



Effects of *Hydrilla verticillata* (L.F) Royle on Phosphorus Sorption in Sediments

LIZHI WANG^{1,*}, GUOXIANG WANG¹, XUGUANG GE², QIUMIN CHEN¹, XIANKUN GU¹ and ZHENFEI YU¹

¹College of Geographical Science, Nanjing Normal University, Jiangsu Key Laboratory of Environmental Change and Ecological Construction, Nanjing 210046, P.R. China

²Department of Geographical Science, Hubei Normal University, Huangshi 435002, P.R. China

*Corresponding author: E-mail: wjljy@163.com

(Received: 11 October 2010;

Accepted: 14 May 2011)

AJC-9941

In order to know the effects of *H. verticillata* on the mechanism of phosphorus sorption, a simulated experiment was done. The effects of *H. verticillata* on the phosphate sorption isotherm and sorption kinetics were investigated. The results show that the concentrations of NaOH extracted phosphorous (NaOH-P), inorganic phosphorus, organic phosphorus, total phosphorus, Olsen-phosphorus, organic matter, cationic exchange capacity, Fe, Al, exchangeable Fe (Fe_{ox}) and exchangeable Al (Al_{ox}) were lower of the sediments with *H. verticillata* than those of the control. The sediments with *H. verticillata* had stronger phosphorus sorption ability. *H. verticillata* did not significantly affect the trends of the sorption isotherms and sorption kinetics on the sediments. *H. verticillata* decreased both phosphate sorption efficiency and the amount of the phosphorus that can be released from sediments. The study states that *H. verticillata* can significantly increase the ability of phosphorus sorption is one of the mechanism of *H. verticillata* maintain lower phosphorus levels of the overlying water. *H. verticillata* can increase the ability of phosphorus sorption through affecting the contents of NaOH-P, inorganic phosphorus, organic phosphorus, Olsen-phosphorus, total phosphorus, organic matter, cationic exchange capacity, Fe, Al, Fe_{ox} and Al_{ox} in sediments.

Key Words: Phosphate sorption, Kinetics, Sorption isotherm.

INTRODUCTION

Lake eutrophication is a serious problem deriving directly from the significant human modifications to the natural biogeochemical cycles of nitrogen and phosphorus¹. Phosphorus is the limiting nutrient for primary productivity in many lakes². The phosphate sorption at the sediment-water interface in lakes were important processes affecting phosphorus transport, bioavailability and fate of phosphorus in the overlying water, particularly in shallow lakes³. One of the most important factors affecting phosphorus concentration of the overlying water in lakes is the phosphorus release from sediments⁴. The phosphorus release may have a significant impact on the water quality and may result in continuous eutrophication in eutrophic lakes, especially when external pollution is reduced^{5,6}.

Submerged macrophytes play an important role in phosphorus cycling, especially in shallow lakes⁷. It has been reported that water quality can be significantly improved by reintroducing submerged macrophytes and areas with dense submerged macrophytes usually have clear water and low concentrations of nutrients and phytoplankton⁸⁻¹¹.

H. verticillata is a widespread submerged vascular plant native to the warm water region of Asia. It was reported to have a high biological purification capability and to reduce

the extent of sediment resuspension¹²⁻¹⁵. Submerged macrophyte *H. verticillata* plays an important role in affecting the phosphorus exchange at sediment-water interface in lakes^{12,16,17}. So submerged macrophyte *H. verticillata* is commonly used for the environmental engineering of the controlling of shallow lake eutrophication. But the effects of submerged macrophyte *H. verticillata* on the exchange of phosphorus at sediment-water interface in shallow lakes were not well understood. In order to know the mechanism of phosphorus sorption, this study selected a familiar submerged macrophyte *H. verticillata* in China and evaluated the effects of *H. verticillata* on the phosphate sorption at the sediment-water interface. The effects of *H. verticillata* on the phosphate fractionation and phosphate sorption isotherm and sorption kinetics were investigated.

EXPERIMENTAL

The sediment sample used was obtained from the Moon Lake of Nanjing normal university in China, using a core sampler in July 2008. The sediment samples were taken to the laboratory in sealed plastic bags. After air-dried, sediments were sieved through 0.5 cm sieve to remove coarse debris and mixed. The homogenized sediment was added into high-density polyethylene buckets (top diameter = 55 cm, bottom diameter = 45 cm, height = 75 cm). Each polyethylene buckets

(pretreated by 5 % HCl) containing 4832.80 g dry sediments. 100 L of tap water was slowly added into the buckets.

Submerged macrophyte *H. verticillata* was collected from Gucheng Lake in Nanjing in China for the experiments in June 2008 and pre-incubation in Chinese Jiangsu key laboratory of environmental change and ecological construction greenhouse for 1 month. All plants were spun for 15 s and brushed carefully to remove adherent water and matters. Similarly apical shoots 30 cm in length were selected to determine initial fresh weight. After weighing those plants were assigned randomly to plant in buckets that contained sediments, planting 37 plants per bucket (treatment). The control blank did not plant. Every kind of sediment has three duplicates. All of these buckets always received ambient greenhouse daylight, which denoted by buckets (high light, averaged 1092 and 357 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at 13:00 p.m. for sunny and cloudy days. Low light, averaged 108 and 85 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at 13:00 p.m. for sunny and cloudy days). Water temperature was 15–25 °C (three air conditions were used to control the temperature when necessary), water temperature differences were not more than 2 °C among buckets.

Sampling and analyses: The experiments were conducted during 3 months from August 4, 2008 to November 4, 2008. The sediment samples were collected using hand driven high-density polyethylene corer (diameter = 4.5 cm) and were taken to the laboratory immediately in sealed plastic bags that were put in ice boxes, were then freeze-dried and sieved (< 2 mm).

Olsen-phosphorus was extracted from 1 g sediment by 20 mL of 0.5 M NaHCO_3 (pH = 8.5) for 0.5 h¹⁸. Organic matter content was determined after treatment of the sample with $\text{K}_2\text{Cr}_2\text{O}_7/\text{H}_2\text{SO}_4$ according to the walkley-black method¹⁹. Cationic exchange capacity was analyzed using EDTA- NH_4^+ method, total phosphorus was measured using the concentrated H_2SO_4 digestion method, Fe was measured using the HF- HNO_3 - HClO_4 digestion method, Al was measured using the HClO_4 - HNO_3 digestion method. Determination of Fe_{ox} and Al_{ox} involved shaking sediment samples with 0.175 M acidified ammonium (pH = 3) in the dark for 2 h at a sediment/solution ratio of 1:30²⁰.

Sorption isotherms: There were 0.5 g dried sediment samples added in a series of 100 mL acid washed centrifuge tubes with 50 mL of phosphate solution (anhydrous KH_2PO_4). The low initial concentrations of 0, 0.01, 0.02, 0.05, 0.08, 0.1, 0.15, 0.2 phosphorus mg/L and the high initial concentrations of 0, 2.0, 5.0, 8.0, 10.0, 15.0, 20.0 phosphorus mg/L were used. The centrifuge tubes were capped and placed at 25 \pm 1 °C in an orbital shaker at 250 rpm for 24 h to ensure the equilibrium. After equilibrium and centrifugation (5,000 rpm for 10 min) the suspension was filtered through 0.45 μm membrane and its phosphate concentration (equilibrium concen-

tration) was measured using the ascorbic acid method²¹. The quantity of sorbed phosphate was calculated through the decrease of the phosphate concentration in the solutions²². The triplicate experiments were carried out, the results demonstrated the high repeatability of the sorption method and experimental error was within 6 %.

Phosphate sorption kinetic experiments: Dried sediment samples (0.5 g) were added in a series of 100 mL acid-washed screw-cap centrifuge tubes with 50 mL phosphate solution (KH_2PO_4 , containing 1 mg /L phosphorus). The centrifuge tubes were capped and incubated at 25 \pm 1 °C in an orbital shaker at 250 rpm for different time intervals, varying within 72 h (0.5, 1, 1.5, 3, 5, 7, 12, 24, 48, 60 and 72 h). The sample solution was immediately centrifuged at 5000 rpm for 10 min and then filtered through 0.45 μm GF/C filter membrane. The filtrate was taken for phosphate analyses²¹. The phosphate sorption capacity of sediments was obtained from the difference between the initial phosphate concentration and the equilibrium phosphate concentration^{23,24}. For all samples, triplicates were analyzed and the data were expressed as the average.

Phosphorus fractionation: Fractionation procedure was primarily based on SMT protocol. The protocol consisted in three extraction procedures that were applied to 0.2 g aliquots of sediment samples:

An extraction (16 h) using 1 mol/L NaOH is performed to remove the extractable phosphorus (NaOH-P). The residue of this extraction is extracted (16 h) with 1 mol/L HCl (apatite phosphorus, associated with carbonates) and an aliquot of the 1 mol/L NaOH extract is treated (16 h) with 3.5 mol/L HCl (non-apatite inorganic phosphorus, the forms associated with oxides and hydroxides of Fe, Al, or Mn). In a separate sample, an extraction (16 h) using 1 mol/L HCl is performed to remove inorganic phosphorus (IP). The residue from this extraction is placed in a porcelain crucible and calcined in a furnace for 3 h at 450 °C. After this, the residue is extracted (16 h) again with 1 mol/L HCl to remove the phosphorus associated with the organic matter of the sediment (OP). To obtain the total phosphorus (TP), after the calcination of a separate sample (3 h, 450 °C), a simple extraction (16 h) with 3.5 mol/L HCl is performed. For all cases, phosphate was determined in the extracts by the spectrophotometric procedure. Spectrophotometric determination of phosphate in all extracts was carried out using the molybdenum blue method proposed by Murphy and Riley²⁵. Measurements were made at 886 nm.

RESULTS AND DISCUSSION

Characteristics of the sediments: The general features and the chemical component contents of sediments are presented in Table-1. The variety of phosphorus status among different

TABLE-1
GENERAL AND P RELATED PROPERTIES OF THE STUDIED SEDIMENTS

Items	Sampling time	NaOH-P (mg kg ⁻¹)	HCl-P (mg kg ⁻¹)	Inorganic phosphorus (mg kg ⁻¹)	Organic phosphorus (mg kg ⁻¹)	Total phosphorus (mg kg ⁻¹)	Olsen-phosphorus (mg kg ⁻¹)	Organic matter (mg kg ⁻¹)	CEC (cmol kg ⁻¹)	Fe (mg g ⁻¹)	Al (mg g ⁻¹)	Fe _{ox} (% of total)	Al _{ox} (% of total)
Treatment	4-Aug	300.07	287.50	516.49	232.98	762.22	76.32	39.58	229.66	28.043	1.08	0.011	0.81
	26-Sep	275.68	278.30	468.83	220.48	732.79	70.50	24.71	222.74	26.051	0.95	0.009	0.75
	4-Nov	269.90	281.48	452.10	224.53	720.91	72.94	25.36	231.25	24.175	0.84	0.008	0.63
Control	4-Aug	300.07	287.50	516.49	232.98	762.22	76.32	39.58	229.66	28.043	1.08	0.011	0.81
	26-Sep	284.13	284.05	491.56	224.77	760.64	80.26	34.90	214.18	27.551	0.97	0.009	0.79
	4-Nov	281.00	276.43	486.16	220.82	750.52	75.98	33.84	209.45	27.031	0.96	0.009	0.73

sediments was attributed to *H. verticillata*. NaOH-P, organic phosphorus, inorganic phosphorus and Olsen-phosphorus were often used to express phosphorus availability of soil and can also be used to indicate the risk of phosphorus release from soil and sediments²⁴. NaOH-P is exchangeable and phosphorus bound to metal oxides (mainly Al and Fe)²⁶, which is used for the estimation of available phosphorus in the sediments and is an indicator of algal available phosphorus²². This fraction can be released for the growth of phytoplankton when anoxic conditions prevail at the sediment-water interface²⁷. organic phosphorus is considered mainly refractory and only the labile portion can be released from surface sediments by bacterial remineralization²⁸. In this study, the contents of NaOH-P, organic phosphorus, inorganic phosphorus and Olsen-phosphorus of the sediments with *H. verticillata* were lower than those of the control sediments. This indicates that the phosphorus availability and the risk of phosphorus release from sediments with *H. verticillata* decreased.

Effects of *H. Verticillata* on the phosphate sorption on different sediments: Phosphate sorption isotherms of the different sediments at high and low initial phosphate concentrations are shown in Figs. 1 and 2, respectively. The phosphate sorption isotherms at lower initial concentration were best fitted by the linear model.

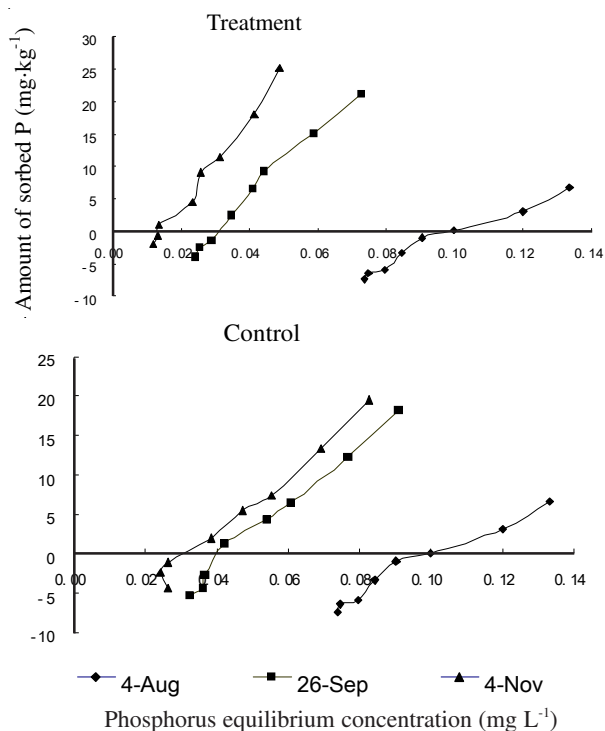


Fig. 1. Phosphate sorption isotherms of the sediments from different sampling time at low initial phosphate con

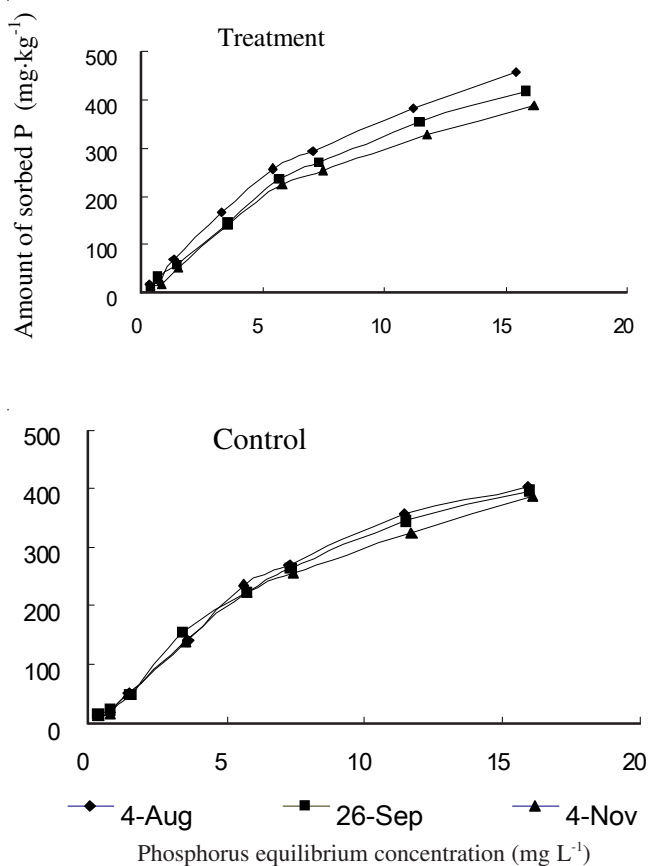


Fig. 2. Phosphate sorption isotherms of the sediments from different sampling time at high initial phosphate concentration

$$Q = m \cdot C - NAP$$

where C is the phosphate sorption equilibrium concentration (mg/L), Q is the phosphate sorption capacity (mg/kg dry weight). m is the slope and is a measure of the phosphate sorption efficiency of sediments (L/kg). NAP is the y-intercept which describes the phosphate released at low initial phosphate concentrations²⁹. Both m and NAP reflect the ability of phosphate sorption on sediments at a certain extent at lower initial phosphate concentration condition³⁰.

In contrast, the Langmuir model can effectively describe the phosphate sorption isotherms with well fitting to the data at high initial concentration.

$$Q = Q_{max} \cdot C / (Kd + C)$$

where C is the phosphate sorption equilibrium concentration (mg/L), Q is the phosphate sorption capacity (mg/kg dry weight). Q_{max} is the maximum phosphate sorption capacity (mg/kg dry weight), Kd is the half saturation concentration (mg/L). Q_{max} and Kd, reflect the ability of phosphate sorption on sediments at a certain extent^{15,31}.

Parameters	Treatment			Control		
	4-Aug	26-Sep	4-Nov	4-Aug	26-Sep	4-Nov
Q_{max}	277.78	416.67	454.55	277.78	370.37	384.62
NAP	20.69	15.91	9.41	20.69	15.65	12.06
m	203.8	524.52	622.66	203.8	368.62	371.55
Kd	6.56	7.5	9.31	6.56	8.3	9.14
EPC ₀	0.10	0.03	0.02	0.10	0.04	0.03

To further study the effects of *H. verticillata* on the phosphate sorption on different sediments, stepwise multiple regression analyses were performed. Q_{max} , K_d , m and NAP of the different sediments are shown in Table-2.

Phosphate sorption efficiency is related to many factors, such as metal content in sediments, temperature, dissolved oxygen, redox potential, pH and so on and vary greatly^{4,32}. In all factors metal content in sediments appeared to be the main factor due to the high specific surface of the Fe/Al (hydr) oxides^{33,34}. In some cases, the phosphate sorption sites were occupied by Fe and Al, thus resulting in the low phosphate sorption efficiency^{2,35}.

The most efficient sediments removing phosphate from the overlying water were those having lower contents of Al and Fe²⁴. Organic matter of the sediments with *H. verticillata* was higher than that of the control sediments; this may be attributed to the lower concentrations of Fe, Al, Fe_{ox}, Al_{ox} and NaOH-P. The concentrations of Fe, Al, Fe_{ox}, Al_{ox} and NaOH-P were decreased for *H. verticillata*'s uptake.

NAP was also related to many factors, such as organic matter, cationic exchange capacity, total phosphorus, inorganic phosphorus, organic phosphorus, Fe/Al-phosphorus and total nitrogen in the sediments. Previous studies have shown that there were significant correlations between NAP , organic matter, cationic exchange capacity, total phosphorus, inorganic phosphorus, organic phosphorus, Fe/Al-phosphorus and total nitrogen in the sediments from shallow lakes in the middle and lower reaches of the Yangtze River in China²³. NAP of the sediments with *H. verticillata* was higher than those of the control sediments at 4 August and 26 September; but NAP of the sediments with *H. verticillata* was lower than those of the control sediments at the end of the experiment; this is because the submerged macrophyte promoted the phosphorus release from sediments at the end of the experiment³⁶; and this may be attributed to the higher concentrations of cationic exchange capacity.

EPC_0 was also determined and was defined as the phosphate equilibrium concentration at which there was no net sorption or release of phosphate on sediments. It can be calculated from the x-intercept of the regression equations of linear model²³. EPC_0 has been highlighted in recent studies as it helps to understand the direction and size of soluble reactive phosphorus (SRP) flux^{23,37}. The higher EPC_0 was the lower risk of the phosphorus releasing from the sediments into the overlying water³⁷. EPC_0 was easy to measure and provided useful information on whether sediments can release or extract SRP. The kinetics of the interactions of SRP with natural sediments had been formulated in terms of EPC_0 of the surface sediments^{38,39}.

The values of EPC_0 of sediments with *H. verticillata* were lower than those of the control sediments. This may be because temperature was higher during the experiment course. The temperature was controlled by air conditions. *H. verticillata* developed hearty and uptook more nutrients from sediments and the overlying water and led more phosphorus released from sediments¹¹.

Based on the above discussion, the submerged macrophyte *H. verticillata* resulted in the decrease in both phosphate sorption efficiency and the amount of the phosphorus that can be released from sediments.

Effects of *H. verticillata* on sorption kinetics in sediments: The phosphorus sorption kinetic curves of the studied sediments are shown in Fig. 3. For all sediments phosphorus sorption process was composed of two steps *i.e.*, the quick and slow reaction processes. The first process was the quick reaction and then was the slow reaction. Similar to a previous report⁴⁰, submerged plant *H. verticillata* did not change this trend. The quick sorption process in sediments mainly occurred within 10 h in this region.

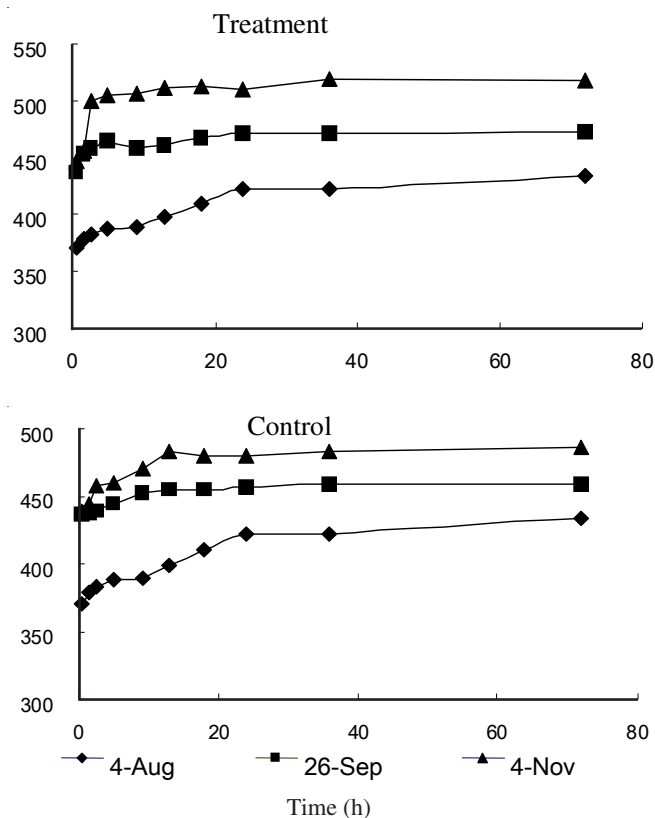


Fig. 3. Effect of *H. verticillata* on the phosphate sorption kinetics on sediments.

The phosphate sorption kinetics on sediments was often analyzed using kinetic models. In this study the capacity of phosphate sorption of sediments increased. Three common kinetic models (Power function model, Parabolic diffusion model and Simple Elovich model) were used to describe these processes. Those kinetic models were as follows²³.

Power function model: $q = Kt^a$

Parabolic diffusion model: $q = B + Kt^{1/2}$

Simple Elovich model: $q = B + K \ln t$

where t is time (h), q is the phosphorus sorption capacity (mg/kg dry weight), a , B and K are the constant. All parameters can be determined by regression of the experimental data (the capacity of phosphate sorption per gram of dry sediment was plotted against time). The estimated parameters of kinetic models are shown in Table-3. It was found that power function model and simple Elovich model can satisfactorily describe the phosphorus release kinetics ($R^2 = 0.79\sim 0.97$), whether there have submerged plants or not.

The phosphate sorption kinetic results were shown in Fig. 3. The phosphate sorption capacity increased rapidly with

TABLE-3
CALCULATED PARAMETERS OF KINETIC EQUATION OF PHOSPHATE SORPTION ON SEDIMENTS

Items	Sampling Time	q = B + K ln t			q = Kt ^a			q = B + Kt ^{1/2}		
		k	B	R ²	k	a	R ²	k	B	R ²
Treatment	4-Aug	13.17	372.08	0.90	372.56	0.03	0.91	8.57	368.81	0.94
	26-Sep	6.26	448.41	0.84	448.36	0.01	0.84	3.51	448.90	0.65
	4-Nov	14.70	467.69	0.79	467.18	0.03	0.78	7.66	470.91	0.53
Control	4-Aug	13.17	372.08	0.90	372.56	0.03	0.91	8.57	368.81	0.94
	26-Sep	5.57	438.10	0.92	438.13	0.01	0.92	3.31	437.83	0.80
	4-Nov	10.70	446.48	0.94	446.50	0.02	0.94	6.10	446.92	0.75

TABLE-4
SORPTION RATES[mg/(kg·h)] OF PHOSPHATE ON DIFFERENT SEDIMENTS AT DIFFERENT SAMPLING INTERVALS

Items	Sampling Time	Sample intervals									
		0-0.5	0.5-1.5	1.5-2.5	2.5-5	5-9	9-13	13-18	18-24	24-36	36-72
Treatment	4-Aug	761.93	0.79	1.24	1.13	0.14	0.74	0.64	0.45	0.03	0.16
	26-Sep	875.60	10.60	1.84	1.38	0.13	0.09	0.04	0.08	0.03	0.01
	4-Nov	894.25	6.09	17.28	1.02	0.22	0.38	0.07	0.03	0.06	0.05
Control	4-Aug	761.93	0.79	1.24	1.13	0.14	0.74	0.64	0.45	0.03	0.16
	26-Sep	874.80	0.80	0.20	1.06	0.84	0.13	0.09	0.04	0.08	0.01
	4-Nov	878.95	3.77	5.33	0.42	1.22	0.69	0.07	0.03	0.01	0.06

time increasing within 10 h. After 10 h, the sorption process reached equilibrium.

As mentioned in earlier sections, the constants K and B can be used to describe the ability of the phosphorus sorption of sediments. K and B of the sediments with *H. verticillata* are higher than those of the control sediments, phosphorus sorption mainly depends on the physical and chemical properties of the sediments, especially the concentrations of Fe, Fe_{ox}, total phosphorus and organic matter^{41,42}. The higher K and B of the sediments with *H. verticillata* may be attribute to the lower concentrations of Fe, Fe_{ox}, total phosphorus and organic matter.

The sorption rate was used to describe the phosphate sorption by the sediments. The sorption rates of the sediment samples with different sampling time are shown in Table-4. The average sorption rates of 0-0.5 h were the highest within 72 h. This indicates that a quick sorption process mainly occurred within 0.5 h. The sorption rates of 0-0.5 h of the sediments with *H. verticillata* were higher than those of the control. This suggests that *H. verticillata* restrained the phosphorus release from sediments, which was another important mechanism that the submerged macrophyte maintained the lower phosphorus levels in the overlying water⁴³. phosphorus sorption can be described simply as an initial fast rate and then a slower rate. There was a higher proportion of bound phosphorus in the fast pool at the different sampling time for the sediments with *H. verticillata* as compared to those of the control sediments. This is another reason for the high sorption rates of the sediment with *H. verticillata*.

Conclusion

Based on the above discussion, the ability of phosphorus sorption on sediments with *H. verticillata* increased and the phosphorus sorption efficiency and the risk of phosphorus release decreased. The effects of the submerged macrophyte *H. verticillata* on phosphorus sorption were mainly as a result of its effect on sediment properties. Submerged macrophyte *H. verticillata* can reduce the contents of NaOH-P, phosphorus, organic phosphorus, total phosphorus, Olsen-phosphorus, organic matter, Fe, Al, Fe_{ox} and Al_{ox}.

Submerged macrophyte *H. verticillata* did not significantly affect the trends of the sorption isotherms and kinetics of the phosphorus sorption kinetics on the sediments. The quick reaction mainly occurred within 0.5 h and slow reaction after 0.5 h. Submerged macrophyte *H. verticillata* can significantly increase the sorption rates of the sediments, especially in 0-0.5 h. One of the mechanisms *H. verticillata* maintained lower phosphorus levels of the overlying water through affecting sediment properties.

ACKNOWLEDGEMENTS

The authors wish to thank for National Natural Science Foundation of China (40873057), Department of Scientific and Technological, Jiangsu Province, China (BE2008677).

REFERENCES

1. B.Q. Qin, *J. Lake Sci.* **14**, 193 (2002).
2. W. Stumm, *Wat. Res.*, **7**, 131 (1973).
3. B. Bengt, M. Jens and S.F. Anderson, *Hydrobiology*, **229**, 170 (1988).
4. L. Lijklema, *Environ. Sci. Tech.*, **14**, 537 (1980).
5. M.M. Abrams and W.M. Jarrell, *J. Environ. Qual.*, **24**, 132 (1995).
6. X.C. Jin, S.R. Wang, Y. Pang and F.C. Wu, *Environ. Pollut.*, **139**, 288 (2006).
7. P.A. Chambers and J. Kalff, *Aquat. Bot.*, **22**, 253 (1985).
8. P. Denny, *J. Ecol.* **60**, 819 (1972).
9. J.B. Bole and J.R. Allan, *Wat. Res.* **12**, 353 (1978).
10. M. Scheffer, M. Van Den Berg, A. Breukelaar, C. Breukers, H. Coops, R. Doef and M.L. Meijer, *Aquat. Bot.*, **49**, 193 (1994).
11. I. Blindow, G. Andersson and A. Haregy, *Fresh Biol.*, **30**, 159 (1993).
12. S.R. Wang, X.C. Jin, H.C. Zhao and F.C. Wu, *Aquat. Bot.*, **89**, 23 (2008).
13. S.R. Carpenter and D.M. Lodge, *Aquat. Bot.*, **26**, 341 (1986).
14. X. Jin, J. Chu and S. Wang, *Chin. J. Appl. Environ. Biol.* **13**, 200 (2007).
15. M. Mozaffari and J.T. Sims, *Soil Sci. Soci. Am. J.*, **157**, 97 (1994).
16. B. Gu, M.J. Chimney, J. Newman and M.K. Nungesser, *Ecol. Eng.*, **27**, 345 (2006).
17. T.A. DeBusk, K.A. Grace, F.E. Dierberg and S.D. Jackson, M.J. Chimney and B. Gu, *Ecol. Eng.*, **23**, 1 (2004).
18. S.R. Olsen, C.V. Cole, F.S. Watanable and L.A. Dean, Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate (USDA Circular 939), Washington DC, USA, (1954).
19. K.H. Tan, Soil Sampling, Preparation and Analysis, Marcel Dekker Inc., New York, p. 154 (1996).
20. Institute of Soil Science; Chinese Academy of Sciences Phy.-chem. Ana. of Soil; Shanghai Science and Technology Publishing Company: Shanghai, p. 179 (1978).

21. AWWA-APHA-WPCE, Standard Method for the Examination of Water and Wastewater American Public Health Association: Washington, DC, 253, (1998).
22. Q.X. Zhou, C.E. Gibson and Y.M. Zhu, *Chemosphere*, **42**, 221 (2001).
23. X.C. Jin, S.R. Wang, Y. Pang, H.C. Zhao and X.N. Zhou, *Colloid Surf. A*, **241**, 254 (2005).
24. S.R. Wang, X.C. Jin, H.C. Zhao, X.N. Zhou and F.C. Wu, *Water Air Soil Pollut.*, **181**, 327 (2007).
25. J. Murphy and J. Riley, *Anal Chim. Acta.* **27**, 31 (1962).
26. A. Kaiserli, D. Voutsas and C. Samara, *Chemosphere*, **46**, 1147 (2002).
27. D.S. Ting and A. Appan, *Wat. Sci. Technol.*, **34**, 53 (1996).
28. R. Gachter and J.S. Meyer, *Hydrobiologia*, **253**, 103 (1993).
29. S.G. Wang, X.C. Jin, Y. Pang, H.C. Zhao, X.N. Zhou and F.C. Wu, *J. Colloid Interf. Sci.*, **289**, 339 (2005).
30. P. Lopez, X. Lluch, M. Vidal and J.A. Morguá, *Estuarine Coast. Shelf Sci.*, **42**, 185 (1996).
31. T.E. Boub and E.A. Rochette, *Commun. Soil Sci. Plant Anal.*, **34**, 1177 (2003).
32. J.A. Mckeague and J.H. Day, *Can. J. Soil Sci.*, **46**, 13 (1966).
33. A.G. Brinkman, *Hydrobiologia*, **253**, 31 (1993).
34. M.D. Lucotte and B. Anglejan, *J. Coast. Res.*, **4**, 339 (1988).
35. R. Carman and F. Wu IV, *Estuarine Coast. Shelf Sci.*, **29**, 447 (1989).
36. W.H. Hendershot and M. Duquette, *Soil Sci. Soc. Am. J.*, **50**, 307 (1986).
37. S.R. Wang, X.C. Jin, H.C. Zhao and F.C. Wu, *J. Hazard. Mater.*, **161**, 1551 (2009).
38. W.A. House, F.H. Denison, J.T. Smith and P.D. Armitage, *Environ. Pollut.*, **89**, 263 (1995).
39. K.R. Reddy, M.R. Overcash and R. Khaled, *Soil Sci. Soc. Am. J.*, **59**, 1782 (1995).
40. S.R. Wang, X.C. Jin, H.C. Zhao, Y. Pang, X.N. Zhou and J.Z. Chu, *Environ. Sci.*, **26**, 8 (2005).
41. C.P. Slomp J.F.P. Malschaert and W. Van Raaphorst, *Limn. Oceano.*, **43**, 832 (1998).
42. X.C. Jin, S.R. Wang, Q.Y. Bu and F.C. Wu, *Water Air Soil Pollut.*, **233**, 176 (2006).
43. B.Q. Liu, W.X. Wang, C.L. Song, X.Y. Cao and Y.Y. Zhou, *J. Wuhan Bot. Res.*, **22**, 394 (2004).