



Comprehensive risk assessment and source apportionment of heavy metal contamination in the surface sediment of the Yangtze River Anqing section, China

Yafeng Liu¹ · Honghui Huang² · Ting Sun¹ · Yuan Yuan¹ · Ye Pan¹ · Yujing Xie¹ · Zhengqiu Fan¹ · Xiangrong Wang¹

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Abstract

The Yangzi River has been seriously affected by intensive anthropogenic activities in recent years. In this study, the levels and distribution, risk assessment, and source apportionment of heavy metals in sediments were investigated in the Yangtze River (Anqing section). The heavy metal concentration and chemical characteristics (Cu/Pb/Zn/Cd/Cr/As/Hg) of 16 samples over four sections were measured using Atomic Fluorescence Spectrometry and Graphite Furnace Atomic Absorption Spectrometry. The metal concentration in the study area showed variance in different sampling sites. The mean heavy metal content was also higher than the background value. Vertical analysis of metal concentration showed the decreasing order from surface sediment. The analysis of Hakanson's potential risk assessment indicated that the total potential ecological risk of these elements amounted to a considerable pollution level in the study area. The result of geo-accumulation index indicated that the risk of the studied metals had the following decreasing order: Cd > Hg > Pb > Cu > Zn > As > Cr. Based on the result of enrichment factor and principal component analysis, Cr, As, Hg, and partly Zn, Cu, and Cd mostly originated from natural sources. Pb and partly Cu and Zn mostly originated from gas companies, industries, and traffic sources, whereas Cd and partly Zn represented agricultural activities, such as fertilizer and pesticide consumption.

Keyword Heavy metals · Spatial distribution · Sources apportionment · Risk assessment · Sediments · The Yangtze River

Introduction

Due to the toxicity, persistence, and bioaccumulation in the environment, heavy metal contamination has attracted much more attention and becomes a worldwide environmental concern in recent years (Yong et al. 2013). In the last 40 years, because of the rapid industrialization of China, heavy metals have been discharged into the environment through all kinds of natural and anthropogenic inputs, whether intentionally or not.

Sediments in river ecosystems, as a reservoir or sink for heavy metals, can act as a source of heavy metals for aquatic organisms when environmental conditions change (Mihajlovic et al. 2014), which may accumulate to toxic concentrations and have toxic effects on benthic fauna and other aquatic organisms (Li et al. 2017; Zhao et al. 2014). Previous studies have shown that significant amounts of heavy metals (such as Cu/Pb/Zn/Cd/Cr/As/Hg) have accumulated in river sediments in highly urbanized areas and show a relatively high ecological risk (Alves et al. 2014; Hu et al. 2014; Martínez and Poleto 2014; Xun and Xuegang 2015). Heavy metals can be bio-accumulated and biomagnified through the food chain, resulting in elevated levels in freshwater organisms (Rajmohan et al. 2014), such as fish, which ultimately does harm human health. Therefore, the source apportionment and risk assessment of heavy metals in sediments are essential in understanding the possible changes of sediment quality caused by intensive anthropogenic activities (Massey et al. 2013; Yang et al. 2014; Yuan et al. 2014; Wang et al. 2014a, b; Martínez-Graña et al. 2016).

✉ Zhengqiu Fan
zhqfan@fudan.edu.cn

✉ Xiangrong Wang
rxrxwang@fudan.edu.cn

¹ Department of Environment Science and Engineering, Fudan University, Shanghai 200433, China

² Key Laboratory of Fisheries Ecology Environment, Ministry of Agriculture, Guangzhou 510300, China

Understanding the sources and assessment of pollutants in aquatic sediments is important for the pollution control. Multivariate statistical methods are useful in assessing the interrelationships among measured data and are widely used in geochemical studies (Deng et al. 2014; Wang et al. 2014a, b). Statistical approaches, such as principal component analysis (PCA), are frequently used for the apportionment of contamination sources by grouping sampling sites and metals (Wu et al. 2014; Yuan et al. 2014; Wang et al. 2014a, b; Zhang et al. 2017); enrichment factors are often calculated to evaluate the status of anthropogenic discharge into the sediment (Cui et al. 2014a, b; Zang et al. 2017). Risk assessments of the environmental pollution are also critical for sediment analysis. Numerous indexes have been developed to assess the environmental risk of heavy metals in river surface sediment based on the total content, bioavailability, and toxicity (Cui et al. 2014a, b; Rajmohan et al. 2014). The geo-accumulation index (I_{geo}) of individual heavy metals in sediment are calculated using their total content, background value (Ma et al. 2016, 2017). Potential ecological risk index was used widely to assess the comprehensive risk of multiple heavy metals in sediment (RI) (Martínez and Poletto 2014; Alves et al. 2014).

The Yangtze River basin is now causing serious environmental pollution problems with heavy metals being discharged into the river. Anqing, a city located at midstream of The Yangtze River, is a highly industrialized city with a large number of factories, such as petrochemical plants, electroplating plants, steel mills, and so on. Heavy metals contamination in river sediments from these areas has occurred over the last several decades (Chen et al. 2013). It is very urgent and important to maintain the sustainable development of the study area by strengthening the understanding of the level and risk of heavy metals pollution in the river sediments. However, until now few studies that assess the ecological risks posed by heavy metals contamination and their spatial and temporal differentiations of river sediments have been reported in the Yangtze River Anqing section, where it is closely related to abundant human activities.

Therefore, it is important to investigate heavy metals distributions, the degree of pollution, and the potential ecological risk in this area. The main objectives of this study were as follows: (1) to determine the levels and distribution of the toxic heavy metals in sediment; (2) to explore the degree of contamination and pollution impacts using comprehensive pollution indicators; and (3) to investigate the nature and origin of the contamination of the river sediments.

Materials and methods

Study area and sediment sampling

In this study, the sediment samples from 16 sampling sites in the study area were collected in April, 2014. The sampling sites are shown in Fig. 1. Among those sampling sites, section A was around agricultural area, section B was closed to residential area, section C was around industrial regions, and section D was around natural area. A composite sample was collected at each site by mixing 4–5 random samples. Composite sediments (0–20 cm) were taken using a grab sampler. Vertical samples were collected by sedimentary column sampler; the core samples (0–100 cm) were cut apart every 10 cm. All samples were sealed in clean plastic bags and delivered to the laboratory immediately.

Chemical analysis

The sediment samples were air-dried, homogenized, ground, and sieved with a 100-mesh nylon screen with the stones and plant fragments removed (Yuan et al. 2014; Cui et al. 2014a, b; Hu et al. 2014). Coarse particles were used to determine pH and electrical conductivity (EC), and the fine particles were used to analyze sediment organic matter and heavy metals. pH was measured in a suspension ratio of 1:5 sample to distilled water using an Artorius PB-10 Standard pH meter after 30 min of agitation. EC was measured in a 1:5 ratio of soil to water suspension using a Model DDS-307 Conductometer after equilibration for 30 min and subsequent filtering. Soil organic carbon was determined through wet oxidation at 185 °C with a mixture of potassium dichromate and titration with ferrous ammonium sulfate. A coefficient factor of 1.724 was used to convert organic carbon to organic matter (Xun and Xuegang 2015).

To analysis of heavy metals Cu, Pb, Zn, Cd, and Cr, 0.2 g of dry sediment was weighed in Teflon beakers with an added mixture of concentrated HF-HClO₄-HNO₃ (5:5:2) and was then digest in a microwave oven, analyzed by Graphite furnace AAS. The sample solutions were then filtered and adjusted to 25 ml with deionized water. As and Hg were analyzed using Atomic Fluorescence Spectrometry (AFS). Fe was measured using Graphite Furnace Atomic Absorption Spectrometry (GF-AAS) (Sakan et al. 2009; Varol and Şen 2009).

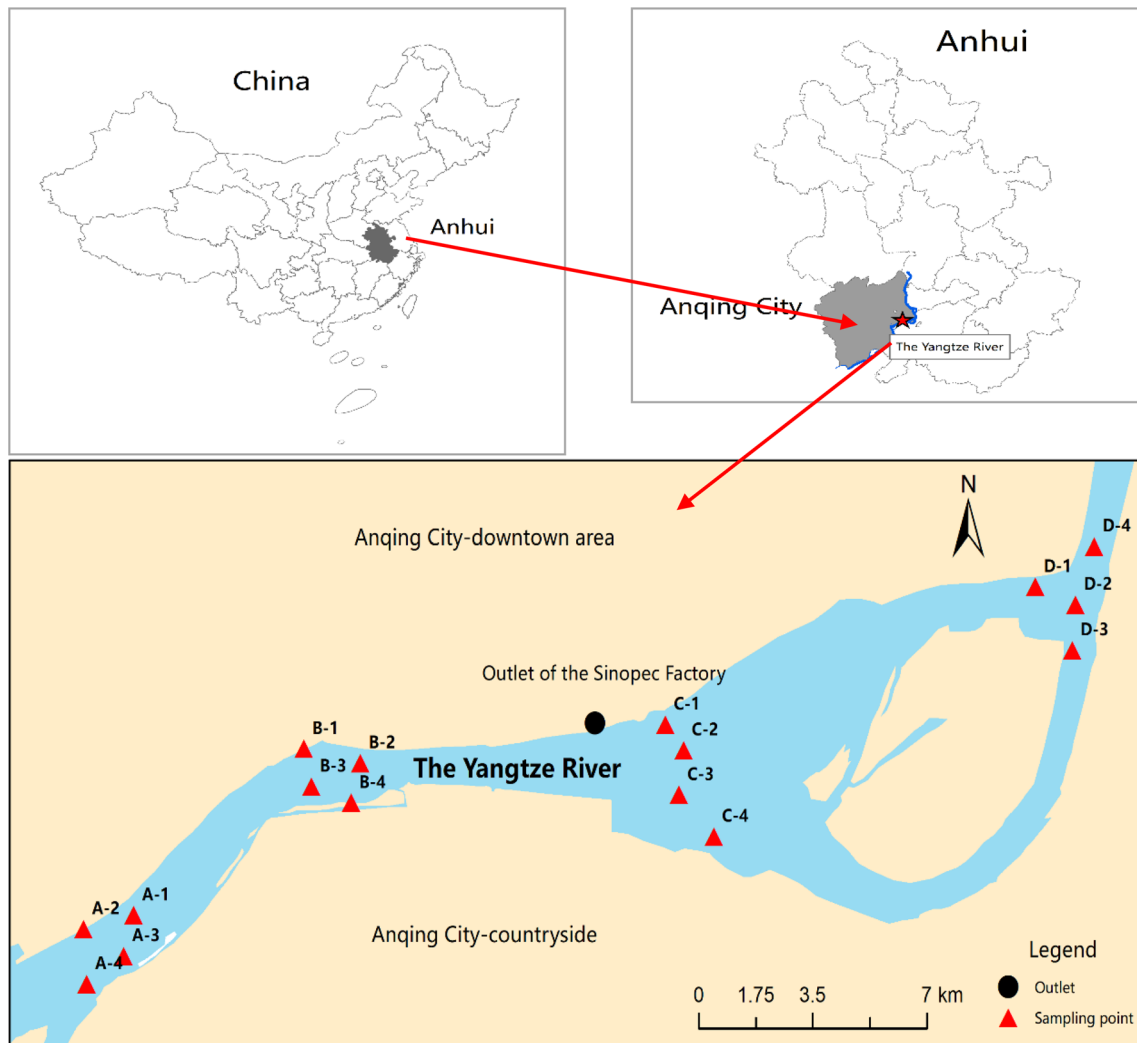


Fig. 1 Map of sediment sampling sites in the Yangtze River of the Anqing section

Pollution and potential ecological risk assessment

Geo-accumulation index

The Geo-Accumulation Index (I_{geo}) is defined by the equation:

$$I_{geo} = \log_2 \left[\frac{C_n}{KB_n} \right],$$

where C_n is the concentration of heavy metals examined in sediment and B_n is the background concentration of the heavy metals. Factor K was defined 1.5 as the background matrix correction factor caused by lithospheric effects. The I_{geo} consists of seven classes that are listed in Table 1.

Table 1 Grades of heavy metal pollution by geological accumulative index (I_{geo})

I_{geo} class	I_{geo} value	Sediment quality
0	$I_{geo} \leq 0$	Not contaminated
1	$0 < I_{geo} < 1$	Not contaminated–moderately contaminated
2	$1 < I_{geo} < 2$	Moderately contaminated
3	$2 < I_{geo} < 3$	Moderately–highly contaminated
4	$3 < I_{geo} < 4$	Highly contaminated
5	$4 < I_{geo} < 5$	Highly–extremely contaminated
6	$I_{geo} \geq 5$	Extremely contaminated

Potential ecological risk index

The Hakanson Pollution Index, reflecting the concentration of a specific heavy metals in the sediment, is used to evaluate the pollution of heavy metals in the sediment (Bianchini

Table 2 Potential ecological risk assessment index with pollution grades

C_f^i		C_d		E_r^i		RI	
<1	Low	<8	Low	<40	Low	<150	Low
1–3	Moderate	8–16	Moderate	40–80	Moderate	150–300	Moderate
3–6	Considerable	16–32	Considerable	80–160	Considerable	300–600	Considerable
≥6	High	≥32	High	160–320	High	≥600	High
				≥320	Very high		

et al. 2012). The potential ecological risk of heavy metals is classified into five levels according to the values of E_r^i and RI (Table 2). The formula for the single heavy metals is:

$$C_f^i = C_i / C_n^i$$

$$C_d = \sum C_f^i,$$

where C_f^i is the pollution coefficient for heavy metal i , which reflects the characters of the pollution of the investigated region but cannot reveal the ecological effects and hazards. C_i is the measured values of heavy metals in surface sediments. C_n^i is the background values for calculation. Background concentrations of heavy metals were set as 21.02, 26.39, 74.33, 0.07, 63.71, 9.13, 0.02, and 10.14 mg/kg for Cu, Pb, Zn, Cd, Cr, As, and Hg, respectively.

RI is used separately to assess the pollution degree and biological effect of multiple heavy metals pollution in sediment

$$E_r^i = T_r^i \times C_f^i$$

$$RI = \sum E_r^i = \sum T_r^i \times C_f^i = \sum T_r^i \times C_i / C_n^i,$$

where E_r^i is the pollution degree of a single heavy metals in sediment, and T_r^i is the toxic response factor for a given substance (e.g., Cu=5, Pb=5, Zn=1, Cd=30, Cr=2, As=10, and Hg=80). Four classes of RI are defined as followed Table 2.

Statistical analysis

Enrichment factors

Enrichment factors (EFs) were widely used to analyze the source of heavy metals in sediment and were calculated by comparing the sediment sample to an uncontaminated reference material (Alves et al. 2014; de Andrade Lima and Bernardes 2017). The uncontaminated soil representing the background was chosen as the reference material. Meanwhile Al was chosen as the reference element in the EFs calculation. EFs was calculated by:

$$EF = \frac{\left(\frac{x_i}{Al_i}\right)_{\text{sample}}}{\left(\frac{x_0}{Al_0}\right)_{\text{sample}}},$$

where x_i and x_0 are the concentrations of the individual metal in the sample and the background soil, respectively. Al_i and Al_0 are the concentrations of Al in the sample and the background soil, respectively. The degree of contamination is usually graded based on the EF values: EF < 2, minimal enrichment; EF 2–5, moderate enrichment; EF 5–20, significant enrichment; EF 20–40, high enrichment; and EF > 40, extreme enrichment. In addition, we use EF = 1.5 to recommended as an evaluation standard because when EF < 1.5, the trace metal may be entirely from natural sources, whereas when EF ≥ 1.5, a considerable part of the trace metal may originate from anthropogenic source. Background concentrations of heavy metals were set as 21.02, 26.39, 74.33, 0.07, 63.71, 9.13, 0.02, and 10.14 mg/kg for Cu, Pb, Zn, Cd, Cr, As, and Hg, respectively.

Principal component analysis

Principal component analysis (PCA) was used to investigate the association among the seven heavy metals and infer the hypothetical source of heavy metals (i.e., nature and anthropogenic) (Wang et al. 2014a, b; Duan et al. 2015). The components of the PCA were rotated using a varimax rotation. The Kaiser–Meyer–Olkin and Bartlett's sphericity tests were performed to examine the appropriateness of the data for PCA. ArcGIS (version 10.2) and SPSS statistical software (version 19.0) were used for all the data analyses.

Results and discussion

Physical and chemical characteristics of surface water and sediment

The mean pH, EC, DO, COD_{mn}, BOD₅, ammonia nitrogen, TN, and TP values of the surface water and the pH, EC, and TOC of the sediment in every section are shown in Table 3.

Table 3 Values of the physicochemical properties of the surface water and sediment

Site	Surface water								Sediment		
	pH	EC	DO (mg/L)	COD _{mn} (mg/L)	BOD ₅ (mg/L)	N-NH ₄ (mg/L)	TN (mg/L)	TP (mg/L)	pH	EC	TOC/%
A ^a	7.63	7.63	10	10	2	0.214	2.50	2.50	8.07	70.8	0.34
B ^a	7.65	7.65	9.9	9.9	2	0.244	2.40	2.40	8.11	72.1	0.19
C ^a	7.64	7.64	9.7	9.7	2.9	0.246	2.50	2.50	7.98	73.6	0.61
D ^a	7.61	7.61	9.8	9.8	2.7	0.220	2.53	2.53	8.13	62.4	0.23

^aHere is the average result of each section with four sampling sites

As shown in Table 3, the pH of the surface water and sediment ranged from 7.61 to 7.65 and 7.98 to 8.13, respectively. Slightly variance was observed in the pH of the sediment, indicating that the sediment studied in this study was alkaline and had different of sediment acidifications. Different sediment compositions, such as grain-size distribution, natural heavy metals concentrations, and sediment pH can influence the mobilization of heavy metals. In addition, Sakan et al. (2009) had confirmed that the mobilization of heavy metals is limited and that the plant uptake effect can be decreased. Sediment properties have effects on surface water; the speed of heavy metals stored in sediment released into the water is also inferenced by the sediment properties, such as pH, EC, and TOC. In the study area, the properties of the surface water properties showed the same trend, at sampling sites C, as a drain outlet site in the city showed the worst situation among all the sites. EC and organic matter have an important role in the physical, biological, and chemical properties of sediment that can affect stability, nutrient availability, porosity, and cation exchange capacity. Therefore, the chemical and physical properties between surface water and sediment are related which is very important to analysis.

Spatial distribution characteristics of heavy metal pollution

Table 4 shows a summary of the statistics for the monitoring results, including the concentration ranges, mean, standard

deviation (SD), and variable coefficient (CV) of the seven measured heavy metals (Cu, Pb, Zn, Cd, Cr, As, and Hg). The results of the Kolmogorov–Smirnov test ($p < 0.01$) show that the contents of the elements in the sediment fit a normal distribution.

The concentration of the seven heavy metals, shown in Table 4, varies markedly. The mean average concentration of the heavy metals exhibits the following decreasing order: Zn > Cr > Pb > Cu > As > Cd > Hg. Large variances among the sites are observed for Pb (18.24–144.43 mg/kg) and Zn (50.55–351.24). There are no significant differences between the four sampled areas among most heavy metals. The average concentrations of Cu, Zn, and Hg are almost twice as high as the background values. The sample section C has the highest values, and section D also suffers from high levels. The highest concentrations of Pb and Cd are located in sample site C-2, whereas the lowest are in site B-1 and site B-4. The average concentrations of these two elements are almost three times of their background values. The average concentrations of Cr and As reach the content of the background values. The sites with the highest concentrations are also located in section C, and those with the lowest concentrations are located in section D.

In addition, these heavy metals have similar distribution patterns; all seven elements have the highest concentration in sample section C, where the main drain outlet of SIN-OPEC is located. Sample section A, which is located in the upstream of the study area, shows relatively low concentration of heavy metals. This may be because no industries

Table 4 Metal concentrations in the sediment samples

	A ^a	B ^a	C ^a	D ^a	Median	Max	Min	CV (%)	SD
Cu	36.85 ± 14.17a	38.62 ± 21.15a	54.60 ± 12.29a	49.26 ± 12.12a	43.94	72.34	8.51	59.3	2.80
Pb	55.90 ± 10.08a	28.25 ± 7.14a	115.20 ± 26.46b	55.58 ± 18.41a	57.60	144.4	18.24	37.7	8.33
Zn	101.13 ± 92.04a	119.27 ± 38.64a	209.38 ± 116.18a	90.53 ± 3.99a	93.14	351.2	115.9	38.1	3.51
Cd	0.17 ± 0.03a	0.17 ± 0.05a	0.38 ± 0.08b	0.15 ± 0.02a	0.17	0.45	0.12	11.5	4.54
Cr	73.84 ± 21.41a	63.46 ± 7.58a	138.50 ± 22.53b	67.54 ± 6.14a	69.28	165.7	51.81	54.1	8.81
As	15.49 ± 1.83b	11.80 ± 2.25b	27.34 ± 5.35c	4.14 ± 0.54a	13.75	35.17	3.45	97.8	1.26
Hg	0.06 ± 0.01ab	0.05 ± 0.03ab	0.09 ± 0.04b	0.03 ± 0.03a	0.06	0.13	0.01	85.4	0.01

^aThe average value of heavy metals in four different sites

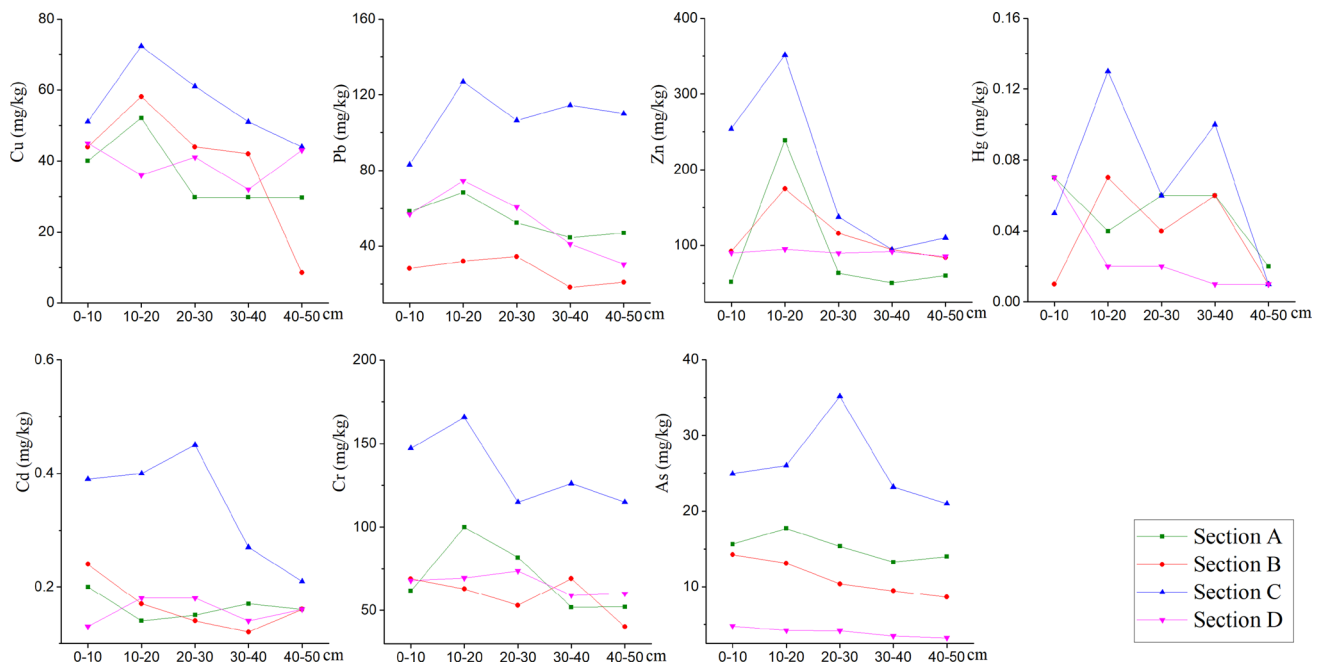


Fig. 2 Vertical content curves of the heavy metals in the sample core

were located here, given that this area is an agriculture zone. However, the overuse of fertilizers has caused the concentration of Zn, Cr, and As in some sites to be higher than average. The section B and section D may have the lowest heavy metal concentrations because the water intake of the city is close to section B, whereas section D is located downstream of the study area with no industries or residents there. Water self-purification may also be a reason for the low concentration of heavy metals in section D. These results suggest that the sediment in the study areas had received anthropogenic discharge.

Vertical distribution characteristics of the heavy metal pollution were analyzed in this study (Fig. 2). The results show that these heavy metals have a relatively high content at 10–20 cm, which clearly demonstrates an anthropogenic contribution. The Cd and As contents in the 20–30 cm layer of the core profile increase gradually and remarkably, which means that external sources contribute the most content. It also shows that most of the samples in vertical concentration exceed the local background values, except at section D. The results showed that Cd, Zn, Cu, and Pb occur at high concentrations in section C, especially in the 10–20 cm layer. Many paper-making industries, petrochemical plants, steel industries, and small workshops, which do not have waste water treatment equipment, are distributed in section C.

With the analysis of vertical heavy metal monitoring, Pb and Cd show the highest enrichment extent in the sediment and originate mainly from anthropogenic activities (Bolan et al. 2017; Han et al. 2017; Li et al. 2017), such as industrial wastewater and traffic emissions. The Pb and Cd contents

with the detected average value of 126.84 mg/kg in section C, which has a petrochemical factory, is much higher than its background value. Given that Pb is added to gasoline, the use of gasoline-powered machines and oil spill disasters represents an anthropogenic source of Pb and can cause high pollution levels. The values of Cu and Hg follow closely and are mostly attributed to agriculture waste water influenced by farmland, aquaculture, and paddy field areas located to the west of the city. Zn, Cr, and As show a slight enrichment especially for Cr, which indicates less input from anthropogenic activities, such as fertilizer and pesticide consumption (Agarwal et al. 2009; El Azhari et al. 2017).

Risk assessment of heavy metal contamination in sediment

The concentrations of heavy metals in sediment were used to assess the quality of life in an environment under the risk of heavy metal exposure. Geo-accumulation and potential ecological risk assessment were used to assess the risk of the study area.

Geo-accumulation index assessment in sediment

According to the comparison between the obtained mean I_{geo} and the I_{geo} classification in Table 1, the mean values exhibit in the following decreasing order: Cd > Hg > Pb > Cu > Zn > As > Cr. Cr and As remain in Class 0 (practically unpolluted), and Cu, Pb, Zn, Cd, and Hg in Class 1 (unpolluted to moderately polluted), whereas Cd

is nearly Class 2 (moderately polluted). The spatial distribution of I_{geo} and the class for each heavy metal show that only Cd and Hg have moderate to heavy levels of pollution, while Cr and As had practically unpolluted to moderate levels of pollution. The remaining metals show no level to low levels of pollution in all locations. The moderately polluted areas for Cd occur in sample site C-2, and most Class 2 levels of pollution occur in section C, where the main drain outlet of the city is located. As for Hg, 7 of the 16 locations are over Class 2 (including Class 2); section C shows most samples which exceed. The vicinity of section A and section B shows moderate levels of pollution of As. The moderately polluted areas that are mostly located in section C should be identified as the priority regions for environmental monitoring and management. The I_{geo} of Cd and Hg in the most samples are significantly higher than the background values in local sediment. Cd presents moderate to significant level, these show that the sources of Cd, Hg, and Pb the sediment are related to the local anthropogenic activities (Fig. 3).

The potential ecological risk index assessment in sediment

The pollution index (C_f^i) and the potential ecological risk index (RI) of the seven heavy metals in the surface sediment

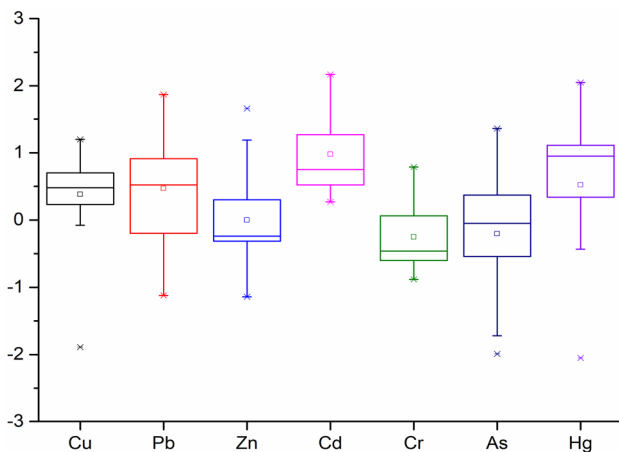


Fig. 3 Box plots display the distributions of the geo-accumulation indexed

of the Yangtze River in the Anqing section were calculated using the method described by Hakanson (1980) and Kucuksezgin (2008). The results are shown in Table 5.

Cu, Pb, and Hg vary from 0.41 to 3.44, 0.69 to 4.81, and 0.36 to 6.21, respectively. The highest concentration of Cu was located in C-1, while the highest value of Pb was located in C-2, probably because it is the drain outlet of SINOPEC. The mean C_f^i values of Cu, Pb, and Hg are 2.13, 2.42, and 2.67, respectively, indicating a moderate level of sediment pollution in the Anqing section. However, Hg shows extremely high levels of pollution. For Zn, Cr, and As, the mean values of C_f^i also show moderate levels of pollution. However, the values are lower than Cu, Pb, and Hg. The values of Zn, Cr, and As vary from 0.68 to 4.73, 0.81 to 2.60, and 0.38 to 3.85, respectively. Half of the locations in section A show low contaminations of Zn and Cr, while section D has low pollution level of As, indicating low pollution levels in this position. The C_f^i values of Cd vary from 1.04 to 6.75 with a mean value of 3.14, indicating high level pollution. Sample section B and section D, which located in a water protection zone with very low vehicular traffic, have relatively low contamination, while section C has the highest values of contamination. This result varies from other research results: Wang found there was no obvious pollution of As in the Yangtze River (Wang et al. 2014a, b); Wang hui observed that the pollution index of Cd values indicated low pollution in the mainstream (Li et al. 2013).

E_r^i of the seven heavy metals and metalloids exhibit the following decreasing order: Hg > Cd > As > Pb > Cu > Cr > Zn. The total RI of the seven heavy metals in the surface sediment of the study area is classified as considerable pollution. Among the seven metals, Cu, Pb, Zn, Cr, and As have a potential ecological risk below 40, indicating a low risk level. By contrast, the E_r^i of Cd and Hg are 94.25 and 213.57, which indicate considerable and high potential ecological risk levels, respectively. As shown in Table 6, 2 of 16 samples had an RI value below 150 and 4 of 16 samples had an RI value between 150 and 300, indicating low and moderate risk. 56% samples have defined as considerable to high potential for ecological risk, and one sample site (C-2) is over 600, indicating an extremely high potential risk. The distribution of the total potential ecological risk exhibits the

Table 5 Single and multiple coefficient values of heavy metal pollution

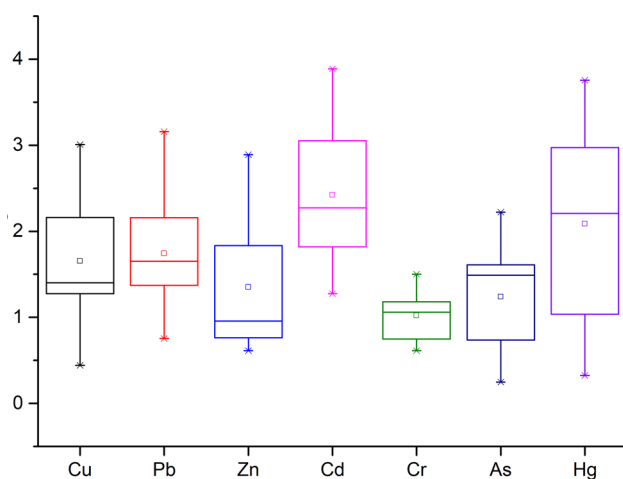
Section	C_f^i							C_d
	Cu	Pb	Zn	Cd	Cr	As	Hg	
A ^a	1.42	1.99	0.85	1.04	1.28	1.68	2.95	11.21
B ^a	2.76	1.21	2.35	2.48	0.99	1.44	3.24	14.47
C ^a	3.44	3.15	3.42	5.84	2.31	2.73	2.70	23.59
D ^a	3.10	2.30	1.28	1.97	1.07	0.52	3.37	13.61
Mean	2.13	2.42	1.75	3.14	1.35	1.61	2.67	15.07

^aHere is the average result of each section with four sampling sites

Table 6 Potentially ecological hazard coefficient values and ecological risk indexes

Section	E_r^j							RI
	Cu	Pb	Zn	Cd	Cr	As	Hg	
A ^a	7.08	9.93	0.85	31.15	2.57	16.82	236.40	304.79
B ^a	10.45	6.53	1.27	62.00	1.66	11.38	169.39	262.69
C ^a	17.21	15.73	3.42	175.34	4.62	27.33	215.90	459.56
D ^a	8.77	10.77	1.21	64.64	2.18	4.58	62.91	155.06
Mean	10.66	12.08	1.75	94.25	2.69	16.09	213.57	351.10

^aHere is the average result of each section with four sampling sites

**Fig. 4** Box plots display the distributions of the enrichment factor

following order: $C > B > A > D$. The SINOPEC drain outlet may be the reason why section C has the highest concentration among all the 16 samples. The concentrations of Cd and Pb in the most samples are significantly higher than the background values in local sediment. Cd presents moderate to significant potential ecologic risk index; these show that the sources of Cd, Pb, and Hg sediment are related to the local anthropogenic activities (Mihajlovic et al. 2014).

Source identification in study area

Enrichment factors

The reliability of the EFs analysis will depend on the chosen reference element. Therefore, the reference element must be conservative and natural origin. The reasons that we chose Al as the reference list are as follow: first, the content of Al in crustal rocks is generally stable; moreover, Al has a similar conservative behavior during chemical weathering, and it has few anthropogenic sources of Al in the environment. Meanwhile, Al was ascertained as being a natural and conservative element in this region. The EFs for the individual heavy metals in the sediment samples are shown in Fig. 4.

The EF values show apparent differences among the heavy metals and exhibit the following sequence: $Cd > Hg > Pb > Cu > Zn > As > Cr$. The mean EF value of Cd and Hg are the highest in sediment, reaching 3.10 and 2.98 on average, respectively, indicating significant enrichment. Cr has the lowest average EF value implying moderate enrichment in the study area. Most sediment samples show low EF values, except in the section C.

The analysis of the EFs of all the heavy metals for the individual samples that reveals a marked change in the middle of the study area, which locates at sample section C, presents a stronger enrichment than the other sampling sites. The EF values in the sample D sites decrease in the downstream because of river self-purification and dilution.

EF values were interpreted with the support of the classification (Macdonald et al. 2000; Lu et al. 2017; Tepanosyan et al. 2017); sediment with higher metal enrichment values are influenced by anthropogenic discharge. The result shows that the enrichment in section C is attributable to the dense population and gas industry, suggesting that the sediment was severely enriched. Enrichment of Pb can be attributed to the outlet of a gas factory; previous studies that also reported elevated concentrations of Pb in the city are influenced by SINOPEC, a national gas factory set in the downtown city. Section B shows a relatively high enrichment value located in a residential area and may have been polluted by domestic sewage (Liu et al. 2016).

Principal component analysis

Principal component analysis (PCA) was used to investigate the association among the seven heavy metals that were studied and infer the hypothetical source of heavy metals (i.e., nature and anthropogenic) (Wang et al. 2014a, b; Duan et al. 2015).

The analysis results of PCA for the heavy metal contents are presented in Fig. 5; PCA was analyzed both in heavy metal contents and sampling sites. With the different heavy metals, the PCA of the entire data reveals three principal components with eigenvalues > 1 , which explains about 85.16% of the total variance in the sediment quality data. Three major components were identified in this study. The

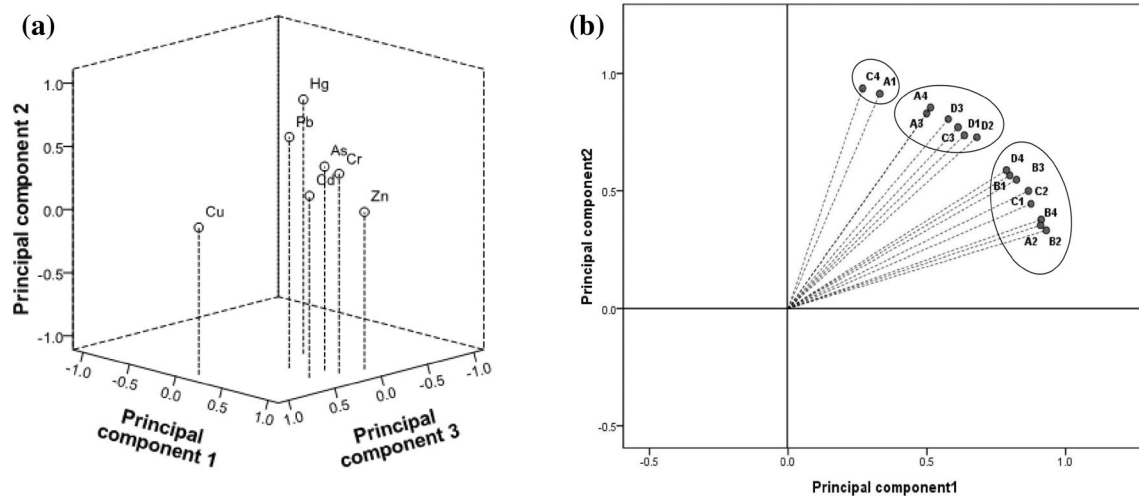


Fig. 5 Principal component analysis of heavy metal distribution. **a** PC 1 is explained as accounts for 53.36% of variance, while PC 2 is explained 21.25% of variance; **b** the components of all sampling sites

first component explains 39.33% of the total variance and consists of Zn, Cd, and Cr. These three elements were extensively caused by producing stainless steel and traffic; also with the outlet by the gas industry, the high-value zone of Pb, Zn, and Cr from study area is located in the section C where the petrochemical factory is. Results also indicate that Zn and Pb have the same sources in the area. Pb, Cr, and Cd are extensively used to produce stainless steel and gas industry (Li et al. 2004), which can also be confirmed by the spatial distributions of Cd, Cu, and Pb. The high-value zones of Pb, Cr, and Cu were located in section C and show they might mainly come from human sources. Cu is deficiency to minimal enrichment, indication that they mainly came from natural sources, which partly stems from anthropogenic sources (Li et al. 2004; Yi et al. 2011; Chen et al. 2013).

The second component explains 27.76% of the total variance and correlated with Hg and Pb, which showed that PC1 versus PC2 corresponds to the distribution of heavy metals in the surface sediment (Fig. 5a). Figure 5 also indicates the existence of close relationships among Cd, Zn, and Cu, which are positively associated and displayed over Axis X, which also indicate that Cr, As, and Hg have the same sources. The third component explains 18.08% of the total variance with Cu, which indicates that Cu has a natural source.

Cu is a component of alloys used in mechanical parts due to its desirable qualities such as corrosive resistance and strength (Hu et al. 2014; Guo et al. 2015). Pb is also represented in brass automotive radiators due to its high corrosive resistance and high thermal conductivity (Yang et al. 2011), and is often used in car lubricants (Hu et al. 2014; Guo et al. 2015). Pb alloy and galvanized board are widely used in motor vehicles (Zhang et al. 2010). Pb is also added to tires during the

vulcanizing process, comprises from 0.3 to 4.5% of the resulting tire tread (Doni et al. 2015; Gołdyn et al. 2015). Deterioration of the mechanical parts in vehicles over time results in Cu and Pb being emitted to the surrounding environment (Abdel-Satar and Goher 2015; Giri and Singh 2015; Xun and Xuegang 2015; Massey et al. 2016). Cu and Zn being released into the urban environment is a result of wear of automobile oil pumps or corrosion of metal parts which come into contact the oil (Cui et al. 2015; Tepanosyan et al. 2017; Yu et al. 2017).

Cu is not correlated with the other heavy metals considered and it is separated from the first two principal components in the PCA, which showed that Pb has a different source than other heavy metals. The metals are extensively used in alloys, coating materials, paints, and pigments. This is because the reconstruction of the section C produced the pollution. It also suggests that some metals in the study area are originated from the building construction or car pollution, as well as weathering and corrosion of building materials (Acosta et al. 2014; Brito et al. 2015).

Meanwhile, the results of PCA analysis for sampling sites are also presented in Fig. 5b. The results also indicated that PCA led to a reduction of the initial dimension of the dataset to the two components which explained 96.74% of the data variation. The first component explained 51.54% of the total variance and was loaded highly by sampling sites A2, B2, B4, C1, and C2. The second component accounted for 45.2% of the total variance and loaded highly by A1, A3, A4, C4, and D3. The reason of sampling sites B and C contributes to high variance that may be caused by the discharge of the chemicals in Sinopec.

Conclusions

In this study, the levels and distribution, risk assessment, and source apportionment of heavy metals in sediments were investigated in the Yangtze River (Anqing section), China. The main conclusions were as following:

1. The concentration of heavy metals showed different spatial variations and pollution levels in the study area. The mean concentration of all the heavy metals in the surface sediment is higher than the background values. The sampling sites which are close to urbanized areas and industrial areas generally have higher potential ecological risks among the seven studied heavy metals.
2. The heavy metal contamination in the sediment of the study area was assessed through RI, I_{geo} . The total pollution status reaches considerable degrees of potential ecological risk, especially in the section C. Cd and Hg were determined to be the main contamination indicators, given their higher toxicity and high concentrations than those of the other heavy metals. Pb also shows a relatively high level of contamination. Therefore, Pb, Hg, and Cd were considered as the most important elements in the environment in the study area.
3. Based on multivariate statistical analyses, the enrichment degree of the studied metals exhibits the following decreasing order: Cd > Hg > Pb > Cu > Zn > As > Cr. Cr, As and partly Zn, Cu mostly originate from natural sources. Pb and partly Cu and Zn mainly originate from gas companies, industry, and traffic, whereas Cd and partly Zn represent agricultural activities, such as fertilizer and pesticide consumption.

The results presented in this study can facilitate planning, risk assessment, and decision making in the environmental management of the study area. However, more detailed studies in the study area would be required to draw such a conclusion.

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