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Distribution and Pollution Evaluation of Nutrients, Organic Matter and Heavy Metals in Surface Sediments of Wanghu Lake in the Middle Reaches of the Yangtze River, China

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Abstract: Nutrients, organic matter (OM), and heavy metals (HMs) in lake sediments are critical elements contributing to water pollution. In April 2019, surface sediments from Wanghu Lake were collected, and the nutrient, organic matter, and heavy metal content of the sediments were determined. We mainly evaluated the sediment pollutants through four evaluation methods to assess pollution and provide a reference for pollution control in Wanghu Lake. The results indicated that the averages of total phosphorus (TP) and total nitrogen (TN) were (1045.74 ± 190.17) mg/kg, (945.27 ± 203.56) mg/kg; most of them showed serious pollution and moderate pollution, respectively. OM was (32.31 ± 5.11) g/kg. Among them, TP and OM in the northwestern Wanghu Lake were significantly higher than those in the eastern lake ($p < 0.05$). It shows that nutrients are greatly affected by historical aquaculture and urban human activities. TP was the most serious in the center of the lake, and the source of pollution was mainly the historical deposition. The average of Cd, Cr, Cu, Ni, Pb, Zn, Hg, and As in the sediments were 2.15, 1.09, 1.93, 1.37, 1.28, 1.49, 2.60, 1.77 times that of the soil background values of Hubei Province, respectively. Hg and Cd were the main factors contributing to the surface sediments, with levels at considerable and moderate risks, respectively.

Keywords: surface sediments; nutrients; organic matter; heavy metals; pollution evaluation

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1. Introduction

Sediment is an important component of lake ecosystems. It can provide a living environment for aquatic macrophytes, benthic animals, and other organisms in the lake and is also the carrier and destination of pollutants in the aquatic ecosystem environment [1,2]. Sediments receive sands and pollution inflow from atmospheric deposition, surface runoff, and soil erosion in the basin, thus sediment is the "sink" of lake pollution [3]. Nevertheless, when the environmental conditions (temperature, dissolved oxygen (DO), and pH) change, nutrients and organic matter (OM) in sediments are released into overlying water by the ways of decomposition, diffusion, and resuspension, causing secondary pollution [4,5]. Heavy metals (HMs) can also be released into the overlying water through interstitial water by changing the speciation of heavy metals, dissolution, and concentration diffusion [6–8]. Therefore, the surface sediments of lakes are both the "source" and "sink" of nutrients and pollution [9]. Urbanization and industrialization have aggravated lake pollution. The discharge of domestic sewage has increased the sources of nitrogen (N) and phosphorus

(P) in sediments, and fence breeding aggravates P pollution [10]. While industrial and agricultural production produce N, P, and OM pollution, HMs also accumulate in sediments, which is arguably a more serious issue, making the ecological environment more fragile [11].

Endogenous pollution caused by the release of N, P, and OM is a critical factor in lake eutrophication, and sediments are a useful way to study this [12]. The HMs pollution in sediments will endanger the health of humans and aquatic organisms [13,14]. The eastern part of Meixi Lake in Changsha City was severely polluted with nutrients and OM closely related to N and P pollution [15]. TP pollution in the surface sediments of Longyang and Moshui Lake in Wuhan was more severe than that of TN, and Cd pollution was also a problem. In the sediments of Nansi Lake, the proportion of Cd pollution in RI was up to 76% [16]. Lakes such as Ulansuhai Nur, Dongting, Gehu, and Luoma Lake was affected by agricultural nonpoint source pollution to varying degrees, and the contents of TP, TN, Cd, As, and Hg were relatively high [17–19]. In recent decades, N, P, and OM in lakes have increased to varying degrees, and the level of OM pollution has increased [20]. The content of HMs in lots of lakes in China are more than the background values of soil, and there is a serious ecological risk [20]. Currently, methods used to evaluate nutrient pollution are those such as the comprehensive pollution index and organic index [1,12,21], whereas HMs were evaluated by the potential ecological risk (RI), geo-accumulation (Igeo), Nemero comprehensive, and pollution load index [14,22,23]. In addition, correlation, factor, and hierarchical cluster analyses have been recommended to analyze pollution sources [1,15,19]. As an internationally important habitat for migratory birds, many birds feed and reproduce in Wanghu Lake annually. Therefore, sediment pollution of the lake not only affects water quality, but also affects the habitat and reproduction of migratory birds. At present, due to the rapid development of agriculture, aquaculture, and urbanization, the diffuse pollution in Wanghu Lake basin has increased. It caused eutrophication of Wanghu Lake, and it also destroyed the ecological environment. In the past, most of the studies on Wanghu Lake basin focused on the evaluation of the water quality or nutrient occurrence and pollution assessment within the lake basin [10,24]. In the evaluation of sediment pollution, most of the analysis and evaluation were carried out from the perspective of the release fluxes of N and P pollution in sediments at different depths [25]. For heavy metals in sediments, a single evaluation method was used to evaluate the vertical distribution characteristics, source analysis, and risk of heavy metals in sediments [11]. In this study, a variety of analytical methods was used to study the nutrients, organic matter, and heavy metals in surface sediments through a number of indicators in order to carry out a comprehensive understanding of the surface sediment pollution of the lake.

An aim of this study is to explore the distribution and pollution evaluation of nutrients, organic matter, and heavy metals in the surface sediments of Wanghu Lake. Simultaneous determination of TN, TP, OM, and eight heavy metals elements was conducted. The comprehensive pollution index and organic index method were used to evaluate the nutrients and OM of the sediments. Additionally, RI and Igeo were used to evaluate the distribution characteristics and hazard risks of the corresponding eight heavy metals in the lake basin. We proposed three hypotheses: (1) Due to the fact that the northwest was close to the Wanghu Lake aquaculture area and human accumulation areas, TN and OM pollution caused by aquaculture and human activities over here may were higher than other areas. (2) Whereas the central lake has a relatively stable sedimentary environment, nutrients, organic matter and heavy metal pollution are easy to accumulate here, consequently, pollutions were easy to accumulate here. (3) The northeast of Wanghu Lake is the port channel connecting the Yangtze River; the water has a strong exchange capacity over there. The pollution was difficult to deposit here, so the pollution degree was light. This study provides targeted measures and schemes for pollution identification, control, and ecological restoration in specific areas of lake.

2. Materials and Methods

2.1. Study Area

Wanghu Lake (115°14′00″–115°25′42″ E, 29°45′11″–29°56′38″ N) is located in Yangxin County (114°43′–115°30′ E, 29°30′–30°09′ N), Huangshi City, Hubei Province (Figure 1). It is adjacent to the Yangtze River in the east, Fushui River in the south, and Xingguo Town, north is adjacent to Taogang Town and Banbishan Management Area [10]. Wanghu Lake is connected to the densely populated Yangxin County through the Lianhua Lake Group. Saiqiao Lake district and Xiasi Lake in the northwest of Wanghu Lake are the main sites of the state-owned aquaculture in Yangxin. Lianhua Lake district, including Zhulintang, Daquan Lake, and Shihuisai Lake are located in the west of Wanghu Lake, which is the pearl breeding area for surrounding farmers. Wanghu Lake is in a subtropical monsoon climate with a humid climate and abundant precipitation. The average annual temperature of Yangxin Station is 16.3~17.6 °C, and the annual average precipitation is between 883.5~1888.9 mm [26]. Wanghu Lake is a part of the Fushui river system and receives abundant precipitation. Atmospheric precipitation and surface runoff are the main sources of lake recharge. The basin area is wide, the water area is about 33.2 km^2, the average elevation of water in Wanghu Lake is 15.5 m, and the average depth is 3.51 m [24,25]. In 2018, the Wanghu Wetland Nature Reserve was included in the "International Important Wetland List", with a total protected area of 204.95 km^2 [11].

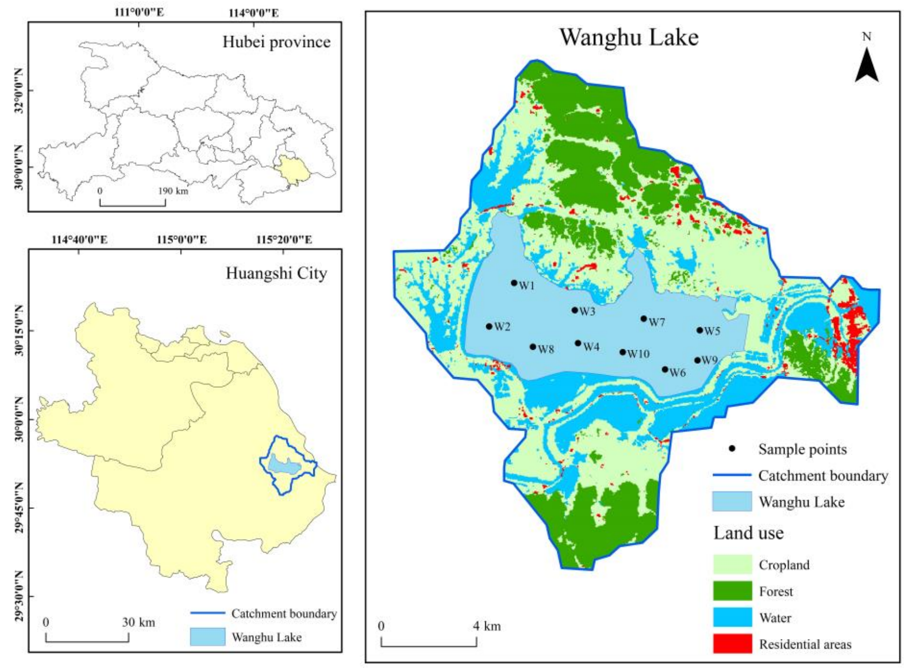


Figure 1. Map of Study area.

2.2. Sample and Determination Methods

On 11 April 2019, considering the morphological characteristics of Wanghu Lake and the surrounding land use, 10 sample points were evenly selected (Table 1). At each point, approximately 1500 g of surface sediment (0–10 cm) was collected three times using the Peter mud snapper and placed in a clean, dry, sealed bag, separately. After transporting the samples back to the laboratory, the samples were mixed and weighed. A total of 200 g of sediment was dried in an oven until reaching a constant weight. Next, impurities were removed, then the sediment was ground to fine particles and passed through an 80-mesh sieve for the determination of TP, TN, OM, and HMs (Table 2) [11,27,28].

Table 1. Surface sediment sampling sites.

Point	Location
W1	115.306293° E, 29.882947° N
W2	115.268325° E, 29.875496° N
W3	115.323389° E, 29.870880° N
W4	115.294078° E, 29.921601° N
W5	115.383743° E, 29.880354° N
W6	115.341942° E, 29.850387° N
W7	115.355005° E, 29.871430° N
W8	115.306719° E, 29.858454° N
W9	115.374597° E, 29.852024° N
W10	115.335075° E, 29.853131° N

Table 2. The main index determination method.

Index	Method
TP	Potassium persulfate oxidation spectrophotometer
TN	Alkaline potassium persulfate oxidation ultraviolet spectrophotometer
OM	Potassium dichromate volumetric method
Cu, Cr	Flame atomic absorption spectrophotometry
As, Hg	Atomic fluorescence spectrophotometry (AFS)
Ni, Zn	Atomic absorption spectrometry (ABS)
Cd, Pb	Graphite furnace atomic absorption spectrophotometry

2.3. Pollution Assessment Method

2.3.1. Evaluation of Pollution Index

The comprehensive pollution index has been used to evaluate the pollution status of nutrients in sediments [1,14,21]. The formula is as follows:

$$S_i = \frac{C_i}{C_s} \tag{1}$$

$$F = \frac{S_{TN} + S_{TP}}{2},\ F_{\max} = Max(S_{TN}, S_{TP}) \tag{2}$$

$$FF = \sqrt{\frac{F^2 + F_{\max}^2}{2}} \tag{3}$$

In the above formula, S_i is the single-factor evaluation index; i is the evaluation factor; C_i represents the measured value; C_s denotes the standard. The standard for TP and TN were 550 and 600 mg/kg, respectively. F represents the average of S_i, and F_{max} is the maximum of S_i. The pollution levels are shown as follows (Table 3):

Table 3. Pollution levels of lake sediments [1,14,21].

S_{TN}	S_{TP}	FF	Level
<1.0	<0.5	<1.0	Clean
1.0–1.5	0.5–1.0	1.0–1.5	Mild Pollution
1.5–2.0	1.0–1.5	1.5–2.0	Moderate Pollution
>2.0	>1.5	>2.0	Serious Pollution

2.3.2. Organic Index

The organic index (OI) can identify the degree of pollution of N and OM by calculating organic nitrogen (ON) and organic carbon (OC). The organic index can reflect the pollution of nutrients in sediments, and organic nitrogen can evaluate the degree of nitrogen pollution in sediments [12,15,27]. The formula is as follows:

$$\text{ON (\%)} = \text{TN (\%)} \times 0.95 \quad (4)$$

$$\text{OC (\%)} = \text{OM (\%)} \div 1.724 \quad (5)$$

$$\text{OI} = \text{ON (\%)} \times \text{OC\%} \quad (6)$$

where ON, OC, and OM are the content of ON, OC, and OM, respectively. The evaluation criteria have shown in Tables 4 and 5.

Table 4. Evaluation criteria of organic index [27].

	Organic nitrogen			
	<0.033	0.033–0.066	0.066–0.133	>0.133
Level	Clean I	Mild pollution II	Moderate pollution III	Organic nitrogen pollution IV

Table 5. Evaluation criteria of organic index [12].

	Organic index			
	<0.05	0.05–0.20	0.20–0.50	>0.50
Level	Clean I	Mild pollution II	Moderate pollution III	Organic pollution IV

2.3.3. Geo-Accumulation Index

Geo-accumulation index was used to measure the enrichment degree of heavy metals, which compare the measured value with the background concentration in Hubei Province [9,29]. The formula is as follows:

$$I_{geo} = \log_2\left(\frac{C_i}{kB_i}\right) \quad (7)$$

C_i is the mass fraction of element i in the sediment; k is the change in rock caused by weathering in different places, generally taking 1.5 as the coefficient; B_i is the geochemical average natural background level of element i. The environmental background of heavy metals (Table 6) and the level of the Igeo pollution index are as follows (Table 7).

Table 6. Soil background values and toxicity coefficients of HMs in Hubei Province [30].

Standard	Cd	Cr	Cu	Ni	Pb	Zn	Hg	As
Background (mg/kg)	0.17	86	30.7	37.3	26.7	83.6	0.08	12.3
Toxicity coefficient	30	2	5	5	5	1	40	10

Table 7. Geo-accumulation index coefficient and pollution level [5].

Igeo	Level
<0	Uncontaminated
0~1	Slight pollution
1~2	Moderate pollution
2~3	Moderate to heavy pollution
3~4	Heavy pollution
4~5	Severe pollution
≥5	Extreme pollution

Cite: Toxicity coefficient is a unified standard method and scale for representing and comparing the toxicity of poisons, that is, reference values or indicator values.

2.3.4. Potential Ecological Risk Index

Potential ecological risk index was used to evaluate the potential hazards of heavy metals in the sediments to aquatic environments (Table 8). Compared with geo-accumulation index, this method introduces the toxicity coefficient to evaluate the potential ecological risk of HMs [14]. The formula is as follows:

$$\mathrm{RI} = \sum_{i=1}^{n} E_r^i = \sum_{i=1}^{n} T_r^i \times c_f^i = \sum_{i=1}^{n} T_r^i \times \frac{c^i}{c_B^i} \quad (8)$$

In the above formula, RI is the potential ecological risk index of heavy metals; E_r^i is the potential risk coefficient of the element i. T_r^i is the toxicity coefficient corresponding to the element i. c_f^i represents the pollution index of the element i. c^i represents the measured value; c_B^i denotes the background value. The potential ecological risk is known according to the sediment heavy metals Er and RI.

Table 8. Classification of potential ecological risk index criteria [14].

E_r^i	RI	Potential Ecological Risk
<40	<150	Low risk
40~80	150~300	Moderate risk
80~160	300~600	Considerable risk
160~320	≥600	High Risk
≥320	/	/

2.4. Data Processing

The study area and interpolation maps were created using ArcGIS 10.2 (Esri, Redlands, CA, USA). SPSS Statistics 23 (IBM, Armonk, NY, USA) was used for statistical analysis, and the data mapping was completed using Origin 2021 (OriginLab). Data are expressed as mean ± SD.

3. Results

3.1. Distribution and Pollution Evaluation of Nutrients and Organic Matter

3.1.1. Distribution of Nutrients and Organic Matter

There were spatial differences in the average contents of nutrients and OM (Figure 2). TP content was 664.73–1333.22 mg/kg, the average was (1045.74 ± 190.17) mg/kg. The average of TN was (945.27 ± 203.56) mg/kg. Compared with TP, the spatial difference in TN content was relatively large, with a coefficient of variation (CV) of 0.216. The content of OM was 18.29–37.16 mg/kg, the average value was (32.31 ± 5.11) g/kg, and the CV was 0.157. Therefore, the spatial differences in TN and TP content were significantly greater than that of OM ($p < 0.05$). In terms of spatial distribution, the contents of TP, TN, and OM were the lowest in the northeast of Wanghu Lake. Particularly, OM levels were significantly lower than those of others ($p < 0.05$). The highest TN and OM contents were observed in the northwestern part of the lake, and the most severe TP pollution was distributed in the middle of the lake area.

3.1.2. Nutrient Pollution

The S_{TP} was 1.108–2.222 (Figure 3), with an average of (1.74 ± 0.32). Spatially, the northeastern part of Wanghu lake (W5) and western part (W2) had moderate pollution, and the rest of the sample points had severe pollution. The S_{TN} was 0.959–2.525, with an average of (1.72 ± 0.37). The north-eastern part of the lake, which was clean, had the lowest degree of pollution, whereas the north-western part (W1), which was severely polluted, had the most serious pollution. The comprehensive pollution index (FF) of Wanghu Lake was 1.036–2.133, with an average of (1.74 ± 0.30). Except for the northeast of the downstream outlet (W5), which had mild pollution, the northwest (W1) and middle of the lake (W4) had serious pollution, and other areas had moderate pollution.

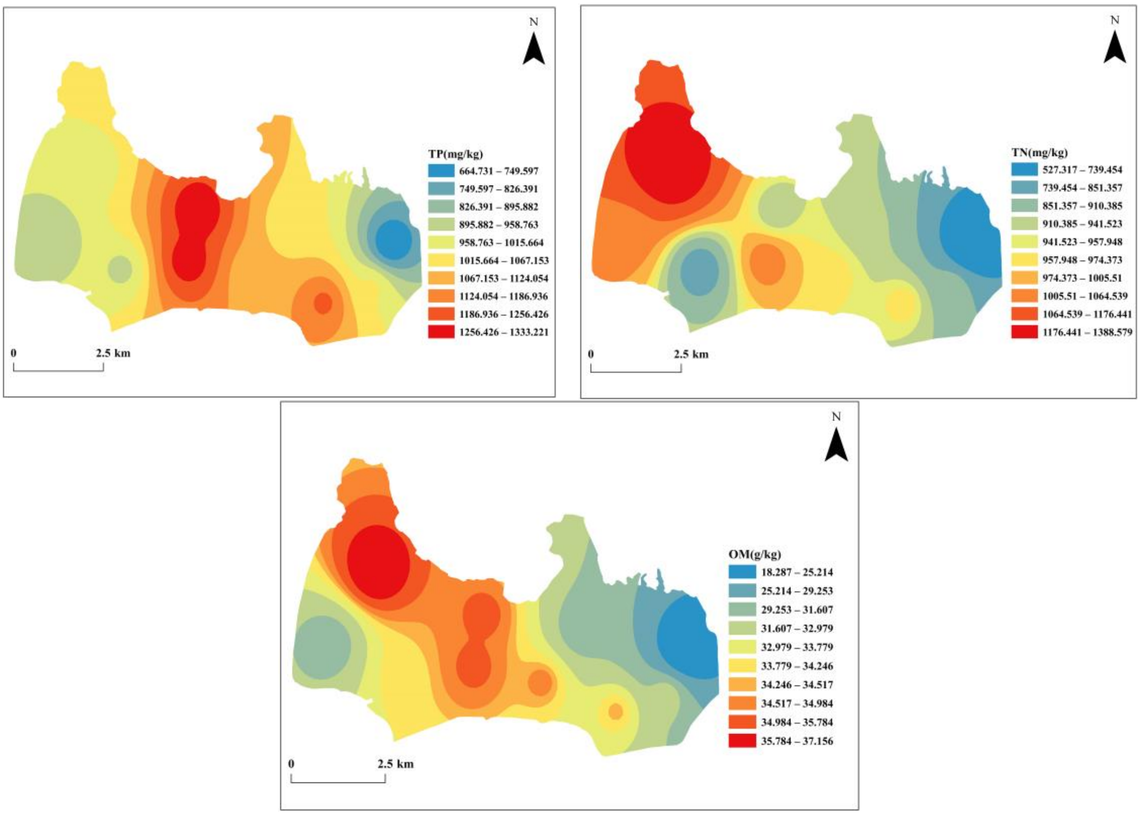


Figure 2. Distribution of total phosphorus, organic matter, and organic matter content.

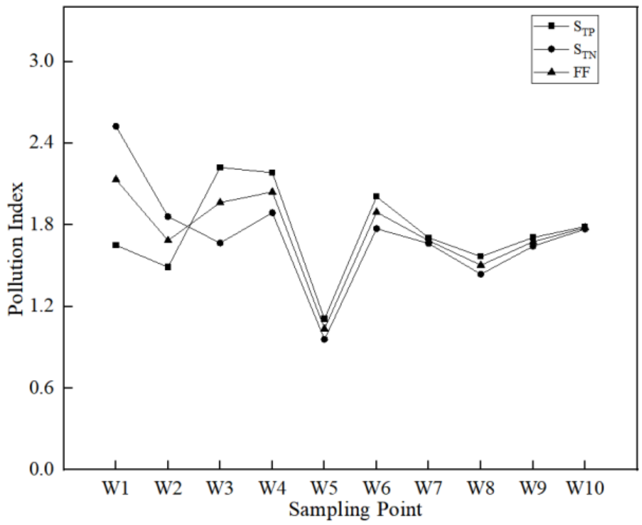


Figure 3. The comprehensive pollution index of Wanghu lake.

3.1.3. Organic Pollution

Organic nitrogen was between 0.05 and 0.13, with an average of (0.09 ± 0.02). The surface sediments had moderate pollution (III) except for W5, which experienced mild pollution (II). The evaluation results of OI were basically consistent with the evaluation results of ON (Figure 4). The maximum and minimum values of OI and ON were distributed in the northwest and northeast of the lake, respectively. The average OI index was (0.17 ± 0.05), and the CV was 0.311. Among them, the pollution level of W1 and W4 was level III, which the organic pollution level was higher than other areas of the lake. Organic index pollution in Wanghu Lake was always higher than organic nitrogen pollution.

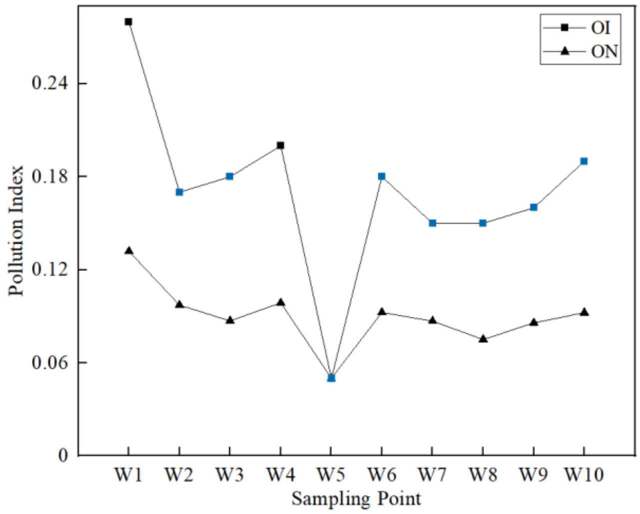


Figure 4. Organic pollution in Wanghu Lake (Blue: mild pollution, black: moderate pollution).

3.2. Distribution and Pollution of Heavy Metals in Sediments of Wanghu Lake

3.2.1. Distribution of Heavy Metals

In different areas, Wanghu Lake was polluted by heavy metals to varying degrees (Figure 5). The average contents of Cd, Cr, Cu, Ni, Pb, Zn, Hg, and As were (0.37 ± 0.07) mg/kg, (93.48 ± 24.87) mg/kg, (59.23 ± 13.62) mg/kg, (51.00 ± 16.81) mg/kg, (34.11 ± 9.24) mg/kg, (124.20 ± 41.27) mg/kg, (0.21 ± 1.99) mg/kg, and (21.75 ± 7.51) mg/kg, respectively. The lowest content of eight HMs was distributed northeast of Wanghu Lake, whereas the highest content differed in spatial distribution. Among them, the Cr, Hg, and As levels were significantly higher in the middle of the lake compared to the sides of the lake ($p < 0.05$). Additionally, the Cu content was significantly higher in the northwest area of the lake than in others regions ($p < 0.05$), with a high value of 84.6 mg/kg. The distribution of As was special, and the pollution tends to decrease from the center to the east and west sides. The southern part of the lake had the highest Ni content. Regarding spatial distribution, the pollution distribution characteristics of Pb and Zn were similar. Two high-value areas appeared in the northwest and middle of Wanghu Lake, whereas the degree of pollution was significantly lower in the southwest and northeast areas of the lake ($p < 0.05$).

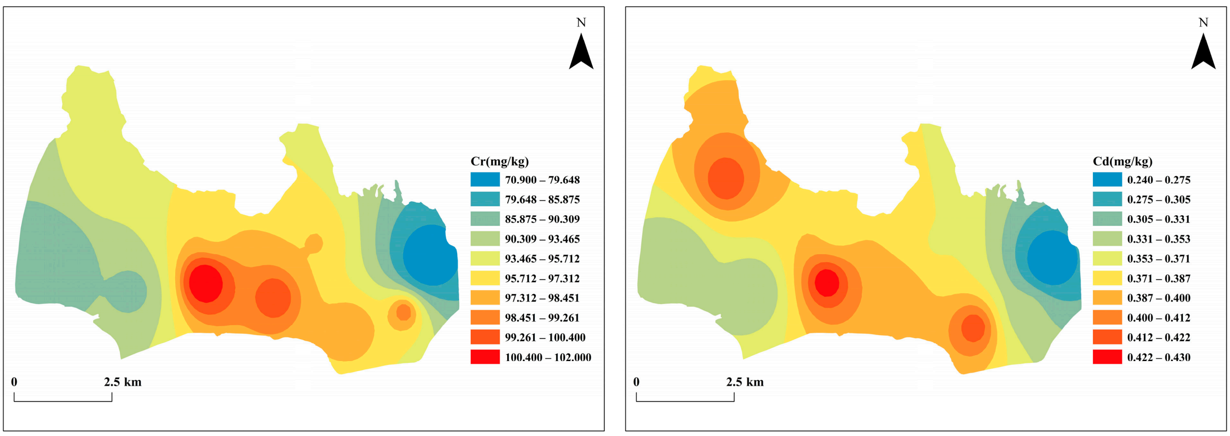


Figure 5. *Cont.*

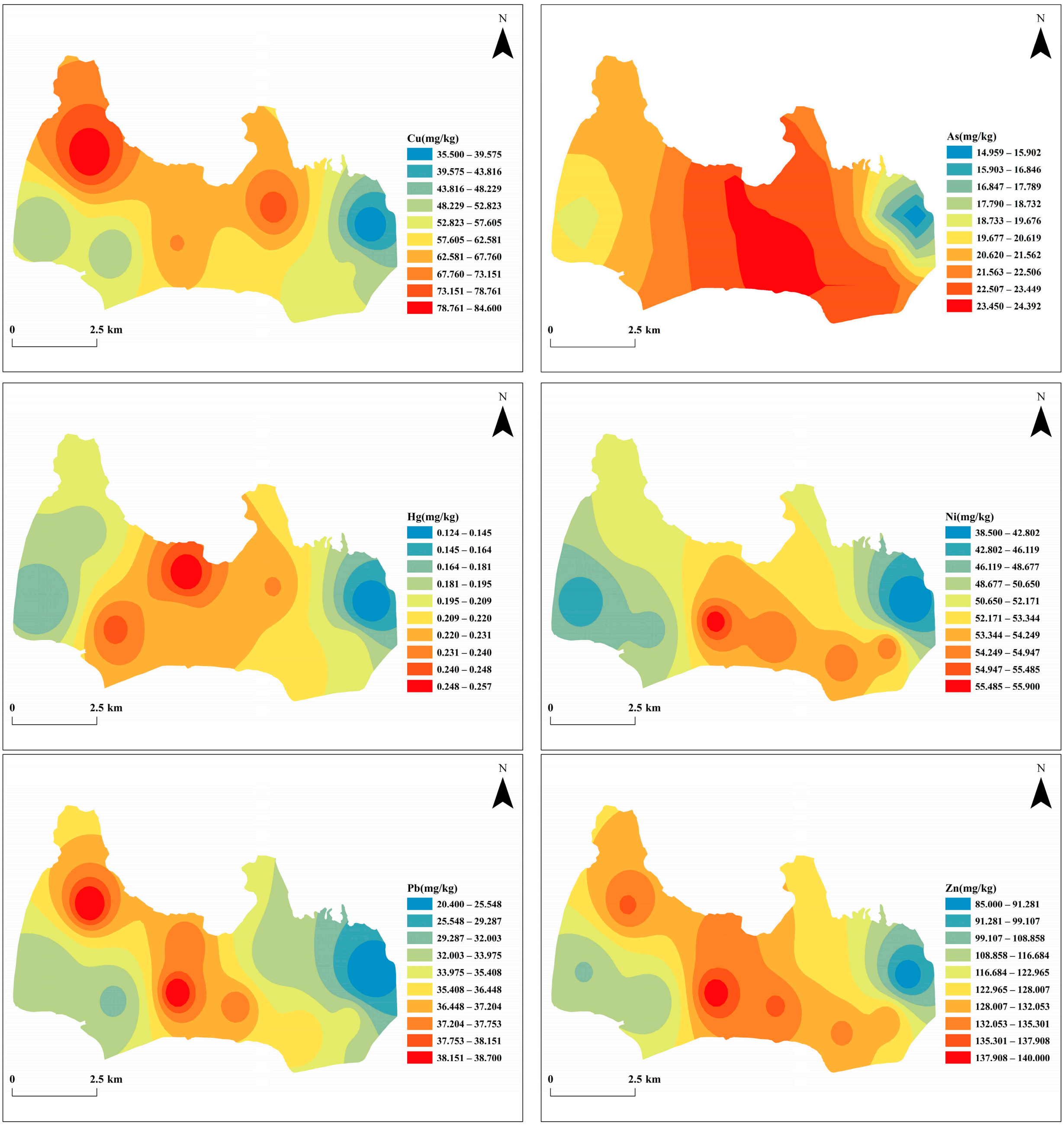


Figure 5. The distribution of heavy metals content.

3.2.2. Evaluation of Geo-Accumulation Index

The degree of heavy metals pollution in sediments was Hg > Cd > Cu > As > Ni > Zn > Pb > Cr, and Igeo was 0.044~1.101, −0.073~0.749, −0.375~0.877, −0.419~0.419, −0.539~−0.001, −0.564~0.163, −0.976~−0.050, −0.863~−0.340 (Figure 6). Cr, Ni, and Pb were uncontaminated. Hg had moderate pollution in the north bank of the center (W3) and the south bank west of the lake (W8), whereas the rest had slight pollution. The distributions of Cd, Cu, and As pollution were similar, except for the northeast (W5), which was uncontaminated, and the remaining areas showed slight pollution. Approximately 70% of Wanghu Lake area was slightly polluted by Zn, while the northeast and southwest were uncontaminated; Hg pollution was the most serious.

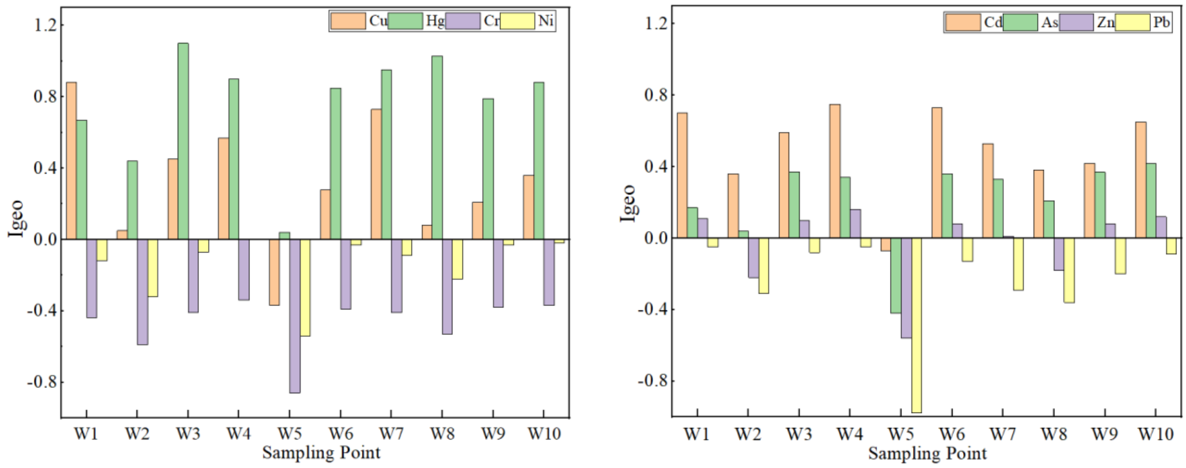
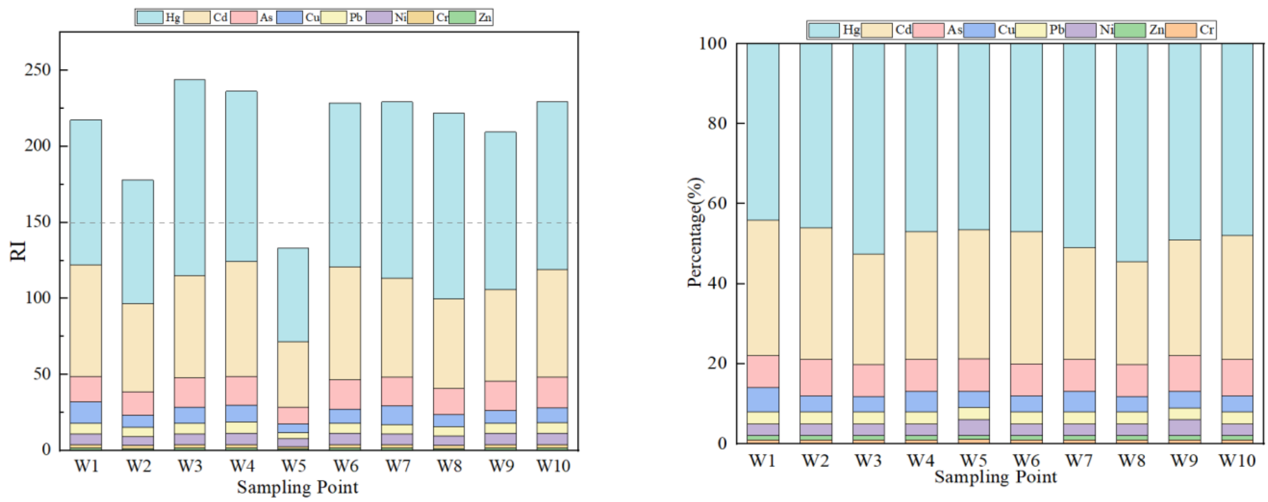


Figure 6. Geo-accumulation index in the surface sediment.

3.2.3. Evaluation of Potential Ecological Risk Index

Based on potential ecological risk index (RI) evaluation results (Figure 7a), the risks of heavy metals were as follows: Hg (103.88) > Cd (64.60) > As (17.68) > Cu (9.65) > Ni (6.84) > Pb (6.39) > Cr (2.17) > Zn (1.49). The contributions of Hg and Cd were 54% and 34%, respectively, of which the two heavy metals contribute the most to the risk of RI (Figure 7b). Cd was at a moderate risk and Hg was at a moderate risk in the northeastern part of Wanghu Lake, but others were at a considerable risk. Except for Cd and Hg, the single hazard coefficients for the other six heavy metals were low. Owing to the high toxicity of Cd and Hg, the sediments were at a strong risk by these HMs. The RI of eight HMs was between 133.26 and 243.88, with an average of (212.68 ± 98.65). The RI of the northeastern part of Wanghu Lake, which was a low-risk area, was 135.25; others were more than 150, indicating moderate risk.



(**a**) (**b**)

Figure 7. The distribution (**a**) and proportion (**b**) of potential ecological risk index in Wanghu Lake (the dotted line in the Figure is the dividing line of medium and low risk).

4. Discussion

4.1. The Source of Nutrients and Heavy Metals in Sediments

Nutrients and OM in sediments are mostly derived from production, agricultural nonpoint source pollution, surface runoff, and aquatic macrophytes [6]. The most serious TN and OM pollution in the northwest and west of Wanghu Lake may be due to its low terrain, which is affected by drainage in Yangxin County. At the same time, the northwest and west are connected to the Saiqiao Lake and Lianhua Lake groups, respectively [25]. Lianhua Lake is close to Yangxin County. In recent years, with the increase of urban population in Yangxin County, the point source pollution of production and living emissions has increased. Sewage discharge causes nutrients and OM in the water to accumulate in sediments [31]. Although sewage treatment plants have been built in towns in the basin, domestic sewage has been largely intercepted. However, the coverage of the sewage treatment plant pipe network is not comprehensive enough, and this means the sewage cannot be completely intercepted. The Saiqiao Lake group has a history of reproductive activity. In the sediments, nutrient sources and OM may be fertilizers and agricultural fertilizers produced by aquaculture [32]. The high TP content in the center of the Wanghu Lake area may be related to long-term fertilization and breeding. At the same time, due to its unique geographical location and relatively stable sedimentary environment, pollutants are easily deposited here and cause serious pollution [15]. Surface sediment pollution in lakes is also closely related to aquatic macrophytes. Decline in aquatic macrophytes results in a large amount of litter, which increases the accumulation of nutrients in sediments, resulting in endogenous pollution [33]. Wanghu Lake is rich in aquatic macrophytes in some areas, such as *Myriophyllum verticillatum*, *Nymphoides peltatum*, *Trapa*, and *Phragmites australis* [34]. Although aquatic macrophytes can purify water quality and adsorb nutrients, in the period of plant decline, plant residues will also become an important source of nutrients and OM. An increase in nutrient and OM contents in sediments caused by the corruption of aquatic macrophytes was also observed in Taihu Lake and Honghu Lake [35,36].

Heavy metals are related to the discharge of sediment parent materials and anthropogenic emissions from basins in sediments [22]. As heavy metals are persistent and difficult to decompose, they easily accumulate in sediments, causing heavy metal pollution [32]. Wanghu Lake is a habitat for migratory birds, therefore, bird feeding and the large input of bird droppings are also sources of HMs in sediments. In Tongli wetland, Poyang Lake migratory bird habitat, the South China Sea Islands, and other polar regions, HM pollution was also affected by bird manure input [37–40]. In Wanghu Lake, the results of the Igeo were the same as RI. The high risk of HMs in sediments was mainly related to Hg and Cd [41], which was 2.4 and 2.8 times the soil background, respectively. On the one hand, the toxicity coefficient of Hg and Cd was higher [41]; on the other hand, it showed that Hg and Cd were mainly derived from human activities. The area surrounding the lake was less affected by industrial pollution, and the pollution mainly originates from production activities such as planting, agriculture, and aquaculture [42]. In the process of agricultural production, chemical fertilizers and pesticides containing Hg, Cd, and Zn has increased dramatically, and these can enter lakes through atmospheric precipitation, surface runoff, and underground leakage, resulting in non-point source pollution [43]. Studies have shown that in general, heavy metals with strong migration abilities flow into lakes with runoff, whereas those with weak migration abilities only have a small amount of elements with surface runoff or sediment into lakes [32]. Hg has a relatively high migration and conversion rate and can be enriched in aquatic macrophytes, thereby exacerbating pollution. The low pollution level of Cr and its weak migration ability may be attributed to the emissions of parent lake materials [44]. Sediment accumulation mainly occurred in the center of Wanghu Lake and showed a decreasing outward trend, which was related to the low migration and transformation ability of As [5]. In addition, the migration and transformation of HMs are closely related to their chemical forms, environmental pH, redox conditions, and the presence of OM and microorganisms [45]. Wanghu Lake is one of the main fish-producing areas in Yangxin County, China. Aquaculture was mainly concentrated on the northwest and south banks. The bait contained HMs such as Zn, Cu, and Cd. Unfed bait is directly deposited in the sediment, and the ingested portion is excreted and discharged through aquatic macrophytes, resulting in the enrichment of HMs [32]. The higher Cd content in the southeast may be due to the diversion of the Fuhe River into the lake during the wet season; Pb may come from the discharge of nonferrous metal smelting, manufacturing, and ore- or lead-containing industries, and daily sewage discharges may also contribute small amounts of Pb [23]. Atmospheric deposition affected the production and enrichment of Ni and As. Agricultural irrigation water, rock weathering, and decay of animal and plant residues also affect the Ni content of sediments, whereas As may be produced by the application of arsenic-containing pesticides, residues, and coal burning [5].

4.2. The Correlation between Nutrients and Heavy Metals in Sediments

Studies have shown that OM was closely related to the mobility, transformation, and bioavailability of HMs [46]. The correlation between pollutants in Wanghu Lake (Table 9) indicates that the sources of pollution may be similar. OM was significantly positively correlated with TN ($p < 0.01$, r = 0.769) and TP ($p < 0.05$, r = 0.748), indicating that OM in sediments may be homologous to N and P [47,48]. This may be due to the growth, the decay and decomposition of plant residues, resulting in an increase in the OM and TN content in sediments [48]. The correlation between TN and TP was insignificant ($p > 0.05$), indicating that N and P may have originated from different sources.

Table 9. The correlation of nutrients, organic matter, and heavy metals.

	Cd	Cr	Cu	Ni	Pb	Zn	Hg	As	TP	TN	OM
Cd	1.00										
Cr	0.882 **	1.00									
Cu	0.770 **	0.671 *	1.00								
Ni	0.864 **	0.991 **	0.63	1.00							
Pb	0.937 **	0.920 **	0.705 *	0.894 **	1.00						
Zn	0.924 **	0.970 **	0.748 *	0.968 **	0.956 **	1.00					
Hg	0.61	0.770 **	0.47	0.762 *	0.675 *	0.695 *	1.00				
As	0.779 **	0.964 **	0.52	0.960 **	0.852 **	0.898 **	0.857 **	1.00			
TP	0.812 **	0.837 **	0.50	0.846 **	0.832 **	0.850 **	0.771 **	0.818 **	1.00		
TN	0.787 **	0.60	0.796 **	0.54	0.800 **	0.703 *	0.24	0.44	0.42	1.00	
OM	0.870 **	0.861 **	0.651 *	0.824 **	0.952 **	0.867 **	0.751 *	0.825 **	0.748 *	0.769 **	1.00

** and * represent significant correlations at 0.01 and 0.05 levels (double tail), respectively.

The correlation between heavy metals may be related to similar long-term sedimentary environments and sources [45]. The correlation between Hg and other elements was low, indicating that the source of Hg was not homologous to that of other elements. OM was significantly correlated with Pb, Cd, Zn, Cr, As, and Ni ($p < 0.01$). OM pollution in the northwest, middle, and south of the lake was more serious, which may have been owing to the presence of these HMs in OM. Studies have found strong correlations between HMs concentrations and OM. There was a significant correlation between OM, Pb, and As in Houguan Lake [41] and between TOC and Pb in sediments in the Liaohe River [49].

4.3. Comparison of Pollution in Surface Sediments of Different Areas

According to the comparison results of N, P, OM, and HM in sediment from different areas (Table 10), the contents of TN and TP in Wanghu Lake were higher than those in Hongze Lake and Dongping Lake [50,51] and also higher than those in Changdang Lake and Dongting Lake, which are both located in the middle and lower reaches of the Yangtze River [6,17]. However, the TN content was lower than that of Baiyangdian Lake, Ulansuhai Nur, Qingshan Lake, Wuhu Lake, and Yilong Lake significantly [1,52,53]. The content of TP was higher than that of other lakes while it was lower than that of Ulansuhai Nur in the northern region and Qingshan Lake in the same area [1,52]. The OM content was also at a high level, only lower than that of the plateau lake Yilong Lake, urban lake Qingshan Lake, and Dongping Lake [51,53], and the difference between the content of Baiyangdian was small [5]. Therefore, compared to other lakes in China, the nutrients and OM in Wanghu Lake were relatively high.

Compared with other lakes in China, the contents of Cu, Ni, Cr, and Zn in Wanghu Lake were at a high level, as far as Hg and As were at a general level [54–60], and Cu and

Ni were second only to those of Gehu Lake [18]. The pollution levels of Cd and Pb were relatively low, but Pb was 5.82 times that of Ulansuhai Nur, and Hg was 10.5 times higher than Ulansuhai Nur [1]. Therefore, in the process of protection and restoration of Wanghu Lake, it is necessary to control the main pollution sources, and combine ecological dredging, reasonable planting of aquatic plants, and other measures to reduce the degree of pollution.

Table 10. Comparison of nutrient, organic matter, and heavy metal contents in surface sediments from different study areas.

Study Area	Nutrients and OM			References	Heavy Metal (Unit: mg/kg)								References
	TN (mg/kg)	TP (mg/kg)	OM (g/kg)		Cd	Cr	Cu	Pb	Zn	Hg	Ni	As	
Taihu Lake	-	-	-	-	0.610	68.85	35.53	29.70	109.32	0.145	36.19	16.99	[54]
Hongze Lake	985	276	10.93	[48]	0.23	66.78	25.35	27. 20	74. 77	-	33.89	16.55	[55]
Changdang Lake	995	695	24.7	[6]	0.37	83.6	39.5	32.8	136.5	0.05	44.9	11.41	[6]
Dongping Lake	647	336	87.658	[50]	0.23	80.67	37.28	26.14	68.52	-	40	17.53	[56]
Gehu Lake	2207.94	708.62	-	[18]	2.34	307.98	59.54	168.97	766.59	0.41	122.67	350.66	[18]
Baiyang Lake	3300	700	36.1	[5]	0.30	79.8	30	45.4	93.8	0.07	33.5	12.7	[5]
Ulansuhai Nur	7910	1890	-	[1]	0.43	43.11	53.74	5.86	94.69	0.02	46.33	3.64	[1]
Shijiu Lake	776.45	585.12	30.25	[57]	0.17	94.92	38.42	35.92	124.33	0.05	41.25	16.48	[57]
Dongjiang Lake	-	-	-	-	2.25	67.58	33.01	47.4	113.9	-	33.66	80.80	[61]
Dongting Lake	1029	697	-	[17]	1.913	93.47	37.98	36.05	147.2	0.317	34.47	21.234	[17]
Qingshan Lake	3476	3279	112.38	[51]		59.17	201.16	82.48	300.18	-	46.26	-	[62]
Wuhu Lake	3517	935	31.8	[63]	0.42	103.7	40.76	42.27	113.38	0.083	50.73	16.33	[58]
Tangxun Lake	2093.13	716.46	-	-	0.66	85.28	51.28	41.60	145.01	0.17	40.49	-	[58]
Qinghai Lake	-	-	-	-	0.21	45.44	18.02	35.1	109	-	43.9	-	[59]
Yilong Lake	4250	590	157.42	[53]	0.58	77.6	22.6	41.8	80	0.06	28.8	20.4	[60]
Meixi Lake	1654.68	512.6	28.4	[15]	-	-	-	-	-	-	-	-	-
Wanghu Lake	1045.74	945.27	32.31	-	0.37	93.48	59.23	34.11	124.20	0.21	51.00	21.75	-

5. Conclusions

In the pollution evaluation results, the TP of the surface sediment of Wanghu Lake was severely polluted, while the organic pollution and the comprehensive pollution evaluation results were consistent. Both the RI and Igeo evaluation results showed that Hg and Cd levels were at considerable and moderate risks, respectively. However, due to the large number of evaluation indicators, the source of each pollutant was not analyzed in sufficient depth.

(1) Due to the effect of aquaculture water, the TN and OM in the northwest were always higher than other areas. There were high concentrations of Cd, Cu, Pb, and Zn, which may be related to the aquaculture wastewater and uneaten bait. The connected channel connected to the Yangtze River in the east makes the water exchange capacity stronger here. The sedimentary environment was unstable, and the pollution was difficult to deposit, so that the pollution of nutrients, organic matter, and heavy metals was light. So we need to take the northwest of the lake as the key for the control of pollution and ecological restoration area in the future.

(2) Compared with other lakes in China, TN in the surface sediments of the Wanghu lake was at a medium level, and the content of TP and OM was at a high level. In terms of heavy metals, Ni, Cu, As, and Hg were at a high level, Cr and Zn were at a medium-high level, while Cd and Pb were at a medium-low level.

(3) According to the evaluation results, TP pollution was serious. Organic pollution and organic nitrogen pollution showed mild pollution and moderate pollution, respectively. Igeo in the surface sediments was Hg > Cd > Cu > As > Ni > Zn > Pb > Cr. Similar to the single risk factors (Er), Hg and Cd were the main factors contributing to the surface sediments,

with levels at considerable and moderate risks, respectively. Therefore, it is necessary to control the sources of TP, Hg, and Cd in Wanghu Lake to prevent further pollution.

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