In-homogeneity of wind field caused by local terrain conditions and its influence on surface flow in lakes

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Abstract: *A CFD-based wind flow model and a hydrodynamic model were coupled to investigate the influence of in-homogeneity of wind field caused by local terrain on the surface flow in Lake Fuxian. And the results indicated that the surface flow directions and circumfluence in the lake showed some changes under the in-homogeneous wind condition. And different changes could be found in the northern and southern half-lake as different terrain conditions. These changes may to some extent affect the transportation process of mud and contaminant in the lake, and thus should be taken into account in precise modeling.*

Key Words: hydrodynamics, wind, terrain, CFD.

1. Introduction

Wind is one of the main driving forces of current in lakes, to some extent determining the characteristics of flow field, as well as the transportation process of mud and contaminants. Homogeneous wind field conditions are usually used in current hydrodynamic models when computing flow filed in lakes. However, large in-homogeneity may exist in the wind field over the lake surface as a result of regional topographical variations. Thus some researchers tried to couple meso-scale atmospheric models, such as MM5 and BRF, into hydrodynamic models to simulate the hydrodynamic characteristics of lakes, and have gained some success. But these meso-scale atmospheric models often have course spatial decision (usually kilometers), and problems such as integral overflow may take place when local topography changes very sharply [1]. Thus these models couldn't fully satisfy the requirement of precise computation of hydrodynamics in lakes. CFD based wind simulation models have strong capability in dealing with complex terrain, and can gain higher spatial resolution [2]. Thus they can simulate the influence of local topographical changes on the wind field more precisely, and have gain researchers' attention.

Lake Fuxian is located in Yuxi City, Yunnan Province, China. It has the shape of an inverted gourd, and covers an area of about 216.6km^2 when the altitude of water surface is 1722.5m. It is the 2nd deepest lake in China, with the maximum depth of 158.9m and the average depth of 95.2m. As there are small hills along the west and east banks of the lake, wind will be disturbed and then in-homogeneity may exist. This paper coupled a CFD based wind simulation model with a hydrodynamic model, to investigate how the local terrain changes affected the wind filed and its influence on the surface flow in the lake.

2. Materials and Methods

2.1. The wind model

2.1.1. Basic equations for the wind simulation model

The wind simulation model in this paper was implemented in the CFD module of COSMSOL Multiphysics® (Comsol Inc, Burlington, MA, USA), which is capable of modeling fluid dynamics in the turbulent flow regime using either the *k*-*ε* or the *k*-*ω* model, and offers user-friendly graphical interfaces for the fluid property and boundary condition settings. Here the 3D turbulent flow module was selected, in which the turbulence model type is RANS, and the turbulence model is the *k*-*ε* model. The generalized forms for the main equations were as follows [3]:

$$\rho(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\cdot\left[-p\mathbf{I} + (\mu+\mu_T)\left(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T\right) - \frac{2}{3}(\mu+\mu_T)(\nabla\cdot\boldsymbol{u})\mathbf{I} - \frac{2}{3}\rho k\mathbf{I}\right] + \mathbf{F} \qquad (1)$$

$$\nabla \cdot (\rho \mathbf{u}) = 0 \quad (2)$$

$$\rho(\mathbf{u} \cdot \nabla) k = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right] + P_k - \rho \varepsilon \quad (3)$$

$$\rho(\mathbf{u} \cdot \nabla) \varepsilon = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_e} \right) \nabla \varepsilon \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} P_k - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} \quad (4)$$

$$P_k = \mu_T \left[\nabla \boldsymbol{u} : \left(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T \right) - \frac{2}{3} (\nabla \cdot \boldsymbol{u})^2 \right] - \frac{2}{3} \rho k \nabla \cdot \boldsymbol{u} \quad (5)$$

Where $\boldsymbol{u}$ is velocity field, m/s; p is pressure, Pa; k is turbulent kinetic energy, m^2/s^2; ε is turbulent dissipation rate, m^2/s^3; ρ is density, kg/m^3; μ is the dynamic viscosity, Pa·s; μ_T is turbulent viscosity, Pa·s; C_μ =0.09; $C_{\varepsilon 1}$ =1.44; $C_{\varepsilon 2}$=1.92; σ_ε=1.3; σ_k=1.0.

2.1.2. Studying area and computational mesh

The studying area is a 50km (north to south) by 30km (west to east) rectangle, with Lake Fuxian lying in the center. Figure 1 gives the digital elevation map (DEM) of the studying area, from which it can be seen that there are high mountains along both the west and east side of the lake. The DEM data was obtained from the ASTER GDEM database (Version 2) of NASA. And its spatial resolution is about 30 meters. Then the data was imported into COMSOL to build the computational mesh. First, the DEM data was used to generate a parametric surface. Then, the parametric surface was converted into a solid area. And last, the solid one was split into mesh elements. Figure 2 gives the final mesh of the studying area, which includes 1,144,603 elements.

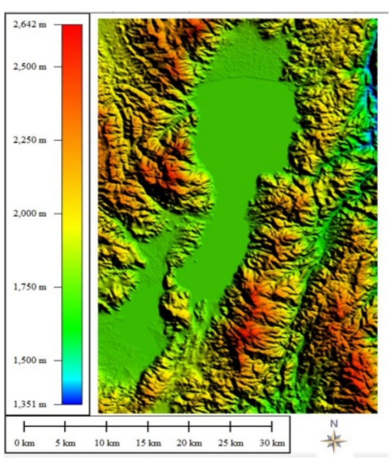


Figure 1. DEM map for the Study area

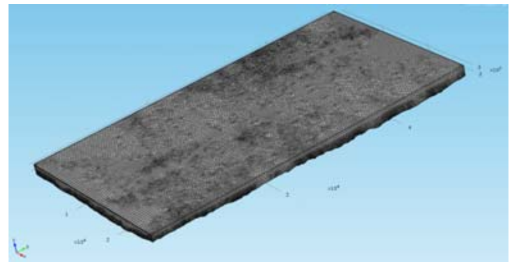


Figure 2. Computation mesh for the wind model

2.1.3. Initial and boundary conditions

In this paper, the south-wind condition was considered. The wind blew from the south to the north, with speed of 10m/s. Thus the south end was set as velocity inlet, and the north end was set as outlet. The left, right, and the top side were set as smooth solid boundary. As there was no observed vertical distribution of wind speed, a zero wind speed for the whole zone was given as the initial conditions.

2.2. The hydrodynamic model

2.2.1 Main equations

Wind-induced surface flow of the lake was simulated in MIKE3 FM, which is a software package for three dimensional hydrodynamic computations from the DHI Company. The model is based on the solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations, subject to the assumptions of Boussinesq and of hydrostatic pressure. The local continuity equation is written as [4]:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = S \quad (6)$$

And the two horizontal momentum equations for the x- and y-component are as:

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial vu}{\partial y} + \frac{\partial wu}{\partial z} = fv - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho_0}\frac{\partial p_a}{\partial x} - \frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial x} dz - \frac{1}{\rho_0 h}\left(\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xx}}{\partial y} \right) + Fu + \frac{\partial}{\partial z}\left(v_t \frac{\partial u}{\partial z} \right) + u_s S \quad (7)$$

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial wv}{\partial z} = fu - g\frac{\partial \eta}{\partial y} - \frac{1}{\rho_0}\frac{\partial p_a}{\partial y} - \frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial y} dz - \frac{1}{\rho_0 h}\left(\frac{\partial s_{yx}}{\partial x} + \frac{\partial s_{yy}}{\partial y} \right) + Fv + \frac{\partial}{\partial z}\left(v_t \frac{\partial v}{\partial z} \right) + v_s S \quad (8)$$

Where t is the time, s; x, y, and z are the Cartesian coordinates, m; u, v, and w are the velocity components in the x, y, and z direction, m/s; η is the surface elevation, m; *d* is the still water depth, m; *h* is the total water depth, m; *f* is the Coriolis parameter; ρ is the water density, kg/m^3; S_{xx}, S_{xy}, and S_{yx} and S_{yy} are the components of the radiation stress tensor; v_t is the vertical turbulent viscosity, Pa·s; P_a is the atmospheric pressure, Pa; *S* is the magnitude of the discharge due to point sources.

2.2.2. Computational mesh

Unstructured triangular mesh was used in the model. The boundary of the lake was extracted from the DEM map, and imported into the mesh generator. Then the lake area was triangulated, and interpolated and optimized with the bathymetry data. Figure 3 showed the final horizontal mesh, which included 1035 nodes and 1689 triangular elements. And there were 6 vertical layers. The relative depth (total depth was 1.00) of each layer (from the top to the bottom) was 0.05, 0.08, 0.12, 0.20, 0.25, and 0.30, respectively.

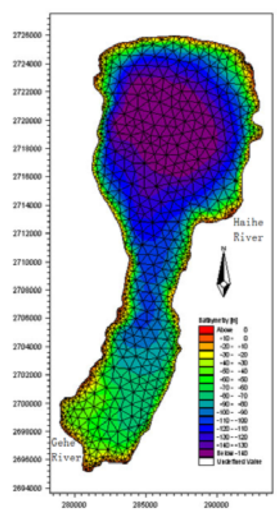


Figure 3. Horizontal mesh for the hydrodynamic model

2.2.3. Initial and boundary conditions

River inflow was neglected as the flow rates of the rivers were small. Two open boundaries were set. One is Gehe River lying on the southwest bank, and the other is Haihe River lying on the northeast bank. Their locations were shown in Fig.3. The open boundary condition was given as: z=0. And zero initial velocity was given as initial condition, i.e. u=0, v=0, w=0.

3. Results and Discussions

3.1. Wind simulation results

South wind with speed of 10m/s was simulated to investigate the effect of local terrain changes on the wind field. Figure 4 gives the horizontal wind speed profiles at different distances from the water surface. It can be seen from the figure that the horizontal variations of wind speed decrease obviously with altitude increasing. At the altitude of 1km (distance from the water surface), there're only a little differences among the whole horizontal plane. It is suggested that local terrain changes mainly affect the horizontal homogeneity of wind within 1km altitude from the water surface, as the hills on the west and east bank of the lake are all low hills, with altitude of several hundred meters. It can also be seen that wind speed near the west and east bank is small than that of the middle and the middle area is less affected where wind in-homogeneity is relatively small.

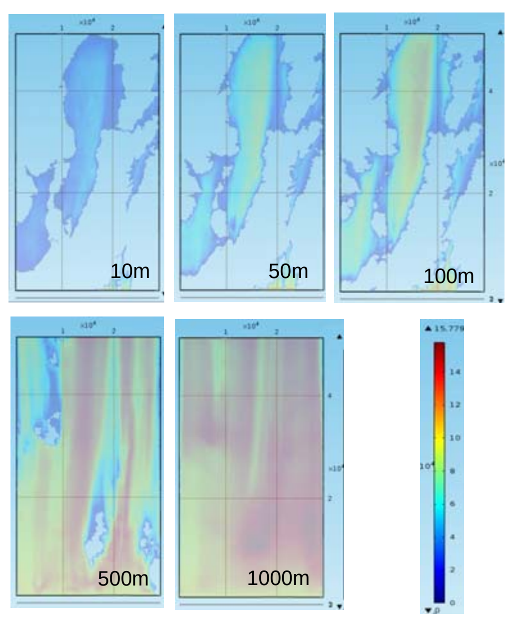


Figure 4. Horizontal profile of wind speed at different distances from the water surface

In hydrodynamic models, the wind at 10m above the water surface is usually used. Figure 5 gives the horizontal wind vector plot at 10m above the water surface. The simulation results showed that there was large in-homogeneity in the wind field on top of the water surface as a result of the local terrain conditions, where hills lie on the eastern and western banks, and the northern and southern banks are relatively plain. In the northern half lake area, wind speed was lager in the middle part than that on the two sides. Also, the wind direction on the two sides showed a small deviation from the main wind direction, i.e. south wind. While in the southern half lake area, wind direction showed an obvious deviation to the east. It is suggested that both wind speed and wind direction are affected by the local terrain, and the influences are not uniform among the horizontal plane, i.e. the influence is spatially different. And this un-uniform wind was then taken as input of the hydrodynamic model to investigate its influence on the surface flow of the lake in the next section of this paper.

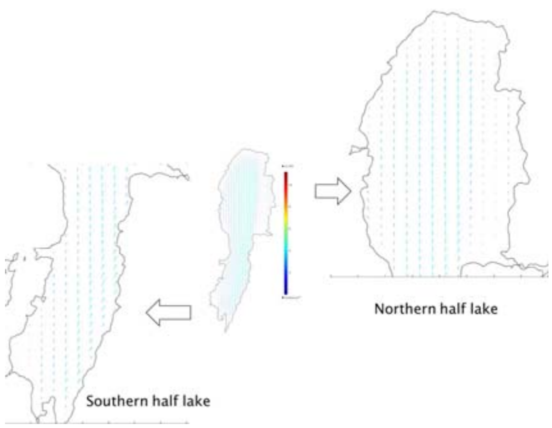


Figure 5. Horizontal wind fields at 10m above the water surface

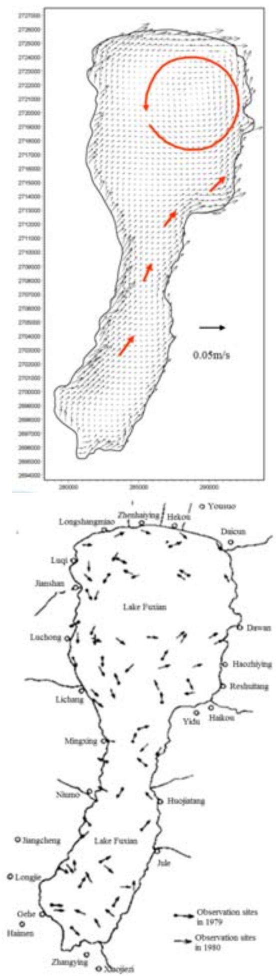
3.2. Surface flow simulation results

3.2.1. Validation of the hydrodynamic model

The hydrodynamic model was first calibrated and validated with field monitoring data. The monitoring data was from the investigation program between 1979 and 1980[5]. Here we used the most common wind (southwest wind with speed of 5m/s) for Lake Fuxian to simulate the wind condition. The simulation results and monitoring data were shown in Figure. 6. It can be seen that the simulated flow direction was nearly in agree with the monitored, where the major flow was from south to north, and there was a large counter-clockwise circumfluence in the northern half lake.

3.2.2. Comparison between uniform and un-uniform wind conditions

In order to investigate the influence of in-homogeneity of wind on the surface flow of the lake, two wind conditions were chosen: (1) uniform south wind with speed of 10m/s; (2) un-uniform wind filed from the simulated results before. The two wind conditions were separately taken as input of the hydrodynamic model, and the simulation results of surface flow were compared (see Figure 7).



(a) (b)

Figure 6. Comparison between simulation results and monitoring data, (a) simulated surface flow with SE wind of 5m/s; (b) filed data from the year of 1979-1980

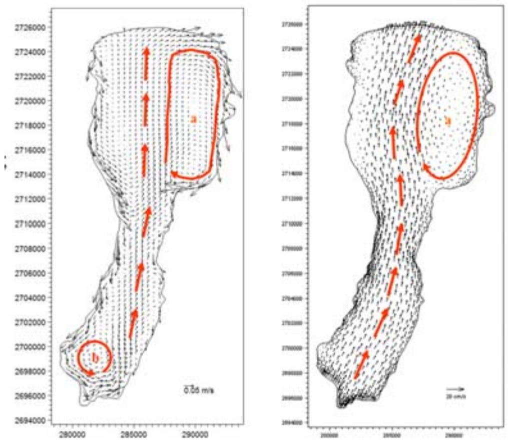


Figure 7. Comparison of simulation result for surface flow field between the two wind conditions. A. Homogeneous wind; B. In-Homogeneous wind

It could be seen that the in-homogeneity of wind obviously influenced the computational results of surface flow field in the lake. Compared to the simulation results with homogeneous wind condition, the clockwise circumfluence in the northern lake area is roughly the same, but the current direction in the middle shows a slightly deviation to the east. In the southern lake area, the main current direction is roughly the same, but the counter-clockwise circumfluence disappeared under the inhomogeneous wind condition. These results suggested that hills on the west and east sides disturbed the wind flow and lead to in-homogeneity in the wind filed over the lake surface. This in-homogeneity caused changes in the surface flow field such as current direction and circumfluence. And the southern lake area was more influenced than the northern part was.

Conclusions

In this paper, a CDF based wind simulation model and a hydrodynamic model is coupled, to investigate the in-homogeneity of wind filed caused by local topography changes and its influence on the surface flow field in Lake Fuxian. The results showed that local topographic changes could cause in-homogeneity of the wind field above the lake surface, which may then affect the surface flow of the lake such as current direction and circumfluence. Thus, this effect should be taken into account in precise modeling of hydrodynamics as well as transportation of mud and contaminants when large variations of local terrain shape occur.

Acknowledgements

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