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Effects of internal loading on phosphorus distribution in the Taihu Lake driven by wind waves and lake currents

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A B S T R A C T

Wind-driven sediment resuspension exerts significant effects on the P behavior in shallow lake ecosystems. In this study, a comprehensive dynamic phosphorus (P) model that integrates hydrodynamic, wind wave and sediment transport is proposed to assess the importance of internal P cycling due to sediment resuspension on water column P levels. The primary contribution of the model is detailed modeling and rigorous coupling of sediment and P dynamics. The proposed model is applied to predict the P behavior in the shallow Taihu Lake, which is the third largest lake in China, and quantitatively estimate the effects of wind waves and lake currents on P release and distribution. Both the prevailing southeast winds in summer and northwest winds in winter are applied for the simulation, and different wind speeds of 5 m/s and 10 m/s are also considered. Results show that sediment resuspension and the resulting P release have a dominant effect on P levels in Taihu Lake, and likely similar shallow lakes. Wind-driven waves at higher wind speeds significantly enhance sediment resuspension and suspended sediment concentration (SSC). Total P concentration in the water column is also increased but not in proportion to the SSC. The different lake circulations resulting from the different prevailing wind directions also affect the distribution of suspended sediment and P around the lake ultimately influencing where eutrophication is likely to occur. The proposed model demonstrates that internal cycling in the lake is a dominant factor in the lake P and must be considered when trying to manage water quality in this and similar lakes. The model is used to demonstrate the potential effectiveness of remediation of an area where historical releases have led to P accumulation on overall lake quality.
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1. Introduction

Excessive nutrient has led to the appearance of eutrophication and massive harmful algal blooms (Elser et al., 2007; Xu et al., 2010). Phosphorus (P) is the key nutrient for phytoplankton growth and production (Schindler, 2006), and the biogeochemical characteristics of P play a significant role in eutrophication processes (Wang et al., 2003a). At present, lake restoration is mainly focused on reducing the external loading of nutrients, e.g. P (Jeppesen et al., 1998; Wang et al., 2015). However, internal cycling of historical P accumulation due to sediment resuspension may limit the effectiveness of source control (Søndergaard et al., 2003; Zhang et al., 2008). Thus, the influence of sediment resuspension and P release must be considered in the design of potential lake remediation strategies (Istvánovics and Somlyódy, 2001; Jeppesen et al., 2007; Marsden, 1989; Søndergaard et al., 2007).

Sediment P release is affected by various factors such as light, temperature, pH value, oxygen concentration, biological activity, and *Microcystis* blooms etc. (Jiang et al., 2008; Jin et al., 2006b; Xie et al., 2003), while sediment resuspension is the most important factor affecting sediment P release in shallow lakes (Cyr et al., 2009; Fan et al., 2004; Istvánovics et al., 2004; Sun et al., 2006). 70% of freshwater lakes in China are shallow lakes (Qin et al., 2006a), e.g. Taihu Lake. Wind waves exert apparent disturbances at the sediment-water interface due to the shallow water depth, leading to a large amount of sediment resuspension (Lu et al., 2015; Zheng et al., 2015). Meanwhile, P is released into the overlying water in both dissolved and particulate phases, and the release rate is directly related to the intensity of the sediment disturbance (Wang et al., 2009, 2015). Søndergaard et al. (1992) investigated the impact

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of resuspension on internal P loading in Lake Arresø, and found that the release of soluble reactive P (SRP) might be enhanced by 20–30 times due to sediment resuspension. Fan et al. (2001) have recently shown that the internal P loading induced by resuspension was 8–10 times greater than the release from undisturbed sediment. Søndergaard et al. (2007) concluded that the enhanced wind speeds in Vest Stadil Fjord resulted in a factor 5–10 increase in total P concentration within a two-day period. Thus, the disturbance induced by wind waves can significantly enhance the internal P loading, subsequently affecting the P behavior in lake ecosystems.

Efforts to model P release and distribution within a lake has typically involved only crude models of sediment release (Ahlgren et al., 1988; Mao et al., 2008). A two-box lake P model was proposed by Imboden (1985) to estimate the response to different restoration strategies in Lake Baldegg, where a constant P exchange rate was assumed at the sediment-water interface, i.e. without considering the sediment dynamics. Jørgensen et al. (1986) estimated the generality of a dynamic P model using 16 case studies with a relatively detailed description of sediment-water P exchange, and found that modifications should be considered due to the specific characteristics of individual lakes, especially the sediment resuspension in the shallow lakes. Wang et al. (2003a, b) developed a sediment P model to predict P release fluxes across the sediment-water interface in Chesapeake Bay considering dissolved, exchangeable and organic particulate P, while lacking a consideration of P release caused by sediment resuspension and the subsequent transport in water column. Hu et al. (2011) established an empirical relation between the sediment resuspension rate and flow velocity using a flume experiment, based on which a water quality model coupling lake current and sediment pollution of Taihu Lake was developed, i.e. a simplification of the realistic sediment resuspension and P release processes. The status of these models indicates a significant weakness of the current sediment transport models in P dynamics prediction. The accurate representation of the role of sediments is the prerequisite for an improved prediction of P behavior (Wang et al., 2003b). Thus, more sophisticated sediment transport model should be incorporated to assess the importance of internal P cycling on water column P levels. A particularly difficult component of this problem is the relation between wind-induced wave action and sediment resuspension and this process is likely dominant in shallow lake systems.

The sediment resuspension and P release models should also be coupled to lake circulation dynamics to define the relationship between source sediment and water quality in receiving area. Sediment resuspension under wind waves causes the P release from the bottom sediment, and then the released P is transported by the wind-driven lake currents. The currents result in uneven spatial and temporal distribution of P concentration in the shallow lakes, which is important to defining the resulting lake water quality (Qin et al., 2004).

The goal of this paper is to develop a modeling tool with a more rigorous coupling to surficial sediment as well as dynamics of P sorption and release, and use the model to explore the importance of wind-driven sediment transport in shallow lakes. In this model, the aerobic and anaerobic layers are distinguished to study the chemical reactions related to redox conditions and the corresponding P distribution in the active sediment layer. The bed deformation is included to characterize the P resuspension and deposition at the bed surface. A surface complexation model is applied to analyze the P adsorption by suspended sediment particles. A wave sub-model is incorporated to consider the enhancement of sediment resuspension and P release due to the shallow water depth. These models are then coupled to a lake circulation model to predict subsequent sediment and P redistribution. The proposed model is applied to predict P release and transport in the shallow Taihu Lake, which is the third largest lake in China. The resulting model is expected to be a useful tool to evaluate mitigation strategies, both in-lake remediation and external source control, for Taihu Lake as well as similar shallow lake systems.

2. Materials and methods

2.1. Description of study area

Taihu Lake, a shallow freshwater lake, situated in 30°25′40″-31°32′58″ N, 119°52′32″-120°36′10″ E, with a total surface area of 2338 km^2 and an average depth of 1.89 m (Gao et al., 2006). The whole lake is divided into Zhushan Bay, Meiliang Bay, Gonghu Bay, west/south/east littoral zone, central area and east Taihu Lake (see Fig. 1). With a maximum depth of only 3 m, turbid Taihu Lake is prone to eutrophication (Stone, 2011), especially the west and north regions such as the Zhushan Bay, Meiliang Bay and Gonghu Bay. In May 2007, a severe cyanobacterial bloom occurred in Taihu Lake, leaving more than 2 million people without drinking water for a week (Guo, 2007). In 2014, the sub-lakes including Zhushan Bay, Meiliang Bay, Gonghu Bay, west/south littoral zone, and central area are moderate eutrophic, i.e. accounting for 80.9% of the whole lake area, with the mean concentration of chlorophyll *a* of 64.90, 33.35, 25.60, 48.65, 22.20 and 32.76 mg/m^3 respectively. The rest regions are mild eutrophic, i.e. 11.24 and 10.16 mg/m^3 chlorophyll *a* for east Taihu Lake and east littoral zone respectively (Taihu Basin Authority of MWR, 2014).

According to the observations of wind conditions in Taihu Laboratory for Lake Ecosystem Research (TLLER), Taihu Lake is experiencing the monsoon climate with prevailing southeast winds in summer and northwest winds in winter (Qin et al., 2006b). From 1997 to 1999, daily maximum wind speeds (calculated as hourly average wind speed) higher than 5 m/s occurred 89.5% of the time, and wind speeds higher than 8 m/s occurred 34.2% of the time (Fan et al., 2004). In Taihu Lake, the average wet density of sediment is 1300 kg/m^3 (the porosity ε is derived as 0.82) with the median particle size D_{50} of 0.017 mm, and the mean thickness of sediment is 0.65 m in the whole lake area (Qin, 2008). The distribution of total P concentration in the bottom sediment refers to Fan et al. (2009), with an average concentration of 0.637 mg/g, i.e. 0.304 kg/m^3 (see Fig. S1). Generally, high values of total P concentration are observed in the northwest regions of Taihu Lake, where the lake is linked with polluted inflowing rivers and adjacent to urban districts, e.g. Zhushan Bay, Meiliang Bay and the west littoral zone (Yuan et al., 2011; Zhu et al., 2013).

2.2. Mathematical model

Delft3D accounts for the effects of waves on mean flow by: (1) including radiation stress gradients in the flow momentum equations; (2) enhancing the bed shear.

2.2.1. Wave model

The waves are described with the 2-D wave action density spectrum $N(\sigma, \theta)$ through the wave action balance equation (Booij et al., 1999), i.e.

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}c_x N + \frac{\partial}{\partial y}c_y N + \frac{\partial}{\partial \sigma}c_\sigma N + \frac{\partial}{\partial \theta}c_\theta N = \frac{S}{\sigma} \tag{1}$$

where c_x and c_y are the propagation velocities in the x- and y-directions, σ is the relative frequency, θ is the wave direction. The term S at the right-hand side of Eq. (1) is the source term representing the effects of generation by wind, dissipation (white-capping, bottom friction, depth-induced breaking) and nonlinear

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