**New model to assessing nutrient assimilative capacity in
plant-dominated lakes: Considering ecological effects of
hydrological changes**

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Abstract: Assessing nutrient assimilative capacity of water body is an essential component of the Total Maximum Daily Load program. Nutrient assimilative capacity of lakes is affected by hydrological changes through physical effects on the dilution capacity of water body and ecological effects on nutrient removal processes. Previous research has focused on the effects of hydrological changes on dilution capacity, but rarely considered the ecological effects on nutrient assimilative capacity. In this study, a process-based model considering both ecological effects and dilution effects of hydrological changes is proposed for assessing nitrogen and phosphorus assimilative capacities of plant-dominated lakes. Plant uptake and biological denitrification are two crucial nutrient removal processes. Water depths in a lake affect plant growing area. Lake submerged condition affects nutrient accumulation capacity of plants and the intensity of biological denitrification. The model considered dynamic variations of lake water depths and submerged condition, and the associated effects on nutrient removal by plant nutrient uptake and biological denitrification in lake systems. It is a discrete 0D model depending on a small amount of data and has satisfactory simulation accuracy. We chose the largest freshwater lake in northern China (Baiyangdian Lake) as a case. The annual total assimilative capacity in the lake was 1536 t for nitrogen and 157 t for phosphorus. Assimilative capacity during plant-growing season accounted for over 90% of the annual total capacity. The results determined by the new model were less than half of that from previous model, demonstrating the significance of considering ecological effects of hydrological changes. The new assessment model offers a useful tool for directing pollutant emission control and eutrophication prevention in global plant-dominated lakes.

Keywords: eutrophication; TMDL; hydrology; ecological process; mechanistic model

1. Introduction

Nutrient assimilative capacity is defined as the maximum allowable nutrient load that can be discharged into a water body without exceeding water quality criteria set by statutory regulatory agencies (Landis, 2008), which can be used for directing pollutant emission control in the Total Maximum Daily Load (TMDL) program (Faulkner, 2008; Peternel-Staggs et al., 2008). Nitrogen and phosphorus are important pollutants of freshwater lakes around the world (Bernhardt, 2013; Li et al., 2015). They are among the main control targets of the TMDL program (Mirchi and Watkins, 2013; USEPA, 1991) for their widespread threats to water resource security and lake ecosystem health (Stone, 2011). Assessing nitrogen and phosphorus assimilative capacities of lakes is significant for preventing lake eutrophication and protecting freshwater environments.

Common models for assessing nutrient assimilative capacity include mass balance models, statistical models and complex water quality modelling software (Jesiek et al., 2007). Complex water quality modelling software (e.g., Water Quality Analysis Simulation Program; Environment Fluid Dynamics Code) is a comprehensive package that can simultaneously simulate hydrological and nutrient cycles in lakes (Liu et al., 2008; Peternel-Staggs et al., 2008; Wang and Bi, 2016). They can be used for simulating complex environmental conditions, but their set-up processes and data inputs are complicated. Statistical models obtain empirical relationships between management measures and water quality through statistical methods (Alameddine, 2011; Faulkner, 2008; Richardson and Qian, 1999). They are simple while depend on large amounts of statistical data. Mass balance models are widely used due to the satisfactory compromise between accuracy and simplicity (Havens and James, 2005; Khanal et al., 2014; Kim et al., 2013; Rucinski et al., 2009). They focus on mass

balance calculation in lakes through quantifying the transport and transformation processes of nutrients (Doerr et al., 1996; Rucinski et al., 2007). Biological denitrification is an important and commonly occurring nitrogen removal process (Havens and Schelske, 2001; Seitzinger et al., 2006), and harvested plants also remove significant quantities of nitrogen and phosphorus in plant-dominated lakes (Gottschall et al., 2007; Marion and Paillisson, 2003). Biological denitrification and plant uptake are highlighted in assessments of nutrient assimilative capacity for plant-dominated lakes due to their prominent contributions to nutrient removal.

Hydrological conditions are crucial factors affecting nutrient assimilative capacity in lakes. Lake hydrological conditions differ in different hydrological years (wet, average, or dry years) as well as in different months of the same year. As extreme weather events and artificial water regulations (e.g., upstream reservoir operation) increase, hydrological changes in lakes are more frequent and severe (Barnett et al., 2008; Piao et al., 2010). Thus, the influence of hydrological changes on nutrient assimilative capacity should receive more attention. It is well known that hydrological changes affect lake's nutrient assimilative capacity through the physical effects on nutrient dilution capacity of water body, while hydrological changes also lead to ecological effects on nutrient assimilative capacity through affecting lake's nutrient removal processes.

We focus on ecological effects of hydrological changes on plant uptake and biological denitrification, two crucial nutrient removal processes in plant-dominated lakes. Plant-dominated lake is a common and important type of lake with high species richness and service value (Burks et al., 2006; Jones and Waldron, 2003). Hydrological conditions determine plant growing areas in lakes, because plants normally only grow in suitable water-depth condition (Bucak et al., 2012; Pagter et al.,

2005). Within the available growing zones, nutrient uptake capacities of plants differ in seasonally flooded zones and continually flooded zones (Lawniczak et al., 2010; Sollie and Verhoeven, 2008). Hydrological changes affect both growing area and nutrient uptake capacity of plants. In addition, biological denitrification is also affected by hydrological changes due to effects on sediment water content, nitrogen availability, and oxidative or reductive conditions (Berglund and Berglund, 2011; Song et al., 2010). Biological denitrification in seasonally flooded conditions is stronger than that in continuously flooded conditions (Yang et al., 2012). These experimental studies have found that the effects of hydrological changes on plant growth and biological denitrification were significant and should be paid much attention. However, existing mass balance models did not consider these effects, which would lead to huge error in lake water quality simulation. A new model considering the ecological effects of hydrological changes is needed urgently.

In this study, we developed a new mass balance model for assessing nitrogen and phosphorus assimilative capacities of plant-dominated lakes, simultaneously considering the ecological effects and dilution effects of hydrological changes. A lake is divided into several hydrological zones based on hydrological difference, and the effects of hydrological difference on plant uptake and biological denitrification were determined. The model considers dynamic area variations caused by hydrological changes in each hydrological zone and differences in plant uptake and biological denitrification. The plant area also varies with hydrological changes and plant death caused by unsuitable hydrological changes is considered. Hydrological conditions and plant nutrient uptake capacity vary monthly, so the model calculates the assimilative capacity of lakes monthly instead of yearly, to reflect its seasonal variations. We

chose Baiyangdian Lake, the largest freshwater lake in northern China, as a case study to demonstrate this new model.

2. Materials and methods

2.1 Study area

Baiyangdian Lake (38°43'N to 39°02'N and 115°45'E to 116°07'E) is a famous plant-dominated lake located in Anxin County, Hebei Province, China (Yin and Yang, 2013; Zhao et al., 2012). It is important for controlling floods, regulating regional climate, and providing biological habitats. The common reed [*Phragmites australis* (Cav.) Trin. ex Steud.] is the dominant plant species in the lake with a large growing area of about 80 km². The growing season lasts from April to September. After September, reeds senesce and are harvested to prevent the release of nutrients in the lake. In recent years, many dams and reservoirs were constructed in the upstream regions, changing the natural hydrological conditions of Baiyangdian Lake. The lake water level can fluctuate between 6 m and 8.8 m and the surface area ranges from 46 km² to 308 km² from month to month. Now Baiyangdian Lake faces a threat of eutrophication from increased industrial, agricultural, and urban sewage pollutant inputs. Water quality protection has become a primary mission.

2.2 Model development and application

The model for assessing nitrogen and phosphorus assimilative capacities of plant-dominated lakes is developed and applied in Baiyangdian Lake as a case study. To facilitate view and analysis, the model framework is shown in Fig. 1.

#The approximate position of Figure 1#

2.2.1 Hydrological changes

Hydrological changes can be determined based on the water quantity balance. In general, lake replenishment depends on rainfall and inflows from upstream regions. As artificial water regulation increases, inflows from upstream regions are under tighter control by upstream reservoirs. In this study, we set the inflows for Baiyangdian Lake as recommended by Chen et al. (2013), who proposed an inflow management regime for the lake based on environmental flow requirements. On the other hand, water losses of lakes mainly result from outflows, evapotranspiration, and deep drainage. Evapotranspiration calculation in plant-dominated lakes is a complex process. Both water surface evaporation and plant transpiration should be considered in plant-growing season. The evapotranspiration capacity of Baiyangdian Lake can be found in the research by Xu et al. (2014). Annual average precipitation is 461.9 mm and the permeability coefficient of the lake bottom is 3 mm per day (Xu et al., 2014). Baiyangdian Lake has no natural outflows and little artificial water consumption (Yang et al., 2011). The equations to calculate monthly variations of water volume in lakes are:

$$W_i = W_{i-1} + W_{i,in} + W_{i,r} - W_{i,o} - W_{i,e} - W_{i,d} \quad (1)$$

$$W_{i,e} = W_{i,ev} + W_{i,tr} \quad (2)$$

where W_i is the lake water volume in month i ; $W_{i,in}$ is the water replenishment through inflows in month i ; $W_{i,r}$ is the water replenishment through rainfall; $W_{i,o}$ is the water loss through outflows; $W_{i,e}$ is the water loss through evapotranspiration; $W_{i,d}$ is the water loss through deep drainage; $W_{i,ev}$ is the water loss due to water surface evaporation; and $W_{i,tr}$ is the water loss due to plant transpiration. The units of all parameters in equations (1) and (2) are $\times 10^8 \text{ m}^3$.

2.2.2 Nutrient mass balance

Natural lakes have strong decontamination capacity. Generally, the pathways for phosphorus removal from lake water mainly include plant uptake, exchange with sediments, and outflows. Nitrogen removal is more complex. Besides these pathways for phosphorus, nitrogen can also be removed through biological denitrification, chemical denitrification, and ammonia volatilization (Zhao et al., 2012). Our model focuses on the nutrient assimilative capacity of lakes and does not consider load allocation among pollution sources. Thus, we set one input parameter for each kind of nutrient and did not set parameters for different pollution sources. On the basis of nutrient mass balances, the equations to calculate monthly variations of nutrients in lakes are:

$$N_i = N_{i-1} + N_{i,\text{in}} - N_{i,\text{o}} - N_{i,\text{e}} - N_{i,\text{p}} - N_{i,\text{b}} - N_{i,\text{c}} - N_{i,\text{a}} \quad (3)$$

$$P_i = P_{i-1} + P_{i,\text{in}} - P_{i,\text{o}} - P_{i,\text{e}} - P_{i,\text{p}} \quad (4)$$

where N_i and P_i are the total amounts of N and P in the lake water in month i ; $N_{i,\text{in}}$ and $P_{i,\text{in}}$ are the amounts of each nutrient flowing into the lake in month i ; $N_{i,\text{o}}$ and $P_{i,\text{o}}$ are the amounts removed by outflows; $N_{i,\text{e}}$ and $P_{i,\text{e}}$ are the amounts removed by exchange with sediments; $N_{i,\text{p}}$ and $P_{i,\text{p}}$ are the amounts removed by plant uptake; $N_{i,\text{b}}$ is the amount of nitrogen removed by biological denitrification; $N_{i,\text{c}}$ is the amount of nitrogen removed by chemical denitrification; and $N_{i,\text{a}}$ is the amount of nitrogen removed by ammonia volatilization. The units of all parameters in equations (3) and (4) are $\times 10^2$ t.

Chemical denitrification normally takes place in acidic conditions and ammonia volatilization is negligible when pH ranges from 7.5 to 9.3 (Zhao et al., 2012). The pH of Baiyangdian Lake is approximately 8.0, so chemical denitrification and ammonia volatilization can be ignored. Plant uptake in Baiyangdian Lake mainly depends on the common reed, which absorbs nutrients mainly through its rhizome system

(Ailstock et al., 2001). Available nitrogen and phosphorus for reed use mainly exist in soluble form in lake water and interstitial water in sediments (Wetzel, 2001).

2.2.3 Ecological effects of hydrological changes

To consider the ecological effects of hydrological changes, four new processes are included in the model:

- (1) Hydrological changes affect plant area by affecting water depths in lakes;
- (2) The variation of plant area affects hydrological cycle through the effects on lake evapotranspiration;
- (3) Hydrological changes affect nutrient accumulation capacity of plants and the intensity of biological denitrification;
- (4) The variation of plant area affects nutrient removal by biological denitrification.

Hydrological changes lead to water-depth variations in lakes. Plants normally grow in suitable water depths, which range from -0.64 to 1.01 m for the common reed in Baiyangdian Lake (Xu et al., 2014). As water depth varies, plant area also has variations accordingly. When water depths in some plant growing zones become unsuitable due to hydrological changes, these plants die and should be harvested, stopping absorbing nutrients in next months. In the model, the varying plant area is calculated based on the initial plant area and the lake water-depth condition during the modelling period. Besides water depth variations, hydrological changes also lead to water surface area variations, consequently affecting lake submerged condition. Based on the difference of submerged conditions, a lake can be divided into three hydrological zones: the aquatic zone, which is continually submerged; the aquatic-terrestrial ecotone zone, which is intermittently submerged; and the terrestrial zone, which is never submerged. Only the submerged lake zones are available to remove nutrients from lake water body. Thus, the terrestrial zone can be excluded in assessing

nutrient assimilative capacity. The nutrient accumulation capacity of plants and the intensity of biological denitrification differ in different hydrological zones. The effects of hydrological changes on lake water depths and submerged conditions are considered in the model. To reflect the water surface area and depth variations caused by hydrological changes, the model builds the relationship among lake water volume, water surface area, and water level, based on historical data.

Biological denitrification varies in different hydrological zones. Even in the same hydrological zone, the intensity of biological denitrification is different in zones with plants and without plants, because the plant rhizosphere facilitates biological denitrification by improving the exchange of aerobic and anaerobic processes (Højberg et al., 1996). Thus, plant area variations in lakes affect not only plant uptake but also biological denitrification. Based on differences of plant uptake and biological denitrification, we divided the submerged lake area into four zones: the aquatic zone with plants; the aquatic zone without plants; the ecotone zone with plants; and the ecotone zone without plants (Fig. 1). Nutrient accumulation capacity of plants and the intensity of biological denitrification in a unit of various zones are determined by experiments. The areas of all these four zones may vary with hydrological changes. The model considered the dynamic hydrological changes in lakes and considered the influences of hydrological changes on the areas of these zones. Based on the zone division, the equations to calculate the total amounts of nutrients removed by plant uptake and biological denitrification in lakes are:

$$A_i = A_{i,a,p} + A_{i,a,np} + A_{i,e,p} + A_{i,e,np} \quad (5)$$

$$N_{i,p} = (n_{i,ap,a} + n_{i,bp,a}) \times A_{i,a,p} + (n_{i,ap,e} + n_{i,bp,e}) \times A_{i,e,p} \quad (6)$$

$$P_{i,p} = (p_{i,ap,a} + p_{i,bp,a}) \times A_{i,a,p} + (p_{i,ap,e} + p_{i,bp,e}) \times A_{i,e,p} \quad (7)$$

$$N_{i,b} = n_{i,b,ap} \times A_{i,a,p} + n_{i,b,anp} \times A_{i,a,np} + n_{i,b,ep} \times A_{i,e,p} + n_{i,b,enp} \times A_{i,e,np} \quad (8)$$

where A_i is the total area of the submerged lake zones in month i (km^2); $A_{i,a,p}$ is the area of the aquatic zone with plants (km^2); $A_{i,a,np}$ is the area of the aquatic zone without plants (km^2); $A_{i,e,p}$ is the area of the ecotone zone with plants (km^2); $A_{i,e,np}$ is the area of the ecotone zone without plants (km^2); $n_{i,ap,a}$ ($p_{i,ap,a}$) and $n_{i,bp,a}$ ($p_{i,bp,a}$) are the amounts of nitrogen (phosphorus) absorbed by aboveground and belowground parts of reeds in a unit area of the aquatic zone (10^2 t km^{-2}); $n_{i,ap,e}$ ($p_{i,ap,e}$) and $n_{i,bp,e}$ ($p_{i,bp,e}$) are the amounts of nitrogen (phosphorus) absorbed by aboveground and belowground parts of reeds in a unit area of the ecotone zone (10^2 t km^{-2}); $n_{i,b,ap}$ ($n_{i,b,anp}$) are the amounts of nitrogen removed by biological denitrification in a unit area of the aquatic zone with plants (without plants) (10^2 t km^{-2}); and $n_{i,b,ep}$ ($n_{i,b,enp}$) are the amounts of nitrogen removed by biological denitrification in a unit area of the ecotone zone with plants (without plants) (10^2 t km^{-2}). $A_{i,e,p}$ and $A_{i,e,np}$ are zero in months when the ecotone zones are wholly unsubmerged.

2.2.4 Nutrient assimilative capacity

The model focuses on holistic mass balances in lake systems and does not consider spatial distribution of nutrients, so average nutrient concentrations in a lake can be obtained based on the total amounts of nutrients and the water volume. To protect the ecosystem and benefit water consumers, water quality should be maintained at an acceptable level with nutrient concentrations no higher than the target values. In Baiyangdian Lake, water quality is expected to meet requirements of the Grade III level in the Chinese water quality standard according to the local government, which means that the concentrations of total nitrogen (TN) and total phosphorus (TP) should be no higher than 1.0 and 0.05 mg L^{-1} , respectively (SEPAC, 2002b). The equations to calculate the nutrient assimilative capacity of lakes are:

$$C_{N,i} = \frac{N_i}{W_i} = \frac{N_{i-1} + N_{i,in} - N_{i,o} - N_{i,e} - N_{i,p} - N_{i,b} - N_{i,c} - N_{i,a}}{W_{i-1} + W_{i,in} + W_{i,r} - W_{i,o} - W_{i,e} - W_{i,d}} \leq C_{N,i}^* \quad (9)$$

$$C_{P,i} = \frac{P_i}{W_i} = \frac{P_{i-1} + P_{i,in} - P_{i,o} - P_{i,e} - P_{i,p}}{W_{i-1} + W_{i,in} + W_{i,r} - W_{i,o} - W_{i,e} - W_{i,d}} \leq C_{P,i}^* \quad (10)$$

$$M_{N,i} = \max N_{i,in} / M_{P,i} = \max P_{i,in} \quad (11)$$

where $C_{N,i}$ and $C_{P,i}$ are the concentrations of TN and TP in the lake water in month i (mg L^{-1}); $C_{N,i}^*$ and $C_{P,i}^*$ are the maximum acceptable concentrations of TN and TP in month i (mg L^{-1}); and $M_{N,i}$ and $M_{P,i}$ are the nitrogen and phosphorus assimilative capacities of the lake in month i (10^2 t).

2.3 Determination of model parameters

To determine some important model parameters, field experiments were conducted in Baiyangdian Lake, through which the effects of different hydrological conditions on plant uptake and biological denitrification were quantified. We focused on the aquatic and ecotone zones in assessing nutrient assimilative capacity of lakes. Plant uptake in Baiyangdian Lake is driven by the common reed, which has strong nutrient assimilation capacity. Field sampling in the aquatic and ecotone zones determined the nutrient assimilation capacity of reeds under different hydrological conditions. The sampling sites were representative because the physical and chemical indicators of water quality at the sampling sites were close to the corresponding average values in Baiyangdian Lake. From May to September 2010, we collected aboveground parts (leaves and stems) and belowground parts (roots) of reeds from the lake and samples were placed in sealed containers and transported to the laboratory. The TN and TP concentrations of reed tissues were measured by the Nesslerization colorimetric and Mo-Sb-Vc spectrophotometric methods as recommended by the State Environmental Protection Administration of China (SEPAC, 2002a).

The nutrient absorption of aboveground reed tissues can be directly obtained by multiplying the aboveground biomass by the nutrient concentrations in the tissues. In contrast, it is difficult to obtain the nutrient absorption of belowground tissues in a one-year cycle, because belowground tissues are perennial and it is difficult to distinguish new tissues from old tissues. Fiala (1976) studied reed growth for years and built a relationship between aboveground and belowground biomass. He proposed that the annual increment of belowground biomass was about 45% of the maximum aboveground biomass, so we used that percentage in our model. After measuring the nutrient concentrations of belowground tissues, the annual nutrient absorption by belowground parts also can be obtained.

Biological denitrification is also affected by hydrological conditions. We measured nitrous oxide emissions in different hydrological zones of Baiyangdian Lake through field mesocosm experiments, and found that the intensity of biological denitrification in the ecotone zone was 17.8% greater than that in the aquatic zone (Yang et al., 2012). The nitrogen removed by biological denitrification comes from the water body as well as the sediments. We are mainly concerned with nitrogen removed from the water body in assessing assimilative capacity. Thus, field simulation experiments were conducted in Baiyangdian Lake from April to September 2010 to determine the amount of nitrogen removed from the water through biological denitrification. We only simulated the aquatic zone, because denitrification in the ecotone zone was previously shown to be 17.8% greater than that in the aquatic zone. We sampled water, sediments, and reed rhizomes from Baiyangdian Lake in April 2010. Because plant growth affects biological denitrification, we established one group with growing reeds and another without reeds, each in triplicate, to simulate the aquatic zone. The amount of nitrogen removed by biological denitrification and exchange with

sediments was determined by measuring the decrease of nitrogen in the water body. In the group with growing reeds, nutrients absorbed by the reeds were subtracted. We obtained the amount of phosphorus removed from the water through exchange with sediments using the same method. The experiment results are used to determine parameters in the assessment model.

3. Results

3.1 Plant uptake and denitrification in different conditions

Through field sampling and experiments in Baiyangdian Lake, we can quantify the effects of hydrological conditions on plant uptake and biological denitrification. Nutrients absorbed by aboveground and belowground reed tissues were determined for the ecotone and aquatic zones (Table 1). Nitrogen and phosphorus absorbed by reeds in unit areas of the ecotone zone are 21.4% and 22.4% more than what is absorbed by reeds in the aquatic zone, as measured at the end of the growing season. Our experiment results also showed that averages of 57.6 mg m^{-2} TN and 6.5 mg m^{-2} TP were removed monthly from the water through biological denitrification and exchange with sediments in the aquatic zone without reeds. The amount of nitrogen removed through biological denitrification in the zone with reeds was about two times higher than in the same hydrological zone without reeds.

#The approximate position of Table 1#

3.2 Nutrient assimilative capacity of Baiyangdian Lake

The new model was applied in Baiyangdian Lake to assess nutrient assimilative capacities (Fig. 2). The N and P assimilative capacities of the lake vary monthly and range from 2.41 to 973.51 t for N and from 0.45 to 92.12 t for P. During the reed growing season, plant uptake plays a dominant role in improving nutrient assimilative

capacity because the reed area in Baiyangdian Lake is very large and nutrient assimilation capacity of reeds is strong. Outside the reed growing season, biological denitrification and exchange with sediments are the main factors affecting assimilative capacity. Biological denitrification can also remove a large amount of nitrogen from the lake, but most of the nitrogen removed by biological denitrification comes from the sediments and only a small amount of nitrogen comes from the lake water. In assessing nutrient assimilative capacity, we are concerned only with nutrients removed from the water. Thus, nutrient assimilative capacity during the reed growing season (May–September) is much higher than at other times.

#The approximate position of Figure 2#

Assimilative capacity is highest in June because of the large amounts of nutrients absorbed by reeds. Reeds also absorb a large amount of nutrients in July, but the assimilative capacity in July is only about 20% of that in June due to the high evapotranspiration of the lake in July. The high evapotranspiration leads to great loss of water. Dilution capacity of water body decreases and so does the submerged reed area. The decrease of submerged reed area reduces the amounts of nutrients absorbed by reeds from the water. This explains the decrease of assimilative capacity in July, August, and September. When N and P inputs are kept below the nutrient assimilative capacity (Fig. 2), water quality in Baiyangdian Lake can meet the Grade III level of the Chinese water quality standard throughout the year.

4. Discussion

4.1 Comparison with previous mass balance models

Mass balance models have been widely used for water quality simulation due to their satisfactory compromise between accuracy and simplicity (Juston et al., 2013;

Sharifi et al., 2013). Different mass balance models have different focuses. Rucinski et al. (2007, 2009) proposed a dual discharge strategy for water management through applying a mass balance model. This model focused on the nutrient removal caused by water discharge. Obviously, water discharge is a physical process and directly removes large amounts of nutrients in water bodies with high exchange capacity, but it is not significant in enclosed water bodies. The models used by Doerr et al. (1996) and Havens and James (2005) focused on nutrient exchange between overlying water and sediments. The exchange processes include settling of nutrient particulate fraction, physical adsorption by gravel particles and sediment release (Mandal et al., 2015). Exchange with sediments is thought as the dominant process for phosphorus removal in enclosed water bodies (Zaaboub et al., 2014; Zhang et al., 2013). The modelling results in this study demonstrated this and found that the phosphorus removal efficiency by exchange with sediments reaches an average of 19.6 kg day^{-1} in plant non-growing season in Baiyangdian Lake. Besides, biological processes for nutrient removal also have been emphasized in a significant number of existing mass balance models (Chung et al., 2008; Havens and Schelske, 2001; Khanal et al., 2014; Zhou and Hosomi, 2008). Nutrient removal by plant uptake and biological denitrification was considered in these models and their research results demonstrated the importance of considering biological processes, especially in plant-dominated lakes. However, these models rarely considered the effects of hydrological changes on biological processes. In recent years, more and more researches (e.g., Berglund and Berglund, 2011; Lawniczak et al., 2010; Yang et al., 2012; Zhao et al., 2012) have found that the effects of hydrological changes on plant uptake and biological denitrification were significant and must be considered in simulating plant-dominated water environment. Thus, this study firstly considered the ecological effects of

hydrological changes in developing mass balance model. Here we will discuss the significance of considering these effects through comparing the results from the new model and previous mass balance model.

Baiyangdian Lake is still chosen as the case. The previous mass balance model (Wu et al., 2013; Zhou and Hosomi, 2008) did not consider plant area variations caused by hydrological changes, and set it as a constant value. Besides, they also did not consider differences in plant uptake and biological denitrification of different hydrological zones, so we use the data measured in the aquatic zones to set the nutrient removal capacities by reeds and denitrification. The results from the new model and previous mass balance model are shown in Fig. 3.

#The approximate position of Figure 3#

The comparison (Fig. 3) shows that the annual nitrogen (phosphorus) assimilative capacity determined by the new model is 41% (45%) of the capacity from previous model. From January to April, the phosphorus assimilative capacity shows no difference, but the nitrogen assimilative capacity resulting from the new model is higher than that of the previous model. This is because the intensity of biological denitrification in the ecotone zone is higher than in the aquatic zone and the previous model treated the whole submerged zone as the aquatic zone. During the plant growing season (from May to September), the differences in the results of the two models are obvious. Reeds in the ecotone zone have higher absorbing ability than those of the aquatic zone in May and lower absorbing ability than those of the aquatic zone in June. The previous model treats the whole submerged zone as the aquatic zone, so the assimilative capacities from the previous model are lower in May and higher in June compared with the new model. The evapotranspiration of reed communities is several times higher than water surface evaporation. As a result of

high transpiration by reeds in May and June, the lake volume greatly decreases and the submerged reed area also decreases. The previous model did not consider the decrease of submerged plant area caused by hydrological changes. Thus, the nutrient assimilative capacities from the previous model are much higher than those from the new model from July to September. The previous model overestimated the nutrient assimilative capacity in the middle and late plant growing season.

The previous model set the submerged plant area as a constant, but the submerged plant area decreases with water loss. The previous model overestimates the submerged plant area, and also overestimates plant transpiration. Thus, at the end of the growing season, the lake volume under the previous model is less than that from the new model. Less water volume means a smaller submerged zone, which has two opposite effects on assimilative capacities in the following months. On the one hand, a smaller submerged area leads to fewer nutrients removed through biological denitrification and exchange with sediments. On the other hand, it also leads to less water lost through evaporation. These opposite effects explain why the assimilative capacity for nitrogen is higher with the previous model from October to December, while the assimilative capacity of phosphorus is lower with the previous model in November and December.

4.2 Comparison with statistical and complex water quality models

Besides mass balance models, statistical models and complex water quality modelling software are also widely used for assessing nutrient assimilative capacity (Jesiek et al., 2007). Statistical models obtain empirical relationships between nutrient inputs and water quality by analyzing long-term monitoring data (Alameddine, 2011; Faulkner, 2008; Hale et al., 2015). These models do not consider the transport and transformation processes of nutrients in lakes and avoid calculation errors occurring

in quantifying each process (Borsuk et al., 2003; Safaie et al., 2016). Richardson and Qian (1999) conducted a statistical analysis of a North American Wetland Database and found a “One Gram Assimilative Capacity Rule” for phosphorus, which meant that average phosphorus assimilative capacity in North American wetlands was $1 \text{ g m}^{-2} \text{ yr}^{-1}$. The results of this study showed that the average phosphorus assimilative capacity in Baiyangdian Lake was $1.15 \text{ g m}^{-2} \text{ yr}^{-1}$, which was a little higher than previous statistical result in North American wetlands. One of the main reasons leading to the difference is that plant-dominated wetlands normally have stronger nutrient assimilative capacity and previous statistical results only showed the average value in North American wetlands. Besides this, statistical rules found in a particular area are often not accurately applicable in other areas, due to the differences of geographical location and environmental condition. The biggest challenge for applying a statistical model is the lack of long-term monitoring data in most lakes around the world (Shi et al., 2016).

Complex water quality modelling software is chosen due to the high simulation accuracy (Liu et al., 2008; Peternel-Staggs et al., 2008; Wang and Bi, 2016). This study chose the Environmental Fluid Dynamics Code (EFDC), a state-of-the-art hydrodynamic and water quality model recommended by USEPA (Camacho et al., 2014; Yi et al., 2016), to demonstrate the modelling performance of the new model. We applied EFDC in the case of Baiyangdian Lake. The results showed that the annual total assimilative capacities of N and P in Baiyangdian Lake were 1402 and 141 t, which were approximately 9% lower than the results from the new model. One of the main reasons for the difference is that the new model only considered the average nutrient concentration in a lake while EFDC considered the spatial difference of lake water quality. Obviously, when the average pollutant concentration reaches

the standard, water quality in heavily polluted zones of the lake would be beyond the standard. Thus, the assimilative capacity from complex water quality modelling software is commonly lower than that from mass balance models. Although there is a little difference (9%) between the results from the new model and EFDC, it is acceptable in most occasions. It also can be found that the results from EFDC were approximately 60% lower than that from previous mass balance model, which demonstrated that the improvement of the new model was significant. Besides this, the results from EFDC also showed that the nutrient assimilative capacity during the plant-growing season accounted for over 90% of the annual total capacity, which was consistent with the results of this study. It demonstrated that plant growth played a crucial role in removing nutrients in plant-dominated lakes. Although complex water quality modelling software normally has high simulation accuracy, its set-up processes are complicated, including grid generation, parameter determination and data inputs (Chapra 2008; Sikorska et al., 2015). General data required include hydrological data, meteorological data, thermal data, water quality data, boundary and bottom topography, vegetation and sediment conditions, and so on. Parameter uncertainty and data deficiency are difficulties in the application of complex water quality modelling software (Abbaspour et al., 2015; Song et al., 2015). For the ease of future model selection, data inputs and strengths/limitations of different kinds of models are compared in Table 2. Researchers can choose an appropriate model based on the data availability and accuracy demand in reality.

#The approximate position of Table 2#

The new model effectively improves the simulation accuracy, but it depends on more data inputs than previous mass balance models. The data on nutrient removal capacity of plants and biological denitrification can be obtained through experiments

or consulting existing research. Many studies on researching the effects of hydrological condition on plant growth and biological denitrification have been proposed in recent years (e.g., Berglund and Berglund, 2011; Lawniczak et al., 2010; Song et al., 2010; Yang et al., 2012; Zhao et al., 2012), which offered useful references for data acquisition of the model. Besides, the model considered dynamic hydrological changes in lakes, including the variations of water level and lake surface area. Thus, it is important to find the relationship between lake water volume, water level and water surface area. These three hydrological parameters are common and can be easily obtained through hydrological monitoring.

5. Conclusion

A new model was developed in this study to assess nutrient assimilative capacity of plant-dominated lakes, which considered the ecological effects of hydrological changes in addition to the dilution effect. The hydrological changes affected plant uptake and biological denitrification, which are important biological processes affecting nutrient assimilative capacity. We divided Baiyangdian Lake into three hydrological zones and determined the nutrient removal abilities of reed uptake and biological denitrification in each zone. The experiment results showed that reed uptake and denitrification in the ecotone zone removed more nutrients from the water body than in the aquatic zones. The submerged area variations and plant area variations caused by hydrological changes are considered in the assessment model.

The model was applied to assess nitrogen and phosphorus assimilative capacities in Baiyangdian Lake throughout one year. Monthly variations of assimilative capacities were obvious. Nutrient assimilative capacities were higher in the early part of the plant growing season than in the later part due to decreased submerged plant area. The previous approach did not consider the decrease of the submerged plant area caused

by hydrological changes, so the nutrient assimilative capacities of the lake were overestimated in the middle and late parts of the growing season. The annual nitrogen (phosphorus) assimilative capacity determined by the new approach is 41% (45%) of the capacity without considering ecological effects, demonstrating the importance of considering the ecological effects of hydrological change. This study offers a useful tool for assessing nutrient assimilative capacity, which is important for directing water resources protection and management in worldwide plant-dominated lakes.

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Figure captions:

Fig. 1. The framework of the model to assessing nutrient assimilative capacity in plant-dominated lakes (PU = plant uptake; BD = biological denitrification; AZP = aquatic zone with plants; AZNP = aquatic zone without plants; EZP = ecotone zone with plants; and EZNP = ecotone zone without plants.)

Fig. 2. Monthly nitrogen and phosphorus assimilative capacities of Baiyangdian Lake

Fig. 3. Comparison of nutrient assimilative capacities in Baiyangdian Lake from the new model and the previous approach

Figure 1

Figure 2

Figure 3

Table 1. Nutrient storage in aboveground and belowground reed tissues in different hydrological zones of Baiyangdian Lake

Month	Ecotone zone (g m ⁻²)				Aquatic zone (g m ⁻²)			
	Aboveground		Belowground		Aboveground		Belowground	
	TN	TP	TN	TP	TN	TP	TN	TP
May	4.2	0.5	1.2	0.2	3.6	0.4	1.1	0.1
June	21.5	2.3	3.4	0.8	23.1	2.4	3.4	0.6
July	42.7	4.2	17.9	2.8	34.4	3.4	9.2	1.4
August	58.3	6.1	18.8	3.2	54.3	5.3	13.6	2.2
September	66.7	6.7	23.4	3.7	58.5	6.2	15.7	2.3

Table 2. Comparison of data inputs and strengths/limitations of different models

Model type	Data inputs	Strengths	Limitations
Mass balance model	Hydrological data; Vegetation & sediments; Microorganism;	Simple set-up process; Weak data dependency; Strong universality	Normal accuracy
Statistical model	Long-term data on nutrient inputs & water quality	Simple set-up process	Strong data dependency; Weak universality
Complex water quality modelling software	Hydrological data; Meteorological data; Thermal data; Water quality data; Boundary & topography; Vegetation & sediments; Microorganism;	High accuracy; Strong universality	Complex set-up process; Strong data dependency; Parameter uncertainty; Long running time