Distribution, sources and ecological risk assessment of heavy metals in surface sediments from Lake Taihu, China

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Abstract
The distribution, sources and ecological risk of heavy metals in surface sediments from Lake Taihu were studied. Results showed that the measured heavy metals had varied spatial distribution patterns, indicating that they had complex origins and controlling factors. Pearson’s correlation analysis revealed that the total phosphorus and the loss on ignition were positively correlated with the measured metals except Cd. Principal component analysis and cluster analysis demonstrated that Hg, Cu, Cr, Cd and Pb might originate from domestic sewage and industrial wastewater, whereas As predominantly originated from natural processes. Potential ecological risk indices indicated that sediment from Wuli Lake, Gonghu Bay and the Northwest Area suffered high pollution, whereas other areas of Lake Taihu were moderately polluted. A comparison of metal levels with the effects range low (ERL) and effects range median (ERM) showed that metals exceeded their corresponding ERL limit at 13.6–72.3% (72.3% for As, 52.4% for Pb, 27.7% for Cu, 22.8% for Cd, 16.0 for Hg and 13.6% for Cr) of the sites investigated. Moreover, 3.90% and 0.50% of the sites sampled exceeded the ERM thresholds for Hg and Pb, respectively.

Keywords: heavy metals, ecological risk assessment, surface sediments, Lake Taihu, China

1. Introduction
Lake Taihu, which is the third-largest lake in China, is located at the junction of Shanghai City, Jiangsu Province and Zhejiang Province. The lake has a surface area of 2338 km² and a catchment area of 36,985 km². Although the area of the Taihu watershed only accounts for 0.4% of the land area of China, its population and GDP account for 3% and 10% of that of the entire nation, respectively, and its fiscal revenue accounts for more than 14% of that of the nation [1]. Lake Taihu is one of the main drinking water resources for the cities of Shanghai, Wuxi, Suzhou, Jiaxing and Huzhou. Specifically, the lake supplies 3.57 x 10⁷ t of drinking water per day to about 40 million people in the Taihu watershed. The lake also provides about 2 x 10⁴ t of fish and 8 x 10³ t of crab for human consumption each year and is used for irrigation and tourism purposes as well [1]. Therefore, Lake Taihu is of great significance to the social, economic and daily life of the local residents and the Taihu watershed.

Unfortunately, overpopulation, rapid urbanization, improper management of water resources, and point and non-point pollution in the watershed have all greatly affected the water quality of Lake Taihu [2]. Furthermore, large quantities of untreated wastewater from those plants and mills were directly discharged into rivers during past decades, and these ultimately entered the lake [2]. Many of these wastes were potential sources of heavy metal contamination that have the potential to threaten public health and impact the balance of the lake ecosystem. Therefore, it is crucial to have a detailed investigation and assessment of ecological risks of heavy metals in Lake Taihu.
Sediments are known to be the ultimate sinks for heavy metals discharged into the environment [3, 4]. Thus, the sediment could be a potential source of heavy metals that will be released into the overlying water via natural and anthropogenic processes [5, 6], where they could have an adverse effect on the drinking water quality and human health. Moreover, benthic biota or other organisms can ingest metal particles or contaminated water, which results in metals accumulating in their tissues and ultimately entering the food chain [7, 8]. Understanding the levels, distribution and sources of heavy metals in sediments can aid environmental managers and facilitate the supervision of lake water quality, which is always based on the appraisal of sediment quality by sediment quality guides (SQGs) [9]. Therefore, the objective of this study was to (1) characterize the heavy metal contents and distribution patterns; (2) to identify the possible sources of heavy metals; and (3) to assess the ecological significance of target metals in the study area by comparison with sediment quality guidelines (SQGs), thereby enabling ranking and prioritization of sites and metals of concern.

2. Materials and methods

2.1. The study area

Lake Taihu is usually divided into eight parts according to the morphography of the lake (figure 1). Zhushan Bay (ZB), Meiliang Bay (MB) and Wuli Lake (WL) are hypereutrophic areas that are mainly dominated by cyanobacteria from April to mid-November each year. Sediments of these areas have been reported to be heavily contaminated with total nitrogen (TN), total phosphorus (TP) and heavy metals [10]. Gonghu Bay (GB) is an important drinking water resource to the cities of Wuxi and Suzhou. Water in GB is often subject to odor problems due to excessive algae in the overlying water. This is especially true during summer, when algae tend to aggregate in the bay due to the action of wind. The Northwest Area (NA) contains many inlet rivers, most of which are polluted by chemical factories scattered in the river network of this area. Pollutants ultimately enter NA via these rivers, and macrophytes are seldom found in this area. East Lake Taihu (ELT) is a mesotrophic area, and more than 90% of this region is covered by submerged macrophytes [11]. Enclosures for crabs provide the main source of income for residents in this area. The East Area (EA) is similar to the ELT in that it is mostly covered with macrophytes. The Lake Center Area (LC) comprises a large part of Lake Taihu and contains Xishan Island in the northeast. This island has been developed for tourism for several decades, which has resulted in large quantities of vessels for fishery, as well as tourism and pollution in this area. Six trace metals (As, Hg, Pb, Cd, Cr and Cu) outlined as priority control pollutants by China’s 12th five-year plan were evaluated in the eight areas of Lake Taihu described above. Fe and Mn were also analyzed in order to give a better understanding of the relationships among these metals.

2.2. Sediment sampling

A core sampler equipped with Perspex tubes (8 cm inner diameter, 30 cm long) was used to collect surface sediments from 206 sites in Lake Taihu in August and September of 2007 (figure 1). The sediment cores were carefully extruded and the top 5 cm were sliced, after which they were placed in polyethylene bags and kept in a cooler on ice. The samples were then immediately transported to the laboratory and preserved under nitrogen at below 4°C. In addition, subsamples were freeze dried, disaggregated, passed through 0.063 mm mesh sieves and stored at 4°C in the dark before analysis.
2.3. Physicochemical property analysis

Grain size was determined using a Malvern automated laser optical particle size analyzer (Mastersizer-2000). In general, the sediment textures were divided into clay (<4 µm), silt (4–64 µm) and sand (>64 µm). The sediment redox potentials (Eh) were measured using an oxidation–reduction potential (ORP) Pt electrode after equilibrating the electrode for several minutes during sediment slicing (calibrating the electrode using quinhydrone solution before using). Final readings were corrected by adding the potential of a calomel reference electrode. The sediment pH was determined using a pH meter. The sediment water content was determined on the basis of the weight loss after drying at 105°C for 24 h. Loss on ignition (LOI) was determined by heating the dry sediment at 550°C for 4 h. The total nitrogen (TN) of the sediment was measured using a CN analyzer (CE-440), while the total phosphorus (TP) was analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES; Perkin-Elmer). The precisions of duplicate analyses of sediment TN and TP were all within 10%.

Total heavy metal analysis was conducted using the microwave-assisted acid digestion procedure with slight modification [12, 13]. In brief, about 0.1250 g dry sediment was weighted into PTFE digestion vessels, in which a mixture of concentrated 3 ml HNO3 and 4 ml HF were added, and these sealed vessels were heated to a temperature of 180°C for 20 min in a microwave digestion system (Berghof MWS-3 Digester). After cooling, these solutions were quantitatively transferred into PTFE beakers, and 0.5 ml of HClO4 added; the mixture was then heated to a temperature of 200°C and maintained there until some residues were left. We then add several milliliters of 1:1 HNO3 and 1:1 HCl to completely dissolve the residue and made a final 25 ml solution with Milli-Q water. The concentrations of Pb, Cd, Cu and Cr in the samples were then analyzed by ICP-AES. Inductively coupled plasma mass spectrometry (ICP-MS, Agilent-7500) was used to analyze samples for which metals were present in levels below the detection limit of ICP-AES. Cold vapor atomic fluorescence spectrometry (CV-AFS) was used to analyze the concentrations of sediment Hg and As. The reagent blanks were monitored throughout the analysis and were used to correct the analytical results. Two certified reference materials (GBW07309 for Pb, Cd, Cu, Cr and GBZ50013-88 for Hg and As) obtained from the General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China were used to control the detection quality of Pb, Cd, Cu, Cr, Hg and As. Differences between the certified and measured results were less than 10% for all metals evaluated in this study. The analytical precision (RSDs) was within 10% for all measured metals and the recoveries were good (91–103%).

2.4. Statistical analysis

Relationships among the variables considered were tested using Pearson’s correlation with statistical significance at p < 0.05 and p < 0.01. Principal components analysis (PCA) extracts eigenvalues and related loadings from the covariance matrix of original variables to produce new orthogonal variables, through varimax rotation, which are linear combinations of the original variables. The new orthogonal variables allow data reduction with minimum loss of original information, and provide information on the most meaningful parameters for the description of the whole data set. In our study, PCA was used to extract significant principal components and to further reduce the contribution of variables with minor significance; these PCs were subjected to varimax rotation generating original variables. The eigenvalues >1 were selected as the new orthogonal variables. Cluster analysis (CA) was further used to assess the relationships of sediment properties and heavy metal contents in surface sediments from Lake Taihu. All the statistical analyses were performed using SPSS 13.0 for Windows.

3. Results and discussion

3.1. General sediment properties

Many studies have revealed that sediment properties such as pH, Eh, grain size and nutrient values are well correlated with metal concentrations [14–16]. Figure 2 presents the mean, minimum and maximum major sediment properties from Lake Taihu and its eight parts. The results showed that silt (4–64 µm) was the main component of all sediment samples, being present at levels ranging from 51.9% to 89.9% and having a mean value of 70.5%. The NA had the highest mean silt content (74.3%) and the lowest mean sand content (20.5%). This was due to most of the sampling sites being located in the vicinity of the mouths of the inlet rivers of Lake Taihu. In contrast, samples collected from the mouth of Liangxi River in Wuli Lake had the lowest mean silt content (61.4%) and the highest mean sand content (25.8%). There was relatively static water movement and no rivers along the EA, which had the highest mean clay content (15.1%).

The water contents ranged from 41.1% to 80.9% for all of Lake Taihu, with WL having the highest mean values (68.1%) and NA having the lowest mean value (53.1%). The water content in sediments is partially determined by sediment texture. In general, when sediments have higher levels of silt they are more compact, which results in the water content being lower. In contrast, sand dominated sediments will have a higher water content [15]. This is evidenced in table 1, which shows that the water content was highly correlated with silt and sand. The sediment pH values ranged from slightly acidic to basic (5.85–8.64), with the sediments in MB, ZB and GB in Northern Lake Taihu being acidic. This was partially due to the decomposition of dead algal deposits, which results in the release of various organic acids [16]. Northern Lake Taihu has large quantities of algae in the surface water during July and August, most of which are deposited on the sediment after death. Sediment Eh values ranged from ~269.5 to 390.4 mV, indicating that sediments in Lake Taihu varied from strongly reducing to an oxidizing environment.

The distribution of LOI was similar to that of the TN contents, which all had high values in the sediments of Northern Lake Taihu (WL, ZB, MB, GB) and the ELT. The
northern areas of Lake Taihu have been reported to receive a large quantity of waste water and untreated domestic sewage from nearby cities and towns via inlet rivers [2, 10], which probably caused an elevation of TN and TP in the sediments. High LOI and TN values in the sediments of ELT probably resulted from the undecomposed plant debris in the area. It has been reported that over 90% of the ELT was covered by macrophytes [10]. The highly positive coefficient of correlation between LOI and TN (0.85) indicated that the nitrogen primarily came from organic matter and was likely present in organic form. Similar to the TN case, high sediment TP values were also observed in Northern Lake Taihu, indicating that they had the same possible source. Furthermore, a significant positive correlation was also observed between TN and TP in table 1. Unlike the TN case, the sediment mean TP contents in the ELT were relatively low (0.47 g kg$^{-1}$). Biological uptake of phosphate by a dense population of macrophytes may account for the lower $p$-concentration in this area.

3.2. Levels of heavy metals and their spatial distribution

Table 2 lists the mean, minimum and maximum concentrations of heavy metals in the surface sediments from Lake Taihu and the eight studied areas. The measured metal concentrations varied greatly as follows: As, 1.96–65.5 mg kg$^{-1}$; Hg, 0.01–1.22 mg kg$^{-1}$; Cr, 7.33–229 mg kg$^{-1}$; Pb, 1.66–277 mg kg$^{-1}$; Cd, 0.05–3.61 mg kg$^{-1}$; Cu, 9.01–211 mg kg$^{-1}$; Fe, 11.2–96.6 mg g$^{-1}$; Mn, 0.22–2.50 mg g$^{-1}$. The mean concentrations of As, Hg, Cr, Pb, Cd and Cu in surface sediment from Lake Taihu were found to be 1.43, 1.00, 0.71, 3.30, 3.48 and 1.94 times greater, respectively, than the background values in Lake Taihu Basin (table 2). These findings indicate that surface sediments from Lake Taihu have suffered from mild to serious anthropogenic effects. A comparison of the present data with those for other lakes from China and the world is shown in table 3. The results showed that the maximum metal concentrations of As, Hg, Pb, Cu and Cr were all higher than for other lakes [18–25], whereas the Cd concentrations in Lake Taihu were lower than those in Lake Dianchi and Lake Manchar [18–25].

A contour map for the eight measured heavy metals is presented in figure 3. The varied distribution patterns of the measured metals suggests that the sediment metals had a complex origin and were regulated by multiple factors. A relatively high As concentration was found in WL and ZB, which had mean values of 21.0 mg kg$^{-1}$ and 21.9 mg kg$^{-1}$, respectively (table 2 and figure 3). Sediments in the vicinity of the river mouths contained high levels of As (figure 3); this was obviously caused by anthropogenic effects. Conversely, the other studied area had similar As levels. The highest concentrations of Cr and Cu were found in the vicinity of river mouths in GB. The mean values of Cr and Cu were also higher than in other studied areas, being 95.6 mg kg$^{-1}$ and 53.2 mg kg$^{-1}$, respectively. It has been reported that large
quantities of untreated industrial wastewater were discharged into GB via inlet rivers during the past few decades [2, 10]. Surprisingly, the highest concentrations of Hg and Pb were observed in the LC. This was contrary to our previous assumption that high concentrations of heavy metals were always present in river inlets. Long transportation of metal loaded particles or vehicular accidents may be the cause of this abnormal increase. The highest concentration of Cd was found in the mouth of the Dapu River in NA. This was similar to the findings of an earlier study that revealed a high Cd concentration in this region [17]. The high concentration of Cd was probably due to effluents of nonferrous metal processing or municipal sewage discharges. Additionally, long-term application of agrochemicals or fertilizers containing P plays an important role in their distribution [15, 16]. However, no correlation between LOI and Hg or Cd was observed. These findings suggest that the two metals were not bound to organic matter. A spectroscopic study showed that mercury mainly occurred as a sulfide phase in anoxic freshwater lake sediments even in oxic environments [26]. Han et al also found that mercury tended to associate with FeS (mackinawite) in ferric rich anoxic estuarine sediment slurries [27]. Therefore, this may be occurring in the sediment of Lake Taihu. Cd in the sediment in Lake Taihu generally binds with sulfide or manganese oxide during summer (July and August). Indeed, Yin et al found that more than 70% of the Cd could be extracted from sediment using dilute HCl [28], which indicated that Cd was probably bound with Fe–Mn oxide (hydroxide) or sulfide. Moreover, a significant coefficient of correlation between Mn and Cd was observed (r = 0.15, p < 0.01).

Similar to the LOI case, sediment TP was also positively correlated with As and Hg, as well as Cr and Cu. Sediment TP and heavy metal contents were all present in high concentrations in Northern Lake Taihu (WL, ZB, MB and GB), which suggested that they were derived from industrial effluents or municipal sewage discharges. Additionally, long-term application of agrochemicals or fertilizers containing P

Table 1. Pearson’s correlation matrix for the measured variables: (a) sediment properties, (b) sediment metal concentrations, (c) sediment properties and metal concentrations.

(a) Variable n pH Eh Water LOI TP TN Clay Slit Sand
pH 206 1.00 0.07 −0.13 −0.21a −0.27a −0.04 −0.27a 0.33a −0.24a
Eh 206 1.00 0.46a −0.49a −0.21a −0.53a −0.25a 0.34a −0.26a
Water 206 1.00 0.60a 0.13 0.67a 0.49a −0.41a 0.19b
LOI 206 1.00 0.58a 0.80a 0.31a −0.39a 0.29a
TP 206 1.00 0.32a 0.14 −0.31a 0.30a
TN 206 1.00 0.30a −0.28a 0.15b
Clay 206 1.00 −0.63a 0.12
Slit 206 1.00 −0.84a
Sand 206 1.00

(b) Metal n As Hg Cr Pb Cd Cu Fe Mn
As 206 1.00 0.18b 0.19b 0.04 −0.09 0.32a 0.16b 0.27a
Hg 206 1.00 0.20a 0.23a −0.11 0.21a 0.02 −0.08
Cr 206 1.00 0.22a 0.01 0.53a −0.09 −0.15b
Pb 206 1.00 0.18b 0.15b −0.19b −0.24a
Cd 206 1.00 −0.02 −0.12 0.15a
Cu 206 1.00 0.13b 0.02
Fe 206 1.00 0.16b
Mn 206 1.00

(c) Metal n pH Eh Water LOI TP TN Clay Slit Sand
As 206 −0.13 0.07 0.04 0.15b 0.32a 0.13 0.17b −0.08 −0.02
Hg 206 −0.26a −0.10 0.07 0.09 0.23a 0.03 0.07 −0.08 0.05
Cr 206 −0.20a −0.26a 0.32a 0.43a 0.45a 0.30a 0.23a −0.31a 0.24a
Pb 206 0.03 −0.13 0.21a 0.20a 0.14 0.12 0.16b −0.19a 0.14
Cd 206 0.24a 0.13 −0.17b −0.13 −0.05 −0.18b −0.19b 0.14 −0.05
Cu 206 −0.29a −0.16b 0.18b 0.49b 0.73a 0.28a 0.16b −0.29b 0.26a
Fe 206 −0.25a −0.10 −0.19b 0.00 0.25a −0.14 0.12 −0.18b 0.15b
Mn 206 0.18b 0.26a −0.39a −0.20a 0.11 −0.17b −0.28a 0.27b −0.15b

a Level of significance: p < 0.01. b Level of significance: p < 0.05.
Table 2. Level of heavy metals in surface sediment for the whole of Lake Taihu and each studied area.

| Region | As a | Hg b | Cr c | Pb c | Cd c | Cu c | Fe b | Mn b |
|--------|------|------|------|------|------|------|------|------|
| WL     | Min. | 8.06 | 0.06 | 35.3 | 35.7 | 0.54 | 35.2 | 23.1 | 0.37 |
| n = 5  | Max. | 35.6 | 0.34 | 143  | 153  | 1.55 | 126  | 66.6 | 1.35 |
|        | Mean | 21.0 | 0.16 | 75.1 | 74.9 | 0.95 | 91.2 | 43.8 | 0.84 |
|        | CV   | 0.55 | 0.14 | 0.55 | 0.65 | 0.16 | 0.16 | 0.41 | 0.51 |
| MB     | Min. | 4.67 | 0.02 | 22.4 | 20.4 | 0.32 | 15.1 | 20.3 | 0.36 |
| n = 22 | Max. | 29.3 | 0.90 | 138  | 101  | 1.45 | 137  | 91.0 | 1.39 |
|        | Mean | 12.5 | 0.12 | 70.6 | 44.0 | 0.66 | 49.1 | 45.8 | 0.83 |
|        | CV   | 0.31 | 0.31 | 0.41 | 0.48 | 0.18 | 0.67 | 0.35 | 0.41 |
| ZB     | Min. | 4.58 | 0.01 | 11.9 | 25.9 | 0.05 | 16.7 | 16.1 | 0.38 |
| n = 17 | Max. | 65.5 | 0.88 | 203  | 64.8 | 1.2 | 140  | 73.1 | 2.09 |
|        | Mean | 21.9 | 0.16 | 77.5 | 44.3 | 0.49 | 49.7 | 44.8 | 1.28 |
|        | CV   | 0.86 | 0.12 | 0.69 | 0.23 | 0.19 | 0.73 | 0.46 | 0.41 |
| GB     | Min. | 5.76 | 0.02 | 22.4 | 20.4 | 0.32 | 15.1 | 20.3 | 0.36 |
| n = 18 | Max. | 42.1 | 1.20 | 229  | 88.8 | 1.58 | 211  | 54.1 | 0.65 |
|        | Mean | 15.2 | 0.33 | 95.6 | 75.1 | 0.95 | 91.2 | 43.8 | 0.84 |
|        | CV   | 0.70 | 0.27 | 0.41 | 0.48 | 0.16 | 0.41 | 0.35 | 0.41 |
| ELT    | Min. | 4.67 | 0.02 | 22.4 | 20.4 | 0.32 | 15.1 | 20.3 | 0.36 |
| n = 14 | Max. | 12.5 | 0.14 | 113  | 75.6 | 1.31 | 43.9 | 58.5 | 0.80 |
|        | Mean | 7.13 | 0.03 | 53.4 | 54.0 | 0.97 | 31.3 | 34.5 | 0.51 |
|        | CV   | 0.38 | 0.20 | 0.38 | 0.27 | 0.11 | 0.18 | 0.49 | 0.24 |
| EA     | Min. | 7.40 | 0.01 | 7.33 | 29.6 | 0.29 | 17.5 | 23.4 | 0.22 |
| n = 10 | Max. | 31.2 | 0.09 | 70.2 | 142  | 1.18 | 50.1 | 211  | 0.59 |
|        | Mean | 16.0 | 0.05 | 40.8 | 64.4 | 0.86 | 35.1 | 50.4 | 0.48 |
|        | CV   | 0.42 | 0.12 | 0.57 | 0.52 | 0.1  | 0.26 | 0.44 | 0.23 |
| NA     | Min. | 4.66 | 0.01 | 17.9 | 20.4 | 0.33 | 11.5 | 12.6 | 0.43 |
| n = 69 | Max. | 40.6 | 1.11 | 92.9 | 83.6 | 3.61 | 48.9 | 96.5 | 2.15 |
|        | Mean | 12.7 | 0.05 | 44.7 | 48.9 | 1.28 | 28.4 | 38.9 | 0.99 |
|        | CV   | 0.60 | 0.53 | 0.28 | 0.33 | 0.15 | 0.25 | 0.46 | 0.35 |
| LC     | Min. | 1.96 | 0.01 | 8.75 | 17.2 | 0.30 | 9.01 | 13.4 | 0.23 |
| n = 51 | Max. | 27.8 | 1.22 | 82.2 | 277  | 1.84 | 46.1 | 72.6 | 2.50 |
|        | Mean | 12.2 | 0.13 | 46.9 | 55.2 | 0.79 | 29.3 | 37.7 | 0.63 |
|        | CV   | 0.50 | 1.75 | 0.34 | 0.62 | 0.13 | 0.23 | 0.35 | 0.59 |
| Total  | Min. | 1.96 | 0.01 | 7.33 | 1.66 | 0.05 | 9.01 | 11.2 | 0.22 |
| n = 206| Max. | 65.5 | 1.22 | 229  | 277  | 3.61 | 211  | 96.6 | 2.50 |
|        | Mean | 13.5 | 0.11 | 56.2 | 51.8 | 0.94 | 36.7 | 39.5 | 0.79 |
|        | CV   | 0.68 | 1.90 | 0.54 | 0.47 | 0.54 | 0.73 | 0.42 | 0.53 |
| Background c | 9.4 | 0.11 | 79.3 | 15.7 | 0.27 | 18.9 | 36.7 | 0.51 |
| ERL d | 8.2 | 0.15 | 51.0 | 46.7 | 1.2 | 34.0 | — | — |
| ERM d | 70.0 | 0.71 | 370.0 | 218.0 | 9.6 | 270.0 | — | — |

a mg kg\(^{-1}\) dry weight. b mg g\(^{-1}\) dry weight. c Reference [10]. d ERL: effects range low; ERM: effects range median.

may have led to an increase in P contents as well as heavy metal accumulation in the surface sediment from Lake Taihu. Zhang et al reported that there was high P runoff from paddy soil in the Taihu region [29]. Therefore, the associated heavy metals may have entered Lake Taihu simultaneously with P.

A significant correlation was observed between As and Hg, As and Cr, Pb and Cd, and Pb and Cu at the 0.05 level. In addition, a highly positive correlation was observed between As and Cu, Hg and Cr, Hg and Pb, Cu and Cr, and Cu and Cr at the 0.05 level. Finally, no statistically significant correlation was observed between As and Pb, As and Cd, Hg and Cd, Cr and Cd, or Cu and Cd. These findings suggest that metals from Lake Taihu have complicated contamination sources or controlling factors.

Principal component analysis (PCA) was conducted on the main sediment properties and the measured heavy metals to better understand the relationship among these variables and identify their origins. As shown in table 4, the first five principal components with eigenvalues greater than 1 accounted for 77.40% of the total variance. Therefore, these five components play an important role in explaining contamination with heavy metals and their source in the studied area. The results demonstrated that the first principal components (PC1) accounted for 30.21% of the total variance and had high loadings of LOI, TP, Cu, TN and Cr. Cu and Cr are primarily derived from painting industries, metal industries and machinery processing [10]. The close relationship between Cu, Cr and nutrients (TP and TN) suggested that Cu and Cr also came from municipal wastewater and sewage. The second PC (PC2) accounted for 14.68% of the total variance, with positive loading on As and Mn. Mn is known to originate from natural sources of weathering of parent mineral and subsequent pedogenesis [30]. Therefore, the close relationship between As and Mn indicates that As predominantly originates from natural sources of weathering of parent mineral and subsequent pedogenesis [30]. These findings also indicated that As was likely bound to Mn oxide (hydroxide) [30]. The third PC (PC3) accounted for 11.94% of the total variance, with high loadings of Hg and Pb, and
moderate loadings of As. Hg and Pb concentrations are largely influenced by the pesticide and battery industries and fuel combustion [10, 15]. The moderate loading of As suggested that, in addition to natural sources, pesticide usage or fuel combustion were contributing to the As in the studied area. The fourth and fifth PCs accounted for 10.81% and 9.76% of the total variance, respectively, and were mainly loaded with Fe, Cd and Pb, respectively. Fe is a key component of the
Table 4. Total variance explained and component matrices for sediment properties and metal concentrations (principal component analysis with varimax rotation).

| Component | Total eigenvalues | Rotation sums of squared loadings |
|-----------|------------------|----------------------------------|
|           |                  | Initial eigenvalues |        | Cumulative % | Total % of variance | Cumulative % | Total % of variance | Cumulative % |
| 1         | 3.50             | 30.21                | 30.21  | 3.50         | 30.21                | 30.21        | 3.50         | 30.21        |
| 2         | 1.64             | 14.68                | 44.89  | 1.64         | 14.68                | 44.89        | 1.64         | 14.68        |
| 3         | 1.31             | 11.94                | 56.83  | 1.31         | 11.94                | 56.83        | 1.31         | 11.94        |
| 4         | 1.18             | 10.81                | 67.64  | 1.18         | 10.81                | 67.64        | 1.18         | 10.81        |
| 5         | 0.76             | 6.31                 | 82.71  | 0.76         | 6.31                 | 82.71        | 0.76         | 6.31         |
| 6         | 0.72             | 5.00                 | 87.71  | 0.72         | 5.00                 | 87.71        | 0.72         | 5.00         |
| 7         | 0.55             | 3.56                 | 91.27  | 0.55         | 3.56                 | 91.27        | 0.55         | 3.56         |
| 8         | 0.47             | 2.91                 | 94.18  | 0.47         | 2.91                 | 94.18        | 0.47         | 2.91         |
| 9         | 0.44             | 2.70                 | 96.88  | 0.44         | 2.70                 | 96.88        | 0.44         | 2.70         |
| 10        | 0.24             | 2.04                 | 98.92  | 0.24         | 2.04                 | 98.92        | 0.24         | 2.04         |
| 11        | 0.13             | 1.07                 | 100.00 | 0.13         | 1.07                 | 100.00       | 0.13         | 1.07         |

| Component | Variables | 1 | 2 | 3 | 4 | 5 | Communalities |
|-----------|-----------|---|---|---|---|---|---------------|
| LOI       | 0.88      | −0.17 | −0.09 | −0.12 | −0.15 | 0.85 |
| TP        | 0.77      | 0.23 | 0.19 | 0.32 | 0.05 | 0.79 |
| Cu        | 0.74      | 0.20 | 0.25 | 0.20 | 0.12 | 0.71 |
| TN        | 0.74      | −0.15 | −0.18 | −0.36 | −0.29 | 0.81 |
| Cr        | 0.65      | −0.08 | 0.27 | −0.01 | 0.17 | 0.53 |
| Silt      | −0.49     | 0.44 | −0.07 | −0.37 | 0.10 | 0.59 |
| Mn        | −0.08     | 0.82 | −0.14 | 0.15 | 0.12 | 0.74 |
| As        | 0.32      | 0.59 | 0.48 | −0.09 | −0.15 | 0.62 |
| Hg        | 0.07      | −0.01 | 0.86 | 0.01 | −0.12 | 0.76 |
| Pb        | 0.22      | −0.40 | 0.58 | −0.10 | 0.46 | 0.64 |
| Fe        | 0.03      | 0.06 | −0.05 | 0.89 | −0.11 | 0.82 |
| Cd        | −0.05     | 0.09 | −0.14 | −0.09 | 0.89 | 0.84 |

Earth’s crust. High loading with Cd indicated that Cd was a primary pollutant. Cd is primarily derived from nonferrous metal smelting, electroplating and stabilizers and additives used in the manufacture of synthetic rubber [10]. Pb loaded in PC3 and PC5 simultaneously, suggesting that Pb had mixed contamination origins resulting from anthropogenic activities.

The dendrogram obtained from R-model cluster analysis (CA) is presented in figure 4. Distance metrics were based on the Euclidean distance single-linkage method (furthest neighbor). In the present study, LOI, TN, TP, Cu and Cr were grouped into one cluster. These findings further demonstrated the close relationship between these variables and Cu and Cr derived from the same origin. It was also seen that Hg and Pb were associated and that the two metals were grouped into the Hg, Pb and As cluster. Cd was closely associated with Mn, implying that it was partially associated with Mn oxide. As discussed above, the results from correlation analysis, principal component analysis and cluster analysis were fairly consistent.

3.4. Sediment quality assessment and its ecological significance

Overaccumulation of heavy metals in sediment will pose a potential ecological risk to freshwater ecosystems [7, 15]. Therefore, a potential ecological risk index (RI) was used to assess the degree of heavy metal contamination in surface sediments from Lake Taihu; it was originally suggested by Hakanson [31]. The calculated mathematical formula for RI is expressed as

\[
RI = \sum_{i=1}^{n} E_i
\]

\[
E_i = T_i \frac{C_i}{C_0}
\]
where $E_i$ is the monomial potential ecological risk factor for a given substance; $T_i$ represents the metal toxic factor of a certain metal (e.g., $Hg = 40$, $Cd = 30$, $As = 10$, $Cu = Pb = 5$, $Cr = 2$); $C_i$ is the metal content in the sediments and $C_0$ represents the regional background value of heavy metals in the sediments. The RI values for the surface sediments from Lake Taihu and each studied area are presented in table 5 and figure 3. The sediment RI values varied for each studied area from 41.5 to 655 and had a mean value of 188. These results indicate that surface sediments in Lake Taihu posed a low to high potential ecological risk. Among the eight studied areas, WL, GB, and NA suffered the most serious pollution, which posed a high contamination ecological risk, whereas all other areas had a moderate degree of pollution according to the mean RI values (table 5 and figure 3). Among the six studied heavy metals, Hg and Cd presented higher ecological risks than any other metals because of the higher toxicity coefficient, despite the lower concentrations of the two heavy metals. Among the 206 sampling sites, the $E_i$ of Cd and Hg was larger than 80 in 59% and 30% of the total sampling sites respectively. The other heavy metals had a lower potential ecological risk. Overall, these findings indicate that Cd is the largest ecological risk contributor, while Hg is the second-largest contributor; therefore, these metals should be given special consideration.

The established empirical sediment quality guidelines (SQGs) are often used to assess sediment quality worldwide [10, 16, 30]. Among these, the effects range low (ERL) and effects range moderate (ERM) developed by the United States Environmental Pollution Agency (US EPA) have been widely applied and found to be effective predictive tools [10, 16, 30]. The ERL is the tenth percentile of the effects database, below which harmful effects on aquatic biota are rarely observed. The ERM represents the fiftieth percentile of the effects data and is indicative of concentrations above which harmful effects are often observed [32]. The ERL and ERM are not toxicity thresholds; rather, they estimate safe concentrations, below which toxicity is least likely [32].

As listed in table 6, most sites (72.4%) had As concentrations in excess of the ERL limit. This was especially true in ZB, where the As value exceeded the ERL threshold at 90% of the studied sites. This increases the incidence of adverse biological effects by 11% [32]. However, none of the sampling sites exceeded the ERM criterion for As. More than 50% of the investigated sites had Pb concentrations exceeding the ERL threshold, with the incidence of effects increasing to 90.2% [32]. More than 50% of the investigated sites in WL, GB, LC, NA, and EA exceeded the ERL threshold for Pb, indicating that special consideration should be given to these areas. However, only 0.50% of the studied sites had Pb concentrations that exceeded the ERM limit, and these were all located in LC. Moreover, 13.6% and 27.7% of the studied sites exceeded the ERL limit for Cr and Cu, respectively, while none of the sampling sites exceeded the ERM limit for Cr and Cu. Cd exceeded the ERL threshold at 27.7% of the sites, with an increase in the incidence of effects to 36.6% being observed. However, none of the investigated sites exceeded the ERM criterion for Cd. There was also a relatively low percentage of sites (16.0%) that exceeded the ERL limit for Hg, whereas a high percentage of sites (3.90%) exceeded the ERM criterion. These findings indicate that the incidence of effects

| Region | As  | Hg  | Cr  | Pb  | Cd  | Cu  | RI | Pollution degree |
|--------|-----|-----|-----|-----|-----|-----|----|-----------------|
| WL     | Min | 8.57| 20.6| 0.89| 11.4| 59.7| 9.31| 119             |
|        | Max | 37.9| 124 | 3.62| 48.7| 172 | 33.3| 355             |
|        | Mean| 22.3| 57.0| 1.89| 23.9| 106 | 24.1| 235             |
| MB     | Min | 4.97| 8.15| 0.57| 6.50| 35.9| 4.00| 71.5            |
|        | Max | 31.2| 327 | 3.49| 32.0| 161 | 36.3| 477             |
|        | Mean| 13.3| 45.0| 1.78| 14.0| 73.0| 13.0| 160             |
| ZB     | Min | 4.87| 2.86| 0.30| 8.26| 5.67| 4.42| 23.4            |
|        | Max | 69.7| 319 | 5.11| 20.6| 133 | 37.1| 426             |
|        | Mean| 23.3| 58.7| 1.95| 14.1| 54.7| 13.1| 156             |
| GB     | Min | 6.13| 8.07| 0.71| 9.82| 29.9| 3.24| 85.9             |
|        | Max | 44.8| 436 | 5.78| 28.3| 175 | 55.8| 656             |
|        | Mean| 16.1| 121 | 2.41| 18.2| 94.9| 14.1| 267             |
| ELT    | Min | 3.10| 1.70| 0.71| 9.11| 40.4| 6.24| 86.7            |
|        | Max | 13.0| 50.0| 2.84| 24.1| 146 | 11.6| 222             |
|        | Mean| 7.58| 11.6| 1.35| 17.2| 107 | 8.28| 153             |
| EA     | Min | 7.87| 2.23| 0.18| 9.43| 32.2| 4.63| 82.2            |
|        | Max | 33.2| 33.2| 1.77| 45.3| 131 | 13.3| 198             |
|        | Mean| 17.1| 16.7| 1.03| 20.5| 95.1| 9.28| 160             |
| NA     | Min | 4.96| 2.39| 0.45| 6.49| 37.2| 3.05| 92.6            |
|        | Max | 43.2| 404 | 2.34| 26.6| 401 | 12.9| 535             |
|        | Mean| 13.6| 19.3| 1.13| 15.6| 143 | 7.50| 200             |
| LC     | Min | 2.09| 1.59| 0.22| 5.48| 33.7| 2.38| 80.7            |
|        | Max | 29.6| 444 | 2.10| 88.2| 304 | 12.2| 556             |
|        | Mean| 13.0| 47.6| 1.20| 17.6| 87.7| 7.70| 175             |
| Total  | Min | 2.09| 1.59| 0.18| 0.53| 5.67| 2.38| 41.5            |
|        | Max | 69.7| 444 | 5.78| 88.2| 401 | 55.8| 656             |
|        | Mean| 14.3| 41.4| 1.42| 16.5| 104 | 9.71| 188             |
increased to 42.3% [32]. Higher concentrations of measured metals were observed in GB, ZB, LC and NA, indicating that these sites should be given priority for further investigation and management decisions.

4. Conclusions

The results obtained from the analysis of 206 surface sediment samples indicated that the metal concentrations in Lake Taihu varied greatly. The mean contents of these metals were 0.71 to 3.48 times the background values, indicating that metal in Lake Taihu suffered from different anthropogenic effects. Sediment LOI was a more important factor than other sediment properties for controlling the metal distribution in Lake Taihu. A significant correlation between TP and trace metals was observed, indicating that, in addition to municipal sewage, long-term application of P containing agrochemicals or fertilizers may also lead to an increase in P contents as well as the accumulation of heavy metals in the surface sediment of Lake Taihu. Principal component analysis (PCA) and cluster analysis (CA) revealed that Hg, Cu, Cr, Cd and Pb might originate from domestic sewage and industrial wastewater, whereas As predominantly originated from natural processes. The sediment RI values suggested that WL, GB and NA were seriously contaminated with heavy metals, whereas the other five studied areas showed moderate pollution. The sediment quality was again evaluated on the basis of the effects range low (ERL) and effects range median (ERM). The results showed that metals exceeded their corresponding ERL limits at 13.6–72.3% (72.3% for As, 52.4% for Pb, 27.7% for Cu, 22.8% for Cd, 16.0 for Hg and 13.6% for Cr) of the sites investigated. Moreover, 3.90% and 0.50% of the sites exceeded the ERM thresholds for Hg and Pb, respectively. This research will be of great importance to management decisions.

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