Int. J. Environ. Res., 7(4):1021-1028,Autumn 2013
ISSN: 1735-6865

Internal Loads of Nutrients in Lake Chaohu of China: Implications for lake Eutrophication

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Received 2 Nov. 2012; Revised 10 June 2013; Accepted 17 June 2013

ABSTRACT: This study investigated the impact of internal nitrogen and phosphorus loading on water quality of Lake Chaohu, China. Results showed that the overall mean concentration of TN and TP in lake water was 1.09±0.84 and 0.15±0.84 (SD) mg/L, respectively, indicating Lake Chaohu was highly eutrophic during the study period. Mean benthic flux of NH_4^+, NO_3^-, and PO_4^{3-} were 3.56±1.52 mg N/m^2/d, -0.14±0.40 mg N/m^2/d, and -1.54±21.94 µg P/m^2/d in summer and were 3.16±1.83 mg N/m^2/d, -0.03±0.30 mg N/m^2/d, and -0.11±2.58 µg P/m^2/d in fall, respectively. In this study, lake sediments acted as both a source of NH_4^+ and a sink of PO_4^{3-}. A scenario was used to understand the role of sediments on lake water quality. Results showed that Lake Chaohu would be eutrophic within a month under the impact of internal NH_4^+ loading when water was diverted to the lake. This indicates that an integrated project combining both a diversion project and dredging of sediments would be necessary for future lake restoration.

Key words: Benthic fluxes, Lake Chaohu, Nitrogen, Phosphorus, Eutrophication

INTRODUCTION

Lake eutrophication caused by excessive inputs of phosphorus and nitrogen is a worldwide problem, and can lead to water quality deterioration with significant losses of biodiversity, goods and services (Akdeniz *et al.,* 2011; Raicevic *et al.,* 2011; Schindler 2006; Dokulil and Teubner 2006). Lake sediments can have higher nitrogen and phosphorus levels due to the decomposition of aquatic flora and fauna (Gerhardt *et al.,* 2010; Graca *et al.,* 2004). Nutrients in lake sediments can be released into the water column due to physical, chemical and biological processes, which is termed internal loading, contrasting to external loading (Petterson 1998). As a result, lake sediments may play an important role in nutrient cycling and water eutrophication (Håkanson 2004). For instance, external nitrogen and phosphorus loads have been reduced by 40-80% in China during recent decades (Xu *et al.,* 2003); however, more than 90% of Chinese lakes are still eutrophic. Thus, an evaluation of the impact of internal loading on water quality is necessary when a lake recovery strategy is considered. Lake Chaohu in China once played an important role in supporting local development (Yang *et al*., 2011). However, this lake has been eutrophic since the 1970s due to increased nutrient inputs (Shang and Shang 2007). Since 2006, the Chinese government implemented a diversion project, called "Transferring Water from the Yangtze River to Lake Chaohu (TWFYTC)," as an emergency strategy to control the lake eutrophication. Unfortunately, water quality in Lake Chaohu showed no significant improvement. Thus, research, monitoring, and evaluation activities are essential for characterizing eutrophication in this lake. There is especially a need to understand the role of internal nutrient loading in lake water quality. To the best of our knowledge, previous studies report on nitrogen and phosphorus distribution in water and sediment profiles in Lake Chaohu (Pan *et al.,* 2007), while *in situ* measurements on benthic fluxes of nutrients across the sediment-water interface are sparse. In this study, *in situ* measurements were conducted in June and September 2008 to investigate benthic fluxes of nitrogen and phosphorus in Lake Chaohu. In addition,

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we designed a scenario to model the impact of internal nitrogen and phosphorus loading on lake water quality. This study will provide valuable information that can be used for control of eutrophication in the future.

MATERIALS & METHODS

Twelve sampling sites were selected throughout Lake Chaohu (Fig. 1). Sediment (5 cm) samples were collected with a Piston sampler and water samples were collected with a Niskin water sampler. The upper-layer sediment samples were centrifuged at 4500 r/m to obtain the interstitial water of the sediments. The centrifuged water samples were filtrated through a 0.45μm filter and the concentration of NH_4^+, NO_3^-, PO_4^{3-}, TN, and TP were measured with a segmented flow auto-analyzer. In the non-centrifuged water samples, TN and TP were determined using a digestion method (Mckee *et al.,* 2000; Venterink *et al.,* 2003). TN, TP, and organic matter in the lake sediment samples were measured according to Chen *et al*. (2010).

Benthic fluxes of NH_4^+, NO_3^- and PO_4^{3-} were calculated using the equation given by Berner (1980):

$$F = -D_S\Phi(\partial C / \partial x)_{x=0} \quad (1)$$

where F is the benthic flux of nutrients (mmol/m²/h); Ds is the molecular diffusion coefficient (cm²/s) calculated as in Krom & Berner (1980); Φ is the sediment porosity (%) calculated by the equation $\Phi = W / \{(100 - W)\varphi + W\}$, W and ö are the sediment moisture content (%) and the bulk density (g/cm³), respectively; $(\partial C/\partial x)_{x=0}$ (mmol/L/m) is the concentration gradient of nutrients between the sediment's interstitial and overlying water. Here, a negative flux means that the water nutrients were consumed by sediments and a positive flux means that the nutrients were released from the sediments to the water column.

RESULTS & DISCUSSION

Our data showed that Lake Chaohu was eutrophic during the experimental period. Overall, concentrations of NO_3^- NH_4^+, PO_4^{3-}, TN, and TP in surface water ranged from 0.08~1.93, 0.05~1.81, 0.02~0.16, 0.25~3.67, and 0.07~0.29 mg/L (Table 1), respectively. Nitrogen and phosphorus concentrations showed no significant seasonal differences. Significantly higher levels of nitrogen and phosphorus in the western lake indicated spatial variation in Lake Chaohu. This is a result of large amounts of nitrogen and phosphorus discharge into the western lake by two major badly polluted tributaries, the Nanfei and Hangbu Rivers (Shang and Shang 2007).

Three sediment types (clay, sand, and mud) were investigated on a whole lake basis (Table 2). Data showed that lake sediments were enriched with organic matter, TN, and TP, with a range of 0.56~1.51%, 0.22~0.92 g/kg, and 0.11~0.66 g/kg, respectively. Porosity of lake sediments exhibited a range of 11.8~79.3%, with higher porosity in sandy sediments. No differences in seasonal or spatial distribution of sediment characters were found in this lake.

The benthic flux of nitrogen and phosphorus was calculated according to equation 1 based on the concentration gradient of nutrients (³%concentration) between interstitial and overlying water of sediments. Concentrations of NH_4^+, NO_3^-, and PO_4^{3-} in the sediment interstitial and overlying water are presented in Fig.2.

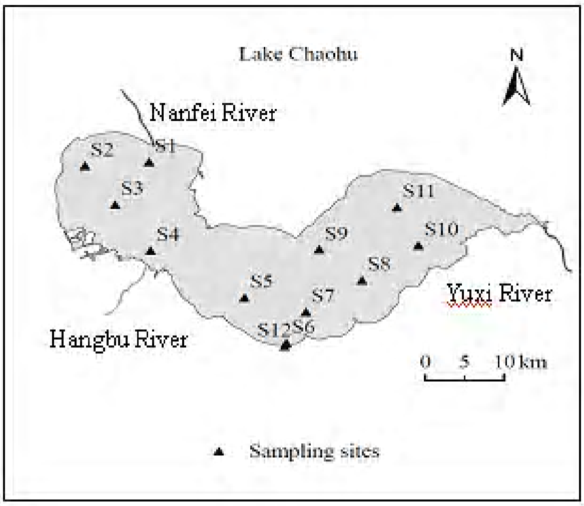

Fig. 1. Location of sampling sites in Lake Chaohu

Table 1. Nitrogen and phosphorus concentrations in surface lake water (mg/L)

Site	NO_3^-		NH_4^+		PO_4^{3-}		TN		TP	
	Jun.	Sep.	Jun.	Sep.	Jun.	Sep.	Jun.	Sep.	Jun.	Sep.
S1	0.65	1.93	0.46	1.81	0.16	0.09	1.67	3.67	0.29	0.24
S2	0.45	0.94	0.05	0.22	0.02	0.07	2.12	1.62	0.20	0.26
S3	0.77	0.35	0.09	0.23	0.03	0.05	3.27	1.05	0.24	0.21
S4	0.47	0.22	0.19	0.31	0.02	0.05	0.92	0.69	0.14	0.07
S5	0.10	0.13	0.16	0.12	0.03	0.04	0.83	0.80	0.14	0.07
S6	0.08	0.17	0.16	0.13	0.03	0.03	0.66	0.57	0.18	0.09
S7	0.08	0.11	0.23	0.10	0.02	0.04	0.84	1.00	0.12	0.16
S8	0.09	0.11	0.25	0.16	0.02	0.04	0.70	0.25	0.11	0.15
S9	0.08	0.12	0.49	0.16	0.02	0.04	0.58	0.70	0.11	0.18
S10	0.08	0.11	0.08	0.19	0.05	0.03	0.63	0.45	0.10	0.14
S11	0.08	0.08	0.07	0.21	0.02	0.05	0.82	0.63	0.09	0.11
S12	0.18	0.27	0.12	0.13	0.02	0.03	0.97	0.68	0.12	0.19
Mean	0.26±0.25	0.38±0.54	0.20±0.14	0.31±0.47	0.03±0.04	0.05±0.02	1.17±0.81	1.01±0.91	0.15±0.06	0.16±0.06

Data are presented as “mean±SD”

Table 2. Sediment characterization data of Lake Chaohu

site	Sediments type	Porosity (%)		Organic matter (%)		TN (g/kg)		TP (g/kg)	
		Jun.	Sep.	Jun.	Sep.	Jun.	Sep.	Jun.	Sep.
S1	clay, mud	64.3		1.51		0.54		0.37	
S2	clay, mud	62.9		1.13		0.63		0.49	
S3	sand	70.9		0.71		0.73		0.61	
S4	clay, mud	49.8		0.91		0.92		0.66	
S5	sand	79.3	75.6	0.64	0.71	0.81	0.78	0.63	0.65
S6	clay	37.5		1.32		0.86		0.64	
S7	mud	42.2	40.8	0.91	1.21	0.22	0.92	0.14	0.15
S8	sand, mud	73.5	72.5	0.65	0.55	0.39	0.76	0.11	0.13
S9	sand, mud	70.2	68.6	0.62	0.72	0.31	0.53	0.13	0.11
S10	mud	52.8	50.3	0.87	0.91	0.35	0.54	0.20	0.16
S11	sand, mud	78.1	72.6	0.56	0.76	0.39	0.87	0.27	0.12
S12	clay	11.8		1.17		0.37		0.24	
Mean of all samples		57.8±19.9	63.4±14.3	0.92±0.31	0.81±0.23	0.54±0.24	0.73±0.16	0.37±0.22	0.22±0.21

Data are presented as “mean±SD”, six sampling sites (S5, S7-S11) were sampled in September.

Overall, NH_4^+ concentrations in the sediment’s interstitial water were higher than the overlying water, while NO_3^-, and PO_4^{3-} concentrations in the sediment’s interstitial water were lower than that in the overlying water at most of the sampling sites.

Benthic fluxes of NH_4^+, NO_3^-, and PO_4^{3-} ranged from 0.19~8.26 mg N/m²/d (mean 3.56), -0.83~0.05 mg N/m²/d (mean -0.14) , and -27.46 ~ 6.27 μg P/m²/d (mean -1.54) in June (Fig. 3), respectively. Six sampling sites (S5, S7-S11) were sampled in September. Benthic fluxes of NH_4^+, NO_3^- and PO_4^{3-} in September ranged from 0.87~5.84 mg N/m²/d, -0.18~0.03 mg N/m²/d, and -10.61~ -3.77 μg P/m²/d, with mean values of 3.16 mg N/m²/d, -0.04 mg N/m²/d, and -6.19 μg P/m²/d, respectively (Table 3). The overall mean PO_4^{3-} flux of the six sampling sites in September was significantly higher than that in June (One-way ANOVA; $\alpha = 0.05$, $P = 0.002$).

Compared to other studies, benthic fluxes of nitrogen and phosphorus in Lake Chaohu were relatively lower. For example, Höhener and Gächter (1994) reported that the benthic flux of NH_4^+ ranged from 15.4~225.4 mg N/m²/h, and the benthic flux of NO_3^- ranged from -33.6~-155.4 mg N m²/h in Lake Sempach. Qin and Zhu (2006) surveyed the lakes from the middle to lower reaches of the Yangtze River basin, and found that mean TN and NH_4^+ release rates were 166 and 46

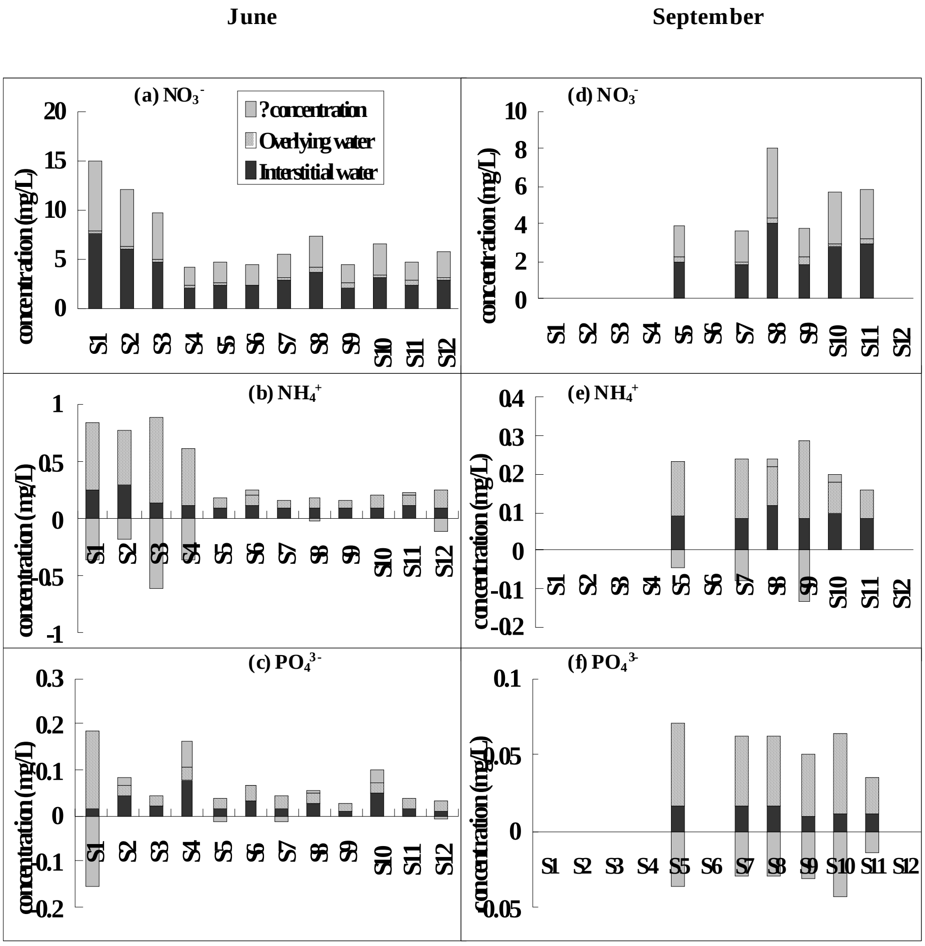

Fig. 2. Concentration of NO_3^-, NH_4^+ and PO_4^{3-} in interstitial and overlying water in Lake Chaohu

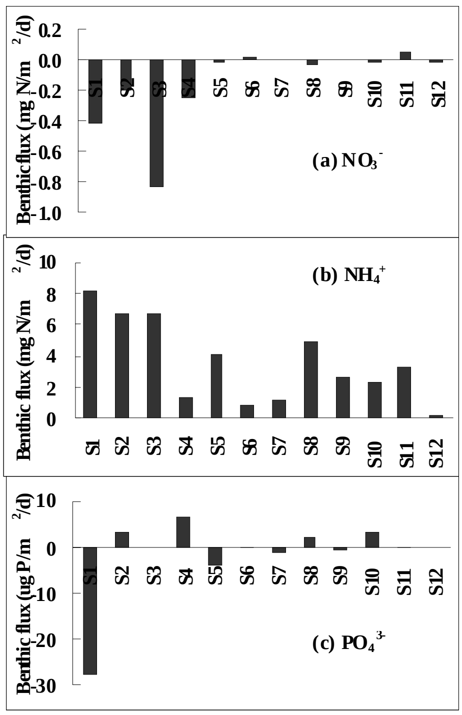

Fig. 3. Benthic flux of NO_3^-ÿNH_4^+ and PO_4^{3-} in Lake Chaohu in June

Table 3. Benthic flux of nitrogen and phosphorus in Lake Chaohu in September

Observation time	Sampling site	Benthic flux		
		NH_4^+	NO_3^-	PO_4^{3-}
		mg N/m²/d		µg P/m²/d
September	S5	3.24	-0.09	-10.61
	S7	0.87	0.01	-3.77
	S8	5.84	0.03	-6.98
	S9	2.19	-0.18	-6.74
	S10	2.11	0.02	-5.15
	S11	4.68	0.01	-3.87
	Mean	3.16±1.83	-0.03±0.08	-6.19±2.56
June	Mean	3.09±1.30	-0.03±0.30	-0.11±2.58
Significance test	P	0.95	1.00	0.002*

Mean values are presented as "Mean ± SD"; *indicates a significant difference at 0.05 test level

mg N/m²/h, respectively. In other reports, PO_4^{3-} fluxes ranged from -53~937 mg P/m²/d (Gibbs and Özkundakci 2010; Perrone *et al.,* 2008; Punning and Kapanen, 2009; Penn *et al.,* 2000), and our results occur at the bottom of this range.

Results indicate that sediments in Lake Chaohu act both as a source of nitrogen and as a sink of phosphorus. This is consistent with other reports on various lakes. When taking the total area of lake sediment (750 km²) into consideration, it is estimated that approximately 925 tons of NH_4^+ were released to the water column from sediments while 0.87 tons of PO_4^{3-} were consumed by sediment annually. Existing data had shown that approximately 9500 tons of TN and 490 tons of TP were discharged to the Lake Chaohu annually. Thus, about 9.7% of the nitrogen input to the lake was contributed by internal NH_4^+ loading while 0.2% of the phosphorus was consumed by sediments in the form of PO_4^{3-}.

It has become evident that nutrient exchange between sediments and water is highly complex and includes interrelated chemical, biological and physical processes (Holdren and Armstrong, 1980). A variety of ecological responses in lakes would result in nutrient exchanges from the sediments to the overlying water column. Consequently, a number of environmental factors are important in benthic nutrients fluxes in aquatic ecosystems (Pettersson, 1998; Malecki *et al.,* 2004). In our study, benthic flux of NH_4^+ was significantly correlated with porosity of sediment (R^2=0.38, P=0.006; Table 4), but there were no significant correlations between benthic nutrient fluxes and other measured environmental factors. This may indicate that other environmental factors, such as sediment bacteria and aquatic plankton, could regulate the exchange of nitrogen and phosphorus in Lake Chaohu. This has been reported in other lakes. For example, Pettersson (1998) found that the cyanobacteria *Gloeotrichia echinulata* contributed significantly to internal loading of phosphorus in Lake Erken. In Lake Vallentunasjön, Boström *et al* (1988) reported that microbial metabolism had a number of direct effects on phosphorus mobility, which would control the exchange of phosphorus between the sediments and the overlying water column. Thus, it is necessary that more detailed biogeochemical data be obtained in future studies in order to distinguish the dominant regulatory factors on benthic nutrient fluxes in Lake Chaohu.

Many studies have supported the hypothesis that internal loading can often determine the eutrophication status of a lake and that there is a time lag for recovery after the reduction of external loading (Søndergaard *et al.,* 2003; Mitamura *et al.,* 1995). Thus, even if only a very small amount is released, it will have a significant impact on lake water quality (Présing *et al.,* 2001). In this article, a scenario was designed to model the potential risk of eutrophication by internal loading. The "TWFYTC" project was performed twice a year from 2006 to the present, and was sustained for several days each time. Therefore, our scenario was made based on the assumptions that: 1) lake water was completely replaced by the transferred water; 2) external loading had no significant impact on water quality during the "TWFYTC" project. Here, the implication of internal loading for lake water quality was studied by calculating the recurrence time (T) of eutrophication:

$$T = (V \times C) / (A \times F) \quad (2)$$

Table 4. Correlation analysis between benthic nutrients fluxes and environmental factors

Dependent	Independent	R^2	P
NH_4^+ flux	Water temperature	0.06	0.33
	TN content in sediment	0.003	0.82
	Organic matter in sediment	0.01	0.77
	Porosity of sediment	0.38	0.006*
NO_3^- flux	Water temperature	0.14	0.12
	TN content in sediment	0.01	0.66
	Organic matter in sediment	0.01	0.78
	Porosity of sediment	0.02	0.59
PO_4^{3-} flux	Water temperature	0.02	0.59
	TP content in sediment	0.003	0.86
	Organic matter in sediment	0.10	0.19
	Porosity of sediment	0.05	0.38

*indicates a significant correlation at 0.05 test level (n=18)

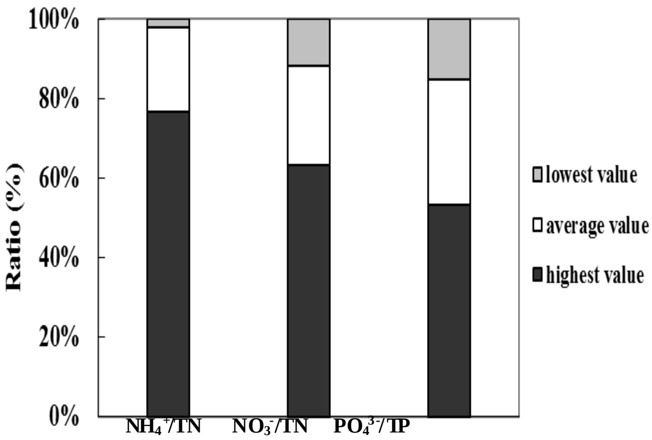

Fig. 4. Ratios of NH_4^+/TN, NO_3^-/TN, and PO_4^{3-}/TP in lake water

Table 5 . Assessment of eutrophication risk from by internal loading in Lake Chaohu

	C_S (mg/L)	C_W (mg/L)	F (mg/m^2/d)	CL (ton)	T
		0.045	3.43	1.7	31 (d)
NH_4^+	3.46	0.030	3.44	27.5	31 (d)
		0.015	3.46	53.3	30 (d)
		0.036	0.09	6.9	2.8 (yr)
NO_3^-	0.13	0.024	0.10	27.5	2.5 (yr)
		0.012	0.11	48.2	2.3 (yr)
		0.009	0.006	3.4	7.8 (yr)
PO_4^{3-}	0.03	0.006	0.007	8.6	7.4 (yr)
		0.003	0.008	13.8	7.2 (yr)

Where V is the lake storage capacity (1.72×10^9 m^3); A is the lake sediment area (750 km^2); F is the benthic flux of nutrients; C is the critical limit concentration of TN (0.2 mg/L) and TP (0.02 mg/L) meets the definition of eutrophication in a lake (according to Chinese standard methods for a lake eutrophication survey) (Jin and Tu 1990). In this study, the ratios of NH_4^+/TN, NO_3^-/TN and PO_4^{3-}/TP in lake water were 23%, 20% and 57% (Fig.4), respectively. Therefore, we assumed that Lake Chaohu would be eutrophic when NH_4^+, NO_3^- and PO_4^{3-} had reached the thresholds of 0.046, 0.04 and 0.011 mg/ L, respectively.

Three concentration levels for NH_4^+, NO_3^- and PO_4^{3-} in the transferred water were modeled. Results showed that when concentrations of NH_4^+, NO_3^- and PO_4^{3-} in the transferred water varied from 0.015 to 0.045, 0.012 to 0.036, 0.003 to 0.009 mg/L, respectively, the lake water would be eutrophic within about a month (Table 5). We can also conclude that internal NH_4^+ loading regulates the eutrophication status of Lake Chaohu. However, it is important to note that the impact of internal loading on the lake eutrophic condition might be overestimated since the reduction processes of the nutrients were not considered. Monitoring data showed that monthly TN and TP concentrations ranged from 0.54~6.59 and 0.08~0.56 mg/L, respectively, from 2006 to the present in Lake Chaohu (unpublished data), meaning this lake was still eutrophic. This is consistent with the result of our scenario that Lake Chaohu would be eutrophic within a month after the "TWFYTC" project would be performed. This strongly suggests that an integrated project combining both a diversion project and dredging of sediments would be necessary for improving the water quality of Lake Chaohu in the future.

C_S is the mean concentration of nitrogen and phosphorus in sediment interstitial water from this study; *F* is the benthic flux of nitrogen and phosphorus calculated according to equation 1. CL is the critical limit internal loading of nitrogen and phosphorus that meets the definition of lake eutrophication.

CONCLUSION

The overall mean concentration of TN and TP in the lake water was 1.09±0.84 and 0.15±0.84 (SD) mg/L, respectively, indicating that Lake Chaohu was highly eutrophic. Lake sediments acted as both a source of NH_4^+ and a sink of phosphate. It is estimated that about 9.7% of the nitrogen input to the lake was contributed by internal NH_4^+ loading while 0.2% of phosphorus was consumed by sediments in the form of PO_4^{3-}. A scenario showed that Lake Chaohu tends to be eutrophic within about a month under the influence of internal NH_4^+ loading after the "TWFYTC" project would be performed. This strongly suggests that an integrated project combining both a diversion project and dredging of sediments would be necessary for the control of eutrophication.

ACKNOWLEDGEMENTS

This work was supported by the National Science-technology Support Project of China (No. 2010BAC69B02) and National Natural Science Foundation of China (No.41203080).

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