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Simulation on water flow and water quality in Wuliangsuhai Lake using a 2-D hydrodynamic model

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Abstract

In order to study the hydrologic characteristics and water quality of Wuliangsuhai Lake, this paper combined measured monitoring data such as water flow, velocity, water depth and wind speed data with spatial data, developed the hydrodynamic model suitable for Wuliangsuhai to simulate its water flow and water quality, based on lake two-dimensional water hydrodynamic model. The water quality state variables in this model included TN and TP. The simulation of the mass transformation processes of TN and TP was based on the unsteady diffusion equations. First we made a coordinate transformation on control equations under Cartesian coordinates, then discretized equations of the model with alternating direction implicit method (ADI method) and solved the equations by LU decomposition. This study applied the sliding boundary method to process Body-Fitted Grid, which improved the regional orthogonal precision, and accelerated iteration convergence ratio obviously. The results showed that in Wuliangsuhai, the wind-driven current was an important presentation of lake current, while the concentration of water quality item was decreasing from drains to surround because of the external pollutant loading. The simulation also showed that, the convection was the main process in water drains of the lake and pollutants spread out from water inlet to the lake area through convection diffusion in Wuliangsuhai watershed and it would take a relatively long time for concentration field to achieve a stable status and its self-purification ratio is quite slow. The simulated result could be used to quantitative study of water quality changes in lakes pollution process, and has an important significance for the comprehensive management of ecological restoration of the water environment.

Key words: Wuliangsuhai, two-dimensional water hydrodynamic model, concentration field.

Introduction

Recently, the problem of eutrophication of lakes has been very serious, and how to govern it effectively has become a hot topic. Lake water dynamics is an important research issue and base of water environment study, which determines the macro change process of water quality in a large extent. So far, a lot of work within many meaningful results on lake water dynamics has been carried out by using numerical simulation methods. For example, Chen *et al.* [1] and Bacopoulos *et al.* [2] studied the hydrodynamic response of northeastern Gulf of Mexico to hurricanes and the role of meteorological forcing on the St. Johns River (Northeastern Florida) with water hydrodynamic model. The research in this field in China started late and made a lot of meaningful progresses, though Liu *et al.* [3] simulated Yuqiao reservoir in Haihe river basin with a coupled model of hydrodynamics and water quality and Zhang *et al.* [4] studied the river, lake and network system in the Jingjiang reach on the unstructured quadrangles with two-dimensional hydrodynamic model for instance. The Wuliangsuhai Lake is not only the largest lake in the valley of the Yellow River but also the biggest wetland in the same latitude on the earth with a relatively high eutrophication level, the major sources of intake of the lake are farmland drainages. Using two-dimensional water hydrodynamic model to simulate water flow and water quality quantificationally and the consequence would be significant for comprehensive management of ecological restoration of the water environment.

Study Area

The Wuliangsuhai Lake is a typical macrophyte-dominanted lake (40°36’ - 41°03’ N, 108°43’ - 108°57’ E) located in Wulate County, Inner Mongolia, China. It is in the end of the Hetao plain, its west is Hetao Irrigation District and its east is the western of Urals. There are three main water inlet, the total drainage, the eighth drainage and the ninth drainage, and a waste canal. The lake is 35-40 km in length and 5-10 km in width according to the interpreted Landsat-TM images of April 2008. It covers an area of approximately 316.41 km^2, in which reed and swamp area is 208.72 km^2, account for 66% of the whole area. It is located in arid and semi-arid areas with a capacity, water elevation and depth of $3.22 \times 10^8 m^3$, 1018.58 m and 0.5-3.2 m, respectively [5]. In recent years, with the development of population and economy and the expanding scale of city, the pollutant loads into Wuliangsuhai Lake is becoming heavier, which made the degree of lake eutrophication deeper and the water quality worse.

Data and Methods

Establishing model: The water depth of Wuliangsuhai Lake is relatively small (average depth is about 2.5 m), the horizontal scale is much larger than the vertical scale, the change of water quality parameters (such as flow rate, water depth, pollutant concentration, etc.) in vertical direction is smaller than horizontal direction, and its flow field can be shown by the average flow volume along the water depth. Introducing vertical averages by vertical integral in the N-S equations, we can get the following two-dimensional shallow water Hydrodynamic water quality model equations:

(1) The continuity equations of water flow:

$$\frac{\partial z}{\partial t}+\frac{\partial}{\partial x}(Hu)+\frac{\partial}{\partial y}(Hv)=0$$

(2) The motion equations of water flow:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial z}{\partial x}+fu-\Omega v=\frac{\upsilon}{H}\nabla^2(Hu)+\lambda u_a$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial z}{\partial y}+fu+\Omega v=\frac{\upsilon}{H}\nabla^2(Hv)+\lambda v_a$$

where z is water level; H is water depth, $H = z - z_B$, z_B is elevation; u is vertical mean velocity in x direction, v is vertical mean velocity in y direction; f is drag coefficient, which $f = f_1 + f_2$, f_1 is friction coefficient of river bottom, and $f_1 = g\frac{\sqrt{u^2+v^2}}{C^2H}$, C is Chezy coefficient, which reflects the resistance to water flow from the bottom, f_2 is partial friction coefficient, and $f_2=\xi\frac{\sqrt{u^2+v^2}}{\Delta l}$, ξ is partial resistance coefficient; $\Omega = 2\omega\sin\psi$ is Coriolis force coefficient, reflecting the Coriolis force effects of earth rotation, ω is the rotational angular velocity of the earth, which is equal to $2\pi / (24 \times 3600)$, and ψ is the latitude of the lake; υ is turbulence vortex viscosity coefficient; $\lambda=\frac{C_w\rho_a w}{\rho_w H}$ is wind stress coefficient, where ρ_a, ρ_ω and w denote air density, water density and wind speed, respectively, u_a represents its component of vector in x direction, v_a represents its component of vector in y direction; Cw is wind resistance coefficient, and Wa is average wind speed at 10 m over the lake surface.

(3) Water quality equations:

$$\frac{\partial(Hc)}{\partial t}+\frac{\partial(uHc)}{\partial x}+\frac{\partial(vHc)}{\partial y}=\frac{\partial}{\partial x}\left(HE_x\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(HE_y\frac{\partial c}{\partial y}\right)+f(c)+S$$

where c is water salinity with its unit "mg/l"; E_x and E_y are the sum of turbulent diffusion coefficient and the scattered coefficients in x and y direction, respectively; $f(c)$ is biochemical item, which simplified as $f(c) = -kHc$, where k is self-purifying coefficient; S is source sink term.

The calculation method of model: The fundamental equations mentioned above belong to nonlinear partial differential equations in mathematics, which is still difficult to solve practical problems by their theoretical analysis. However, fundamental equations with a relatively simple form and standard type generally belong to mixed nonlinear partial differential equations, so they are suitable for numerical calculation, that is, translating fluid dynamics physics problems into numerical solution of initial-boundary value problems of partial differential equations. First, this paper used curvilinear coordinates $\xi^i = (\xi, \eta)$ instead of Cartesian coordinates $x^j = (x, y)$ and translated physical plane into calculation plane to get body-fitted grids. For improving the accuracy of orthogonal, in this paper, we dealt with finite grids with the slip boundary method when we built body-fitted grids in this article. While (x, y)coordinate represented the physical plane, (ξ, η) coordinate represented the calculation plane. Then we made coordinates conversion for fundamental equations, that is, transforming control equations from Cartesian coordinate system into curve coordinate system, using alternating direction method (ADI method) [6] on model equation for discretization, and using LU decomposition on equation group for numerical solution in a certain initial boundary value conditions, thus, we get physical quantity of all nodes in calculation regions, and simulate two-dimensional flow field and pollutant concentration field in Wuliangsuhai Lake.

The definite conditions control of model:
(1) Initial conditions: Getting the water level H_0 of given lake, initial concentration c_0 and initial velocity u_0 and v_0, we set them as initial conditions for equations.
(2) Boundary conditions: In this paper, we use following boundary conditions:

$$V\cdot\vec{n}=0;\ \frac{\partial z}{\partial n}=0;\ \frac{\partial c}{\partial n}=0;\ u_\Gamma=u(t);\ Q_\Gamma=Q(t);\ z_\Gamma=z(t)$$

For water quality equations, taking upstream and downstream boundary condition: $c_\Gamma = c(t)$. In addition, to ensure solute quality conservation, the relationship between flow velocity and concentration gradient is:

$$\frac{\partial c}{\partial t}+\vec{V}\frac{\partial c}{\partial\vec{n}}=0$$

Results and Discussion

The primary drainage system of Wuliangsuhai consists of the total drainage, the eighth drainage and the ninth drainage, but only one waste canal is included. This paper simulated 48-hours-flow-field of water quality and flow in Wuliangsuhai when pollutants such as TN and TP flow into the field (Fig. 1).

As can be seen from Fig. 1, pollutants spread out from water inlet to the lake area through convection diffusion. With the time of water diversion going, there is a decline trend in pollutant concentration. However, concentration field does not reach a stable status, which means it will take a relatively long time for concentration field to achieve a stable status. After pollutants with nitrogen and phosphorus were discharged into lake through main drainages, they dispersed rapidly to the whole lake with the main drainages as the centres. In the diffusion process, the amount of TN has almost no reduction, which means that the diffusion ratio is speeding up. However, the self-purification ratio is quite slow. Compared to TN, spreading rate of TP is relatively slow, which indicates that it must take quite a long time to clear away or diluted thoroughly. This also verifies that the comprehensive degree of detriment of TN and TP to Wuliangsuhai.

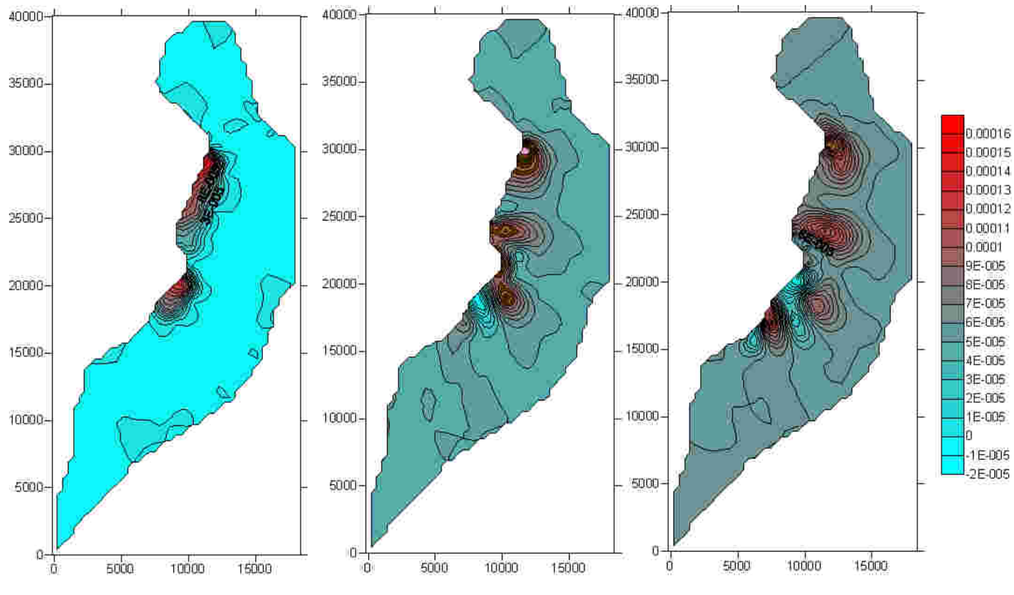

Figure 1. Distribution of flow field and TN concentration field in Wuliangsuhai.

Conclusions

Based on the previous studies, this paper established a Body-Fitted-Orthogonal-Grid coordinate system and simulated water quality and water flow evolution for the irregular boundary lake. Firstly, the continuity equations of water flow, the motion equations of water flow and water quality equations were set up, discretized using the upwind different scheme and solved by numerial simulation. This study selected Wuliangsuhai Lake as a case area to validate the robust of the model. When establishing Body-Fitted-Orthogonal-Grid coordinate system, this study applied the sliding boundary method to process Body-Fitted Grid, which improved the regional orthogonal precisions, and accelerated iteration convergence rate obviously. If model control equations dispersed, staggered grid was adopted to promote the stability of the model, and it is convenient for equations discretized to use alternating direction implicit method. Lastly, this study simulated the distribution of water flow and concentration field of Wuliangsuhai Lake, and the results accord with the objectives facts basically. Therefore, the rout of constructing the model for lake is correct, and the calculation method is effective.

It is a long time for concentration and flow fields to reach a stable status especially for the flow field. With time going, pollutants diffuse from main drainage to the other lake area gradually. Because concentration of pollutants and distribution of flow field in every moment could be simulated, some corresponding measures for the different results simulated could be taken to control the area which is polluted severely. The result of simulation for Wuliangsuhai has an important significance to ecological restoration and comprehensive treatment of the basin. Local government should make the comprehensive plan to control water pollution in Wuliangsuhai basin. It is needed to conduct industrial wastewater treatment in the basin, at the same time, and it is demanded to promote the environment bearing capacity through taking the measure of industrial structure adjustment, water-saving society construction and ecological agriculture promotion.

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