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# 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.



## 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

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through statistical methods (Alameddine et al., 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′–39°02′ N and 115°45′–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 $km^2$. 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 $km^2$ to 308 $km^2$ 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.

#### 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:

$$W_i = W_{i-1} + W_{i,\mathrm{in}} + W_{i,\mathrm{r}} - W_{i,\mathrm{o}} - W_{i,\mathrm{e}} - W_{i,\mathrm{d}} \tag{1}$$

$$W_{i,\mathrm{e}} = W_{i,\mathrm{ev}} + W_{i,\mathrm{tr}} \tag{2}$$

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