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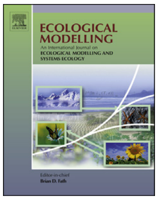

Research Paper

Development of a two-dimensional eutrophication model in an urban lake (China) and the application of uncertainty analysis

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ABSTRACT

Urban lakes in China, particularly those with relatively small surface areas and closed watersheds, have suffered from severe eutrophication over the past few years. To investigate the causes and to examine the underlying mechanisms, a two-dimensional uncertainty eutrophication model was developed. The model reflected the interactions between nutrients, phytoplankton and zooplankton. Moreover, it can be utilized to describe seasonal and regional water quality changes. The two-dimensional hydraulic model was set up using Navier-Stokes equations and was calculated by applying the finite volume method. The Bayesian method was employed to calibrate the model parameters and obtain the parameter posterior distribution. The two-dimensional hydraulic information and the parameter posterior distribution were utilized to calculate a two-dimensional uncertainty eutrophication model, for which the 95% confidence interval (uncertainty bounds which can provide the trend and range for water quality changes) and mean value of every water quality index (nitrate, ammonia, phosphate, Chl. a and dissolved oxygen) were simulated. Comparisons between the model simulations and the field data indicated that the models were able to calculate the hydrodynamic information and the eutrophication dynamics with reasonable accuracy (all the relative errors lower than 11%). The simulated concentrations of water quality indexes (nitrate, ammonia, phosphate and Chl. a) in the vicinity of the lake were higher than that in the middle of the lake during the simulation period, indicating that the nutrient load of the rainwater runoff had significant impacts on algal blooms and water quality. Therefore, the urban lake was vulnerable to the influence of rainwater runoff. To reduce the eutrophication risk, rainwater runoff needs to be controlled. Two-dimensional uncertainty eutrophication models, such as those used in this study, can provide a powerful management tool that will continue to improve prediction reliability.

1. Introduction

Eutrophication has been a primary problem in worldwide surface waters (Martins et al., 2008; Smith and Schindler, 2009; Wu and Xu, 2011). Due to the complex nonlinear cause-and-effect relationship between nutrient sources and water quality responses, eutrophication control and water quality restoration for impaired waters pose a challenging problem for environmental management (Diaz and Rosenberg, 2008). Because urban lakes are typically shallow and exhibit low self-purification abilities, these lakes are vulnerable to changes in water quality through nutrient enrichment (Birch and McCaskie, 1999). Eutrophication risks and water quality deterioration in urban lakes have been issues of increasing significance in China. It is certain that nutrient loading control can efficiently improve water quality and decrease eutrophication risks (Liu et al., 2008; Zou et al., 2009; Yang et al., 2016a,b). To control eutrophication risks and water quality deterioration, mechanistic models are often used to reflect the quantitative response relationships between eutrophication risks and water quality for total exogenous nutrient loading decision-making (Zhao et al., 2013). Eutrophication models have been well developed in the past few decades and have successfully served as scientific tools to support decision-making for the control of nutrient loading (Purandara et al., 2012; Yang et al., 2016a,b).

The development of eutrophication models led to some models being so complicated that calibrating the parameters and simulating the model results are difficult to use a traditional calibration method. To address this problem, the Bayesian method

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was used to solve complicated eutrophication models and calculate uncertainty simulation results. The Markov chain Monte Carlo (MCMC) method, as the basic algorithm of the Bayesian method, has been extensively used, especially under conditions of limited and highly variable ecological data. It can solve two main problems in environmental modelling. First, the application of any modelling construction involves substantial uncertainty contributed by model structure, parameters, and other associated inputs (Ramin et al., 2011). Second, some models depicting average ecosystem behaviour are inadequate for water quality analysis. However, in the context of Bayesian method integration of mechanistic eutrophication models, some models are drastic simplifications of a lake, which merely approximate "a piece of water", such that these models cannot clearly or spatially reveal water quality information (Zhao et al., 2013). In other words, most the uncertainty eutrophication models apply zero-dimensional models in current studies, although some modelers have divided the lake into two segments in the vertical direction to solve uncertainty eutrophication models (Ramin et al., 2011). There are few studies describing the uncertain variability of water quality indexes in horizontal space. Therefore, a two-dimensional hydraulic calculation was integrated with the uncertainty eutrophication model in this study.

Considering the necessity of resolving the complicated eutrophication model and spatial variables, the two-dimensional uncertainty eutrophication model was established as the computational platform for developing the necessary model. The main objective of this study is to build and calibrate a two-dimensional uncertainty eutrophication model. The two-dimensional hydraulic model was setup based on Navier-Stokes equations, and hydraulic information was obtained using the finite volume method. The Bayesian method was used to calibrate the parameters in the eutrophication model. Then, the calibrated parameters were integrated with the hydraulic information to calculate the uncertainty eutrophication model. The eutrophication model in this study consisted of 12 state variables (three types of phytoplankton, two types of zooplankton, nitrate, ammonium, organic nitrogen, phosphate, organic phosphorus, dissolved oxygen, and sediment) and 43 parameters. Finally, the simulation results and the influence of nutrient loading were analysed with this model platform.

2. Modelling framework

2.1. Study area

The examined urban lake is situated in Tianjin, China, and has a surface area of 19.8 ha and an average depth of 2.5 m (Fig. 1). Currently, the lake recharge water primarily comes from rainwater runoff. There are four field observation points in this urban lake. The positions of the field observation points are shown in Fig. 1. The rainwater runoff water quality index concentrations were obtained by field measurements, which lasted for a year. The rainwater runoff was sampled at sampling sites near the urban lake. Most urban lakes in China (including the urban lake in this study) have been artificially expanded to their current scale. The urban lake always has a lower depth that is subject to change. The two-dimensional uncertainty eutrophication model is adequate to describe an urban lake eutrophication situation. From summer to early fall, nuisance algae often bloom and influence the water quality in this urban lake.

2.2. Hydraulic model

The hydraulic model was developed using the Navier-Stokes equations, which are widely used to simulate the temporal and spatial variations in hydraulic information (Li et al., 2012). Seasonal short periods and local stratifications of an urban lake, such as the lake in our study, can be neglected. The diversity of abiotic conditions in the urban lake water body can be adequately described by two-dimensional hydraulic models. Two-dimensional hydraulic models are constructed for these types of urban lakes (Menshutkin et al., 2013), making these models well known and widely used by researchers (Vol Tsinger and Pyaskovskii, 1977). In this paper, we consider the motion of an incompressible and viscous fluid in two-dimensional Euclidean space. The velocity of this type of fluid is described by the Navier-Stokes equations:

$$\begin{aligned} &\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = \frac{1}{\rho} \nabla p + v \nabla^2 \mathbf{u} + \mathbf{F} \\ &\nabla \cdot \mathbf{u} = \mathbf{0} \end{aligned} \tag{1}$$

where $\mathbf{u}$ is the velocity field; p is the pressure field; v is the kinematic viscosity; ρ is the density, which is constant in space and time; and $\mathbf{F}$ is the mass density of the body forces.

The hydrodynamic model was evaluated using water temperature data because the urban lake is relatively closed and the flow rate is relatively low compared with natural lakes. Therefore, validating the hydrodynamic model using the urban lake flow rate is difficult. To better express the conditions, the lake water temperature was used to validate the hydrodynamic model (Zhao et al., 2013). The lake water temperature of this type of fluid is described by the following equation:

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \mathbf{D}_T \cdot \nabla^2 T + S_T \tag{2}$$

where T is the lake water temperature (°C); $\mathbf{D}_T$ is the diffusion coefficient (m^2/s); and S_T is the temperature exchange between the air and lake water.

2.3. Eutrophication model

The interplay between the mass balance of multiple chemical elements and the trophic dynamics are explicitly considered (Zhang et al., 2004). We developed a eutrophication model that considers the interactions among two biological functional groups, phytoplankton (diatoms, greens, cyanobacteria) and zooplankton (copepods, cladocera), and among three nutrient cycles: nitrogen [nitrate (NO_3), ammonium (NH_4), organic nitrogen (ON)], phosphorus [phosphate (PO_4), organic phosphorus (OP)], and dissolved oxygen (DO). The conceptual diagram for the ecosystem model is shown in Fig. 2. The mass balance equation for a state variable is expressed as:

$$\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla C = \mathbf{D} \cdot \nabla^2 C + S + D \tag{3}$$

where C is the concentration of a state variable (mg/L); $\mathbf{D}$ is the diffusion coefficient (m^2/s); S is the source/sink term (nutrition loading); and D is the reaction term.

Next, we will provide a description of the eutrophication model design. The flow topology of the nitrogen and phosphorus cycles in the model are depicted in Fig. 2, and the definitions of the model parameters, along with the mathematical equations, can be found in the Electronic Supplementary Material.

2.3.1. Phytoplankton

The eutrophication sub-model simulates three phytoplankton functional groups, including diatoms, greens and cyanobacteria (see Fig. 2). We consider their different strategies for resource competition (nitrogen, phosphorus, light, and temperature), metabolic rates and settling velocities. The biochemical interaction term for phytoplankton accounts for phytoplankton