

Sediment phosphorus fractions and profile distribution at different vegetation growth zones in a macrophyte dominated shallow Wuliangshai Lake, China

Zhenying Liu · Zhaohui Jin · Yawei Li ·
Tielong Li · Jiujun Gu · Si Gao

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Abstract Sediment phosphorus (P) fractions and profile distribution at submerged macrophyte growth zone, emergent macrophyte growth zone and open-water zone were studied in Wuliangshai Lake, China, as well as the correlations among water content, grain size, and organic matter and P fractions. Among the three surveyed zones, the highest concentrations of most P forms occurred in the surface sediment and the lowest between a depth of 12 and 22 cm, except HCl-P and NaOH-P. Sediment phosphorus was mainly associated to inorganic forms (>50%) in three surveyed areas, and the highest value of inorganic phosphorus (IP) in the surface sediment was obtained from submerged macrophyte growth zone. Submerged and emergent macrophytes increased the IP content by 107 and 44 $\mu\text{g/g}$, respectively, in the surface sediment compared with open-water zone. Vertical profiles of IP in the three surveyed zones showed that the concentrations decreased from surface to 12 cm depth and then increased. There was a similar trend in the sediment profiles of organic phosphorus (OP) and total phosphorus (TP), but the highest concentration of OP and TP in surface sediment was obtained from the emergent macrophyte growth zone. Compared with open-water zone, the emergent macrophyte increased TP content in surface sediment by 1.73 times to 1,320 $\mu\text{g/g}$, while submerged macrophyte enhanced TP

content in the surface sediment by 1.13 times to 865 $\mu\text{g/g}$. It was observed that in macrophyte growth zones, a strong linear correlation existed between organic matter and OP ($r > 0.98$), and the maximum concentrations of OP were present in the areas with maximum concentrations of organic matter. Results show that, although rooted macrophyte could uptake directly P from sediments, it is responsible for increasing the internal P loading especially OP by reducing current velocities, attenuating wave energy and generating organic residue in Wuliangshai Lake.

Keywords Phosphorus fractions · Profile distribution · Emergent macrophyte · Submerged macrophyte · Open-water

Introduction

Phosphorus (P) availability is regarded as the most important factor for determining the trophic status of lakes. Attempts to improve the trophic status of many lakes have led to the knowledge of the complex nature of the phosphorus cycle in sediments (Søndergaard et al. 2003; Li Gao et al. 2005; Bryan M. Spears et al. 2006). Aquatic macrophyte may affect P retention by increasing the water residence time and by acting as a filter for suspended particulate organic matter (Jorga and Weise 1977; Reddy et al. 1996). On the other hand, by reducing the concentration of the dissolved oxygen through respiratory activities or by elevating pH values during intensive photosynthesis, aquatic macrophyte may substantially prevent P resuspension and release (Jukka Horppila and Leena Nurminen 2003). Such effect is of importance, since P loading in sediments

Z. Liu · Z. Jin (✉) · T. Li · J. Gu · S. Gao
College of Environmental Science and Engineering,
Nankai University, Tianjin 300071, China
e-mail: jinzh@nankai.edu.cn

Y. Li
Inner Mongolia Environment Protection Bureau,
Hohhot 010018, China

will often determine the eutrophication status of the lake and the time lag after reduction in external P loading. However, not all the forms of P are likely to be released and thereby increase eutrophication. Li Gao et al. (2005) reported that the total concentration of P in sediments cannot predict the potential ecological danger and the available P fractions are important parameter for determining future internal P-loading. Chemical fractionation of sedimentary P has served as a tool to predict the P binding capacity of sediments under different environmental conditions.

Different macrophyte species have variable effects on P hydrodynamics and consequently P resuspension. This is due to the architecture and distribution of plant tissue over the water column varying substantially among growth form and species (Duarte and Kalff 1990). Most studies on sediment P fractions influence of macrophytes have been focused on submerged species (Neil Rooney and Jacob Kalff 2003; Susanne Schneider and Arnulf Melzer 2004; Jukka Horppila and Leena Numinen 2003), and sediment P fractions influence of emergents have been more rarely investigated (Dieter 1990; Jukka Horppila and Leena Numinen 2001). However, few studies (Jukka Horppila and Leena Numinen 2005; Marcus Schulz et al. 2003) have attempted to quantify the effect of two main growth forms in a lake on sediment P fractions. This is a shortcoming, since in many lakes where different vegetation is coexistent; maybe two species or more are dominant and cover large water areas.

The aim of this study was to quantify sediment P fractions at different vegetation zones in order to evaluate the effects of different macrophyte growth

forms on sediment P fractions in eutrophic Wuliangshuai Lake, China (Fig. 1).

Study area

This study was carried out at Wuliangshuai Lake (40°47′–41°03′N, 108°43′–108°57′E) in Inner Mongolia Autonomous Region, China. It is linked to Hetao Irrigation Catchment in the west, to Wula Mountains in the east, and located at the east tip of the Hetao Plain. The lake is 35–40 km long (N–S) and 5–10 km wide (E–W), with an area of about 293 km². Its approximate location is given in Fig. 1. The average elevation of the lake over the years is 1018.5 m, steered by an outlet dam, and with a capacity of 250–300 million m³. It has a maximum depth of less than 4 m, while the average depth is only about 1.0 m. Annual average temperature in the area is 7.3°C, annual sunshine 3184.5 h, average annual rainfall 224 mm, potential average annual evaporation 1,502 mm. The lake is normally covered by ice from November to March, and only 152 days per year are frost-free (Li 2002). Wuliangshuai Lake has been increasingly eutrophicated as a result of non-point pollution from Hetao Irrigation District, where the total nitrogen and phosphorus concentrations have been 3.47 and 0.14 mg/l, respectively. Almost half of the lake is covered by emergent vegetation, mainly common reed (*Phragmites australis* (Cav.) Trin. Ex Steud.). Among the reed community there are also scattered *Typha latifolia* L. and *Scirpus acutus*. In the open-water area, *Potamogeton pectinatus* L. is the most common submerged macrophyte. There is approximately 0.2–0.4 m

Fig. 1 Map of the study area (1 submerged macrophyte growth zone, 2 emergent macrophyte growth zone, 3 open-water zone; E Erdian station, N Nantianmen station, H Huxin station, X Xidatan station)



of recent plant litter in the bottom which rested on sediment layers consisting primarily of organic matter.

Materials and methods

Sites were selected on a depth transect designed to represent key regions (Erdian station, Nantianmen station, Huxin station, Xidatan station) of the lake, 12 sediment cores being collected respectively from the submerged macrophyte (*Potamogeton pectinatus*) growth zone, emergent macrophyte (*Phragmites australis*) growth zone and open-water zone at depths between 36 and 67 cm (Fig. 1). According to the data obtained from the 12 sediment cores, no significant differences in the sediment characteristics could be detected among sediment cores from the same zone. Therefore, a single sediment core per vegetation growth zone or open-water zone is selected to characterize the sediment P fractions in Wuliangshuai Lake.

The samples were collected using handy piston core sampler, pushed manually into the sediment to a depth that permitted to collect 36–67 cm of the sediment column. The corer was sliced into sections at 2 cm interval and immediately frozen and taken into the laboratory for further analysis. In the laboratory, grain size was determined using Laser diffraction particle seizer (LS 13320, Backman coulter). Water content ($W\%$) was calculated from the difference between wet and dry weight (air-dried at room temperature), while total organic matter was determined by weight loss (% of dry weight) on ignition (550°C for 5 h). The concentration of P fractions (expressed in mg/g sediment) was determined by using the standards, measurements and testing (SMT) harmonized procedure of the European Commission. The so-called SMT scheme allows the definition of the following forms: NaOH-extractable P (NaOH-P; P bound to Al, Fe, Mn oxides or hydroxides), HCl-extractable P (HCl-P, Ca-bound P), organic P (OP), inorganic P (IP), concentrated HCl P (total P, TP). The protocol consisted in three extraction procedures that were applied to 0.2 g aliquots of sediment samples. An extraction (16 h) using 20 mL of 1 mol L^{-1} NaOH was performed and after centrifugation and separation of the supernatant liquid, the residue was extracted again with 20 mL of 1 mol L^{-1} HCl (16 h). HCl-P was determined in the extract. 4 mL of 3.5 mol L^{-1} HCl was added to one aliquot of 10 mL of the 1 mol L^{-1} NaOH extract and let stand for 16 h to precipitate organic matter. NaOH-P was determined in the supernatant liquid. An extraction (16 h) with 20 mL of 1 mol L^{-1} HCl was performed to determine IP. The residue of this extraction was placed in a porcelain

crucible and calcined in a furnace for 3 h at 450°C . Then, the residue was extracted again (16 h) with 20 mL of 1 mol L^{-1} HCl. After centrifugation, OP was determined in the extract. After sample calcinations during 3 h at 450°C , a single extraction (16 h) with 20 mL of 3.5 mol L^{-1} HCl was carried out, and TP determined in the extract (Ruban et al. 2001).

Results

Sediment characteristics

The cores taken from Wuliangshuai Lake that show the depth profiles for loss-on-ignition (LOI%) and water content ($W\%$) are shown in Fig. 2. In the submerged macrophyte growth zone, the upper part (0–6 cm) of the profile consists of organic-rich (LOI ~15%) gyttja. The organic content decreases between 6 and 12 cm as sediment turns into dark gray gyttja. The appearance of the core does not change but the color fades to gray between 12 and 30 cm. This dense sediment section, between 30 and 67 cm, is yellow in color and is low in water content. In open-water zone, the change both in organic matter (LOI ~11%) and water contents (about 70%) is slight in upper layer (0–12 cm). There is a decrease in organic and water contents which incline to immobile till 30 cm as the color begins to change from gray to yellow. In emergent macrophyte growth zone, the abrupt decrease in organic matter and water content occurs in 0–10 cm depth. The organic content does not change while water content continues to decrease until the bottom.

In surface sediment (0–2 cm) of three surveyed areas, both organic matter and water content in macrophyte growth zones are bigger than those in open-water zone, of which the highest value was obtained in emergent macrophyte growth zone. In macrophyte growth zones, the roots associated with the macrophytes penetrate deep into the underlying gyttja and appear to be in their original position, and the macrophyte layer was also found at approximately the same level in the sediment. The aquatic plant remains are overlaid by 12 cm of gyttja, most probably deposited in the recent 20 years.

Grain size changes depending on the location (Fig. 3). Silt (2–63 μm) was the dominant size in three surveyed zones, with a low percentage of clay and sand. Since sand (>63 μm) content never exceeded 6%, the finest sediments were always found in submerged macrophyte growth zone. In emergent macrophyte growth zone, sediments presented a wide range of grain size, from fine clay (<2 μm) to coarse sand (>125 μm).

Fig. 2 Vertical distributions of sediment loss-on-ignition (LOI%) and water content (W%) in three surveyed zones (SM submerged macrophyte growth zone, OW open-water zone, EM emergent macrophyte growth zone)

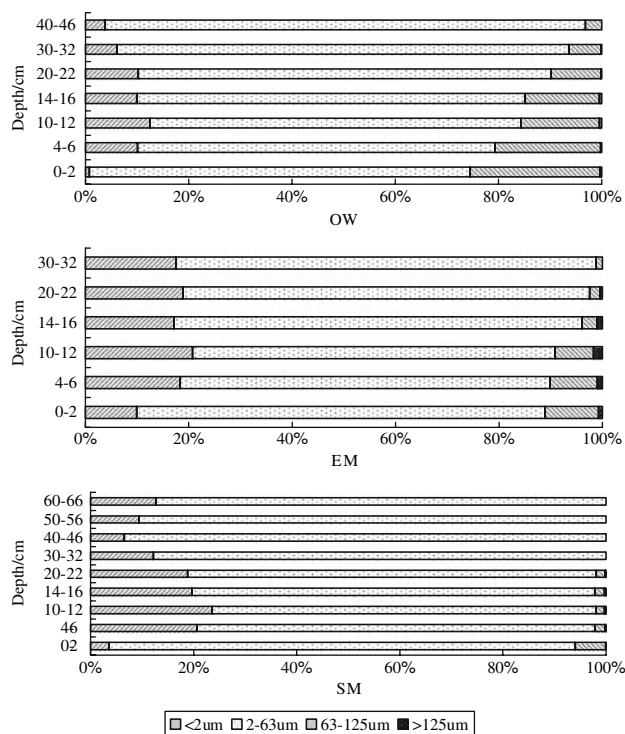
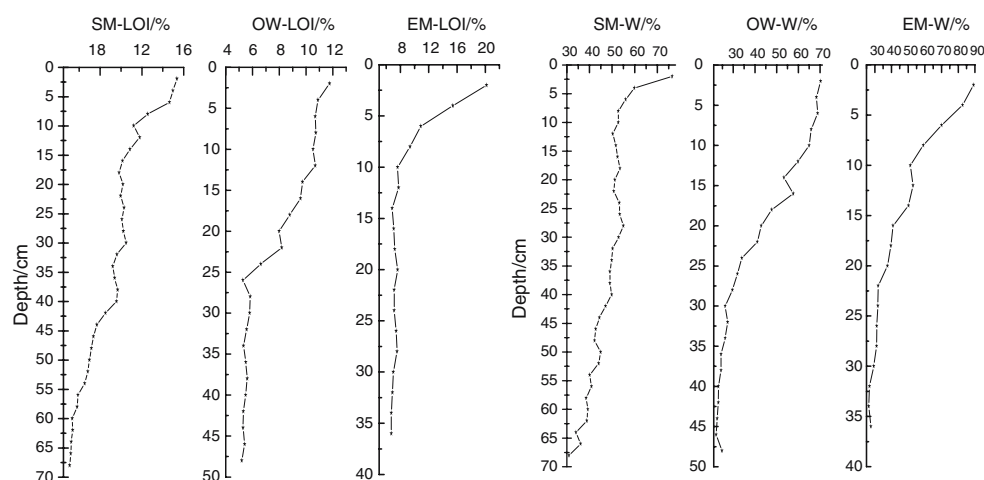


Fig. 3 Profile distributions of sediment grain size in three surveyed zones

Compared with macrophyte growth zones, higher percentage of sand was obtained from open-water zone.

Phosphorus fractions

The P forms found in the three surveyed areas are summarized in Fig. 4. TP concentration ranges in submerged macrophyte growth zone (668–865 $\mu\text{g/g}$) and emergent macrophyte growth zone (462–1,320 $\mu\text{g/g}$) were higher than that in open-water zone (451–763 $\mu\text{g/g}$). The changing tendency of the TP concen-

tration in the sediment profiles was close in open-water zone and emergent macrophyte growth zone, but different in submerged macrophyte growth zone where the concentration decreased below 32 cm depth. In general, the highest TP content in every surveyed zone occurred in the surface sediment.

P is mainly associated to inorganic forms (>50%) in three surveyed areas, and the highest value of IP in the surface sediment was obtained in the submerged macrophyte growth zone. Vertical profiles of IP showed that the concentrations decreased from surface to 12 cm depth and then increased in the three surveyed zones. There was a similar trend in the sediment profiles between OP and TP in the three surveyed zones; however, the highest concentration of OP and TP in surface sediment was in emergent macrophyte growth zone. It was observed from Fig. 4 that the sum of phosphorus contents in the organic fraction and inorganic fraction in general agreed with extracted TP.

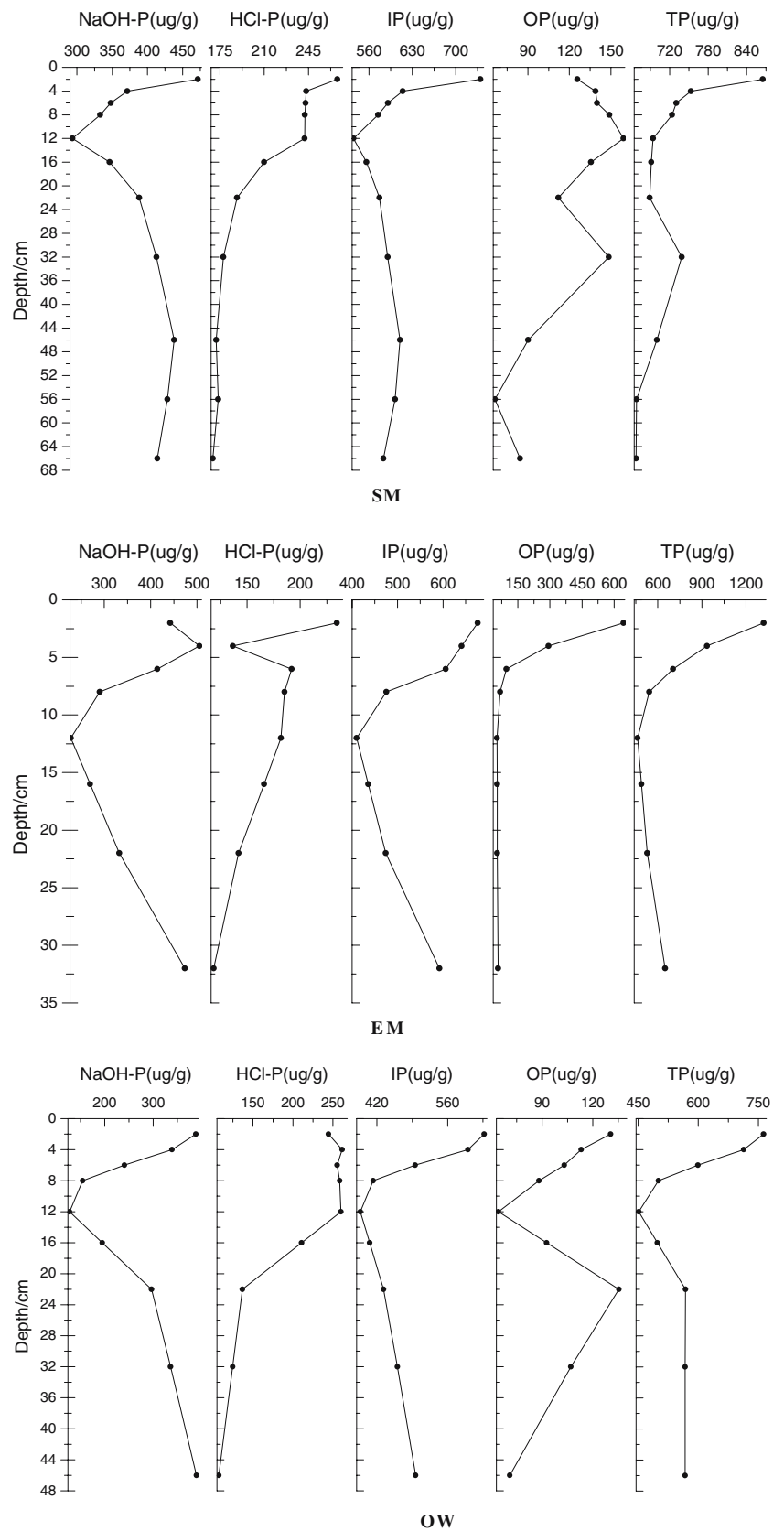
The highest concentrations of most P forms occurred in the surface sediment and the lowest between a depth of 12 and 22 cm, except HCl-P and NaOH-P. HCl-P was the smallest fraction in all forms, whose concentration range was 23–72 $\mu\text{g/g}$ in the three surveyed zones. Differed from emergent macrophyte growth zone, where higher concentrations were in surface layers, the extreme concentration of HCl-P and NaOH-P appeared in some deeper (>32 cm) sediment layers in open-water zone and submerged macrophyte growth zone.

Discussion

Sediment characteristics and P forms

While the characteristics of bottom sediments partially depends on the characteristics of the overlying water

Fig. 4 Sediment P forms and profile distributions in three surveyed zones



(Adriana Jorcín 2000), sediment P is also determined by underlying geology, external inputs, sediment particle size, major elements and organic matter (Søndergaard et al. 2003; Li Gao et al. 2005). In Wuliangshai Lake, the measured variables are significantly correlated and presented in Tables 1 and 2. Significant Pearson's correlation coefficients (calculated as 'r') have values significantly different from 0.

Sediment water content may be related to the water permeability of the sediment, which is in turn related to grain size and sediment depth. Sediment water content was a function of the fine materials in sediments of Wuliangshai Lake, such as organic matter and fine sand (63–125 µm), since it had strong linear correlation with organic matter and fine sand ($r > 0.95$), except organic matter in emergent macrophyte growth zone ($r = 0.84$). Adriana Jorcín (2000) also reported there was a significant positive correlation between water content and organic matter concentration. Several other factors may contribute, including OP ($r = 0.928$, in submerged macrophyte growth zone) and the distribution pattern of grain size. Some studies (McComb et al. 1998) showed that a small increase in water content might correspond with a large decrease in grain size, a large increase in organic matter and P content. The close correlation between organic matter, OP and water content in this system may suggest a simple, cost effective method for using water content as a proxy for estimating OP content in these sediments.

Organic matter was another important factor affecting variation in P fractions, especially OP. OP has been tentatively examined as a function of the organic content of the sediments using the few available organic matter data. It was observed (in Table 1) that in macrophyte growth zones, a strong linear correlation existed between organic matter and OP ($r > 0.98$), and the maximum concentrations of OP were present in the areas with maximum concentrations of organic matter. Sediments in this system had higher OP and organic matter concentration than the sediment in open-water zone. Generally, the samples with organic matter content over 10% generally had a higher variation in OP content in sediments of Wuliangshai Lake. Similar correlations were found between organic matter and TP, organic matter and fine sand ($r > 0.8$) in macrophyte growth zones. The correlation between TP and organic matter appears to reflect combinations of both factors, consistent with a view that the association between organic matter and phosphorus is a major product of selective sedimentation and hydrological sorting. From the accumulated information in Wuliangshai Lake there was evidence that OP is generated

Table 1 Pearson's correlation coefficients in macrophyte growth zones

Variables	Depth	NaOH-P	HCl-P	IP	OP	TP	Grain size (µm)			LOI%	W%	
							<2	2–63	63–125			>125
Submerged macrophyte growth zone												
Depth	1											
NaOH-P	-0.594	1										
HCl-P	-0.543	0.978**	1									
IP	-0.293	0.745	0.615	1								
OP	-0.582	0.996**	0.980**	0.746	1							
TP	-0.510	0.991**	0.969**	0.791	0.995**	1						
Grain size (µm)	0.560	-0.973**	-0.985**	-0.596	-0.960**	-0.947*	1					
	0.045	0.664	0.771	0.269	0.665	0.682	-0.766	1				
	63–125	-0.885*	0.678	0.702	0.776	0.744	-0.674	0.059	1			
	>125	-0.875	0.180	-0.163	0.157	0.065	-0.208	-0.294	0.564	1		
LOI%	-0.664	0.990**	0.946*	0.785	0.987**	0.978**	-0.939*	0.555	0.857	0.246	1	
W%	-0.953*	0.784	0.713	0.537	0.766	0.717	-0.737	0.139	0.960**	0.707	0.843	1
Emergent macrophyte growth zone												

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

Table 2 Pearson’s correlation coefficients in open-water zone

Variables	Depth	NaOH-P	HCl-P	IP	OP	TP	Grain size (µm)				LOI%	W%
							<2	2–63	63–125	>125		
Depth	1						Open-water zone					
NaOH-P	–0.086	1										
HCl-P	0.586	0.344	1									
IP	–0.237	0.344	0.033	1								
OP	–0.790	0.357	–0.444	0.710	1							
TP	–0.360	0.370	0.118	0.953**	0.765	1						
Grain size (µm)	<2	–0.167	–0.384	–0.272	–0.909*	–0.386	–0.792	1				
	2–63	0.958**	0.041	0.691	0.013	–0.655	–0.113	–0.411	1			
	63–125	–0.959**	0.160	–0.610	0.467	0.923**	0.545	–0.079	–0.876*	1		
	>125	–0.846*	–0.099	–0.727	–0.025	0.480	–0.017	0.322	–0.856*	0.760	1	
LOI%	–0.909*	–0.237	–0.813*	0.241	0.737	0.290	0.147	–0.906*	0.911*	0.835*	1	
W%	–0.975**	0.032	–0.734	0.255	0.827*	0.340	0.147	–0.959**	0.971**	0.831*	0.956**	1

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

mainly from organic matter accounted for about 10–20% of TP in macrophyte growth zones, but it is still difficult to establish a clear mechanism for a correlation between phosphorus and organic matter. In addition, organic matter in open-water zone was only correlated with various grains, including silt ($r = -0.906$), fine sand ($r = 0.911$) and coarse sand ($r = 0.835$) (Table 2).

Significant correlations with certain P fractions could be found for clay, silt, fine sand and coarse sand, depending on different zones. Good positive correlations with fine sand were observed for OP in emergent macrophyte growth zone and open-water zone ($r > 0.86$; Tables 1, 2). This shows that, in some sandy sediment, organic matter is also associated with larger particles (adsorbed or in the form of bacterial film). Negative correlations between clay and IP were obtained in submerged macrophyte growth zone and open-water zone. There were negative correlations between other P fractions except IP and clay in emergent macrophyte growth zone. Moreover, in macrophyte growth zones NaOH-P was correlated negatively with clay. These have been attributed to the fact that some IP and OP mainly adsorbed on loose fine particles not on compact clay. The distribution pattern of HCl-P over the size classed was more variable, with no marked feature. In general, most correlations with P fractions occurred in fine grain size ($<63 \mu\text{m}$), which is in agreement with the results of other studies (Andrieux-Loyer and Aminot 2001). This shows the particular nature of the fine fraction and phosphate sorption on hydroxides and oxides adsorbed at the surface of the fine particles.

There were strong correlations between TP and OP in macrophyte growth zones, while good correlations

exist between TP and IP in submerged macrophyte zone and open-water zone (Tables 1, 2). This indicates that it is possible to influence the distribution of P by plant. And OP is normally associated with organic matter accumulated in vegetation growth areas. HCl-P and NaOH-P content were strongly correlated with OP and TP content in emergent macrophyte growth zone, and NaOH-P content was also correlated with IP and TP in submerged macrophyte growth. These relations might be due, at least partially to the fact that metal hydroxides or oxides remained by macrophyte. The correlations between phosphorus forms and sediment components suggest a high affinity between these sediment components, despite the highly dynamic environment which differs from site to site.

The effect of different vegetation on P fractions

In shallow lakes, macrophytes may influence the P cycle both negatively and positively by their effects on P dynamics, sedimentation and resuspension (Søndergaard et al. 2003). The P fractions in lake sediments are important components in the P cycle, and depend on the origin of sediments and ecological environment.

In Wuliangsu Lake, submerged and emergent macrophytes increased the IP content by 107 and 44 µg/g, respectively, in the surface sediment compared with open-water zone. This was consistent with the distribution result of fine grain size. These were probably attributed to finer materials, potentially with a high affinity for IP, tended to deposit where there is less water movement. Fine particles may aggregate with organic materials (e.g. organic coatings) to form mixtures as if they were uniform composition; the

lower the energy level, the higher the accumulation of these particles at a site. Moreover, owing to the enhanced nutrient recycling rate within the macrophyte stand, fine grains also absorbed more IP from the water and plant. On the other hand, since submerged macrophyte in Wuliangshuai Lake had dense beds with high fine materials sedimentation by reducing current velocities and attenuating wave energy, IP was well kept in surface sediment. Therefore, the effects of submerged macrophyte on IP and grain size seemed to be stronger than those of emergent species.

Compared with open-water zone, emergent macrophyte increased TP content in surface sediment by 1.73 times to 1,320 $\mu\text{g/g}$, while submerged macrophyte enhanced TP content in surface sediment by 1.13 times to 865 $\mu\text{g/g}$. Similar distributions were found in OP content of surface sediment. Mainly because emergent macrophyte appeared in the surrounding zones where the water depth was under about 2.0 m, whereas the submerged macrophyte could be found at deeper water depth, amount of particulate organic matter with OP first was remained by emergent macrophyte, and then by submerged macrophyte. Schulz et al. (2003) also concluded that macrophytes considerably contributed to the phosphorus retentions (up to 25%) by increasing deposition of particulate organic matter. In addition, the relationships can be established between IP/(IP + OP) ratio and organic matter content in the sediments of macrophyte growth zones (SM, $r = -0.857$; EM, $r = -0.987$), which indicated the distribution of phosphorus between the organic and inorganic fractions appeared to be related with the organic matter content in an obvious way. Furthermore, organic matter in surface sediment of Wuliangshuai Lake was accumulated more in macrophyte growth zones than in open-water zone, which contributed to adsorb more OP, and increased TP content.

However, continuous accumulation of organic matter may lead to the death of macrophytes. Koch (2000) showed that more than 5% organic matter in the sediment may lead to the loss of marine macrophytes, while a similar limitation of freshwater macrophyte growth by sediment organic content was found in laboratory tests by Barko and Smart (1983, 1986). Thus, it is very possible to increase organic matter and other matter content in sediments of Wuliangshuai Lake, since organic matter content from submerged macrophyte growth zone was more than 5%, which also contributed to increase in OP content correlated with organic matter in sediments.

Because sediments are the primary source of P to macrophytes, and because they reflect both the direct effects of anthropogenic nutrient loading and the

background conditions of the lake, sediment P concentration may be a better predictor of macrophyte growth in lakes than open-water nutrients. In the past, the dominant species was *Chaca* spp. that is a submerged plant in Wuliangshuai Lake. Due to eutrophication and the decrease in water depth of the lake, this plant was displaced by emergent plant. To date, the area of emergent macrophyte has increased 50-fold from 1950s in study site. Correspondingly, since organic residues with low specific gravity tended to co-exist with inorganic materials, forming an organic and phosphorus-rich layer on surface sediments in Wuliangshuai Lake, IP, OP and TP content in surface sediments increased and greatly went beyond that in bottom sediments, which indicated that the lake sediments had a great potential to supply phosphorus to the overlying water (Marsden 1989). Therefore, the effect on sediment P fractions by macrophyte should be taken into account in future restoration projects in Wuliangshuai Lake.

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