Pol. J. Environ. Stud. Vol. 29, No. 6 (2020), 4139-4150
DOI: *10.15244/pjoes/118205* ONLINE PUBLICATION DATE: 2020-06-01

Original Research

Ecological Assessment of Heavy Metals in Sediments from Jianhu Lake in Yunnan Province, China

Bo Li[1, 2, 3], Hang Wang[1, 2], Qingguo Yu[1, 2]*, Feng Wei[4], Qi Zhang[5]

[1]College of Wetlands, Southwest Forestry University, Kunming Yunnan, China
[2]National Plateau Wetlands Research Center, Kunming Yunnan, China
[3]Institute of Environmental and Ecological Engineering, Guangdong University of Technology, Guangzhou Guangdong, China
[4]College of Ecology and the Environment, Southwest Forestry University, Kunming Yunnan, China
[5]College of Eco-Environmental Engineering, Guizhou Minzu University, Guiyang Guizhou, China

Received: 4 September 2019
Accepted: 14 February 2020

Abstract

Cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb) and zinc (Zn) in the sediments of Jianhu Lake were measured by an inductively coupled plasma-optical emission spectrometer (ICP-OES) to determine their spatial distribution characteristics and ecological risks. The results showed that the average concentrations of Cd, Cr, Cu, Pb and Zn in surface sediments (0-5 cm) were 0.41±0.34, 143.89±90.07, 46.14±30.08, 56.38±45.71, and 146.52±96.50 mg/kg, while those in core sediments (0-75 cm) were 0.51±0.44, 228.35±174.52, 89.94±74.63, 74.92±65.69, and 208.89±171.55 mg/kg, respectively. The total concentrations of heavy metals were highest in the western area of Jianhu Lake, and were higher in the bottom layer (70-75 cm) than in the surface layer (0-5 cm) in the entire Jianhu Lake region. The potential ecological risks of Cd in sediments were greatest, and the comprehensive potential ecological risks of the five tested heavy metals in sediments were highest in the western area of Jianhu Lake. Using the geoaccumulation index (I_{geo}), we found that pollution in sediments due to Cr was the most serious of all the heavy metals, and the degree of pollution due to these five heavy metals in each area varied greatly in Jianhu Lake. In addition, we found that the short-term release contribution of Pb and Zn was large, while both the short- and long-term release contributions of Cr were small.

Keywords: sediment, heavy metal, spatial distribution, ecological assessment, release contribution

*e-mail: 1111907015@mail2.gdut.edu.cn

Introduction

Northwest Yunnan Province is located in the transitional zone from the Qinghai-Tibet Plateau to the Yunnan-Guizhou Plateau. It is in the world-famous Three Parallel Rivers Region. This special natural environment has a rich biodiversity. It is not only one of the 25 “hot spots” of biodiversity in the world [1], but is also the first zone of 17 key biodiversity preferential conservation areas in China [2]. The group of lakes in northwest Yunnan Province plays an important role in the conservation of biodiversity and the maintenance of water ecological security in the Three Parallel Rivers Region, and thus it has high value in conservation and research. Sediments are an integral component of an aquatic ecosystem and provide habitat, feeding, spawning and rearing areas for many aquatic organisms [3-4]. However, they are also important carriers of heavy metals in aquatic ecosystems [5]. In recent years, studies on lake sediments in northwest Yunnan Province have shown that heavy metal pollution in sediments is serious, such as in the Napaihai wetland [6] and Chenghai Lake [7]. In addition, the concentration of heavy metals in sediments from plateau lakes in China has increased year by year [8]. Heavy metals are one of the most worrying pollutants in our natural environments due to their toxicity, persistence and bioaccumulation [9]. Direct toxicity to human and aquatic life and indirect toxicity through the accumulation of metals in aquatic food chains are a focus of scientific research [10].

In recent years, research on heavy metals in lake sediments of Yunnan Plateau in China has focused mainly on such lakes as Dianchi [11], Chenghai [7], and Yangzonghai [12] and so on, and less attention has been was paid to Jianhu, which is one of the group of lakes in northwest Yunnan Province, China. Jianhu is a well-preserved plateau lake wetland in northwestern Yunnan Province. It is a typical plateau erosional lake and is one of the types of small plateau shallow lake wetlands in China. Therefore, if there is heavy metal contamination in the sediments of Jianhu Lake, it is more difficult for the lake to recover compared with lakes in other regions [13]. Furthermore, most of the plateau lakes are in a relatively closed geographical environment [14]. Thus, the oxidation-reduction environment in plateau lakes is unique, and the accumulation and release of heavy metals in sediments are also different from lakes in other districts.

Surface sediments are often exchanged with suspended matter in water and reflect current environmental conditions [5], while bottom sediments have a relatively stable history of human and natural processes [15]. Meanwhile, the assessments of heavy metal pollution and ecological risk in sediments are of prime importance to improve management and prevention strategies and have been taken into serious consideration [16-17]. In order to comprehensively evaluate the current heavy metal pollution status and ecological risk in the sediments of Jianhu and determine the process of heavy metal deposition, sediments were collected from the lake. Research on the release contribution of heavy metals in vertical profile is rarely performed. In the present study, based on the release contribution of phosphorus in core sediments [18], the release contribution of heavy metals in sediments from Jianhu Lake was analyzed. In general, heavy metals such as cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb) and zinc (Zn) can threaten the health of entire ecosystems in addition to humans [19-21]. The purpose of determining Cd, Cr, Cu, Pb and Zn was to reveal the horizontal and vertical spatial distribution characteristics, ecological risks, pollution levels and release contributions of these heavy metals in the sediments from Jianhu. The results may also provide a base for the prevention and control of heavy metal pollution in the sediments of Jianhu Lake.

Materials and Methods

Study Area

Jianhu Lake, located in Jianchuan County, Dali Bai Nationality Autonomous Prefecture, Yunnan Province, China, is part of the Mekong River (called the Lancang River in China) Basin. The Jianhu Basin covers a large area of approximately 883 km^2, and the pollution sources in the basin are extensive, while Jianhu Lake is only about 6 km^2. There are rivers, such as the Yongfeng, Jinlong and Gemei (Fig. 1) near Jianhu Lake, and the water in Jianhu flows from the Haiwei River. There are many rivers around Jianhu, but only one river out of the lake. Therefore, the water retention period is relatively long due to the closed geographical environment. There are some potential sources of heavy metal contamination in Jianhu Lake Basin, such as a lead-zinc heap, municipal and domestic sewage and garbage, wood carving industries and so on. Jianhu was listed as a provincial wetland nature reserve by the government in 2006 and is located in the wetland ecological natural preservation zone. It was listed as the first batch of provincial-level important wetlands by the government in 2016. The lake is not only a gathering point and a stopping place for migratory birds, but also a wintering habitat for migratory waterfowl, and it is also an important area for biodiversity conservation in northwest Yunnan Province, China.

Sediment Collection

Sediments were sampled according to the shape of Jianhu Lake, conditions of the rivers, human disturbance, and industrial and agricultural distribution in June 2017; 12 sampling points in total were established marked as 1 to 12 (Fig. 1). In order to restore Jianhu Lake and expand the lake area, the Yunnan Jianhu Wetland Provincial Nature Reserve Administration implemented

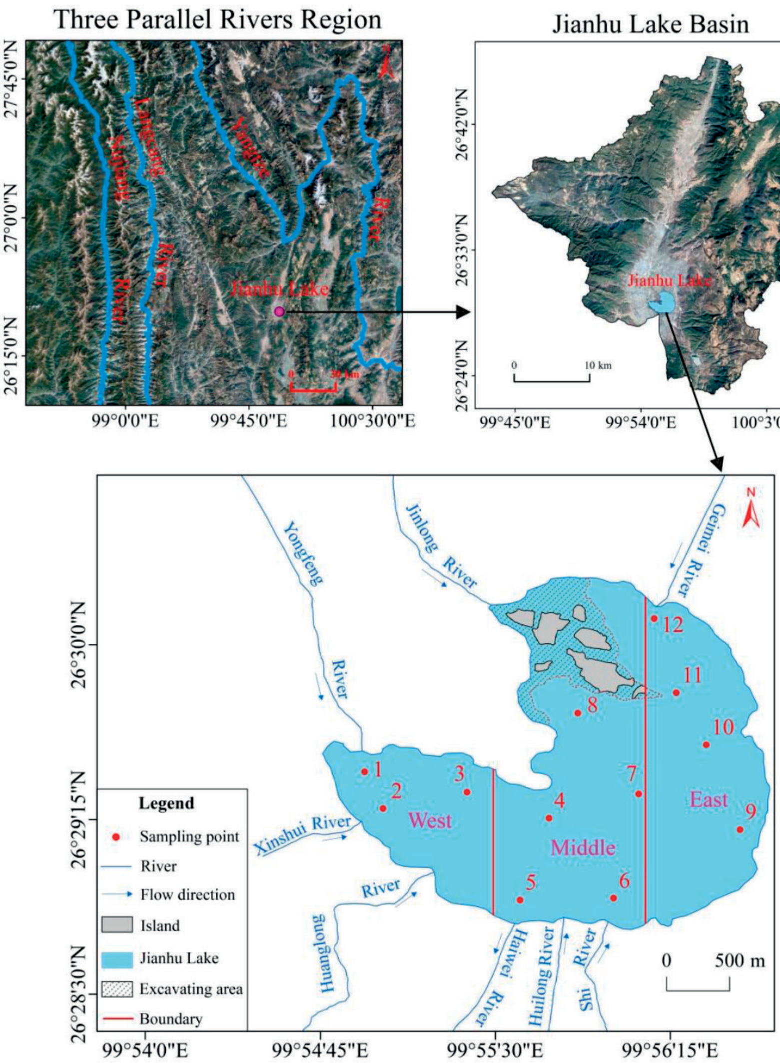

Fig. 1. Distribution of sediment sampling points in Jianhu Lake.

a dredging project in the Jinlong River estuary in the first half of 2016, which resulted in a large disturbance to the sediments; thus, sediments in this area were not collected. All sediment samples were collected using a deep-hole drill (Eijkelkamp 0423SA, Netherlands). A core sediment sample (0-75 cm) was taken at each sampling point and divided into 15 layers from top to bottom (5 cm per layer). There were 180 samples in total, and all sediment samples were placed in clean plastic zip-lock bags, transferred to an icebox and then transported to the laboratory for further processing within one week.

Laboratory Analytical Methods

The samples were dried, passed through a 100-mesh nylon sieve for easy digestion until the sediment residue disappeared and the solution turned into white or light yellow, sealed to avoid contamination, and then stored at room temperature until analysis. For heavy metal testing, 0.2000 g of sediment sample was weighed accurately and 8 ml HNO_3, 8 ml HCl, and 10 ml HF were added to a screw-top polytetrafluoroethylene high-pressure microwave digestion tank. The samples were dissolved in the microwave digestion instrument for 70 min, and then heated to near dryness with a constant temperature digestion instrument. After shaking for 20 min with an ultrasonic cleaner, the liquor was adjusted to 50 ml with 1% HNO_3, and then the content of heavy metals was measured by an inductively coupled plasma-optical emission spectrometer (ICPE-9820, Japan). In this study, 10% of samples were selected randomly for three repeated experiments due to the large number of samples, and one blank sample was analyzed to correct for contamination during the experimental process. A Chinese Standard Substance (GBW 07309) was included for quality control. The results showed that the coefficient of variation of all replicates of each tested sample and the coefficient of variation of standard substances were less than 10%. In order to confirm the accuracy of our measurements, 5% of sample solutions were randomly selected for three repeated measurements during the testing process. The repeated measurement results showed that the coefficient of variation was less than 5%, indicating that the stability of the instrument was high and the results met the requirements.

Pollution and Ecological Risk Assessment

Common methods for evaluating heavy metals in sediments include the potential ecological risk index [17], geoaccumulation index [15], sediment quality guidelines [22], enrichment factor [5], and the sediment pollution load index [23]. These methods have different characteristics and scope of application, and they also have their own limitations in practical applications, but the geoaccumulation index and potential ecological risk index are currently the most commonly used methods [24].

The geoaccumulation index (I_{geo}) is a quantitative indicator proposed by Müller [25]. This method evaluates whether sediments are contaminated by heavy metals and effectively indicates the environmental quality of sediments [15]. Additionally, human disturbance factors and geochemical background are considered in this method; therefore, it can objectively evaluate the degree of heavy metal pollution in sediments, and the obtained values mainly represent the influence of human activities in the process of heavy metal enrichment. This index is calculated as follows:

$$I_{geo} = \log_2\left(\frac{C_n}{1.5\times B_n}\right)$$

…where C_n is the concentration of metal n in sediments, B_n is the background concentration value for metal n, and factor 1.5 is used because of possible variations in the background data due to lithological variations [26]. In this study, the arithmetic mean content of soil elements in the A layer (0-20 cm) of Yunnan Province was used as the background concentration value (Cd = 0.218, Cr = 65.2, Cu = 46.3, Pb = 40.6, Zn = 89.7 mg/kg) in the evaluation process, and the range values of Cd, Cr, Cu, Pb and Zn are 0.009-3.409, 13.7-126.0, 6.2-208.9, 9.5-490.0 and 14.0-281.0 mg/kg (n = 73), respectively [27], and to reflect the degree of pollution in contrast to the local background data [17]. According to the values of I_{geo}, the degree of heavy metal pollution in sediments can be graded, and the classification criteria are shown in Table 1 [28].

The potential ecological risk index (RI) was introduced by Hakanson from the perspective of sedimentology to evaluate the ecological risk of heavy metals in sediments [29]. The toxicity of heavy metals and the difference in regional background values are considered in this method. The index can be calculated as follows:

$$\mathrm{RI}=\sum_{i=1}^{m} E_r^i \text{, where } E_r^i = T_r^i \times \frac{C^i}{C_n^i}$$

… where E_r^i is the potential ecological risk index of single element i in sediments, and m is the amount of heavy metal elements. T_r^i is the toxicity response coefficient of element i, where T_r^i for Cd, Cr, Cu, Pb and Zn are 30, 2, 5, 5 and 1, respectively [29]. C^i is the measured concentration of heavy metal i and C^i is the reference value of heavy metal i collected from the natural geochemical background concentration of heavy metals in the A soil layer (0-20 cm) in Yunnan province [27]. The classifications of RI and E_r^i are related to the type and quantity of pollution, and this study only includes five heavy metals (which is different than the eight types of pollution studied by Hakanson) [29]. Therefore, the classification criteria were adjusted according to the methods by Hou Qian et al. [30]. The standard is shown in Table 2.

Release Contribution

Sediments can adsorb heavy metals in water and in turn reduce the level of water pollution. However, the pollutants can be released from the sediments when environmental conditions such as magnetic properties, particle size, organic carbon, total nitrogen, and total phosphorus change in the sediments, and can cause secondary pollution in the water environment [31-32]. Therefore, it is necessary to study the release of heavy metals in sediments.

Heavy metals would be released and distributed again and produce secondary pollution due to the change of hydrodynamic conditions and the influence of biological activities [33]. Huang et al. have justified that the heavy metals in bottom sediments can be released to surface environment and diffused in vertical profile [34]. According to the first law of Fick regarding steady-state diffusion, the diffusion flux of materials in vertical space is proportional to the concentration in the area [35]. In addition, the migration of elements has continuity in time and space. This means that the migration and release of heavy metals in core sediments depend on the concentration between the two adjacent layers. In this study, based on the release contribution of

Table 1. Geoaccumulation index and classification of degree of pollution.

Grade	I	II	III	IV	V	VI	VII
I_{geo}	≤0	0-1	1-2	2-3	3-4	4-5	>5
Pollution degree	Clean	Low	Very slight	Slight	Moderate	High	Very high

Table 2. Grading standard of potential ecological risk evaluation.

Grade	I	II	III	IV	V
E_r^i	E_r^i<30	30≤E_r^i<60	60≤E_r^i<120	120≤E_r^i<240	E_r^i≥240
RI	RI<40	40≤RI<80	80≤RI<160	RI≥160	
Risk status	Low	Moderate	High	Very high	Extremely

phosphorus in core sediments, the release contribution of heavy metals in sediments was divided into two types: short-term release contribution (V_1) and long-term release contribution (V_2) [18]. Release contribution can be calculated as follows:

$$V_1 = \frac{(k_1 - k_2)}{\sum_{i=1}^{n} |k_1 - k_2|} \times 100\% \quad , \quad V_2 = \frac{(k_1 - k_3)}{\sum_{i=1}^{n} |k_1 - k_3|} \times 100\%$$

…where n is the number of heavy metal elements in sediments, and k_1, k_2 and k_3 are the average content of heavy metal elements in sediments from the first layer (0-5 cm), the second layer (5-10 cm) and the bottom layer (70-75 cm), respectively. Generally speaking, the value is positive, indicating that this heavy metal element has the potential for release; negative values indicate that this heavy metal element has the potential for retention.

Results

Heavy Metal Concentrations in Surface Sediments

The contents of Cd, Cr, Cu, Pb and Zn in the surface sediments (0-5 cm) of Jianhu Lake were 0.412±0.341, 144±90.1, 46.1±30.1, 56.4±45.7 and 147±96.5 mg/kg, respectively. The spatial distribution is illustrated in Fig. 2. The average heavy metal concentrations in the surface sediments of Jianhu Lake, with the exception of Cr, showed the order west>middle>east, while Cr showed the order of middle>west>east. In addition, the concentration of these five heavy metals was relatively high in the vicinity of the Xinshui River estuary and low at the entrance to the Gemei River and excavation area of Jianhu Lake, and the concentrations of Cd and Pb were high in some areas of the eastern section. In addition, to facilitate the evaluation and comparison, the average concentrations of national aquatic sediments and south aquatic sediments in China are also shown in Table 3. It can be seen from Table 3 that the average values of heavy metals in the surface sediments of Jianhu were all higher than the average concentrations in national aquatic sediments and south aquatic sediments in China. The contents of Cd and Cr in sediments from the lake were 1.83 times and 2.53 times that of the average concentration in national aquatic sediments. The concentrations of Cd, Cr and Zn in sediments from Jianhu were 1.51, 2.37, and 1.39 times the soil background value in Yunnan Province, respectively, while the concentrations of Cu and Pb were close to the soil background value in Yunnan Province.

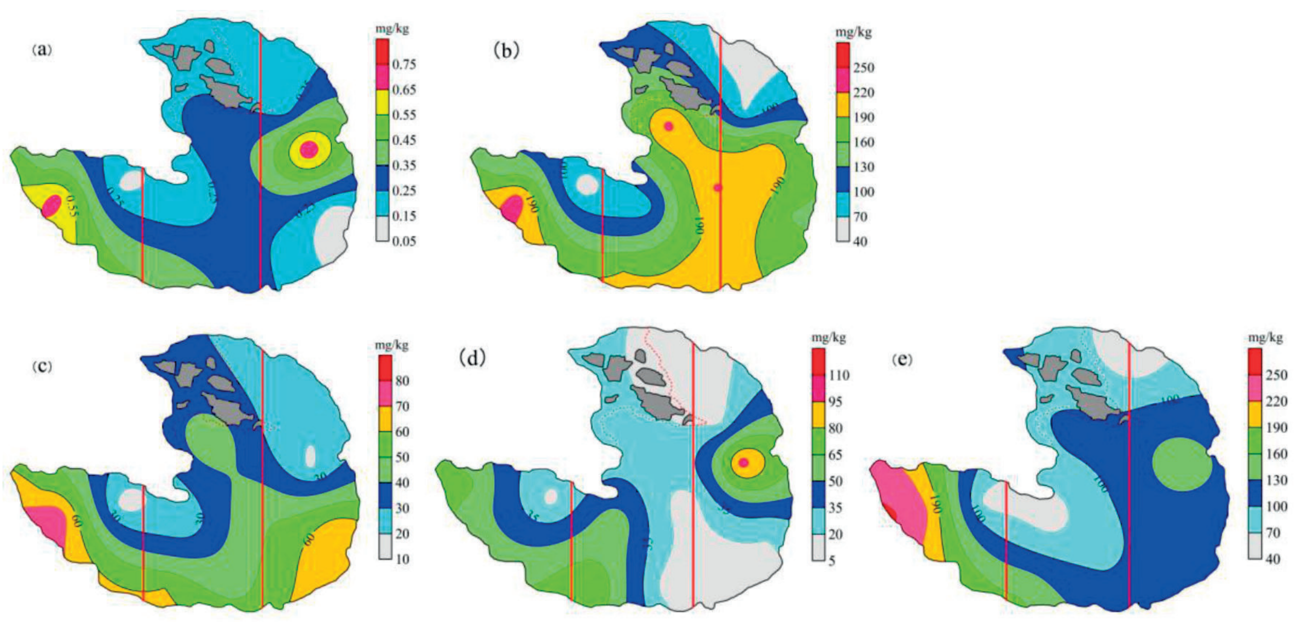

Fig. 2. Horizontal distributions of Cd a), Cr b), Cu c), Pb d) and Zn e) in Jianhu Lake surface sediments.

Table 3. Average concentrations of Cd, Cr, Cu, Pb and Zn in sediments from Jianhu Lake compared with other sediments (mg/kg).

	Cd		Cr		Cu		Pb		Zn	
	Surface	Core	Surface	Core	Surface	Core	Surface	Core	Surface	Core
East of Jianhu lake	0.42	0.42	144.01	171.06	50.32	57.08	45.68	34.07	178.97	189.34
Middle of Jianhu lake	0.31	0.35	185.49	218.78	45.13	55.46	37.63	34.53	106.38	145.66
West of Jianhu lake	0.29	0.33	122.97	230.64	33.46	45.02	37.52	46.24	105.89	137.27
Entirety of Jianhu lake	0.33	0.36	154.28	210.80	42.53	52.38	39.61	38.32	124.36	153.78
National aquatic sediments in China	0.18		61.00		23.00		27.00		71.00	
South aquatic sediments in China	0.23		57.00		25.00		32.30		81.00	
Soil background value of Yunnan Province	0.22		65.20		46.30		40.60		89.70	

Notes: the results of the average concentrations in national aquatic sediments and south aquatic sediments in China were from the study by Ren et al. and Cheng et al [36-37], respectively. The soil background value in Yunnan Province was from the survey by the China National Environmental Monitoring Center [27].

Heavy Metal Concentrations in Core Sediments

The concentrations of Cd, Cr, Cu, Pb and Zn in the core sediments of Jianhu Lake were 0.513±0.442, 228±175, 89.9±74.6, 74.9±65.7, and 209±172 mg/kg, respectively. It can also be seen from Table 3 that the concentrations of different heavy metal elements varied greatly in core sediments in different areas of the lake. The average concentrations of Cd, Cu and Zn followed the order of west>middle>east, and the average concentrations of Cr and Pb were in the order of east>middle>west. The average concentrations of all heavy metal elements in core sediments exceeded the mean values in national aquatic sediments and south aquatic sediments in China. Pb was close to the soil background value in Yunnan Province, and the average concentrations of other elements were higher than the soil background value in the province.

The vertical spatial distribution of heavy metals in core sediments from Jianhu is shown in Fig. 3. The average coefficients of variation of Cd, Cr, Cu, Pb and Zn were 36%, 29%, 35%, 49% and 38%, respectively. The highest concentrations of Cd, Cr and Pb appeared at sampling point number 10, while the highest concentrations of Cu and Zn appeared at sampling points 8 and 1. The average concentrations of Cd, Cr, Cu, Pb, and Zn in the bottom layer (70-75 cm) were 1.24, 1.33, 1.41, 1.23, and 1.26 times that in the surface layer (0-5 cm). In addition, the highest average concentrations of Cd, Cu and Zn appeared in the 60-65 cm layer, and the highest average concentrations of Cr and Pb appeared in the 45-50 cm and 70-75 cm layers, respectively. In general, the total concentration of heavy metals in surface sediments was lower than that in the bottom sediments from Jianhu Lake, and the concentrations of some heavy metals tended to decrease from the bottom layer to the surface layer.

Pollution and Ecological Risk Assessment

The geoaccumulation index of heavy metals in the sediments from Jianhu Lake is shown in Fig. 4. The average I_{geo} of Cd, Cr, Cu, Pb and Zn were -0.27, 0.47, -0.90, -1.08, and -0.28 in surface sediments, respectively. In surface sediments, the degree of Cd, Pb and Zn pollution followed the order of west>midde> east, and the degree of Cr and Cu pollution was middle>west>east. The average I_{geo} in core sediments were 0.00, 0.96, -0.56, -1.02, and 0.01, respectively. In surface sediments, the degree of Cd, Cr, and Zn pollution followed the order of west>middle>east, the degree of Cu pollution was middle>west>east, and the degree of Pb pollution was east>middle>west. The degree of heavy metal pollution in Jianhu sediments was markedly different, and the degree of Pb pollution was lowest and Cr pollution was greatest. The I_{geo} of Cr at the 12 sampling points in surface and core sediments was greater than 1 at 42%, which demonstrated very slight pollution, while 25% and 58% of I_{geo} were between 0 and 1, respectively, indicating a low pollution level, and the remaining sites were clean. Furthermore, the average I_{geo} of Cr in the surface (0.47) and core (0.96) sediments of Jianhu all exceeded that of Yunnan Provin ce (0.19) in the study by Xu et al. [17].

The potential ecological risk assessment of heavy metals in sediments from Jianhu is shown in Fig. 5. The average E_r^i of Cd, Cr, Cu, Pb and Zn were 45.59, 4.73, 4.59, 4.88 and 1.39 in surface sediments, respectively. In surface sediments from Jianhu, 33% of the 12 sampling points had an RI of more than 80, which is a high ecological risk level, and 25% had an RI between 40 and 80, which is a moderate ecological risk level, and the remaining sampling sites had a low ecological risk level. The average E_r^i of Cd, Cr, Cu, Pb and Zn in core sediments were 49.81, 6.47, 5.66, 4.72 and 1.71, respectively. In core sediments from Jianhu Lake, 25% of the 12 sampling points had an RI more than 80,

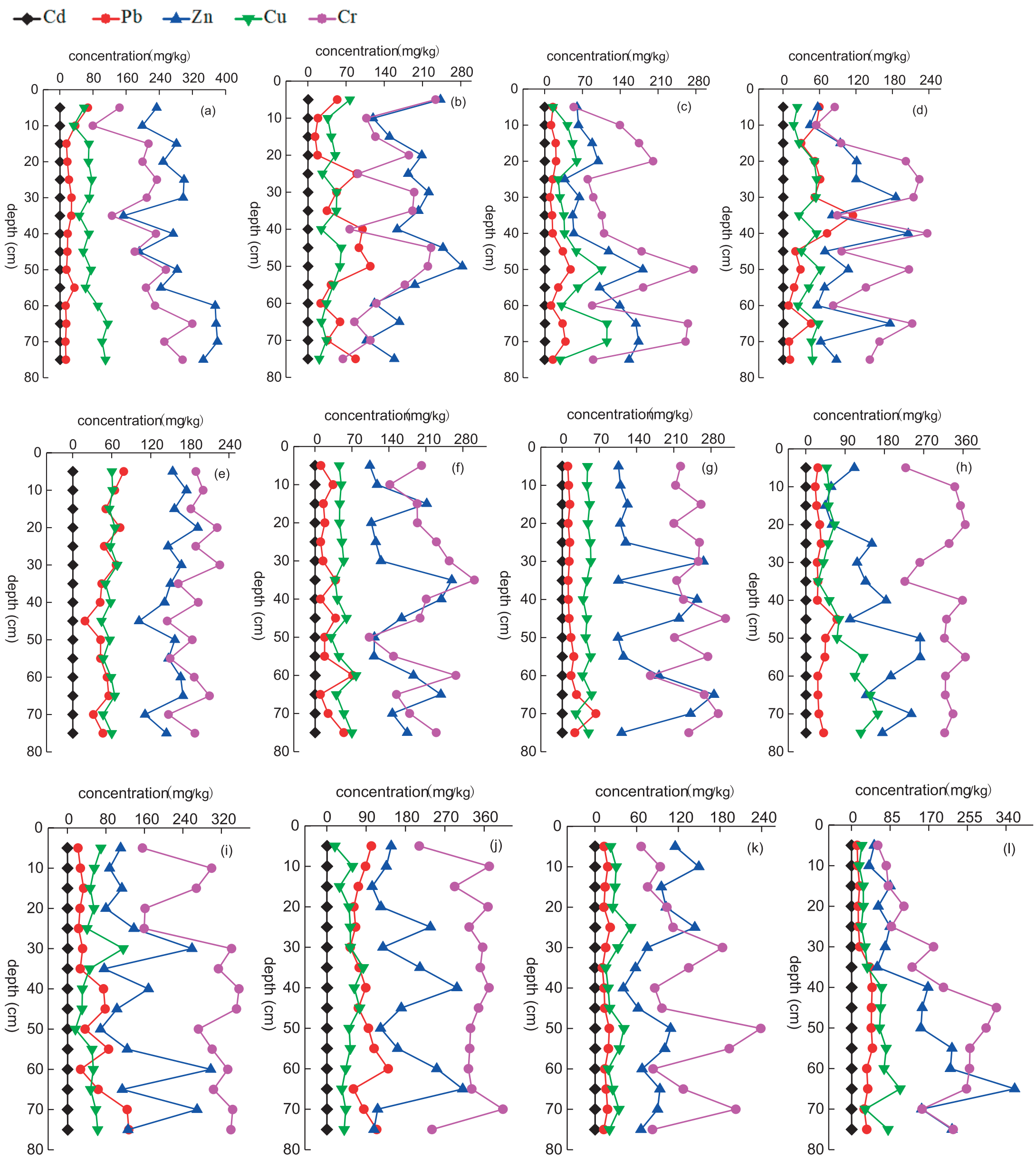

Fig. 3. Vertical distribution of heavy metals in Jianhu Lake core sediments (a to l show the sampling points 1 to 12).

which is a high ecological risk level, and 67% had an RI between 40 and 80, which is a moderate ecological risk level, and the remaining sampling sites had a low ecological risk level. The average E_r^i of Cd in surface and core sediments exceeded 30, which is a moderate risk, while the average E_r^i of Cr in the surface (4.73) and core (6.47) sediments exceeded that of Yunnan Province (3.40) in the study by Xu et al. [17]. The RI showed the order of west>middle>east in Jianhu Lake, and indicated that Cd contributed the greatest risk and Zn the lowest risk.

Release Contribution

The release contribution of heavy metals in Jianhu core sediments is shown in Table 4. At the 12 sampling points, the average short-term release contributions of Cd, Cr, Cu, Pb, and Zn were 67%, 42%, 50%, 58%, and 58%, and the average long-term release contributions were 42%, 17%, 33%, 42%, and 33%, respectively, and mainly were released. The average short- and long-term heavy metal release contributions were 55% and 33%, which equal the release status at the 12 sampling points, respectively, indicating that heavy metals in Jianhu sediments were released for a short time and stagnated for a long time. Due to the large difference in vertical spatial distribution characteristics of heavy metals in the sediments of Jianhu, and the difference in release contribution of the western, middle and eastern sections of the lake (which was also large), the overall order was west>middle>east. Moreover, the short-term release contribution of Pb and Zn was large, and the short-term and long-term release contributions of Cr were small. The release contribution of heavy metals

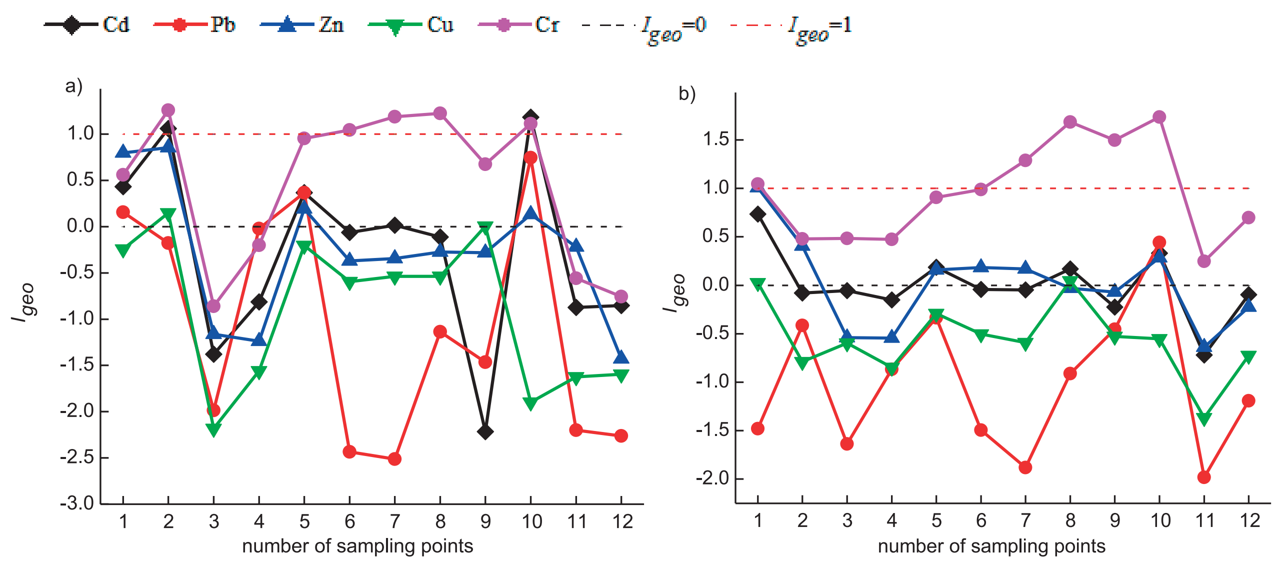

Fig. 4. Geoaccumulation index of heavy metals in surface a) and core b) sediments from Jianhu Lake.

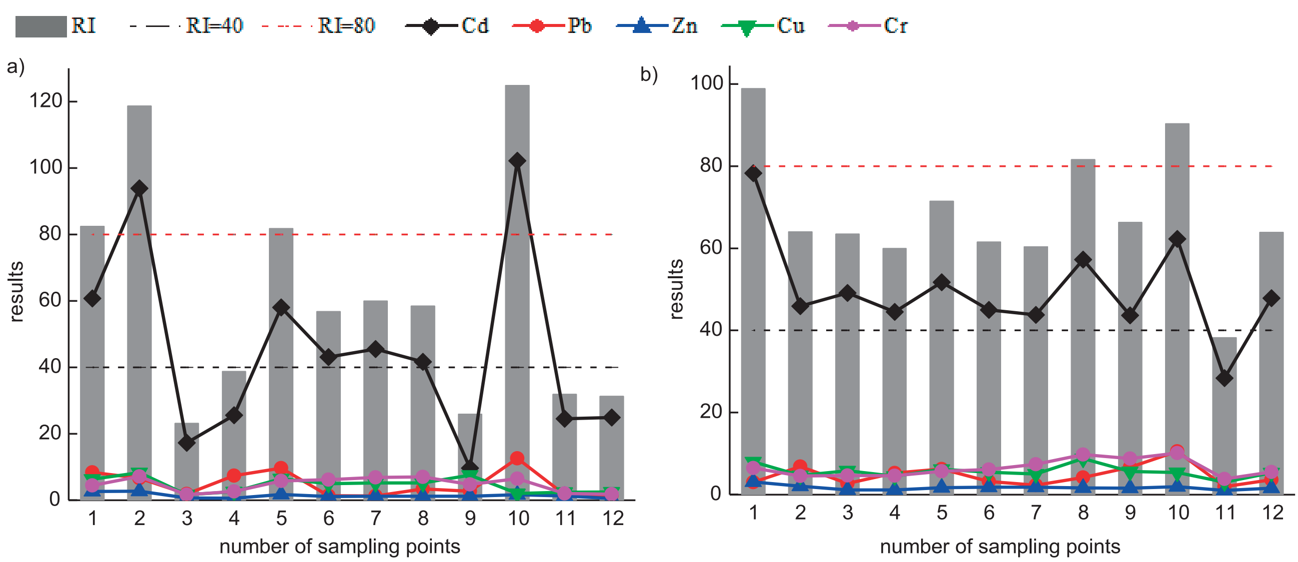

Fig. 5. Potential ecological risk index of heavy metals in surface a) and core b) sediments from Jianhu Lake.

varied considerably due to uncertainties in the sediment chronologies, particularly for heavy metals that have large variability in sediment [38].

Discussion

Concentrations of Heavy Metals in Surface and Core Sediments

Heavy metal pollution in lakes is mainly concentrated in the sediments and is transformed between the solid and liquid phases through the exchange reaction in the interface of water-sediment [39]. In addition, the most frequent exchange of substances and energy is between water and sediment in surface sediments [40]. The results of the comparison with average concentrations in national aquatic sediments, south aquatic sediments in China and the soil background value in Yunnan Province showed that there was different enrichment of heavy metals in surface sediments of Jianhu Lake. The differences in the concentrations between Cu, Pb and soil background value in Yunnan Province were small, indicating that these elements were mainly affected by regional geological background values, and human activities had little interference in these elements. Table 5 shows that there were significant positive correlations between Cd, Cr, Cu, and Zn in Jianhu surface sediments, indicating that they had the same source of contamination or that the heavy metals had a certain relationship, and this is in agreement with the findings of Khaled et al. [22]. The concentrations of the

Table 4. Release contributions of heavy metals in core sediments from Jianhu Lake (%).

Sampling point	Cd		Cr		Cu		Pb		Zn	
	V_1	V_2	V_1	V_2	V_1	V_2	V_1	V_2	V_1	V_2
1	0.12	-0.11	41.70	-41.15	16.18	-13.96	19.62	14.35	22.37	-30.44
2	0.12	0.15	38.80	49.28	12.43	16.21	10.80	-9.77	37.85	24.59
3	-0.15	-0.06	-71.92	-24.68	-22.71	-9.23	2.94	0.08	-2.28	-65.96
4	0.08	-0.07	55.92	-35.68	11.30	-15.40	9.69	29.84	23.02	-19.01
5	0.04	0.07	-23.56	3.36	-2.34	0.41	29.05	74.06	-45.00	22.10
6	0.01	-0.09	59.73	-16.71	-3.73	-14.47	-22.98	-26.10	-13.56	-42.63
7	-0.02	0.03	59.24	-42.34	6.66	-5.13	-10.44	-36.09	-23.68	-16.41
8	0.03	-0.13	-63.61	-36.40	-3.03	-31.83	3.35	-5.42	29.98	-26.22
9	-0.11	-0.18	-77.51	-58.95	7.36	2.17	-2.71	-33.84	12.30	-4.86
10	0.03	0.45	-71.20	-28.50	-17.86	-20.74	5.96	-11.85	4.96	38.46
11	-0.08	0.03	-36.73	-24.17	-10.70	2.26	-7.08	0.64	-45.41	72.89
12	0.12	-0.08	-50.07	-39.88	16.50	-13.85	-2.89	-5.06	30.42	-41.13

Notes: V_1 and V_2 represent short-term release contribution and long-term release contribution, respectively

five heavy metals in surface sediments were relatively high in the western section of the lake, as shown in Figs 1 and 2, and this indicated that the Xinshui and Yongfeng rivers were the main sources of heavy metal pollution. On the one hand, there was a lead-zinc heap upstream of the Xinshui, and the heavy metals in the mine slag entered Jianhu Lake by river transportation or soil infiltration [41], and settled near the estuary due to the decrease in water hydrodynamics at the estuary. On the other hand, the Yongfeng River was the main polluted river in Jiangchuan County, and municipal sewage increased heavy metal concentrations in the lake [17], while the quality of overlying water was closely related to sediments and increased heavy metal concentrations in the estuary sediments. In addition, the concentrations of Cd (0.08 mg/L), Pb (0.02 mg/L), and Zn (0.01 mg/L) in water from the Yonfeng are higher than other tributaries according to the information provided by the Dali Jianhu Lake Wetland Provincial Nature Reserve Management and Conservation Bureau. The concentrations of Cd and Pb were high in some parts of the eastern area of Jianhu Lake as this section is close to a rural residential area, and domestic sewage and garbage are directly discharged into the lake through small ditches. This section is also near a farming region, and phosphate fertilizer is used during local agricultural cultivation. Furthermore, phosphate fertilizer is mainly derived from apatite, and most or all Cd in apatite in the phosphate fertilizer [42] caused the accumulation of Cd in that area. The concentration of Cr was high in the Shihe River estuary, which was due to the Shihe River that flows through Shihe Village. There are a large number of woodcarving industries in Shihe Village. The use of wood preservatives increased the content of Cr in the soil and soil exudates [43], and are imported into Jianhu Lake from the river. In addition, the Jinlong River was the main contaminated river due to pollution from agriculture mostly in Jianchuan County; however, the heavy metal concentrations in sediments nearby were low in the Jinlong River estuary as the sediments had been excavated in the first half of 2016, indicating that excavation can effectively remove heavy metal pollutants and reduce the concentrations of heavy metals in sediments, and this is similar to the results by Chen et al. [21].

Sediments are carriers in the lake, and continuously receive most of the pollutants from the basin. The concentrations of heavy metals in a particular layer of sediment can show the loss intensity caused by natural and human activities in the basin during this period [44]. Significant correlations were also observed between Cd, Cr, Cu and Zn in core sediments of Jianhu Lake, which further indicated that the sources of pollution have commonality. Natural and human activities are distinctive in different areas and different periods of Jianhu Lake; therefore, the vertical distribution of heavy metals varied greatly in some areas. In addition, the vertical distribution characteristics of heavy metals in sediments are not only affected by pollution sources and geological background, but also by factors such as aquatic plants, oxidizable organic carbon, chlorides, electrical conductivity and grain size [45], and the large differences in vertical distribution characteristics of heavy metals in sediments from Jianhu Lake may also be related to these factors. Some studies have suggested that heavy metals in sediments are mainly concentrated in the surface layer, and it is possible to transfer to the lower layer only when the surface layer

Table 5. Correlation coefficients of heavy metals in Jianhu Lake sediments.

	Surface sediments					Core sediments				
	Cd	Cr	Cu	Pb	Zn	Cd	Cr	Cu	Pb	Zn
Cd	1					1				
Cr	0.614*	1				0.501	1			
Cu	0.217	0.705*	1			0.852**	0.646*	1		
Pb	0.560	0.347	0.158	1		0.324	0.448	0.213	1	
Zn	0.655*	0.684*	0.656*	0.516	1	0.794**	0.440	0.641*	0.253	1

Note: *Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level.

reaches saturation [46-47]. However, the heavy metal concentrations in Jianhu sediments were higher in the bottom layer than in the surface layer, indicating that heavy metal pollution is decreasing year by year in the lake, which is related to governmental protection and prevention measures, such as sediment dredging, plant harvesting, education propaganda and so on. The order of distribution was different from those in marine and coastal sediments [32, 47], and this may be attributed to complex reactions such as adsorption, precipitation and redox changes in the sediments [48].

Ecological Assessment

The I_{geo} and potential ecological risk of heavy metals in sediments in the western section was higher than that in other areas of Jianhu Lake, and this was related to the greater input of pollutants from the Yongfeng River and the serious loss of lead-zinc mining upstream of the Xinshui River. Human activities increased the accumulation of heavy metals in the sediments of the lake. Urban development, residential life, industrial activities and agricultural cultivation around Jianhu may increase heavy metal pollution in sediments. The most effective way to reduce heavy metal pollution in lakes is efficient control of pollution sources and strict enforcement of environmental regulations – especially wastewater discharge [17]. The I_{geo} and potential ecological risk of heavy metals in sediments in the excavation area were relatively low, indicating that the digging of sediments can effectively reduce the ecological risk and degree of heavy metal pollution, and is an effective measure for controlling the heavy metal pollution of sediments. Jianhu Lake is rich in biodiversity and plants, and some of the heavy metals in plants and animals can endanger human health through the food chain [43]. The pollution and risk degree for Cd are all relatively high according the assessment methods of geoaccumulation index and potential ecological risk index. Therefore, we consider that Cd was at a dangerous level. To be more convincing, the results obtained in our study are similar to the reports for freshwater lake sediments in China [17]. Cd is a carcinogen in humans, which can cause damage to the kidneys after enrichment in the human body, and can also cause acute bone deformation, while Cr poisoning can cause digestive disorders, convulsions and so on [43].

The release contribution of heavy metals in sediments from Jianhu Lake was very different mainly due to the large difference in vertical spatial distribution of the heavy metals. With the large variability in release contribution of heavy metal, we recommend that future studies account for the uncertainties associated with the sediment chronology because of the similarity to the research by Lintern et al. [38]. The release contributions of Pb and Zn were large, and Pb and Zn are harmful to humans and animals. Sludge, livestock manure, and automobile exhaust are all sources of Pb and Zn pollution [43]. Jianhu Lake is close to National Highway 214, and the sludge, livestock manure and automobile exhaust from residential areas and the highway may increase the content of Pb and Zn in sediments of Jianhu Lake. These heavy metals will be released again when they reach saturation in sediments, and will then pollute water and the ecological environment. Heavy metals in Jianhu sediments were released for a short time and stagnated for a long time, indicating that pollution needs to be processed in time. In addition, restoring ecosystems along the lakeshore can effectively intercept pollutants and prevent their migration [17].

Conclusions

Jianhu Lake is a small shallow lake in the plateau section of Yunnan Province, China. For each heavy metal measured, the spatial distribution characteristics in surface and core sediments were different, and the concentrations of each metal also varied greatly. The overall heavy metal concentrations were in the order of west>middle>east, and the concentrations in the bottom layer (70-75 cm) were higher than those in the surface layer (0-5 cm), and were mainly influenced by factors such as human activities and pollution source discharge. The average concentrations of heavy metals in surface and core sediments from Jianhu Lake were all higher than those in national aquatic sediments and south aquatic sediments in China, and there were significant positive correlations between Cd, Cr, Cu and Zn. The ecological risks and degree of pollution in surface sediments of Jianhu Lake showed the following trend: Cd>Pb>Cr>Cu>Zn and Cr>Cd>Zn>Cu>Pb, respectively. The ecological risks and degree of pollution in core sediments of Jianhu lake showed the following trend: Cd>Cr>Cu>Pb>Zn and Cr>Zn>Cd>Cu>Pb, respectively. In the short-term, most heavy metals in the sediments of Jianhu Lake had the potential for release, while in the long-term, they had the potential for retention.

Acknowledgements

We thank International Science Editing for editing this manuscript and the Dali Jianhu Lake Wetland Provincial Nature Reserve Management and Conservation Bureau for providing the heavy metal concentrations of tributaries. This study was supported by the Joint Agricultural Projects of Yunnan Province (Grant No. 2017FG001-018).

Conflict of Interest

The authors declare no conflict of interest.

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