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Modeling nutrients, oxygen and critical phosphorus loading in a shallow reservoir in China with a coupled water quality – Macrophytes model

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ABSTRACT

Many macrophyte-dominated clear lakes switch to a phytoplankton-dominated turbid state when the lake becomes eutrophic. An existing Yuqiao Reservoir Water Quality Model (YRWQM) and the macrophyte submodel were coupled to simulate the effect of submerged macrophytes on nutrients and dissolve oxygen cycles in a shallow reservoir in China. The level of phosphorus loading in a transition from a clear to turbid state was addressed using the integrated model. The model runs from seedling establishment until dying out, from March 1 to July 18 in 2009. The simulations were performed for a contingent range of P loadings, starting from three different initial conditions. The results indicated that the integrated model improves accuracy of predictions compared to YRWQM. The concentrations of nutrients declined slightly during the macrophyte growth period in the reservoir and dissolved oxygen increased slightly. Although nutrient concentrations increased by submerged macrophyte release during the extinction period, the effect on the nutrients was less than that of transfer with nutrient-rich water. More released nutrients may enhance increases in substantial abundance. The critical phosphorus loading level during a switch from the clear to turbid state was estimated by these scenarios. The threshold for the switch is ~6.1 $mgP\,m^{-2}\,d^{-1}$ with an initial total phosphorus concentration of 160 $\mu g\,l^{-1}$. Moreover, the results demonstrated that the switch was also dependent on the initial total phosphorus concentration. These results suggest that the reservoir in a clear water state is at risk of a switch as nutrient levels are close to the critical levels.

1. Introduction

Shallow lakes may have two alternative stable states, a 'clear' state with submerged macrophytes (SM) or a 'turbid' state dominated by phytoplankton (Scheffer et al., 1993a; Janse et al., 2008, 2010). SM are considered an important aspect for lake restoration (e.g., Li et al., 2007; Kosten et al., 2009; Moreno, 2011; Spoljar et al., 2012). SM communities contribute to the removal of phosphorus in the SM-dominated lake, wetland, and river systems (e.g., Knight et al., 2003; Dierberg et al., 2005). Recent studies in microcosm ^{15}N enrichment experiments have demonstrated that nitrate removal is dominated by submerged macrophyte uptake rather than denitrification (Veraart et al., 2011).

Over the past 30 years, numerous process-based models have been developed and applied to study water quality and eutrophication, such as CE-QUAL-W2 (Cole and Buchak, 1995; Berger and Wells, 2008), CE-QUAL-ICM (Cerco and Cole, 1993, 1994), EFDC (Hamrick, 1992), WASP (Wool et al., 2002). For shallow lakes, several three-dimensional hydro-environmental models have been developed to simulate hydrodynamics and nutrient cycling as well as algae dynamics (Jin et al., 2007; Li et al., 2011; Zhang et al., 2013; Chen et al., 2013, 2014). These models also show performance in short-term forecasting of water quality and phytoplankton. However, few models combine nutrient cycles, phytoplankton and macrophytes in a dynamic way (Janse et al., 2010).

Computer technology has helped create complex ecosystem models with a macrophyte component, such as Megaplant (Scheffer et al., 1993b), SAGA (Hootsmans, 1994, 1999), PCLake (Janse, 1997; Janse et al., 2008, 2010), SAVM (Cerco and Moore, 2001; Cerco et al., 2002; Jin et al., 2007), M-SAVM (Zhang et al., 2015), and Charisma (Van Nes et al., 2002, 2003). The macrophyte models are capable of simulating SM biomass or coverage and its interactions with water quality. Additionally, they simulate the critical phosphorus loading of different types of shallow lakes and the consequences for

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management, e.g., PCLake. The switch points during a transition from clear to turbid and vice versa were calculated by the model. Affecting nutrients and dissolved oxygen cycles as well as estimating the critical phosphorus loading for shallow lakes with the ecosystem model are of interest.

The objectives of this paper are to complement the Yuqiao Reservoir Water Quality Model (YRWQM) (Zhang et al., 2013) with the macrophyte submodel M-SAVM and then to apply the integrated model for estimating nutrients and dissolved oxygen cycles and the critical phosphorus loading in the Yuqiao Reservoir. The specific goals are: (1) to combine the YRWQM and submodel M-SAVM; (2) to utilize the model to analyze the effect of SM on nutrients and dissolved oxygen cycles; and (3) to estimate the critical phosphorus loading level when a change occurs from a clear to turbid state. This study provides information for the management of P loading in the shallow reservoir.

2. Material and methods

2.1. Study area

The Yuqiao Reservoir (Fig. 1) is located in northeast Tianjin, China, and has been the only water supply source in Tianjin since 1983. This shallow reservoir (Z_{max} 12.16 m, Z_{mean} 4.74 m) has a watershed area of 2060 km^2, a storage capacity of 385 million m^3 and a surface area of 86.8 km^2. The reservoir is located in temperate monsoon climate.

The Lin, Sha and Li Rivers are the contributing tributaries of the reservoir and the Zhou culvert is the outflow of the reservoir to Tianjin. The annual average volume of the water resource is 190 million m^3, with an evaporation amount of 60 million m^3 in the watershed (Zhang et al., 2013). As a water supply reservoir, the water resource experienced a diversion of 530 million m^3 of water from the Luan watershed to the Yuqiao watershed through the Li River during two periods in 2009, April 26–June 18, October 10–December 10. A previous study suggested that the reservoir was a phosphorus-limited environment with high N:P ratios ranging from 52.61 to 78.75 (Chen et al., 2012). Macrophyte communities in the whole lake were mostly composed of six emergent, 13 submerged, and two floating macrophytes species, in which *Potamogeton crispus* Linn. dominated with ~35.0–61.5% coverage of area (Zhang et al., 2015). The reservoir is in a 'clear' state with SM.

2.2. Data description

Hydrodynamic, water quality and meteorological data observed at monitoring stations and during sampling surveys has been previously described (Chen et al., 2012; Zhang et al., 2013; Zhang et al., 2015). In 2009, monthly to semimonthly, 22 water quality parameters and *P. crispus* biomass from 7 permanent monitoring stations were collected. *P. crispus* biomass was estimated by first determining the average biomass per individual stem at each sampled location and then multiplying this value by the number of stems per square meter. Individual stem biomass was obtained by the subsampling method (Silva et al., 2010). For each station,

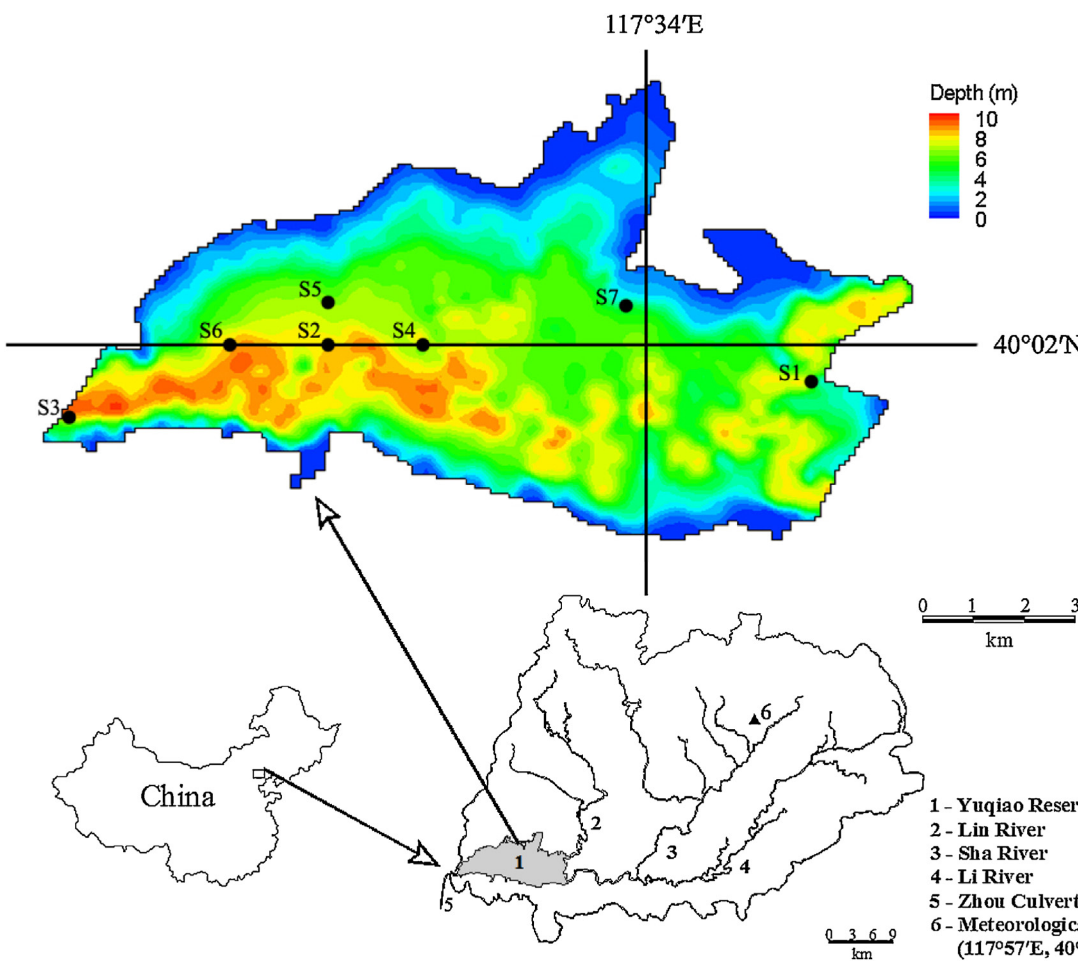

Fig. 1. Yuqiao Reservoir (117°34′ E, 40°02′ N) watershed and the monitoring stations (S1–S7).