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Three-Dimensional Hydrodynamic and Water Quality Integrative Simulation System Based on GIS of Donghu in Wuhan

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Abstract. The three-dimensional hydrodynamic and water quality integrative simulation system is established based on the coupling of three-dimensional hydrodynamic model and WASP water quality model and GIS control technology in this paper. It integrates the functions of unstructured grid generation, three-dimensional hydrodynamic and water quality simulation and three-dimensional visual display. When the basic lake data is imported, the system can simulate and display the three-dimensional dynamic change process of lake hydrodynamic parameters and water quality parameters in a one-stop way. Numerical simulation was carried out on its hydrodynamic and water quality, taking Donghu in Wuhan as the study area. The system was tested with topographic data, water quality monitoring data, hydrological data and meteorological data of Donghu in 2018. Compared with the measured results, the error is small, which shows that the system could be used for hydrodynamic and water quality simulation of inland lakes.

1. Introduction

Under the both of human activities and climate change factors, Lake Eutrophication is becoming increasingly prominent, as a common environmental problem in the global water ecosystem. A common phenomenon of eutrophication is planktonic algae mass-propagation and frequent algal bloom. To further study the mechanism of algal bloom formation in eutrophic lakes and the relationship between various environmental factors and bloom, it is necessary to develop the prediction technology of algal bloom. It can provide scientific theoretical basis and decision-making support technology for Lake Eutrophication management, ecological restoration and watershed comprehensive management, and help to improve the ability of environmental management departments to reduce the ecological hazards and health risks caused by algae blooms, which is of great ecological and environmental significance.

At present, the main research methods include field observation, remote sensing inversion, physical model experiment and numerical simulation. However neither site observation nor remote sensing observation can fully and continuously express the spatio-temporal information of lakes. Physical models are too complex to get the data it need. Numerical simulation has the advantage of low operating cost and controllable process, which can not only reshape the historical dynamic evolution of water environment, but also predict its future trend. It has been widely used in the modeling and simulation of water ecosystems such as rivers, estuaries, lakes and oceans.

The establishment of a numerical model of lake ecological dynamics through the coupled hydrodynamic and water quality model can simulate the continuous evolution of water quality ecological variables in time and space and provide an efficient platform for data integration and

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process understanding of the interaction between lake hydrodynamic water quality and water ecology under complex spatio-temporal background.

For example, Fu et al. coupled WASP with EFDC hydrodynamic model and integrated USEPA WASP model in a GIS platform [1]; Ng et al. integrated a GIS with a three-dimensional hydrodynamic sediment and heavy metal transport numerical model and applied to the Pearl River Estuary in China [2]. Therefore, many achievements have been made in establishing hydrodynamic water quality models based on GIS. However, there are several weaknesses associated with the existing systems, especially for lake modeling [3]. The formation mechanism of algal bloom is very complex, which limits the application scope of the model. The ecological dynamics model needs to be parameterized and discretized to describe the process of water state change and introduce various errors. The calibration of multiple parameters in mathematical model needs to be improved. The natural flow trend of lakes is relatively weak, and the existing one-dimensional and two-dimensional water environment models cannot accurately reflect the three-dimensional structure of water flow, so it is difficult to correctly simulate the flow of lakes. The limitations of existing research methods have brought great challenges to researchers to accurately understand the evolution mechanism of lake blooms, grasp the development trend of blooms, and take feasible measures to control and prevent blooms.

In this paper, we present the lake three dimensional hydrodynamic and water quality integrative simulation system based on GIS. This system integrates some key technologies, such as ELCOM, WASP water quality model, GIS and component development. The functions of it include multi-source remote sensing image management, electronic map management, unstructured grid automatic generation, 3d hydrodynamic water quality coupling simulation, spatial data and attribute data comprehensive query, water quality thematic map making, etc. The applicability of the system is illustrated by a case study in Lake Donghu in Wuhan. Relying on Landsat8 image, domestic high-resolution image, DEM data, GIS data and other data in Donghu, it organically integrates remote sensing, GIS, coupled modeling, big data technology and other disciplines, to realize the integrated management of lake property, vector, image and elevation data.

2. Model

The system has been embedded with a self-compiled 3D hydrodynamic model.

Based on the Navier-Stokes three dimensional water flow equation, the model adopts vertical static pressure assumption, unstructured triangular grid in horizontal direction and σ coordinate transformation in vertical direction. The calculation formula of sigma coordinates is defined as:

$$\sigma = \frac{z-\xi}{h+\xi} = \frac{z-\xi}{H} \tag{1}$$

Where σ is the transformed vertical coordinate, $\sigma \in (0,-1)$, where σ=0 corresponds to the static water surface, where σ=-1 corresponds to lake bottom; z is the water level in the actual physical domain, z=0 is the reference static water surface; ξ is the water level of the water surface relative to z=0; h is the water depth from the base still water surface to the bottom of the lake; $\mathrm{H} = \mathrm{h} + \xi$ is the total water depth. The hydrodynamic control equation in the coordinate system is defined as

$$\frac{\partial\xi}{\partial t} + \frac{\partial Hu}{\partial x} + \frac{\partial Hv}{\partial y} + \frac{\partial\omega}{\partial\sigma} = 0 \tag{2}$$

Momentum conservation equation is defined as:

$$\frac{\partial Hu}{\partial t} + \frac{\partial Hu^2}{\partial x} + \frac{\partial Huv}{\partial y} + \frac{\partial uw}{\partial\sigma} = -gH\frac{\partial\xi}{\partial x} + \mathrm{BV3}_x + \frac{1}{H}\frac{\partial}{\partial\sigma}\left(\mu_v\frac{\partial u}{\partial\sigma}\right) + F_x + fvH \tag{3}$$

$$\frac{\partial Hv}{\partial t} + \frac{\partial Hv^2}{\partial x} + \frac{\partial Hv^2}{\partial y} + \frac{\partial vw'}{\partial\sigma} = -gH\frac{\partial\xi}{\partial y} + \mathrm{BV3}_y + \frac{1}{H}\frac{\partial}{\partial\sigma}\left(\mu_v\frac{\partial v}{\partial\sigma}\right) + F_y - fuH \tag{4}$$

$$\mathrm{BV3}_x = -\frac{gH}{\rho_0}\left[\frac{\partial}{\partial x}\int_\sigma^0(\rho-\rho_0)d\sigma + (\rho-\rho_0)\sigma\frac{\partial H}{\partial x}\right] \tag{5}$$

$$\mathrm{BV3}_y = -\frac{gH}{\rho_0}\left[\frac{\partial}{\partial y}\int_\sigma^0(\rho-\rho_0)d\sigma + (\rho-\rho_0)\sigma\frac{\partial H}{\partial y}\right] \tag{6}$$

$$F_x = \frac{\partial}{\partial x}\left(\mu_h H \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_h H \frac{\partial u}{\partial y}\right) \tag{7}$$

$$F_y = \frac{\partial}{\partial y}\left(\mu_h H \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial y}\left(\mu_h H \frac{\partial v}{\partial y}\right) \tag{8}$$

Where u, v and w are the x, y, z velocity components, respectively; p is the hydrodynamic pressure; ρ_0 is reference density of water body; $\mu_h$is turbulent viscosity coefficients in horizontal; μ_v is vertical directions; f is coriolis force coefficient, $f = 2\Omega\sin\theta, \Omega = 2\pi/86184$, θ is the rotation frequency of the earth, g is the acceleration of gravity; $BV3_x$ and $BV3_y$ are the x, y baroclinic gradient term, F_x and F_y are the x, y horizontal diffusion term of momentum [4].

The system uses the Water Analysis Simulation Program (WASP) as water quality model. The model includes eight water quality indicators, including inorganic phosphorus (OPO4), organic phosphorus (OP), ammonia nitrogen (NH)-N), nitrate nitrogen (NO3--N), organic nitrogen (ON), chlorophyll a (chl-a), dissolved oxygen (DO) and carbon biochemical oxygen demand (CBOD) [5].

Integrating the three-dimensional hydrodynamic model, WASP and GIS controls, the system establishes the three-dimensional hydrodynamic water quality model, which can simulate the eutrophication status of the lake and display it in the form of 3D.

3. Introduction to System

The overall framework of the system is shown in figure 1. Using C# language, basing on ArcGIS Engine, it provides unstructured grid automatic generation function, three-dimensional hydrodynamic water quality numerical simulation function and three-dimensional visualization function.

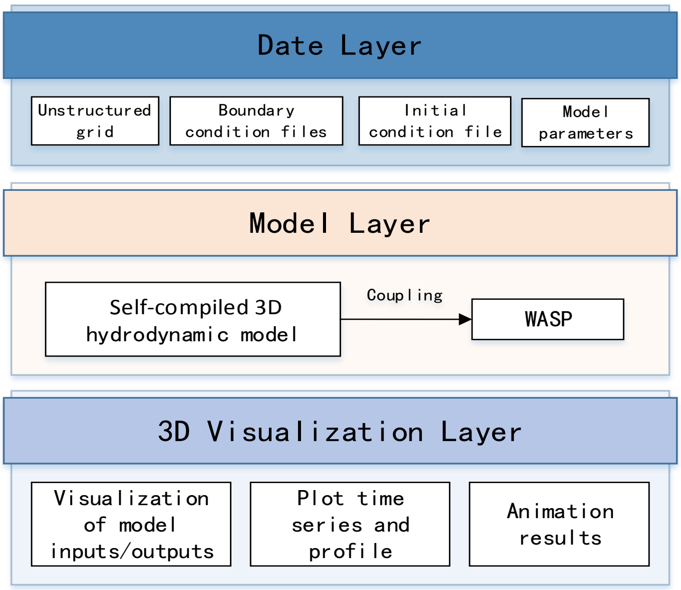

Figure 1. Frame diagram of system

3.1. Unstructured Grid Automatic Generation Function

In view of the problem that the existing structure grid can‘t deal with the complex flow field boundary and variable bottom elevation, this system uses Delaunay triangulation algorithm control to provide fast and automatic generation of unstructured grid based on GIS. This system provides simple mesh and fine mesh and terrain interpolation tools. After grid generation is completed, the system provides statistics and histogram drawing functions to facilitate users to analyze the quality of generated grid [6].

First, import the shapefile file of Lake Boundary and Lake Topography document. The next step is to set the grid generation parameters. Then the unstructured grid is generated automatically. Figure 2 presents mesh generator.

3.2. Three-dimensional Hydrodynamic Water Quality Numerical Simulation Function

Coupled three-dimensional hydrodynamic model and WASP water quality model, the hydrodynamic water quality model was established to simulate eutrophication of lakes.

Firstly, set the initial conditions in the initial conditions interface. Initial conditions include initial water temperature, initial concentration of water quality variable (chlorophyll water nitrogen and phosphorus concentration water temperature dissolved oxygen suspended matter transparency lake mud nitrogen and phosphorus) initial wind speed and so on. Figure 3 presents initial water quality variable concentration parameter setting interface.

Figure 2. Mesh generator

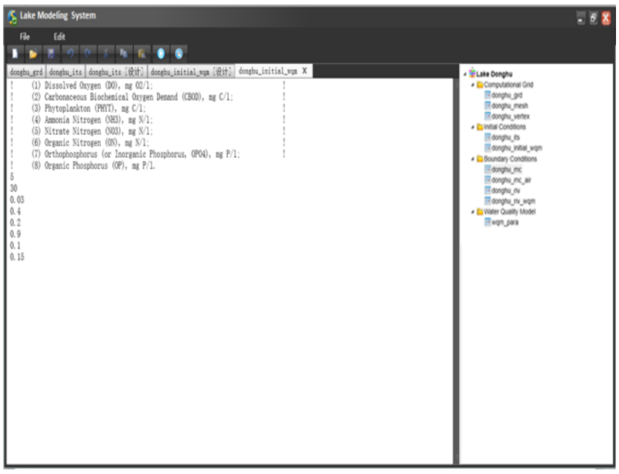

Figure 3. Initial water quality variable concentration parameter setting interface

Then set the boundary conditions in the boundary conditions interface, including atmospheric drive data, inflow and outflow boundary discharge, concentration of pollutants in the inflow and outflow and so on. Figure 4 presents setting interface of pollutant concentration data in Inflow and Outflow Rivers.

Finally, set the model parameters, including model time step, depth stratification coefficient, bottom roughness, turbulence model parameters, degradation parameters of pollutants, temperature coefficient and atmospheric reoxygenation parameters. Figure 5 presents water quality model parameter setting interface.

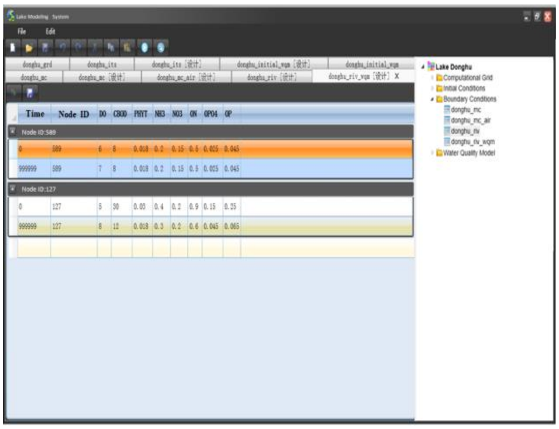

Figure 4. Setting interface of pollutant concentration data in Inflow and Outflow. Rivers

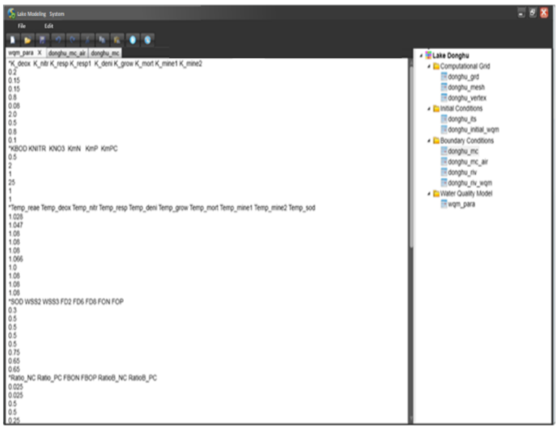

Figure 5. Water quality model parameter setting interface

After completing all settings, click run. The 3D-hydrodynamic water quality numerical model began to operate. The numerical simulation results are stored in the spatio-temporal database. Figure 6 presents model operation interface.

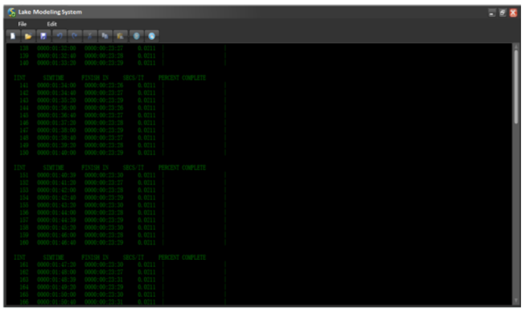

Figure 6. Model operation interface

3.3. Three-dimensional Visualization Function

Three-dimensional Visualization Function module shows the result of hydrodynamic water quality simulation of lakes, using digital elevation model and real projective processing, modeling and visualization of large-scale terrain simulation, dynamic 3D scene interaction, all kinds of control chart. Through the selection and editing of three-dimensional simulation elements, the three-dimensional velocity field, temperature field and water quality concentration field of lakes under different hydrological conditions are displayed.

4. Case

4.1. Study Area

Wuhan Donghu, located in the central city of Wuhan, covers an area of 33 square kilometers. It is a typical shallow inland lake, which is seriously eutrophication due to sewage generated by human activities around the lake, aquaculture, etc. This section takes Wuhan Donghu as the study area, and runs this system to simulate the water quality of the lake.

4.2. Model Run

First according to the remote sensing image of December 2018, extract the water body boundary of the Donghu applies water body extraction technology. According to the DEM data of Donghu, extract and obtain the terrain elevation data of lake. Then import the boundary file and elevation data file of Donghu into the system, adjust the parameters, and automatically generate the unstructured grid. Figure 7 is complex mesh of Donghu.

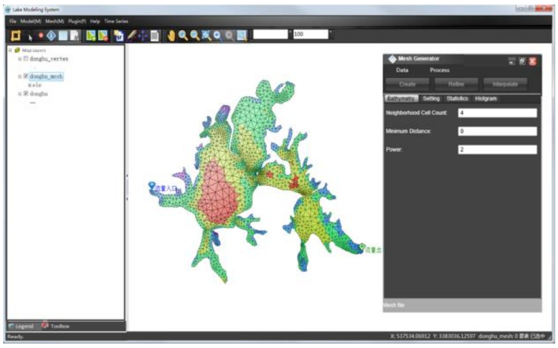

Figure 7. Complex grid

Then import the Donghu initial condition file and boundary condition file to determine the model parameters. When all the Settings were completed, the model was run to obtain dynamic variation characteristics of hydrodynamic parameters and water quality parameters (dissolved oxygen, ammonia, nitrogen, nitrate, nitrogen, organic nitrogen, inorganic phosphorus, organic phosphorus, carbon, biochemical oxygen demand, and chlorophyll a). Figure 8 is 3D visualization simulation results of CBOD of Donghu.

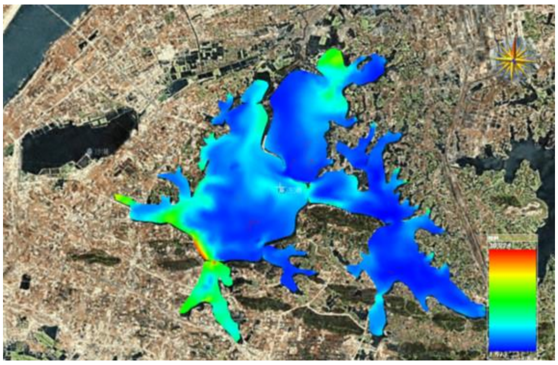

Figure 8. 3D visualization simulation results of CBOD of Donghu

5. Conclusion

In this paper, a three-dimensional hydrodynamic water quality simulation system is built based on GIS. Its main functions include (1) Providing the functions of pre-processing and post-processing of three-dimensional hydrodynamic water quality numerical calculation based on GIS control, and realizes the integrated management and comprehensive query of multi-source and heterogeneous data; (2) Providing a technique for rapid generation of unstructured grids; (3) Providing lake 3D visualization simulation tool based on 3D GIS, realizing the fine simulation and trend prediction of the dynamic process of the evolution of lake hydrodynamic water quality under different hydrological conditions.

The case study shows that the system can well simulate and display the dynamic process of water quality evolution.

6. Acknowledgement

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