

Heavy metal pollution status and ecological risks of sediments under the influence of water transfers in Taihu Lake, China

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Abstract The effects of water transfer projects on water channels and the receiving water involved need to be understood. In this research, the compositions and particle size distributions of surface sediment and the Cd, Cr, Cu, Ni, Pb, and Zn contents and distributions in the sediment along a water transfer route from the Wangyu River to Taihu Lake, China, were studied. The correlative relationship between the grain size trend and heavy metal content distribution suggested that heavy metals in Wangyu River sediment have affected the heavy metal contents of Taihu Lake sediment through silt and clay migrating in the transferred water. Enrichment factors and potential ecological risk values were calculated. Low levels of potential ecological risks are posed at 20 sampling sites in Taihu Lake, but higher-to-serious risks (potential ecological risk values >275) are posed at all Wangyu River sites. Toxicity of heavy metals (Cd, Cu, Zn, and Ni) in the Wangyu River sediments is more serious than those in the Taihu Lake, but is similar to the entrance of Gonghu Bay. Multivariate statistical analyses (Pearson correlation, cluster, and factor analyses) suggested heavy metals in the study area have many sources, and the relationships between particle migration and heavy metal contents indicated transferring water are likely to lead to adverse ecological risks being posed in Taihu Lake.

Keywords Heavy metals · Sediment · Water transfer route · Grain size trend · Ecological risk assessment · Wangyu River

Introduction

Taihu Lake is the third largest freshwater lake in China, with a surface area of approximately 2338 km². There are many economically developed cities around Taihu Lake. Industrial and agricultural wastewater discharges into Taihu Lake have led to the water being seriously polluted (Jin et al. 2010; Wang et al. 2014). Water transfer is an important way of restoring lakes (Hosper and Meyer 1986; Jagtman et al. 1992; Wu et al. 1999; Hu et al. 2008). A water transfer project has been formally running since 2002 to improve water quality and decrease the risk of algal blooms occurring in Taihu Lake (Hu et al. 2008). Water from the Yangtze River is transferred to Taihu Lake through the Wangyu River, and water is discharged from Taihu Lake into the Taipu River. Water transfer has had clearly positive effects on Taihu Lake by decreasing total phytoplankton and nitrogen concentrations and improving the eutrophication status of the lake (Liu et al. 2007; Qian et al. 2008; Hu et al. 2008; Li et al. 2011). However, water transfer could cause heavy metals in sediment to be transported into Taihu Lake or sediment in the lake to be resuspended, increasing the risks of heavy metals having toxic effects in the lake ecosystem. A number of studies have focused on changes in nitrogen and phosphorus concentrations in Taihu Lake, but few studies of the effects of water diversion on heavy metal pollution in Taihu Lake have been performed (Fan et al. 1997; Liu et al. 2007; Qian et al. 2008; Li et al. 2011).

Heavy metals are considered to be the most persistent pollutants of sediment because they cannot be decomposed under natural conditions (Zheng et al. 2013). Some heavy metals are required by organisms but can be toxic if their concentrations

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are too high. Heavy metals were easily deposited on the sediment surfaces and immobilized through adsorption and coagulation (Jain et al. 2008). It has been shown in many studies that sediment may act as both a sink and a source of contaminants in an aquatic system (Adams et al. 1992; Burton and Scott 1992; Delgado et al. 2002; Wang et al. 2012). Zheng et al. (2008) found that more than 90 % of heavy metal contents were related to the suspended particles and sediments. The distributions of heavy metals in sediments can provide evidence of anthropogenic influences on aquatic systems.

The Wangyu River is the most important channel involved in the diversion of water from the Yangtze River to Taihu Lake. A large amount of sediment is suspended during the transfer of water through the Wangyu River (Wang et al. 2013). Pollutants in the Wangyu River may be brought into Taihu Lake by water transfer and may affect water quality in Taihu Lake. Due to the high-content suspended particles of Yangtze River, the heavy metal pollutants with the suspended particle movement were deposited into the sediments of the main stream and lake (Zhai et al. 2010). Disturbances caused by the water diversion scheme can cause heavy metals in sediment in the Yangtze River and the Wangyu River to be released into the water or the sediment to be resuspended, potentially affecting the quality of the diverted water. It is therefore vital that the heavy metal pollution statuses of the Wangyu River and Yangtze River are determined so that the effects of the water diversion scheme can be understood.

Hydrodynamic changes can lead to the redistribution of suspended particles and the nutrients and heavy metals associated with the particles. The deposition and resuspension of suspended particles mean that the sedimentary environment can constantly change. Sediment transport paths and hydrodynamic changes can be determined by identifying changes in grain size parameters (Petitjohn and Ridge 1938; Plumley 1948; Gao and Collins 1991). These spatial variations like mean, sorting, skewness, and kurtosis are called grain size trends (Jia et al. 2003; Poizot and Me'ar 2010). According to the McLaren model, sediment transport in natural environments follows two patterns. In the downstream direction, sediment tends to become finer, better sorted, and more negatively skewed or coarser, better sorted, and more positively skewed. Information on sediment transport paths can help gain an understanding of the transport of heavy metals (McLaren and Little 1987).

As mentioned above, water is transferred from the Yangtze River to Taihu Lake through the Wangyu River to improve water quality in Taihu Lake, which suffers eutrophication, and prevent cyanobacteria accumulating. Large amounts of sediment carrying heavy metals and other pollutants have been deposited along the Wangyu River and in Taihu Lake. It is important to determine whether the water transfer project has affected the heavy metal contents of

Taihu Lake sediment and the potential risks posed by heavy metals in Taihu Lake sediment. There is no systematical research and reporting on the topic. We collected surface sediment samples from along the water transfer route and determined grain size parameters for the samples and the spatial distributions of the heavy metals Cd, Cr, Cu, Ni, Pb, and Zn in the Wangyu River and Taihu Lake. Our aim was to assess the potential ecological risks posed by sediment transported along the water transfer route and to assess the effects of the water diversion project on particle migration and heavy metal contents. The study was performed with the intention of providing data to support the operation and management of the Yangtze River to Taihu Lake water transfer project and similar projects elsewhere in China and around the world.

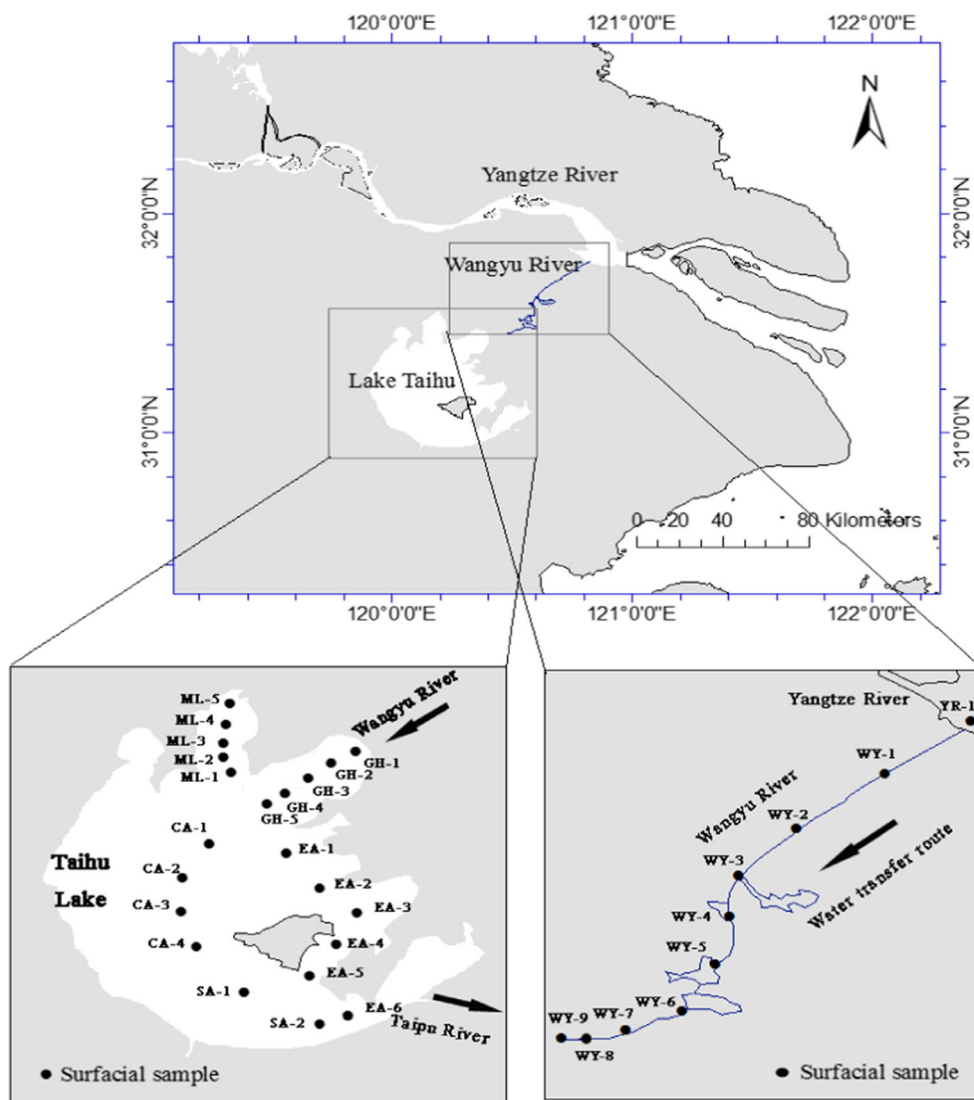
Materials and methods

Study area and sediment sampling

Taihu Lake (30° 56'–31° 33' N, 119° 53'–120° 36' E) is a large, shallow (mean depth 1.9 m) lake adjacent to the Yangtze River. The Wangyu River, to which Taihu Lake provides many tributaries, is the main channel through which water is transferred from the Yangtze River to Taihu Lake (Fig. 1). Water was transferred intermittently between 2002 and 2013. When the Taihu Lake water quality required, a sluice gate in the northeastern part of Taihu Lake was opened to allow water to run from the Yangtze River into Gonghu Bay, which has a surface area of 163.8 km² (Wang et al. 2014). Water balance in Lake Taihu was maintained by discharging water from the lake through the Taipu River. Between 1 January and 5 October 2013, about 1670 × 10⁶ m³ of water was transferred from the Yangtze River and about 927 × 10⁶ m³ of that entered Lake Taihu, with about 438 × 10⁶ m³ being discharged through the Taipu River.

Significant horizontal differences have been found in the water quality and ecosystem structure of Taihu Lake. The northern and western parts of the lake have worse water quality than the eastern and southern parts (Hu et al. 2008; Li et al. 2011). Li et al. (2011) used the Lagrangian particle tracking concept and a three-dimensional environmental fluid dynamic code model to assess the environmental impacts on Taihu Lake of transferring water from the Yangtze River. They marked test “particles” with red triangles and released them in the inlets of Gonghu Bay, then marked the end positions of the particles that were recovered on a map to find the pathways water parcels followed through the polluted part of the lake. In previous studies, it was found that transferring water through the Wangyu River, as an emergency

Fig. 1 Water transfer route and sampling locations in Taihu Lake, the Yangtze River, and the Wangyu River. *YZ* Yangtze River, *WY* Wangyu River, *ML* Meiliang Bay, *GH* Gonghu Bay, *EA* east coast area, *SA* south coast area, *CA* central area



measure, could temporarily improve the water quality and mitigate algal blooms in some parts of Lake Taihu (Gonghu Bay, Meiliang Bay, the central part of the lake, the east coast area, and the south coast area) (Hu et al. 2008; Li et al. 2011; Zhai et al. 2010). We collected sediment samples at 32 locations along the route along which transferred water passes in July 2013. The sampling sites are marked on Fig. 1. The sampling sites were on the Yangtze River (YZ-1) and the Wangyu River (WY-1–WY-9), in Gonghu Bay (GH-1–GH-5), Meiliang Bay (ML-1–ML-5), the central part of Taihu Lake (CA-1–CA-4), in the south coast area (SA-1–SA-2), and the east coast area (EA-1–EA-6).

Grain size measurements

A Malvern 2000 laser analyzer (Malvern Instruments, Malvern, UK) was used to determine the grain size distribution of each sediment sample. Grain size parameters

were calculated using a moment method (McManus 1988), and the results are shown in Table 1. The mean particle size and the sorting, skewness, and kurtosis parameters were used to simulate the grain size trends in the sedimentary environment (McLaren 1981).

Heavy metal analyses

Each sediment sample was freeze-dried, ground, and homogenized. A 0.2-g aliquot of the sample was then digested in a mixture of 6 ml HNO₃, 1 ml H₂O₂, 4 ml HF, and 0.5 ml HClO₄ (all ultrapure) on a hot plate. When digestion was complete, the sample was allowed to become almost dry, then the residue was redissolved in 1 mmol/l HNO₃ (McLaren and Bowles 1985). The Cd, Cr, Cu, Ni, Pb, and Zn concentrations in the solution were then determined by inductively coupled plasma atomic emission spectroscopy using an automatic filling procedure. Each sample was

Table 1 Methods used to calculate the particle size parameters

Parameters	Moment method (McManus 1988) ^a
Mean (ϕ)	$\mu = \sum_1^n P_i x_i$
Sorting	$\sigma = \left[\sum_1^n P_i (x_i - \mu)^2 \right]^{\frac{1}{2}}$
Skewness	$S_k = \left[\sum_1^n P_i (x_i - \mu)^3 \right]^{\frac{1}{3}}$
Kurtosis	$K_u = \left[\sum_1^n P_i (x_i - \mu)^4 \right]^{\frac{1}{4}}$

^a i is the size class, P_i is the percent of particles of size x_i (in ϕ units), and n is the total number of size classes. The sediment samples were classified using the scheme presented by Gao (1995)

analyzed in triplicate. Blank extractions (i.e., with no sediment sample) were also performed.

Enrichment factors and potential ecological risks

The enrichment factor (EF) is an effective method for assessing the contamination status of sediment. We calculated EFs using the method described by Franco-Uria et al. (2009). EFs can help gain an understanding of anthropogenic contributions to heavy metal pollution. The EFs were calculated using the equation

$$EF = \frac{(C_n/C_{ref})_{\text{sample}}}{(B_n/B_{ref})_{\text{background}}},$$

where C_n is the content of the heavy metal of interest in the sediment, C_{ref} is the reference element content of the sediment, B_n is the content of the heavy metal of interest in unpolluted sediment, and B_{ref} is the reference element content of unpolluted sediment. The background contents were determined from the appropriate minimum contents, which can be considered to be the natural heavy metal contents of Taihu Lake sediment (Selvaraj et al. 2004; Wang et al. 2014). The reference element was selected taking the stability of the element under natural conditions and the degree to which anthropogenic pollution affects the content of the element in the environment into consideration. Aluminum, iron, and some radioactive elements are usually used as reference elements (Zhang and Liu 2002; Franco-Uria et al. 2009; Tang et al. 2014), but different researchers have used different elements.

The potential ecological risk (PER) index concept was also used to assess the ecological risks posed by heavy metals in the sediment samples (Guo et al. 2010). The PER is a comprehensive potential ecological risk index and reflects the

sensitivity of a biological community to toxic substances. The PER was calculated using the equations

$$C_f^i = \frac{C^i}{C_n^i},$$

$$C_d = \sum_{i=1}^n C_f^i,$$

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

$$\text{and } PER = \sum_{i=1}^m E_r^i,$$

where C_f^i is a single element contamination factor, C^i is the content of the element in the sediment, and C_n^i is the background content of the element. The background contents of sediments in continental environments can be considered to be the natural heavy metal contents of Taihu Lake sediment. The background contents we used for Cd, Cr, Cu, Ni, Pb, and Zn were 0.1, 70, 20, 28, 20, and 65 mg/kg, respectively (Antonio and Ricardo 2003). We called the sum of the C_f^i values for Cd, Cr, Cu, Ni, Pb, and Zn the integrated degree of pollution (C_d). The E_r^i value is the potential ecological risk index for a single element, and the T_r^i value is the biological toxicity factor of a single element. The toxic factors used for Cd, Cr, Cu, Ni, Pb, and Zn were 30, 2, 5, 6, 5, and 1, respectively (Guo et al. 2010; Fu et al. 2009).

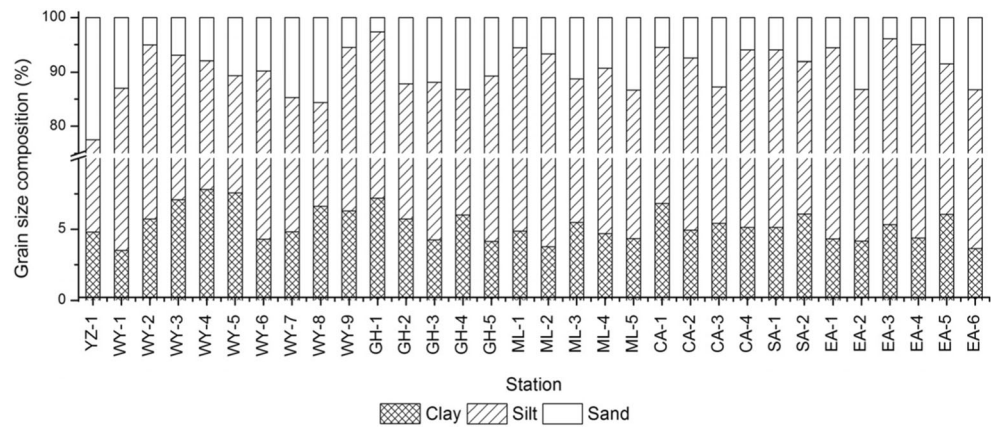
Results

Sediment compositions and grain size distributions

As shown in Fig. 2, the sediment samples were predominantly composed of silt, and sand was the next most abundant component. The clay contents of most of the samples were <7 %. The mean silt content of the Taihu Lake sediment was 84.25 %, and the mean sand and clay contents were 10.57 and 5.18 %, respectively. The mean silt content of the Wangyu River sediment was 81.97 %, and the mean sand and clay contents were 12.18 and 5.85 %, respectively. The sand content of the YZ-1 sample (22.5 %) was clearly different from the sand contents of the Taihu Lake and Wangyu River samples. The differences between the sand contents of the other samples were not significant. The fine fraction (clay + silt) content generally decreased moving down the Wangyu River, but the sample from station WY-9, which was the nearest Gonghu Bay, had the highest fine fraction content of all nine samples collected along the river. The grain size distributions at stations GH-1 and WY-9 were similar.

The grain size parameter distributions for the samples collected from the Yangtze River, Taihu Lake, and Wangyu River are shown in Fig. 3. According to the grain size

Fig. 2 Spatial variations in the particle size distributions of the surface sediment samples

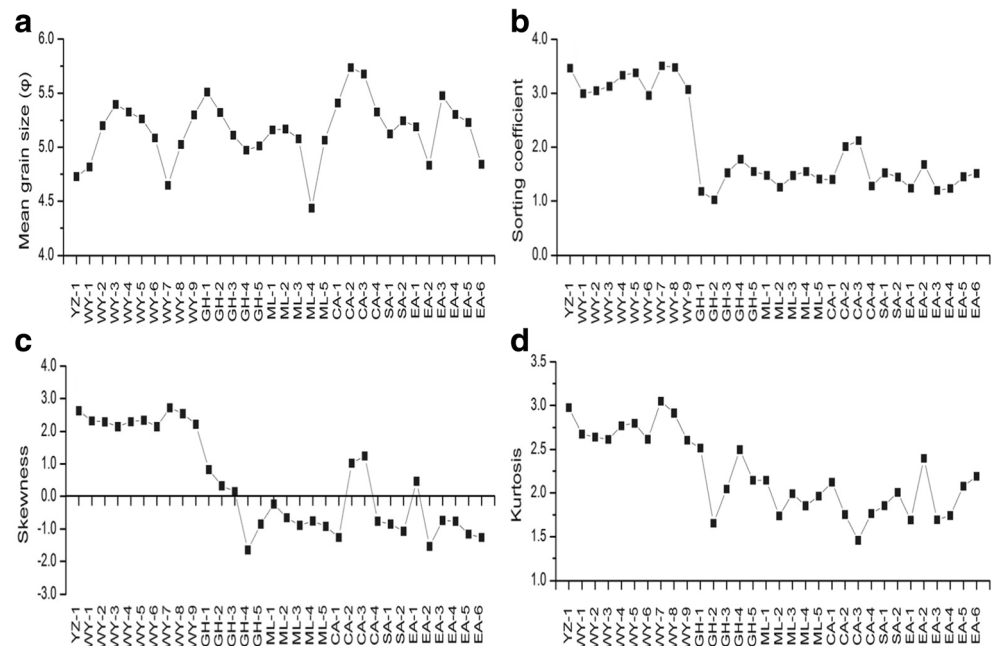


classification standards (Folk and Ward 1957; Gao 1995), we found that the predominant sediment in Taihu Lake and the Wangyu River was coarse silt with a mean particle size of about 5.0ϕ . The main component of the Yangtze River sediment samples was very fine sand (VFS, 4.7ϕ), and except at station WY-7, the particle size did not obviously change along the Wangyu River from Ehu to Caohu and to Shengtanh Lake. The mean grain size increased from 5.5 to 4.9ϕ from station GH-1 to station GH-5 in Gonghu Bay, and, except for at station ML-4, the particle size changed very little from Gonghu Bay to Meiliang Bay. The highest and lowest particle sizes were found in the central part of Taihu Lake and Meiliang Bay, respectively.

The mean sorting coefficient, skewness, and kurtosis parameters were analyzed using one-way ANOVAs, and the results are shown in Fig. 3b–d. The parameters for the Yangtze River and Wangyu River samples were significantly different from the parameters for the Taihu Lake samples ($p < 0.05$). The sorting

coefficients for the CA-1 and CA-2 samples were lower than the sorting coefficients for the other Taihu Lake samples, but otherwise the sorting coefficients for the Taihu Lake samples varied little. The samples from the Yangtze River and Wangyu River stations all had extremely positive biases, and the samples from stations GH-1 to GH-5 started with positive biases and gradually changed to strongly negative biases. Moving across the central part of Taihu Lake, the samples started with extremely negative biases, changed to positive biases, then changed back to negative biases. Except for the station EA-1 sample (which had a positive bias of 0.47), the samples from the stations in the south and central parts of Meiliang Bay all had negative biases or extremely negative biases. Kurtosis varied in a similar way to skewness. The kurtosis values for the Yangtze River and Wangyu River samples were significantly higher than the values for the Taihu Lake samples. The lowest kurtosis values were found for the Gonghu Bay samples and the samples from the central part of Taihu Lake.

Fig. 3 Distributions of the particle parameters for the sediment samples

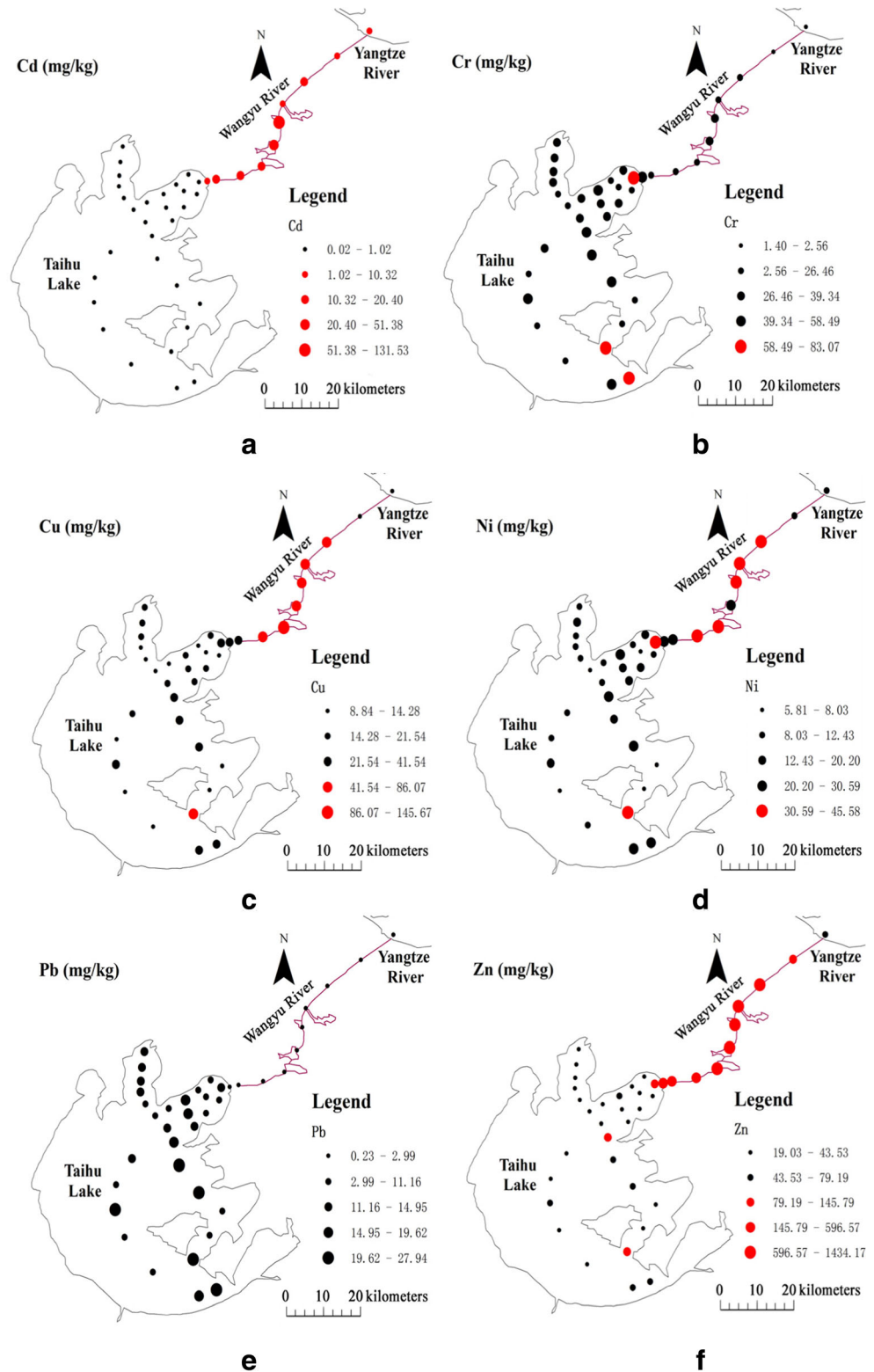


Spatial distributions of the heavy metals in sediment along the water transfer route

The Cd, Cr, Cu, Ni, Pb, and Zn contents of the sediment samples along the water transfer route are shown in Fig. 4.

The differences between the metal contents of the sediment samples in the different parts of the study area were generally significant. The degrees to which Taihu Lake sediment samples and Wangyu River sediment samples were contaminated with heavy metals were different. The Cd, Cu, Zn, and Ni

Fig. 4 Spatial distributions of the **a** Cd, **b** Cr, **c** Cu, **d** Ni, **e** Pb, and **f** Zn contents (mg/kg) of the sediment samples collected along the water transfer route (red dots: the concentration exceeds the soil environmental quality standards primary standard criteria)

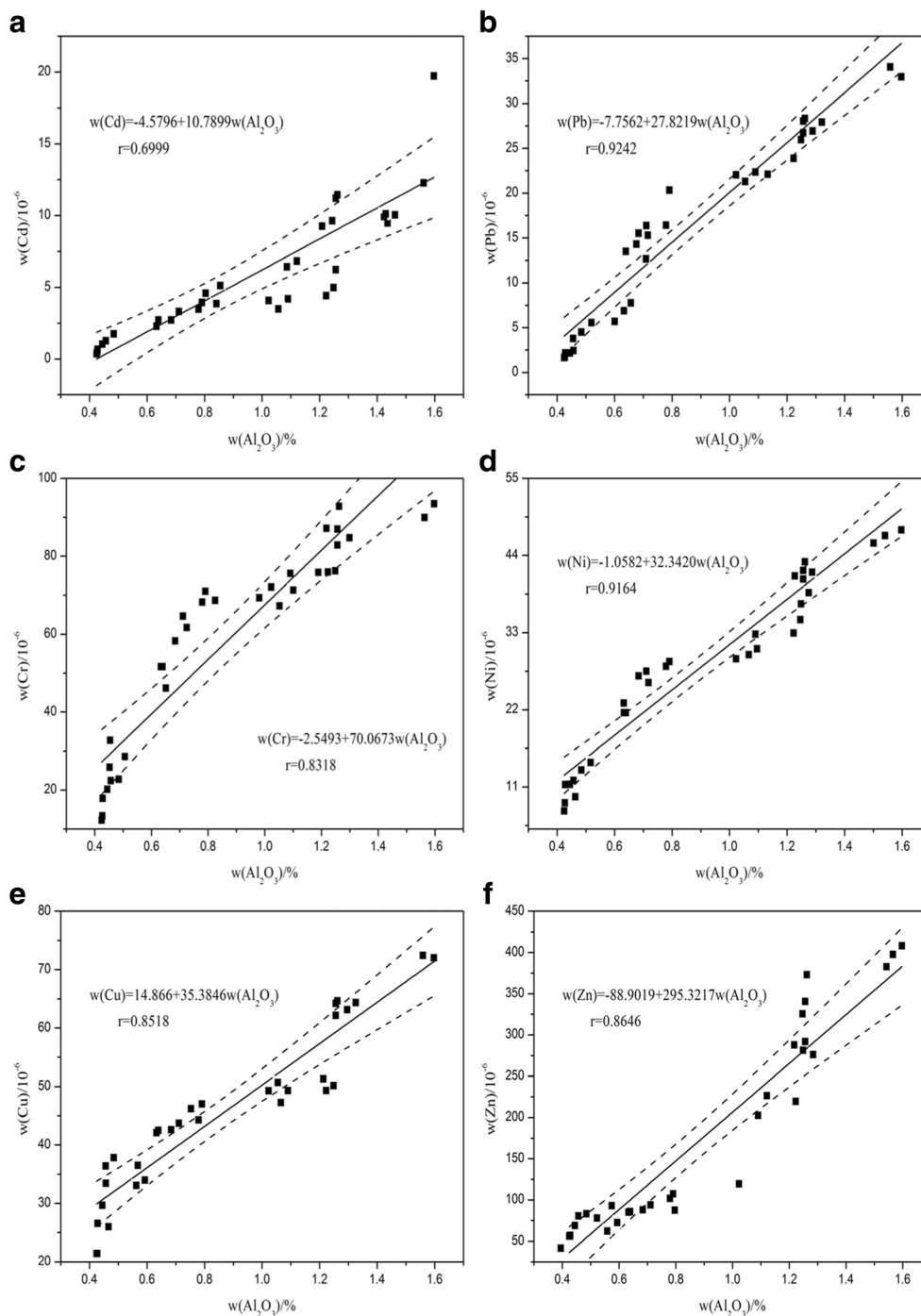


contents were higher in the Wangyu River samples than in the Taihu Lake samples. In contrast, the Cr and Pb contents were lower in the Wangyu River samples than in the Taihu Lake samples. One-way ANOVA analysis indicated that the spatial distributions of the Cd and Zn contents in the Taihu Lake sediment samples were uniform except in Gonghu Bay. However, the Cd, Cu, Ni, and Zn contents of the Gonghu Bay and Wangyu River samples were very similar. In particular, the heavy metal contents were higher at station GH-1 (the entrance to Gonghu Bay) than at the other Gonghu Bay

stations. The metal contents, particularly the Cd, Cu, Ni, and Zn contents, in the Gonghu Bay samples decreased from station GH-1 to station GH-5.

The highest Cd and Zn contents (81.53 and 1434.17 mg/kg, respectively) were found at station WY-4, and the highest Cu and Ni contents (145.67 and 45.58 mg/kg, respectively) were found at station WY-6. These contents were much higher than the contents at all of the other Taihu Lake stations (Fig. 4). However, the highest Cr and Pb contents were found at station EA-5 in Taihu Lake. In particular, the heavy metal contents at

Fig. 5 Scatter plots showing the relationships between the heavy metal contents and the aluminum contents of the sediment samples collected along the water transfer route



station GH-1 (at the entrance to Gonghu Bay) were higher than the heavy metal contents at the other Gonghu Bay stations. Some high contents were found in the central part of Taihu Lake and in the east coast area. The Cd contents varied spatially less than the other metal contents of the Taihu Lake samples.

The total metal contents of the Taihu Lake sediment samples decreased in the order $Zn > Cr > Cu > Ni > Pb > Cd$. The total metal contents of the Wangyu River sediment samples decreased in the order $Zn > Cu > Ni > Cd > Cr > Pb$. It was

clear that the Cd, Cu, Ni, and Zn pollution statuses were more serious in the Wangyu River than in Taihu Lake. The Cd, Cu, Ni, and Zn contents of the samples from Gonghu Bay and the Wangyu River were very similar.

EFs and PER values

Aluminum is one of the most abundant metal elements in the Earth's crust. Aluminum is stable in the environment, so we

Fig. 6 Enrichment factors (EFs) for the heavy metals in the sediment samples collected along the water transfer route

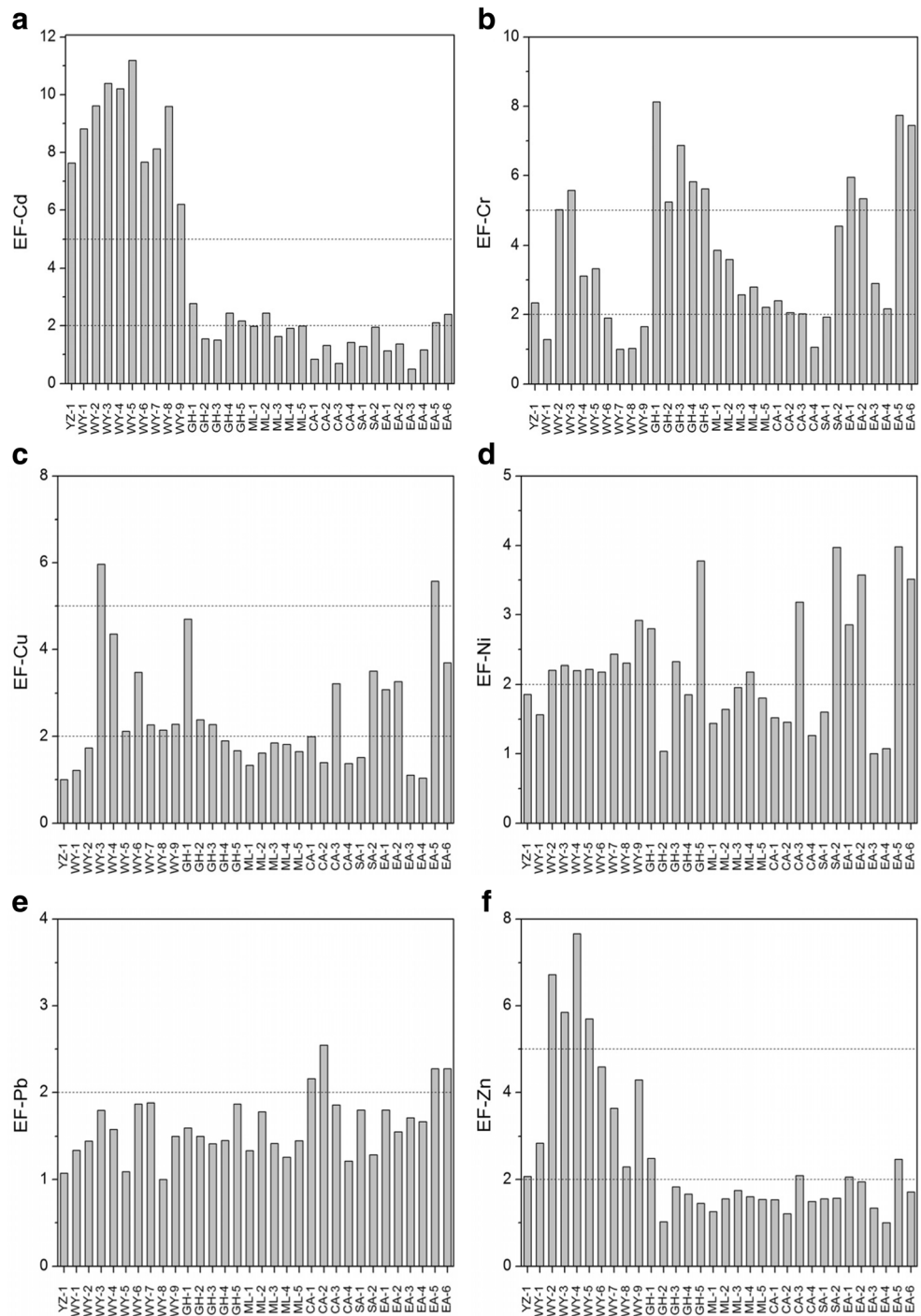


Table 2 Basic statistics for the potential ecological risk (PER) values for the sediment samples

		C_d	Er						PER
			Cd	Cr	Cu	Ni	Pb	Zn	
Taihu Lake	Average	4.96	44.48	1.06	4.96	3.37	3.51	0.69	58.06
	Maximum	16.34	307.44	2.37	12.32	9.51	6.98	2.24	329.75
	Minimum	1.98	6.37	0.51	2.29	1.25	1.93	0.29	13.03
Wangyu River	Average	195	539	0.25	14.56	6.23	0.28	11.66	542.3
	Maximum	533	1541	0.74	36.42	9.77	0.75	22.06	1544.5
	Minimum	34.54	290	0.03	2.21	2.13	0.06	1.22	275.5

used it as a reference element. Scatter plots showed that there were clear relationships between the aluminum content and the Cd, Cr, Cu, Ni, Pb, and Zn contents (Fig. 5), with the data for 50–70 % of the sampling points falling within the 95 % confidence interval around the regression line.

The EF method is a normalization method that is widely used to identify human influences on heavy metal pollution. The calculated EFs for the sediment samples from along the water transfer route are shown in Fig. 6. EFs allow the degree of pollution to be divided into five levels, shown in Table 4. On the whole, the EFs for the different parts of the study area suggested that the different areas had different pollution statuses. The Cd EFs for the Wangyu River and Yangtze River samples were >5, indicating that these samples were clearly polluted. The Cd EFs for the Taihu Lake samples were 0.50–2.77, and the mean was 1.66. Sediments at several sampling points in Gonghu Bay, Meiliang Bay, and the eastern part of Taihu Lake were categorized as moderately polluted with Cd, but the sediment samples from the other sampling points were classed as unpolluted. The highest Cr EF was found at station GH-1, and sediment at this station was classed as clearly polluted. The Cr EFs for the Taihu Lake samples were higher than the Cr EFs for the Yangtze River and Wangyu River samples except for the samples from stations WY-2, WY-3, WY-4, and WY-5. The highest Cu and Zn EFs were found for the sediment from station WY-3, which was clearly polluted. The highest Pb EFs at most stations were <2, suggesting that sediment at these stations is unpolluted with Pb. The Ni EFs at some of the sampling points in Gonghu Bay and the central and eastern parts of Taihu Lake, where the sediment was classed as moderately polluted, were higher than the EFs for the Wangyu River samples.

The different pollution levels are shown in Table 4 (Guo et al. 2010). The calculated PER values for each heavy metal and the comprehensive indices are presented in Table 2. The

degree of metal contamination in the Taihu Lake sediment samples decreased in the order Cd > Cu > Pb > Ni > Cr > Zn. The degree of metal contamination in the Wangyu River sediment samples decreased in the order Cd > Cu > Zn > Ni > Pb > Cr. The C_d range for the Taihu Lake samples was 1.98–16.34, and the mean was 4.96. This indicates that sediment in Taihu Lake suffers low to moderate heavy metal contamination (Fu et al. 2009). However, the C_d range for the Wangyu River samples was 34.54–533, and the mean was 195, indicating that sediment in the Wangyu River suffers high levels of metal contamination.

The mean E_r^i values for heavy metals in the Taihu Lake and Wangyu River sediment samples decreased in the order Cd > Cu > Zn > Ni > Pb > Cr. The PER values for the Taihu Lake samples were 13.03–329.75, and the mean was 58.06. The PER values for the Wangyu River samples were 275.5–1544.5, and the mean was 542.3. The PER values were therefore much higher in the Wangyu River samples than in the Taihu Lake samples.

The lowest and highest PER values were found for the samples from stations EA-3 and WY-5, respectively. The highest PER value (1544.5) may have been caused by the high heavy metal contents of the WY-5 sample. The PER value indicated that sediment at WY-5 poses serious potential ecological risks. The PER values for stations GH-1, GH-5, YZ-1, and WY-1–WY-9 were 250–1544, indicating that higher degrees of ecological risk are posed at these sites. About 93 % (20 sites) of the Taihu Lake stations had PER values <150, so low levels of potential ecological risk are posed at these sites. From Table 3, it can be seen that the PER values in the seven parts of the study area varied greatly, especially at the stations on the Yangtze River and Wangyu River. Severe potential ecological risks are posed by heavy metals in sediment in the Yangtze River and Wangyu River. The PER values were higher for the Gonghu Bay stations than for the stations in the other parts of Taihu Lake (Table 4).

Table 3 Potential ecological risk (PER) values for the sediment samples from different areas

Districts	Yangtze River	Wangyu River	Gonghu Bay	Meiliang Bay	Center area	South coast area	East coast area
PER	376.55	542.33	91.17	35.86	31.70	47.69	48.19

Table 4 Standards used to determine the degree of contamination from the enrichment factors (EFs), E_r^i values, and potential ecological risk (PER) values

EF	Pollution level	E_r^i	Pollution level	PER	Pollution level
<2	Low	<40	Low	<150	Low
2–5	Moderate	40–80	Moderate	150–300	Moderate
5–20	Obvious	80–160	Higher	300–600	Severe
20–40	High	160–320	Much higher	>600	Serious
>40	Serious	>320	Serious		

Multivariate statistical analysis

The correlation coefficients for the relationships between the contents of the different metals in the samples and the sediment parameters are presented in Table 5. Positive correlations were found between the Cd and Zn contents ($r = 0.750$), Cr and Pb contents ($r = 0.919$), Cu and Ni contents ($r = 0.847$), Cu and Zn contents ($r = 0.794$), and Ni and Zn contents ($r = 0.864$) of the sediment samples. We deduced from the good correlations between the Cu, Ni, and Zn contents that these three metals may have been supplied by the same sources and that the other metals did not have common sources. Positive relationships were also found between the PER values and the Cd contents ($r = 0.767$), Cu contents ($r = 0.774$), and Zn contents ($r = 0.807$) of the sediment samples. The sorting coefficient, skewness, and kurtosis positively correlated with each other and also strongly positively correlated with the Cu and Zn contents and the PER values.

The cluster analysis results were the same as the Pearson correlation analysis results, and the cluster analysis dendrogram is shown in Fig. 7a, in which the 15 parameters are grouped into three significant clusters. Cluster 1

included Cr and Pb; cluster 2 included Cd, Cu, Ni, Zn, PER, mean grain size, sorting coefficient, skewness, kurtosis, silt, and clay; and cluster 3 included only sand. Cluster 1 showed that the Cr content was strongly related to the Pb content. Cluster 2 indicated that the Cd, Cu, Ni, and Zn contents were mainly responsible for the PER values and that the mean grain size, sorting coefficient, skewness, and kurtosis were similar and strongly associated with silt and clay grains. Cluster 3 showed that the metal contents were not significantly related to the sand content.

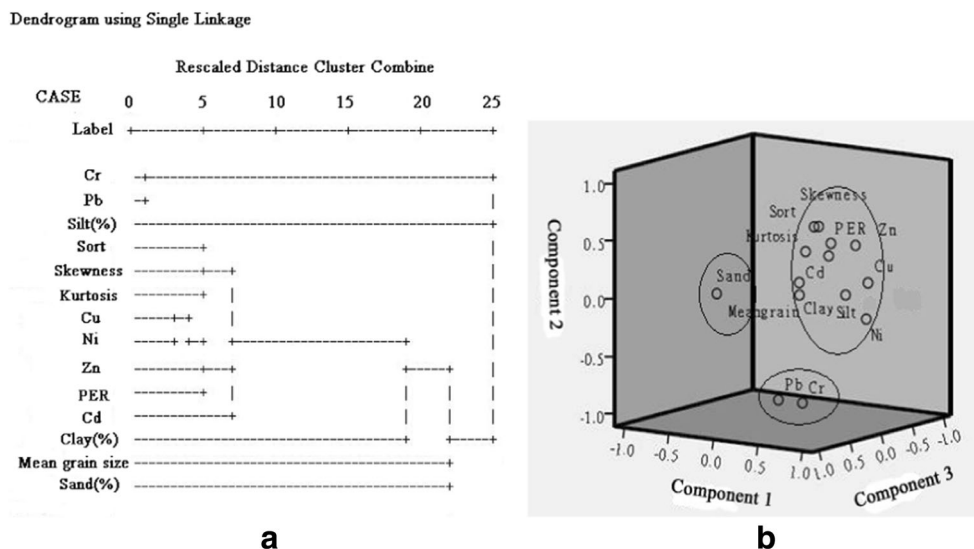
Factor analysis gave two factors with eigenvalues >1 explaining 83.75 % of variability in the parameters (Fig. 7b). The first factor accounted for 76.22 % of variability and had high positive loadings for Cd, Cu, Ni, Zn, PER, mean grain size, sorting coefficient, skewness, kurtosis, silt, and clay. This showed that the Cd, Cu, Ni, and Zn contents made significant contributions to the PER values. Factor 2 accounted for 13.45 % of the variability, mainly in the Cr and Pb contents. Cluster analysis grouped all 15 parameters into three statistically significant clusters, and factor analysis gave two factors, and the cluster and factor analysis results matched the Pearson correlation analysis results well.

Table 5 Pearson correlation coefficients for the relationships between the variables

	Cr	Cu	Ni	Pb	Zn	Cd	PER	Mean grain	Sort	Skewness	Kurtosis	Clay	Silt	Sand
Cr	1.000													
Cu	-0.074	1.000												
Ni	0.252	<i>0.847</i>	1.000											
Pb	<i>0.919</i>	-0.285	-0.018	1.000										
Zn	-0.364	<i>0.794</i>	<i>0.864</i>	-0.574	1.000									
Cd	-0.344	0.459	0.362	-0.383	<i>0.750</i>	1.000								
PER	-0.452	<i>0.774</i>	0.469	-0.521	<i>0.807</i>	<i>0.767</i>	1.000							
Mean grain	0.121	0.070	0.026	0.041	0.098	0.081	0.029	1.000						
Sort	-0.578	<i>0.639</i>	0.472	-0.690	<i>0.748</i>	0.543	<i>0.720</i>	-0.127	1.000					
Skewness	-0.505	<i>0.606</i>	0.435	-0.643	<i>0.676</i>	0.463	<i>0.627</i>	0.133	<i>0.814</i>	1.000				
Kurtosis	-0.417	<i>0.654</i>	0.483	-0.568	<i>0.589</i>	0.427	<i>0.681</i>	-0.286	<i>0.805</i>	<i>0.704</i>	1.000			
Clay	<i>0.793</i>	0.186	0.234	-0.256	0.446	<i>0.763</i>	0.431	0.380	0.222	0.223	0.226	1.000		
Silt	<i>0.794</i>	0.055	0.029	0.235	-0.026	<i>0.680</i>	-0.177	0.290	-0.375	-0.216	-0.419	-0.049	1.000	
Sand	-0.273	-0.091	-0.073	-0.184	-0.060	-0.010	-0.092	-0.361	0.329	0.171	0.372	-0.144	-0.981	1.000

The italicized values indicate positive correlations between variables

Fig. 7 **a** Dendrogram showing the clusters of variables. **b** Three-dimensional diagram showing the factor analysis results



Discussion

Grain size parameters and sediment sources

The amount of a heavy metal that will be bound to sediment will be determined by the sediment particle size distribution, the sediment mineral composition, the redox state of the system, and the physical transmission medium. The main factor that influences the heavy metal distribution is the sediment grain size distribution (Aprile and Bouvy 2008). The continuous deposition of fine particles carrying heavy metals can increase the heavy metal content of sediment (Casado-Martínez et al. 2006). Silt was the main component of the sediment in our study area, accounting for more than 80 % of the total sediment mass. However, sediment from station YZ-1 on the Yangtze River had a lower silt content (about 70 %) than did the sediment from the other stations. During water transfer periods, most of the sand that is transferred will have settled in the estuary and some of the silt will have entered Gonghu Bay from the Wangyu River.

The mean grain size reflects the hydrodynamic intensity (motive energy) of the sedimentary environment, so the hydrodynamic intensity can explain particle size trends (Burghard 2007). Differences between the mean particle sizes in Gonghu Bay and Wangyu River showed that these two areas had high-energy sedimentary environments. The sorting value can indicate the particle sizes and the degree of uniformity (Gao and Collins 1992). The Wangyu River samples had poor sorting characteristics (sorting values >3.0). Skewness can indicate the relative positions of the median and mean particle sizes and reflect energy differences during the deposition process (Gao and Collins 1992). The Wangyu River sample skewness values were 2.0–3.0, and the Gonghu Bay sample

skewness values were 0–1.0. The skewness values for the samples from most of the other areas were <1.0, indicating negative to extremely negative bias. Kurtosis can indicate the main source of sediment and allow the particle size frequency curve to be characterized. The kurtosis values for all of the Taihu Lake and Wangyu River samples were >1.0, indicating that multiple sources or multiple factors affected the sediment in these areas. The results described above were consistent with the sediment components that were identified (i.e., silt was the dominant type of sediment).

In summary, the sediment samples from the Wangyu River estuary had small particle sizes and were well sorted, indicating that suspended solids that settled there had been flushed into the area in diverted water. The sediment samples from Gonghu Bay were coarser, better sorted, more positively skewed, and strongly influenced by the diverted water. The sediment samples from Meiliang Bay, the central part of Taihu Lake, and the east coast of Taihu Lake were finer, better sorted, more negatively skewed, and less affected by the diverted water. Numerous persuasive articles have been published asserting that differences in sediment grain size parameters indicate the hydrodynamic intensity of a sedimentary environment (McLaren and Bowles 1985; Le Roux 1994; Burghard 2007). We concluded that the differences in the grain size parameters indicated that Gonghu Bay was more affected by the diverted water than were the other parts of the study area.

Assessment of ecological risks posed by heavy metals in sediment in Gonghu Bay affected by transferred water

According to Harikumar and Nasir (2010), heavy metal contents below the “effects range low” will influence

biological growth little and heavy metal contents equal to or greater than the effects range low, but less than the “effects range median” will exert medium influences on biological growth. Heavy metal contents at or higher than the effects range median will have strong adverse biological effects. The Pb contents of our samples suggested that Pb will have little or no biological effect in the study area. Cr, Cu, and Zn may have some biological effects in the study area because the contents of these metals fell between the effects range low and effects range median values for the metals. Our results indicated that Ni, Cd, Cu, and Zn are likely to have adverse biological effects in the Wangyu River. The PER index for each metal, the E_r^i , and the pollution degree classifications indicated that each heavy metal except for Cd had a low potential ecological risk. Metal mining, fertilizer production, and electroplating are generally the main anthropogenic sources of Cd to the environment (ATSDR 2008). There are a lot of metal processing plants, agricultural areas, and waste disposal sites around Taihu Lake and the Wangyu River, and these may have been the sources of Cd to sediment in the study area.

The Cd and Zn EFs were higher for the Yangtze River and Wangyu River samples than for the Taihu Lake samples. It was clear that sediment in the study area is polluted with heavy metals because the EFs for most sites were >2. Higher Cd, Cr, Cu, and Zn EFs were found in the Wangyu River and Gonghu Bay samples than in the other samples. The comprehensive PER indices for the Taihu Lake samples indicated that Cd, Cr, Cu, Ni, Pb, and Zn in sediment currently pose low levels of risk. However, the comprehensive PER indices for the Yangtze River and Wangyu River samples indicated that Cd, Cr, Cu, Ni, Pb, and Zn could pose high-to-serious ecological risks. The Gonghu Bay samples had higher PER indices than did the other Taihu Lake samples. These results indicate that transferring water into Taihu Lake may increase the potential ecological risks posed by heavy metals in sediment in Gonghu Bay.

Relationships between particle migration and heavy metal contents

No correlations were found between the contents of some of the metals, suggesting that the metal contents were not controlled by a single factor but by multiple factors. Suresh et al. (2011) found that a high correlation coefficient for the relationship between two metal contents indicates that the metals have a common origin and are transported together. Heavy metals may adsorb to the surfaces of fine particles in sediment. The silt and clay contents of our samples positively correlated with the Cd, Cu, Ni, and Zn contents. The

relationships between sediment parameters and heavy metal contents can provide evidence of anthropogenic effects on an aquatic system and of the potential risks related to the discharge of waste produced by humans (Zhang et al. 2014). Srikanth et al. (2013) and Lin et al. (2002) found that heavy metals may adsorb onto the surfaces of fine particles in sediment. The sand contents of our samples negatively correlated with the heavy metal contents, the PER values, and the mean particle sizes (Srikanth et al. 2013). From the correlations mentioned above, we concluded that the Cd, Cu, Ni, and Zn contents positively correlated with the sorting coefficients, skewness values, and kurtosis values. This suggested that the sorting coefficient, skewness value, and kurtosis value could be used to determine the degree of heavy metal contamination caused by anthropogenic activities.

Conclusions

The Cd, Cr, Cu, Ni, Pb, and Zn contents and spatial distributions, compositions, and particle size characteristics of sediment along a water transfer route were analyzed. The Cd, Cu, Ni, and Zn contents, sorting coefficients, skewness values, kurtosis values, EFs, and PER values were high in the Yangtze River, Wangyu River, and Gonghu Bay samples. These areas have relatively high water flows during water transfer periods. These results suggest that Cd, Cu, Ni, and Zn may cause adverse effects on aquatic ecosystems in Gonghu Bay during water transfer periods. The EFs for the sediment samples indicated that sediment in the study area is polluted to a significant degree with Cd. The PER values indicated that about 93 % of the sampling sites (20 sites) in Taihu Lake suffer only low levels of potential ecological risk from heavy metals in sediment but that all of the Wangyu River sites suffer high-to-serious levels of potential ecological risk. In particular, sediment at station GH-1 had a PER value of 250, indicating moderate potential ecological risk.

The statistical analyses led to the conclusions below.

- 1 The EFs and PER values indicated that Cd, Cu, Ni, and Zn toxicity is more serious in Wangyu River sediment than in Taihu Lake sediment but similar to sediment at the entrance of Gonghu Bay.
- 2 The relationship between particle migration and the heavy metal contents showed that Cd, Cu, Ni, and Zn have the same source and may currently be adsorbed to silt and clay particles in sediment.
- 3 Multivariate statistical analyses indicated that the high toxicity levels in the Wangyu River are likely to pose additional adverse health risks to aquatic ecosystems in Taihu Lake during water transfer periods.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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