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Assessment of Heavy Metal Pollution in Water Sediment and Study on Pollution Mechanism—Taking the Weihe River Basin in China as an Example

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Abstract: To ensure the ecological security of the basin, data on the heavy metal content in the sediments of the Weihe River Basin were collected to analyze the spatial distribution characteristics of heavy metals based on descriptive statistics and geostatistics. The geoaccumulation index and potential ecological risk assessment were conducted, and the number of pollution sources and the contribution rate were determined by combining correlation analysis, principal component analysis, and APCS-MLR. The results showed that the mean values of As, Pb, Zn, Ni, Cr, Hg, Cu, and Cd were 15.42, 27.27, 88.05, 31.05, 75, 0.13, 29.47, and 1.05 mg·kg^{-1}, respectively. I_{geo} is in the order of Cd > Hg > As > Cu > Pb > Zn > Cr > Ni. Cd had the highest potential ecological risk factor, followed by Hg with a critical risk proportion of 12.6%. The traceability analysis showed that the heavy metals come from mixed, industrial, and agricultural sources, among which Pb, Zn, Ni, Cr, and Cu are affected by soil-forming parent materials and industrial comprehensive sources, As is affected by agricultural sources, and Hg and Cd are affected by industrial sources. Industrial and living sources are the main sources of the heavy metals. The results of the study can provide a basis for formulating relevant pollution prevention and control measures in the Weihe River Basin.

Keywords: Weihe River; heavy metals in sediments; spatial distribution; risk assessment; source analysis; APCS-MLR

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1. Introduction

Rivers are an important pathway in the earth's hydrologic cycle, allowing sediment, salt, and chemical elements to enter lakes and oceans [1]. In order to develop the economy and meet the needs of human daily life, a large number of heavy metals are mined from the earth's crust every year [2]. In the mining and production process, heavy metals are discharged into rivers through atmospheric sedimentation or mining wastewater. Only a small fraction is dissolved in water bodies, and the majority is enriched in sediments. Sediments are an indispensable part of aquatic habitats and the basis of food webs. However, they are also the sinks of pollutants [3]. In addition, heavy metal pollution generally exhibits a wide range and long duration and easily accumulates and stabilizes in the environment, posing a threat to human health through direct contact or the food chain [4,5]. Heavy metal pollution in rivers caused by social, economic, and industrial activities has become one of the major environmental problems worldwide [6], which has attracted the attention of many scholars. Akpan used EDXRF (energy dispersive X-ray fluorescence spectrometer) to analyze the heavy metal pollutants in the sediments along the Cros River in Nigeria [7]. Al Mamun evaluated the pollution degree and accumulation behavior of heavy metals in the sediment of the Daleswali River [8]. Eleven heavy metals in the intertidal surface sediment of the Yellow River Estuary in China were analyzed using inductively coupled plasma-mass spectrometry [9]. The assessment and research results of heavy metals in sediments mainly focus on distribution characteristics [10], pollution characteristics [11], pollution assessment [12], ecological risk assessment [13], etc. Source analysis methods mostly include multivariate statistical methods [14], the isotope acing method [15], PMF (positive matrix factorization) [16], the GIS (geographic information system) mapping method [17], etc. These methods are not particularly novel and are widely used in the field of heavy metals, while the APCS-MLR (absolute principal component score/multiple linear regression) was used in only 2.9% of the studies [18]. So far, APCS-MLR has not been used to investigate the heavy metal sources in the Weihe River Basin. The current research mainly focuses on the characteristics and sources of heavy metal pollution in the Weihe River Basin, and the research on the pollution mechanism is still blank.

In recent years, with the rapid development of industry and cities, the Weihe River has been seriously polluted, the water quality has seriously deteriorated, and the ecological function has been continuously weakened, seriously hindering regional economic development [19]. In order to improve the ecological environment in the Weihe River Basin, promote its high-quality development, and ensure the life safety of local people, it is imperative to study the current status and the mechanism of heavy metal pollution in the sediments of the Weihe River Basin. At present, the research on heavy metals in the sediments of the Weihe River Basin is mainly concentrated on small-scale research and assessments of the Shaanxi section [20] and Baoji section [21]. There are very few studies on the overall assessment and analysis of heavy metals in the sediments of the Weihe River Basin. In view of the current situation of the Weihe River Basin, we evaluated the geoaccumulation index and potential ecological hazard of heavy metal pollution in the Weihe River Basin by collecting and sorting out the relevant published research data to clarify the heavy metal pollution status of the sediment in the Weihe River Basin. From the perspective of basin pollution prevention and control, the mixed methods, including Pearson correlation analysis, principal component analysis, and APCS-MLR, were used to explore the main sources and pollution mechanisms of heavy metals in the sediments of the Weihe River Basin, hoping to provide a theoretical basis for the treatment of heavy metal pollution in the sediments of the Weihe River Basin. This research can also provide a reference for other scholars to study heavy metals in the Weihe River Basin in the future.

2. Materials and Methods

2.1. Study Area

Weihe River is the largest tributary of the Yellow River with a drainage area of about 135,000 km^2. Qinling Mountains are located to the south of the Weihe River, and Liupan Mountains are located to the north. Weihe River originates from Birmouse Mountain in Weiyuan County, Gansu Province, flows through Longdong Plateau, Tianshui Basin, and Guanzhong Plain, including the cities of Baoji, Xianyang, Xi'an, Tianshui, and Weinan. It flows into the Yellow River at Tongguan Port, with a total trunk stream length of 818 km. The area above Baoji Gorge is the upper reaches of the Weihe River, the area from Baoji Gorge to Xianyang is the middle reaches, and the area below Xianyang is the lower reaches [22]. Weihe River is located in the middle of Shaanxi Province. It is the largest river in Shaanxi Province and the largest tributary of the Yellow River. It plays an important role in China's economic and cultural development. There are about 4064 industrial enterprises in the Weihe River Basin, mainly in the industries of papermaking, textiles, machinery, electric power, and chemicals. The main pollutants in the industrial wastewater are COD, petroleum, volatile phenol, etc.

2.2. Data Collection and Processing Methods

The relevant documents were collected from databases in China (CNKI, Vip, Wanfang, etc.) and other countries (Web of Science, Elsevier Science Direct, Wiley, etc.) from 2008 to 2021 by searching for the keywords "heavy metals or single metal, sediments, and Weihe River". The data filtering criteria include (1) the article has a clear sampling time and location, and the sampling point is a natural water body; (2) the sampling depth is 0~20 cm; (3) the determination method is tetraacid (HCl-HNO_3-HF-$HClO_4$) digestion method; and (4) inductively coupled plasma mass spectrometry (ICP-MS)[23], inductively coupled plasma emission spectrometry (ICP-OES) [24], atomic absorption spectrometry (AAS) [25] or atomic fluorescence spectrometry (AFS) [26] was used. A total of 707 sampling points from 38 documents were collected according to the above data screening method. The specific sample-point distribution is shown in Figure 1. The sample-point coordinates are directly labeled by relevant documents or picked up by geographical coordinates. Excel 2016 was used for tabulation, and Origin 2018 was used for drawing. Pearson correlation analysis, principal component analysis, and absolute principal component multiple linear regression analysis (APCS-MLR) were performed using IBM SPSS Statistics 26.0 software. The spatial distribution of heavy metals was completed using ArcGIS 10.2.

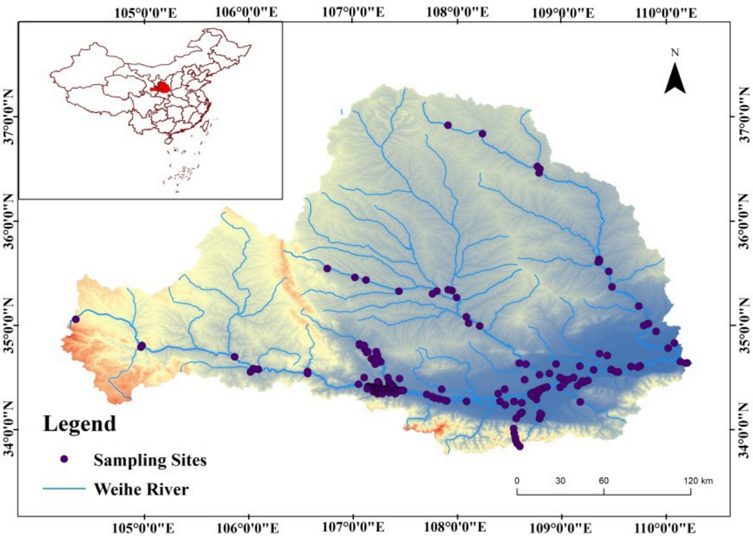

Figure 1. Location of the study area.

2.3. Methods

2.3.1. Assessment Method of Heavy Metal Pollution in Sediment

(1) Geoaccumulation Index

Igeo was proposed by Müller in 1969. It has been widely used to quantitatively evaluate the pollution degree of heavy metals in sediment and soil and distinguish the impact of human activities on the ecological environment [27]. The equation is as follows:

$$I_{geo} = \log_2(C_i/kB_n) \quad (1)$$

where I_{geo} refers to the geoaccumulation index, and Table 1 lists the division standard of geoaccumulation index [28]; C_i is the measured element content in sediment $(mg \cdot kg^{-1})$; B_n is the geochemical background value of this element $(mg \cdot kg^{-1})$, which adopts the soil background value of each province (Table 2); and k is the constant of 1.5.

Table 1. Classification standard of sediment accumulation index.

Class of Pollution	Pollution-Free	Slight Pollution	Moderate Pollution	Heavy Pollution	Serious Pollution
I_{geo}	≤0	0–1	1–2	2–3	≥3

Table 2. Background values of heavy metals in soils of administrative regions in the Weihe River Basin [29]/($mg \cdot kg^{-1}$).

Province	Pb	As	Zn	Ni	Cu	Hg	Cr	Cd
Gansu Province	18.8	12.6	68.5	35.2	24.1	0.02	70.2	0.116
Ningxia Hui Autonomous Region	20.9	11.9	58.8	36.5	22.1	0.021	60	0.112
Shaanxi Province	21.4	11.1	69.4	28.8	21.4	0.03	62.5	0.094

(2) Potential Ecological Risk Index

The potential ecological risk index method [30] was proposed by the Swedish scholar Hakanson and has been widely used to comprehensively evaluate the potential ecological risk of heavy metals. The equation is as follows:

$$C_f^i = C_i / C_n^i \quad (2)$$

$$E_r^i = T_r^i \times C_f^i \quad (3)$$

$$RI = \sum_{i=1}^{n} E_r^i \quad (4)$$

where C_f^i is the pollution index of element i; C_i is the measured content of element i($mg \cdot kg^{-1}$); C_n^i is the geochemical background value of element i($mg \cdot kg^{-1}$), which adopts the soil background value of each province; E_r^i is the potential ecological risk index of metal element i; T_r^i is the biological toxicity factor of a single metal, reflecting the toxicity intensity of heavy metals and the biological sensitivity to heavy metals; RI is the potential ecological risk index composed of multiple metals. The biological toxicity factors of lead, arsenic, zinc, nickel, copper, mercury, chromium, and cadmium are 5, 10, 1, 5, 5, 40, 2, and 30, respectively [31]. Table 3 shows the grading standards of the potential ecological risk index [29].

Table 3. Grading standards of potential ecological risk index.

Project	Risk Level
$RI < 150$	Low risk
$150 \leq RI < 300$	Medium risk
$300 \leq RI < 600$	Heavy risk
$RI \geq 600$	Critical risk

2.3.2. Source Analysis Method of Heavy Metal Pollution in Sediment

Pearson correlation analysis (CA) was used to analyze the correlation between various factors. In a certain research area, the relationship between heavy metals in sediments has a certain stability. The correlation between heavy metals is more obvious when the sediment sources are the same or similar. Through the correlation analysis of heavy metal elements and sediment indicators, the source of heavy metal elements in the Weihe River Basin can be determined [32]. Principal component analysis (PCA) explains the total variance of each variable by reducing dimensions, recombines many indicators with certain correlations into a few comprehensive indicators, and retains most of the original information so that the analysis results have a certain reliability. It is a multivariate statistical analysis method for quantitative research of multidimensional factors and can be used for potential qualitative analysis of pollution sources [33,34]. The absolute factor analysis multiple linear regression receptor model (APCS-MLR) is based on the principal component analysis and converts the principal factor score into the absolute principal component score (APCS). The regression coefficients of different principal factors are obtained through multiple linear regression analysis of the absolute principal factor score and the original data. Finally, the absolute contribution rate was calculated using the regression coefficients [35].

3. Results

3.1. Distribution Characteristics of Heavy Metals in Sediments of the Weihe River Basin

3.1.1. Descriptive Statistics of Heavy Metal Content in Sediments

Table 4 and Figure 2 show the descriptive statistics of the heavy metal content in the Weihe River Basin. Except for Ni, all other elements exceeded the average soil background values in all provinces of the Weihe River Basin. The amounts of As, Pb, Zn, Cr, Hg, Cu, and Cd exceed 1.3, 1.34, 1.34, 1.17, 6.5, 1.31, and 9.09 times, respectively. All elements, except Cd, did not exceed the soil risk screening values. Among the eight elements in the Weihe River Basin, Cd has the largest coefficient of variation, followed by Hg, which indicates that Cd and Hg have strong migration capacity and are greatly affected by human activities and industrial distribution. The coefficients of variation of the other elements are all less than 1, which belong to a medium degree of variation (0.1~1).

Table 4. Descriptive statistics of heavy metal concentrations/(mg·kg^{-1}).

Project	As	Pb	Zn	Ni	Cr	Hg	Cu	Cd
Number of data	123	348	336	258	301	53	321	208
Average value	15.42	27.27	88.05	31.05	75.00	0.13	29.47	1.05
Coefficient of variation	0.69	0.42	0.51	0.26	0.31	1.70	0.51	1.86
Background value of soil elements [36]	11.87	20.37	65.57	33.50	64.23	0.02	22.53	0.11
Soil risk screening value [a]	30	120	250	100	200	2.4	100	0.3

[a] The standard for risk control of agricultural land soil pollution in China (GB 15618-2018).

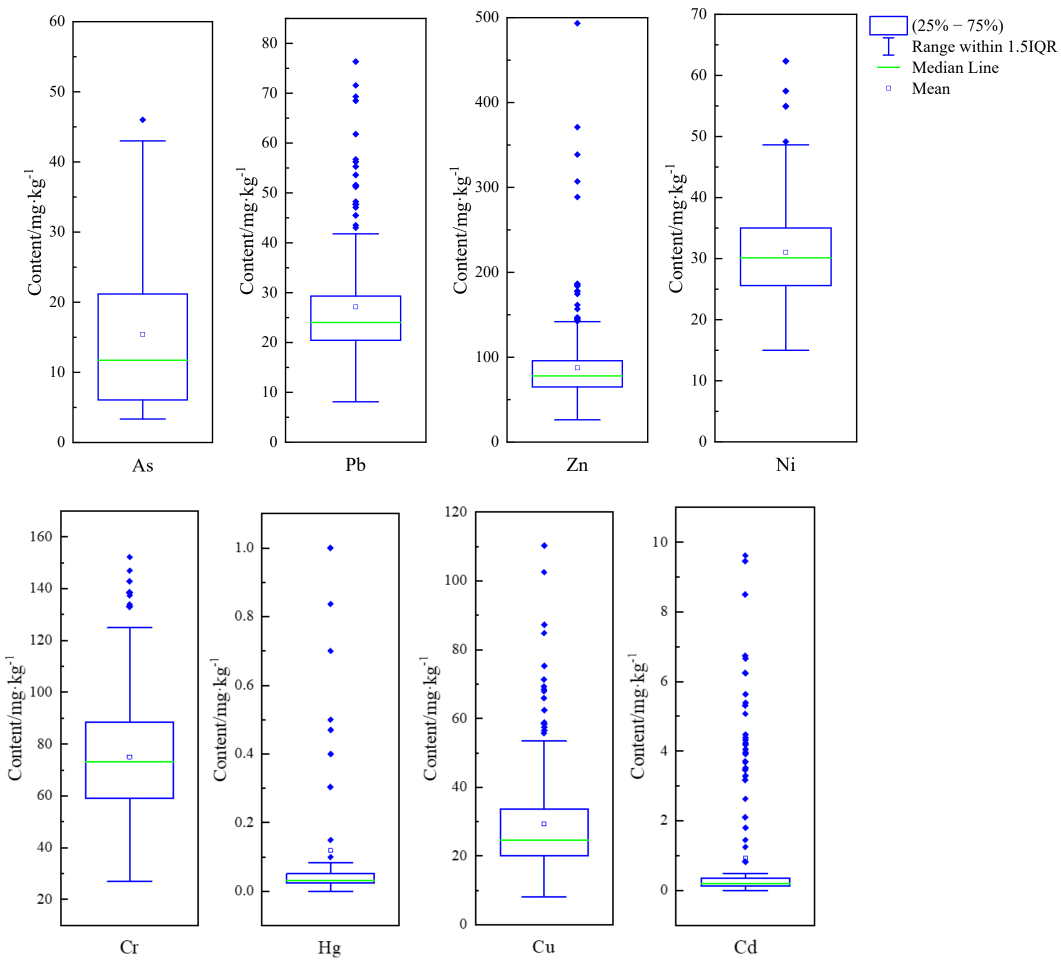

Figure 2. Statistics of heavy metal content in sediments of Weihe River Basin.

3.1.2. Spatial Distribution of Heavy Metals in Sediments

The content of each heavy metal element in the sediment of the Weihe River Basin was marked by ArcGIS10.2, and the spatial distribution of the eight elements was obtained (Figure 3). From the figure, the high values of heavy metals are mostly distributed in the middle and lower reaches, the high values of the heavy metals Pb, As, Zn, Ni, Cr, and Cd are mostly distributed in the middle and lower reaches, the high values of Cu are relatively dispersed, and the high values of Hg are distributed in the middle reaches.

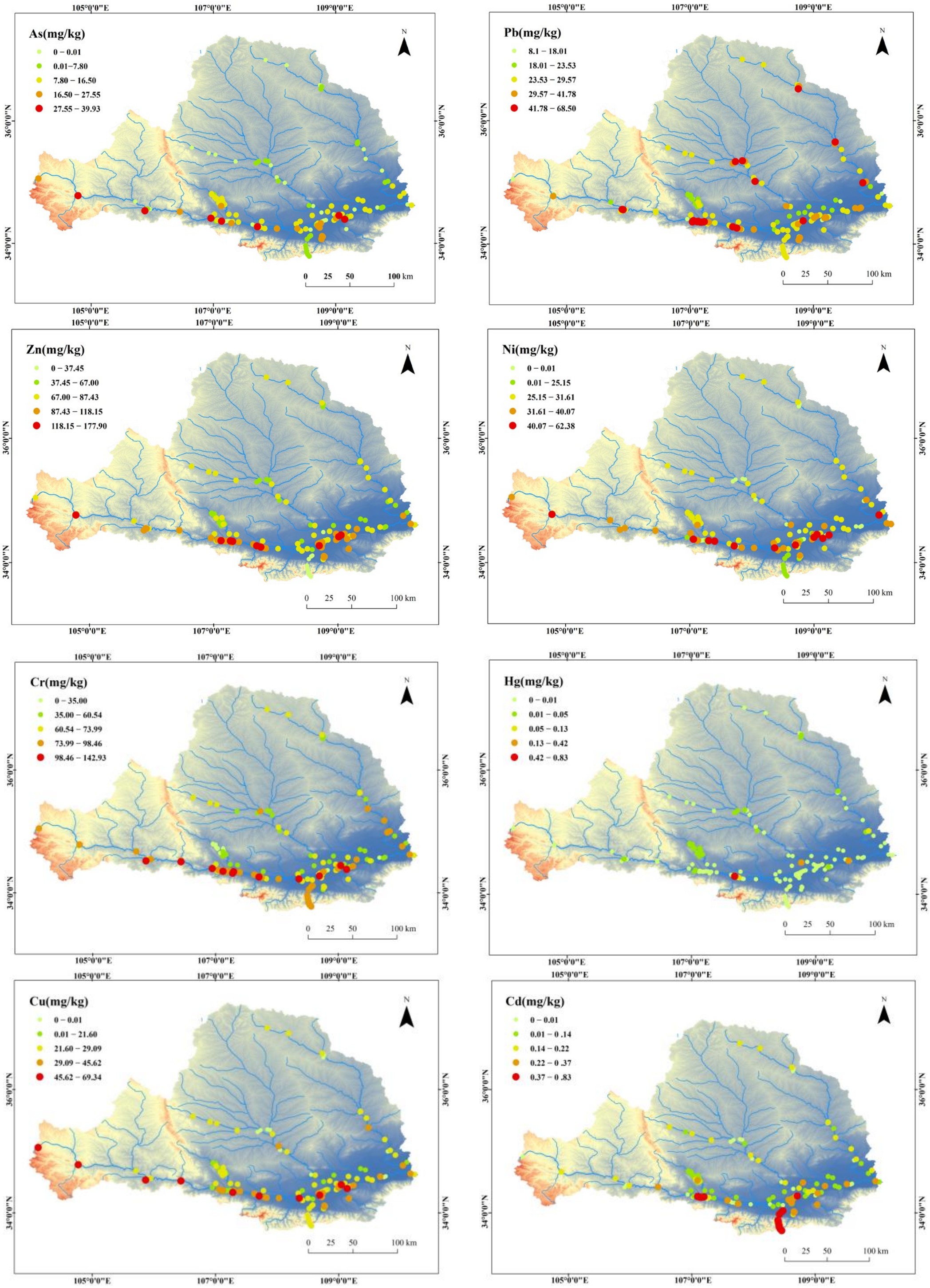

Figure 3. Spatial distribution of heavy metals in sediments of Weihe River Basin.

3.2. Assessment of Heavy metal Pollution in the Sediments of the Weihe River Basin

3.2.1. Evaluation of Geoaccumulation Index

The evaluation result of the geoaccumulation index is shown in Figure 4. From Figure 4, the geoaccumulation indices of As, Pb, Zn, Ni, Cr, and Cu are less than 0, indicating no pollution. Although 4 and 15% Hg accumulation in the sediments indicates serious pollution and more serious pollution, respectively, their average values are less than 0. This means that the pollution level in the Weihe River Basin is non-polluting. According to the Igeo grade and heavy metal pollution degree in Table 1, Cd in the surface sediments of the Weihe River Basin is as high as 6.09, and the average geoaccumulation index of Cd is 1.20, indicating that there is a certain degree of serious pollution. The results showed that the heavy metal pollution of Cd in the sediments of the Weihe River Basin was serious. To sum up, the pollution degree of heavy metals in the surface sediments of the Weihe River Basin is Cd > Hg > As > Cu > Pb > Zn > Cr > Ni.

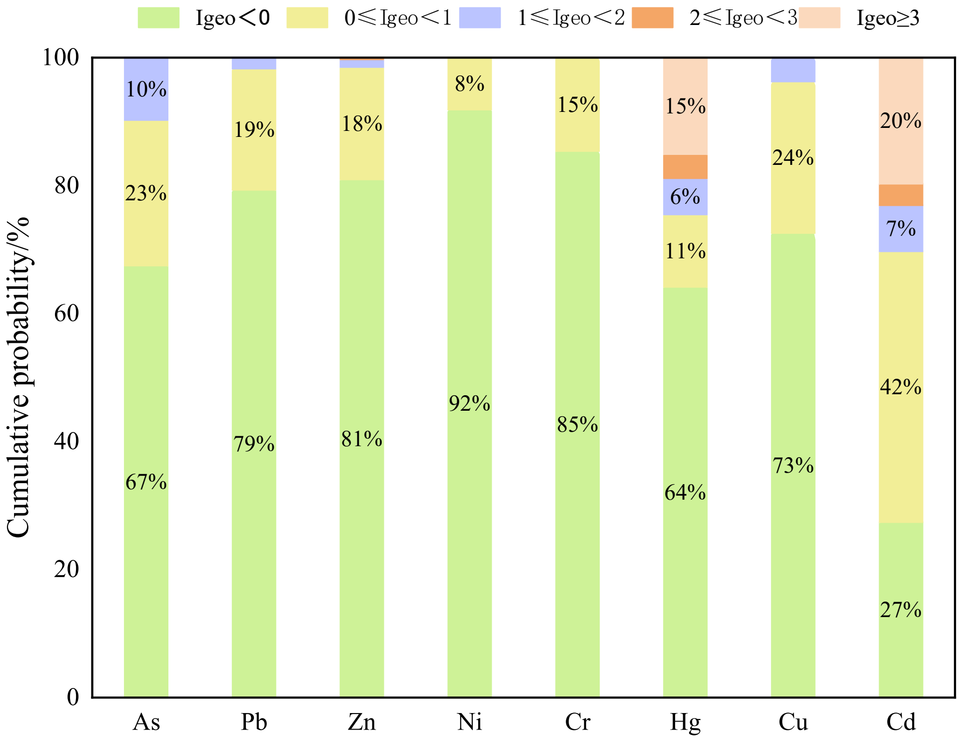

Figure 4. Evaluation of the accumulation index of heavy metals in the sediments of the Weihe River Basin.

3.2.2. Potential Ecological Risk Assessment

According to Equations (2)–(4), the Hakanson potential ecological risk index of the sediment in the Weihe River Basin was calculated, and then the potential ecological risk was assessed. The assessment results are shown in Table 5 and Figure 5. Among the heavy metal pollutants, Cd has the highest potential ecological risk coefficient in the sediments of the Weihe River Basin. It is necessary to further identify the source of Cd pollution to provide a reference for treatment. Hg has the second highest potential ecological risk coefficient, and the average potential ecological risk coefficients are all less than 70. On the whole, most of the Weihe River Basin is at low ecological risk, but the critical risk accounts for 12.6%. The average value of the comprehensive ecological risk index is at moderate ecological risk and should be given high priority.

Table 5. Potential ecological risk assessment results of sediments in Weihe River Basin.

Project	Minimum	Maximum	Average
E_r^{As}	3.02	41.44	13.66
E_r^{Pb}	1.89	17.83	6.45
E_r^{Zn}	0.38	7.11	1.27
E_r^{Ni}	2.60	10.83	5.26
E_r^{Cr}	0.86	4.87	2.37
E_r^{Hg}	1.20	1333.33	174.39
E_r^{Cu}	1.92	25.77	6.79
E_r^{Cd}	15.96	3070.21	334.88
RI	9.70	3094.58	251.44

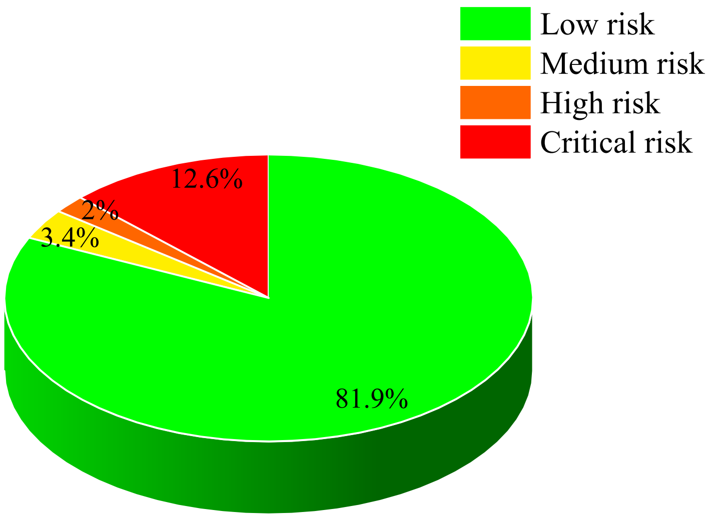

Figure 5. Pie chart of potential ecological risk distribution.

3.3. Source Analysis of Heavy Metal Pollution in the Sediments of the Weihe River Basin

3.3.1. Pearson Correlation Analysis

The relationship between heavy metals can provide information on the heavy metal sources. The correlation analysis results of heavy metals in the surface sediments of the Weihe River Basin are shown in Table 6. The results show that ω(Zn) is significantly and positively correlated with ω(Ni), ω(Cr), and ω(Cu) at the level of $p < 0.01$, which indicates that they are very likely to come from the same pollution source. ω(Ni) is significantly and positively correlated with ω(Cr) and ω(Cu) at the level of $p < 0.01$. There is a significant and positive correlation between ω(Cr) and ω(Cu) at the level of $p < 0.01$.

Table 6. Correlation analysis of heavy metal elements.

Metals	As	Pb	Zn	Ni	Cr	Hg	Cu	Cd
As	1							
Pb	0.123	1						
Zn	0.174	0.181 *	1					
Ni	0.039	0.037	0.346 **	1				
Cr	0.121	0.008	0.414 **	0.410 **	1			
Hg	0.264	0.030	0.014	0.066	0.003	1		
Cu	0.131	0.085	0.340 **	0.329 **	0.346 **	0.036	1	
Cd	0.212 *	−0.131	−0.139	0.030	−0.252 **	0.123	−0.096	1

(Note: * represents the significance at $\alpha = 0.05$; ** represents the significance at $\alpha = 0.01$)

3.3.2. Principal Component Analysis

Through KMO (KMO = 0.673) and the Bartlett test ($p < 0.05$), principal component analysis is suitable for the data. The results are shown in Table 7 and Figure 6. Through principal component analysis, three factors were extracted to explain the total variance, i.e., 74.659%, which can better explain the information on the heavy metals in the sediments.

Table 7. Rotation component matrix of factor analysis.

Metals	Component		
	1	2	3
As	0.437	0.760	−0.085
Pb	0.723	0.366	−0.059
Zn	0.859	0.239	−0.159
Ni	0.774	−0.454	0.258
Cr	0.863	−0.205	−0.018
Hg	0.077	0.457	0.692
Cu	0.753	−0.396	0.261
Cd	−0.319	0.036	0.686
Eigenvalue	3.469	1.383	1.121
% Total variance	43.359	17.283	14.017
Cumulative % variance	43.359	60.642	74.659

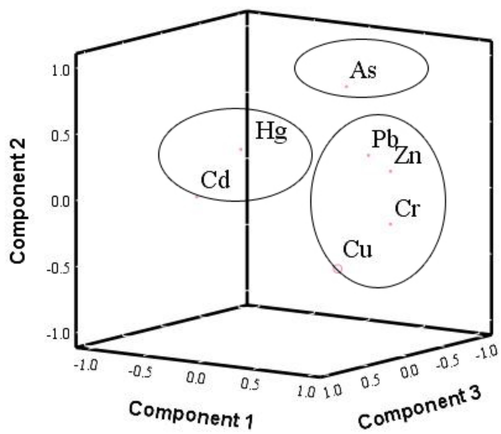

Figure 6. The 3−D plot of PCA loadings.

Factor 1 is the most important factor with a contribution rate of 43.359%, among which Pb, Zn, Ni, Cr, and Cu have large loads. The pollution source of such elements is a mixed source, which is comprehensively affected by natural sources and man-made sources and is mainly affected by the soil parent material and industry under the geological background. The mean value of the Ni content is lower than the soil background value. The results of the geoaccumulation index and potential ecological risk assessment showed that Zn, Ni, and Cr are mostly non-polluting, indicating that the main source of sediment in this area is natural and affected by soil parent material. The combustion of coal and the emission of automobile exhausts are important sources of Pb. At the same time, combined with the results of the principal component analysis, Ni, Pb, Zn, Cr, and Cu are classified into one category and may have similar sources. Therefore, it can be concluded that the five elements are comprehensively affected by natural and man-made sources, and factor 1 may be the soil parent material and industrial mixed source.

The contribution rate of factor 2 is 17.283%, and the heavy metals with large loads mainly include As. Generally, the heavy metals of As are mainly contained in pesticides. Due to the improper use of pesticides and fertilizers, heavy metals enter rivers invisibly, causing the accumulation of As in sediments. Therefore, this type of pollution source can be identified as an agricultural source.

The contribution rate of factor 3 is 14.017%, and the heavy metals with large loads include Hg and Cd. Hg comes from fossil combustion, and Cd mainly comes from industrial production. These two types of heavy metals enter rivers under the action of atmospheric sedimentation and surface runoff. From Figure 4, the geoaccumulation index shows that the high-value regions are mainly distributed in Xianyang and Baoji, both of which are large industrial cities in the Weihe River Basin. Table 5 shows that the potential ecological risk indexes of Hg and Cd are high. Therefore, such pollution sources can be identified as industrial sources.

3.3.3. Quantitative Analysis of Heavy Metal Pollution Sources in Sediments

(1) Reliability Evaluation of APCS−MLR Analysis and Contribution Rate Calculation of Pollution Source

According to the APCS-MLR receptor model, the three principal component scores of the factor analysis were converted into absolute principal component scores, and then the absolute principal component scores and the contents of eight heavy metals were analyzed using multiple linear regression. The multiple linear regression equation of the eight heavy metals was obtained, and then the content-fitting values of each element were derived. Compared with the measured values, the closer the value was to 1, the better the multiple linear regression fit. Figure 7 shows that the fitting/measured values of the heavy metals are close to 1 except for Pb and Cd. In addition, the complex phase correlation coefficients of Pb, Hg, and Cd are all about 0.6, and the complex correlation coefficients of As, Zn, Ni, Cr, and Cu are all close to 0.8. In summary, the APCS-MLR method has high accuracy.

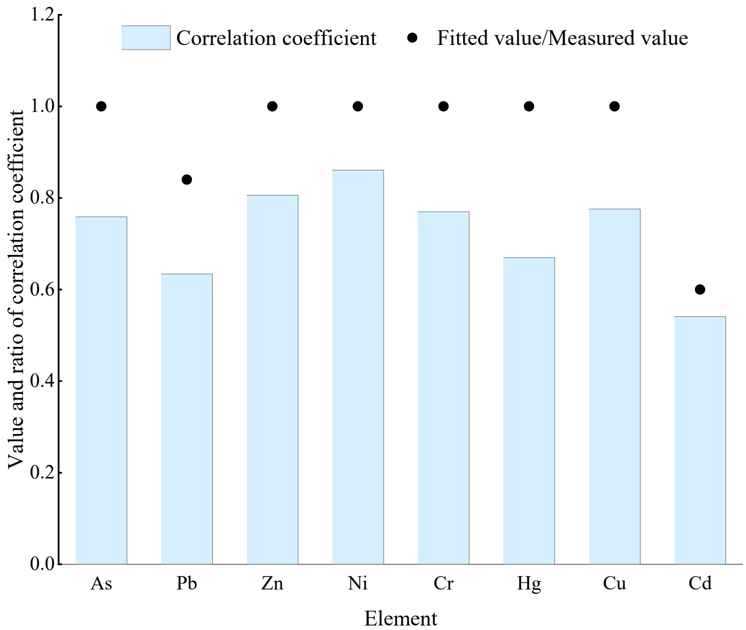

Figure 7. Accuracy characterization of APCS-MLR.

(2) Calculation and Analysis of Pollution Source Contribution Rate Based on APCS-MLR

According to the above analysis methods, such as correlation analysis, principal component analysis, and APCS-MLR analysis, the source contribution rate of the heavy metals in the sediments of the Weihe River Basin is shown in Figure 8. In the sediments of the study area, As is mainly from agricultural sources; Pb, Zn, Ni, Cr, and Cu are mainly from mixed sources, which are greatly affected by natural factors and human activities; and Hg and Cd are inferred to be from industrial sources.

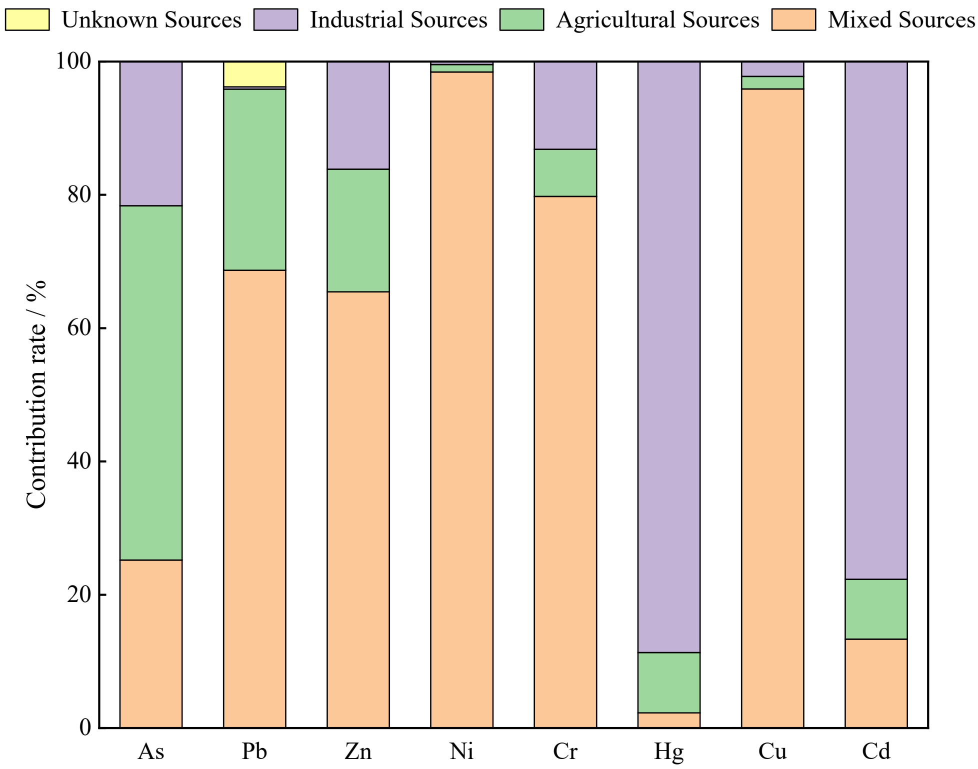

Figure 8. The contribution rate of heavy metal pollution in sediments of Weihe River Basin.

4. Discussion

The potential ecological risk index (RI) proposed by Hakanson is based on eight pollutants (PCB, As, Pb, Ni, Zn, Cu, Hg, Cr, Cd) [30]. In this study, the selected heavy metals were appropriately adjusted, and eight heavy metals (As, Pb, Ni, Zn, Cu, Hg, Cr, Cd) were finally selected by combining RI with the published literature [19,20,37] of the Weihe River Basin, as well as the collected data and the actual situation of the Weihe River Basin. The high values of the heavy metals Pb, As, Zn, Ni, Cr, and Cd are mostly located in the middle and lower reaches, the distribution of the high values of Cu is relatively dispersed, and the distribution of the high values of Hg is in the middle reach. The obtained distribution of the heavy metals is similar to the actual measurement results of Ahamad et al. [38]; that is, heavy metals are mainly concentrated in the middle and lower reaches of the Weihe River Basin. This is mainly due to the dense cities in the middle and lower reaches, the developed industry, large population, massive discharge of industrial wastewater and domestic sewage, and the enrichment of heavy metals in the air dust, which makes the distribution of heavy metals in the Weihe River Basin show this feature. Comparing the heavy metal concentrations in the sediments of the Weihe River Basin with other selected rivers (Table 8), the average concentration of Pb is higher than those of the Hunza River and Ereniku River; the average concentration of Zn is higher than those of the Hunza River, Ereniku River, and Dohezar River; the average concentration of Ni is higher than those of the Lijiang River, Zaarin-Gol River, and Tajan River; the average concentration of Cr is higher than those of the Lijiang River, Hunza River, Zaarin-Gol River, Tajan River, Dohezar River, and Karnaphuli River; the average concentration of Cu is higher than those of the Dohezar River; and the average concentration of Cd is higher than that of the Lijiang River. The results indicate that the input of heavy metals in the sediments of the Weihe River Basin is relatively high.

Table 8. Comparison of heavy metals concentration (mg·kg^{-1}) in sediments of the Weihe River Basin with other selected rivers in the world.

Sample Area	As	Pb	Zn	Ni	Cr	Hg	Cu	Cd	Citation
Weihe River Basin, China	15.42	27.27	88.05	31.05	75.00	0.13	29.47	1.00	This study
Indus River, Pakistan		47.3		128	90.6		71.7	1.41	[6]
Lijiang River, China	18.30	42.8	129.33	22.95	43.62	0.39	31.72	0.97	[3]
Hunza River, Pakistan		14.9	54.3	52.6	62.3		36.4	1.11	[38]
Ereniku River, Kosovo		14.8	157	355.4	625.3		70.6		[39]
Zarrin-Gol River, Iran	21.91		32.68	12.39	37.67				[40]
Tajan River, Iran			27.5	8.33	18.6				[41]
Dohezar River, Iran		25.1	68		64		18		[42]
Kabul River, Pakistan		29.4	94.7	86.3	75.2			3.8	[43]
Karnaphuli River, Bangladesh	81.9				20.3				[44]

The correctness of APCS-MLR is somewhat different from the results of Huo [45] and Zhang [46] due to different research areas, research scope, sampling point distributions, and data acquisition methods, but the overall difference is not significant. Therefore, APCS-MLR is reliable in analyzing heavy metal pollution sources in the Weihe River Basin sediments.

The traceability analysis shows that the main pollution sources of the Weihe River Basin are industrial sources and living sources, followed by agricultural sources. The unknown sources in Figure 7 need to be further studied. The heavy metals in the sediment are a collection of multiple sources. The greater the impact of human activities, the more widespread the sources. Due to warmer weather and more acid rain, rock weathering has become the main source of heavy metal pollution in water [47]. Ni is widely present in the crust, and its mass concentration is highly correlated with soil and rock and affected by the geological environment and soil-forming process [48]. The Weihe River Basin is located in the inland area of China, where rock weathering is serious. Ni has a low coefficient of variation, and the average content is lower than the soil background value. The results of the geoaccumulation index and the potential ecological risk assessment show that Ni is non-polluting, indicating that the main source of sediment in this area is natural and affected by the soil parent material [49]. Pb is often regarded as a symbolic element of vehicle pollution, mainly from coal combustion and automobile exhaust emissions [15]. The Pb content in sediments is relatively high in areas with dense traffic and industrial coal combustion. Pb, Zn, Cr, and Cu mainly come from industrial activities, transportation sources, and natural sources [50]. Cr mainly comes from metal processing, electroplating, and tanning industries, while Pb mainly comes from rubber synthesis and fossil fuels. Zn, Cr, and Cu come from the cement industry, metallurgy, and agricultural fertilizers and pesticides [51]. Ismail believes that Cr and Cu pollution in the Malacca Strait may be the result of wastewater discharge from tin mines and sewage treatment plants [52]. Therefore, it can be concluded that Pb pollution mainly comes from the combination of automobile exhaust and industrial coal combustion. At the same time, combined with the results of the principal component analysis, Ni and Pb, Zn, Cr, and Cu are classified into one category and may have similar sources. Therefore, these five elements are comprehensively affected by natural and human sources and may come from soil parent materials and industrial mixed sources. As is an important component of agricultural pesticides and herbicides, and As pollution is caused by the application of chemical fertilizers and pesticides in agricultural production and the use of plastic films [48]. Since As mainly comes from the agricultural sources of pesticides and fertilizers [53], it can be considered to be from agricultural sources. Hg mainly comes from fuel combustion, mining, smelting, garbage incineration, etc. [48]. It is also widely used as an electrode in the battery manufacturing industry [54]. Cd pollution is caused by mining development, sewage treatment, and the sewage outfall of various factories [55]. Cechinel believes that Cd may be associated with chemical and petrochemical emissions [56]. Salam suggests that the main potential source of Cd may be dye complexes related to other human activities [57]. These two heavy metals enter rivers under the action of atmospheric sedimentation and surface runoff. Table 5 shows that the potential ecological risk index of Hg and Cd is high. Cd in the sediments of the Weihe River Basin may mainly come from oil drilling and production, railway equipment companies, EFI repair plants, and other production. Therefore, it can be inferred that such pollution sources are industrial sources.

The mechanism of heavy metal pollution in the sediments is the increasing industrial pollution and domestic pollution sources, followed by the continuous accumulation of agricultural pollution, the reduction in river runoff, and the construction of water conservancy projects in the Weihe River Basin. The structure and composition of sediments are complex, and the spatial distribution of heavy metal pollution is often the result of a variety of natural and environmental factors, rather than a single factor. River sediment is a mixture of organics and minerals transported and deposited by rivers, and it is one of the important sources of internal pollution in the ecological environment of the Basin [58]. Due to weathering and erosion, heavy metals are separated from parent rocks and mineralized deposits, transported by fine-grained material, and become natural components of sediments with different concentrations [59]. After a series of physical changes such as adsorption, accumulation, and deposition, heavy metals will eventually be deposited in the riverbed [60]. The cities and towns along the Weihe River are densely populated and have concentrated industrial enterprises. A large number of industrial enterprises are distributed on both banks in a string of beads. There are 206 sewage outlets in the mainstream of the Weihe River. The wastewater treatment rate of industrial enterprises is relatively low, and the discharge does not meet the standards. Under the influence of dry and wet dust reduction, rainfall, and runoff, a large number of industrial and domestic pollutants are transported to the river network, then rapidly oxidized and decomposed, and settled into the sediment, resulting in a relatively high content of heavy metals in the sediment [60]. Therefore, industrial wastewater and domestic waste plastics are the main sources of heavy metal pollution. The Weihe River Basin has a long history of land development, a large area of arable land, and a large number of agricultural fertilizers. Pesticides and fertilizers left on the surface and soil flow into the river with rainfall washing and surface runoff washing, causing water pollution in the river, which is another major source of pollution [61]. The Weihe River is also a river with a lot of sediment, a wide channel, and a small gradient. The water flow speed is slow, and the water layer is shallow, so it is easy for sediment to adsorb and settle heavy metal ions. The Weihe River flows through Baoji, Xianyang, Xi'an, Weinan, and other cities. Organic pollutants have been repeatedly polluted and have exceeded their dilution and self-purification capabilities. Since the 1960s, the inflow of the Weihe River has shown a significant downward trend. Even in the dry season, most rivers are stored by dams for agricultural irrigation. Therefore, the retention of water for environmental purposes is very limited. Most of the riparian land is occupied by urban construction activities, resulting in the loss of riparian vegetation and biodiversity, further weakening the water purification function [62]. Therefore, heavy metal pollution in the sediments of the Weihe River Basin is mainly caused by human activities. Changes in the river channels, precipitation, and vegetation coverage affect the level of heavy metal pollution to a certain extent. It is recommended to start at the source, pay attention to the pollution control and water quality control of the tributaries, and improve the water quality of the mainstream with the improvement of the water quality of the tributaries. In addition, we should carry out comprehensive treatments of the tributary water environment, significantly reduce the pollution load of tributaries, and establish demonstration projects for water pollution treatment in a specific industry along the Weihe River. Furthermore, we should accelerate the construction of sewage treatment plants and sewage pipe network facilities and promote the utilization of sewage resources using scientific and technological means. Meanwhile, it is also recommended to carry out a water ecological restoration demonstration and build a green ecological corridor.

5. Conclusions

The mean values of Pb, As, Zn, Ni, Cu, Hg, Cr, and Cd contents in the sediments of the Weihe River Basin are 27.27, 15.42, 88.05, 31.05, 29.47, 0.13, 75, and 1.05 mg·kg^{-1}, respectively. All elements in the provinces of the Weihe River Basin, except Ni, exceed the mean soil background values, and all elements, except Cd, do not exceed the soil risk screening values. The mean values of the cumulative index are in the following order: Cd > Hg > As > Cu > Pb > Zn > Cr > Ni. Cd has the highest potential ecological risk coefficient, followed by Hg with the critical risk proportion of 12.6%. Based on the results of the Pearson correlation analysis, principal component analysis, and APCS-MLR receptor model, the sources of eight heavy metals in the Weihe River Basin can be divided into three categories: soil parent materials and industrial mixed sources, industrial sources, and agricultural sources. In order to reduce heavy metal pollution in the Weihe River Basin, the results of this study suggest controlling the increase in industrial and life pollution, reducing agricultural pollution emissions, increasing vegetation coverage, and reducing the construction of the water conservancy project of the Weihe River Basin.

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