MATEC Web of Conferences **203**, 07007 (2018) https://doi.org/10.1051/matecconf/201820307007
ICCOEE 2018

Numerical Study of the Flow Fields in the Vegetated Baihe Lake

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Abstract. Wetland is a multifunctional and biodiversity ecosystem on the earth, and it is also one of the most important living environments for human beings. Large shallow lakes play an important role in providing water and maintaining ecosystem diversity in wetlands. Vegetation growing in lakes and could affect the water flow by drag force. In the paper, a two-dimensional hydrodynamic model is developed and is applied to a large shallow lake, Baihe Lake in North China and the lattice Boltzmann method is selected as the simulation approach. The water velocity field of the lake is produced by the model and the distribution of the study area is investigated. Then, the hydrodynamic characteristics of lakes under different vegetation density are studied to find its influence on the water flow. This study provides a theoretical basis through a numerical tool for the administration of local hydraulic and ecological engineering.

1 Introduction

Aquatic vegetation, as an important part of ecosystems, is widely distributed in open channels, lakes and wetlands [1,2]. It grows on the river bank with the developed roots, which can resist the erosion of water flow and protect river banks to maintain its stability [2]. The flow characteristics of rivers or lakes are affected by many factors, such as the shape of the cross section and the topography of the river bottom. [3]. Vegetation usually makes flows more complex, the flexibility of which plays a significant role in flow regime. It can be divided into rigid vegetation and flexible vegetation. The former doesn't bend under the influence of water flow, while the latter does along the direction of water flow [4]. The bending degree of vegetation will significantly affect its resistance on water flow. Experiments show that compared with rigid vegetation, flexible vegetation will reduce the resistance to water flow [5]. Considering in the vertical direction, there are two types of vegetation, being submerged vegetation and unsubmerged vegetation [4, 5, 6]. according to the current researches, the influence of unsubmerged vegetation on water flow is more obvious [7]. It can consume energy and momentum of the water flow, helping explain that the roughness of rivers with unsubmerged vegetation is much bigger than those with less such vegetation.

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There are many wetlands in the northeast of China. In recent decades, because of the gradual shrinking of the wetland area, it is important to explore how to restore and protect the wetland [8]. There are many shallow lakes and rivers in the wetlands in northeastern China. Many kinds of aquatic vegetation in wetland and the vegetation play an important role in the water flow. Therefore, it is very important to establish the hydrodynamic model of the effect of vegetation on the water. Generally, the Environmental Fluid Dynamics Code (EFDC) and MIKE model are widely used in hydrodynamic simulation. But these model neglect the drag force by vegetation, resulting in the inaccurate simulation.

The lattice Boltzmann method (LBM) is a new numerical method to solve hydrodynamic problem. Compared with with traditional computational fluid dynamics (CFD) based on direct approach of flow equation, it proposes a new solution of flow equation [9]. The method is characterized by simple calculation, easy handling of boundary conditions. In recent years, it has become a very potentially promising approach in computational fluid dynamics. The use of lattice Boltzmann method to simulate shallow water flows such as open channel flows, tidal flows and dam-break flows are becoming more and more popular over recent decade. Guo (2002) [10] developed a thermal LBM for Boussinesq equations with BGK scheme. O'Brien et al. (2002) [11] used lattice Boltzmann scheme for reactive transport in porous media. Zhou (2007) improved the LBM for groundwater flow [12]. Tubbs and Tsai (2009) [13] deduced the parallel computation for multi-layer shallow water flows. Liu and Zhou (2014) studied the wetting-drying problems of LBM in shallow water flows [12, 14]. Yang (2017) presented rigid vegetation model based on two-dimensional shallow water equations by the lattice Boltzmann method in an open channel flow [15].

This paper aims to use lattice Boltzmann model with drag force treatment to simulate the temporal and spatial characteristics of the hydrodynamic changes in the Baihe Lake. The aquatic vegetation is treated as rigid vegetation. The results of both high and low vegetation densities are obtained and then discussed on the flow pattern.

2 Materials and methods

2.1 Study area

Momoge Wetland (45° 45'~46° 10'N, 122° 27'~124° 04'E) is the important wetland in northeastern China, as shown in Fig. 1. It is a National Nature Reserve in the east of Zhenlai County, Jilin province. The total area of the wetland is 1440 km^2. Momoge Wetland is the main migration path for northern migratory waterfowl birds in the Chinese eastern region. The region is flat, and the relative elevation is only 2–10 m (Datum: the Yellow Sea level). The dominant types of land-use are cultivated fields, grasslands and other land-use types. The wetland has a uniquely important value from the perspectives of biodiversity and habitat originality. The Baihe Lake is a typical and the largest lake in Momoge Wetland. The geographical location and topographic conditions of Baihe Lake has shown in Fig. 1. The total area of the lake is about 15.6 km^2. The drainage of farmland in the upstream protected area flows into the the lake through the inlet and then flows outinto the downstream river. The Baihe Lake is the key area in protecting stability of Momoge wetland ecosystem, with its It provides significant self-purification and biodiversity for the wetland [16].

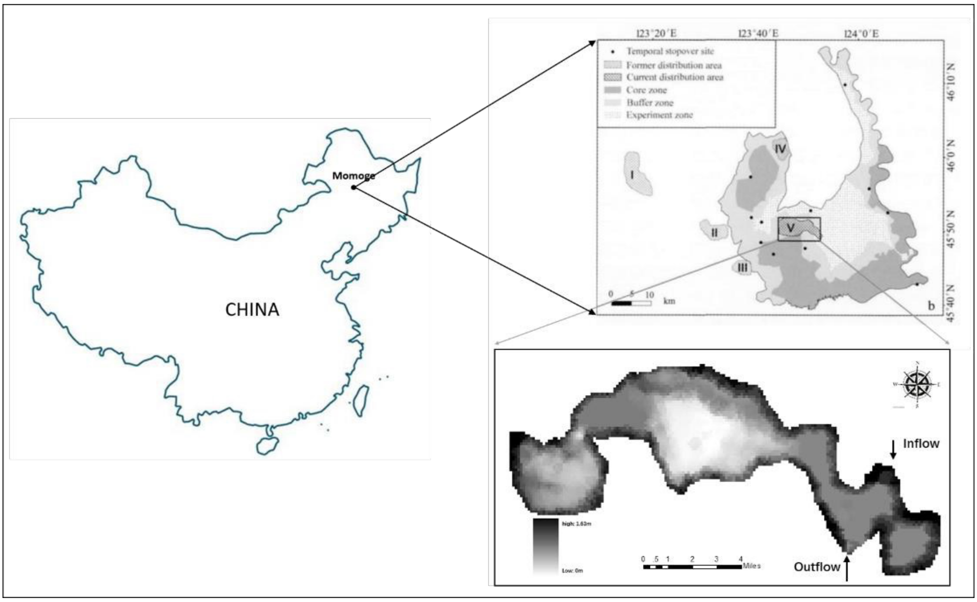

Fig.1. The geographical location and topographic conditions of Baihe Lake. The topography is determined by the basic point (45°56'N, 122°45'E).

2.2 Governing equations

The Baihe Lake is a typical shallow lake where the horizontal scale is much larger than the vertical scale [3]. Therefore, the horizontal two-dimensional hydrodynamic model can be well applied to the Baihe Lake [15]. The two-dimensional shallow water equations derived from the incompressible Navier-Stokes equations are:

$$\frac{\partial h}{\partial t}+\frac{\partial (hu_j)}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial (hu_i)}{\partial t}+\frac{\partial (hu_iu_j)}{\partial x_j}=-\frac{g}{2}\frac{\partial h^2}{\partial x_i}+\nu\frac{\partial^2 (hu_i)}{\partial x_j\partial x_j}+F_i \tag{2}$$

where t is the time; h is the water depth; the subscripts i and j are the space directions based on the Einstein summation convention; x_i and u_i are the distance and instantaneous velocity components in the i direction; g is the gravitational acceleration, which is equal to 9.81m^2/s; v is the kinematic viscosity, and F_i is the force term could be written as follows by ignoring the Coriolis force:

$$F_i=-gh\frac{\partial z_b}{\partial x_i}+\frac{\tau_{wi}}{\rho}-\frac{\tau_{bi}}{\rho}+S_{vi} \tag{3}$$

where z_b is the bed elevation; ρ=1000kg/m^3 is the water density; τ_{wi} is the wind shear stress that can be expressed as:

$$\tau_{wi}=\rho_a c_w u_{wi}\sqrt{u_{wj}u_{wj}} \tag{4}$$

where ρ_a is the air density, c_w is the resistance coefficient, u_{wi} and u_{wj} are the wind velocity in i and j direction. τ_{bi} is the bed shear stress can be expressed as:

$$\tau_{bi} = \rho c_b u_i \sqrt{u_j u_j} \tag{5}$$

In which c_w is the bed friction coefficient can be calculated by $c_b=gn^2/h^{1/3}$, n is Manning's coefficient at the bed.

2.3 Drag force caused by aquatic vegetation

There are large numbers of vegetation in the Baihe Lake, such as reed and bulrush. The vegetation with high toughness is generally higher than the water free surface. This type of vegetation can be simplified as unsubmerged rigid vegetation [6].

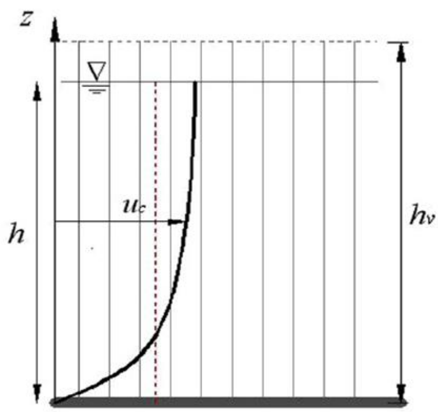

Fig.2. Flow over unsubmerged rigid vegetation.

Yang (2017) presents rigid vegetation model based on two-dimensional shallow water equations. In case of unsubmerged rigid vegetation, the magnitude of velocity in the entire water-vegetation body is significantly affected [15, 17]. We treated it as vertical cylinder. The drag force caused by the vegetation can be expressed as:

$$S_{vi} = \frac{1}{2} \lambda C_d h u_{vi} \sqrt{u_{vj} u_{vj}} \tag{6}$$

where C_d is drag force coefficient and usually in the range of 1and1.2; u_{vi} is the apparent velocity on the vegetation elements in the i direction; λ is the projected area of vegetation normal per unit volume of water are calculated by

$$\lambda = \frac{4\alpha_v c}{\pi D_v} \tag{7}$$

where α_v represent shape factor, c is density of the vegetation zones (%), D_v is the vegetation stems diameter. u_{vi} is equal to the average velocity u_i.

2.4 Lattice Boltzmann method

In this paper, the lattice Boltzmann method (LBM) for two-dimension shallow water equation with the vegetation drag force is used. There are three main components in lattice Boltzmann method: the kinetic equation, the lattice pattern, and the equilibrium distribution [18].

$$f(x+e_\alpha \Delta t, t+\Delta t) = f_\alpha(x,t) - \frac{1}{\tau_t}[f_\alpha(x,t) - f_\alpha^{eq}(x,t)] + \Delta t F_\alpha \tag{8}$$

where f_α is the particle distribution function; e=Δx/Δt; Δx is the lattice size; Δt is time step; the external force F_α is calculated by:

$$F_\alpha = \frac{1}{6e^2} e_{\alpha i} F_i \tag{9}$$

According to the method proposed by Zhou [19], F_α can be written as

$$F_\alpha = 3\omega_\alpha \frac{1}{e^2} e_{\alpha i} F_i \tag{10}$$

where ω_α is the weigh factor: ω_α=4/9 for α=0; ω_α=1/9 for α=1, 3, 5, 7; ω_α=1/36 for α=2, 4, 6, 8.

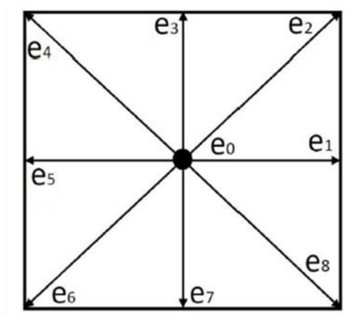

Fig.3. D2Q9 lattice pattern.

$e_{\alpha i}$ is the particle velocity in the *i* direction. The nine-velocity square lattice has shown in Fig.3. Each particle moves one lattice unit at its velocity along the eight links represented by numbers 1-8, while 0 represents a particle at rest with zero speed. The velocity vector of the particles is defined by

$$e_\alpha = \begin{cases} (0,0) & \alpha=0 \\ e\left[\cos\frac{(\alpha-1)\pi}{4}, \sin\frac{(\alpha-1)\pi}{4}\right] & \alpha=1,3,5,7 \\ \sqrt{2}e\left[\cos\frac{(\alpha-1)\pi}{4}, \sin\frac{(\alpha-1)\pi}{4}\right] & \alpha=2,4,6,8 \end{cases} \tag{11}$$

The local equilibrium distribution function f_α^{eq} is defined as

$$f_\alpha^{eq}=\begin{cases} h-\dfrac{5gh^2}{6e^2}-\dfrac{2h}{3e^2}u_iu_i, & \alpha=0 \\ \dfrac{gh^2}{6e^2}+\dfrac{h}{3e^2}e_{\alpha i}u_i+\dfrac{h}{2e^4}e_{\alpha i}e_{\alpha j}u_iu_j-\dfrac{h}{6e^2}u_iu_i, & \alpha=1,3,5,7 \\ \dfrac{gh^2}{24e^2}+\dfrac{h}{12e^2}e_{\alpha i}u_i+\dfrac{h}{8e^4}e_{\alpha i}e_{\alpha j}u_iu_j-\dfrac{h}{24e^2}u_iu_i, & \alpha=2,4,6,8 \end{cases} \tag{12}$$

The macroscopic variables--water depth h and flow velocity u_i can be expressed:

$$h=\sum_\alpha f_\alpha, \qquad u_i=\frac{1}{h}\sum_\alpha e_{\alpha i}f_\alpha \tag{13}$$

2.5 Boundary conditions

A general treatment at the inlet has constant velocity and water depth. Also, a specified water depth is imposed at the outlet, while the velocity components u and v are obtained through a zero-gradient condition [14, 20].

The basic method of boundary conditions called bounce-back scheme is that an incoming particle towards the boundary is bounced back into the fluid. At the upper boundary:

$$f_6=f_2, f_7=f_{3,} f_8=f_4 \tag{14}$$

Also, at the lower boundary:

$$f_2=f_6, f_3=f_{7,} f_4=f_8 \tag{15}$$

A special situation in boundary conditions is that the grids in corner, as shown in Fig. 4. At the boundary corner point, there will be multiple directions without particle input due to the proximity of the model boundary. It cannot be calculated by bounce-back scheme or macro variable boundary conditions. It is necessary to calculate the missing particle distribution according to the depth and velocity of the adjacent grids. The computational formula can be expressed as:

$$\begin{cases} f_1=\dfrac{2h_{x+1,y+1}u_{x,y}}{3e}+f_5, \\ f_2=f_6+\dfrac{h_{x+1,y+1}u_{x,y}}{6e}+\dfrac{h_{x+1,y+1}v_{x,y}}{2e}, \\ f_3=f_7, \\ f_4=\dfrac{1}{2}(h_{x+1,y+1}-f_1-f_2-f_3-f_5-f_6-f_7-f_9), \\ f_8=f_4\text{。} \end{cases} \tag{16}$$

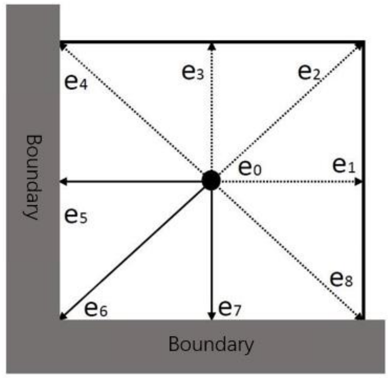

Fig.4. Grids in corner.

3 Results

3.1. Initial condition

The drainage of farmland converges with inlet and discharge into the Baihe Lake at an average rate of 0.53 m/s from May 11, 2017 to June 25 and an average rate of 0.32 m/s from October 10, 2017 to November 21, 2017. A 2D hydrodynamic model was established by using lattice Boltzmann method. The Manning's roughness is set to 0.025. The wind speed in the lake ranges from 1 m/s to 3.5 m/s and the average speed is equal to 1.78 m/s in the northeast direction.

3.2. Vegetation distribution

Figure 5 is the vegetation distribution obtained by geographic information system and field investigation. There are a large number of reeds in Baihe Lake, which are higher than the water surface and have high rigidity. From the figure, it could be seen that the vegetation is mainly distributed in the northwest and southeast of the lake. It could be found that vegetation density is significantly different in different mouths and the density is greatest from July to August and the minimum in January to March. In order to confirm the effect of drag force caused by the vegetation, two situations, involving high and low vegetation density, are tested in the model. In order to study the effect of different vegetation density on the flow field, two simulations are considered in this paper. For high vegetation density, c is 0.2; and for low density, c is 0.03. In the computation, vegetation element shape factor and drag coefficient C_d is equal to 1.0.

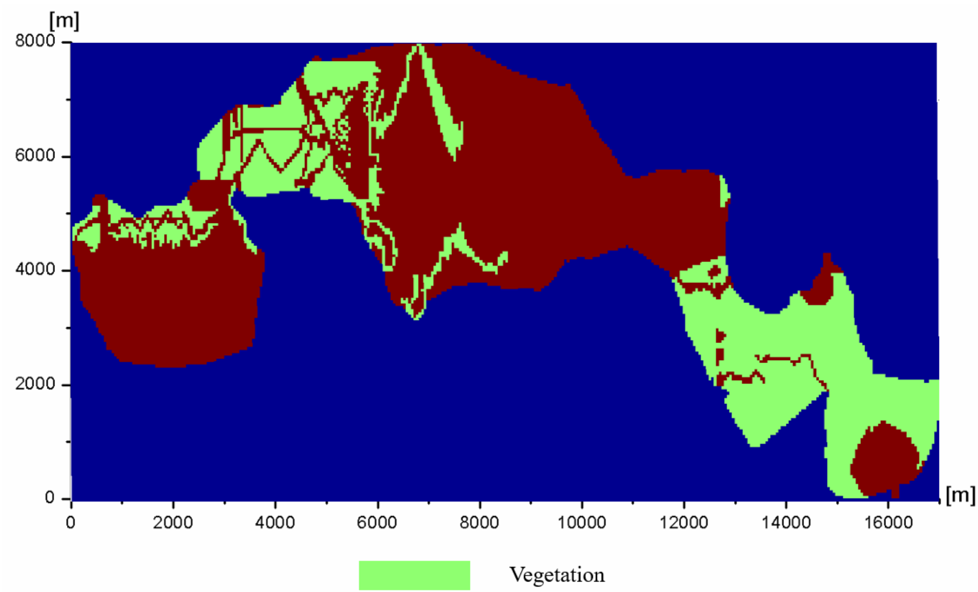

Fig.5. The vegetation distribution in the Baihe Lake.

3.3. Numerical tests

In the model, the Baihe Lake is covered by 50 m*50 m grids. The inflow velocity is given by 0.5 m/s. The initial water depth is shown in Fig.6. Overall, water depth in the western and eastern parts of the lake is relatively shallow compared with that in the middle area. The average water depth is 1.4 m, and the deepest area is 2.14 m.

The study simulates the flow field with time from one day to five days to discuss the hydrodynamic characteristics in the lake. Figure.6 presents the flow field in the Baihe Lake after 5 days for c=0.2. The water velocity field presents a special distribution form：

(1) The western part of the lake is far away from the inlet, so the velocity of water flow is very slow. The average velocity is about 0.16 cm/s and the water depth is 1.32m.

(2) The middle part of the lake is the main area for local fishermen. It has sparse vegetation and water is deep. The average velocity is about 0.36 cm/s and the water depth is 1.89m.

(3) A large amount of vegetation is distributed in the southeast part of the lake. The velocity of the flow is slow except for the outlet or inlet. The velocity is about 0.026 m/s in outlet and in inlet is about 0.063 m/s. The average velocity in other area is about 0.32 cm/s.

Figure8 presents water velocity fields with two situations about high vegetation density (c=0.2) and sparse density (c=0.03) in the southeast area of the lake. It can be seen that the velocity with high density (average rate is 0.32cm/s) is slower than sparse density (average rate is 0.28cm/s). Figure9 denotes the water depth and the velocity near the outlet of the Baihe Lake. The simulated time is from 1 day to 5 days. From the figure, the slope of the high density is flat than that of low density. In addition, the flow velocity of high density is faster than the low. At 200000 seconds, the flow rate of high density is 0.405 m/s and 0.451 m/s of sparse density. This situation indicates that vegetation drag force as an external force can significantly affect the water flow [21].

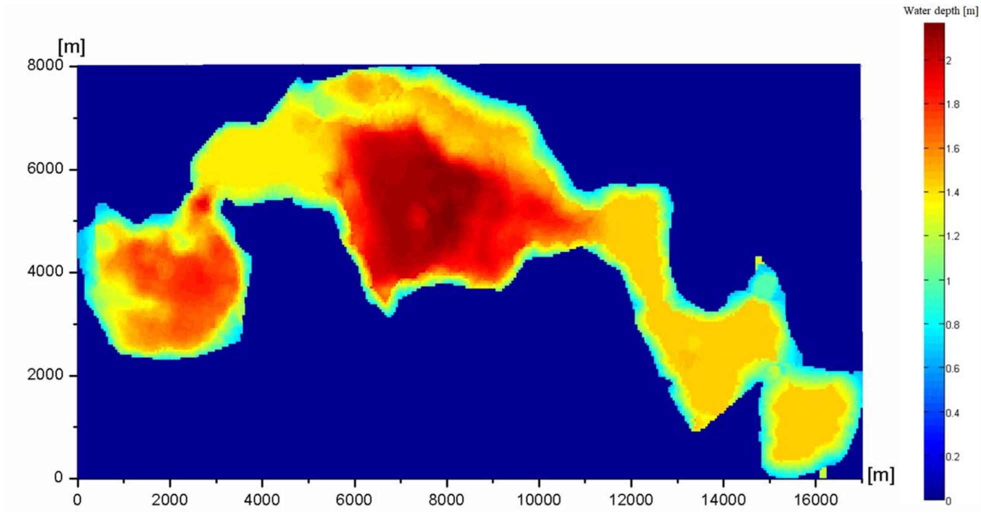

Fig.6. Initial water depth in Baihe Lake.

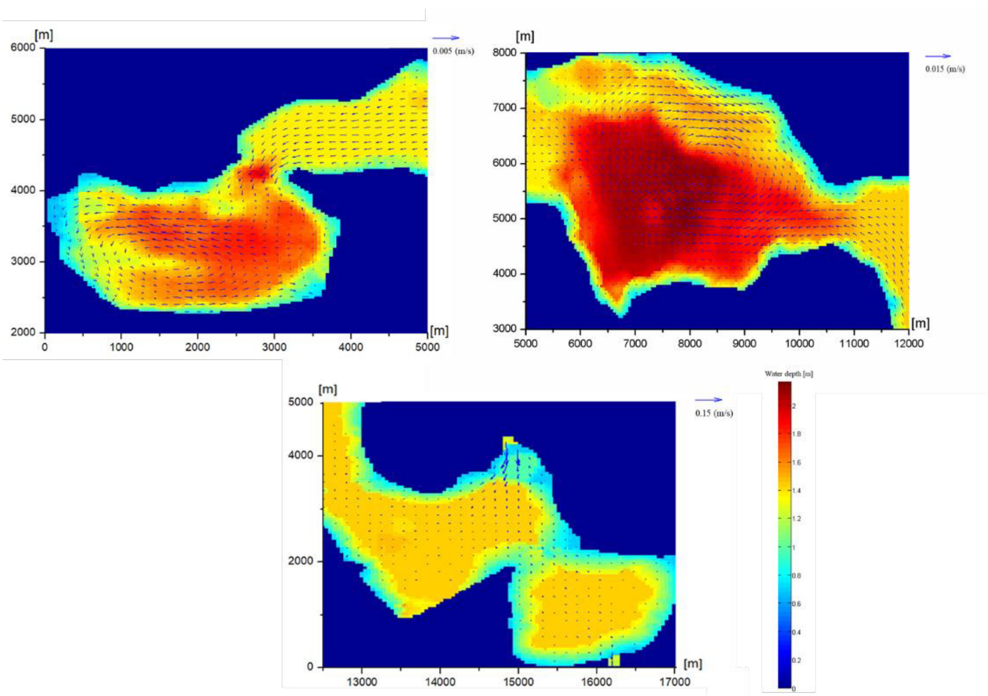

Fig.7. Water depth and velocity figures after 5 days (c=0.2).

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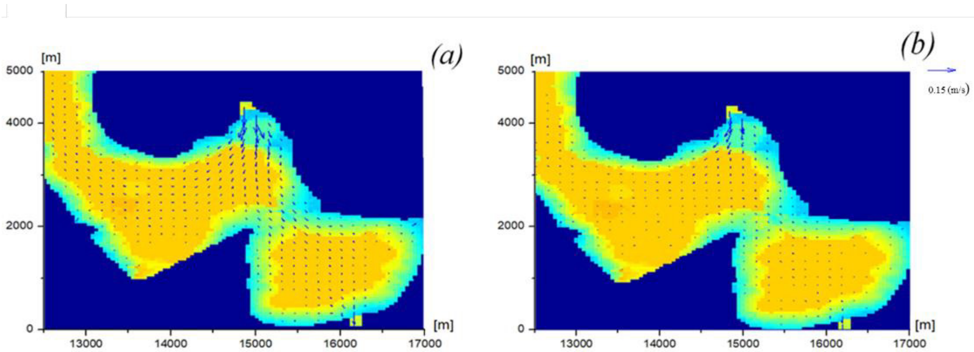

Fig.8. Water velocity fields with two situations ((a) low density (c=0.03) and (b) high density (c=0.2)) in southeast area of the Baihe Lake after 5 days.

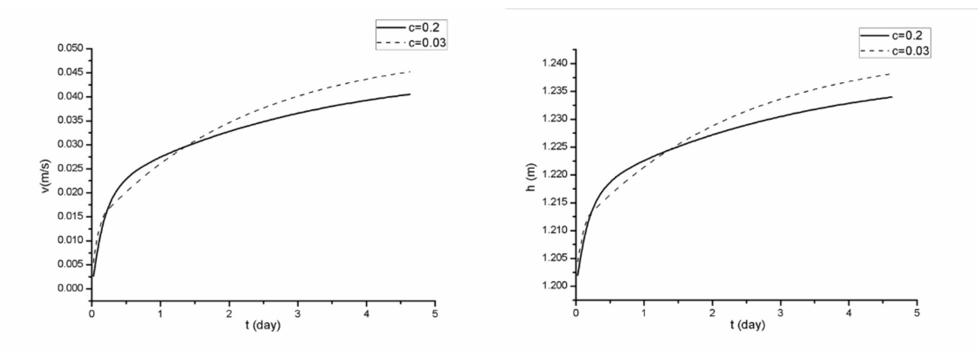

Fig.9. Comparison of the simulated results with high vegetation density (c=0.2) and low vegetation density (c=0.03) in outlet: (a) Case 1 (water velocity); (b) Case 2 (water depth).

4 DISCUSSION

Because of the specificity of the hydrological and geographical conditions of the lake, the simulation results show the particularity of the flow field in the Baihe Lake. From Fig. 7, both the outlet and the inlet of the lake are located in the southeast corner of the lake and most of the water bodies are far away from the region. Therefore, as a whole, the hydrodynamic conditions of the lake and the hydrological connectivity of the various parts of the lake are poor, and the flow velocity is relatively low. The Baihe Lake is an important lake in the Momoge wetland, and it connects with the local farmland at the entrance of the lake. The water of drainage from farmland is rich in various organic materials [3]. Considering the lack of water exchange of the Baihe Lake, it can be presumed that the polluted water stays in the lake for a long time, which will threaten the overall water quality. On the other hand, it can be seen that there are a lot of aquatic vegetation in the lake by vegetation distribution figure (mainly Reed). Stephan and Gutknecht (2002) proved that vegetation can significantly affect the flow velocity [4]. Stone and Shen (2002) established a mathematical model of vegetation and demonstrated the effect on water flow through analytical solution [17]. Different from the above methods, this paper attempts to use a new numerical simulation method to study the shallow water distributed in vegetation. Compared with the distribution figure of water velocity after 5 days, the velocity in the region with vegetation distribution and its surrounding area is obviously smaller than that in the region without vegetation distribution. Thus, the drag force of vegetation on the water body hinders the flow, which is reflected by external force in the model [22]. By analyzing the flow field in two cases in Fig. 8, we can conclude that the vegetation obviously reduces the flow velocity and reduces the fluidity of lake. Figure 9 reflects the effect of vegetation on lake flow field under different vegetation densities. From the result of simulation, the density of vegetation can affect the water flow, the velocity of water flow with high vegetation (c=0.2) density is smaller than with low vegetation (c=0.03) density. It can be seen from the results that the aquatic vegetation can significantly affect the flow velocity distribution of the lake [8, 21, 22]. Therefore, it is necessary to accurately determine the specific distribution of the vegetation and consider the density of the vegetation in the distribution area which plays an important role in improving the applicability and accuracy of the model. Also, it can be deduced that the influence of vegetation on water flow under the condition of high vegetation density in spring and summer is greater than that the condition of sparse vegetation in autumn and winter. If other conditions unchanged, vegetation density can obviously affect the velocity of flow.

5 CONCLUSION

In this study, a two-dimensional hydrodynamic model for a vegetated shallow lake was setup through lattice Boltzmann method. The resistance caused by vegetation is taken into consideration. Overall, the flow velocity is relatively small except for those areas near the inlet and outlet, as the normal inflow and outflow rates are low. The results also show that the velocity in the region distributed with vegetation is obviously smaller than that without vegetation. The density of vegetation can obviously affect the water flow velocity, characterized by that water flow with high vegetation (c=0.2) density is smaller than that with low vegetation (c=0.03) density. This numerical tool can be further developed to analyze and consider local different scenarios of local engineering operations and economic development.

The financial supports of the National Key R&D Program (2016YFC0500402) and the National Natural Science Foundation of China (51779011) are gratefully acknowledged.

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