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Characterization of heavy metals in typical river sediments on the west bank of Taihu Lake, China

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Abstract

In this study, nine heavy metals (Cd, Cr, As, Hg, Pb, Cu, Ni, Be, Sb) in typical river sediments of Wujin and Yixing, two cities on the west bank of Taihu Lake, were determined. Variety of statistical methods were applied to analyze the distribution, sources, pollution status and the potential ecological risk of these metals. The results showed that the mean concentrations for most of the heavy metals in sediments exceeded their local background values, except for Hg and Be. Geoaccumulation index (I_{geo}) and potential ecological risk index (RI) analysis showed the partially serious contaminated status and strong potential ecological risk for Cd in most sites. The highest contamination level was observed in the estuary of Taihu Lake and most of the sediment samples were polluted and under risk. Principal component analysis (PCA), Cluster analysis (CA) and correlation analysis demonstrated that Ni, Sb, Cr and Cu were controlled by industrial sources, whereas the other metals appeared to be

influenced by complex origins including industrial, agricultural and natural sources.

Keywords: Heavy metals, Sediments, Risk assessment, Source

Declarations

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the online repository or supplemental files.

Code availability

Not applicable

Authors' contributions

FW designed the research, and was a major contributor in writing the manuscript. XR and YQ analyzed and interpreted the data regarding the risk of heavy metals. JC, YC, and LW conducted statistical analysis using variety of methods. LZ, SZ and XW assisted in the experiment. All authors read and approved the final manuscript.

Ethics approval

Not applicable

Consent to participate

Not applicable

Consent for publication

Written informed consent for publication was obtained from all participants.

1. Introduction

With rapid population growths, urbanization and industrialization, river ecosystem are subject to various contamination (Suthar et al. 2009). Heavy metals are one of the serious pollutants due to their toxicity, persistence and bioaccumulation (Jang et al. 2006; Zhuang 2009) which may come from both human activities and natural sources, such as industrial production, agricultural activity, vehicle exhaust, weathering, etc. They can be adsorbed by suspended particles and enriched in sediments once entering the water. However, under the influence of human activities, wind or other disturbance, heavy metals may release from sediments and cause “Secondary Pollution” (Liu et al. 2008; Abuduwaili et al. 2015). It is necessary to evaluate the contaminated status of heavy metals in sediments with effective methods which also reflect the environmental quality in rivers (Mwanamoki et al. 2015). Taihu Lake is the important river in China that provides various services, including drinking, aquaculture, farming, fisheries, etc. However, it has attracted much attention

because of its severe pollution (Chen et al. 2003; Qin et al. 2007; Hai et al. 2010). Studies show that the risks posed by heavy metals in Taihu have increased since 1980 (Yao and Xue 2010). Wujin and Yixing with rivers distributed throughout are located on the west bank of Taihu. The rivers connected to Taihu Lake have carried large amounts of sanitary sewage and industrial wastewater into the lake (Chen 2013; Niu et al. 2019). Wastewater discharges from industrial sources need to be monitored and prevented more effectively here (Wenchuan et al. 2001). In addition, non-point source pollution arising from aquaculture and agriculture need to be paid attention to (Li et al. 2018).

The objectives of this study were to determine the concentration and distribution of various heavy metals from river sediments in the two cities and assess the pollution status and the potential ecological risk of the heavy metals. The metal pollution possibly caused by industries and other factors were focused on and it was expected to provide reference for prevention and control of metal pollution from the perspective of source in Taihu Basin.

2. Materials and methods

2.1. Study area

Wujin (31°19'-32°04'N, 119°38'-120°12'E) and Yixing (31°07'-31°37'N, 119°31'-120°03'E), two cities upstream of Taihu Lake, are situated in southeast Jiangsu Province, China. Twenty-three sampling sites were selected considering the morphology of the rivers and the location of human activities around it, especially industries. According to the industrial distribution, five samples were collected

besides the outlet of the wastewater treatment plants (W1 to W5) and eleven from industrial district (I1 to I11). The other samples were collected including five from the estuary of Taihu Lake (E1 to E5) and two from drinking water sources (D1, D2) (Fig. 1). D1 and D2 were considered as the control sites located far from the industrial units. Five sites (I2 to I5, W2) were situated in the mainstream of the Grand Canal. The GPS coordinates and characteristics of the sampling sites are given in the supplementary information (Table S1).

2.2. Sample collection and analysis

A total of 23 sediments were collected from the top 5cm layer at each site in June 2019 using a stainless steel grab sampler, and then kept in the pre-cleaned amber glass bottle. Following the collection, all samples were immediately stored in a refrigerator and transported to laboratory.

In laboratory, sediment samples were dried, sieved and homogenized before analyzing. As, Sb and Hg were measured using an atomic fluorescence spectrometer (Jitian, Beijing, China), and the sediment samples were digested with HCl-HNO₃. The concentrations of Cd, Cr, Pb, Cu, Ni, and Be were determined by inductively coupled plasma and atomic emission spectrum (PerkinElmer, AvioTM200, USA) and the sediment samples were digested with aqua regia. The details of the analytical methods and quality controls conformed to National environmental protection standards of China (HJ 680-2013, HJ 803-2016). The average recoveries of the heavy metals were ranged from 86.8% to 117%, and the relative standard deviation (RSD) was less than 7.7%. The limit of detection (LOD) defined as the concentration that was three times

the signal-to-noise ratio (S/N) were 0.002–1.4 mg/kg.

2.3. Geoaccumulation index (I_{geo}) and potential ecological risk index (RI) analysis

Geoaccumulation index (I_{geo}) introduced by Müller (1969) in order to determine and define metal contamination in sediments by comparing current concentrations with pre-industrial levels. The I_{geo} is calculated by the following equation:

$$I_{geo} = \log_2 \left(\frac{C_i}{1.5B_i} \right) \quad (1)$$

where C_i is the measured concentration of the metal i in the sediment, and B_i is the geochemical background concentration of the metal i . Factor 1.5 is the background matrix correction factor due to lithogenic effects.

The potential ecological risk index (RI) developed by Hakanson (1980) was used to evaluate the ecological risk of heavy metals in sediments of this area. The RI can be calculated as follows:

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

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

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

where C_f^i is the contamination factor of the metal i , C_i and B_i are the measured concentration and the geochemical background value of the metal i , respectively. E_r^i is the ecological risk index and T_r^i listed in Table1 (Hakanson 1980; Zhuang et al. 2018) is the toxicity coefficient of the metal i . RI is the sum of ecological risk indices for the heavy metals in sediments of a single site. The I_{geo} and RI values of heavy metals can be categorized into different levels, as displayed in Supplementary Table S2.

2.4. Statistical analysis

Spearman correlation matrix was applied for different metals to investigate the correlations among element trace the common sources of pollutants. PCA was used for identifying the potential sources of metals and the first two or more principal components (PC) were retained with considering the most significant factors. CA comprises an unsupervised classification procedure that involves measuring either the distance or the similarity between objects to be clustered (Tokalioglu et al. 2015). IBM SPSS Statistic 21 and Origin 2018 were used for data analysis. The statistically significant difference reported in this study was at the $P < 0.05$ levels.

3. Results and discussion

3.1. Concentration of heavy metals

As shown in Table 1, the mean concentrations for most of the heavy metals in the sediments were higher than their local background values (China Environmental Monitoring Station 1990) except for Hg and Be. In particular, 100% of Cd and Cu samples, 96% of Ni and Sb, 87% of As, 65% of Pb exceeded their background values. The contents of Cr, Cu, Ni and Sb showed similar spatial distributions, and their contents are significantly higher at sites I3, I10, I11, W3 and E3(Fig.2). Cr, Cu, Ni and Pb with the large standard deviation and coefficient of variation, showed the relatively high spatial variation, indicating that the metals might be the major enriched contaminants in the sediment because of anthropogenic activity(Dong et al. 2019; Tume et al. 2018). Compared with published data (Table 2), the mean concentrations of Cd, Cr, Cu and Ni in this study are relatively higher. In particular, the maximum concentrations of Cd (3.08 mg/kg), Cr (447 mg/kg), Cu (338 mg/kg) and Ni (107

mg/kg) are significantly greater than most lakes.

Fig. 1. Study area and sampling sites

Fig. 2. Concentration of heavy metals in the sampling sites

Table 1. Descriptive statistics of heavy metals in sediment

3.2. Risk assessment of heavy metals

I_{geo} and RI are important indices used to discriminate anthropogenic and natural sources of metals, and assess the contamination level of sediments(Xie 2011; Liu et al. 2009). As shown in Fig.3, the mean I_{geo} values showed the decreasing order $Cd > Cu > Sb > As > Ni > Pb > Cr > Be > Hg$. The I_{geo} values of Cd were from 2.9 to 4.0, indicating partially serious contaminated status for Cd in most sites. Cu with the I_{geo} values from -0.49 to 3.34 showed uncontaminated to partially serious contaminated status. The range of I_{geo} values for other metals, including Sb, As, Ni, Pb, Cr, Be and Hg in all the sites are between -3.6 and 2.0, showing uncontaminated to partially moderate contaminated status. The mean I_{geo} values of the studied sites followed the order $E3 > I10 > W3 > E4 > I11 > I3 > I1 > W1 > E5 > W5 > I7 > W2 > I5 > I4 > E2 > I9 > D1 > I2 > I6 > E1 > D2 > W4 > I8$. It showed that the highest contamination level was observed in the estuary of Taihu Lake and most of these sediment samples were polluted.

Fig. 3. Box plots of the I_{geo} values for heavy metals in the sampling sites

Fig. 4. E_r^i values for heavy metals in the sampling sites

The mean E_r^i values showed the decreasing order $Cd > Sb > Hg > Cu > As > Be > Ni > Pb > Cr$. The E_r^i values of Cd were from 325 to 711, indicating severe potential ecological risk for Cd in all sites. Sb showed low to moderate ecological risk in most sites. The E_r^i values for other metals were generally below 40, showing a low probability of ecological risk in sediments. As shown in Fig.4, The RI values of the studied sites were in the order $E3 > I1 > E4 > W3 > I10 > E5 > W1 > I7 > I11 > I5 > I3 > W2 > I6 > W5 > I4 > D1 > E2 > E1 > I9 > I2 > I8 > D2 > W4$. The estuary of Taihu Lake showed the highest ecological risk level which in agreement with the results of the I_{geo} value.

In this research, Cd and Sb were showing higher level of contamination and ecological risk, especially in the sites E3, E4, W3 and I10. As reported in a previous study, Cd was the most important pollutant and the main contributor to potential ecological risk of Taihu Lake sediments (Niu et al. 2019) and Sb was known as the typical pollutant of the dyeing and finishing textile industries in Taihu Basin. Upstream of the estuary E3 and E4, the intensive aquaculture and agriculture activities may significantly influence the Cd in the sediments. Studies has shown that the Cd can be discharged from agriculture by the fertilizer of potassica and phosphate (Bu et

al. 2010; Zhang et al. 2014). Additionally, Yincungang canal upstream of E3 is one important tributary of the Taihu Lake which carries much more wastewater into Taihu Lake than other tributaries every year. The pollution emission from agriculture along the river requires much more attention (Yang et al. 2012). The heavy pollution of W3 and I10 was likely due to industrial discharges surrounding the sites, such as textile.

3.3. Possible sources of pollutant inputs

Recently, multivariate statistical approaches such as correlation analysis, CA, PCA have been increasingly in use for environmental studies for tracing the sources of pollutants (Bengrane and Marhaba 2003; Li et al. 2009). To explore the common sources of the heavy metals, Spearman correlation matrices was used to analyze the relationships between the concentrations of different metals, and the results were listed in Table 3. In the sediments, most of studied metals were significantly correlated with each other ($p < 0.01$), especially the pairs Pb/Ni ($R = 0.803$), Pb/Cd ($R = 0.759$), Pb/Cr ($R = 0.768$), Cu/Cr ($R = 0.772$), Ni/Cr ($R = 0.777$), As/Be ($R = 0.799$), Cu/Ni ($R = 0.768$), Ni/Sb ($R = 0.754$) and Cu/Sb ($R = 0.779$), indicating that these metals may have the common sources and similar environmental behavior (Pan et al. 2016).

Table 3. Correlational matrix of heavy metal contents in sediments

The PCA results were listed in Table 4. Also, a 3-D plot of the PCA loadings is presented in Fig.5. The results indicated that there were three eigenvalues higher than one, and these three factors explain 81.1% of the total variance. The first factor

explains 44.9% of the total variance and loads heavily on Cr, Cu and Ni. According to spearman correlation matrices, significant positive correlations were observed between them ($p < 0.01$, $R > 0.65$), indicating similar sources or environmental behavior. Studies have reported that Cr, Cu and Ni primarily come from industrial and urban activities, such as machinery and electronics, chemical production and vehicle exhaust (Hong et al. 2014; Ying et al. 2016). The sediment samples with the highest concentration of these three metals were mainly distributed in the north of Wujin where many factories located. It can be inferred that the pollution emissions from industries have contributed to the accumulation of Cr, Cu and Ni. Factor 2, dominated by Be, As and Cd accounts for 23.4% of the total variance, which may relevant to agriculture and natural sources. As and Be with the absence of a strong correlation with other elements suggested that this group may be not controlled by a single factor. The sampling sites D1 and D2 are the drinking water sources which far away from the townships and industries. The sediment samples from the two sites containing higher amount of Be and As, indicated that the metals may originate from the natural sources. As discussed above, Cd was discharged from agricultural processes. Therefore, Be, As and Cd are assumed to originate from complex sources, especially from natural sources and agricultural activities. Factor 3 is loaded primarily by Hg and Pb accounting for 12.8% of the total variance, this source for the factor may be explained by contributions mainly from industrial or agricultural activities. Hg and Pb is greatly impacted by anthropogenic origins, such as vehicles, agrochemicals and industrial wastes (Krishna et al. 2009; Chen et al. 2013). In this study, the highest concentration

of Hg and Pb was found in E3 and W3, which influenced by upstream industries and agricultural activities seriously.

The results of CA for the variables standardized were shown in Fig.6 as dendrogram. The cluster had three subgroups. The first group containing the variables Cd, Be, As and Pb mainly originated from natural sources and agricultural activities. The second one including Ni, Sb, Cr and Cu may be related to industrial sources according to the analysis above. The third one Hg was associated with industrial sources and agricultural activities because the correlation analysis which showed positive correlations between Hg and Cu, Ni, Sb revealed that the pollution emissions from industries have contributed to the accumulation. Additionally, the distribution of Hg especially in proved that it was affected by agricultural activities as well. The results of CA basically coincided with those obtained from PCA.

Table 4. Rotated component matrix for heavy metal contents in sediments

Fig.5. 3-D plot of the PCA loadings

Fig.6. Hierarchical cluster analysis of heavy metals

4. Conclusions

In this study, Wujin and Yixing, two cities on the west bank of Taihu Lake were evaluated for contamination potential from heavy metals (Cd, Cr, As, Hg, Pb, Cu, Ni,

Be, Sb) in the surface sediments. This work was expected to provide reference for prevention and control of metal pollution in Taihu Basin. The following conclusions were drawn.

(1) The mean concentration of certain heavy metals exceeded the background values of Jiangsu province except for Hg and Be. Compared with published data, Cd, Cr, Cu and Ni in this study showed relatively higher mean concentrations. In particular, the maximum concentrations of Cd (3.08 mg/kg), Cr (447 mg/kg), Cu (338 mg/kg) and Ni (107 mg/kg) were significantly higher than other researches.

(2) The mean I_{geo} and E_r^i values followed the decreasing order $Cd > Cu > Sb > As > Ni > Pb > Cr > Be > Hg$ and $Cd > Sb > Hg > Cu > As > Be > Ni > Pb > Cr$, respectively. The risk assessment of heavy metals demonstrated that Cd with serious contamination and ecological risk need more attention to be controlled. The highest contamination level was observed in the estuary of Taihu Lake and most of the sediment samples were polluted and under risk.

(3) The multivariate statistical analysis indicated that Ni, Cr, Cu and Sb mainly originated from the industrial emission, Cd, Be and As were relevant to natural sources and agricultural activities, Hg and Pb was greatly impacted by industries and agricultural activities.

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Fig. 1 Study area and sampling sites

Fig. 2 Concentration of heavy metals in the sampling sites

Fig. 3 Box plots of the I_{geo} values for heavy metals in the sampling sites

Fig. 4 E_r^i values for heavy metals in the sampling sites

Fig.5 3-D plot of the PCA loadings

Fig.6 Hierarchical cluster analysis of heavy metals

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