Modeling the effect of external nutrient reduction on algal bloom in hyper-eutrophic Lake Taihu, China

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Abstract: Harmful algal blooms in Lake Taihu, China, are getting plagued due to excess nutrients loads. Despite several recent strict nutrient management strategies, especially to reduce the external nutrient loads, Lake Taihu still receives large amounts of nutrients from its tributaries. As a result, frequency and intensity of algal blooms have not abated as expected. In this study, a three-dimensional eutrophication model was used to identify the limiting factors for algal growth and the effect of external nutrient loads reduction on water quality. The modeling results showed that the limiting factor for the dominant algae (cyanobacteria) depended on seasonality and location. Water temperature affected algal growth in winter, while light was important for deeper water columns in all seasons. Phosphorus (P) and Nitrogen (N) impacted algal growth from spring to autumn. Results showed that Chlorophyll a (*Chl-a*) concentrations only decreased about 38%, 26% and 24% in Meiliang Bay, Zhushan Bay and Northwest Zone, respectively when implementing high nutrient reduction scenario (external N and P inputs reduced up to 80% and 50%). External nutrient reduction for both N and P is a prudent and likely most practical solution for reducing bloom potentials and overall trophic state of this currently hypereutrophic system. However, achieving observable algal control is not likely in the short term and other ecological restoration tools will be required to battle with the legacy of several decades of nutrient over-enrichment.

Keywords: EFDC; eutrophication; load reduction; nutrient management; water quality

1. Introduction

Many ecologically and economically important freshwater bodies have experienced harmful algal blooms and water quality degradation in recent decades (Qin et al., 2007 and 2015; Schindler and Hecky, 2009). Comprehensive water quality management is essential and urgent to control eutrophication and protect aquatic ecosystem (Conley et al., 2009; Liu et al., 2008). Reducing external nutrient inputs to aquatic ecosystem is critical and often the primary practical approach available to water quality managers (Ahlvik et al., 2014; Kagalou et al., 2008; Paerl et al., 2011 and 2014c; Qin et al., 2010; Wang et al., 2014; Xu et al., 2010). However, the immediate effect on water quality response to external nutrient is often unpredictable and variable among impacted ecosystems. It is not easy to discern roles between external vs. internal nutrients contributed by sediment resuspension in shallow eutrophic water bodies. A major constraint is a lack of long term monitoring data to reveal this relationship. Furthermore, lake water quality often responds to the external nutrient reduction non-linearly with a delayed manner due to existing nutrients in the sediments. Water quality modeling (WQM) might be one of the tools to support nutrient management (Kagalou et al., 2008; Wang et al., 2014).

Recently, WQM has been widely used to understand the environmental response to nutrient load reduction and to evaluate the effectiveness of restoration efforts (Wang et al., 2014; Zhao et al., 2013; Zou et al., 2009 and 2014). For example, Gurkan et al. (2006) developed a structurally dynamic model to assess the effects of restoration on Lake Fure, Denmark. Liu et al. (2008) used a Bayesian approach in the model to estimate effects of nutrient reduction. Wang et al. (2014) predicted lake water quality response to load reduction in Dianchi Lake, China using a three-dimensional modeling approach for total

maximum daily load.

Developing a robust WQM involves many parameters. Identifying limiting factors for algal growth is critical for developing appropriate nutrient management strategies. Previous research suggest that algal growth is linked to multiple factors including elemental nutrients (Nitrogen, N and Phosphorus, P), light, temperature and salinity in aquatic ecosystem, especially in lakes and coastal regions (Conley et al., 2009; Xu et al., 2010 and 2015). Identifying likely limiting nutrients is a major challenge in limnological research so that a helpful nutrient management strategy can be developed. N and P are the most common nutrients limiting algal growth in marine and freshwater systems, respectively (Hecky and Kilham, 1988; Nixon, 1995). P control has been widely implemented to deal with eutrophication in many freshwater lakes (Schindler and Vallentyne, 2008). P reduction strategies have eased eutrophication and lowered algal bloom risks in many North American and European lakes (Schindler and Hecky, 2009). Recently, new research point to a dual-nutrient-reduction (co-limitation of P and N) leading to improved water quality in the freshwater and coastal ecosystems (Conley et al., 2009; Elser et al., 2007; Lewis et al., 2011; Paerl, 2009). For example, P-only reduction strategy may not be sufficient to ease algal bloom scenarios in the Lake Taihu, a hyper-eutrophic lake in China (Paerl et al., 2014a). The non-N-fixing cyanobacteria, *Microcystis* spp. has now become the dominated phytoplankton due to the substantially changed nutrient load structure in the past decades (Paerl et al., 2011; Xu et al., 2015). In a shallow lake like Taihu, P is rapidly recycled between sediments and water. *Microcystis* can consume P at the sediment-water interface and excessive N loads can stimulate biomass production, exacerbating the blooms (Conley et al., 2009; Paerl et al., 2014a).

Accordingly, reducing anthropogenic inputs of both N and P has been recommended to control harmful cyanobacterial blooms in eutrophic ecosystems (Conley et al., 2009; Lewis et al., 2011)

Lake Taihu, the third largest shallow lake in China, has suffered from nutrient over-enrichment over the past several decades (Qin et al., 2010). Many efforts have been undertaken by both government entities and researchers since 1990 for restoring the lake. The local government has closed a large number of heavily polluting industries, built several wastewater treatment plants, and banned the use of P-bearing detergents (Qin et al., 2007). Additionally, other measures have been put in place such as use of macrophytes, sediment dredging, wetland construction, and water transfer projects (Chen et al., 2009; Li et al., 2011b and 2013; Xiao et al., 2009). However, despite these efforts, the lake water quality has not shown significant improvement (Qin, 2009). Large amounts of external nutrient loads to the lake have not abated, and as a result the lake has maintained its hyper-eutrophic condition. Thus, this study is aimed at: (1) quantifying and analyzing the spatiotemporal distribution of external nutrient inputs via tributaries to the lake; (2) identifying the limiting factors in the heavily polluted lake regions using a calibrated mathematical model for the lake; and (3) predicting various scenarios of nutrient loads reduction.

2. Methods

2.1 Study area

Lake Taihu, a large shallow lake, is located in the lower Yangtze River delta between 30°56'-31°33' N and 119°53'-120°36' E, with an area of 2338 km² and a mean depth of 1.9 m (Fig. 1). Lake Taihu is governed by Jiangsu Province, Zhejiang Province, Anhui

Province and Shanghai city (Fig. 1). Among these, nutrients from Jiangsu and Zhejiang Provinces contribute the most to the eutrophic status of Lake Taihu. The river network around Lake Taihu is very complicated with a river density of 3.24 km/km² and most of these rivers are regulated by dams (Qin et al. 2007). In this study, Lake Taihu is divided into eight sub-areas: Zhushan Bay, Meiliang Bay, Gonghu Bay, Northwest Zone, Southwest Zone, Central Zone, East Epigeal Zone and Dongtaihu Bay (Fig. 1). There are 30 water quality monitoring sites in the lake (Fig. 1). Among them, Meiliang Bay, Zhushan Bay and western lake regions are the most polluted regions, as they receive large amount of nutrients directly from the inflow rivers. To simplify, the tributaries are grouped into 30 rivers and numbered as 1-30 (Fig. 1; Li et al., 2011b).

2.2 Nutrients in the tributaries

The nutrient inputs data are obtained from the health status report of Taihu Lake (BLTB, 2008~2012). Spatial distribution of water quality variables (chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP)) in the lake are based on the 30 monthly sampling sites covering all the lake subzones (Fig. 1). The water quality variables in the tributaries were collected monthly by the water quality monitoring center of Lake Taihu Basin.

2.3 Model setup

The Lake Taihu eutrophication model initially developed by Tang et al. (2015) based on the Environmental Fluid Dynamics Code (EFDC) was used to simulate the hydrodynamic, nutrient cycling and biological processes in the lake. The EFDC model was initially developed by the United States Environmental Protection Agency (Hamrick, 1992). It has been successfully applied to simulate hydrodynamics, sediment transport,

toxic contaminant transport and water quality-eutrophication components in coastal regions, estuaries, lakes, reservoirs, rivers, and wetlands (e.g., Ji, 2008; Li et al., 2011b and 2013).

The hydrodynamic module of EFDC solves 3-D, vertically hydrostatic, free surface and turbulent average equations for a variable-density fluid (Craig, 2011; Hamrick, 1992). The water quality-eutrophication module is directly and dynamically coupled to hydrodynamic module. The water quality module of EFDC simulates the spatiotemporal distribution of 22 state variables (Tetra Tech, 2007). In this study, we simulated 16 state variables including cyanobacteria, various components of carbon (refractory particulate organic carbon, labile particulate organic carbon, dissolved organic carbon), nitrogen cycles (refractory particulate organic nitrogen, labile particulate organic nitrogen, dissolved organic nitrogen, ammonium nitrogen, nitrate nitrogen), phosphorus cycles (refractory particulate organic phosphorus, labile particulate organic phosphorus, dissolved organic phosphorus, total phosphate), dissolved oxygen, COD and total active metals (Tetra Tech, 2007). The key processes are focused on nitrification, denitrification, mineralization, hydrolysis and algal processes (e.g., algal growth, basal metabolism, predation, settling, and external loads) (Tetra Tech, 2007). The sediment flux module was used to simulate diagenesis of organic matters in the bed and the resulting fluxes of inorganic substances (i.e., phosphate (PO_4^{3-}), ammonium (NH_4^+), nitrite-nitrate (NO_2^- - NO_3^-)) and sediment oxygen demand (SOD) back to the water column (Di Toro and Fitzpatrick, 1993). The water quality module, directly coupled with the sediment flux module, simulates comprehensive dynamics and cycle of nutrients between the overlying body of water and sediment. The detailed mass conservation equations for each state

variable are documented in Craig (2011), Hamrick (1992) and Tetra Tech (2007).

A detailed model setup, calibration and validation process with respect to hydrodynamics and water quality variables in Lake Taihu can be found in the supplementary material (Li et al., 2011b; Tang et al., 2015). The previous results showed that the model reproduced the main features of wind-driven circulation, water level and water quality state variables quite well.

2.4 Limiting factors for cyanobacteria growth

The algae kinetic process is described as Eq. 1.

$$\left(\frac{\partial B_c}{\partial t}\right) = (P_c - BM_c - PR_c)B_c + \frac{\partial}{\partial Z}(WS_c \cdot B_c) + \frac{WB_c}{V} \quad (\text{Eq. 1})$$

where B_c is algal biomass of cyanobacteria (gC/m^3); t is time (days); P_c is production rate of cyanobacteria (day^{-1}); BM_c is basal metabolism rate of cyanobacteria (day^{-1}); PR_c is predation rate of cyanobacteria (day^{-1}); WS_c is positive settling velocity of cyanobacteria (m/day); WB_c is external loads of cyanobacteria (gC/day); V is cell volume (m^3).

Multiple factors limit cyanobacteria growth in Lake Taihu. Cyanobacteria growth (P_c) in Eq.1 is presented as the multiplication of maximum cyanobacteria growth rate (PM , day^{-1}), a nutrient limiting function ($f_1(N)$, $0 \leq f_1 \leq 1$), a light limiting function ($f_2(I)$, $0 \leq f_2 \leq 1$), a temperature limiting function ($f_3(T)$, $0 \leq f_3 \leq 1$), and a salinity limiting function ($f_4(S)$, $0 \leq f_4 \leq 1$) (Eq. 2). Since Lake Taihu is a freshwater body, the salinity effect on cyanobacteria growth is not considered in this study.

$$P_c = PM_c f_1(N) f_2(I) f_3(T) f_4(S) \quad (\text{Eq. 2})$$

(1) Nutrients

The nutrient limitation for cyanobacteria growth is expressed as:

$$f_1(N) = \left(\frac{NH_4 + NO_3}{KHN_c + NH_4 + NO_3}, \frac{PO_{4d}}{KHP_c + PO_{4d}} \right) \quad (\text{Eq. 3})$$

where KHN_c is the nitrogen half saturation constant for cyanobacteria; KHP_c is the phosphate half saturation constant for cyanobacteria; PO_{4d} is the dissolved portion of total phosphate, and f_{1N} and f_{1P} refer to the nitrogen and phosphorus limitation function, respectively. This equation is not applicable for some cyanobacteria (e.g., *Anabaena*) which can fix nitrogen from atmosphere and are not limited by nitrogen.

(2) Light

The light limitation for cyanobacteria growth derives from a daily and vertically integrated form of Steele's equation (Steele, 1992).

$$f_2(I) = \frac{e \cdot FD}{K_{ess} (Z_B - Z_T)} (e^{-\alpha B} - e^{-\alpha T})$$

$$\alpha B = \frac{I_{wsavg}}{FD \cdot I_{sc}} e^{-K_{ess} Z_B} \quad (\text{Eq. 4})$$

$$\alpha T = \frac{I_{wsavg}}{FD \cdot I_{sc}} e^{-K_{ess} Z_T}$$

where FD is the fractional day length ($0 \leq FD \leq 1$); K_{ess} is the total light extinction coefficient (m^{-1}); Z_B is the distance from water surface to layer bottom (m); Z_T is the distance from water surface to layer top (m); I_{wsavg} is daily total light intensity at water surface (ly/day); I_{sc} is the optimal light intensity for cyanobacteria (ly/day).

(3) Temperature

The temperature dependency of cyanobacteria growth can be represented by a Gaussian probability curve (Park et al., 1995; Cerco and Cole, 1994):

$$f_3(T) = \begin{cases} e^{-KTG1(T-TM1)^2} & T \leq TM1 \\ 1 & TM1 < T < TM2 \\ e^{-KTG2(TM2-T)^2} & T \geq TM2 \end{cases} \quad (\text{Eq. 5})$$

where T is the water temperature; $TM1$ and $TM2$ are lower and upper optimum temperatures for cyanobacteria growth, respectively; $KTG1$ and $KTG2$ are the constants related to the effect of water temperature below $TM1$ and above $TM2$ on algal growth, respectively.

2.5 Nutrient reduction scenarios

Developing effective and feasible nutrient reduction targets is necessary to improve trophic status and reduce bloom potentials. In this study, two nutrient reduction modeling scenarios were conducted to assess water quality response to nutrient load reductions (Table 1). The two scenarios were made according to the water quality targets for the main inflow rivers. The target for Scenario one (low reduction scenario) was that the nutrient concentrations in the inflow rivers are supposed to meet the Class V (total nitrogen (TN) 2 mg/L, total phosphorus (TP) 0.4 mg/L) according to environmental quality standards for surface water in China (GB3838-2002). The Class V for surface water is used for agricultural irrigation purpose. Since TP concentrations in the inflow rivers were less than 0.4 mg/L, there was no reduction for P in this scenario; while TN reduction percent spatially varied from 1.3% to 68.8% in different tributaries. Scenario one was also called N reduction scenario. The target for the Scenario two (high reduction scenario) was that the nutrient concentrations in the inflow rivers meet Class III (TN 1 mg/L, TP 0.2 mg/L) which is the lowest standard for drinking water source. TP reduction percent varied from zero to 48.2% while TN reduction percent changed from 50.7% to 84.4% in the tributaries, respectively. Scenario two was also called N and P reduction

scenario. Although this reduction scenario is perhaps difficult to achieve in the field, but this scenario is to provide a general picture of lake system response when drastic efforts are made to reduce external nutrients.

3. Results and Discussions

3.1 Nutrient inputs

The annual TN and TP loads to Lake Taihu from its tributaries in the past 15 years showed that the lake received a large amount of nutrients (Fig. 2). The data were obtained from previous literature (Ma et al., 2010; Paerl et al., 2011; Xu et al., 2005; Yan et al., 2011; Zhai et al., 2006) and local government (BLTB, 2008~2012). It is difficult to estimate nutrient loads precisely due to its complex river network systems around the lake and sometimes dual nature of the flow depending on tidal variations and gate controls. The previously estimated results showed that the nutrient loads evidently increased in the past five years than before (Fig. 2). Recent nutrient inputs were almost twice than that in the year 1987. During 1998 to 2007, TP loads remained stable or went down slightly in some years, while TN loads kept increasing. This maybe because in the history of controlling nutrient loads strategy, P, and not N, has been hypothesized as the priority nutrient controlling lake eutrophication (Li et al., 2011a). However, changing anthropogenic activities have caused imbalances in P and N loading, making it difficult to control eutrophication by reducing only one nutrient.

The nutrient loads from rivers during the period of 2008-2012 were studied in details. The loads have been divided into Jiangsu and Zhejiang Provinces (i.e., north and west regions around the lake) (Fig. 3), the most polluted regions of the lake located in the north and northwest. During these five years, N loads were much higher than P loads (Fig.

3). The ratios of TN to TP loads were from 19.1 to 23.6 in these years. Additionally, the nutrient loads from Jiangsu Province were four times than that from Zhejiang Province. It was because the ratios of inflow volume from Jiangsu Province to Zhejiang Province were about 3:1 and the nutrient concentrations of inflow-rivers in Jiangsu Province were relatively higher than in Zhejiang Province. The TN and TP concentrations in the main 15 inflow rivers in Jiangsu Province (Fig. 1) directly impact Meiliang Bay, Zhushan Bay and Northwest Zone from 2009 to 2013 are shown in Fig. 4. Most of these rivers largely exceeded the lowest standard for surface water quality (Class V: TN 2 mg/L; TP 0.4 mg/L). Due to the government efforts (e.g., waste water treatment, non-phosphorus detergent) for controlling phosphorus, TP concentrations in most rivers have shown a decreasing trend in these years (Fig. 4a). TP concentrations varied from 0.07 to 0.4 mg/L and mainly distributed around 0.2 mg/L. However, TN concentrations either exhibited an increasing trend or remained stable (Fig. 4b). TN concentrations in all 15 inflow-rivers exceed 2 mg/L (Class V standard). The government's emphasis of P over N control and increased chemical N fertilizer use in agricultural regions of the Taihu watershed, as well as atmospheric deposition likely caused higher N enrichment relative to P (Paerl et al., 2011; Wang and Wang, 2009; Zhai et al., 2009). Excessive N loads are now as large a concern as P loads in freshwater system (Paerl et al., 2011 and 2014a). This suggests that a proper understanding of limiting nutrient is important prior to implementing restoration efforts.

Nutrient concentrations in Lake Taihu showed various spatiotemporal distribution patterns (Fig. 5). From 2005 to 2012, TN and TP concentrations in Lake Taihu fluctuated and decreased slightly but remained unstable. However, compared with water quality

prior to 2000, the nutrient concentrations evidently increased (Qin, 2008). TN and TP concentrations showed strong spatial distributions decreasing from northwest to southeast, which are associated with inputs from major tributaries discharging into the north and west lake regions. Zhushan bay, Meiliang Bay and the Northwest Zone with worst water quality undertook large amounts of external nutrient loads. These three lake regions are the most heavily polluted areas and require attention. TP concentrations in these regions ranged from 0.075 to 0.2 mg/L, meanwhile the concentration in other lake regions were around or less than 0.05 mg/L (Fig. 5a). TN concentrations in more than half lake regions were larger than 2 mg/L. TN concentrations exceeded 5-6 mg/L in Zhushan Bay (Fig. 5b).

3.2 Limiting factors for cyanobacteria growth

The limiting factors for cyanobacteria growth were calculated based on Eqs. 1~5. The temporal variations of limitation functions (Eqs. 3~5) and summaries of limiting factors in Meiliang Bay (S2), Zhushan Bay (S7) and Northwest Zone (S25) are shown in Figs. 6 and 7. The limiting factors for algal growth in the upper water layer (about 0~1 m below the surface) varied depending on location and season (discussed below), while light appears to be the main limiting factor below one meter to the bottom due to higher turbidity. Smaller values of the limiting factors' functions indicated stronger control to cyanobacteria growth (i.e., $f=0$ means strong limit and $f=1$ means no limit) (Fig. 6).

Water temperature limited algal growth in winter in all lake regions (limitation function ~ 0.2). Cyanobacteria grows well when temperature is in the range of 25-35 °C (Paerl and Paul, 2012). In other seasons, with rising water temperature, nutrient availabilities became more important. In Meiliang Bay (S2), P limitation prevailed from

April to middle of July. N and P co-limitation occurred from July to August (experiencing a transitional process). During this period, cyanobacteria growth rates and nutrient demands were highest suggesting that both N and P were required for optimal algal growth. In autumn and winter, the limiting factors gradually changed from P to water temperature again (Fig. 6a and Fig. 7). In Zhushan Bay (S7), algae were P limited from the middle of March to November. Especially in the later autumn (from October to November), both P, N and temperature limitation existed (Fig. 6b and Fig. 7). In the Northwest Zone, P restricted the algal growth all around the year except in winter when water temperature was too low (Fig. 6c and Fig. 7). Generally, water temperature controlled algal growth in winter, while nutrient impacted in other seasons. Particularly, P dominated in other seasons while N limitation also occurred in summer and autumn in some lake regions (Fig. 7).

Identifying limiting factors for algal growth is essential to restore water quality to an acceptable level. Various assessment methods have been put in place to examine the limiting factors in Lake Taihu based on geochemical, ecological and physiological processes. Dokulil et al. (2000) suggested that light and P were the limiting factors in Lake Taihu. Chen et al. (2003) claimed that algal biomass measured as *Chl-a* was positively and significantly correlated with TP, while NO_3^- concentrations were inversely related. Yang (2004) suggested that P, and not N, was the nutrient limiting algal growth based on these findings. However, with the intervention on the nutrient inputs to the lake assuming only P is the priority nutrient controlling lake eutrophication, nutrient loading dynamics have changed substantially in the past decades (Paerl et al., 2011 and 2014b). The imbalances of P and N loadings have made it difficult to ease the eutrophication

status by reducing only one nutrient (Paerl et al., 2014a). More focus on P rather than N resulted in excessive N loads at a rate much higher than P, which has now promoted the non-N-fixing cyanobacteria blooms (e.g., *Microcystis*). Recently, Xu et al. (2010) found that phytoplankton was N limited in northern Meiliang Bay and part of the Central Zone in late summer, and P limited in winter and spring based on field data. Paerl et al. (2011) suggested that P limitation prevailed in winter and spring, while N limitation occurred in summer and fall based on the nutrient addition bioassays. Li et al. (2014) suggested that the limitation factor for the dominant algal growth depended on seasonality and location and it was necessary to reduce both N and P inputs in order to achieve a long-term algal control in this hyper-eutrophic system. In this study, our model results also indicated that besides the impact of water temperature on algal growth in winter and light availability in deeper water columns, both P and N effect was significant from spring to autumn. Our data supports the hypothesis that Lake Taihu tends to be co-limited by P and N. Therefore, reducing both N and P loads will be required for lowering bloom risks.

3.3 System response to nutrient reduction

There is a possibility that water temperature could be altered by climate change in the future which is not easy to control. However, anthropogenic nutrient reduction to prevent algal bloom is a direct and potentially achievable step that can be taken (Qin et al., 2010; Xu et al., 2010 and 2015; Paerl et al., 2011 and 2014c). Two modeling scenarios were conducted to assess water quality response to external nutrient loading reduction in the lake. We focused on water quality responses in the heavily polluted lake regions (including Meiliang Bay, Zhushan Bay and Northwest Zone), since those lake regions are directly connected to the tributaries that are highly enriched in both nutrients (Fig. 1). The

results indicated that external nutrient reduction modeled in this study helped decrease nutrient concentrations in the lake to some extent; however, achieving observable algal control will require drastic nutrient reduction. For example, in the low nutrient reduction scenario (only N reduction), TN concentrations decreased by 24%, 26%, and 22% in Meiliang Bay (S2), Zhushan Bay (S7) and Northwest Zone (S25), respectively (Fig. 8 a-c). In the high nutrient reduction scenario (both N and P reduction), TN concentrations reduced by 38%, 39% and 37% in three lake regions, respectively, while TP concentration dropped by 17%, 14% and 13% accordingly (Fig. 8 a-f). The *Chl-a* concentrations showed different responses to the modeled nutrient reduction schemes (Fig. 8 g-i). In response to the Scenario one with only N reduction, the *Chl-a* concentrations showed no change in Northwest Zone, while concentrations decreased about 23% in Meiliang Bay, especially in summer and autumn. In the Scenario two (both N and P reduction), the *Chl-a* concentrations decreased about 38% (average concentration 24.3 µg/L), 26% (35.4 µg/L) and 24% (33.6 µg/L) in Meiliang Bay, Zhushan Bay and Northwest Zone, respectively. This also indicated that algal growth in Meiliang Bay is controlled by both N and P, while Northwest Zone is P limited area, which was consistent with the bioassay and mesocosm studies on heavily polluted segments of the lake by Xu et al. (2010 and 2015) and Paerl et al. (2011 and 2014b).

Although the Scenario two (both N and P reduction) is quite large reductions and perhaps difficult to achieve in the near future, when taking historic increases in nutrient loads that have occurred in this lake, those proposals are probably quite realistic. Recently, Xu et al. (2015) proposed that 61-71% TN and 20-46% TP reductions were necessary to bring Taihu's phytoplankton biomass to "acceptable" sub-bloom conditions

of less than 20 $\mu\text{g/L}$ *Chl*-a, based on estimates of nutrient loading and observed stoichiometry of phytoplankton biomass which was quite close to what was determined using model in this study. Reduction of external nutrients has already been emphasized in earlier studies, which seems to be a prudent and likely most practical solution for reducing bloom potentials and overall trophic state of this currently hypereutrophic system (Qin et al., 2010; Xu et al., 2010 and 2015; Paerl et al., 2011 and 2014c). Reducing external P and N by using water treatment for point source and aggressive non-point source control could significantly reduce the overall nutrient loads. In the last few decades, the Chinese government has undertaken a wide range of activities in an effort to reduce external nutrient loads and improve lake water quality, including closing a number of heavy polluting factories, banning the use of phosphorus-bearing detergents, building additional wastewater treatment plants etc (Li et al., 2011a).

In this study, internal nutrient fluxes were incorporated into the model simulations. The benthic flux rates (i.e., PO_4^{3-} , NH_4^+ , NO_2^- - NO_3^- and SOD) in different lake regions were set according to the previous field experiments in Lake Taihu (Hu et al., 2006; Jiang et al., 2008; Luo et al., 2006; Tang et al., 2015; Trolle et al., 2009). The results clearly indicated that external nutrient reduction is critical to help mitigate eutrophic status but the amount of reduction needed to achieve the goal seems much higher than modeled in this study. Internal loading from sediment resuspension and sediment-water column exchange, as well as atmospheric N loading, should also be considered, as they are quantitatively important. According to a prior estimate, nutrient inputs from sediments can be two to six times more than external nutrient loads, especially for P (Qin et al., 2006); while the nutrients from atmospheric depositions were estimated about 20% of the

loads from watershed (Zhai et al., 2009). The significant internal nutrient storage resulting from the legacy of nutrient loading may take several decades to achieve a "turnaround" in trophic state and bloom potentials. However, this is the price that has to be paid for years of neglect with regard to excessive nutrient loading to the lake. Recently, the local government is using dredging to remove sediments in the heavily polluted northern regions of the lake, which may speed up recovery of water quality with proper disposal of sediments (possibly outside of the lake watershed). Reductions in atmospheric deposition will take many years, because they are regional and national and will depend on major energy-generation policy changes. Overall, there is no question that controlling the external nutrients from the main tributaries is important, and a comprehensive environmental policies and management solutions will be required to deal with internal and atmospheric nutrient loadings in the long term.

4. Conclusions

Large amounts of continuous external nutrient loads have left Lake Taihu into a perennial hyper-eutrophic status. More focus on P reduction rather than both N and P has resulted in the lake being in a nutrient imbalanced condition. A three-dimensional eutrophication model (EFDC) was used to identify the limiting factors for algal growth and investigate effect of external nutrient loads reduction on water quality in Lake Taihu. The results showed that limiting factor for the dominant algal growth depended on seasonality and spatiality. Besides the impact of water temperature on algal growth in winter and light in deeper water columns, P dominated in other seasons while N limitation also occurred in summer and autumn in some lake regions. It was found that Lake Taihu tends to be co-limited by N and P. P load reduction has been a critical part

of nutrient management in Lake Taihu, however, controlling N inputs cannot be ignored. The nutrient reduction Scenarios showed that *Chl-a* concentrations decrease about 38%, 26% and 24% in the Meiliang Bay, Zhushan Bay and Northwest Zone, respectively, despite reducing external N and P by 50.65-84.4% and 0-48.2%, respectively. The results indicated that already accumulated nutrients (both N and P) in water and sediments are very high to prevent repeated occurrence of algal blooms in a short duration. Thus, stricter external nutrient management combined with other ecological restoration tools will be required to ease algal blooms and improve water quality in Lake Taihu.

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Table 1 Nutrient reduction scenarios for tributaries

Scenarios	Water quality targets	Reduction percent for tributaries
Scenario one (Low reduction scenario)	Class V TN 2 mg/L; TP 0.4 mg/L	N only reduction TN 1.3-68.8%; TP 0%
Scenario two (High reduction scenario)	Class III TN 1 mg/L; TP 0.2 mg/L	N and P reduction TN 50.7-84.4%; TP 0-48.2%

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Fig. 1 Location of study area, surrounding rivers (grouped as 1-30), and water quality monitoring stations (S1-S30) in Lake Taihu, China. The eight sub-areas of Lake Taihu are: Zhushan Bay, Meiliang Bay, Gonghu Bay, Northwest Zone, Southwest Zone, Central Zone, East Epigeal Zone, and Dongtaihu Bay. Blue lines represent major heavily polluted rivers in Jiangsu Province

Fig. 2 TP (a) and TN (b) loading to Lake Taihu from its tributaries in past 14 years. Data are sourced from previous literature (Ma et al., 2010; Paerl et al., 2011; Xu et al., 2005; Yan et al., 2011; Zhai et al., 2006) and Health Status Report of Lake Taihu (2008-2012)

Fig. 3 Annual TN and TP loading to Lake Taihu from Jiangsu Province and Zhejiang Province from 2008 to 2012, respectively

Fig. 4 Annual average TP (a) and TN (b) concentrations in the main 15 inflow rivers in Jiangsu Province from 2009 to 2013. Note: Dash lines indicate different standards for surface water in China. Class III-TN 1 mg/L, TP 0.2 mg/L; Class V -TN 2 mg/L, TP 0.4 mg/L

Fig. 5 Spatial distributions of TP (a) and TN (b) concentrations in Lake Taihu from 2005 to 2012

Fig. 6 Temporal variations of limitation functions in Meiliang Bay (S2) (a), Zhushan Bay (S7) (b) and Northwest Zone (S25) (c). $f(N)$, $f(P)$, $f_2(I)$ and $f_3(T)$ represent nitrogen, phosphorus, light and water temperature limiting functions, respectively

Fig. 7 Summaries of seasonal and spatial patterns of limiting factors in the surface water of Meiliang Bay, Zhushan Bay and Northwest Zone

Fig. 8 Temporal variations of model-simulated (filled red circles: observation data; solid black lines: base case; unfilled purple circles: Scenario one; unfilled light circles: Scenario two) TN, TP and *Chl*-a concentrations in Meiliang Bay (S2), Zhushan Bay (S7) and Northwest Zone (S25), respectively

Fig. 1

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