic and assessment of soil heavy metal pollution in the iron mining of Baotou in Inner Mongolia. *Environ Sci* 32(10):3099–3105
- Hakanson L (1980) An ecological risk index for aquatic pollution control: a sediment logical approach. *Water Res* 14:975–1001
- Kang Z, Bai H (2005) Discussion on the necessity of legislation of grassland environmental protection. *Environ Dev* 17(1):65–66
- Lei M, Zhang Y, Khan S (2010) Pollution fractionation and mobility of Pb, Cd, Cu, and Zn in garden and paddy soils from a Pb-Zn mining area. *Environ Monit Assess* 168:215–222
- Li Z, Ma Z, Jan T, Der KV, Yuan Z, Huang L (2014) A review of soil heavy metal pollution from mines in China: pollution and health risk assessment. *Sci Total Environ* 468–469:843–853
- Li J, Zhang S, Zhou X, Xin R, Wang W (2008) Study on pollution and potential ecological risk assessment of heavy metals in soil in Daqing city. *Chin Agric Sci Bull* 24(11):428–432
- Liao G (2005) Research on the pollution assessment and the transport characteristics of heavy metals in a typical nonferrous metal mine. Dissertation, Central South University
- Micó C, Recatalá L, Peris M (2006) Assessing heavy metal sources in agricultural soils of an European Mediterranean area by multivariate analysis. *Chemosphere* 65(5):863–872
- Nemerow NL (1974) Scientific stream pollution analysis. Scripta Book Co, Washington
- Qin F, Wei C, Zhong S, Huang X, Pang W, Jiang X (2016) Soil heavy metals and risk assessment in vicinity of a coal mining area from southwest Guizhou, China. *J Cent South Univ* 23:2205–2213
- Rukeya S, Nijat K, Balati M, Li H, Abdugheni A, Abdusalam A, Miradil K (2018) Pollution characteristics and health risk assessment of heavy metals in the vegetable bases of northwest China. *Sci Total Environ* 642:864–878
- Sibson R (1981) A brief description of natural neighbor interpolation. Chap. 2 in interpolating multivariate data. Wiley, New York, pp 21–36
- Wu Y, Xu Y, Zhang J, Hu S (2010) Evaluation of ecological risk and primary empirical research on heavy metals in polluted soil over Xiaoqinling gold mining region, Shaanxi, China. *Trans Nonferrous Metals Soc China* 20(2010):688–694
- Xing R, Chen Y (2008) Comparison of several norms for soil contamination evaluation—an example from Hefei area. *Geol Anhui* 18(1):42–46
- Zeng Y, Luo T, Gu K, Xiao T, Zhang Q, Mao J, Gu C (1999) Environmental effect during the exploitation process of Zhimudang gold deposit: comparison of pollution situations. *Geol Geochem* 27(2):1–8
- Zhang L, Li H, Huang X, Li Y, Jiao K, Sun P, Wang W (2016) Soil heavy metal spatial distribution and source analysis around an aluminum plant in Baotou. *Environ Sci* 37(3):1139–1146
- Zhao R, Guo W, Bao Y, Yang H, Wang J (2012) Characteristics of heavy metals in soils from Bainaimiao copper mining area of grassland ecosystem in Inner Mongolia. *Chin J Soil Sci* 43(2):496–500
- Zhou H, Guo X (2015) Soil heavy metal pollution evaluation around mine area with traditional and ecological assessment methods. *J Geosci Environ Prot* 3:28–33
- Zou J, Sun J, Dai W, Yao Z, Yang T, Liu N (2013) Evaluation and analysis of heavy metals in cultivated soils in the suburbs of Beijing. *J Beijing For Univ* 35(1):132–138