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Research article

Hydrological management for improving nutrient assimilative capacity in plant-dominated wetlands: A modelling approach

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ABSTRACT

Wetland eutrophication is a global environmental problem. Besides reducing pollutant emissions, improving nutrient assimilative capacity in wetlands is also significant for preventing eutrophication. Hydrological management can improve nutrient assimilative capacity in wetlands through physical effects on the dilution capacity of water body and ecological effects on wetland nutrient cycles. The ecological effects are significant while were rarely considered in previous research. This study focused on the ecological effects of hydrological management on two crucial nutrient removal processes, plant uptake and biological denitrification, in plant-dominated wetlands. A dual-objective optimization model for hydrological management was developed to improve wetland nitrogen and phosphorus assimilative capacities, using upstream reservoir release as water regulating measure. The model considered the interactions between ecological processes and hydrological cycles in wetlands, and their joint effects on nutrient assimilative capacity. Baiyangdian Wetland, the largest freshwater wetland in northern China, was chosen as a case study. The results found that the annual total assimilative capacity of nitrogen (phosphorus) was 4754 (493) t under the optimal scheme for upstream reservoir operation. The capacity of nutrient removal during the summer season accounted for over 80% of the annual total removal capacity. It was interesting to find that the relationship between water inflow and nutrient assimilative capacity in a plant-dominated wetland satisfied a dose-response relationship commonly describing the response of an organism to an external stressor in the medical field. It illustrates that a plant-dominated wetland shows similar characteristics to an organism. This study offers a useful tool and some fresh implications for future management of wetland eutrophication prevention.

1. Introduction

Nutrient assimilative capacity is defined as the maximum allowable nutrient load that can be received by a water body without significant damage to water consumers and ecosystem health (Landis, 2008). It is commonly used for directing pollutant emission control in the Total Maximum Daily Load (TMDL) program (Faulkner, 2008; Hall et al., 2014). With the rapid increase of water consumption, nutrient assimilative capacity in many wetlands has been damaged (Haddeland et al., 2014; Rost et al., 2008), while external nutrient discharge has greatly increased and brought intense pressure on water environments (Shantz and Burkepile, 2014; Zhang et al., 2015). Improving nutrient assimilative capacity is significant and necessary for protecting water resources and aquatic ecosystems in worldwide wetlands.

Hydrological management can improve nutrient assimilative capacity in wetlands (Mangangka et al., 2015; Sha et al., 2013). Water release from upstream reservoirs is a common measure for wetland hydrological management. Many studies on reservoir operation have focused on water release for improving downstream water quality (e.g., Belayneh and Bhallamudi, 2012; Kunz et al., 2013; Yoon et al., 2014). Several models for simulating downstream water quality were linked to reservoir operation optimization models (Dhar and Datta, 2008; Soltani et al., 2010). Water quality protection is now an important target in water quantity allocation (Castelletti et al., 2013; Ferreira and

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Teegavarapu, 2012). New multi-objective optimization approaches were developed as a result of multiple reservoir operation targets (Adeyemo, 2011; Kurek and Ostfeld, 2013; Reddy and Kumar, 2007). Some creative operating approaches and rules were proposed for decision makers to resolve the interest conflicts of multiple stakeholders (Kerachian and Karamouz, 2006; Teegavarapu et al., 2013). These studies provided useful tools for directing reservoir operation and planning for downstream water quality protection.

Upstream reservoir release can improve the nutrient assimilative capacity in downstream wetlands by improving the nutrient dilution capacity of water bodies, while it also affects nutrient assimilative capacity through ecological effects on wetland nutrient removal processes, which rarely has been considered. This study focuses on the ecological effects of hydrological regulation in a plant-dominated wetland, which is a common and important wetland type with high species richness and service value (Jones and Waldron, 2003). Plant uptake and biological denitrification are two crucial nutrient removal processes in plant-dominated wetlands (Havens and Schelske, 2001; Marion and Paillisson, 2003). They play important roles in determining nutrient assimilative capacity of these wetlands, due to their prominent contributions to nutrient removal (Borges et al., 2016; Gottschall et al., 2007).

Hydrological condition is an important wetland characteristic affecting plant uptake and biological denitrification. Most plants only grow in specific, suitable water-depth conditions (Bucak et al., 2012; Pagter et al., 2005), so hydrological conditions largely determine plant area in a wetland. Within suitable growing zones, the biomass and nutrient accumulative capacity of plants differ significantly in seasonally flooded and continuously flooded conditions (Ahn and Dee, 2011; Sollie and Verhoeven, 2008). Besides plant uptake, biological denitrification is also affected by hydrological regulation through the effects on nitrogen availability, soil moisture, and redox 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 works demonstrated the effects of hydrological differences on plant uptake and biological denitrification, but existing reservoir operation research rarely has considered ecological effects of water release on the two processes. Without considering these, upstream water release may damage plant uptake and biological denitrification, resulting in negative effects on nutrient assimilative capacity in downstream wetlands. A reservoir operation approach simultaneously considering the dilution effects and ecological effects of water release is needed urgently for rational use of upstream water resources and protection of downstream water quality.

In this study, a reservoir operation optimization model is proposed for maximizing nutrient assimilative capacity in the downstream plant-dominated wetland under limited water resource availability. This model simultaneously considers the improvement of dilution capacity caused by increased water and the ecological effects of hydrological changes on nutrient cycles in wetlands. We divided the entire wetland area into several hydrological zones and determined the differences of plant uptake and biological denitrification in various zones though experiments. Nitrogen (N) and phosphorus (P), two significant nutrient pollutants in global freshwater wetlands (Bernhardt, 2013; Conley et al., 2009), are both considered in the model. We applied a genetic algorithm to solve the model and suggest an optimal operation scheme for upstream reservoirs. Last, based on the optimization model, we attempt to find the relationship between upstream water release and nutrient assimilative capacity in the downstream plant-dominated wetland, and offer some implications for future water resources management and protection.

2. Material and methods

2.1. Study area

Baiyangdian Wetland (Fig. 1) is a famous and typical plant-dominated wetland located in Hebei Province, China. The maximum water surface area is 308 km^2 when the wetland's water level reaches 8.8 m, and the minimum area is 46 km^2 when the water level decreases to 6 m. The common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) is the dominant plant species and covers approximately 80 km^2. The reed growing season is from April to September. Harvested reeds remove large amounts of nutrients from the wetland and bring significant economic benefits to the local residents. However, in recent years, the services and functions provided by Baiyangdian Wetland have been damaged due to water quality deterioration resulting from excessive N and P input. Water consumption by upstream reservoirs decreases inflows to the wetland and reduces wetland nutrient assimilative capacity. Now, water release to increase nutrient assimilative capacity in Baiyangdian Wetland has become an important target for upstream reservoir operation.

2.2. Optimization model development and application

A dual-objective reservoir operation optimization model aimed at improving both N and P assimilative capacities in wetlands is developed and applied in Baiyangdian Wetland as a case study. The model framework is shown in Fig. 2.

2.2.1. Wetland water balance

Water volume is an important factor affecting nutrient assimilative capacity in wetlands. Monthly variations of wetland water volume can be obtained based on water balance. In general, wetland water replenishment depends on local precipitation and inflows from upstream regions, and water losses occur through outflows, deep drainage, and evapotranspiration (Ranieri, 2003). Evapotranspiration calculation for plant-dominated wetlands is a complex process. In the plant growing season, both water surface evaporation and plant community transpiration need to be considered. Plant area is affected by hydrological conditions, so plant area variations caused by hydrological changes are considered in calculating wetland evapotranspiration. The evapotranspiration capacity of zones with reeds or without reeds in Baiyangdian Wetland is determined based on the research by Xu et al. (2014). The wetland now has little outflow, which can be ignored. The rate of deep drainage water loss is 3 mm per day and average annual precipitation in the wetland area is 461.9 mm (Xu et al., 2014). Inflows from upstream regions are controlled by upstream reservoirs, which will be optimized in this study. The equation to calculate monthly wetland water volume is:

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

where W_i is the wetland water volume in month i (1–12) ($\times 10^8$ m^3); $W_{in,i}$ is the water replenishment through inflows ($\times 10^8$ m^3); $W_{r,i}$ is the water replenishment through rainfall ($\times 10^8$ m^3); $W_{o,i}$ is the water loss through outflows ($\times 10^8$ m^3); $W_{e,i}$ is the water loss through evapotranspiration ($\times 10^8$ m^3); and $W_{d,i}$ is the water loss through deep drainage ($\times 10^8$ m^3).

2.2.2. Nutrient mass balances

Natural wetlands have strong capacity to remove nutrients from wetland water. Generally, both nitrogen and phosphorus can be removed from water bodies through outflows, plant uptake, and exchange with sediments, while nitrogen can also be removed