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Research paper

3-D hydro-environmental simulation of Miyun reservoir, Beijin

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Abstract

Water quality deterioration of reservoir served as municipal water source has been a potential threat to public health. Crowned as one of the largest reservoirs and water resource, Miyun reservoir has been paid attention to water quality protection. For the purpose of effective reservoir protection and management, comprehensive understanding of water quality spatiotemporal pattern is demanded. In this study, three dimensional (3-D) dynamic Environmental Fluid Dynamics Code (EFDC) model was used to simulate hydrodynamic and algal processes for Miyun reservoir. Main challenge was to demonstrate the water quality pattern and implying impacts on variations. Model structure and functionality were briefly described. Field data and estimated loads were used as nutrient forces. Calibration and summary statistics were presented. Results showed that spatiotemporal pattern of water temperature, dissolved oxygen, chlorophyll-a, total phosphorous, nitrate and ammonia were consistent with in situ measurements. Several important impacts on the water quality variations in Miyun reservoir were discussed. It indicated that the existence of the patterns were highly related to the geomorphogical and hydrological characteristics as well as nutrient inputs. Temporal tendency was also linked to the seasonal climate. It proved that EFDC model was feasible for hydro-environmental simulation in Miyun reservoir, providing managers an efficient tool for strong supports on water quality management and water source protection.

Keywords: Water quality; Reservoir; EFDC model; Spatiotemporal pattern

1. Introduction

Developing countries are confronted with a potential threat as human activities have been continuously influencing physical and chemical characteristics of water bodies (Moshood, 2008). Specific attention has been paid to the pattern study on lakes and reservoirs revealing the changes and heterogeneity of major water quality variables like temperature, nitrate, ammonia, phosphorus, dissolved oxygen (DO) and chlorophyll-a (Chla). It is particularly the case for spatiotemporal pattern recognition via hydro-environmental modeling approaches which can be well justified by the fact that water quality potentially affects public health. To this end, studies have been carried out with regard to reveal negative impacts on aquatic system caused by water quality deterioration (Djukic et al., 1994; Wetzel, 2001). The importance of water quality for human societies underscores the necessity of understanding how water quality heterogeneity in time and space could be recognized. Better understanding of water quality pattern is quite essential for stakeholders toward effective water source protection and management (Cerco and Cole, 1994; Zilov, 2001; Imevbore, 1970; Anadu et al., 1990; Miranda, 2009; Chioma and Isimaikaiye, 2010; Franceschini and Tsai, 2010; Wu and Xu, 2011). In northern China, reservoirs have been regarded as important domestic water

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supplement due to water shortage. Government and researchers have been making continuous efforts on water quality protection and restoration. However, wash-out and runoff from agricultural lands largely contribute to the impairment of water body caused by nutrient enrichments with sediments, dissolved organic/inorganic substances causing eutrophication. Changing properties of water body have been detected and explored implying different responses of forces and conditions, exerting impacts on water quality variables. Marcela et al. (2008) explained the mechanisms of high temperature causing increased ecological stress. Wu and Xu (2011) studied the relationship between Chla and algal blooming in Daoxiang lake. Scholars indicated that phosphorus load should be reduced to control blue-green algal blooming in Lake Mendota, Wisconsin (Richard et al., 1998). Muttil and Chau (2006) took the advantages of the combination of neural networks and genetic programming for modeling coastal algal blooms. In addition, the properties of seasonal water quality at multiple spatial scales can also be affected by land cover, topography and nutrient loads. Relation between water quality patterns and topographical conditions were revealed in articles (Lindim et al., 2009, 2011; Zheng et al., 2004).

Numerical models are commonly used in hydro-environmental simulations for water quality pattern recognition. Numerical models are comparatively accurate, efficient and stable. It is capable of visualizing spatial information. Typically, numerical model solves a set of physically based governing equations describing flow and transportation of contaminants (Zeinab et al., 2011). Based on water balance equations, numerical models are deterministic in simulating water column variables. Ecological models used to simulate eutrophication processes have been accepted as strong instruments for predicting and diagnosing water quality pattern. Usually, water quality models are integrated with hydrodynamic models. Worldwide accepted hydro-environmental modeling tools such as Delft3D (van Vossen, 2000), WASP (Ambrose et al., 1993) and CE-QUAL-W2 (Cole and Well, 2008) have been used to simulate responses of a system to the nutrient loads. Environmental Fluid Dynamic Codes (EFDC) model is a comprehensive 3-D dynamic tool for all features required studies (Hamrick, 1992). EFDC model is developed by Hamrick in Virginia Institute of Marine Science which is featured as: (a) finite difference element instructed grid, (b) wetting-drying boundary processes, (c) heat exchange with atmosphere, (d) and water quality variable simulation. EFDC model comprises an advanced 3-D surface water modeling scheme for hydrodynamic and reactive transport simulations of rivers, lakes, reservoirs, wetland system, estuaries and coastal oceans.

EFDC can be used for understanding and predicting the environmental fluid flows with transportation and mixing of associated dissolved or suspended materials. Applications includes salinity intrusion study of river estuary (Suscy et al., 1998), stratified thermal simulation of lakes (Hamrick, 1996; Hamrick and Mills, 2000), ecological and sediment transportation in many others (Park et al., 1995). EFDC model is regarded as a technically defensible 3-D hydro-environmental modeling tool for pollutant and pathogenic organism transport and fate from point and non-point sources, simulation of power plant cooling water discharges, simulation of oyster and crab larvae transport, and evaluation of dredging and dredge spoil disposal alternatives (Kuo et al., 1996; Suscy et al., 1998; Shen et al., 1999; Hamrick and Mills, 2000; Moustafa and Hamrick, 2000; Wu and Xu, 2011). It is strongly recommended by US EPA as a standard 3-D hydro-environmental simulation tool.

As one of largest reservoirs in northern China, Miyun reservoir is important to the society. However, former scenario study (Wang et al., 2005) has shown that Chla concentration might exceed 10 ug/l in many areas of Miyun reservoir indicating eutrophic condition. Satellite imagery showed that water quality in the western section of Miyun reservoir was consistently higher than in the eastern section with a tendency for eutrophication (Wang et al., 2008). In this paper, we investigated spatiotemporal water quality pattern via EFDC modeling of Miyun reservoir and reveal some important impacts on water quality changes. This paper was organized as follows: In methodology part (Section 2), hydro-environmental functionalities and governing equations of EFDC model were briefly introduced. Section 3 presented the modeling steps including study area, boundary settings and model calibration. Section 4 followed the spatiotemporal pattern analysis. Discussions were made on simulation results. Finally, Section 5 summarized significant results, insufficiencies and conclusions.

2. Methods

2.1. EFDC model

EFDC model solves 3-D vertically hydrostatic, free surface, turbulent averaged equations of motions for a variable density fluid. It uses a stretched sigma vertical coordinate and Cartesian or curvilinear, orthogonal horizontal coordinates. EFDC solves hydrostatic momentum and continuity equations for turbulent flow in coordinate system containing major functional components such as: hydrodynamics, salinity/temperature, tracer, sediment transport, toxics, and water quality columns with sediment diagnosis.

2.1.1. Hydrodynamics

Hydrodynamic formulas for vertically hydrostatic momentum and continuity of EFDC model are solved in a coordinate system that is curvilinear and orthogonal in the horizontal and stretched or topography-free surface in vertical direction. The momentum and continuity equations in EFDC model (Hamrick and Mills, 2000) are given:

$$\partial_t\left(m_x m_y H u\right) + A(u) - m_x m_y f_e H v = -m_y H \partial_x\left(p + gH + g z_b^*\right) + m_y\left(\partial_x z_b^* + z\partial_x H\right)\partial_z p + m_x m_y \partial_z\left(H^{-1} A_v \partial_z u\right) + Q_u \quad (1)$$