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Original Research

Vertical Distributions of Phosphorus Fractions in Sediments of Three Typical Shallow Urban Lakes in P.R. China

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Abstract

Sediment cores were sampled from three typical shallow urban lakes in China. The Standards, Measurements and Testing (SMT) programme, proposed by the European Commission, was employed to characterize the vertical distributions of phosphorus fractions in sediment profiles. The results showed that TP contents ranged from 1,198.9 to 1,897.3, 1,289.1 to 1,652.1, and 611.7 to 760.3 mg kg^{-1} in sediment profiles of Daming Lake, Mochou Lake, and Xuanwu Lake, respectively. Within the 50-cm sediment profiles, phosphorus distributed mainly in IP, and the OP contents only accounted for 9.7%--16.3% of TP. For IP in sediments, the AP was the predominant fraction for Daming Lake and Mochou Lake, accounting for 92.8%, and 71.4%, respectively. While for Xuanwu Lake the proportion of NAIP to IP was higher than that of AP (41.7%±6.0%), indicating that the Xuanwu Lake was polluted more heavily than the other two lakes. The phosphorus concentration in pore-water (TDP) correlated significantly to the P fractions in sediments, especially to the OP and NAIP contents, which could be predicted by: TDP (mg L^{-1}) = 0.005 OP (mg kg^{-1}) – 0.001 NAIP (mg kg^{-1}) + 0.138 (R^2 = 0.836, P<0.01). The physicochemical properties of sediments presented significant correlation to the contents of P fractions, highlighting the importance of the physicochemical properties of sediments for the phosphorus fraction distributions in lake sediments.

Keywords: phosphorus, chemical fraction, sediment, shallow urban lake

Introduction

Lake eutrophication has become one of the critical water pollution problems throughout China [1, 2]. It is widely recognized that phosphorus plays an important role in the lake productivity [3]. The main sources of phosphorus in lakes are external point and non-point sources such as runoff, industrial and municipal effluents. Moreover, results of previous relative studies show that phosphorus released from lake sediments is also an important internal source for overlying water of lakes [3-5].

Sediments act as a sink where phosphorus can be stored, and also as a source of phosphorus for the overlying water and biota [6.7]. However, the amount of phosphorus released from sediments to overlying water depends more on its contents of available fractions than on its total contents in sediments. Thus, more efficient information for predicting potential ecological danger of phosphorus could be provided by investigation of available fraction of phosphorus than by that of total phosphorus contents in lake sediments [1, 8]. For this purpose, phosphorus frac-

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tions have been widely investigated to evaluate the long-term behavior of sediment-bound phosphorus in promoting lake eutrophication [6, 9, 10].

There are many shallow urban lakes scattered in most cities of China, which are usually served as landscaping and recreational sites. Previous studies on the phosphorus in lakes sediments were mostly focused on those larger natural lakes. Whereas little information can be found about the phosphorus fractions in sediments of these shallow urban lakes. These shallow lakes might play a more important and close role in the human health of local inhabitants than the other big natural lakes. Therefore, sediments were collected from three typical shallow urban lakes in China. The vertical distributions of phosphorus fractions in these lake sediments were investigated by employing the sequential extraction scheme proposed by the European Commission (now the Standards, Measurements and Testing Programme, SMT) to provide some useful information about the potential mobile and cycling trends of phosphorus in these lakes.

Materials and Methods

Site Description

The studied lakes, Xuanwu Lake and Mochou Lake, are located in Nanjing city of Jiangsu Province in China, and Daming Lake is located in Ji'nan city of Shandong Provice in China, which are all typical shallow urban lakes. In this study, three sampling sites in each lake were chosen respectively. The main characteristics of the studied lakes were shown in Table 1.

Table 1. Main characteristics of the studied lakes.

Parameters	Xuanwu Lake	Daming Lake	Mochou Lake
Surface area (km^2)	3.68	0.46	0.33
Mean depth (m)	1.65	2.75	1.45
TDN (mg L^{-1})	0.22~0.77	4.11~4.21	1.52~1.94
DO (mg L^{-1})	3.89~6.48	5.36~7.38	3.73~3.84
pH	8.79~9.54	7.69~8.03	8.83~9.06
Eh (mV)	114~132	141~155	70~98
Conductivity (μS cm^{-1})	198~261	546~559	412~418

Sediment Sampling and Pre-Treatment

Undisturbed sediment cores were collected in June 2006 by using a Beeker sampling device with a 100 cm length and 5 cm diameter cylinder tube. Three sampling sites were selected for each studied lake, and sampling points were shown in Fig.1. Three individual sediment cores were taken from the bottom surface down to 50 cm of depth within the diameter of 3m around each sampling points. After sampling, sediment cores were cut immediately into the following sections: 0~5, 5~10, 10~15, 15~20, 20~30, 30~40, and 40~50 cm. After measuring the redox potential and pH values, triplicated depth sections of each individual sediment cores taken from the same sampling point were combined into composite samples. These sediment samples were taken to the laboratory in air-sealed plastic bags and kept at 4°C. A portion of each wet sediment sample was centrifuged at 6000 rpm for gaining the pore-water sample, and the rest of the sediment sample was freeze-dried, homogenized and ground, and sieved to 0.25 mm, and finally stored at 4°C in plastic bags for later analyses.

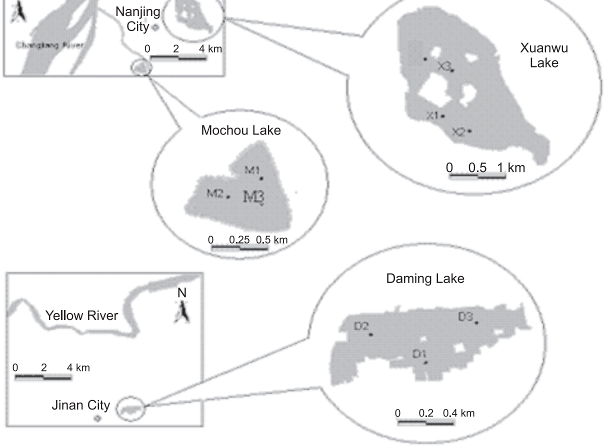

Fig. 1. Map of the studied area with sampling sites.

Analytical Methods

Water content and loss on ignition (LOI) content measurements were based on weight losses after drying and combustion of the sediments at 105, 450°C for 3 hours, respectively. The pH of sediment samples was measured on sediment extract at a sediment/de-ionized water ratio of 1:10 (w/v) using a digital pH meter. Total nitrogen (TN) and cation exchange capacity (CEC) were determined by the methods described by Lu [11]. The physicochemical properties of sediment samples were summarized in Table 2.

The SMT protocol, proposed by the Community Bureau of Reference, was employed to extract different phosphorus fractions[12]. The SMT protocol leads to obtaining five phosphorus fractions: non-apatite inorganic phosphorus (NAIP), bound to Al, Fe and Mn oxyhydrates; apatite phosphorus (AP), bound to Ca; inorganic phosphorus (IP); organic phosphorus (OP) and total phosphorus (TP). And detailed experimental procedures and conditions were described as follows.

Total phosphorus (TP): 0.2000g dried sediment was put into a porcelain crucible and calcined in a furnace at 450°C for 3 h, then transfered the calcined sediment into a 50-ml plastic centrifuge tube, and mixed with 20 ml 3.5 mol l^{-1} HCl. These tubes were shaken for 16h at room temperature and then centrifuged for 15 min (4000 rpm). The concentration of phosphorus was determined in the extract.

Inorganic phosphorus (IP): To extract IP, 20 ml 1.0 mol l^{-1} HCl was added to a 50-ml centrifuge tube to mix 0.2000 g sediment, the mixture was shaken for 16 h at room temperature. The extraction process and measurement were the same as in the step above. The residual was washed twice with 12ml 0.1 mol l^{-1} NaCl after the residual liquid was removed, and then dried in a oven.

Organic phosphorus (OP): The residue from the extraction of IP was calcined in a furnace for 3 h at 450°C. The calcined sediment was extracted (shaken for 16 h at room temperature) again with 20 ml 0.1 mol l^{-1} HCl to obtain OP. The same extraction process and measurement were conducted as mentioned above for TP.

Non-apatite inorganic phosphorus (NAIP): 20 ml 1.0 mol l^{-1} NaOH was added into a 50-ml plastic centrifuge tube contained 0.2000g dried sediment to extract NAIP. After shaking 16 h at room temperature and centrifuging 10 min at 4000 rpm, 10 ml clear supernatant was mixed with 4 ml 3.5 mol l^{-1} HCl, let the mixture stand for 16 h at room temperature, then measured the content of P by using the molybdenum blue method. The sediment was washed twice with 12ml 0.1 mol l^{-1} NaCl after the residual liquid was removed, and then dried in an oven.

Apatite phosphorus (AP): 20 ml 1.0 mol l-1 HCl was added to the residue from extraction for NAIP, and the tubes were shaken 16 h at room temperature and then centrifuged for 10 min (4000 rpm). The clear supertatant was used for determination of P by the molybdenum blue method.

Phosphate in pore-water and in extract of each fraction was determined by UV-Vis spectrophotometry, using the molybdenum blue method [13].

Results are average values of triplicate determinations. All the reagents used were of analytical-reagent grade. All solutions were prepared using de-ionized water (>18MΩ), and all glassware and plastic-ware were cleaned and rinsed three times with de-ionized water after being soaked in 0.3% HCl overnight. A quality control procedure was applied throughout the different steps of sample preparation and analysis. The data was treated using Excel 2000 and SPSS 11.0 for Windows.

Results and Discussion

General Physicochemical Properties of Sediments

The general physicochemical properties of sediments collected from three typical shallow urban lakes of China were presented in Table 2. Water contents (y,%) of sediments decreased significantly with the depth of sediment(x, cm), which could be calculated by: y = -0.4026 x + 65.627, (R^2=0.92, p<0.01), y = -0.4243 x + 71.566 (R^2=0.88, p<0.01), and y = -0.4387 x + 65.919 (R^2=0.87, p<0.05) for sediment profiles of Xuanwu Lake, Daming Lake, and Mochou Lake, respectively. The contents of total nitrogen (TN) exhibited similar vertical variation trends as that of water contents of sediments. The mathematic description for sediments of Xuanwu Lake, Daming Lake, and Mochou Lake could be described as: y = -371.7 x + 79.313 (R^2=0. 89, p<0.05), y = -412.83 x + 107.24 (R^2=0. 84, p<0.05), and y = -443.26 x + 101.37 (R^2=0.82, p<0.05), respectively, where y and x represented TN contents (mg kg^{-1}) and the depth of sediments (cm), respectively. Similar vertical variation trends could be found for the organic matter, expressed as loss on ignition (LOI), of sediments from all lakes, exhibiting decreasing trends with depth (Seeing Fig 2(a)). For the pH of sediments, no similar vertical variation trends could be identified for all lakes studied in present work (Seeing Fig 2(b)). The pH values increased slightly with the depth of the sediment cores for Daming Lake and Mochou Lake, while decreased significantly with the depth of the sediment core for Xuanwu Lake. It was evident from data of Table 2 that no obvious variation trends could be identified for the electric conductivities (EC) and CEC in sediments of these studied lakes.

Dissolved Phosphorus Concentrations in Pore-Water of Sediment Profiles

Pore-water of sediment plays an important role in the geochemical cycle of elements in lake system, which could be regarded as the via media of phosphorus exchange between the overlying water and the sediments. The vertical distribution of phosphorus in pore-water mainly influenced by the decomposition of organic matters, concentrations of iron oxide, pH value, redox condition, microbial activities, and so on[14.15]. The vertical variation of phosphorus concentrations in pore-water of sediments collected from three typical urban lakes in China are shown in Fig. 3.

There were no homothetic vertical variation trends for the phosphorus concentrations in pore water of sediments of these three studied lakes. The phosphorus concentrations in pore-water of Daming Lake were much higher than those of the other two lakes. No significant difference of P concentrations in pore-water could be identified between Xuanwu Lake and Mochou Lake (p>0.05). For Xuanwu Lake and Mochou Lake, there were no significant changes for phosphorus concentrations in pore-water within the 50-cm profile (p>0.05). However, significant vertical changes could be identified for that of Daming Lake (p<0.05), showing that the phosphorus concentration diminished with depth. The highest concentrations of P were found in the upper 5-cm layer of the sediment profile for Daming Lake (2.01 mg L^{-1}) and Mochou lake (0.28 mg L^{-1}), and the lowest concentrations were both in the 30-40cm layer. For Xuanwu Lake, the highest and lowest phosphorus

Table 2. Physicochemical properties of sediments of three typical shallow lakes of China*.

Lakes	Depth (cm)	Water Content (%)	pH (1:10, w/v)	LOI (%)	TN (%)	CEC mmol L^{-1}	EC (μs cm^{-1})
Xuanwu Lake	0~5	65.9 ± 4.1	7.13 ± 0.35	11.0 ± 2.6	0.21 ± 0.01	54.6 ± 18.4	654.3 ± 235.8
	5~10	59.9 ± 5.4	6.46 ± 0.73	10.5 ± 1.7	0.16 ± 0.01	40.3 ± 12.6	343.4 ± 133.7
	10~15	59.3 ± 4.7	6.27 ± 0.62	9.5 ± 2.0	0.18 ± 0.09	36.7 ± 3.4	368.1 ± 152.3
	15~20	57.3 ± 5.6	6.21 ± 0.53	9.4 ± 3.1	0.15 ± 0.09	36.8 ± 4.9	412.0 ± 123.9
	20~30	52.1 ± 13.0	5.75 ± 0.56	8.7 ± 3.8	0.13 ± 0.04	31.7 ± 7.9	595.0 ± 428.3
	30~40	51.0 ± 15.6	5.82 ± 0.58	8.1 ± 3.6	0.13 ± 0.01	32.2 ± 7.1	336.8 ± 162.2
	40~50	53.5 ± 11.2	5.83 ± 0.69	8.0 ± 3.3	0.08 ± 0.07	32.9 ± 2.9	292.3 ± 139.8
Daming Lake	0~5	70.9 ± 2.1	7.48 ± 0.15	10.7 ± 0.3	0.26 ± 0.02	129.7 ± 31.0	709.5 ± 173.3
	6~10	64.4 ± 2.1	7.69 ± 0.08	9.9 ± 0.7	0.21 ± 0.05	109.8 ± 8.2	516.7 ± 62.5
	10~15	66.1 ± 2.4	7.76 ± 0.06	9.7 ± 0.4	0.23 ± 0.01	111.5 ± 8.4	482.3 ± 58.8
	15~20	62.5 ± 1.9	7.81 ± 0.04	10.2 ± 1.2	0.21 ± 0.01	118.5 ± 3.5	562.7 ± 73.1
	20~30	61.4 ± 6.2	7.76 ± 0.09	9.9 ± 1.2	0.18 ± 0.03	113.6 ± 5.7	572.0 ± 77.8
	30~40	53.2 ± 8.9	7.94 ± 0.10	7.8 ± 2.0	0.16 ± 0.02	115.0 ± 5.6	398.0 ± 121.1
	40~50	55.2 ± 8.5	7.89 ± 0.18	8.3 ± 2.3	0.16 ± 0.04	110.3 ± 6.2	558.7 ± 213.4
Mochou Lake	0~5	63.6 ± 2.6	7.39 ± 0.19	9.3 ± 1.1	0.23 ± 0.03	60.2 ± 0.2	784.8 ± 113.5
	5~10	60.5 ± 0.9	7.68 ± 0.13	9.1 ± 0.0	0.19 ± 0.02	59.7 ± 2.0	484.5 ± 2.1
	10~15	57.6 ± 0.1	7.56 ± 0.08	7.9 ± 0.1	0.18 ± 0.04	59.4 ± 1.2	667.5 ± 256.7
	15~20	59.5 ± 0.1	7.81 ± 0.08	8.0 ± 0.3	0.17 ± 0.01	59.2 ± 0.9	324.0 ± 75.0
	20~30	55.7 ± 1.8	7.83 ± 0.05	8.1 ± 0.2	0.18 ± 0.05	56.1 ± 3.0	267.5 ± 7.8
	30~40	45.9 ± 4.5	7.90 ± 0.10	5.1 ± 1.5	0.14 ± 0.02	56.4 ± 3.5	321.0 ± 56.6
	40~50	49.2 ± 7.9	7.95 ± 0.07	5.6 ± 2.6	0.13 ± 0.02	57.6 ± 5.5	372.0 ± 166.9

***** Values were represented by the "Average ± Standard Deviation" of three sampling sites for each lake.

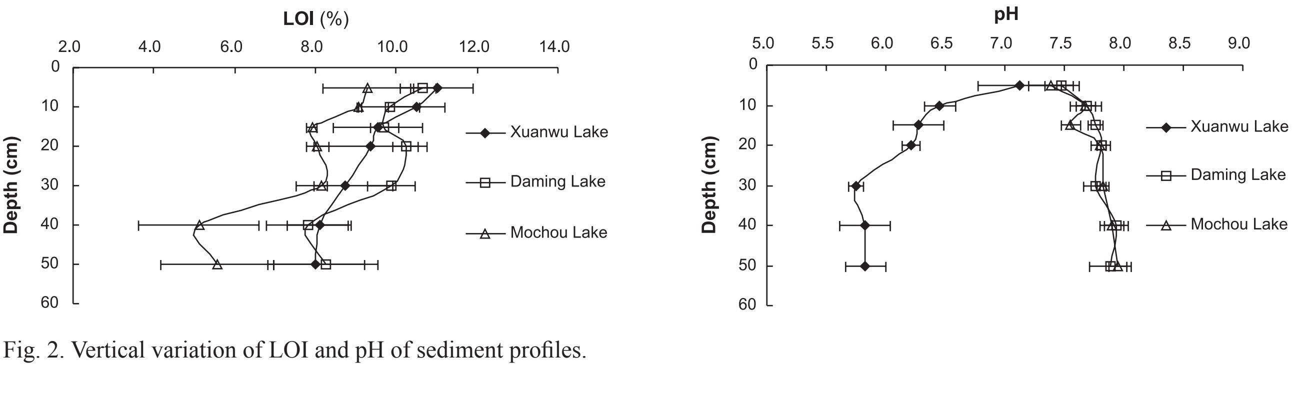

Fig. 2. Vertical variation of LOI and pH of sediment profiles.

concentrations were found in the 30-40cm, and 0-5cm layer of the sediment profile, respectively. This difference might be caused by the fact that the vertical distribution of phosphorus in pore-water was strongly influenced by the decomposition of organic matter, reduction of iron oxides and microbial activity in sediments [14.15].

Vertical variation of total phosphorus in sediment profiles

Total phosphorus (TP) contents in sediment profiles of the studied lakes were shown in Fig.4. There was no significant difference of TP contents in sediment profiles between Daming lake and Mochou Lake ($p>0.05$), rang-

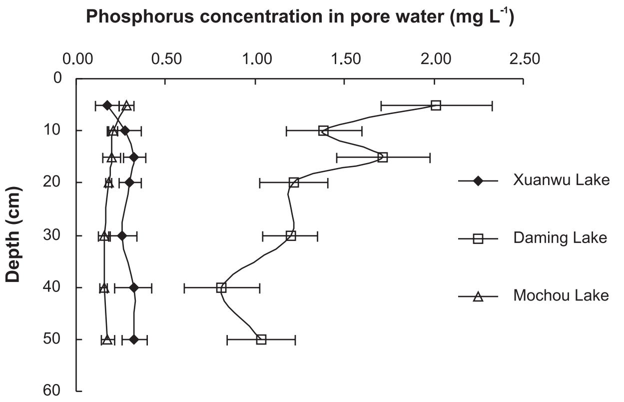

Fig. 3. Phosphorus concentration in pore-water of sediment profiles.

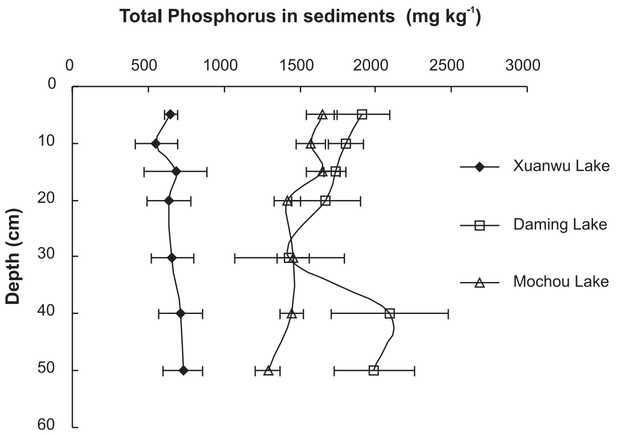

Fig.4. Total phosphorus contents in sediment profiles.

ing from 1198.9 to 1897.3 mg kg^{-1}, and 1289.1 to 1652.1, respectively. However, the TP contents in sediments of Xuanwu lake were much lower than those of the other two lakes ($p<0.05$), ranging from 611.7 to 760.3 mg kg^{-1}. The major differences of TP concentration among the three shallow urban lakes mainly resulted from different geographical locations, anthropogenic P sources, sediment types, and so on [6, 16]. Additionally, the lower TP contents in the sediment of Xuanwu lake might be caused by dredging activity conducted five years ago.

No significant difference could be found for the TP contents within the 50-cm sediment profile of Xuanwu Lake ($p>0.05$). For Mochou Lake, the TP contents increased with the depth in the upper 20 cm of the profiles, reaching the highest value at the depth of 15 cm, and then diminished slightly in the deeper 30 cm of the profiles with the lowest value at the depth of 50-cm. And for the Daming Lake, no significant difference of the TP contents could be found in the upper 20 cm ($p>0.05$), and then diminished gradually with the depth in the next 30 cm of the profile ($p<0.05$), reaching the lowest value at a depth of 40 cm.

The vertical variation of the TP contents in sediment profiles reflected the variations of phosphorus inputs and the pollutant status of these lakes at various periods in recent years [17, 18]. For all three studied urban lakes, the TP contents increased with the depth in the upper 10-cm of sediment cores, suggesting that the pollution status of these lakes turned more and more serious with the development of industry and economy of these cities.

Vertical Distribution of Phosphorus Fractions in the Sediment Profiles

The vertical distribution of phosphorus in sediment profiles is recognized as the net result of the history of phosphorus sedimentation as well as many transformation processes [17]. According to the program of SMT, total phosphorus (TP) could be represented by the sum of organic phosphorus (OP) and inorganic phosphorus (IP), and the IP could be divided into non-apatite inorganic phosphorus (NAIP) and apatite phosphorus (AP). These relations could be described by the following formula: TP = OP + IP, and IP = NAIP + AP. The recovery rate was 97.2%-103.2% for TP, and 95.5%--104.7% for IP in most cases in present work, and this recovery rate was reasonable [12]. The vertical distribution of extracted phosphorus fractions in sediment profiles was shown in Fig.5.

Inorganic phosphorus (IP) is sensitive to redox and pH variations of the system [19]. Within the 50-cm profiles, IP was the predominant fraction of the TP in all sediment cores, with the proportion of 90.3%±1.9%, 83.7%±2.9%, and 84.6±3.6% of TP for Mochou Lake, Daming Lake, and Xuanwu lake, respectively. Significant differences could be found among the composition of the IP in sediments. Most of the IP in sediments of Daming Lake was presented in AP (92.8%±7.2), and for Mochou Lake, the ratio of AP was much lower than that of Daming Lake (71.4%±4.3%). While for Xuanwu Lake, the AP accounted for 41.7%±6.0% in IP, which was a little lower than that of NAIP. It is reported that the sum of Al-P and Fe-P contents in lake sediments was one of the pollution parameters, and the NAIP contents in the sediments partly related to the pollution degree [20.21]. Higher proportion of NAIP to IP in sediment profiles of Xuanwu Lake indicated that the Xuanwu Lake catchment was polluted more heavily than the other two lakes.

The NAIP contents were a little higher in the upper 5-cm profiles than the rest of the sediment profile, and no significant difference could be found throughout the remaining sediment profiles for Daming Lake and Mochou Lake ($p>0.05$). This reflected on the rapid development of urbanization and industrialization of these cities accelerated the pollution status of these lakes in recent years [21, 23]. While for Xuanwu Lake, the NAIP contents in the 40-50 cm layer of the sediment profile was much higher than the upper 40-cm profile ($p<0.05$). The AP was relatively stable under alkaline conditions. The contents of AP exhibited similar vertical changes as that of IP in the sediments of Daming Lake and Mochou Lake,

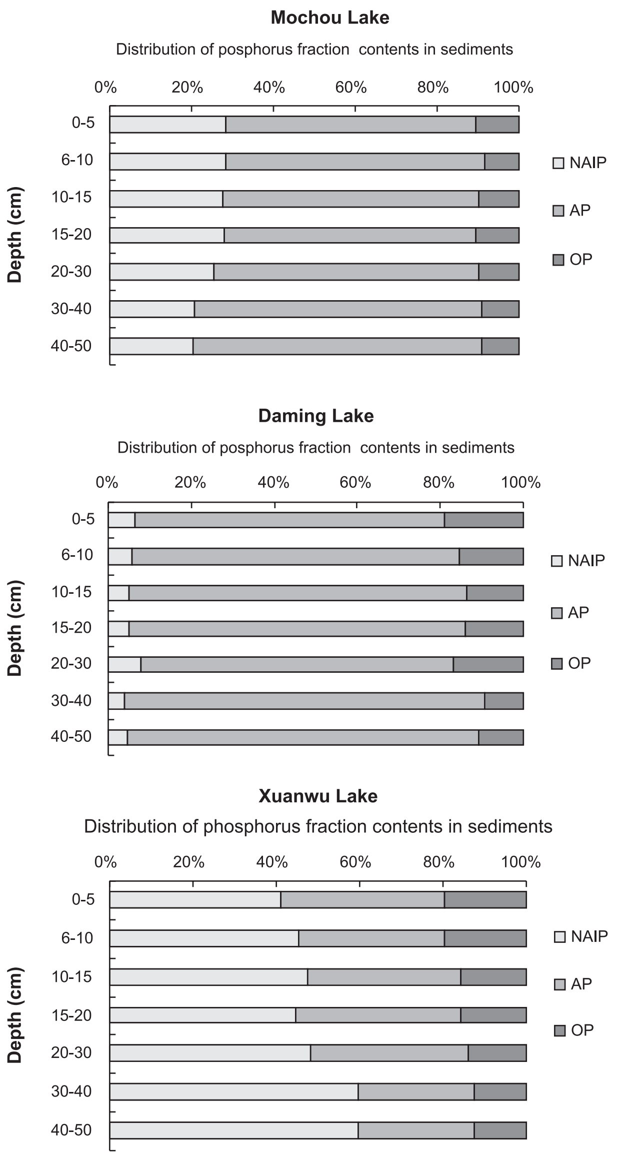

Fig. 5. Vertical distributions of phosphorus fractions in sediment profiles.

increasing in the upper and then decreasing in the rest with the depth of the sediments. However, no significant difference could be found for the contents of AP, as well as for IP, in sediments of Xuanwu Lake (p>0.05). The OP contents accounted for 9.7%-16.3% of TP in sediments of the three studied lakes. Similar vertical distribution of OP was found for Daming Lake and Mochou Lake, with a little higher content in the upper 5-cm profiles than the rest, which might be caused by the mineralization of organic matters in sediment with the depth [19, 23]. OP is an important phosphorus fraction buried in the sediment due to this fraction contributes to the pool of inorganic phosphorus, and might be released to the overlying water, and thus directly affects the availability levels of dissolved phosphorus for primary production [24].

The percentage of phosphorus fraction in TP in lake sediment could be used to identify the main sources of pollutants of lakes[25]. Higher portion of NAIP in lake sediments indicates that the main factors contributing to the pollution status of this lake were caused by industrial and the domestic sources. The higher portion of OP in lake sediments suggests the importance of agricultural non-point sources to the pollution status of this lake. And the higher portion of AP indicates that external pollutant sources had been successfully diminished and the environmental status of the lake had been improved. Therefore, the highest portion of NAIP and OP in Xuanwu lake sediments reflected its most serious pollution status among these three studied lakes. And the decreasing order for the pollution status of three lakes was:

Xuanwu Lake > Mochou Lake > Daming Lake.

Relationship among the Phosphorus Fractions in Sediments, Phosphorus in Pore-Water, and the Physicochemical Properties of Sediments

The relations among phosphorus fractions, phosphorus concentrations in pore-water, and the physicochemical properties of sediments were investigated using statistic correlation analysis. And the obtained correlation coefficients were shown in Table 3. The TP contents were well correlated to the contents of NAIP, AP, and OP, which could be calculated by:

$$\mathbf{TP}\ (\mathrm{mg\ kg^{-1}}) = 1.015\ \mathbf{AP}\ (\mathrm{mg\ kg^{-1}}) + 1.215\ \mathbf{NAIP}\ (\mathrm{mg\ kg^{-1}}) + 0.629\ \mathbf{OP}\ (\mathrm{mg\ kg^{-1}})$$

$$R^2 = 0.996,\ P = 0.001,\ n = 63 \quad (1)$$

The pore-water played an important role in the exchange and cycle of matters between the overlying water column and the sediments. The concentrations of phosphorus in pore-water significantly correlated positively to the contents of AP, IP, OP, and TP, with the correlation coefficient (r^2) of 0.74, 0.56, 0.89, and 0.62, respectively, and significantly correlated negatively to the contents of NAIP ($r^2 = -0.83$, $p<0.01$). Stepwise regression results indicated that the phosphorus concentration in pore-water (TDP) could be well predicted by the contents of NAIP and OP:

$$\mathbf{TDP}\ (\mathrm{mg\ L^{-1}}) = 0.005\ \mathbf{OP}\ (\mathrm{mg\ kg^{-1}}) - 0.001\ \mathbf{NAIP}\ (\mathrm{mg\ kg^{-1}}) + 0.138$$

$$R^2 = 0.836,\ P = 0.001,\ n = 63 \quad (2)$$

It was evident from the data in Table 3 that the CEC (Cation Exchange Capacity) and the pH values of the sediments would strongly influence the distributions of different phosphorus fractions and TP in sediments. Water content and organic matters (LOI) were more important to the distribution of NAIP, OP, and TDP than to the AP, IP, and TP. And the electronic conductivity of sediments significantly correlated positively to the OP contents in sediment

Table 3. Correlation coefficients among contents of each P fraction, P concentrations, and the physicochemical properties of sediments (Sample number: n=63).

	NAIP	AP	IP	OP	TP	**TDP** [a]
AP	-0.68**	1				
IP	-0.44*	0.96**	1			
OP	-0.78**	0.74**	0.58**	1		
TP	0.47*	0.96**	0.99**	0.66**	1	
TDP [a]	-0.83**	0.74**	0.56**	0.89**	0.62**	1
Water Content	-0.45*	0.43	0.33	0.69**	0.39	0.58**
LOI	-0.45*	0.22	0.08	0.58**	0.14	0.51*
CEC	-0.89**	0.86**	0.69**	0.94**	0.74**	0.91**
pH	-0.52*	0.82**	0.82**	0.51*	0.79**	0.39
EC	-0.23	0.20	0.15	0.48*	0.21	0.33

** Correlation is significant at the 0.01 level (2-tailed);
* Correlation is significant at the 0.05 level (2-tailed);
[a] Total concentrations of P in pore-water of sediments, TDP.

profiles. These results suggested that the physicochemical properties of sediments would strongly influence the distribution of phosphorus fractions in lake sediments, and thus influenced the behavior of P in the lake system.

Conclusion

The Standards, Measurements and Testing (SMT) programme, proposed by the European Commission, was employed to characterize the vertical distributions of phosphorus fractions in sediments collected from three typical shallow urban lakes in China. The results showed that the TP contents in sediment profiles ranged from 1,198.9 to 1,897.3, 1,289.1 to 1,652.1, and 611.7 to 760.3 mg kg^{-1} for Daming Lake, Mochou Lake, and Xuanwu Lake, respectively. Within the 50-cm sediment profiles, the phosphorus distributed mainly in IP, accounting for 90.3%±1.9%, 83.7%±2.9%, and 84.6±3.6% of TP for Mochou Lake, Daming Lake, and Xuanwu lake, respectively. The OP contents accounted for 9.7%-16.3% of TP in sediments of the three studied lakes. AP was the main fraction of IP in sediment profile for Daming Lake and Mochou Lake, accounting for 92.8%±7.2, and 71.4%±4.3%, respectively, while the proportion of NAIP to IP was higher than that of AP (41.7%±6.0%) for Xuanwu Lake, suggesting its most serious pollution status among these three studied lakes. And the distribution of phosphorus fraction also changed greatly with the depth of the sediment profile. The phosphorus concentration in pore-water (TDP) correlated significantly to the phosphorus fractions, especially to the OP and NAIP contents in sediments, which could be predicted by: TDP (mg L^{-1}) = 0.005 OP (mg kg^{-1}) – 0.001 NAIP (mg kg^{-1}) + 0.138 (R^2 = 0.836, P = 0.001). Significant correlation could be found between the physicochemical properties of sediments and the contents of phosphorus fractions, suggesting that the physicochemical properties of sediments would strongly influence the distribution of P fractions in lake sediments.

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References

1. ZHOU Q., GIBSON C.E., ZHU Y. Evaluation of phosphorus bioavailability in sediments of three contrasting lakes in China and the UK [J]. Chemosphere, **42**, 221, **2001**.
2. WANG S.R., JIN X.C., ZHAO H.C., WU F.C. Phosphorus fractions and its release in the sediments from the shallow lakes in the middle and lower reaches of Yangtze River area in China[J]. Colloids and Surfaces A: Physicochem. Eng. Aspects, **273**, 109, **2006**.
3. KAISERLI A., VOUTSA D., SAMARA C. Phosphorus fractionation in lake sediments, Lakes Volvi and Koronia, N. Greece [J]. Chemosphere, **46**, 1147, **2002**.
4. PERKINS R.G., UNDERWOOD G.J.C. The potential for phosphorus release across the sediment–water interface in an eutrophic reservoir dosed with ferric sulphate[J]. Water Res., **35** (6), 1399, **2001**.
5. BALCERZAK W. The protection of reservoir water against the eutrophication process[J]. Polish Journal of Environmental Studies, **15** (6), 837, **2006**.

6. GONSIORCZYK T., CASPER P., KOSCHEL R. Phosphorus binding forms in the sediment of an oligotrophic and an eutrophic hardwater lake of the Baltic district (Germany) [J]. Water Sci. Technol., **37** (3), 51, **1998.**
7. WU F.C., QING H.R., WAN G.J. Regeneration of N, P, and Si near the sediment/water interface of lakes from southwestern China plateau[J]. Wat. Res., **35** (5), 1334, **2001.**
8. RUBAN V., BRIGAULT S., DEMARE D. An investigation of the origin and mobility of phosphorus in freshwater sediments from Bort-Les-Orgues Reservoir, France[J], J. Environ. Monit., **1**, 403, **1999.**
9. GROCHOWSKA J., GAWROŃSKA H. Restoration effectiveness of a degraded lake using Multi-Year artificial aeration[J]. Polish Journal of environmental Studies, **13** (6), 671, **2004.**
10. GONZÁLEZ MEDEIROS J.J., PÉREZ CID B., FERNÁDEZ GÓMEZ E. Analytical phosphorus fractionation in sewage sludge and sediment samples[J]. Anal Bioanal Chem, **381**, 873, **2005.**
11. LU R.K. Methods for Soil and Agricultural Chemistry[M]. Chinese Agriculture Press, Beijing [In Chinese], **2000.**
12. PARDO P., RAURET G., LÓPEZ-SÁNCHEZ J.F. Shortened screening method for phosphorus fractionation in sediments: A complementary approach to the standards, measurements and testing harmonised protocol [J]. Analytica Chimica Acta., **508**, 201, **2004.**
13. APHA, AWWA, WPCF. Standard methods for the examination of water and wastewater [M]. 16th edition, **1985.**
14. SUNDBY B., COBEIL C., SILVERBERG N., MUCCI A. The phosphorus cycle in coastal marine sediments [J]. Limnol Oceanogr., **37**, 1129, **1992.**
15. REDDY K.R., FISHER M.M., IVANOFF D. Resuspension and diffusive flux of nitrogen and phosphorus in a hypereutrophic lake[J]. J. Environ Qual., **25**, 363, **1996.**
16. HUPFER H., GÄCHTER R., GIOVANOLI R. Transformation of phosphorus species in settling seston and during early sediment diagenesis[J]. Aqua Sci., **57**, 305, **1995.**
17. WHITMORE T.J., BRENNER M., JIANG Z., CURTIS J.H., MOORE A.M., ENGSTROM D.R., WU Y. Water quality and sediment geochemistry in lakes of Yunnan Province, southern China[J]. Environ Geol., **32**, 45, **1997.**
18. FRANKOWSKI L., BOLALEK J., SZOSTEK A. Phosphorus in bottom sediments of Pomeranian Bay (southern Baltic-Poland) [J]. Estuar Coast Shelf Sci., **54**, 1027, **2002.**
19. IQBAL M.Z., BROWN E.J., CLAYTON M.E. Distribution of phosphorus in a biologically restricted lake in Iowa, USA[J]. Journal of Hydrology, **326**, 349, **2006.**
20. HISASHI J. Fractionation of phosphorus and releasable fraction in sediment mud of Osaka Bay[J]. Bull Jpn Soc Sci Fish., **49**, 447, **1983.**
21. RUBAN V., LÓPEZ-SÁNCHEZ J.F., PARDO P., et al. Harmonized protocol and certified reference material for the determination of extractable contents of phosphorus in freshwater sediments: A synthesis of recent works[J]. Fresenius J. Anal. Chem., **370**, 224, **2001.**
22. GAO L., ZHOU J.M., YANG H., CHEN J. Phosphorus fractions in sediment profiles and their potential contributions to eutrophication in Dianchi Lake[J]. Environ. Geol., **48** (5), 835, **2005.**
23. ZHU G.W., QIN B.Q., ZHANG L., LUO L.C. Geochemical forms of phosphorus in sediments of three large, shallow lakes in China[J]. Pedosphere, **16** (6), 726, **2006.**
24. EDLUND G., CARMAN R. Distribution and diagenesis of organic and inorganic phosphorus in sediments of the Baltic proper. Chemosphere, **45**, 1053, **2001.**
25. RUBAN V., LOPEZ-SANCHEZ J.F., PARDO P. Harmonized protocol and certified reference material for the determination of extractable contents of phosphorus in freshwater sediments-a synthesis of recent works[J]. Fresenius J. Anal. Chem., **370**, 224, **2001.**