



Quantitative risk analysis of sediment heavy metals using the positive matrix factorization-based ecological risk index method: a case of the Kuye River, China

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Received: 31 May 2023 / Accepted: 13 December 2023 / Published online: 16 January 2024
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Abstract Identifying the sources of heavy metals (HMs) in river sediments is crucial to effectively mitigate sediment HM pollution and control its associated ecological risks in coal-mining areas. In this study, ecological risks resulting from different pollution sources were evaluated using an integrated method combining the positive matrix factorization (PMF) and the potential ecological risk index (RI) model. A total of 59 sediment samples were collected from the Kuye River and analyzed for eight HMs (Zn, Cr, Ni, Cu, Pb, As, Cd, and Hg). The obtained results showed that the sediment HM contents were higher than the corresponding soil background values in Shaanxi Province. The average sediment Hg content was 3.42 times higher than the corresponding background value. The PMF results indicated that HMs in the sediments were mainly derived from industrial, traffic, agricultural, and coal-mining sources. The RI values ranged from 26.15 to 483.70. Hg was the major contributor (75%) to the ecological risk in the vicinity of the Yanjiata Industrial Park. According to the PMF-based RI model, coal-mining activities exhibited the

strongest impact on the river ecosystem (48.79%), followed, respectively, by traffic (34.41%), industrial (12.70%), and agricultural (4.10%) activities. These results indicated that the major anthropogenic sources contributing to the HM contents in the sediments are not necessarily those posing the greatest ecological risks. The proposed integrated approach in this study was useful in evaluating the ecological risks associated with different anthropogenic sources in the Kuye River, providing valuable suggestions for reducing sediment HM pollution and effectively protecting river ecosystems.

Keywords Sediment pollution · Source apportionment · Coal-mining · Potential ecological risks · PMF-based RI model

Introduction

Heavy metals (HMs) are highly toxic and characterized by high cumulative adsorption rates (Liu et al., 2016). Ecological risks associated with HM pollution have become a major concern for both academics and the public (Farkhondeh et al., 2020; Kumar et al., 2022). Indeed, HMs have been considered the main harmful inorganic pollutants threatening ecosystems. The Kuye River in China flows through the Shenfu-Dongsheng coalfield, which is one of the largest coal fields worldwide, where numerous bituminous coal and anthracite mining, washing industries, and other

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industries are located. According to statistics, bituminous coal, anthracite coal, and washing industries account for 78.12% of the total industrial output value of the Kuye River. Raw coal loading and unloading, open-air stacking of coal gangue, and large-scale coal transportation can result in several types of pollution, including particle pollution on the highway along roads and coal combustion-derived soot pollution from industrial activities. These pollution types can lead to HM release, directly or indirectly enriching river sediments (Lu et al., 2015). At present, river sediment management in China has shifted from a concentration-based approach to a strategy aiming to identify the main pollution sources (Wu et al., 2022). It is necessary to ensure green mining and clean production of raw coals through HM source analysis to effectively prevent environmental pollution by HMs.

The partitioning of major sources contributing to HM enrichment in sediments includes their qualitative identifications and quantitative contributions to HM contents (Liu et al., 2019). Numerous researchers have used the positive matrix factorization (PMF) model to quantitatively assess the sources of environmental pollution in several areas worldwide, as it has been recommended by the United States Environmental Protection Agency (USEPA) (Deng et al., 2020; Hao et al., 2022). Previous studies have used several methods to evaluate sediment HM pollution, including the single factor pollution index, Nemerow comprehensive index, geo-accumulation index, pollution load index, and potential ecological risk index (RI) methods (Li et al., 2021; Pandey et al., 2015). The applications of the RI method in sediment HM pollution comprehensively consider HM contents, toxicity levels of HM elements, and their associated pollution risks (Zhang et al., 2021). Indeed, this method is classic and was extensively used in previous studies on sediment HM pollution assessment (Shi et al., 2022a, b).

Due to the differences in the contributions of different sources to HM pollution and different toxicity coefficients of HM elements, the PMF method mainly considers the HM concentrations without taking into account other factors (e.g., toxicity coefficients and background element values). Although some anthropogenic sources may result in relatively high pollutant concentrations, their associated ecological risks may be low (Jiang et al., 2019; Shi et al., 2022a, b). In this context, previous related

studies have used the PMF-based RI approach to quantitatively assess the contributions of anthropogenic sources to HM pollution, taking into account contents, toxicity coefficients, and local background values of HMs in order to implement effective measures to protect ecosystem health (Li et al., 2018; Liu et al., 2018; Shi et al., 2022a, b).

At present, very few studies have quantitatively analyzed the contributions of anthropogenic sources to HM pollution in river sediments in the hinterland of mining areas in Northern Shaanxi, China. The PMF-based RI approach aims to quantify the contributions of different pollution sources and their combined ecological risks to effectively control and ensure ecosystem protection. The objectives of this study were to (1) explore the concentration characteristics and pollution levels of eight HMs (Cu, Zn, Pb, Cd, Ni, Cr, Hg, and As) (Hoshyari et al., 2023) in sediments in the study region; (2) identify and apportion the potential sources of HMs in the sediments using the PMF model; (3) establish an integrated approach to quantitatively assess the contributions of the potential HM sources to ecological risks using the PMF-based RI method. The results of this research provide a useful reference for the quantitative assessment of pollution sources, as well as further insights into the prevention of river sediments from pollution in coal-mining areas.

Materials and methods

Study area

Northern Shaanxi is an important coal base in the Loess Plateau, China, where the Kuye River (109°57'~110° 48' E; 38°24'~39° 28' N) is the main tributary of the middle Yellow River. The upper and middle reaches of the Kuye River are important coal industry production bases in China. These reaches were dominated by coal mining, washing, coking, and coal product manufacturing, as well as by thermal power generation enterprises. Indeed, Shenmu County in the study area was the first coal-producing county in China. On the other hand, large farmland and village areas are distributed downstream of the Kuye River.

Sediment sampling

In total, 59 sediment samples were collected in triplicate in September 2021 from the 0–10 cm sediment layer in the Kuye River. A global positioning system (GPS) instrument was used to record the geographic coordinates of the sampling sites (Fig. 1). Large impurities, such as plants and rocks, were removed from the collected sediment samples. The sediment samples were then placed in black polyethylene self-sealing bags and transported immediately to the laboratory for further analysis.

Sediment sample preparation and analysis

The collected sediment samples were first dried to constant weights in a freeze dryer, then sieved using a 100-mesh sieve and placed into airtight polyethylene bags. 0.5 g sediment samples were placed into a microwave digestion tank, and then 3 mL, 9 mL,

3 mL, and 3 mL of deionized water, concentrated nitric acid, hydrofluoric acid, and hydrochloric acid were added, respectively. The solutions were heated at 180 °C for 5 min, then boiled until reaching a sticky shape. It should be noted that the heating temperature for Hg was set at up to 100 °C. The solution samples were cooled and placed into 50 mL bottles to determine the Cu, Zn, Pb, Cd, Ni, and Cr contents using an inductively coupled plasma mass spectrometer (ICAP-QC, Thermo, USA) according to the HJ803-2016 standard. Whereas the Hg and As contents in the sediment samples were determined using a chromatography-atomic fluorescence spectrometer (AFSS922-SA20, Jitian, China) according to the HJ680-2013 standard. In addition, analytical quality control was performed in this study using GBW07423 soil standards (GSS-9, Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences), showing a recovery rate range of 100 ± 10%. The ultrapure water and chemical reagents

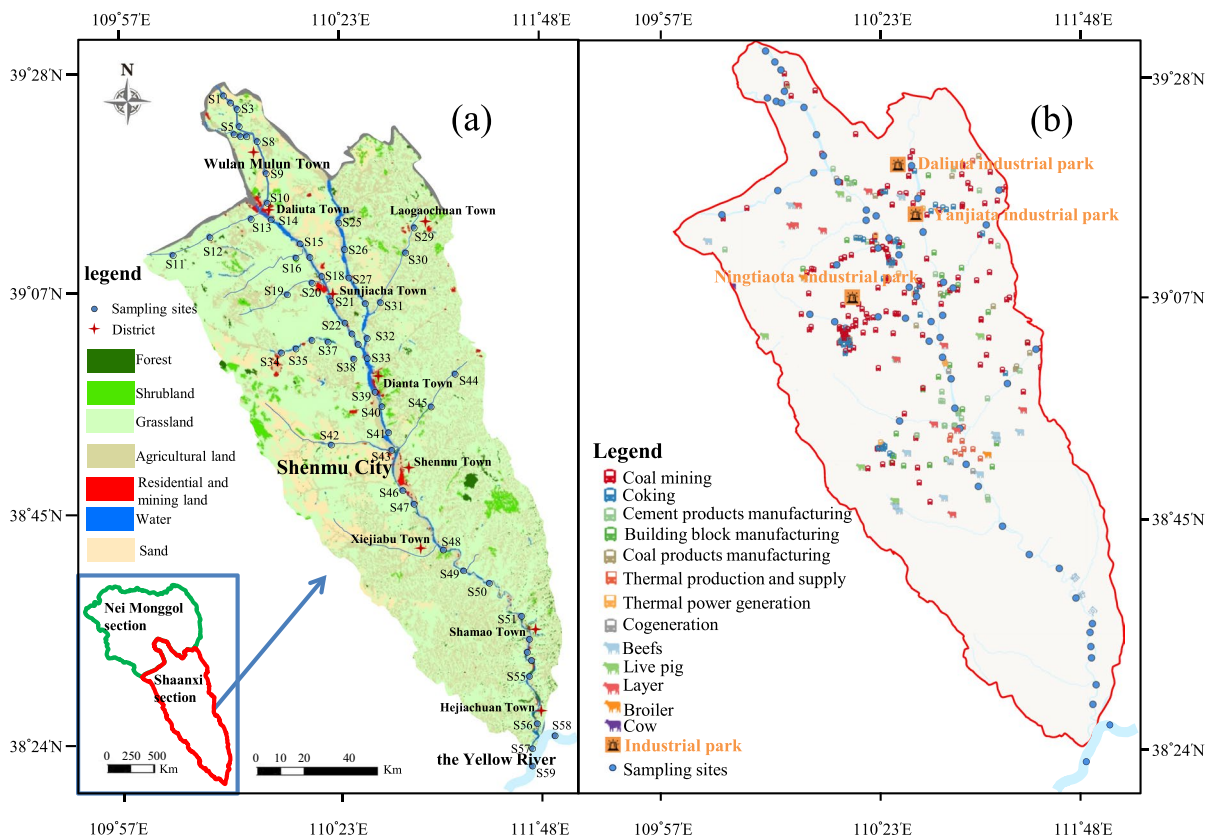


Fig. 1 Geographic locations of the sediment sampling sites in the Kuye River. **a** Sampling sites and land use types; **b** Distribution map of pollution from coal-mining, industrial, and agricultural activities

used in this study were all of analytical grades, while the laboratory utensils were soaked in acid for at least 24 h before use. Three parallel samples were considered for each sediment sample. The analytical error was controlled within an average value of $\pm 8\%$.

Positive matrix factorization (PMF) model

Numerous studies have used the PMF model to assess the main pollution sources and their contribution rates to surface sediments based on the receptor concentration matrix of samples (Guan et al., 2018; Hoshyari et al., 2023; Tan et al., 2016). In addition, the PMF model was applied in previous studies to quantitatively analyze the potential sources of HMs in the Kuye River sediments using EPA-PMF5.0 software developed by US-EPA (Pekey et al., 2013; Scerri et al., 2019). The calculations of the specific model parameters were performed according to Magesh et al. (2021) and Hoshyari et al. (2023). The model input data consisted of the observed sediment HM contents (C), as well as the uncertainty (U_{nc}) and detection limit (MDL) of each HM element. The U_{nc} values were calculated using Eqs. (1 and 2) as follows:

$$\text{If } C < \text{MDL}; U_{nc} = 5/6\text{MDL} \quad (1)$$

Or else,

$$U_{nc} = \sqrt{(\text{EF} \times C)^2 + \left(\frac{1}{2}\text{MDL}\right)^2} \quad (2)$$

where EF denotes the error fraction. This parameter can be determined based on the sampling error, analytical error, chemical activity, and similarity degree between the component concentration and detection limit, ranging from 0.05 to 0.3 (Jiang et al., 2020). In this study, the EF was set at 0.2 following repeated adjustments to ensure the validity of the analysis process. Factor numbers related to the pollution sources were set between 2 and 6, while the reliability of the model was assessed using the $Q_{(\text{Robust})}$ and $Q_{(\text{True})}$ values.

Ecological risk assessment of HMs in the sediments

In this study, the RI method (Hakanson, 1980; Jiang et al., 2020; Li et al., 2021) was used to evaluate the potential ecological risks associated with HMs in the

surface sediments in the Kuye River. This method comprehensively considers several aspects, including the ecological effects, environmental benefits, and toxicological effects of HMs. The calculation and evaluation of the RI were carried out according to the method described by Hoshyari et al. (2023).

PMF-based RI model

In order to further evaluate the ecological risks associated with the HM pollution sources, a PMF-based RI model was established to assess the relative contributions of the potential anthropogenic sources to the ecological risks in the study area. The specific calculation process of this model was divided into two steps. The first step involved the determination of C_{pi} (mg kg^{-1}) and k_p^r using the PMF model; The second step consisted of introducing the contribution rates of the potential pollution sources to HMs (C_{pi}) and element contribution rates (k_p^r) into the RI model to determine the relative contribution value of each pollution source to the ecological risk. The calculations were performed in this study using the following equations:

$$\text{Con}(\text{RI})_i = \text{Con}\left(\sum_{p=1}^n E_{pi}\right) = C_{pi} \left(\sum_{p=1}^n k_p^r \times \frac{T_r}{C_r}\right) \quad (3)$$

$$\omega_n = \left[\frac{1}{59} \sum_{i=1}^{59} \text{Con}(E_{pi}) \right] / \sum_{p=1}^n \left[\frac{1}{59} \sum_{i=1}^{59} \text{Con}(E_{pi}) \right] \quad (4)$$

where $\text{Con}(\text{RI})_i$ denotes the comprehensive potential ecological risk index of all pollution sources at sampling point i ; $\text{Con}(E_{pi})$ denotes the single ecological hazard index of pollution source p at sampling point i ; T_r denotes the toxicity coefficient of HM element r (Peter et al., 2021); C_{pi} denotes the contribution concentration of pollution source p (mg kg^{-1}) at sampling point i calculated by the PMF; k_p^r denotes the contribution rate of HM element r to pollution source p ; C_r denotes the soil background value of HM element r in Shaanxi Province (China Environmental Monitoring Station, 1990) (mg kg^{-1}); n indicates the numbers of the pollution sources. 59 is the number of the sediment sampling points considered in the present study; ω_n denotes the ratio of the average single ecological hazard index value of pollution source p

at the 59 sampling points to the sum of the average single ecological hazard index of n pollution sources, representing the contribution rate of pollution source p . The potential ecological RI values were classified in this study according to Table 1.

Results and discussion

Spatial distributions of the sediment HM contents

Table 2 indicates the descriptive statistic results of the observed sediment HM contents in the Kuye River. The average sediment HM contents followed the order of $Zn > Cr > Ni > Cu > Pb > As > Cd > Hg$. The Zn, Cr, Ni, Cu, Pb, As, Cd, and Hg contents in the surface sediments ranged from 41.03 to 341.43, 28.62 to 199.52, 17.04 to 151.97, 9.47 to 85.72, 8.94 to 57.20, 6.55 to 42.12, 0.02 to 0.27, and 0.01 to 0.25 $mg\ kg^{-1}$, with average contents of 165.76 $mg\ kg^{-1}$, 87.72 $mg\ kg^{-1}$, 68.37 $mg\ kg^{-1}$, 41.31 $mg\ kg^{-1}$, 29.45 $mg\ kg^{-1}$, 19.98 $mg\ kg^{-1}$, 0.11 $mg\ kg^{-1}$, and 0.10 $mg\ kg^{-1}$, respectively. Indeed, Zn, Cr, Ni, Cu, Pb, As, Cd, and Hg exhibited higher contents than the corresponding soil background values in Shaanxi Province by 2.39, 1.40, 2.37, 1.93,

1.38, 1.80, 1.13, and 3.42 times, respectively. The obtained results showed that Hg had the highest deviation from the background HM value as it might evaporate at 0 °C. The evaporation rate of Hg can increase by 1.2 to 1.5 times for every 10 °C increase in temperature. Hg can be volatilized at room temperatures (15–25 °C). In addition, air movement is directly proportional to Hg volatilization (Li et al., 2018; Liu et al., 2018). The Kuye River is located in the transition zone between the wind-sand region and the hilly and gully region, where the terrain is relatively flat. Some suspended particles and volatile HMs can reach the atmosphere through coal mining dust. Indeed, atmospheric Hg might enter river sediments from discharge sources through dry and wet depositions more than ten kilometers away, then adsorbed on the surface of clay particles and organic matter in sediments, resulting in Hg accumulation in sediments (Schroeder et al., 1998; Pirrone et al., 2010; Wang et al., 2012). The coefficient of variation (CV) of the eight HM elements ranged from 0.364 to 0.730, indicating uneven spatial distributions of the HM contents in the study area ($CV > 0.36$). This spatial distribution might be due to the effects of different complex factors on the migration and diffusion process of the HM elements in the mining areas, as well as to other factors, such as topographic features, wind direction, and man-made mining activities (Liu et al., 2016). These effects can be more prominent in areas with open-pit coal mining activities and strong winds, leading to differences in pollutant diffusion through pulverized coals in the atmosphere and, consequently, resulting in large spatial differences in HM contents (Wang et al., 2021).

According to the sum of the eight HM contents at each sampling site (Fig. 2), the average sediment HM contents in the upper and middle reaches

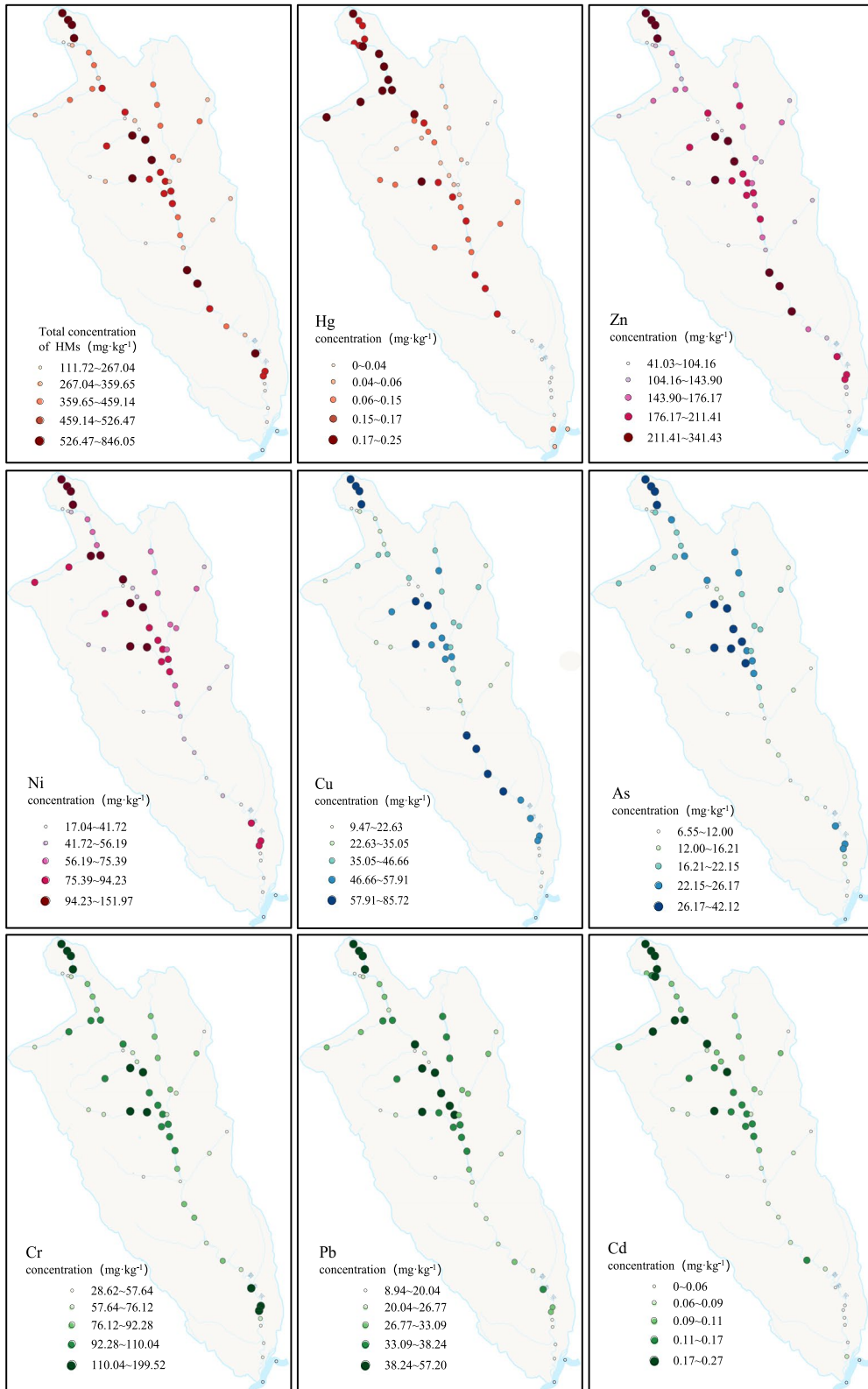
Table 1 Classification of the potential ecological risk index (Feng et al., 2017; Hakanson, 1980; Hoshyari et al., 2023)

Potential risk levels	E_{pi}	Con(RI) _i
Low risk	$E_{pi} < 40$	$Con(RI)_i < 150$
Moderate risk	$40 \leq E_{pi} < 80$	$150 \leq Con(RI)_i < 300$
Considerable risk	$80 \leq E_{pi} < 160$	$300 \leq Con(RI)_i < 600$
Heavy risk	$160 \leq E_{pi} < 320$	$600 \leq Con(RI)_i$
Extreme risk	$320 \leq E_{pi}$	

Table 2 Descriptive statistics of the observed sediment HM contents

SD standard deviation; *CV* coefficient of variation. *BVs* the soil background values in Shaanxi Province (China Environmental Monitoring Station, 1990)

HMs	Max/($mg\ kg^{-1}$)	Min/($mg\ kg^{-1}$)	Mean/($mg\ kg^{-1}$)	SD	CV	BVs
Cu	85.72	9.47	41.31	20.01	0.489	21.400
Zn	341.43	41.03	165.76	72.73	0.443	69.400
Pb	57.20	8.94	29.45	10.61	0.364	21.400
Cd	0.27	0.02	0.11	0.06	0.612	0.094
Ni	151.97	17.04	68.37	31.45	0.464	28.800
Cr	199.52	28.62	87.72	36.33	0.418	62.500
Hg	0.25	0.01	0.10	0.07	0.730	0.030
As	42.12	6.55	19.98	8.46	0.427	11.100



◀**Fig. 2** Sediment HM contents in the Kuye River (The bubble size and color depth represent the HM contents)

(S1~S47) were $435.96 \text{ mg kg}^{-1}$, while that in the downstream part (S48~S59) was $322.03 \text{ mg kg}^{-1}$. These findings were, in fact, consistent with those reported by Chen (2016), showing a higher average HM content in the coal mine area in the upper and middle reaches of the Kuye River than that observed in the non-coal-mining area downstream. In this study, the highest sums of the sediment HM contents were found at S1–S4 in the Shaanxi section entrance of the Kuye River, ranging from 728.54 to $846.05 \text{ mg kg}^{-1}$, followed by those at S20 and S21 in the downstream part of the Yanjiata Industrial Park ($672.20 \text{ mg kg}^{-1}$ to $739.42 \text{ mg kg}^{-1}$). In addition, high sum HM contents were observed at S36–S40 in the Ningtiaota Industrial Park, ranging from 449.57 to $579.97 \text{ mg kg}^{-1}$, as well as at S46 and S47 in the urban area of Shenmu at $590.43 \text{ mg kg}^{-1}$ and $562.32 \text{ mg kg}^{-1}$, respectively.

Sampling sites with high sediment HM contents were, in fact, located in coal-mining areas, industrial parks, coal transport lines, and urban areas (Fig. 2). Among them, bituminous coal and anthracite mining and washing, coking, coal products manufacturing, thermal power generation, coal transportation lines, and livestock and poultry farming around the Shenmu City were the major human activities in these areas. The HM elements can enter the surface river sediments through numerous processes, including atmospheric deposition, runoff, and solid waste stacking, causing HM accumulation. The highest sediment HM contents in the downstream areas were observed at S51–S53 in upstream Shamao Town. This area is characterized by high urban population density and intensive rural activities, resulting in HM enrichment in the surface sediments through precipitation-induced runoff of pesticides, fertilizers, discharged livestock breeding wastewater, and domestic sewage. The above-described results highlighted different sediment HM contamination degrees in the Kuye River due to the presence of different land use types. The S59 sampling site was located downstream from the Kuye River towards the Yellow River. In fact, a low total sediment HM content was observed at this sampling site, indicating that sediment HM pollution in the upper and middle reaches of the Kuye River did not pose a great pollution risk to the Yellow River.

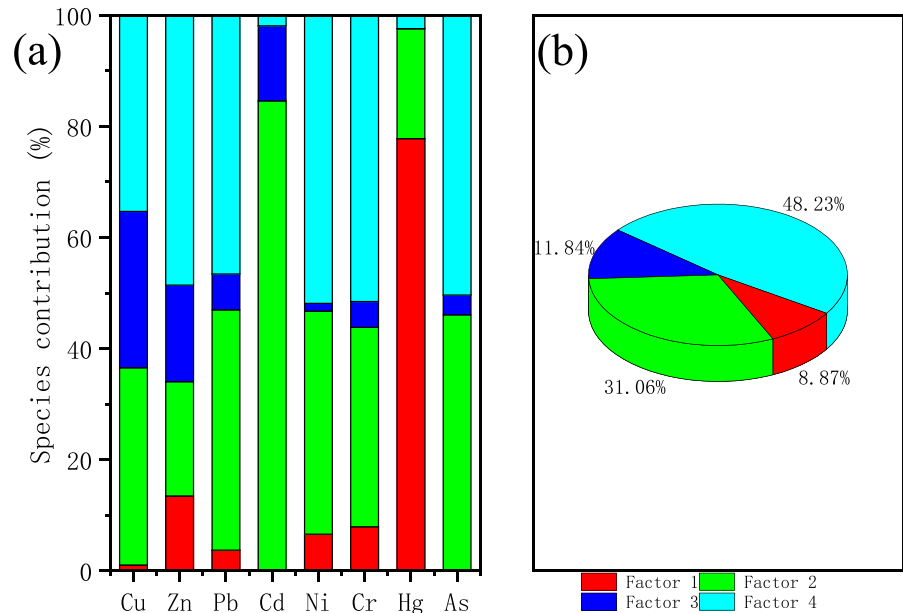
Analysis of the HM sources

After several operations and comparisons, the factor number of the pollution sources was set at 4. In addition, 20 iterations were performed to determine the lowest and most stable $Q_{(\text{Robust})}$ value. The signal-to-noise ratio (S/N) range was 3.44–3.99. In addition, the coefficient of determination (R^2) range between the measured and predicted values of the PMF model was 0.937–0.997, with a residual value range of $-3 \sim 3$. These results demonstrated the reliability of the PMF model in analyzing the potential sources of the eight HM elements in the surface sediments of the Kuye River. The PMF operation results are shown in Fig. 3. The potential sources of HMs were quantitatively analyzed at several iterations of 18, with $Q_{(\text{Robust})}$ and $Q_{(\text{True})}$ values of 46.7.

Factor 1 accounted for 8.87% of the total contribution, of which the contribution rate of Hg was 77.78%. The study area is located in the hinterland of the largest coal field in China, where actual coal reserves account for about 15% of the total discovered coal resources in China (Wu et al., 2023). However, the Hg contents in the raw coals are high due to the overall influence of geological factors in the sedimentary environment and coal-forming process, as well as the strong relationship between Hg and sulfide (Niksa et al., 2010). Therefore, dust pollution from the extraction of large raw coal amounts and coal gangue stacking might result in the accumulation of HMs in the river sediments around the mining area. Some studies have shown that high sediment Hg contents were mainly related to coal gangue dumps (Abliz et al., 2018; Niksa et al., 2010). Therefore, Factor 1 might be related to the coal-mining source in this study.

Factor 2 accounted for 31.06% of the total contribution, of which the contribution rates of Cd and Pb accounted for 84.58 and 43.27%, respectively. High sediment Cd and Pb contents were observed around the highway where traffic pollution is serious. This is due to the main channel connecting the mining area to the coal production units, characterized by a high traffic volume (Huang et al., 2021). The main sources of river sediment Cd and Pb pollution are engine wear (Pizzol et al., 2010), leaded gasoline (Gao et al., 2013), braking (Huang et al., 2021; Men et al., 2019), and other traffic-related sources. Indeed, Cd and Pb can be released from these sources, then deposited

Fig. 3 PMF-based contribution rates of potential anthropogenic sources to sediment HM pollution. **a** factors the sediment HM elements **a**; contribution rates of each factor **b**



and adsorbed in river sediments through precipitation events. Therefore, Factor 2 might be assigned to the traffic source.

Factor 3 explained 11.84% of the sediment HM contents, of which the contribution proportions of Cu and Zn were 28.14% and 17.38%, respectively. In this study, areas with high Cu and Zn sediment contents were mainly observed in the urban areas (Sunjiacha, Dianta, and Shenmu towns), where livestock farms are distributed (Fig. 2). Since Cu and Zn are constituents of livestock diets (Guan et al., 2018), they may be transferred to animal manures. Indeed, these HM elements are biomarkers of livestock manure applications (Belon et al., 2012; Hu et al., 2018; Shazili et al., 2006; Wang et al., 2022). Therefore, long-term and large-scale applications of livestock manures might lead to sediment enrichment by Cu and Zn in the Kuye River, resulting in their accumulation in the surface sediments through surface runoff. Therefore, Factor 3 is related to agricultural pollution derived from poultry breeding.

The fourth and most important factor explained 48.23% of the total contribution, showing high Ni, Cr, and As contribution proportions of 51.87%, 51.52%, and 50.36%, respectively. The highest Factor 4 proportions were observed in the Daliuta, Yanjiata, and Ningtiaota industrial parks. Industrial production (e.g., coking and thermal power generation) requires a large amount of coal combustion to provide power.

In fact, Ni, Cr, and As are indicators of coal combustion activities (Cechinel et al., 2016; Qu et al., 2018; Shi et al., 2022a, b). Hence, Factor 4 was identified as an industrial pollution source.

Potential ecological risk assessment of sediment HMs

The RI of the observed sediment HM contents in the Kuye River were evaluated in this study according to the method described by Hoshyari et al. (2023). The E_{pi} values of Zn, Cr, Ni, Cu, Pb (all sediment samples), and As (93.22% of the collected sediment samples) were lower than 40 (Fig. 4), suggesting minor sediment contamination levels by these HM elements in the Kuye River. On the other hand, 27.11% and 8.47% of the sampling sites showed moderate and considerable Cd ecological risks. In addition, 1.69%, 37.29%, 20.34%, and 25.42% of the sampling sites exhibited extreme, heavy, considerable, and moderate Hg ecological risks, respectively.

According to the calculated RI results, the $Con(RI)_i$ values ranged from 26.15 to 483.7, with an average value of 223.48 (Fig. 5). About 28.8% of the sampling sites exhibited $Con(RI)_i$ values higher than 300, indicating a considerable ecological risk. On the other hand, Hg and Cd had the highest E_{pi} values, contributing significantly to the comprehensive potential ecological risk index by up to 75% and 41%, respectively. This finding is mainly due to the high toxicity coefficients

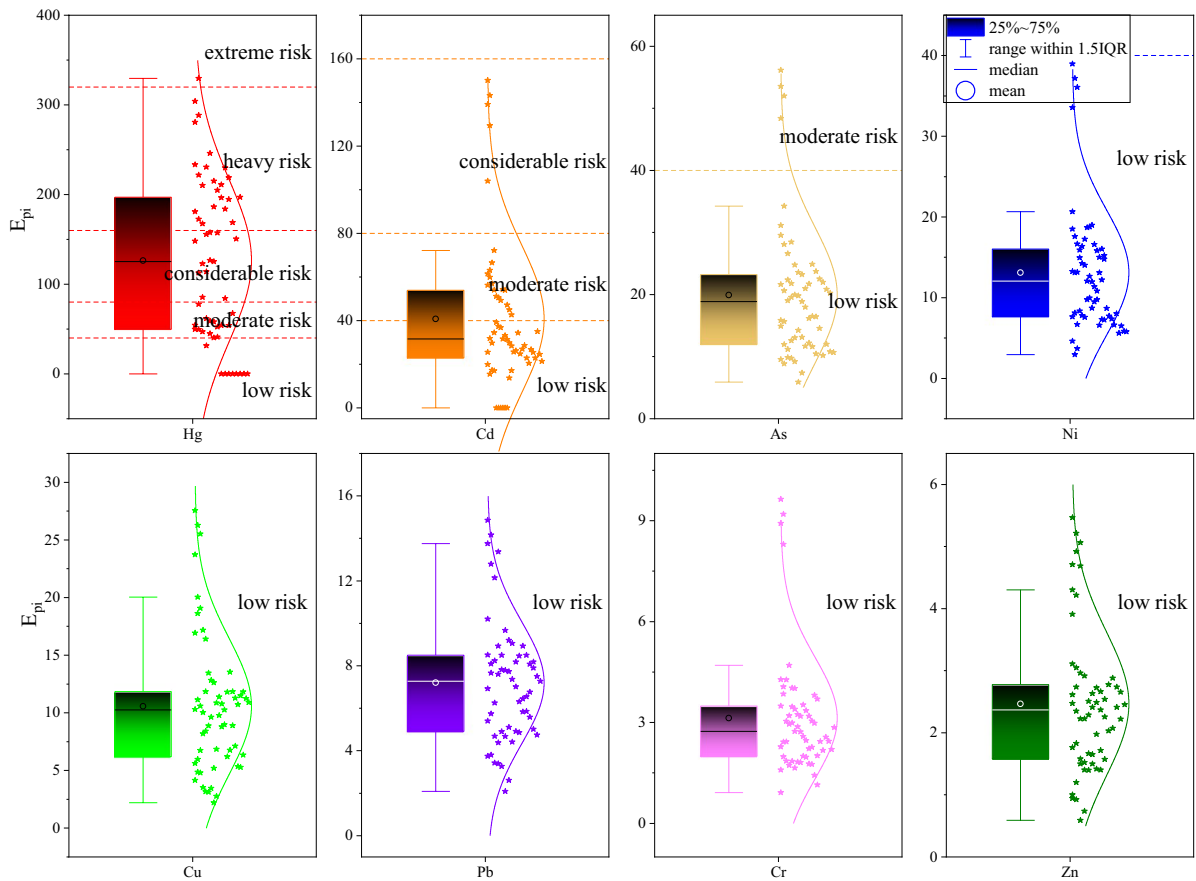


Fig. 4 Potential ecological risks of HM elements in the surface sediments of the Kuye River

of Hg and Cd, resulting in high associated ecological risk indices. Most areas with high $Con(RI)_i$ values were located close to coal-mining areas, coal-burning industrial parks, traffic arteries, and urban areas, further demonstrating that these activities caused considerable ecological risk at the local scale. However, this finding is inconsistent with that reported by Chen (2016), indicating a high ecological risk level in the entire water area of the Kuye River. Therefore, water quality in the Kuye River might be considerably improved in recent years due to the implemented river pollution control and prevention measures by the local government.

Quantification of the potential ecological risks from different sources

The PMF-based RI model was established in this study to quantify the potential ecological risks of the

eight sediment HMs from four identified anthropogenic sources. The potential ecological risk indices of the HM elements from the coal-mining, traffic, agricultural, and industrial activities to the sediments in the Kuye River ranged from 0 to 275.18, 0 to 195.21, 0 to 60.48, and 0 to 73.81, with average values of 107.86, 76.06, 9.07, and 28.07, respectively. Among the four anthropogenic sources, coal mining activities posed the highest ecological risk, almost equivalent to the sum of ecological risk indices of the other three sources. This finding indicated that coal-mining activities were the most predominant source of the HM elements in the Kuye River sediments.

The contribution rates of the four pollution sources to sediment HM pollution at all sampling points are shown in Fig. 6b. The contribution rates of the coal mining and traffic activities at some sampling points near the Daliuta Industrial Park reached 93.11%, demonstrating the great impact of these activities on

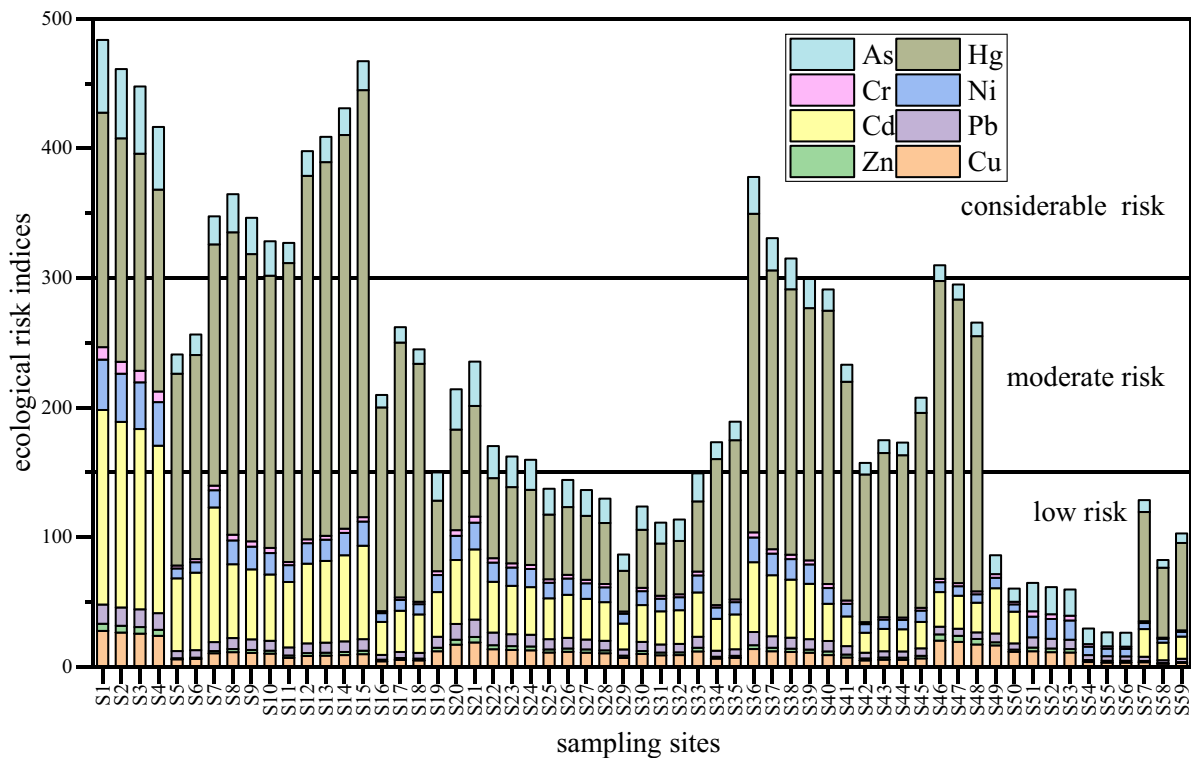


Fig. 5 Single ecological risk indices of the sediment HM elements in the Kuye River

the surrounding river sediments in the upper and middle reaches of the study area. Nevertheless, the contribution rates of the agricultural and traffic activities to sediment HM pollution reached nearly 100% at the sampling sites around Shamao Town in the downstream part of the Kuye River. Therefore, the ecological risk contribution rates of the four different anthropogenic sources varied according to land use patterns in the study area.

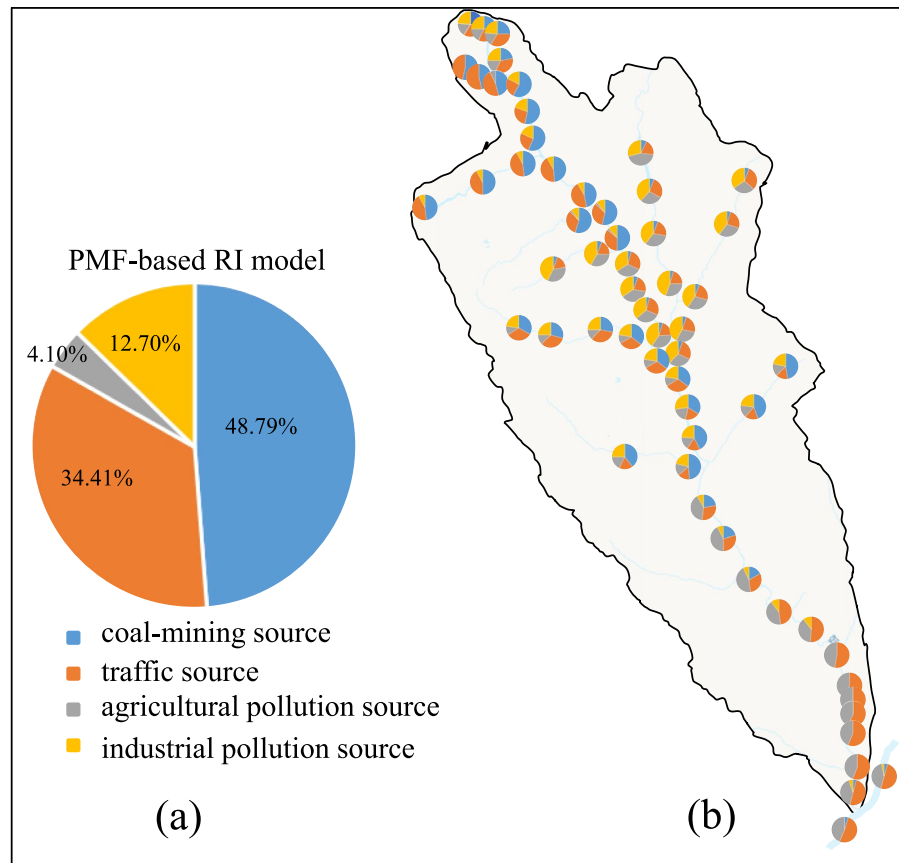
The average contribution rates of the four anthropogenic sources to the HM ecological risks in the Kuye River sediments at the 59 sampling sites are shown in Fig. 6a. Coal mining activities showed the highest contribution rate (48.79%), followed, respectively, by traffic (34.41%), industrial (12.70%), and agricultural (4.10%) activities. However, the PMF-based contribution rates were inconsistent with those obtained using the PMF-based RI model. This indicates that anthropogenic activities with the highest contribution rates to the sediment HM contents do not necessarily pose the greatest ecological risks. This difference might be due to the different factors

considered in the PMF and PMF-based RI models. Indeed, the PMF model only considers the sediment HM contents, while the PMF-based RI model takes into account both HM toxicities and local HM background values. Moreover, as mentioned above, coal-mining activities were the most predominant source contributing to sediment enrichment by HMs. Coal-mining, coal combustion, and traffic are important factors affecting the ecosystem. Therefore, effective control and management measures of these activities are required in the study area to reduce negative associated environmental impacts.

Limitations of this study

This study quantitatively assessed sediment HM contamination and its associated source-specific risks in a coal mining area in China using the PMF-based RI model. However, this study has some limitations. First, we only focused on the contents of eight HM elements (Cu, Zn, Pb, Cd, Ni, Cr, Hg,

Fig. 6 Contribution rates of each pollution source to the ecological risks. **a** The average contribution rates; **b** The contribution rate at each sampling point



and As) in the surface sediments, overlooking some other HMs that may potentially pose ecological risks, such as Mn and Co. Second, some potential influencing factors of the sediment HM contents were ignored in this study, including soil properties (e.g., pH, organic matter content, particle size, and soil texture type) and surrounding environmental characteristics (river dynamics, winds, relative humidity, air temperatures, and distances of industrial areas from the river). Therefore, future related studies need to assess the contents of other HM elements in river sediments, taking into account surrounding environmental characteristics in industrial areas to reduce the assessment bias in subsequent ecological risk analyses. Furthermore, the integration of different assessment methods should be further strengthened to accurately evaluate and validate the pollution source identification results.

Conclusions

In this study, the pollution levels of eight HM elements in the Kuye River sediments, as well as their potential sources, were investigated. The ecological risks associated with some specific anthropogenic sources were also quantitatively evaluated using the PMF-based RI model. The average contents of the eight HM elements in the sediments were higher than the corresponding background values, showing uneven spatial distributions in the study area. The calculated $Con (RI)_i$ values revealed that 28.8% of sampling sites were at high considerable HM ecological risks. The highest ecological risk indices were observed in the coal-mining areas, industrial parks, coal transport areas, and urban areas. The PMF identified four anthropogenic sources of HMs in the Kuye River sediments, namely, industrial, traffic,

agricultural, and coal-mining activities. Ecological risks associated with these sources were quantified under different land use types using the PMF-based RI model. Specifically, the coal-mining and traffic pollution sources demonstrated strong impacts on the upper and middle reaches of the Kuye River, while the traffic and agricultural sources exhibited strong influences on the downstream area of the Kuye River. The PMF-based RI model not only considered the contributions of the observed sediment HM contents in the Kuye River but also other HM-related factors, including the HM toxicity coefficients and local background values, resulting in more reasonable results compared to those obtained using the PMF model. Therefore, it is important to devote more attention to the contributions of the acceptor pollutant concentrations to the ecological risk in the surrounding environment. Moreover, it is crucial to comprehensively consider the HM toxicity coefficients in ecological risk management in the Kuye River to ensure effective formulations of related control measures. The present study suggests strict control of dust treatment in raw coal-mining processes and open-pit coal stacking to enhance river management and protection in the mining areas.

Author contributions YZ: Experiment, Data analysis, Writing-original draft; XW: Conceptualization, Writing-review & editing, Supervision, Funding acquisition; YD: Writing-original draft; JL: Editing.

Funding This work was supported by the National Natural Science Foundation of China (No. 51969031, 52169006), the Shaanxi Science and Technology Innovation Team (No. 2022TD-08), the Open Fund of State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China (No. 2019KFKT-13), the Shaanxi Key Scientific Research Plan of Education Department (No. 22JS045), the Yulin ‘Scientists+Engineers’ Team Project (YLKG-2022–10), and Yulin University Scientific Research Project (1517-2021JJJB13, 1517-2021SKJJB19).

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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