Phosphorus speciation in sediments of Lake Hongfeng, China*

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Abstract This study was conducted to evaluate the distribution characteristics of phosphorus and its species in 14 sediments samples collected from Lake Hongfeng based on sequential extraction. Lake Hongfeng, a major drinking-water source for Guiyang City in southwestern China, is one of the largest artificial reservoirs located in a typical karstic area of the Yunnan-Guizhou Plateau. The results of this study indicate that the average percentages of DP, Al-P, Fe-P, Ca-P and OP in the lake sediments were 0.52, 6.59, 6.09, 42.85 and 40.27, respectively. The concentrations of organic phosphorus (OP) were lower than those of inorganic phosphorus (IP), which consisted mainly of calcium-bound phosphorus (Ca-P). The high concentrations of Ca-P may temporarily control the release of phosphorus from the sediments because it is a relatively stable, inert, and non-bioavailable phosphorus fraction. However, a large number of phosphate solubilizing bacteria can transform insoluble phosphate into bioavailable forms. Moreover, the concentrations of total phosphorus (TP) in the lake sediments were high; thus, the potential for the release of phosphorus from the sediments to the water column and phosphorus bioavailability were still significant. Further statistical analyses of the results revealed significant correlations between phosphorus species in sediments from the lake with two extractable principal component species (PCs) and five selectable cluster levels allowing interpretation of possible origins of phosphorus loading and the release of phosphorus. Furthermore, available remediation measures were briefly assessed for the lake with consideration of its distinctive environmental features.

Keyword: Eutrophication; karstic environment; lake sediments; phosphorus speciation; sequential extraction procedure

1 INTRODUCTION

Lake sediments act as a highly effective sink for contaminants (e.g. phosphorus, nitrogen, heavy metals, etc.) in lakes (Milenkovic et al., 2005). The physical and chemical properties of aquatic systems such as temperature, pH value and redox status play an important role in the release and sorption of phosphorus. When the conditions of sediments are altered, contaminants are released from sediments into the water column (Lee et al., 2008). Due to the effects of currents, thermal stratification, fall overturn and particle transport, the sediments will reverse through cycles of re-suspension, horizontal transport and re-deposition, resulting in the return of significant amounts of the contaminants to the water column. In such cases, lake sediment becomes a secondary source of pollution; therefore, it has always been considered an indicator for the pollution of aquatic ecosystems.

Phosphorus limits primary production in many freshwater ecosystems (Paerl et al., 2004; Surridge et al., 2007), and because of loss from the water column by sedimentation and lack of a gas phase, (An et al., 2002), it is generally regarded as one of the most important limiting factors among nutrients for accelerating eutrophication (Ádám et al., 2005; Chinault et al., 2008; Penn et al., 2008; Conley et al., 2009). Indeed, phosphorus has become one of the main factors leading to eutrophication in Lake Hongfeng,

which has sometimes caused algal blooms, fish suffocation, taste-and-odor problems for water suppliers, and other undesirable effects (Wan, 2009). In addition, some algae can produce toxins that are associated with human health problems (Kotut et al., 2006). Accordingly, analysis of phosphorus in sediments of lakes that are used as drinking-water sources is critically important. Phosphorus concentrations in the water column are regulated by the sediment phosphorus flux, which not only depends on total phosphorus (TP), but also on the chemical association between the phosphorus and the sediments (Beauchemin et al., 2003). Therefore, it is important to understand the different forms in which phosphorus exists in sediments (Pardo et al., 2003; Haggard et al., 2005).

One of the commonly adopted methods of identifying phosphorus species in sediment is the fractionation approach. In this method, the phosphorus is first divided into organic and inorganic forms and the inorganic forms are then divided into dissolved phosphorus (DP), aluminum-bound phosphorus (Al-P), iron-bound phosphorus (Fe-P) and calcium-bound phosphorus (Ca-P) (Jin et al., 1990; Spivakov et al., 1999; Yu et al., 2007; Jiang et al., 2008). This type of partition is based on the diversity of phosphorus bioavailability and release potential in different lake environments.

Recently, the sediments from Lake Hongfeng have been heavily polluted with high levels of nutrients, and eutrophication of the lake has received a great deal of attention from the government and environmental researchers. Previously, Wang et al. (2000) and Wang et al. (2004) investigated the chemical species of phosphorus in sediments from Lake Hongfeng using a sequential extraction technique in which the phosphorus was divided into loosely sorbed P, Fe-P, Ca-P, detrital-P and organic phosphorus (OP). The main objectives of this study were to investigate the distribution characteristics of phosphorus and its species in sediments from the lake based on sequential extraction (Jin et al., 1990) and to analyze the correlations between the phosphorus species with statistical methods to identify possible origins of the phosphorus loadings and the release of phosphorus. In addition, possible remediation measures were briefly evaluated for the lake with respect to the karstic environment.

2 MATERIAL AND METHOD

2.1 Area of Study

Lake Hongfeng, located in 106°24′–106°43′E,

26°31′–26°34′E, is a typical seasonal anoxic lake, with anoxic conditions primarily occurring during autumn (Xiao et al., 2003; He et al., 2006). The lake is one of the largest man-made reservoirs located on the Yunnan-Guizhou Plateau in southwestern China. The lake is situated on a tributary of the Wujiang River that flows into the Three Gorges Reservoir, one of the largest artificial lakes in the world, on the Changjiang (Yangtze) River. Lake Hongfeng was constructed in the 1960s when the first of seven cascade hydropower stations along the Maotiao River, a tributary of the Wujiang River, was established. The lake covers an area of 57.2 km^2 and holds 6.01×10^8 m^3 of water. The lake is also one of the five drinking-water sources for the approximately 3×10^6 people in Guiyang City, the capital of Guizhou Province. The local geology is of typical karstic limestone terrain and rich in phosphate rock deposits. Hongfeng is a multi-functional water body that is used not only for drinking water, but also for hydropower, flood control, shipping, recreation and commercial aquaculture (cage-culture fishing) (Zhang, 1999).

2.2 Sample Collection and Analysis

2.2.1 Sampling

Superficial sediment samples used in this study were collected during October 2008 with a stainless steel grab-sampler at fourteen locations: Matou, Daba, Jinmengyuan, Tielvhejinchang, Daposhang, Beihuhuxin, Tixiao, Huayudong, Huayudongdaqiao, Aoli, Houwu, Xinzhuang, Laohouwu and Houwuhuodianchang (Fig.1), which were predetermined based on the size, shape and direction of water flows in the lake. The precise collection sites were corrected in situ using a global positioning system (GPS). Each sample was obtained by mixing the sediments sampled near the sample location 3 to 4 times. In addition, the Secchi transparency (20 cm disk) was measured at the time of sample collection. Samples were collected in glass bottles (1 000 cm^3 volume) that had been pre-cleaned with 5% HCl (v/v) and 5% HNO$_3$ (v/v), and immediately transported to our laboratory, where the sediments were centrifuged and the supernatant discarded. Subsamples of sediments were dried at room temperature for 1–2 weeks prior to the experiments, then ground into powders and screened through a nylon sieve, after which the < 150 μm particles were analyzed. The sediment powder was oven-dried at 105°C for 24 h to determine the moisture content (Kruopiene, 2007). To determine the pH values of the sediments, 5.000 0 g
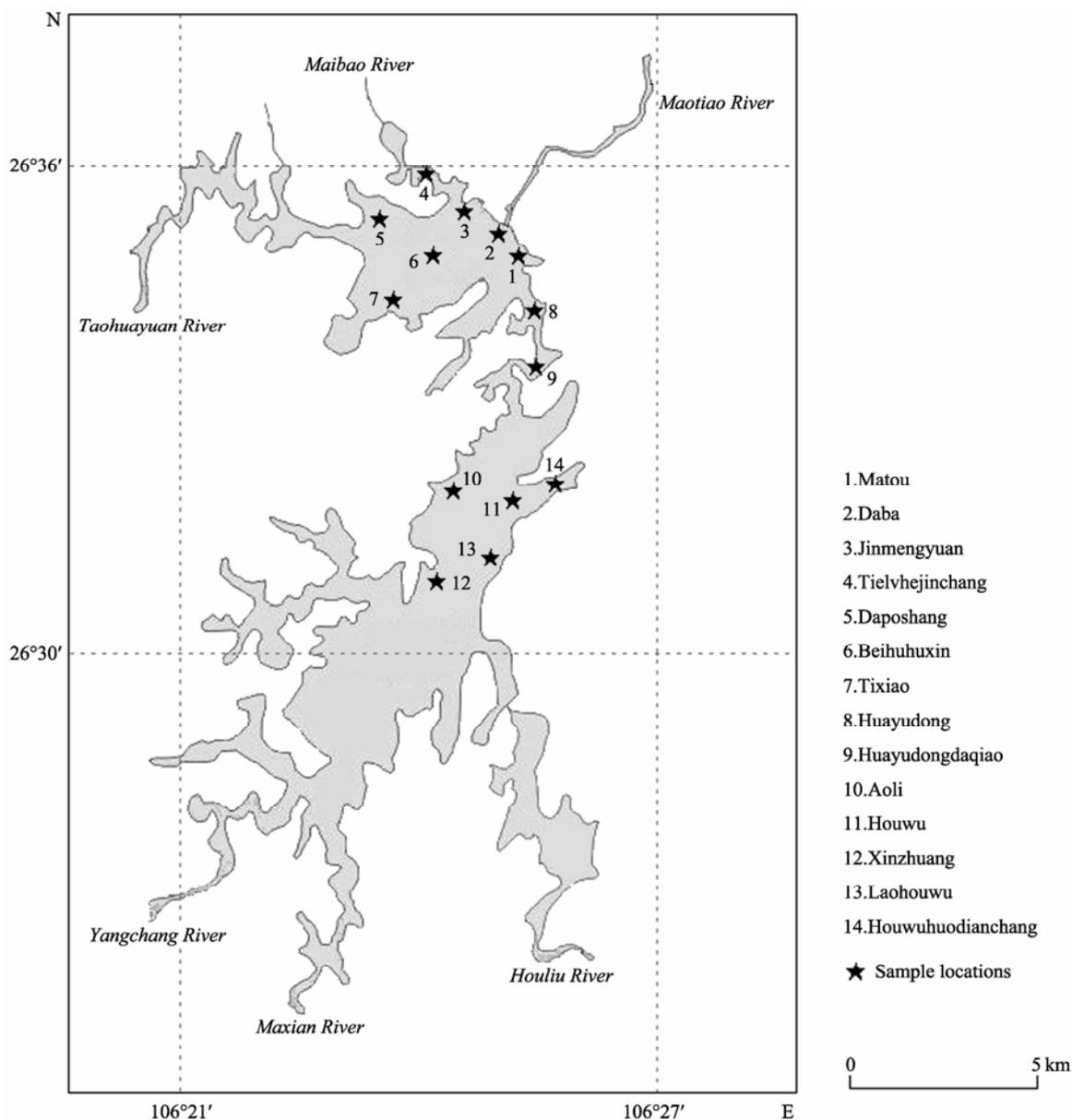
Fig.1 Distribution of sampling sites in Lake Hongfeng

of powdered sediments were weighed into a 50 mL beaker, after which 25 mL of fresh distilled water were added and the sample stirred thoroughly and then allowed to stand for over 1 h. Before analysis, the solution was stirred gently to suspend the sediments. The electrode of a pH meter was then immersed in the solution for 30 s and the pH value was obtained when the reading became stable (Jin et al., 1990).

2.2.2 Analysis of TP in sediments from the lake

For TP determination, a SMT protocol developed by the Standard Measurements and Testing Program of the European Commission was applied in this study (Ruban et al., 2001). Briefly, 0.100 0 g of each

sediment sample (dried at room temperature) was weighed accurately into a crucible and calcined at 450°C for 3 h. The sample from each sediment was then added to 20 mL of 3.5 mol/L HCl and shaken on the aforementioned oscillator at 30 rpm and 25°C for 16 h. The extract was then separated by centrifugation at $4\ 000 \times g$ for 15 min, after which the supernatant was collected for analysis. The concentrations of phosphorus were determined using a spectrophotometric technique based on the formation of heteropoly species of phosphoric acid with ammonium molybdate, the color of which can be enhanced by reducing the molybdophosphoric acid by ascorbic acid in the presence of potassium antimonyl tartrate (Spivakov et al., 1999).

2.2.3 Chemical speciation of phosphorus in sediments from the lake by sequential extraction

The scheme consisted of a sequential extraction procedure, which was designed to target the forms of phosphorus (Jin et al., 1990). *First step* (*DP*): 1.000 0 g of each sediment sample was weighed accurately into a 100-mL centrifuge tube and 50 mL of 1 mol/L NH_4Cl solution were added. The mixture was then shaken for 30 min. The extract was separated from the solid residue by centrifugation at 4 000 × *g* for 15 min. The supernatant was decanted and collected for analysis. *Second step* (*Al-P*): 50 mL of 0.5 mol/L NH_4F solution were added to the residue from the first step and the pH value was adjusted to 7.0. The mixture was then shaken for 1 h, after which the extract was separated as above. *Third Step* (*Fe-P*): 50 mL of 0.1 mol/L NaOH solution were added to the residue from the second step, after which the mixture was shaken for 17 h and the extract was separated as above. *Fourth step* (*Ca-P*): 50 mL of 0.5 mol/L H_2SO_4 solution were added to the residue from the third step, the mixture was shaken for 1 h and the extract was separated as in the previous steps. For inorganic phosphorus (IP) determination, 0.100 0 g of each sediment sample was weighed accurately into a 100-mL centrifuge tube and 20 mL of 1 mol/L HCl solution were added. The mixture was then shaken for 16 h, the extract was separated as above and the supernatant was collected for analysis. The OP was calculated from the difference between TP and IP. The phosphorus concentrations of all extracts were determined as TP described above.

2.3 Quality Control Study

2.3.1 Instrument and reagent

The following instruments were used in the present investigation. (1). A GPS-72 system produced by American Garmin Corporation (Taiwan). (2). A UV-Visible spectrophotometer (Cary 100 Bio) produced by Varian Corp. (USA). (3). A Nex Power water purification system produced by Human Corp. (Korea). (4). A delta-320 pH meter produced by Mettler-Toledo Instruments Ltd. (Shanghai, China). (5). A SHZ-C immersion oscillator produced by Shanghai Medical Instruments Corp. (China). All reagents used in this research were made in China. The hydrochloric acid (HCl), nitric acid (HNO_3) and sulfuric acid (H_2SO_4) were guaranteed reagent (GR) grade, and the other reagents used were analytical reagent (AR) grade. The deionized water was produced using the water purification system listed above.

2.3.2 Quality control

For analytical quality assurance of TP determination, a soil sample from China's National Reference Materials (Sample Code: GBW 07403) was analyzed. The analytical result of the reference material in the present study was consistent with the certified value (Table 1). To determine the forms of phosphorus in the samples, the sum of the percentages of each phosphorus species was compared with that of the TP in the sediment sample to verify the accuracy due to the lack of suitable standard reference material. The sum of percentages ranged from 93.61 to 99.65 (Table 2). For each set of analyses, blanks were also used for background correction. Re-analysis of 15% of the samples to control the analytical quality resulted in relative standard deviations of less than 5%.

Table 1 Concentrations of TP and pH in sediments from Lake Hongfeng (dry weight) and the certified and detected TP concentrations of the standard reference material (GBW-07403)

| Sampling sites		TP (mg/kg)	pH
1. Matou		1 437.00	7.68
2. Daba		2 133.20	7.54
3. Jinmengyuan		1 321.91	7.74
4. Tielvhejinchang		1 105.35	7.73
5. Daposhang		1 625.95	7.60
6. Beihuhuxin		1 651.12	7.63
7. Tixiao		1 620.88	7.60
8. Huayudong		1 695.25	7.66
9. Huayudongdaqiao		850.27	7.89
10. Aoli		1 976.84	7.66
11. Houwu		1 484.09	7.76
12. Xinzhuang		1 852.17	7.71
13. Laohouwu		1 688.82	7.63
14. Houwuhuodianchang		1 222.66	7.82
Mean		1 547.54	7.69
GBW-07403	Certified value	320±18	---
	Detected value	335.89	---

3 RESULT AND DISCUSSION

3.1 Distribution of TP in Sediments from the Lake

The TP in sediments collected from Lake Hongfeng ranged from 850.27 to 2 133.20 mg/kg (Table 1 and Fig.2), and the average value was 1 547.54 mg/kg sediments from Lake Chaohu in Anhui Province and Lake Xihu in Fujian Province, China, ranged from

Table 2 Phosphorus speciation of sediments from Lake Hongfeng (dry weight)

Sampling sites	DP		Al-P		Fe-P		Ca-P		OP		Sum
	mg/kg	%	mg/kg	%	mg/kg	%	mg/kg	%	mg/kg	%	%
Matou	7.82	0.54	85.60	5.96	113.55	7.90	563.37	39.20	603.60	42.00	95.60
Daba	11.04	0.52	261.71	12.27	113.41	5.32	916.00	42.94	784.16	36.76	97.81
Jinmengyuan	5.15	0.39	71.38	5.40	93.48	7.07	497.12	37.61	609.42	46.10	96.57
Tielvhejinchang	5.18	0.47	57.90	5.24	51.08	4.62	395.90	35.82	536.81	48.56	94.71
Daposhang	5.26	0.32	120.53	7.41	163.58	10.06	619.87	38.12	706.04	43.42	99.33
Beihuhuxin	10.58	0.64	158.60	9.61	88.11	5.34	726.92	44.03	561.25	33.99	93.61
Tixiao	7.81	0.48	54.01	3.33	121.95	7.52	705.56	43.53	662.13	40.85	95.71
Huayudong	7.98	0.47	141.46	8.34	97.25	5.74	795.71	46.94	602.31	35.53	97.02
Huayudongdaqiao	7.56	0.89	79.18	9.31	33.69	3.96	353.78	41.61	323.32	38.03	93.80
Aoli	10.54	0.53	138.36	7.00	112.42	5.69	907.97	45.93	739.26	37.40	96.55
Houwu	8.74	0.59	59.19	3.99	60.93	4.11	718.07	48.38	555.23	37.41	94.48
Xinzhuang	10.04	0.54	89.38	4.83	128.91	6.96	966.85	52.20	639.78	34.54	99.07
Laohouwu	7.97	0.47	121.95	7.22	113.24	6.71	783.96	46.42	655.77	38.83	99.65
Houwuhuodianchang	5.23	0.43	29.41	2.41	51.90	4.24	454.09	37.14	615.45	50.34	94.56
Mean	7.92	0.52	104.90	6.59	95.96	6.09	671.80	42.85	613.90	40.27	96.32
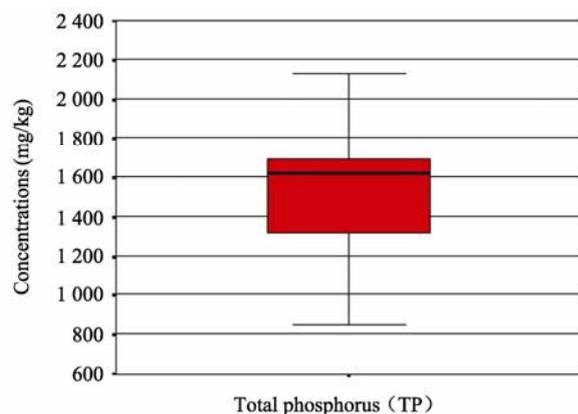
Fig.2 Graphical presentation of statistical parameters for TP in sediments from Lake Hongfeng (the median, quartiles, upper and lower adjacent values, and outliers)

450 to 560 mg/kg and from 750 to 900 mg/kg, respectively (Huang et al., 2003; Su et al., 2005). Thus, it is evident that the phosphorus level in sediments from Lake Hongfeng was high when compared with Lake Chaohu and Lake Xihu, which are both eutrophic lakes. This is likely due to the sources of pollution that are input into Lake Hongfeng. These pollution sources arise from different industries (e.g. fertilizer plants and power plants), urban activities (e.g. use of detergents), agriculture, cage-culture fishing, recreation, coal mining, storm water runoff and atmospheric deposits. Based on its geographical surroundings, it is evident

that the main pollutant sources to Lake Hongfeng are fertilizer plants and rural and urban activities in Pingba County (Zhang, 1999).

The highest value of TP was at the Daba sampling site, followed by the Aoli sampling site, and these two values were much higher than those for the other sites. At the Huayudongdaqiao site, the value of TP was lowest among all sampling sites. This was likely due to the distribution of the point pollution sources around the lake. The majority of the phosphorus that enters aquatic systems is in particulate form, which results in surface sorption onto minerals produced by rock weathering and chemical precipitation, and causes the phosphorus to eventually reach the lake bottom (Spivakov et al., 1999; Li et al., 2007). The water flow is mild around the dam located downstream of Lake Hongfeng; thus, it facilitates sustainable long-term storage of phosphorus in sediments. As a result, the main pollution sources for the Daba site, which is adjacent to the dam, should be urban sewage from Pingba County and wastewater from fertilizer producing companies. Indeed, a large amount of wastewater likely comes from the Pingba Fertilizer Plant, which mainly produces phosphorus-related products. The sewage treatment facilities for these pollution sources have not been very effective and the effluents discharged into the lake from the facilities do not meet the national effluent standards. Although the Pingba Fertilizer Plant has been shut down, its effects on

phosphorus loadings in the lake are still likely considerable. The main pollution sources around the Aoli site are untreated urban sewage from nearby small towns and villages. However, the point source pollution was lower around the Huayudongdaqiao site than the other sites.

3.2 Phosphorus Forms in Sediments from the Lake

The average percentages of DP, Al-P, Fe-P, Ca-P and OP in sediments from Lake Hongfeng were 0.52, 6.59, 6.09, 42.85 and 40.27, respectively (Table 2 and Fig.3). The results obtained in the present study agreed well with previously published semiquantitative characteristics, which suggested that the content of OP in sediments is lower than that of IP consisting mainly of apatitic phosphorus in sediments from calcareous regions (Spivakov et al., 1999). Deposition of phosphorus is limited by the sediment's binding capacity (Moosmann et al., 2006); therefore, the results of the present study are likely attributable to the typical carbonate-rock dissolution environment of the lake, where there is abundant calcium. Ca-P (apatitic phosphorus) in sediments could be easily released at low pH (Jin et al., 1990), while an increase in pH was found to be accompanied with autogenetic processes of calcium carbonate and subsequent elevated Ca-P levels in sediments (Huang et al., 2005). As described in Table 1, the sediment pH exhibits alkalescence; thus, Ca-P in sediments from the lake should be relatively stable. Generally, Ca-P is regarded as having a relationship with local geology and being a relatively stable, inert and non-bioavailable phosphorus fraction. Ca-P may temporarily control phosphorus release from sediments since there are a large number of phosphate solubilizing bacteria that can transform insoluble phosphate into bioavailable forms. Moreover, Fe-P, a bioavailable phosphorus fraction in the absence of oxygen, may be released from sediments in the lake. Because ligand competition between PO_4^{3-} and OH^- in the sediments would cause the availability of binding sites on ferric complexes to decrease with increased pH, the Fe-P in the sediments would also decrease (Huang et al., 2005). Furthermore, the TP in sediments from the lake was high; therefore, the release potential and bioavailability of phosphorus in the sediments of this lake were still high.

The results of this study demonstrated that DP was a minor fraction in TP and was regarded as readily available for uptake by biota. TP primarily consisted
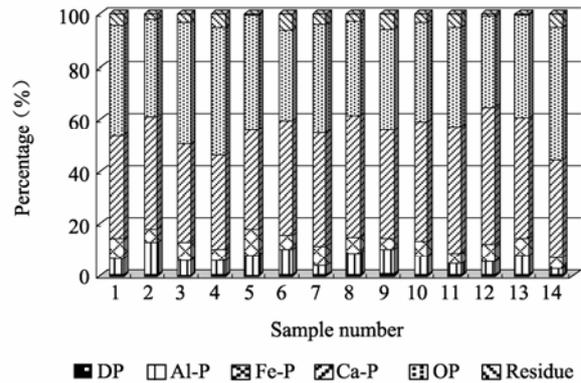

Fig.3 Percentage composition of phosphorus species in sediments from Lake Hongfeng

of Al-P, Fe-P, especially Ca-P and OP. OP was considered to be mainly from rural agricultural cultivation and fertilization and was a slowly but continuously bioavailable fraction of phosphorus. In Lake Hongfeng, the highest value of OP was observed at the Houwuhuodianchang sampling site, followed by the Tielvhejinchang site. These two values were much higher than those for the other sites. The OP was lowest at the Beihuhuxin site. The Houwuhuodianchang and Tielvhejinchang sites are close to the Qingzhen Power Plant and Guizhou Fertilizer Plant, respectively; thus, industrial wastewater and urban sewage around these two sites were more serious, but no industrial wastewater or urban sewage enters the Beihuhuxin site directly. Furthermore, cage-culture fishing used to be very popular around the Houwuhuodianchang site. Although cage-culture fishing was recently prohibited, it likely had a considerable effect on the nutrient (e.g. OP) loadings in that region of the lake. Al-P and Fe-P are regarded as being mainly from industrial wastewater and urban sewage discharges, and Al-P is also the bioavailable phosphorus fraction in the absence of oxygen. As a result, analysis of the phosphorus fractions in sediments can enable the main pollution sources to be assessed and various restoration measures to be adopted for different regions.

To present an in-depth analysis, the correlations between phosphorus species in sediments from Lake Hongfeng were evaluated. As shown in Table 3, DP, Al-P, Fe-P, OP, especially Ca-P, all showed significant positive correlations with TP. These results indicated that TP in sediments from the lake was closely related to its speciation, and that chemical forms of phosphorus in sediments from the lake may be applied as a potential marker to assess the level of phosphorus pollution. The results also

suggest that apatitic phosphorus is the most important fraction of IP in sediments from calcareous regions as presented above. It was also found that Fe-P, Al-P, and especially DP exhibited significant positive correlations with Ca-P, indicating that Ca-P plays an important role in the biogeochemical process of phosphorus. Fe-P and Ca-P showed significant positive correlations with OP, which was likely due to the similar formation process of various forms of phosphorus. Alkaline phosphatase catalyzes mineralization of OP (Deng et al., 2009), after which OP is transferred into a soluble orthophosphate pool that may be removed from the dissolved phase by chemical precipitation with Al^{3+}, Fe^{3+} and Ca^{2+}, subsequently undergoing diagenesis, which is related to the local redox conditions (Spivakov et al., 1999). Al-P exhibited a positive correlation with DP, which may have been due to the bioavailable fraction of phosphorus since these two forms are both readily bioavailable phosphorus fractions.

Table 3 Pearson's correlation coefficients between TP, DP, Al-P, Fe-P, Ca-P and OP in sediments from Lake Hongfeng

	TP	DP	Al-P	Fe-P	Ca-P	OP
TP	1					
DP	0.695[b]	1				
Al-P	0.712[b]	0.645[a]	1			
Fe-P	0.717[b]	0.208	0.393	1		
Ca-P	0.947[b]	0.788[b]	0.606[a]	0.605[a]	1	
OP	0.846[b]	0.267	0.488	0.746[b]	0.673[b]	1

[a] Correlation is significant at the 0.05 level (two-tailed)

[b] Correlation is significant at the 0.01 level (two-tailed)

Principal component analysis (PCA), a multivariate statistical analysis, was also conducted to interpret possible origins of phosphorus loadings and the release of phosphorus in sediment from Lake Hongfeng. PCA can reduce a raw data set consisting of many variables to a smaller set of derived variables having the statistically desirable properties of orthogonality (i.e. the derived variables are uncorrelated with each other). Prior to PCA analysis, Bartlett's test of sphericity (BTS), an indicator of the strength of the relationship among variables, was conducted. Specifically, Bartlett's test of sphericity was used to test the null hypothesis that the variables in the population correlation matrix were uncorrelated. The observed significance level was 0.000, which was small enough to reject the hypothesis and indicated that the strength of the relationship among variables was strong. In addition,

the results of Pearson correlation analysis revealed several correlations among phosphorus species. Therefore, the data set was appropriate for use in the PCA. As shown in Table 4 and Fig.4, PCA demonstrated there were two principal components that could explain 87.3% of the total variance. It should be noted that only loading scores greater than 0.5 were considered in this study. As shown in Table 4, component 1 accounted for 69.5% of the total variance, and TP, DP, Al-P, Fe-P, Ca-P and OP all presented high positive correlations with Component 1. Component 2 accounted for 17.8% of the total variance and DP presented a positive correlation with Component 2, while Fe-P exhibited a negative correlation. Based on these results, Component 1 may be seen as stressing the origins of phosphorus loadings from both terrigenous and external inflows (point and non-point pollution sources), e.g. the geochemical features in this region, industrial wastewater, and the nearby coal mining facilities. Component 2 likely reflects the redox environment of the sediments. Hongfeng is a seasonal anoxic lake. It is generally accepted that in a reductive environment, Fe^{3+} is easily reduced to Fe^{2+} and causes the release of phosphorus to the overlying water (Song et al., 2003).

Hierarchical cluster analysis (HCA), which is a statistical method for identifying relatively

Table 4 Component matrix

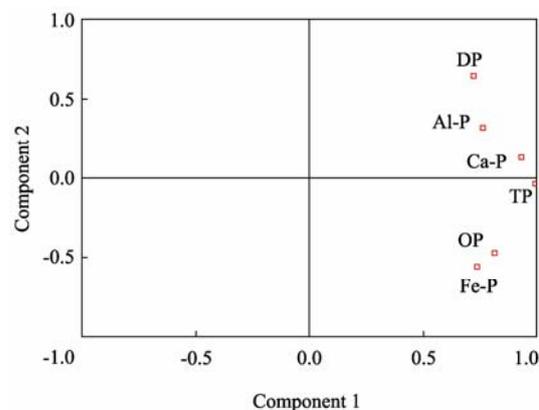|	Principal components	
	Component 1 (69.5%*)	Component 2 (17.8%*)
TP	0.993	—
DP	0.722	0.643
Al-P	0.765	—
Fe-P	0.736	-0.560
Ca-P	0.935	—
OP	0.815	—

* Percentage of variance

Fig.4 PCA of phosphorus species in sediments from Lake Hongfeng

homogeneous clusters of cases based on measured characteristics, was also conducted. This technique begins with each case in a separate cluster and then combines the clusters sequentially, reducing the number of clusters at each step until only one cluster is left. The dendrogram of HCA describing phosphorus and its species in sediments from Lake Hongfeng is shown in Fig.5. Generally, the 5-cluster level was selected for all test locations. The first cluster contains eight locations: Huayudong, Laohouwu, Matou, Tixiao, Houwu, Aoli, Xinzhuang and Beihuhuxin; the second one contains one location: Daposhang; the third one also contains only one location: Daba; the fourth one contains three locations: Tielvhejinchang, Houwuhuodianchang and Jinmengyuan; the last one contains one location: Huayudongdaqiao. Obviously, the pollution status of all of the locations belonging to one cluster is similar, and a greater distance between two clusters is associated with a greater discrepancy in pollution intensity among sediments.
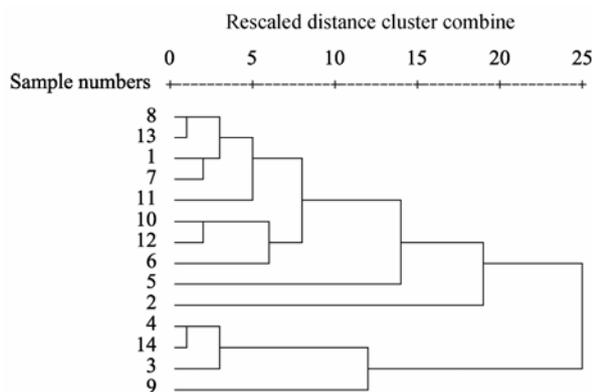

Fig.5 Dendrogram of HCA describing phosphorus and its species in sediments from Lake Hongfeng (the horizontal scale corresponds to the degree of pollution at each location), using average linkage (between groups)

3.3 Methods of Controlling the Release of Phosphorus from Sediments

Phosphorus pollution in lakes includes external inflows from watersheds and release from bottom sediments. Controlling the phosphorus input into Lake Hongfeng is extremely challenging because Guizhou is a major region in China for phosphorus mining by two large-scale phosphorus mining companies, Kaiyang and Wengfu. In addition, this region is used for associated industries such as the production of phosphorus fertilizer and mixed fertilizer. Moreover, even if external phosphorus sources have been curtailed, the release of

phosphorus from sediments is sometimes sufficient to maintain anthropogenic eutrophication for long periods in many lakes and reservoirs (Fisher et al., 2001). Since algal blooms have occurred in Lake Hongfeng during recent years, local governments under the support of central governments are drafting a large-scale comprehensive plan to clean the lake and other local drinking-water sources by decreasing phosphorus and nitrogen pollution. To accomplish this, some researchers have suggested several types of control measures for the release of phosphorus from sediment, such as dredging, sediment capping and in-situ remediation.

For dredging, characterization of the sediment quality is crucial due to the cost, environmental impact and public acceptance (Kinaci et al., 2004). However, it is not possible to obtain comprehensive information regarding the critical sediment characteristics of Lake Hongfeng since the bottom is not as flat as those of Lake Taihu and Lake Dianchi. This is due to its being located in a Karst landform, where there are probably caves and underground rivers under the bottom of the lake that can transport phosphorus pollutants to other locations and cause unknown consequences for a long period of time (Huang et al., 2009). Liu et al. (2006) reported that sediment dredging would cause a temporary risk of water quality deterioration in Lake Taihu. In the case of Lake Hongfeng, sediment dredging will likely destroy the equilibrium of the ecological system, resulting in loss of the self-purification capacity. Moreover, there are a multitude of other contaminants in the sediments, including heavy metals, which will be likely be released to the overlying water in large quantities by dredging, since lake eutrophication is propitious to reduce the heavy metal toxicity to the aquatic organisms in sediments (Liu et al., 2009). Moreover, if the sediments are removed it is necessary to determine a mode of treating the dredged sediments. Although the sediment sludge could be applied to agricultural land as fertilizer because it can supply important nutrients to the soil (Nathalie et al., 2002), this practice may result in the accumulation of pollutants (e.g. heavy metals) from sludge in the soil. Therefore, dredging is not a feasible method for restoration of the water body. Due to their distinctive geophysical characteristics, capping and in-situ remediation also do not appear to be feasible modes of treatment. Additionally, the cost of the capping approach is generally considered too high due to the need for long term monitoring and maintenance. Thus, it will

be extremely difficult to restore this drinking-water source as a result of its unique environmental features. Accordingly, a new method of remediation must be developed.

4 CONCLUSION

The results of this study demonstrate that OP in sediments from the lake was lower than IP, which consisted mainly of Ca-P due to the typical karstic limestone environment of the lake. Ca-P is a relatively stable, inert and non-bioavailable phosphorus fraction that may temporarily control the release of phosphorus from sediments. Moreover, the levels of TP in sediments from the lake were high. Therefore, the potential for the release of phosphorus from sediments to the water column and phosphorus bioavailability was high. Because the variation of pH could cause the mobility of phosphorus in the sediments, and the pH-induced phosphorus mobility in sediments is very important for the highly human-disturbed lake, our future studies may consider the risk of phosphorus release with the variation of pH. The phosphorus loadings in the lake together with other upstream lakes will not only cause local algal blooms, but will ultimately influence the Three Gorges Reservoir on the Changjiang (Yangtze) River via the Wujiang River. This will add to the unpredictable eutrophication of a much larger water body. Therefore, effective measures must be taken to control the release of phosphorus from sediments during the lake restoration in conjunction with reducing the nutrient input from both point and non-point sources of pollution.

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