Honglei Liu¹
Chengqing Yin¹
Hongjun Wang²
Weidong Wang¹
Baoqing Shan¹

¹State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, P. R. China.

²Institute of Botany, Chinese Academy of Sciences, Beijing, P. R. China.

Research Article

Sedimentary Phosphorus Form Distribution and Cycling in the Littoral Subzones of a Eutrophic Lake

Algae which bloom in open water and accumulate in the littoral zones may affect the biogeochemical cycle of phosphorus in eutrophic lakes. To determine such effects, a part of the lakeshore with little allochthonous nutrient input in Taihu Lake, China was selected for this field study. Distinct differences in sedimentary P forms were found among the different littoral subzones. The surface sedimentary total phosphorus (TP) content was 655 mg/kg in the eulittoral subzone and 631 to 641 mg/kg in the infralittoral subzone. Both were much higher than that in the profundal zone (410 mg/kg). Calcium-bound P (Ca-P) was significantly correlated to exchangeable P (Ex-P), and they both had the highest contents in the infralittoral subzone and the lowest in the profundal zone. The aluminum- and iron-bound P (Al-P, Fe-P) contents decreased from land to water along the ecotone section. Lower Fe/P ratios and higher Al-P/Fe-P ratios appeared in the infralittoral subzone, as compared with the profundal zone. This suggested that the accumulated algae could lead to a great deposit of P in the littoral zones. However, the active sedimentary P form transformation in the littoral zones would also result in a partial release of the accumulated P to the overlying water.

Keywords: Algae Accumulation; Littoral Zone; Phosphorus Form; Sediment

Received: June 4, 2007; *revised:* September 14, 2007; *accepted:* October 3, 2007

DOI: 10.1002/clen.200700058

1 Introduction

The biogeochemical cycling of phosphorus has been a focus of limnetic study due to its key role in freshwater eutrophication processes [1]. In sediments, P is present in a number of chemical forms, exhibiting different physical and chemical behavior with respect to mobility and biological availability [2]. P form data could provide much more information regarding its behavior in environments than total phosphorus (TP) content [3]. Results obtained from existing fractionating schemes were analytical estimates of different P forms, which then could be used in predicting P responses to physicochemical changes, and also in understanding the internal P cycling [4, 5].

Healthy littoral zones, as land–water ecotones, can reduce the allochthonous nutrient input efficiently [6–8], and they are also the active biogeochemical areas of lake systems [9, 10]. Several investigations found that the sediments in the littoral zones could serve as an important contributor to internal P load due to their higher TP, loosely bound P, and iron-bound P (Fe-P) contents compared with those in open water [3, 9]. Because of the highly spatial heterogeneity,

the littoral zone could be further divided into three subzones: supralittoral, eulittoral, and infralittoral [11]. In shallow eutrophic lakes, it is common for dense algae to accumulate along the shoreline downwind [12, 13]. As yet, it is still unclear how the accumulated algae affect the P behavior at the littoral subzone level. The spatial heterogeneity and the heavily accumulated algae may make the fate of sedimentary P more complicated in the littoral zones.

The objective of this study was to investigate the sedimentary P form distribution among the profundal and littoral subzones of a lake with frequent algal bloom, and then to evaluate its fate.

2 Materials and Methods

2.1 Study Site and Sediment Sampling

This study was conducted in Meiliang Bay of Taihu Lake (see Fig. 1). Taihu Lake covers a surface area of 2338 km² with an average depth of 1.9 m. The hydraulic retention time is about 309 days, and the secchi depth ranges from 20 to 50 cm. The water quality of Taihu Lake was still good in 1960s, but became eutrophic after 1980s. The mean total nitrogen and TP of water were about 0.9 and 0.03 mg/L in 1981, and increased to 2.3 and 0.1 mg/L in 2000. Heavy algae blooms frequently break out from July to September, and make numerous algae assemble along the littoral zone. The amount of algae in the macrophyte-covered littoral zone could exceed 20 g/L (wet weight), several thousands of times as much as that found in open lake water [14]. Field investigation found that there was no P input from stormwater runoff, groundwater, or point sources.

Correspondence: Prof. C. Yin, State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, CAS, P. O. Box 2871, Beijing 100085, P. R. China.
E-mail: cqyin@263.net

Abbreviations: Al-P, aluminum-bound P; Ca-P, calcium-bound P; DO, dissolved oxygen; Eh, oxidation–reduction potential; Ex-P, exchangeable P; Fe-P, iron-bound P; OM, organic matter; Re-P, residual P; TP, total phosphorus

Figure 1. Sampling site diagram of the study of Meiliang Bay in Taihu Lake; sites A1, A2, A3, A4, and D are located in the land/water ecotones.

Five sampling sites were selected along the perpendicular section from the shore to open water, marked as A1–A4, and D (see Fig. 1). This section was divided into three subzones (eulittoral, infralittoral, and profundal), with the terminology by Wetzel [11]. For sites A1–A4, the interval was 50 m between adjacent sites. Site A1, belonging to the eulittoral subzone, was located in a reed (*Phragmites australis*) belt, and sites A2–A4 belonged to the infralittoral subzone, where few submerged or floating-leaved plants survived in the spring. Site D was located in the profundal zone, about 500 m away from site A4. The water depth at sites A1–A4 and D was about 0.6, 1.0, 1.5, 1.6, and 1.8 m, respectively.

Duplicate sediment cores were collected at each site using a gravity corer in October 2005. The core length was 60 cm and the sediment columns gotten were between 12 and 40 cm. After the overlying water was siphoned off, the sediment columns were sectioned between 1 and 3 cm. Zero to two centimeters were sampled into 1 cm slices; 3 to 8 cm was sectioned into 2 cm slices; 9–11 cm was sectioned into 3 cm slices. All the samples were sealed in clean polyethylene bags and put in a cooled box on site. The cooled samples were transported to the laboratory as soon as possible and stored at 0 to 4°C prior to analysis.

2.2 Physicochemical Characteristics

Organic matter (OM) and pH were determined according to the literature [15]. Grain size distributions in the sediments were determined with a Mastersizer 2000 Laser Grainsize, and the fraction with grain size less than 63 µm was categorized as silt and clay according to the method of Cahoon et al. [16]. The total elements' (Fe, Al, Ca, and P) content of sediments were measured by digesting the samples with HF–HClO₄ [17]. Amorphous and poorly crystalline Fe and Al (hydr)oxides, and the P bound to them were extracted with a mixed oxalic acid and ammonium oxalate solution (pH = 3) [18]. Acid-extractable calcium (Ca) and magnesium (Mg) were extracted from sediments using 0.1 M HCl. All the metals in the leachate above were analyzed using a Perkin-Elmer Elan 6000 ICP-OES.

2.3 Chemical Speciation of P

The P forms were determined successively from sediments using different solvents and conditions according to the procedure of Koski-Vähälä et al. [19]. All the species extracted are exchangeable P (Ex-P, extracted by 1 M NH₄Cl), aluminum-bound P (Al-P, extracted by 0.5 M NH₄F with the pH being adjusted to 8.5), Fe-P (extracted by

0.1 M NaOH), calcium-bound P (Ca-P, extracted by 0.5 M HCl), and residual P (Re-P, calculated by the difference with TP).

2.4 Statistical Analyses

The statistical analyses were conducted by parametrical methods. Correlation, regression, and one-way ANOVA analyses were done using SPSS 11.0, Origin 7.5, and SAS 9.0 software, respectively, and the probability of all significant differences was $p \leq 0.05$.

3 Results

3.1 General Characteristics of the Sediments

Although the shallow depth (only about 1.9 m) might lead to well mixing of the water column, obvious dissolved oxygen (DO) gradient was still found along the water depth. In the open water, DO concentration decreased from 10 mg/L at the surface to only 3 mg/L at the water depth of 160 cm. Obvious oxygen gradient also existed along the ecotone section from land to open water. In the growing season, the average DO concentrations in the open water could even exceed 12 mg/L, while they were less than 5 mg/L in the eulittoral subzone. In the macrophyte-dominated eulittoral subzone, with the increase in depth, the sedimentary Eh value first decreased dramatically from surface to 5 cm, then increased gradually (5–20 cm), and then decreased (>20 cm). The increase of Eh between 5 and 20 cm proved the existence of the oxygen release from the macrophyte roots and rhizomes. However, in other water areas, the sedimentary Eh values kept decreasing with the increase in depth.

The vertical distributions of OM and pH are shown in Fig. 2. For the top 4 cm sediments, OM at sites A2–A4 (the infralittoral subzone) exhibited similar values. They were significantly lower than those at site A1 within the depth from surface to 6 cm, and higher than those at site D. OM contents at all sites decreased with depth. At site A1, pH increased from 5.95 at the surface (top 1 cm layer) to 7.06 at a depth of 8 cm, and then decreased with depth. However, at the infralittoral sites, pH decreased gradually with increasing depth, and in the profundal zone (site D) it decreased dramatically from 7.04 at the surface to 5.66 at a depth of 8 cm. The lower pH values existing in the eulittoral sediment, rather than in the infralittoral sediment, coincided with the observed fluctuation of pH in the above water. The pH of the above water decreased from open water (8.2 ± 0.6) to the eulittoral subzone (7.3 ± 0.9), especially in the growing season. For the top 4 cm sediment, TP content was 668 ± 41 mg/kg in the eulittoral subzone, and 629 ± 30 mg/kg in the

Figure 2. OM, pH, and TP content in sediments at various depths.

Table 1. Some physicochemical characteristics of the sediment samples in form of (mean (SD), $n = 6$).

Site	Silt and Clay (%)	T-Fe (g/kg)	T-Al (g/kg)	T-Ca (g/kg)	Fe _{ox} (mmol/kg)	Al _{ox} (mmol/kg)	P _{ox} (mmol/kg)	Ca _{HCl} (mmol/kg)	Mg _{HCl} (mmol/kg)	P _{HCl} (mmol/kg)
A1	71.9 ± 9.1 ^c	28.6 ± 2.0 ^c	63.0 ± 10.2 ^a	6.9 ± 1.6 ^c	130.6 ± 7.9 ^c	161.7 ± 26.1 ^a	13.7 ± 0.6 ^a	129.0 ± 50.3 ^{cd}	37.2 ± 6.9 ^{cd}	12.7 ± 0.6 ^a
A2	79.6 ± 3.1 ^{ab}	27.7 ± 2.8 ^c	60.9 ± 8.0 ^a	10.0 ± 2.7 ^b	132.0 ± 16.0 ^c	131.3 ± 26.5 ^b	10.3 ± 2.5 ^b	189.6 ± 74.1 ^c	34.9 ± 7.2 ^d	10.6 ± 1.6 ^b
A3	81.6 ± 1.1 ^{ab}	33.7 ± 0.9 ^b	61.5 ± 11.1 ^a	12.6 ± 4.5 ^b	179.3 ± 11.0 ^b	160.6 ± 10.7 ^a	12.6 ± 1.0 ^a	285.8 ± 114.6 ^b	48.6 ± 3.4 ^b	11.3 ± 0.9 ^b
A4	84.0 ± 2.3 ^a	37.7 ± 2.7 ^a	66.2 ± 6.7 ^a	15.6 ± 6.0 ^a	199.4 ± 7.3 ^a	146.3 ± 30.5 ^{ab}	12.8 ± 2.3 ^a	364.7 ± 148.5 ^a	56.7 ± 4.1 ^a	11.2 ± 1.7 ^b
D	77.5 ± 3.4 ^b	36.3 ± 1.4 ^a	61.7 ± 8.9 ^a	5.8 ± 0.7 ^c	209.6 ± 17.3 ^a	57.9 ± 4.4 ^c	6.3 ± 1.4 ^c	93.5 ± 11.8 ^d	41.0 ± 2.6 ^c	6.1 ± 1.3 ^c

T-Fe, T-Al, T-Ca: total Fe, Al, Ca contents, respectively.

Fe_{ox}, Al_{ox}, P_{ox}: Fe, Al, P extractable in ammonium oxalate.

Ca_{HCl}, Mg_{HCl}, P_{HCl}: Ca, Mg, P extractable in 0.1 N HCl.

Different superscript letters (a, b, c) indicate significant differences in contents among subzones.

Figure 3. Regression plot of the contents of total Fe and Al in sediments (dashed lines are the 95% confidence limits).

infralittoral subzone. Both were significantly higher than that in the profundal zone (402 ± 12 mg/kg).

Some properties of the sediments are presented in Tab. 1. From sites A1–A4, the fraction of silt and clay increased from 71.85 to 84.03%, and then decreased to 77.50% at site D. This indicated the presence of an offshore fining phenomenon. The total iron content (g/kg) increased from site A1 (28.6 ± 2.0) to sites A4 (37.7 ± 2.7) and D (36.3 ± 1.4). The mean total aluminum content fluctuated in the

Figure 4. Vertical distribution of the mass T-Fe/TP ratios in sediments.

range of 60 to 66 g/kg at all these sites. From sites A1–A4, calcium content increasing with the distance from the shore indicated a wave-induced transport of biogenic carbonate particles from more shallow littoral areas to deeper parts of the lake. However, site D showed a relatively low and constant value.

The relationships between the total Fe and Al are shown in Fig. 3. It indicated that the sediments at sites A1 and A2 were depleted in Fe (or enriched in Al), compared with the finer sediments at sites A3, A4, and D. The T-Fe/TP ratio distribution is presented in Fig. 4, which shows that the T-Fe/TP ratios were slightly higher at greater depths, and increased from the eulittoral subzone (40–73:1) to the profundal zone (85–125:1).

Figure 5. P contents (mg/kg) in Ex-P, Al-P, Fe-P, Ca-P, and Re-P forms in sediments.

3.2 Chemical Fractionation for P

The sedimentary P contents (mg/kg) in Ex-P (a), Al-P (b), Fe-P (c), Ca-P (d), and Re-P (e) forms are shown in Fig. 5. Significant differences of the sedimentary P form distribution could be observed among these littoral subzones.

Figure 6. Comparison of Al-P/Fe-P ratio in sediments.

At all sites, Ex-P decreased with depth (see Fig. 5a). For the surface layer of the top 1 cm sediment, Ex-P content was 4.1 mg/kg at site A1 (eulittoral subzone), and 5.3–6.1 mg/kg at sites A2–A4 (infralittoral subzone). Both were significantly higher than that at site D (1.3 mg/kg) in the profundal zone.

The sedimentary Al-P (see Fig. 5b) increased with depth at site A1, while it decreased with depth at the other sites. The highest Al-P content (158–182 mg/kg) appeared at sites A2–A4, and the lowest existed at site D (7.58–40.98 mg/kg). Significant positive correlation existed between Al_{ox} and Al-P ($r = 0.94$). At site A1, Al_{ox} increased from 3.91 to 5.57 mg/g from the surface to the depth of 11 cm, while the total Al content decreased from 68.32 to 43.44 mg/g correspondingly.

The highest Fe-P value (174–211 mg/kg) occurred at site A1, and the lowest value existed at site D (89–132 mg/kg) (see Fig. 5c). Fe-P seemed to decrease from land to water along the ecotone section. An obvious tendency of Fe-P to decrease with depth could only be observed at sites A2 and D.

Ca-P content decreased with increasing depth at all sites (see Fig. 5d). Figure 5d shows that Ca-P increased from site A1 (73–111 mg/kg) to site A4 (109–187 mg/kg), and then decreased dramatically to site D (76–101 mg/kg). Ca-P was significantly correlated with the total Ca and Ex-P contents ($r = 0.97$ and 0.86 , respectively).

The distribution of Re-P was similar to that of Ca-P (see Fig. 5e), except that Re-P was very high in the sediments at site A1, especially at the top 6 cm layers (182–206 mg/kg).

The distribution of Al-P/Fe-P ratios (see Fig. 6) shows that at all sites, except at site A1, the ratios were high at the sediment–water interface, and decreased with depth. However, at the eulittoral site A1, which had a domination of reeds, the maximum ratio value (1.05:1) appeared at a depth of 11 cm. The sediments sampled from the littoral zone had significantly higher Al-P/Fe-P ratios (0.45–1.05:1) than those (0.08–0.31:1) from the profundal zone. The sorting effect of Fe/Al in the sediment from land to water (see Fig. 2) can account partly for this polarization of Al-P/Fe-P ratios along the ecotone section.

4 Discussion

4.1 Active Form Transformation of P in the Littoral Zone

The sorting effect of sediment components with high Al/low Fe and low Al/high Fe (see Fig. 3) may result from the offshore fining effect due to the fact that the finer sediments can be enriched in Fe, as compared with the coarser counterparts [20]. The Eh value decreases from open lake water to land, especially during the growing season

Figure 7. Conceptual diagram of P exchange between the littoral and profundal zones in shallow lakes. NWL, normal water level.

[21], which will make the corresponding Fe-P release accompanied with the reduction of iron (III) due to its redox sensitivity [9]. The Al-P/Fe-P ratios in the littoral zone significantly higher than those in the profundal zone suggested that some of the sedimentary Fe-P in the littoral zone were transformed into Al-P, probably due to the equilibrium between Fe-P and Al-P [19]. The increased P saturation on the Al oxide surface can thus contribute to the increase in Ex-P in the littoral zone since the water-soluble P in the soil is controlled mainly by the P saturation on the Al oxide surface [22], which was confirmed by the Ex-P distribution pattern.

Higher concentrations of Ex-P and Ca-P in the littoral zone than in the profundal zone agree with others' findings [3, 9]. The distribution pattern of Ca and Ca-P indicates that they may be transformed or transported along the ecotone section. It was reported that Ca could be transported offshore for that the carbonate particles are lighter and more fragile than quartz particles of the same size [23]. However, the pH fluctuation along this section might also favor the transference of Ca and Ca-P. The acid environment ($\text{pH} < 7$) in the littoral zone might lead to a release of sedimentary calcium oxides. The rapid decomposition of dead algae accumulated in the eulittoral area, the enhanced mineralization rate through a release of oxygen from the roots and rhizomes, and the secreted organic acids by the macrophytes could result in the decrease in pH [21]. It has been found that the production of CO_2 and acidity at oxic respiration of organic carbon decomposition was the driving force for calcite dissolution at the sediment–water interface [24]. Due to the convective offshore undercurrent, the released Ca and P can be carried away from the eulittoral into the profundal water before they precipitate again.

The active P form transformation in the littoral zone indicates that a higher amount of sedimentary P will be released there relative to the profundal zone. This finding is verified by the P release studies in undisturbed sediment cores [9], and the littoral–pelagic P dynamics studies [25]. It can also be confirmed by the lower Fe/P ratios found in littoral zone than in the profundal zone in this study. It has been reported that sediments with lower Fe/P ratios have more extra P available [26]. For the regulating effect of the pH value on the rates of P release from sediments under aerobic conditions [19, 27], the acidic surface sediment in the eulittoral subzone and the alkaline sediment in the infralittoral subzone also make them both release more P to the above water than the neutral sediment in the profundal zone.

4.2 Littoral Zone as the “Sink” of Internal P

Although the littoral zone can serve as the sink of the external loading by retaining most of the allochthonous contaminants [28], it is difficult to define simply the littoral zone as a sink or source for the internal P loading. On one hand, pollutants contained in sediments can return to the above water through diffusion, sediment resuspension, or biological activity [29]. On the other hand, as a result of wave action, various autochthonous materials including nutrients can also accumulate in the lake margin [30].

The internal P loading from the littoral zone can be exchanged with the open water. So the net role of the littoral zone in the whole lake system's internal loading is expected to depend on the hydrological and the consequent material exchange between the littoral and profundal zones. Based on the findings of others [31], a conceptual diagram of P exchange between the littoral and profundal zones in this shallow lake is presented in Fig. 7, with the two main known mechanisms of wind-driven circulation and convective circulation included. The waves breaking at the shore may return as a bottom current. The negative horizontal temperature gradient between the littoral and profundal zones can also give birth to a convective undercurrent [25]. Among the range of wave action forces resulting in the offshore sediment fining, the convective undercurrent (offshore) may play an important role.

Although the self-born algae do not affect the P exchange between profundal and littoral zones, the drift algae due to wind-driven effect do. The algal phosphate will be recycled several times during the growing season, and eventually become sediment phosphate, either as an inorganic or as an organic pool [32]. It has been found that the accumulating algae can make the receiving bay serve as a “special biological nutrient filter”, which prevents nutrients from being brought out by the outflow currents and enhances nutrient deposition [33]. Since there is no external diffuse or point loading from upland, the sedimentary TP content is the net accumulation result of this internal cycling mode. So the higher TP in the littoral zone than in the profundal zone may confirm that such littoral zone with algae accumulation, especially the eulittoral subzone, played an important role as a special biological nutrient filter, that is to say, the sink of the internal P for the whole lake [34]. It means that to harvest the accumulating algae in summer and to dredge the sediment out from the eulittoral subzone are effective means to control internal P, for they cannot only get the enriched P from

open water, but also prevent the release of sedimentary P due to the active biogeochemical activity.

In this study, distinct differences in sedimentary P forms were found among the different littoral subzones in eutrophic Taihu Lake. The sediment in the infralittoral subzone can contribute a relatively large amount of internal P loading due to its high Ex-P contents, high pH values, and low Fe/P ratios. However, due to the immense quantity of algae P, the littoral zone with the heavy accumulation of cyanobacteria can still serve as the net P sink of the whole lake.

Acknowledgments

We are grateful to Janice Willson for correcting the language of this article. This research was supported by National Basic Research Priorities Programs (2006CB403306 and 2002CB412308).

References

- [1] D. L. Correll, The Role of Phosphorus in the Eutrophication of Receiving Waters: A Review, *J. Environ. Qual.* **1998**, 27 (2), 261.
- [2] J. P. Coelho, M. R. Flindt, H. S. Jensen, A. I. Lillebo, M. A. Pardal, Phosphorus Speciation and Availability in Intertidal Sediments of a Temperate Estuary: Relation to Eutrophication and Annual P-fluxes, *Estuar., Coast. Shelf Sci.* **2004**, 61 (4), 583.
- [3] O. G. Olila, K. R. Reddy, W. G. Harris, Forms and Distribution of Inorganic Phosphorus in Sediments of 2 Shallow Eutrophic Lakes in Florida, *Hydrobiologia* **1995**, 302 (2), 147.
- [4] M. Sondergaard, J. Windolf, E. Jeppesen, Phosphorus Fractions and Profiles in the Sediment of Shallow Danish Lakes as Related to Phosphorus Load, Sediment Composition and Lake Chemistry, *Water Res.* **1996**, 30 (4), 992.
- [5] E. Rydin, Potentially Mobile Phosphorus in Lake Erken Sediment, *Water Res.* **2000**, 34 (7), 2037.
- [6] J. Uusi-Kamppa, B. Braskerud, H. Jansson, N. Syversen, R. Uusitalo, Buffer Zones and Constructed Wetlands as Filters for Agricultural Phosphorus, *J. Environ. Qual.* **2000**, 29 (1), 151.
- [7] P. J. A. Withers, I. A. Davidson, R. H. Foy, Prospects for Controlling Nonpoint Phosphorus Loss to Water: A UK Perspective, *J. Environ. Qual.* **2000**, 29 (1), 167.
- [8] W. D. Wang, D. L. Wang, C. Q. Yin, A Field Study on the Hydrochemistry Land/Inland Water Ecotones with Reed domination, *Acta Hydrochim. Hydrobiol.* **2002**, 30 (2–3), 117.
- [9] F. O. Andersen, P. Ring, Comparison of Phosphorus Release from Littoral and Profundal Sediments in a Shallow, Eutrophic Lake, *Hydrobiologia* **1999**, 409 (408/409), 175.
- [10] H. J. Wang, J. W. Lu, W. D. Wang, L. Y. Yang, C. Q. Yin, Methane Fluxes from the Littoral Zone of Hypereutrophic Taihu Lake, China, *J. Geophys. Res.* **2006**, 111, D17109.
- [11] R. G. Wetzel, *Limnology: Lake and River Ecosystem*, Elsevier, New York **2001**.
- [12] J. H. G. Verhagen, Modeling Phytoplankton Patchiness under the Influence of Wind-Driven Currents in Lakes, *Limnol. Oceanogr.* **1994**, 39 (7), 1551.
- [13] I. Valiela, J. McClelland, J. Hauxwell, P. J. Behr, D. Hersh, K. Foreman, Macroalgal Blooms in Shallow Estuaries: Controls and Ecophysiological and Ecosystem Consequences, *Limnol. Oceanogr.* **1997**, 42 (5), 1105.
- [14] H. J. Wang, W. D. Wang, J. W. Lu, C. Q. Yin, Algae Trapping in Macrophyte-Covered Littoral Zone and Water Sources Protection, *China Water Wastewater [in Chinese]* **2006**, 22 (7), 1.
- [15] S. D. Bao, *Chemical Analysis for Agricultural Soil [in Chinese]*, China Agricultural Press, Beijing **2000**.
- [16] L. B. Cahoon, J. E. Nearhoof, C. L. Tilton, Sediment Grain Size Effect on Benthic Microalgal Biomass in Shallow Aquatic Ecosystems, *Estuaries* **1999**, 22 (3B), 735.
- [17] A. Tessier, P. G. C. Campbell, M. Bisson, Sequential Extraction Procedure for the Speciation of Particulate Trace Metals, *Anal. Chem.* **1979**, 51 (7), 844.
- [18] G. M. Pierzynski, *Methods for Phosphorus Analysis for Soils, Sediments, Residuals and Waters*, North Carolina State University, Raleigh **2000**.
- [19] J. Koski-Vähälä, H. Hartikainen, P. Tallberg, Phosphorus Mobilization from Various Sediment Pools in Response to Increased pH and Silicate Concentration, *J. Environ. Qual.* **2001**, 30 (2), 546.
- [20] R. G. Gerritse, P. J. Wallbrink, A. S. Murray, Accumulation of Phosphorus and Heavy Metals in the Swan-Canning Estuary, Western Australia, *Estuar., Coast. Shelf Sci.* **1998**, 47 (2), 165.
- [21] H. J. Wang, *Biogeochemical Processes of Nitrogen in the Littoral zone in Eutrophic Lake-Meiliang Bay, Taihu, Lake*, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing **2006**.
- [22] H. Hartikainen, Water-Soluble Phosphorus in Finnish Mineral Soils and its Dependence on Soil Properties, *J. Sci. Agric. Soc. Fin.* **1982**, 54, 89.
- [23] K. Schmieder, H. P. Piepho, H. G. Schroder, Spatial Models as a Tool to Identify Spatial Patterns of Surficial Sediment Composition and their Contributing Factors in the Littoral Zone of Lake Constance (Germany), *Aquat. Sci.* **2005**, 67 (3), 326.
- [24] B. Muller, Y. Wang, M. Dittrich, B. Wehrli, Influence of Organic Carbon Decomposition on Calcite Dissolution in Surficial Sediments of a Freshwater Lake, *Water Res.* **2003**, 37 (18), 4524.
- [25] W. F. James, J. W. Barko, Littoral-Pelagic Phosphorus Dynamics during Nighttime Convective Circulation, *Limnol. Oceanogr.* **1991**, 36 (5), 949.
- [26] D. T. Vandermolen, P. C. M. Boers, Influence of Internal Loading on Phosphorus Concentration in Shallow Lakes before and after Reduction of the External Loading, *Hydrobiologia* **1994**, 276 (1), 379.
- [27] W. Graneli, Internal Phosphorus Loading in Lake Ringsjon, *Hydrobiologia* **1999**, 404 (0), 19.
- [28] L. B. M. Vought, J. Dahl, C. L. Pedersen, J. O. Lacoursiere, Nutrient Retention in Riparian Ecotones, *Ambio* **1994**, 23 (6), 342.
- [29] J. G. Arnason, B. A. Fletcher, A 40+ year record of Cd, Hg, Pb, and U Deposition in Sediments of Patroon Reservoir, Albany County, NY, USA, *Environ. Pollut.* **2003**, 123 (3), 383.
- [30] E. Pieczynska, Detritus and Nutrient Dynamics in the Shore Zone of Lakes – A Review, *Hydrobiologia* **1993**, 251 (1–3), 49.
- [31] W. F. James, J. W. Barko, Estimation of Phosphorus Exchange between Littoral and Pelagic Zones during Nighttime Convective Circulation, *Limnol. Oceanogr.* **1991**, 36 (1), 179.
- [32] H. L. Golterman, The Distribution of Phosphate over Iron-Bound and Calcium-Bound Phosphate in Stratified Sediments, *Hydrobiologia* **1998**, 364, 75.
- [33] Q. Yang, Algal Bloom in Taihu Lake and its Control, *J. Lake Sci. [in Chinese]* **1996**, 8 (1), 67.
- [34] T. Kairesalo, T. Matilainen, Phosphorus Fluctuation in Water and Deposition into Sediment within an Emergent Macrophyte Stand, *Hydrobiologia* **1994**, 276 (1), 285.