Development of three-dimensional eco-hydrodynamic model for a closed water body under scarce underwater light environment

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1. Introduction

A closed water body such as lake and reservoir plays an important role of water storage, flood control and irrigation water resource. In recent years, their water qualities are influenced negatively due to overloading of organic matter and nutrient salt, and the water environment management is increasingly necessary. The numerical approach by hydrodynamic model coupled with water quality model, eco-hydrodynamic model, can be considered as an effective tool to provide insight into seasonal dynamic in closed water bodies. The No.5 regulation pond in Ito Campus, Kyushu University, characterized by low transparency due to inflow loading of humic substances was selected as the study area in the research. The paper describes the 3D eco-hydrodynamic model with emphasis on its unique features. Excessive loadings of organic matter have significantly impacted on the water quality conditions of the No.5 pond. The modeled results showed the capability in simulating short-term variability and seasonal dynamic of water quality.

2. Materials and methods

1) Water quality survey

The No.5 regulation pond is a reservoir, which has been established by deforestation of forest area and started operating in 2005, and provides the irrigation water for the downstream area. The total catchment area covers 31.3 ha, the pond has a surface area of 13,800 m^2, holds approximately 63,000 m^3 and has a maximum depth of about 8m. The pond has 2 box culverts, collecting runoff water from the watershed. The Ito Campus of Kyushu University was constructed in the area which was used to be forest area before, therefore, the harvested wood chips were scattered over a wide range and large amount of humic substances ended up in the No.5 pond through the box culverts, dramatically transforming the water to severely brown color in the rainy season. This pond is under a scarce underwater light environment such that a transparency of the water is less than 1m in the summer, and thermal stratification is typically formed from July to October. The water quality monitoring was conducted weekly from July-November 2009, water samples were collected at the center of the pond, for each 1 meter vertical interval. The data of water quality items including TN, TP, NO_3^-, NO_2^-, PO_4^{3-}, NH_4^+, TOC, DOC, chlorophyll-a and DO were collected every week. Meteorological data, including air temperature, relative humidity, wind speed, wind direction, solar radiation, accumulated rainfall, transparency were recorded every 10 minutes. The survey on the inflow discharge and loading of the 2 box culverts was conducted to seek for the reasonable *L-Q* equation, which was essential to estimate the inflow loading of pollutants into the pond.

2) The mathematical model

In our study, we try to calibrate the model in order to simulate the hydrodynamics and the water quality including the seasonal change of the concentration of chlorophyll-a, TN, TP, DO and DOC in 6 months in 2009. The model solved 3D, unsteady equation of motion for a variable density fluid. The Boussinesq approximation, hydrostatic conditions, and eddy viscosity concepts were assumed valid. Horizontal eddy viscosity coefficient was solved by Smagorinsky's eddy viscosity model (Smagorinsky, 1963), vertical eddy viscosity and diffusion coefficient were identified by Henderson-Sellers (1985). Momentum equation, temperature equation and continuity equation were illustrated in the control volume grid system and the operator splitting method including 3 steps was utilized to solved the equations (step 1: Adam-Bashforth scheme: advective terms & horizontal eddy viscosity terms, step 2: Crank-Nicholson scheme: vertical eddy viscosity terms & Coriolis terms, step 3: continuity equation & pressure items). The computational grid has 7 x 6 horizontal cells and 64

Photo. 1 An overview of the No.5 regulation pond and inflow loading through a box culvert

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vertically stretched cells. Horizontal cells were 20 m on a side, and each vertical cell had a fractional thickness of 0.25 m. The grid configuration required a 2-min time step for numerical stability. Initial conditions were set for flow velocities, temperature and other water quality items. Velocities were set to 0m/s, water column and bed temperatures were initialized to the value recorded on the first sampling day. Boundary conditions included (1) inflow of the 2 box culverts; (2) inflow/outflow temperatures; (3) air temperature; (4) relative humidity; (5) incoming short-wave radiation and (6) wind velocity. Parameters were adjusted by trial-and-error to get the best match with trends in the observed water quality data.

3. Results and discussions

The model was internally linked with inflow loading of water temperature and organic pollutant. The inflow and outflow loading could be considered for the water surface layer. The inflow loadings of organic pollutants, TOC, DOC, TN, TP, DIN and DIP, were calculated by *L-Q* equations and the outflow discharge could be calculated by summing the inflow rate through 2 box culverts. **Fig. 1** and **Fig. 2** illustrate vertical profiles of predicted water temperature and chlorophyll-a concentration compared with the observed data in 2009. The results indicated that the physical transport processes were rather thoroughly calibrated with the data. In general, the model captures both the seasonal and vertical distribution observed in the data. The change of the mixed layer depth was well captured by the model. The hydrodynamic model developed in this study was capable of simulating the dynamics and thermal structure of the pond, which are considered to be important features regulating biological and chemical processes of a surface water body.

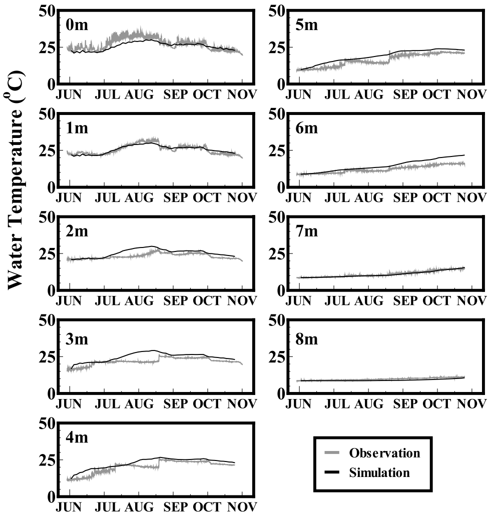

Fig. 1 Comparison between observation and simulation of water temperature

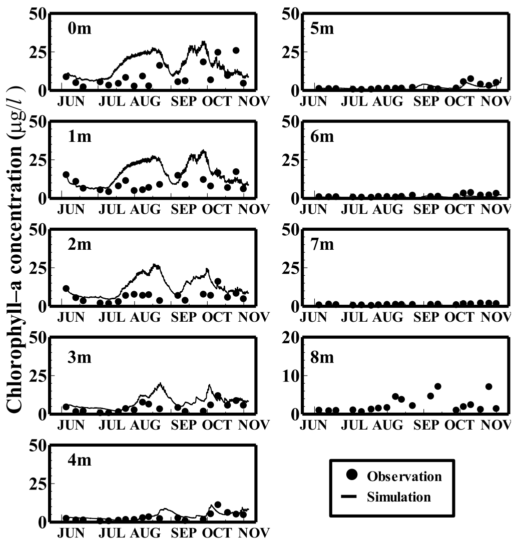

Fig. 2 Comparison between observation and simulation of chlorophyll-a concentration

4. Conclusion

As calibration by the 2009 water quality and thermal data in the No.5 pond, the utilization of 3D hydrodynamic and water quality model overall gave a reasonable production of water quality conditions including the concentration of chlorophyll-a, nutrient, dissolved organic matter, DO and water temperature. One of the unique features of the model is the internal linkage of the 3D eco-hydrodynamic model with the intensive observed inflow loading of organic pollutants from the 2 box culverts in order to achieve reasonable simulated results. The current model can be used for small ponds where knowledge of temperature and density stratification is important for assessing the short-term dynamic of water quality and the water bodies, which is considerably influenced by the inflow discharge of dissolved organic matter.

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Reference:

Henderson-Sellers, B. (1985): New formulation of eddy diffusion thermocline models, *Appl. Math. Modelling*, **9,** pp.441-446

Smagorinsky, J. (1963): General circulation experiments with the primitive equations. I: The basic experiment. *Monthly Weather Rev*. **91**, pp.99-164.