Numerical Modeling of Nutrients and Phytoplankton in a Mississippi Delta Lake by Considering the Sediment Associated Processes

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Abstract

Water quality in inland waterbodies is significantly affected by suspended sediment and bed sediment. Suspended sediment reduces solar radiation penetrate into the water column and limits the growth rate of phytoplankton. Dissolved nutrients can either be released or accumulated on suspended sediment particles due to desorption and adsorption kinetics. Nutrients adsorbed on bed sediment can also be released to the water column due to diffusion. In addition, nutrients attached on the sediment may exchange between the water column and bed layer as sediment resuspension or deposition occurs. Mathematical formulas were derived to quantitatively estimate sediment-associated nutrient fluxes and subsequently tested using field measurements and laboratory data. These formulas were included in the water quality model, CCHE-WQ, developed by the National Center for Computational Hydroscience and Engineering, University of Mississippi, to simulate phytoplankton kinetics, nutrient cycles, and dissolved oxygen balance by considering sediment associated processes. The CCHE-WQ model was applied to simulate concentrations of phytoplankton and nutrients in Beasley Lake, a shallow Mississippi Delta lake with special emphasis on sediment-related processes. The simulated results were compared with field observations collected by the United States Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory. Evaluations of model predictions with measured data showed that the correlation coefficients for temperature, suspended sediment and phosphate were 0.99, 0.78 and 0.74, respectively; while for chlorophyll and nitrate, the correlation coefficients were 0.47 and 0.38, respectively. This study shows that there are strong interactions between sediment-associated processes and water quality constituents in the Mississippi Delta lakes, which are significantly influenced by agricultural practices.

Introduction

The Mississippi Delta is one of the most intensively farmed agricultural areas of the United States. The surface water quality in this area is particularly vulnerable due to excessive sediment, nutrients, and pesticides transported from upland agricultural fields (Locke et al.

2008). Beasley Lake Watershed (BLW) located in Sunflower County, Mississippi, has a total drainage area of approximately 9.15 km^2 (Figure 1). Beasley Lake, a small oxbow lake, formed from a cutoff meander of the Sunflower River. The surface area of the lake is about 0.25 to 0.30 km^2, and the averaged water depth is around 2.1 m. Wind shear is the major driving force for flow hydrodynamics, which makes this relatively closed lake a well-mixed system. The water quality of the lake is significantly affected by the surrounding watershed. Weekly or biweekly samples of suspended sediment, nutrients, chlorophyll a, DO and other selected water quality variables were collected at Stations B1, B2 and B3 by researchers at the National Sedimentation Laboratory (NSL) (Lizotte et al. 2014, Lizotte et al. 2017). In this study, CCHE-WQ model (Chao et al. 2010) was applied to simulate the distributions of water quality constituents in Beasley Lake. The effects of sediment on the water quality constituents were considered. The simulated results were calibrated and validated using field measurements.

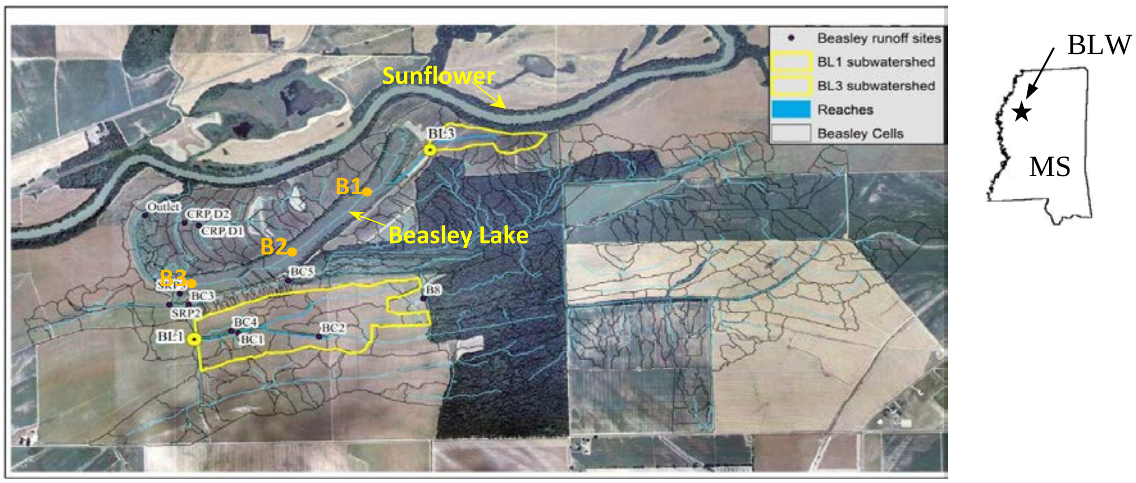

Figure 1. Beasley Lake Watershed in the Mississippi Delta

Method

CCHE-WQ simulates temporal and spatial distributions of general water quality constituents, including ammonia (NH4), nitrate (NO3), inorganic phosphorus (PO4), phytoplankton (as chlorophyll a, Chl), carbonaceous biochemical oxygen demand (CBOD), dissolved oxygen (DO), organic nitrogen (ON) and organic phosphorus (OP). The sediment-associated water quality processes are also considered in the model.

Light intensity is one of important factors affecting the growth of phytoplankton. In the waterbody, light intensity is reduced due to the effects of water, chlorophyll, and suspended sediment (SS), and the light extinction coefficient can be used to calculate the light intensity along the water depth (Stefan et al. 1983). In Mississippi Delta lakes, the light extinction coefficient is significantly affected by the SS concentration and can be estimated by Wool et al. (2001) and Chao et al. (2007):

$$K_a = K_b + 0.0088C_{chl} + 0.054C_{chl}^{0.67} + 0.0452C_s \tag{1}$$

where K_b = background light extinction coefficient; C_{chl} = chlorophyll concentration and C_s = SS concentration.

In the numerical model, the processes of adsorption-desorption between SS and nutrients are described by the Langmuir isotherm and the dissolved and particulate nutrient concentrations can be calculated using the formula proposed by Chao et al. (2010):

$$C_d = \frac{1}{2}\left[\left(C_0 - \frac{1}{K_{ad}} - C_s Q_m\right) + \sqrt{\left(C_0 + \frac{1}{K_{ad}} - C_s Q_m\right)^2 + \frac{4C_s Q_m}{K_{ad}}}\right] \quad (2)$$

$$C_p = \frac{1}{2}\left[\left(C_0 + \frac{1}{K_{ad}} + C_s Q_m\right) - \sqrt{\left(C_0 + \frac{1}{K_{ad}} - C_s Q_m\right)^2 + \frac{4C_s Q_m}{K_{ad}}}\right] \quad (3)$$

where C_d = dissolved nutrient concentration; C_p= particulate nutrient concentrations; C_0 = initial nutrient concentration; K_{ad} = equilibrium partition coefficient; Q_m = maximum adsorption capacity.

The release rate of nutrients from bed sediment is determined by the gradient of dissolved nutrient concentrations across the water-sediment interface, water temperature, dissolved oxygen (DO) concentration, and pH value at the bed sediment layer (Romero 2003). The bed release rate is calculated by:

$$S_{bed} = k_d (C_b - C_d)\theta_b^{T-20}\left(\frac{K_{do}}{K_{do} + C_{do}} + \frac{|pH - 7|}{K_{ph} + |pH - 7|}\right) \quad (4)$$

where S_{bed} = bed release rate of nutrients; k_d = diffusive exchange coefficient at the water-sediment interface; C_b = dissolved concentration of nutrient in bed sediment layer; θ_b = temperature coefficient; C_{do} = DO concentration at the bed sediment layer; K_{do} = release parameter due to the DO concentration; K_{ph} = release parameter due to pH.

Model Application

The parameters in the CCHE-WQ model for simulating Mississippi Delta lakes have been calibrated using the measured data collected by NSL (Chao et al. 2007, Chao et al. 2018). In this study, CCHE-WQ was applied to simulate the time series of water temperature, SS concentration and water quality constituents in Beasley Lake for a three-year period from 1/1/02 to 12/16/04. The inflow boundary conditions of flow discharge and concentrations of sediment and nutrients from upland watershed were obtained from the AnnAGNPS model (Bingner et al. 2018). The field measured data, including temperature, SS, nutrients and chlorophyll (Chl) in the lake, was used for model validation (Figure 2).

Comparisons of simulated to measured results showed high correlation coefficients for temperature, concentration of SS, and PO4. For chlorophyll, the mean value of the model results was generally in agreement with the measured data, and the simulated mean error was about 20%. However, the model was not able to reproduce temporal trends as accurately as the mean value, and the correlation coefficient was about 0.47. It is known the phytoplankton kinetics are affected by nutrients, SS, temperature, light, and algal species. They are highly complex and need further studies to improve our understanding and model simulation.

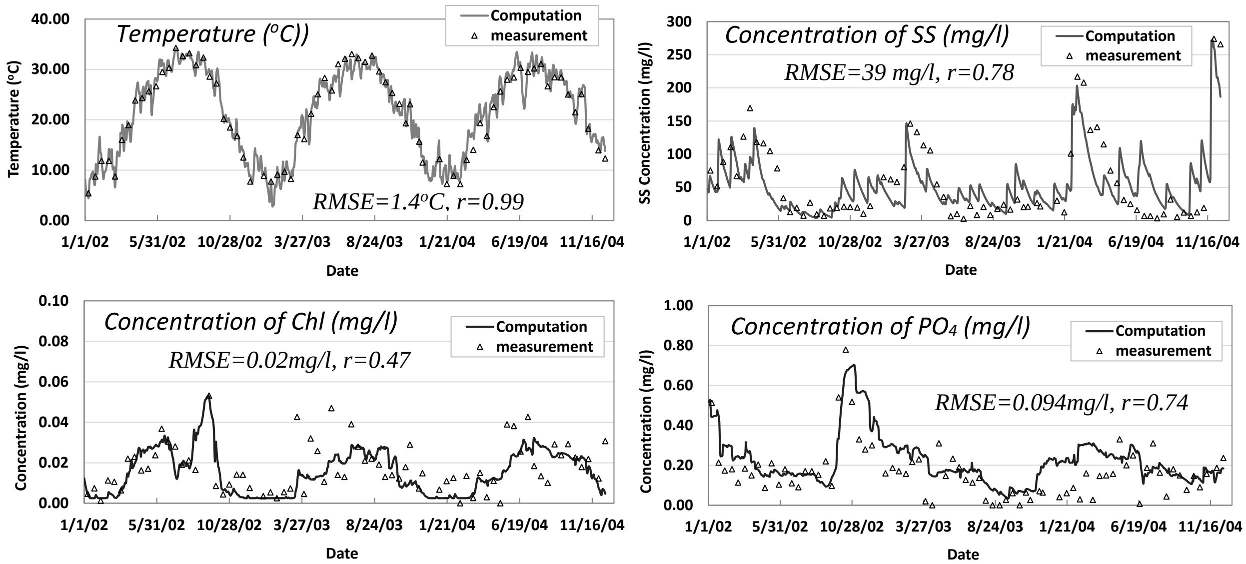

Figure 2. Comparison between model results and field measurements

Conclusions

CCHE-WQ was applied to simulate the temperature, SS, and water quality constituents in Beasley Lake, and the model results were generally in agreement with field measured data. The concentration of chlorophyll in the lake is significantly affected by SS and nutrients: SS limits the growth of phytoplankton, while the nutrients could stimulate its growth. The processes of adsorption and desorption between sediment and nutrients greatly affect the concentration of PO4. In general, the higher SS may limit the concentration of PO4. In addition, the PO4 concentration is also affected by chemical/biochemical processes in the lake. Simulation results show that the bed release processes also affect the nutrient concentrations in the water column. This study demonstrated the capability of CCHE-WQ model for simulating the water quality constituents in receiving waterbodies by considering the sediment-associated processes.

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