

# Heavy metals in surface sediments of the shallow lakes in eastern China: their relations with environmental factors and anthropogenic activities

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**Abstract** The aquatic environment is affected by heavy metal pollution. This study was conducted to test the hypothesis that environmental factors and anthropogenic activities influence the distributions and the risks posed by heavy metals in surface sediments in shallow lakes in eastern China, which is an area affected by rapid urbanization, industrialization, and population growth. Total Cd, Cr, Cu, Ni, Pb, Se, and Zn concentrations in sediment samples were determined using inductively coupled plasma optical emission spectrometry. The  $I_{geo}$  showed that sediments in the lakes were moderately polluted with Cr, Cu, Pb, and Zn, and the EF method showed that Cd and Se were significantly enriched in lakes. The heavy metals were found to pose moderate risks in most of the lakes, except for Gaoyou Lake, Honghu Lake, Poyang Lake, and Weishan Lake. The RI method indicated that very high risks were posed in Dongting Lake and Poyang Lake. Cd was found to pose much higher levels of risk than the other metals. Significant correlations were found between the heavy metal concentrations and the total carbon, nitrogen, phosphorus, and sulfur concentrations. The gross domestic product represented anthropogenic activities well. The gross domestic product of an area and the gross domestic products of primary and secondary industries in an area all had significant relationships with the concentrations of Cu and Pb, indicating that anthropogenic activities have different impacts on pollution with different heavy metals. The gross domestic product index was found to be a driving force behind the pollution of lakes with heavy metals.

**Keywords** Heavy metal · Sediment · Lakes · Environmental factors · Anthropogenic activities

## Introduction

Heavy metal pollution is one of the environmental problems in many countries, especially in the social and economic rapid developing, population-intensive area of eastern China (Gao et al. 2014). In recent years, numerous environmental management schemes have been implemented in China, with the aim of improving water quality, especially in lakes such as the Taihu Lake and Chaohu Lake. The Chinese government is also quite concerned about controlling pollution inputs, and so regulations and projects have been implemented, such as the “Chinese National Water Pollution Control and Technology Management project” and “Implementation Scheme for Eco-environmental Protection of Lakes with Good Water Quality.” Despite recent sustained efforts have been paid to improve water quality, heavy metal pollution still persists in some lakes, which induces deterioration of the lakes’ ecosystem (Ma et al. 2013). Although external heavy metal inputs to lakes have been decreasing, internal release of heavy metal from sediment affects the surface water quality (Fu et al. 2014). Systematic studies about heavy metal concentrations in surface sediment and their relationships with environmental factors and anthropogenic activities are therefore important to support the formulation of effective scientific policies to manage heavy metal pollution.

There are many shallow lakes in eastern China where human activities were concentrated, including agriculture, industrial, urbanization, and breeding industry (Ma et al. 2013). Lake was an important “sink” of the watershed, which was converged pollutant in the drainage basin that supplies it because runoff and sediment are transported into the lake. Most

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of the pollutants entering the lake will be stored in the surface sediment in the lake (Sheykhi and Moore 2013; Mil-Homens et al. 2014). Surface sediment is one of the major sources of heavy metal pollution because of the ability of the sediment to sorb and release pollutants to the overlying water (Fu et al. 2014). The concentrations of heavy metals in surface sediment can be affected by geochemical processes and human activities. Heavy metals discharged into a lake can strongly accumulate in sediment, biomagnify through foodchains, and affect human health (Rashed 2001; Yuan et al. 2004; Chen et al. 2013; Li et al. 2014; Gupta et al. 2015). Heavy metals are not degraded in the environment, so they can often cause toxic effects far from their sources (Guagliardi et al. 2013; Gao et al. 2014). The stabilities of heavy metals in the environment mean that heavy metal distributions in surface sediment can be used to investigate anthropogenic impacts on aquatic ecosystems. Heavy metal distributions in surface sediment can also be used to assess the risks posed by anthropogenic emissions of heavy metals (Zhang and Shan 2008). Heavy metal concentrations in surface sediment are closely related to environmental factors (Wang et al. 2014a, b). Sediment can act as a source of heavy metals when environmental conditions change (Zoumis et al. 2001; Morillo et al. 2002). Researches show acid-volatile sulfides (AVS), organic matter, text (clay, silt and sand), and the variation of pH, redox potential, oxidative-reductive potential (ORP), and nutrition will influence the bioavailability of heavy metal (Zhao et al. 2011; Zhang et al. 2014). Investigating the relationships between heavy metal concentrations and various environment factors can allow the impacts of heavy metals on an ecosystem to be comprehensively evaluated and the pollution of the environment to be characterized (Sin et al. 2001).

In the last two decades, China, as one of the fastest growing economies in the world, has experienced rapid urbanization and industrialization, and equally rapid population growth, most of which has occurred in eastern China (Liu and Raven 2010). As a result, human-induced heavy metal accumulated in the lakes increases the risk of lake ecosystems and human health. Therefore, research on the mechanisms and control of heavy metal pollution are extremely urgent. In this research, ten shallow lakes were selected. These lakes are located in eastern China which was an area with fast economic increase and intensive population, and severely contaminated because of pollutant inputs from, for example, agricultural non-point emissions, industrial and domestic wastewater, and wastewater treatment plant discharges (Fu et al. 2013; Li et al. 2014). We determined the spatial distributions of seven metals (Cd, Cr, Cu, Ni, Pb, Se, and Zn) in the selected lakes, attempted to identify the sources of the metals, and performed correlation analyses on the metal concentrations and environmental parameters. Our main objectives were: (i) to determine the concentrations and distributions of heavy metals in surface sediment in selected lakes, (ii) to assess the ecological risks posed

by the heavy metals, and (iii) to identify relationships between heavy metal pollution with environmental factors and anthropogenic activities.

## Materials and methods

### Study area

Ten lakes in eastern China were studied. They are: Baiyangdian, Chaohu Lake, Dongting Lake, Gaoyou Lake, Honghu Lake, Hongze Lake, Luoma Lake, Poyang Lake, Taihu Lake, and Weishan Lake. The lakes are between 1- and 6-m deep and formed because of the effects of river systems and eustatic sea-level changes. Industry is more developed in eastern China than elsewhere and eastern China has become urbanized more quickly than other parts of China. The selected lakes used to be used as water sources and were considered scenic, but rapid industrialization and urbanization of the areas around the lakes have led to large amounts of industrial and domestic wastewater being discharged into the lakes, causing serious heavy metal pollution (Gong et al. 2006; Yang et al. 2009).

### Field sampling

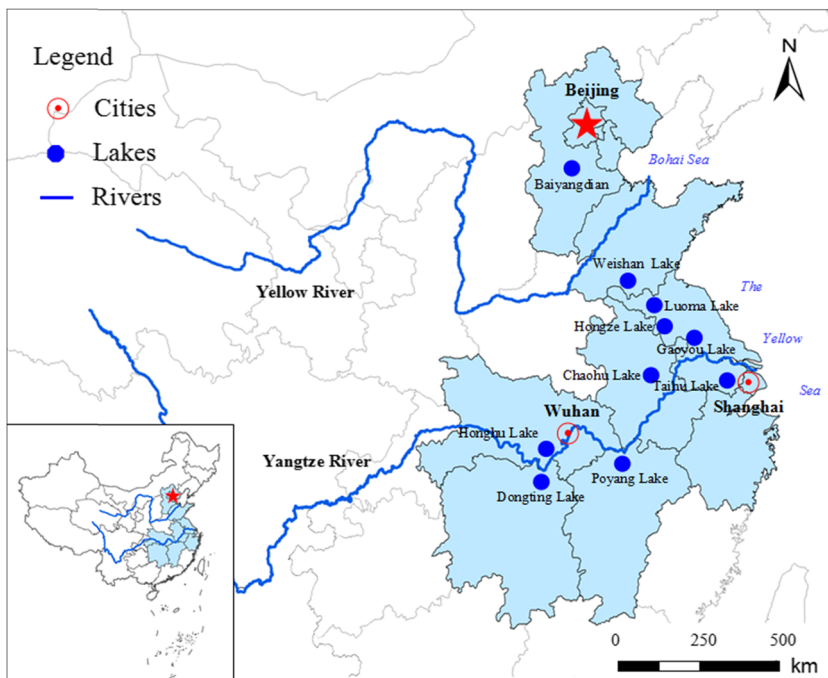
Samples were collected from 25 sampling sites on the ten selected lakes in September 2013. The locations of the lakes are shown in Fig. 1. Different numbers of sampling sites were selected in each lake, depending on the size and shape of the lake. Triplicate surface sediment samples (0–10 cm deep) were collected at each sampling site using a Peterson mud sampler (XDB0201), and the samples were mixed and subsampled to avoid random errors. Approximately 1 kg of the surface sediment from the middle of the mixture was carefully sealed in a plastic bag with a valve and stored at  $-4^{\circ}\text{C}$  in a freezer until it was analyzed.

Sediment pH was determined on sediments suspended in deionized water at a ratio of 1:2.5 (Lu 1999). Total carbon (TC), total sulfur (TS), and total nitrogen (TN) were detected by elemental analyzer (Elementar, German, Vario EL III). Total phosphorus (TP) was determined by inductively coupled plasma optical emission spectroscopy (ICP-OES; using an OPTIMA 8300 instrument; PerkinElmer, Waltham, MA, USA). The GDP of cities around the lake (in the same lake watershed) are calculated through consulting the yearbook of 2013, such as Taihu Lake, which included Wuxi, Suzhou, Huzhou, and Yixing.

### Heavy metal analysis

Each sample was freeze-dried in the laboratory and passed through a 100-mesh sieve (to facilitate digestion),

**Fig. 1** Location of the lakes in eastern China



then stored until it was analyzed. A 0.1-g (dry weight) aliquot of each sediment sample was digested in 8 mL of a 9:3:4 (by volume) mixture of concentrated HCl, HNO<sub>3</sub>, and HF using a MARSXpress instrument (CEM, Matthews, NC, USA). A drop of HClO<sub>4</sub> was added to the digestion tube, then the acid was heated to 150 °C for at least 2 h (Tang et al. 2010). The extract was then diluted to 50 mL with ultrapure water, then passed through a 0.45-μm membrane filter and stored at 4 °C until it was analyzed. The Cd, Cr, Cu, Ni, Pb, Se, and Zn concentrations in the extracts were determined by ICP-OES and by inductively coupled plasma mass spectrometry (ICP-MS; using a 7500a instrument; Agilent Technologies, Santa Clara, CA, USA) (Fu et al. 2013). The Chinese national geo-standard sample GSD-4a was analyzed to allow the quality of the analytical data to be assessed. The heavy metal concentrations found in the GSD-4a samples were all within 10 % of the reference values. All plastic and glass items were cleaned before use by soaking them in 10 % (v/v) HNO<sub>3</sub> for at least 2 days then by soaking them in and rinsing them with ultrapure water. All of the chemicals used were of guaranteed reagent grade. Blank samples were analyzed with each set of samples using the same reagents. All concentrations were calculated using the sample dry weight.

**Geo-accumulation index method**

The geo-accumulation index, also known as the Müller index, takes into consideration changes in background concentrations caused by both natural geological process and

anthropogenic effects (Müller 1969). Müller derived the following equation for the geo-accumulation index  $I_{geo}$ ,

$$I_{geo} = \log_2(C_n / (1.5B_n)),$$

where  $C_n$  is the concentration of metal  $n$  in sediment,  $B_n$  is the background concentration of metal  $n$ , and 1.5 is a fixed coefficient. The  $I_{geo}$  was divided into five grades, as shown in Table 1.

**Enrichment factor method**

The enrichment factor (EF) is an effective method of identifying anthropogenic or natural sources of heavy metals in soil and sediment (Zhang and Shan 2008). In previous studies, EF values have been calculated using the equation

$$EF = \left( \frac{M_x}{N_{ref}} \right)_{sample} / \left( \frac{M_x}{N_{ref}} \right)_{background},$$

where  $M_x$  is the concentration of a heavy metal of interest in the soil or sediment and  $N_{ref}$  is the concentration of a reference element in the soil or sediment.

We used Fe as the reference element when calculating EF values because the Fe concentration of sediment is typically

**Table 1** Grades used for the geo-accumulation index ( $I_{geo}$ )

$I_{geo}$	<0	0–1	1–2	2–3	3–4
Grade	0	1	2	3	4
Level	None	None–moderate	Moderate	Moderate–strong	Strong

little affected by human activities. Five contamination categories defined by the EF value were used: minimal enrichment ( $1 < EF < 2$ ); moderate enrichment ( $2 < EF < 5$ ); significant enrichment ( $5 < EF < 20$ ); high enrichment ( $20 < EF < 40$ ); and extremely high enrichment ( $EF > 40$ ).

**Potential ecological risk methods**

The potential ecological risk index (RI), originally described by Håkanson, is commonly used to assess the degree to which sediment is polluted with heavy metals. The RI is based on the toxicities of heavy metals and the responses of the environment to the heavy metals (Håkanson 1980). Håkanson calculated the potential ecological risk factor  $E_r^i$  using the equation.

$$E_r^i = T_r^i \times \frac{C^i}{C_n^i},$$

where  $C^i$  is the concentration of metal  $i$  in sediment,  $C_n^i$  is the background concentration of metal  $i$ , and  $T_r^i$  is the toxicity factor for metal  $i$ . Håkanson determined that the toxicity factors for Cd, Cr, Cu, Ni, Pb, Se, and Zn are 30, 2, 5, 5, 1, and 1, respectively.

The RI is the sum of the potential ecological risk factors for all of the heavy metals of interest in sediment, calculated as shown below.

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

We calculated the RI for seven metals (Cd, Cr, Cu, Ni, Pb, Se, and Zn). We used five  $E_r^i$  categories and four RI classes, which are shown in Table 2.

**Statistical analysis**

We used SPSS 13.0 software for Windows (IBM, Armonk, NY, USA) to perform statistical analyses. Pearson correlation analysis, hierarchical cluster analysis, and principal components analysis were performed to identify the potential sources

**Table 2** Grades used for the potential ecological risks

Potential ecological risk grades			
Potential ecological risk factor ( $E_r^i$ )		Potential ecological risk index (RI)	
Low	<30	Low	<100
Moderate	30–60	Moderate	100–200
Considerable	60–120	High	200–400
High	120–240	Very high	>400
Very high	>240		

of the heavy metals in sediment samples. The Kaiser-Meyer-Olkin (KMO) and Bartlett’s test were introduced to evaluate the validity of PAC, and  $a > 0.5$  of KMO and significant Bartlett’s test were requisite before the PCA. The Biplot was drawn by the BIPLLOT of IML module in SAS for Windows 9.2 (SAS Institute, Inc., Cary, NC, USA). The vector length in Biplot shows the measure ability of variable for distinguishing the environmental factors. The angle between two environment vectors indicated the relationship between the two vectors. All analysis was performed using standard procedure in Microsoft Excel. All of the data underwent normality testing and obeyed normal distribution.

**Results**

**Environmental factors and anthropogenic activities**

The TN, TC, and TS ranged from 0.10 to 0.83 %, 0.94 to 11.75 %, and 0.02 to 0.67 %, respectively. The average of TN, TC, and TS were 0.23, 3.07, and 0.19 %, respectively. High values of TN, TC, and TS appeared in Honghu Lake sediments. For TP, the concentration of surface sediments ranged from 367.1 to 571.6 mg/kg, and the average concentration of TP was 455.6 mg/kg. The ratio of TC to TN ranged from 6.74 to 23.29, and the average value was 13.49. The pH was above 7.00, which ranged from 7.12 to 8.03, and the average value was 7.73. As a vital economic index, the GDP, which include GDP1, GDP2, and GDP3, was calculated. The GDP2 was the dominant GDP for the lakes, the value of which was 51.80 %, and the GDP3 and GDP1 were as follows. The average value of GDP1, GDP2, and GDP3 were  $0.03 \times 10^4$ ,  $0.17 \times 10^4$ , and  $0.13 \times 10^4$  ¥/m<sup>2</sup>, respectively. The value of GDP1, GDP2, and GDP3 ranged from 0.02 to 0.04, 0.01 to 0.60, and 0.02 to 0.51 ¥/m<sup>2</sup>, respectively.

**Heavy metal concentrations in surface sediments**

The surface sediment samples contained Cd at concentrations of 0.28–1.53 mg/kg (mean 0.90 mg/kg), Cr at concentrations of 88.56–187.23 mg/kg (mean 147.98 mg/kg), Cu at concentrations of 40.37–68.63 mg/kg (mean 55.52 mg/kg), Ni at concentrations of 41.82–89.26 mg/kg (mean 69.63 mg/kg), Pb at concentrations of 43.74–72.83 mg/kg (mean 56.95 mg/kg), Se at concentrations of 0.69–1.97 mg/kg (mean 1.47 mg/kg), and Zn at concentrations of 126.78–210.26 mg/kg (mean 163.06 mg/kg). The heavy metal concentrations found in the sediment samples are summarized in Table 3, and heavy metal concentrations found in other parts of China are also shown (Yi et al. 2011, Fu et al. 2013; Ma et al. 2013; Xing et al. 2013; Zeng and Wu 2013). The mean Cr concentration in our samples was 1.93 times higher than the mean concentration in Chinese sediment, and the mean Ni

**Table 3** Heavy metal concentrations (mg/kg) found in sediment in this study and in previously published studies of Chinese rivers and lakes

Metal	Rivers and lakes in China		This study	
	Range	Mean	Range	Mean
Cr	2.72 to 229.55	76.58	88.56 to 187.23	147.98
Ni	4.71 to 77.41	36.69	41.82 to 89.26	69.63
Cu	1.33 to 924.54	90.98	40.37 to 68.63	55.52
Zn	23.28 to 1250.47	194.09	126.78 to 210.26	163.06
Se	0.00 to 5.20	1.38	0.69 to 1.97	1.47
Cd	0.02 to -81.79	2.97	0.28 to -1.53	0.90
Pb	1.66 to -513.71	90.47	43.74 to -72.83	56.95

and Se concentrations in our samples were 1.90 and 1.07 times higher, respectively, than the mean concentrations in Chinese sediment. However, the mean Cd, Cu, Pb, and Zn concentrations in our samples were lower than the mean concentrations in Chinese river and lake sediment (Niu et al. 2009; Yin et al. 2011; Cheng et al. 2012; Huang et al. 2012; Mao et al. 2013; Wei and Wen 2012;).

## Discussion

### Source identification

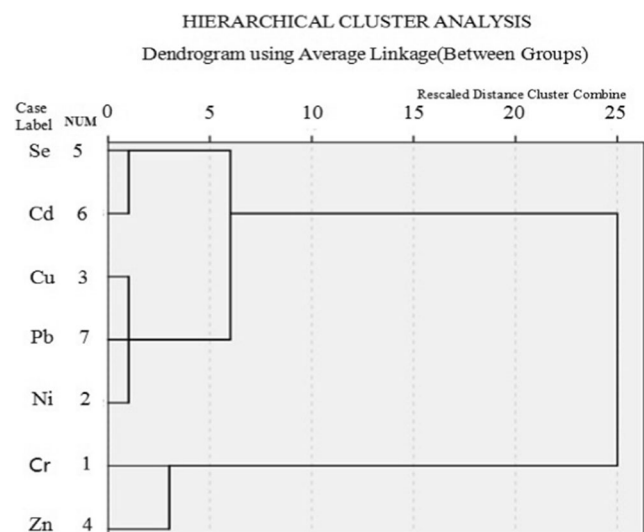
Heavy metals in sediment can come from two sources: natural sources and anthropogenic sources. Natural sources include volcanoes, the degradation of minerals, and forest fires. Natural emissions of heavy metals must be considered when assessing heavy metals in the local and global environment (Adnano 1986). However, anthropogenic sources of heavy metals are usually considered to be the major causes of heavy metals in the environment being higher than background concentrations (Wu et al. 2014). Anthropogenic sources of heavy metals can be divided into three groups: releases of heavy metal impurities during the production of power and heat from coal, mining activities, and other metallurgical activities; releases during the intentional extraction and use of heavy metals (such as during the mining of heavy metals, the production of leather, electroplating processes, and the manufacture of products containing heavy metals); and releases from landfills and plants such as waste incinerators.

The hierarchical cluster analysis clustered the heavy metals roughly into three primary groups. The first cluster contained Cd and Se, the second Cu, Ni, and Pb, and the third Cr and Zn. All seven metals are major pollutants and can be defined as anthropogenic components, but the clustering of the metals into different groups

indicated that different metals may have originated from different sources. Industrial wastewater discharges and agricultural drainage, especially in economically developed areas, could be the major sources of the heavy metals to the lakes that were studied. Cd, Cu, Pb, and Zn may be released from N and P fertilizers and coal burned in power plants and other industrial plants and central heating systems in northern China (Fig. 2).

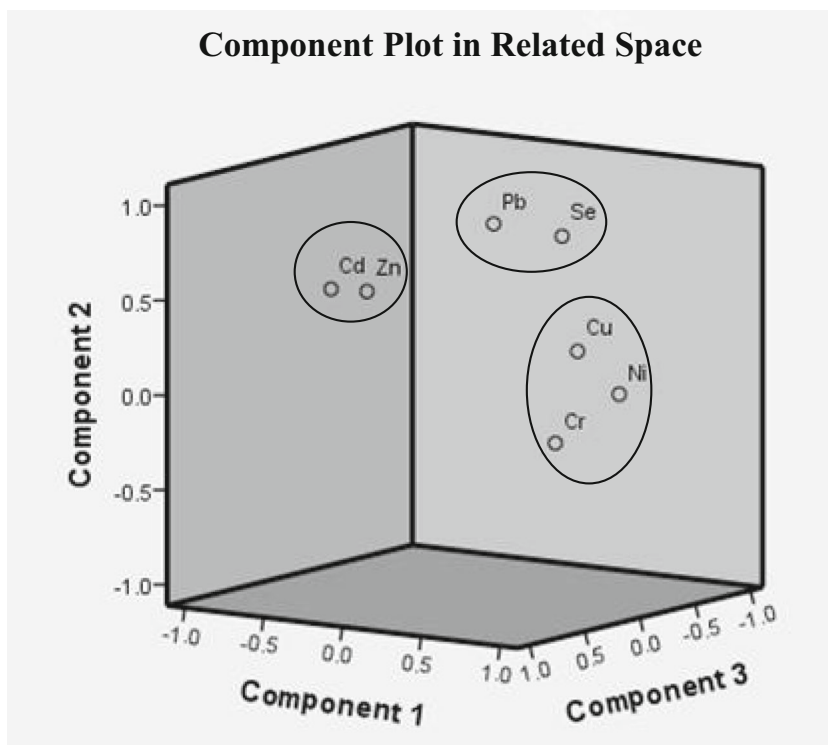
Principal components analysis was used to further identify the anthropogenic sources of the heavy metals. The KMO (0.562) was  $>0.5$ , and the Bartlett's test gave a value of  $<0.001$ , demonstrating that principal component analysis was useful. Three components had eigenvalues  $>1$ , and these three components explained 81.14 % of the total variance. The relationships between the concentrations of the seven metals, based on these three components, are illustrated in three dimensions in Fig. 3. The heavy metals could be divided into three groups: Cr, Cu, and Ni clustered together, indicating that they had similar distribution patterns and sources; Pb and Se formed a second group; and Cd and Zn formed a third group that was far from the other heavy metals in the plot, implying that Cd and Zn had quite different sources from the other metals.

The Pearson correlation coefficients for the relationships between the Cr and Ni concentrations ( $r = 0.843$ ,  $p < 0.01$ ) and Cu and Ni concentrations ( $r = 0.716$ ,  $p < 0.01$ ) confirmed that Cr, Cu, and Ni had common sources. The Pearson correlation coefficients for the relationships between the concentrations of the different metals are shown in Table 3. Cd and Zn in the environment commonly originate in phosphate fertilizers, and Pb and Se are often found in N fertilizers. It therefore appears that heavy metal pollution in lakes in eastern



**Fig. 2** Hierarchical dendrogram for the heavy metals in sediment samples from the lakes in eastern China, produced using average linkages between groups and Pearson correlation coefficients as measured intervals

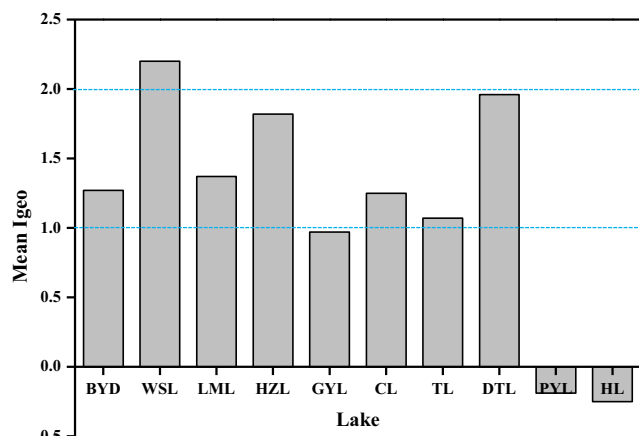
**Fig. 3** Loading plot for the three principal components found when principal component analyses was performed



China is partly caused by agricultural non-point emission sources (Zhao et al. 2010).

**Ecological risk assessment**

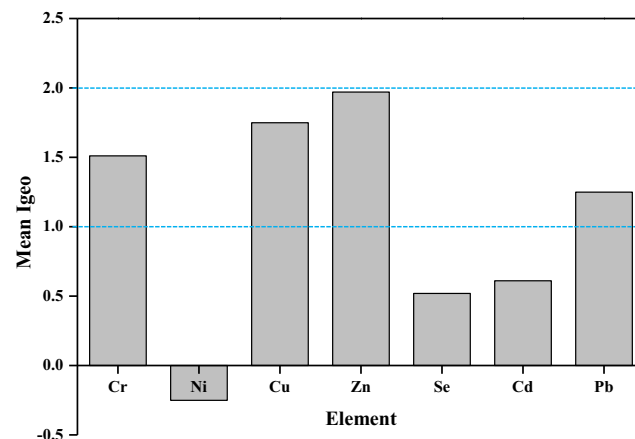
The ecological risks posed by the heavy metals in sediment in the lakes were assessed. According to the mean  $I_{geo}$  values, shown in Fig. 4, the pollution level was grade 0 (unpolluted) for sediment in Honghu Lake and Poyang Lake; grade 1 (unpolluted to moderately polluted) for sediment in Gaoyou Lake; grade 2 (moderately polluted) for sediment in Baiyangdian, Chaohu Lake, Dongting Lake, Hongze Lake,



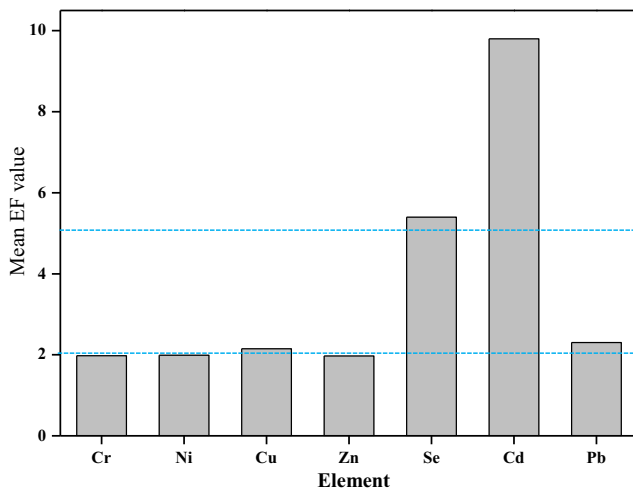
**Fig. 4** Mean geo-accumulation index ( $I_{geo}$ ) values for the sediment samples. *BYD* Baiyangdian, *WSL* Weishan Lake, *LML* Luoma Lake, *HZL* Hongze Lake, *GYL* Gaoyou Lake, *CL* Chao Lake, *TL* Tai Lake, *DTL* Dongting Lake, *PYL* Poyang Lake, *HL* Hong Lake

and Luoma Lake; and grade 3 (moderately polluted to strongly polluted) for sediment in Weishan Lake. The  $I_{geo}$  values for the individual metals are shown in Fig. 5. The mean degree of Ni pollution was grade 0 (unpolluted), the mean degree of Cd and Se pollution was grade 1 (unpolluted to moderately polluted), and the mean degree of Cr, Cu, Pb, and Zn pollution was grade 2 (moderately polluted).

The EF results are shown in Fig. 6. The mean EF values for Cd, Cr, Cu, Ni, Pb, Se, and Zn were 9.80, 1.89, 2.22, 1.98, 2.43, 5.55, and 1.90, respectively, meaning that Cr, Ni, and Zn were minimally enriched, Cu moderately enriched, and Cd and Pb significantly enriched. The mean EF values decreased in the order Cd > Se > Pb > Cu > Ni > Zn > Cr. Cd had an extremely high EF, and Cr had a relatively low EF. This



**Fig. 5** Mean geo-accumulation index ( $I_{geo}$ ) values for the heavy metals



**Fig. 6** Mean enrichment factors (*EF*) for the heavy metals

showed that the EF method was an effective tool for identifying differences between the effects of human activities on different heavy metals. The RI values are shown in Fig. 7. Sediments in Hongze Lake, Luoma Lake, and Weishan Lake were found to pose moderate ecological risks ( $100 < RI < 200$ ), and sediments in Dongting Lake and Poyang Lake were found to pose very high risks ( $RI > 400$ ). Sediments from the other lakes were found to pose high ecological risks ( $200 < RI < 400$ ). For the individual metals, Cd was found to pose considerable or high risks ( $RI > 60$ ), and the other metals were found to pose low levels of risk ( $RI < 30$ ).

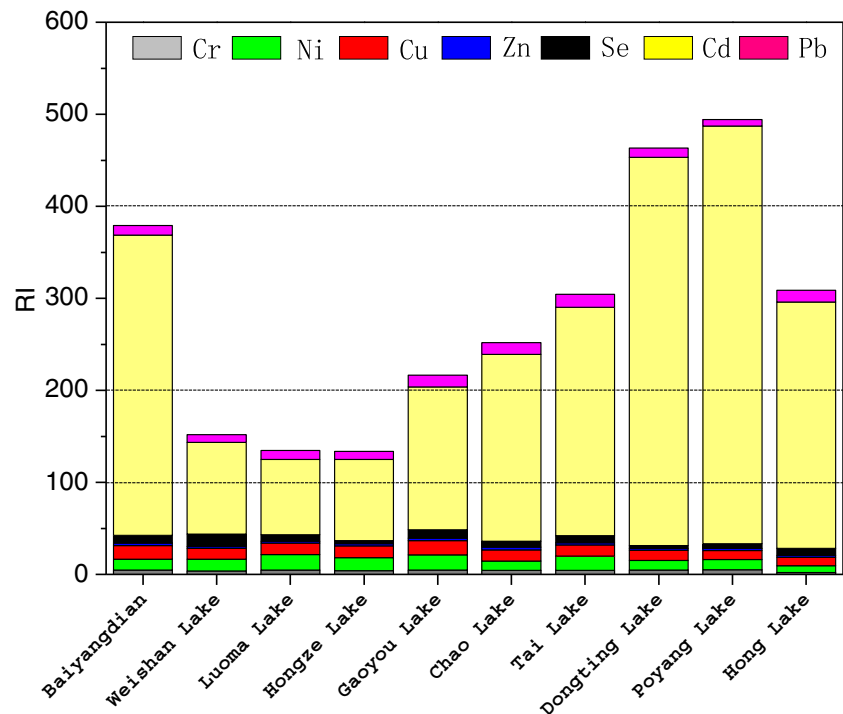
Overall, heavy metals in sediment of lakes in eastern China were found to pose moderate ecological risks. Much higher

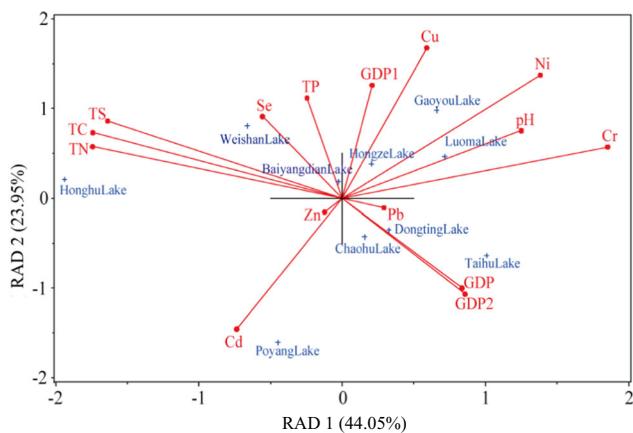
risks were found to be posed by Cd than by the other metals, so Cd should be included in the priority pollutants list in the study area.

### Heavy metal pollution and environmental factors

An individual heavy metal in lake sediment will not affect the ecosystem of the lake alone but will interact with other heavy metals and factors (Agarwal et al. 2005). The concentrations of heavy metals and other chemicals can be used as chemical indices to reflect the contamination status of the sediment. The concentrations of heavy metals in sediment may be affected by water quality indices and anthropogenic activities because heavy metals will exchange among water, sediment, and suspended solids and because human activities will affect both heavy metal concentrations and the water quality (Fu et al. 2014). Toxic substances in contaminated sediment and water can affect human health by biomagnifying through foodchains. Human activities can aggravate sediment and water pollution (Förstner and Wittman 1983). Economic indices reflect human activities and can be used as good representatives of anthropogenic activities (Gao et al. 2014). We used the gross domestic product (GDP) to represent anthropogenic activities to allow the relationships between anthropogenic activities and environmental factors to be assessed. The relationships between the GDP and environmental factors are illustrated in Fig. 8.

**Fig. 7** Ecological risk indices (*RI*) for the sediment samples





**Fig. 8** Plot of the redundancy analysis (RDA) results on two axes, showing the correlations between the heavy metal concentrations and environmental factors and anthropogenic activities for the lakes in eastern China

Pearson correlation analyses showed that chemical properties of the sediment samples and the GDP significantly correlated with the concentrations of the heavy metals (Table 4). Significant negative correlations were found between the TN, TS, TC, and Cr concentrations ( $r = -0.768, p < 0.01$ ;  $r = -0.717, p < 0.01$ ; and  $r = -0.743, p < 0.05$ , respectively). And we also found the significant positive correlations between the TN, TS, TC, and Se ( $r = 0.546, p < 0.05$ ;  $r = 0.504, p < 0.05$ ; and  $r = 0.514, p < 0.05$ , respectively). The nitrogen found in the aquatic environment is typically produced by the metabolic activities and decomposition of organisms and can enter aquatic systems in domestic and industrial wastewater and in runoff containing nitrogenous fertilizers. These discharge processes are accompanied by the co-release of heavy metals. Canonical correlation analysis (CCA) was useful for investigating the driving forces behind the relationships between the TC, TN, TP, and TS and the heavy metal distributions in water. The TC, TN, and TS directions were all similar, indicating that these parameters affected the heavy metal distributions in similar ways. However, the TP direction was a little bit different, indicating that TP can affect

the heavy metal distributions in different ways. A high TC, TN, TP, and TS concentration would indicate that a water body has been highly polluted, and this would drive more heavy metals into the sediment. The pH has a positive relationship with Cr and Ni ( $r = 0.681$  and  $0.696, p < 0.05$ , respectively), indicating that Cr and Ni might be immobilized by sediment under high pH. The value of pH is used to represent the acidity and alkalinity in sediment and strongly affect the solution of heavy metals. High pH indicated adsorption and precipitation while low pH can actually weaken the strength of metal association and impede the retention of metals by sediment (Belzile et al. 2004; Guven and Akinici 2013).

GDP growth is the most comprehensive reflection of the economic health of a country, and GDP is an important index for representing anthropogenic activities. GDP for primary industries can be used to indicate agricultural activities in an area, and GDP for secondary industries can be used to indicate industrial activities in the area. GDP for primary and secondary industries in an area can therefore be used to indicate the magnitudes of agricultural and industrial sources of heavy metal pollution, respectively. Pearson correlation analyses showed that there were significant negative correlations between the GDP for primary industries in an area and Zn concentration ( $r = -0.705, p < 0.05$ ) and Cd concentration ( $r = -0.694, p < 0.05$ ). Anthropogenic impacts on the lakes were analyzed by CCA, and the GDP and GDP for secondary industries by area were all in the same direction. Taihu Lake, which is located in the most prosperous part of China, was more sensitive to the GDP indices than the other lakes. Chaohu Lake and Dingting Lake were also rather sensitive to the GDP indices. GDP is therefore an ideal index for evaluating the impacts of anthropogenic activities on heavy metal pollution in lakes. We found that agricultural activities were closely related to the Cu concentrations and that industrial activities were closely related to the Pb concentrations. This indicated that different anthropogenic activities had

**Table 4** Pearson correlation results for the sediment components

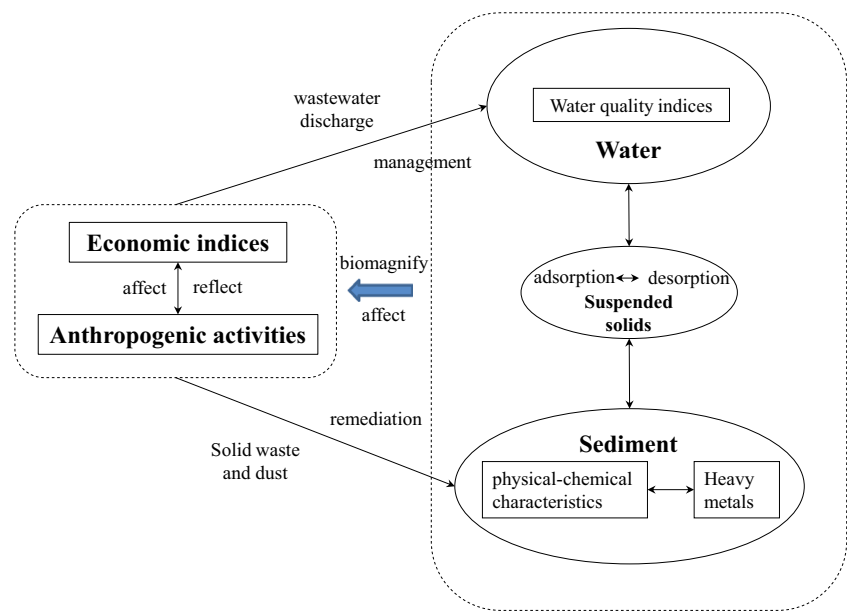
	TN	TS	TP	TC	pH	GDP	GDP1	GDP2
Cr	-0.768**	-0.717*	-0.019	-0.743*	0.681*	0.156	0.169	0.159
Ni	-0.343	-0.305	-0.001	0.316	0.696*	0.109	0.454	0.087
Cu	-0.044	0.011	0.336	0.021	0.519	-0.306	0.337	-0.329
Zn	0.065	-0.087	0.493	-0.053	0.433	-0.176	-0.705*	-0.155
Se	0.546*	0.504*	-0.133	0.514*	0.168	0.075	0.268	0.034
Cd	0.203	0.029	-0.368	0.114	-0.302	0.040	-0.694*	0.051
Pb	0.127	-0.143	-0.316	0.023	0.376	0.349	-0.122	0.335

GDP gross domestic product by area, GDP1 GDP for primary industries for an area, GDP2 GDP for secondary industries for an area

\* $p < 0.05$ ; \*\* $p < 0.01$



**Fig. 9** Relationships between the heavy metal pollution, environmental factors, and anthropogenic activities



different impacts on pollution with different heavy metals (Fig. 9). In this study, the ecological risk and the relationship with the environmental factors and anthropogenic activities have been studied, and the results can support the heavy metal pollution management in eastern China. But we also realize that the mechanism of sediment geochemical properties affects the bioavailability of heavy metal, and the chronic responses of organism and ecosystems relate to toxicity and bioaccumulation need to be deeply and comprehensively studied in the future.

## Conclusions

The heavy metal concentrations in the surface sediment samples from the lakes in eastern China that we studied were not considered to be very high compared with concentrations that have previously been found in Chinese rivers and lakes. Only the mean Cr, Ni, and Se concentrations were higher than the Chinese standards (by factors of 1.93, 1.90, and 1.07, respectively). The natural and anthropogenic sources of the heavy metals were identified using hierarchical cluster analysis and principal components analysis, both of which clustered the heavy metals into three primary groups, indicating that there were various sources of heavy metals in the lakes that we studied. The  $I_{geo}$  method, EF method, and RI method were used to assess the risks posed by heavy metals in the lakes. The  $I_{geo}$  showed that the sediments in the lakes were moderately polluted by Cr, Cu, Pb, and Zn, and the EF method showed that Cd and Se were significantly enriched in the lakes. The heavy metals were found to pose moderate risks in most of the lakes, except for the Gaoyou Lake, Honghu Lake, Poyang Lake, and Weishan Lake. The RI method

indicated that very high risks were posed in Dongting Lake and Poyang Lake. Cd was found to pose much higher levels of risk than the other metals, so more attention should be paid to Cd pollution than to pollution by other heavy metals in lakes in eastern China. Various multivariate methods were used to attempt to identify the sources of the heavy metals and to assess the risks posed by the heavy metals. Different results were found using different methods, indicating that each method had limitations.

A number of environmental factors (the TC, TN, TP, and TS) significantly correlated with the heavy metal concentrations. Heavy metals and some other chemical species were found to be co-released from the sediment. GDP as an economic indicator is an ideal index for evaluating the impacts of anthropogenic activities. The GDP for primary and secondary industries in an area were found to have separate close relationships with the Cu and Pb concentrations and to be the driving forces behind the heavy metal pollution in lakes.

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