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Parameter uncertainty and sensitivity analysis of water quality model in Lake Taihu, China

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A B S T R A C T

Lake Taihu was chosen as a case for parameter uncertainty and sensitivity analysis of water quality simulation in large shallow lakes. Forty parameters in Environmental Fluid Dynamic Code model (EFDC) were filtered and analyzed. The results showed that parameters had a considerable influence on simulation and three groups of parameters related to algal kinetics (i.e. PMc, BMRc and PRRc), light (KeChl) and temperature (KTG1c) were very sensitive. For shallow lakes with frequent algal blooms, light extinction due to Chlorophyll-*a* is also a sensitive parameter. While the temperature effect coefficient for algal growth is sensitive for lakes with seasonal temperature variation. Sensitive parameters and their relevant uncertainty varied spatially. For high nutrients and algae concentration subareas, temperature was more likely to be a limiting factor, whereas sensitive factors could be light in lower concentration subareas. Since most sensitive parameters were related to algae, uncertainty in simulation increased with increasing algal kinetic processes over time and varied in different subareas. Lower nutrients and algae concentration subareas were more easily influenced by model parameters while nearshore areas were highly influenced by boundary conditions. For better simulation of water quality, variable stoichiometry phytoplankton models should be considered and zooplankton need to be integrated into the model explicitly rather than a fixed predation rate.

1. Introduction

Water quality models (WQMs), valuable tools of supporting water quality predictions, have been widely applied in environmental management in recent years (Arhonditsis and Brett, 2005; Li et al., 2015a; Xu et al., 2013; Cerco and Cole, 1993). However, the inherent uncertainty of these models is greatly influenced by factors including model-structure uncertainty, model-input uncertainty, model-parameter uncertainty and measurement errors (Radwan et al., 2002). With the development and application of performance computing technology, many water quality models with good structure and complex parameters have been developed (Wang et al., 2013b). However, an increasing number of parameters has resulted in a sharp increase in computational requirements and thus exacerbated the complexity of these models. Highly interactive parameter spaces and the nonlinear, non-monotonous objective spaces have increased the difficulty of calibration. (Gupta et al., 2000; Herman et al., 2013a,b; Yi et al., 2016).

In order to improve the accuracy and rationality of model predictions and study the parametric uncertainty and sensitivity of models, we conducted several uncertainty and sensitivity studies in different water bodies such as rivers, lakes, reservoirs, estuaries and coasts to identify subsets of important model parameters that significantly influence model outputs have been carried out (Muleta et al., 2005; Neumann, 2012; Yi et al., 2016). Amongst these studies, large shallow lakes are often accompanied with complex hydrodynamic and eutrophication problems. The simulation of water quality is difficult and few studies were conducted on parameters under different situations.

The hydrodynamic conditions in large shallow lakes are highly influenced by wind-wave. They are not like other deep lakes or reservoirs which may be driven by thermal stratification. Parameters related to wind and wave like wind drag coefficient were supposed to be sensitive parameters in simulation (Li et al., 2015b). Some large shallow lakes also face serious eutrophication and algal bloom problems like Lake Taihu. Parametric uncertainty is considerable with parameters related

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to growth, respiration and death of algae and zooplankton generally sensitive in lake eutrophication models (Omlin et al., 2001; Missaghi et al., 2013). Three factors (i.e. nutrients, temperature and light) are considered to control the algal growth but the limitation factors are normally not so clear in many cases. For example, phosphorus was thought to be the limitation factors in Lake Taihu before but the influence of nitrogen is also quite important by recent researches (Tang et al., 2016; Paerl et al., 2011). Some typical large shallow lake models, which have been analyzed with different methods, showed that parameters related to light and temperature were significant, for example in the Venician Lagoon (Pastres and Ciavatta, 2005; Pastres et al., 1997), and Dian Lake, China (Yi et al., 2016). Parameters related to limitation factors will change according to real situation and sensitivities of these parameters need to be investigated. Sediment is also an important source of pollution, and parameters related to settling velocity and mineralization were found to be sensitive in some models (Missaghi et al., 2013). Researches on different models of shallow lakes suggested that the adsorption constant was relatively important in the simulation of total nitrogen, whereas mineralization and settling rates were sensitive to total phosphorus (Janse et al., 2010).

Meteorological and hydrodynamic situations, pollutant inflow and bathymetric variance in lakes and reservoirs results in inherent temporal and spatial variability in water quality (Missaghi et al., 2013). In a multi-dimensional model formulated by physical, chemical, and biological processes, model behavior may vary across the spatial domain whilst time-dependency should also be considered because of time-varying sensitivities (Herman et al., 2013a,b; Wang et al., 2013a;). However, few studies involving complex water quality models of multi-dimensional lakes or reservoirs have been conducted on this problem.

In this research, we choose Lake Taihu, a large shallow lake, the third largest freshwater lake in China, as an example to make relevant analysis. The water quality module of the Environmental Fluid Dynamic Code (EFDC) was chosen for the simulation, and water quality indicators such as ammonia nitrogen, nitrate nitrogen phosphate and chlorophyll-*a* as model outputs. The objectives of this study were thus to: (1) quantify the sensitivity of parameters in simulation of water quality model and evaluate uncertainty caused by it; (2) analyze the spatial-temporal variability of uncertainty and sensitivity; and (3) compare with other lakes and extend the result to a larger modelling community. The results can be utilized in the design of a reasonable water quality model for large shallow lakes and improve the efficiency of calibration of such models.

2. Methods and materials

2.1. Study area

Lake Taihu (longitude 119°08′–122°55′E, latitude 30°05′–32°08′N) is the third largest shallow freshwater lake in China, with a surface area of 2338 km^2 and a catchment area of 36,500 km^2 (Zhu et al., 2007). The average depth of the lake is 1.9 m and the maximum depth is 2.6 m, corresponding to an elevation of 3.0 m a.s.l. (Qin, 2009). The floor of the lake features flat terrain with an average topographic gradient of 0°0′19.66″. Lake Taihu has complex shoreline geometry and is connected to 172 rivers or channels (Qin, 2009), and the mean hydraulic retention time is about 300d. The water quality of the lake is seriously deteriorated. Nuisance algal blooms often occur in summer and early fall in most lake areas, especially Meiliang Bay and Zhushan Bay. The blooms are considered to be the result of a combination of high nutrient loading and weak hydrodynamics (Mao et al., 2008). For the convenience of management and monitoring, Lake Taihu have been divided into eight subareas (Liu et al., 2014; Zhang et al., 2010). Three subareas (i.e. Meiliang Bay, Central Zone and Southwest Zone) represent bay, central and nearshore zones respectively, and represent different hydrodynamic and water quality situations for uncertainty and sensitivity analysis in the water quality model (Fig. 1).

2.2. Model set-up and calibration

The Environmental Fluid Dynamic Code, a three-dimensional hydrodynamic model originally developed by John Hamrick (Hamrick, 1996), is utilized to simulate water quality in Lake Taihu. The model is one of the most widely applied advanced modeling frameworks for simulating hydrodynamics, water quality, eutrophication, and dynamic changes and interactions in sediment transportation in lakes, rivers and estuaries (Park et al., 2012; Kim et al., 2011; Li et al., 2011). A large number of applications have demonstrated that the model has considerable generality, convenient operation, and faster calculation times (Wu and Xu, 2011; Youngteck and Jinhyeog, 2009).

Uniform rectangular grids were utilized to set-up the model for Lake Taihu in the horizontal plane. In the vertical direction, vertical sigma coordinates with an evenly distributed three-layer system were adopted as a trade-off between resolution and stability issues (Li et al., 2015b). The effect of temperature stratification was ignored because the lake was shallow. The model was driven by atmospheric forcing, surface wind stress, tributary inflow/outflow, and benthic fluxes (Fig. 2). Inflow/outflow tributaries were generalized into 30 primary rivers (Fig. 1). Atmospheric precipitation data was obtained by averaging data from eight monitoring stations near the lake (Fig. 1). The wind data was collected from previous field monitoring (Li et al., 2015b). Benthic fluxes were set zonally by field experiment and previous research (Pang and Wang, 1994), and the dry/wet atmospheric deposition was set by field experiment (Song et al., 2005; Yang et al., 2007). We try to run the model for several days with an assumption that the lake surface was level and then the initial hydrodynamic conditions was set by the average value of simulation on the first day. It is also applied in our previous study and can help alleviate the influence of initial conditions on the simulation results. The initial condition of water quality was set by the monitoring data in the first few days of January from the 30 monitoring sites in Lake Taihu, including water temperature and the concentrations of DO, COD, NO_3^--N, NH_4^+-N, TN, $PO4^-$, TP and Chl-a. The simulated time lasted for one year (From 1 Jan to 31 Dec), and a 10-s time step was used as a trade-off between computational speed and stability issues.

Parameters concerned with the hydrodynamic processes were the same as those used in previous studies (Li et al., 2015b), and the results of current calibrations have been presented in previous research (Li et al., 2011). Annual monitoring data of water quality variables from 2005 was used to calibrate the water quality module, and relative errors were less than 30% on the whole. The amount of error remained significant after calibration, and therefore parametric uncertainty was estimated and the most sensitive parameter(s) was investigated in order to improve the model.

2.3. Methods of uncertainty and sensitivity analysis

Uncertainty and sensitivity analysis for the water quality module in EFDC for Lake Taihu was conducted based on the GLUE and RSA methods. The main analysis procedure is shown as follows.

2.3.1. Parameter identification

The simulation of water quality with EFDC involves a large number of parameters. It was not feasible or necessary to take all parameters into consideration (Muleta et al., 2005), so a reduction in the number of parameters based on the actual simulations was performed. Taking into account that the predominant type of algae in Lake Taihu is cyanobacteria, especially when algal blooms happened (Feng et al., 2016; Lu et al., 2016; Yue et al., 2014), we excluded all parameters relating to other algal species, i.e. macroalgae, diatoms, and greens. The competitive relationships between algal groups were omitted to reduce the number of parameters. Sediment is another factor that can have a great impact on the simulation result. The sediments module and water quality module were separated in EFDC model. It is difficult to calibrate