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A numerical model to simulate the vertical velocity distribution in an open channel with double-layered rigid vegetation

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ABSTRACT

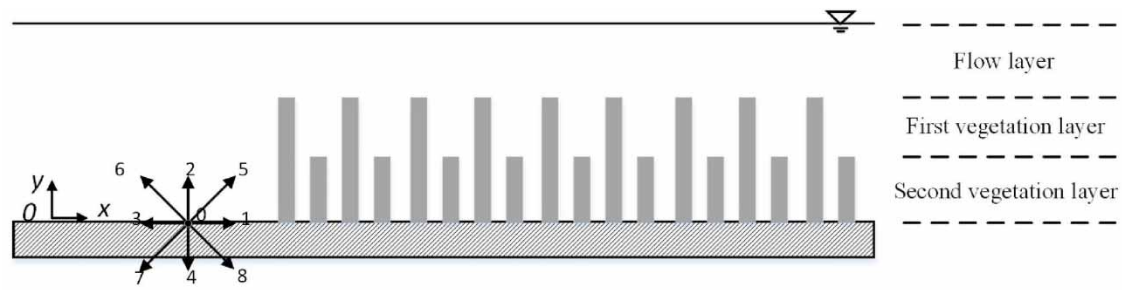
Vegetation flow is more and more widely studied by scholars at home and abroad because it is an important condition affecting river water quality. However, most of the studies were carried out based on the data of indoor experimental flumes, because the vegetation conditions in nature are more complex. The analytical solution of the flow velocity based on indoor conditions often has some problems when applied to practical projects. Therefore, we propose a numerical method based on the lattice Boltzmann method to simulate the vertical velocity distribution in an open channel with double-layered rigid vegetation. This method has high simulation accuracy in different vegetation conditions. At the same time, because the lattice Boltzmann method is more conducive to simulating complex boundary conditions, it is easier to combine with a multi-layered rigid vegetation flow and a flexible vegetation flow in nature after improvement, providing a basis for the application of indoor theoretical results to the outdoor.

Key words: complex boundary conditions, double-layered rigid vegetation, Lattice Boltzmann method, numerical model, vertical velocity distribution

HIGHLIGHTS

- This method has a high simulation accuracy in different vegetation conditions.
- It is helpful to study hydrological processes in the vegetation river.

GRAPHICAL ABSTRACT



INTRODUCTION

In recent years, the international river pollution problem has become more and more serious, which has a relatively important impact on human production and life (Li *et al.* 2021; Zhang *et al.* 2021; Alam *et al.* 2023). Therefore, more and more measures have been applied to the study of river water quality, among which plating vegetation is an effective method of improving water quality (Devi *et al.* 2019; Unigarro Vilotta *et al.* 2022; Cui *et al.* 2023). Vegetation in the river can effectively slow down the velocity of the river, prolong the retention time of the river water body, and increase the absorption of excessive nutrients in the water body by vegetation and bed sediment (Bundschuh *et al.* 2016; Soana *et al.* 2017). Meanwhile, the vegetation may be associated with conditions of excessive eutrophication of the river waters. There is a remarkable congruence between the results of our floodplain vegetation analysis and the longitudinal river eutrophication patterns (Mölder & Schneider 2011).

Hydrodynamic characteristic is one of the research focuses in the vegetation river, which are closely related to the stability of the river structure and the transport of pollutants (Liu *et al.* 2022; Rao *et al.* 2022). Rigid vegetation is a kind of river vegetation, which has also been widely studied by previous scholars (Ratha *et al.* 2018; Caroppi *et al.* 2021). The most common forms of rigid vegetation flow are submerged vegetation flow and emergent vegetation flow. As shown in Figure 1, the velocity in rivers with rigid emergent vegetation is relatively stable (D'Ippolito *et al.* 2019). In the submerged vegetation flow, the velocity in the vegetation layer is relatively stable (Ren *et al.* 2021). However, the riverway vegetation in nature is not uniform in height, and there may be certain height differences between different types of vegetation, thus forming a double-layer vegetation flow (Rao *et al.* 2022). Following the previous research, it can be divided into double-layer submerged vegetation flow and double-layer emergent vegetation flow (Huai *et al.* 2014). Double-layer emergent vegetation flow has a relatively steep velocity transition at the intersection of different vegetation areas, and the velocity in the vegetation area tends to be uniform (Wang *et al.* 2023). The double-layer vegetation submerged flow has the same law as the double-layer vegetation emergent flow in the vegetation area, and the velocity in the non-vegetation layer is basically the same as that in the conventional non-vegetation channel (Tang *et al.* 2021).

The drag force of vegetation has a significant impact on the velocity distribution in a rigid vegetation channel, and the velocity in vegetation area will be uniform (Liu & Zeng 2017). Kumar & Sharma (2022) evaluated and compared the turbulent

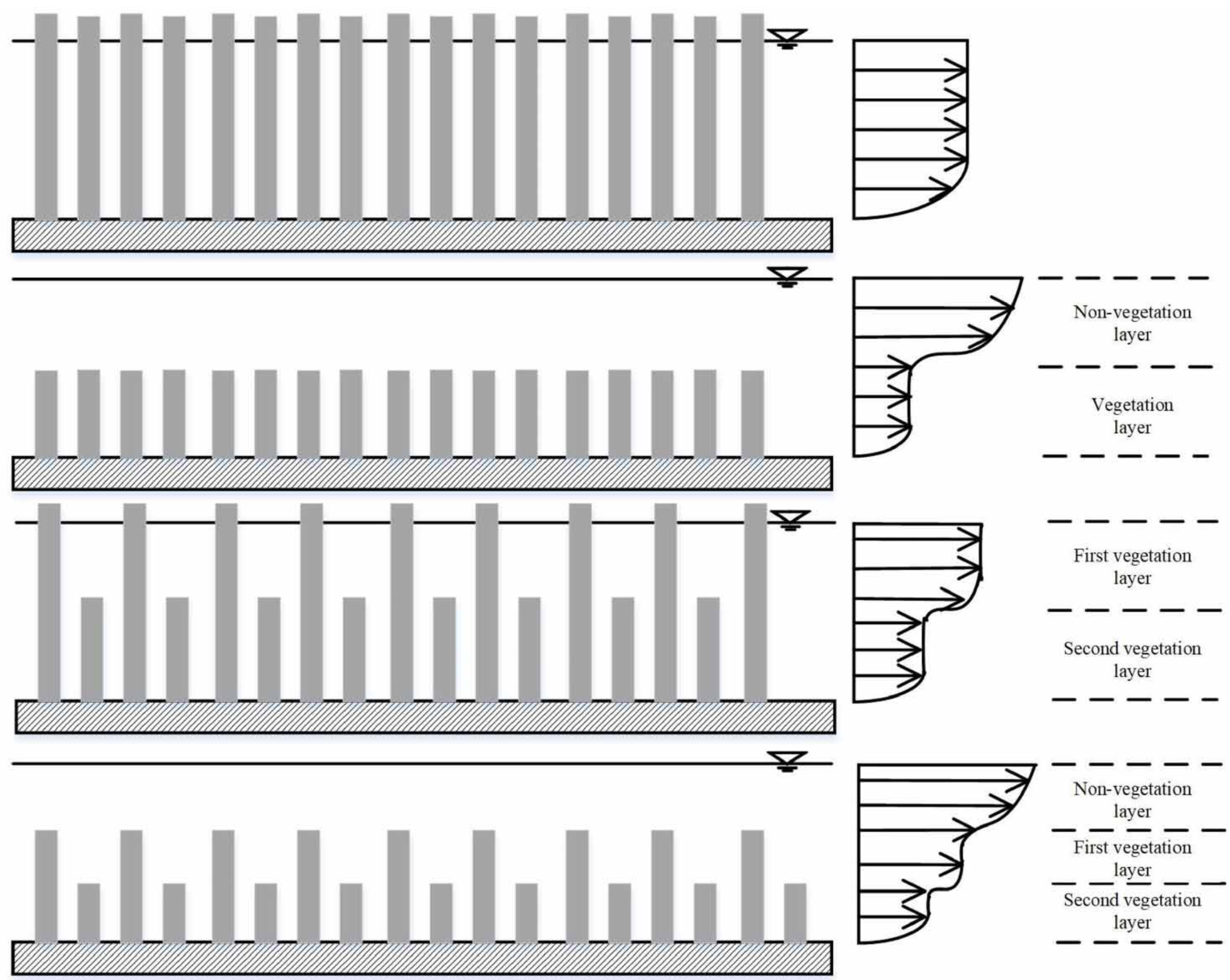


Figure 1 | Flow velocity distribution of different rigid vegetation experiments.

kinetic energy, skewness, and kurtosis of the vegetation area in the emergent vegetation channel, and proved that the presence of vegetation reduced the longitudinal distribution of Reynolds flow, shear stress, and turbulence intensity. The submerged vegetation will form a certain shear vortex at the interface between vegetation and non-vegetation layers, which will cause rapid changes in the velocity at the interface. On this basis, Huai *et al.* (2009) gave the analytical solution of the vertical distribution of velocity in the submerged vegetation channel in combination with the flume experimental study. For a double vegetation flow, Huai *et al.* (2014) analyzed the momentum equation in vegetation and non-vegetation layers, and finally gave the analytical solution of velocity in different layers.

Although the analytical solution can provide accurate velocity distribution, the solution process is relatively complex. At the same time, if the vegetation layout conditions in the river are more complex, such as there are more than two layers of vegetation distribution, or the vegetation is flexible or uneven, the analytical solution is difficult to apply. In order to better apply the theoretical results to practice, it is necessary to establish a numerical model. In view of this problem, this paper establishes a two-layer vegetation velocity distribution model based on the lattice Boltzmann method. This model can better simulate complex boundary conditions, and can easily add a water quality transport module, which provides help for simulating the velocity and pollutant transport of vegetated river under natural conditions.

NUMERICAL MODEL

Governing equations

To solve the hydrodynamic control equation of the vegetation channel, the channel needs to be divided into two areas, one is the water flow area, where the resistance of the water flow is mainly caused by the riverbed, and the other is the vegetation area, where the resistance of the water flow is mainly caused by the bottom slope roughness and vegetation system. According to the Navier–Stokes equation, the hydrodynamic formulas of water flow layer and vegetation layer can be expressed as Equations (1) and (2) (Rao *et al.* 2014):

$$\frac{\partial u_i}{\partial t}+\frac{\partial(u_iu_j)}{\partial t}=(\nu+\nu_e)\frac{\partial^2 u_i}{\partial x_jx_j}-g\frac{\partial z_b}{\partial x_i}-S_{bi} \tag{1}$$

$$\frac{\partial u_i}{\partial t}+\frac{\partial(u_iu_j)}{\partial t}=(\nu+\nu_e)\frac{\partial^2 u_i}{\partial x_jx_j}-g\frac{\partial z_b}{\partial x_i}-S_{bi}-S_{fi} \tag{2}$$

where the Einstein summation convention over Latin indices is adopted; t denotes the time; u_i is the velocity; ν and ν_e represent kinematic and eddy viscosity, respectively; z_b is the bed elevation.

S_{bi} is the bed shear stress term in i direction and is expressed as a Manning formula:

$$S_{bi}=\frac{gn^2}{h^{1/3}}u_i\sqrt{u_ju_j} \tag{3}$$

where n refers to the Manning's coefficient, and h is the water depth.

S_{fi} is the drag force of vegetation which can be obtained by Huai *et al.* (2012):

$$S_{fi}=\frac{1}{2}C_Dau_i^2 \tag{4}$$

where C_D is the coefficient of the rigid vegetation which can be assumed as 1 (Wu *et al.* 1999), a is the vegetation density coefficient and $a=\alpha\times d$, α is the vegetation density, d is the diameter of the vegetation.

Lattice Boltzmann method

The lattice Boltzmann model is used to simulate the channel hydrodynamic changes under the action of vegetation. As a new numerical simulation method, the lattice Boltzmann model is a mesoscopic method between the micro method and the macro method, which is easy to program and is easy to use for complex boundary conditions (Thorimbert *et al.* 2019; Xu & Yan 2023). The lattice Boltzmann method is mainly divided into two processes: collision process and migration process.

These two processes can be expressed by the following equation:

$$f_\alpha(x + e_\alpha \Delta t,\ t + \Delta t) = f_\alpha(x,\ t) - \frac{1}{\tau_t}[f_\alpha(x,\ t) - f_\alpha^{eq}(x,\ t)] + \frac{\Delta t}{N_\alpha e^2} e_{\alpha i} F_i \quad (5)$$

where f_α represents the distribution function of particles; f_α^{eq} is the local equilibrium distribution function; x is the space vector in Cartesian coordinates; $e = \Delta x/\Delta t$; Δx is the lattice size; Δt is the time step; τ_t is the total relaxation time parameter; F_i denotes the external forces.

N_α is a constant which can be defined as follows:

$$N_\alpha = \frac{1}{e^2}\sum_\alpha e_{\alpha i} e_{\alpha i} \quad (6)$$

This simulation adopts the two-dimensional lattice Boltzmann model D2Q9 lattice pattern (Figure 2), $e_{\alpha i}$ can be obtained as:

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

The local equilibrium distribution function f_α^{eq} can be expressed as:

$$f_\alpha^{eq} = \begin{cases} 1 - \frac{5g}{6e^2} - \frac{2}{3e^2}u_i u_i, & \alpha = 0 \\ \frac{g}{6e^2} + \frac{1}{3e^2}e_{\alpha i}u_i + \frac{1}{2e^4}e_{\alpha i}e_{\alpha j}u_i u_j - \frac{1}{6e^2}u_i u_i, & \alpha = 1,\ 3,\ 5,\ 7 \\ \frac{g}{24e^2} + \frac{1}{12e^2}e_{\alpha i}u_i + \frac{1}{8e^4}e_{\alpha i}e_{\alpha j}u_i u_j - \frac{1}{24e^2}u_i u_i, & \alpha = 2,\ 4,\ 6,\ 8 \end{cases} \quad (8)$$

For the relaxation time parameter τ_t, the following formula can be used by Liu *et al.* (2010):

$$\tau_t = \frac{\tau + \sqrt{\tau^2 + 18C_s^2/(e^2)\sqrt{\prod ij \prod ij}}}{1} \quad (9)$$

$$\prod ij = \sum_\alpha e_{\alpha i} e_{\alpha j}(f_\alpha - f_\alpha^{eq}) \quad (10)$$

where τ denotes the single-relaxation time and C_s is the Smagorinsky constant.

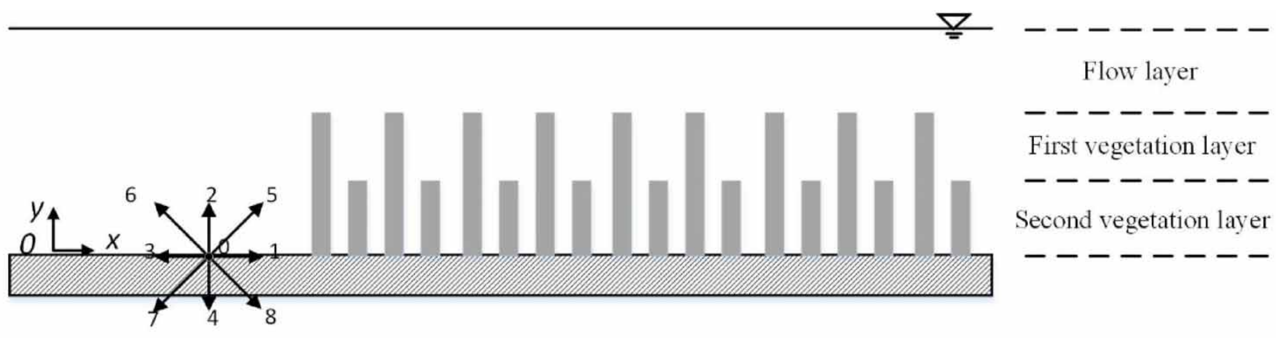


Figure 2 | Distribution functions at the boundaries.

The external forces F_i can be expressed in non-vegetation layer and vegetation layer as follows:

$$\begin{cases} F_i = -g\dfrac{\partial z_b}{\partial x_i} - \dfrac{gn^2}{h^{\frac{1}{3}}}u_i\sqrt{u_j u_j} & \text{Non-vegetation layer} \\ F_i = -g\dfrac{\partial z_b}{\partial x_i} - \dfrac{gn^2}{h^{\frac{1}{3}}}u_i\sqrt{u_j u_j} - \dfrac{1}{2}C_D a_1 u_i^2 & \text{First vegetation layer} \\ F_i = -g\dfrac{\partial z_b}{\partial x_i} - \dfrac{gn^2}{h^{\frac{1}{3}}}u_i\sqrt{u_j u_j} - \dfrac{1}{2}C_D a_2 u_i^2 & \text{Second vegetation layer} \end{cases} \tag{11}$$

where a_1 is the vegetation density coefficient of the first vegetation layer and a_2 is the vegetation density coefficient of the second vegetation layer.

The external force term is assessed at the mid-point between the lattice point and its neighboring lattice point as:

$$F_{\alpha i} = F_{\alpha i}\left(x_i + \frac{1}{2}e_{\alpha i}\Delta t,\ t\right) \tag{12}$$

Boundary conditions

The lattice Boltzmann method needs to set each boundary of the channel, and select the inlet with a constant velocity, the unknown distributions f_1, f_5 f_8 are ascertained by Liu *et al.* (2012):

$$f_1 = f_3 + \frac{2u}{3}rhow \tag{13}$$

$$f_5 = f_7 + \frac{u}{6}rhow \tag{14}$$

$$f_8 = f_6 + \frac{u}{6}rhow \tag{15}$$

$$rhow = \frac{(f_9 + f_2 + f_4 + 2(f_3 + f_6 + f_7))}{(1 - u)} \tag{16}$$

Free outflow conditions for the outlet selection, the unknown distributions f_1, f_5, and f_8, are expressed as (Mohamad 2012):

$$f_1 = 2f_1(x-1) - f_1(x-2) \tag{17}$$

$$f_5 = 2f_5(x-1) - f_5(x-2) \tag{18}$$

$$f_8 = 2f_8(x-1) - f_8(x-2) \tag{19}$$

At the water surface boundary, the unknown distribution functions are expressed as (Mohamad 2012):

$$f_i = f_i(y-1) \tag{20}$$

where r refers to a constant $(0 \le r \le 1)$, $i = 1 - 9$.

At the channel bed boundary, the unknown distribution functions f_2, f_5, and f_6 can be ascertained as (Mohamad 2012):

$$f_2 = f_2(y+1) \tag{21}$$

$$f_5 = f_5(y+1) \tag{22}$$

$$f_6 = f_6(y+1) \tag{23}$$

The simulation steps are as follows:

1. Establish initial conditions.
2. Simulation of particle migration.

3. Redistributing particles.
4. Judge whether it is over, and output the results when it is over; otherwise, continue the particle migration.

DATA SOURCE

We have verified our model based on the data of previous researchers, including emergent vegetation flow, submerged vegetation flow, emergent double-layer vegetation flow, and submerged double-layer vegetation flow. We list the data sources and basic parameters in Table 1. The average velocity and turbulence characteristics were measured using a 3D micro ADV. The sampling time for each measurement is 60 s, and the sampling rate for each measurement point is 200 Hz, which ensures sufficient accuracy. The experimental structure is shown in Figure 3.

MODEL APPLICATION

We used the model to simulate the velocity of the river with different rigid vegetation arrangements, which proves that the model is not a dedicated model and can be applied to different rigid vegetation conditions. Figure 4 shows the simulation results of the flow velocity in rigid emergent vegetation channels. It is found that the model can better simulate the vertical distribution of the flow velocity in vegetation areas. Figure 5 shows the simulation results of the flow velocity of the rigid submerged vegetation channel. The model overestimates the flow velocity at the bottom of the channel, and the flow velocity in the flow part is greatly different from the measured value. According to the theory, the velocity of the submerged vegetation channel in the flow area should increase gradually, which may be caused by turbulence in the velocity measurement due to some factors in the experiment. Figure 6 shows the velocity simulation diagram of a double-layer rigid emergent vegetation channel. It can be seen that the model can better simulate the vertical velocity distribution in the rigid vegetation area, and there is a relatively smooth velocity transition zone between different layers. Figure 7 shows the velocity simulation diagram of a double-layer rigid submerged vegetation channel. It can be seen that the model can better simulate the vertical velocity distribution in the rigid vegetation area, and the velocity growth in the non-vegetation layer is obvious.

DISCUSSION

There are many factors affecting the accuracy of model simulation. The first is the drag coefficient of vegetation (Wu 2008; Kothyari *et al.* 2009; Liu *et al.* 2020). The research on the drag force coefficient of rigid vegetation has been relatively common. It is generally believed that C_D with the characteristic Reynolds number between 800 and 8,000 is 1. In this paper, the Reynolds number ranged from 1,850 to 7,822. If the characteristic Reynolds number is large or small, the value of the drag force coefficient will change. If the Reynolds number is smaller than 800, then $C_D = 3.07$ Reynolds number$^{-0.168}$. If the Reynolds number is larger than 8,000, then $C_D = 1.2$ (Schlichting 1979). At the same time, except for the river where the vegetation is planted artificially, the vegetation in the river is not necessarily arranged in a parallel way. The drag force

Table 1 | Parameters of the verified data

Source	Number	Flume type	Diameter of vegetation (mm)	Density of vegetation (1/m^2)	Water depth (cm)	Note
Kumar & Sharma (2022)	1	13-m long, 0.9-m wide and 0.7-m re-circulating straight rectangular channel	8	30.86	20	Emergent vegetation, select the average value at S1 and S2
Huai *et al.* (2009)	2	20-m long, 0.5-m wide, and 0.44-m deep glass flume	1.5	2,500	9.36	Submerged vegetation, select treatment group A31
Huai *et al.* (2014)	3	20-m long, 1-m wide, and 0.5-m deep glass flume	6	171.5	20.7	Emergent double-layer vegetation, select treatment group X1
Huai *et al.* (2014)	4	20-m long, 1-m wide, and 0.5-m deep glass flume	6	171.5	28.7	Submerged double-layer vegetation, select treatment group X3

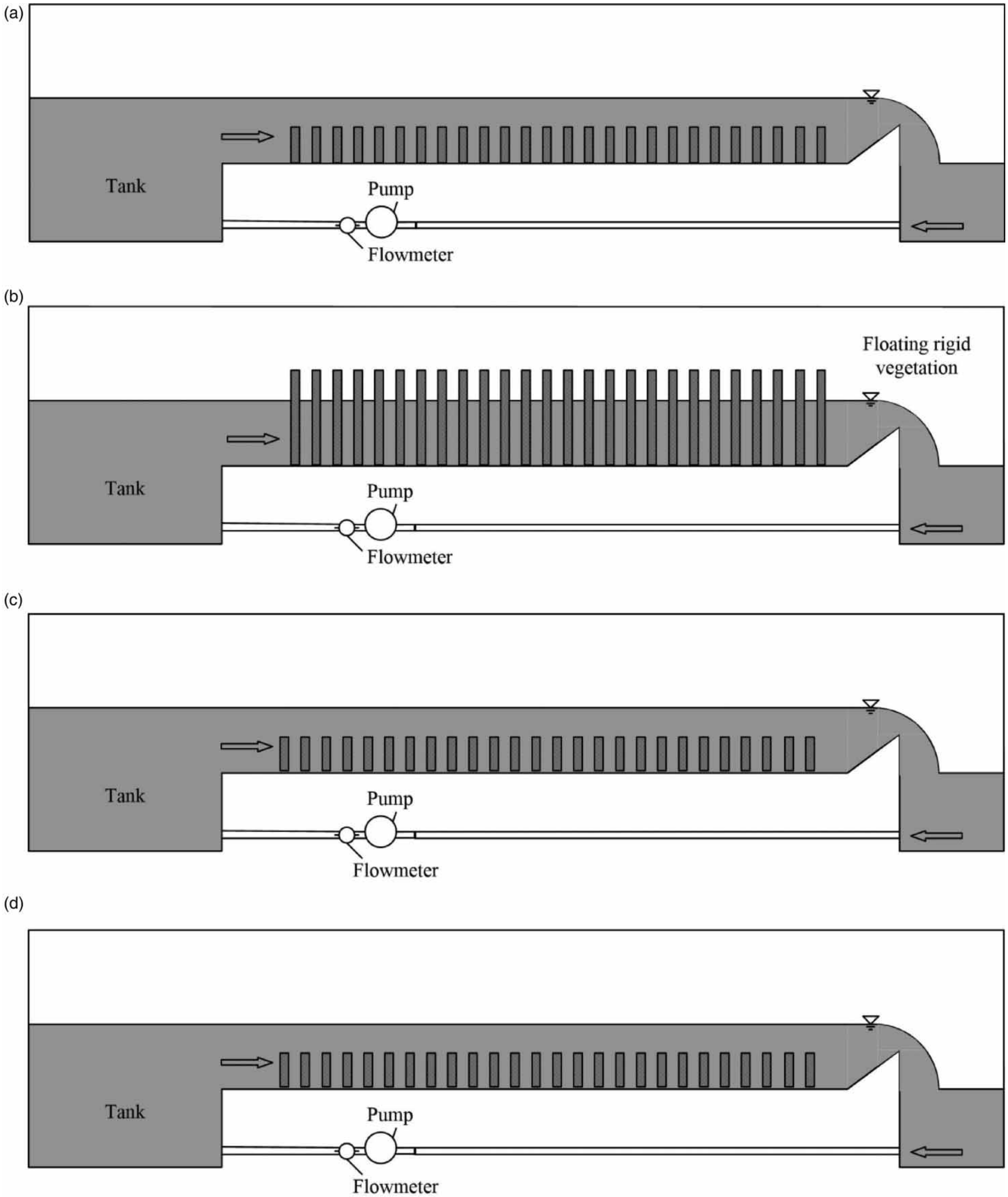


Figure 3 | The structure of experimental flume: (a) emergent vegetation experiment; (b) submerged vegetation experiment; (c) emergent double-layer vegetation experiment; and (d) submerged double-layer vegetation experiment.

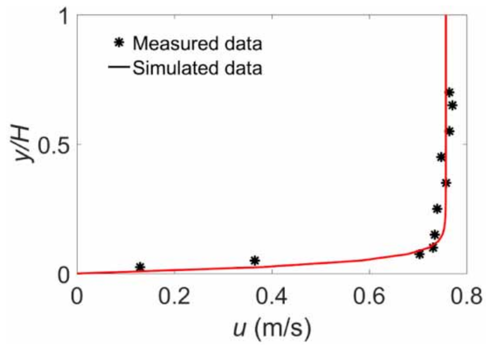


Figure 4 | Comparison between the measured and simulated data of an emergent vegetation channel.

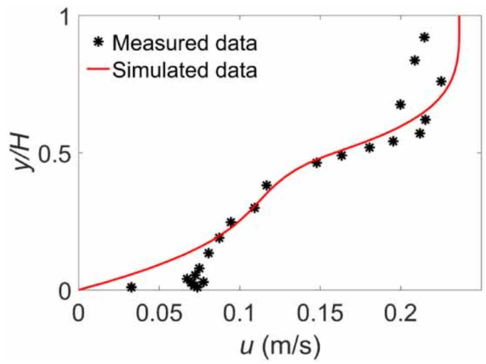


Figure 5 | Comparison between the measured and simulated data of a submerged vegetation channel.

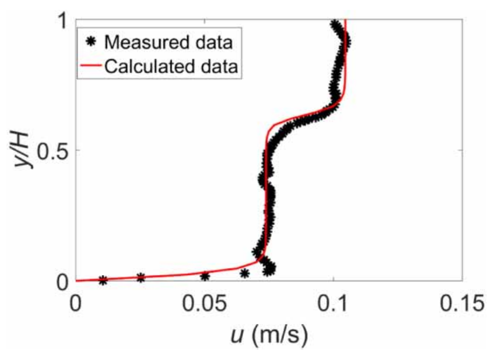


Figure 6 | Comparison between the measured and simulated data of an emergent two-layer vegetation channel.

coefficient of rigid vegetation in the cross the arrangement may be different (Zhang *et al.* 2018). The most common distribution in nature is probably random distribution, whose drag force coefficient is also close to 1 (Li & Shen 1973; Tanino & Nepf 2008).

At the bottom of the vegetated channel, the shear nest effect between the riverbed and the root system is very strong, and the flow velocity measured by the velocity meter is relatively low (Huai *et al.* 2014). Previous simulations of the flow velocity at the bottom of the channel have also exceeded the measured values (Huai *et al.* 2009). Because the stratification of submerged vegetation is more complex than the velocity stratification of emerged vegetation, the shear dimples between the vegetation top and the water flow can also significantly affect the vertical distribution of the flow velocity in the river channel. Therefore, simulating the velocity distribution in submerged vegetation is more difficult, and the simulation accuracy is relatively lower than that of submerged vegetation channels. Compared with the analytical expression model of Huai *et al.* (2014), the flow velocity between two

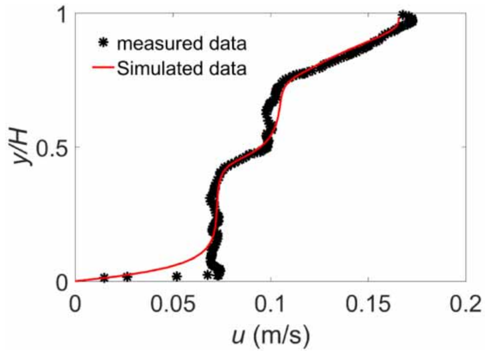


Figure 7 | Comparison between the measured and simulated data of a submerged two-layer vegetation channel.

vegetation layers is connected in a straight line, but the flow velocity is closer to the smooth curve distribution at this time, and the model by Huai *et al.* (2014) cannot simulate the flow velocity distribution between vegetation layers well. The steps of solving analytical expression are complex, and difficult to combine with the pollution transport model.

This article mainly discusses the method of simulating the vertical distribution of flow velocity in layered rigid vegetation channels through numerical models, which divides the drag force of vegetation on water flow based on the density of vegetation in different layers. Studying the hydrodynamic laws of layered rigid vegetation channels helps to explore the impact of water flow on vegetation and riverbed, and can provide assistance in studying the transport laws of pollutants in such channels. The limitation is to study uniform rigid vegetation, and further discussion is needed on the study of uneven rigid vegetation or flexible vegetation. At the same time, the distribution of vegetation is relatively uniform, and research on uneven vegetation distribution should also be carried out in the future.

The numerical model can also simulate multi-layer vegetation such as more complex, uneven vegetation layouts by dividing the river into different layers of vegetation density. Flexible vegetation often exists in the channel, and the deformation of flexible vegetation with the change in the water flow should be considered in velocity simulation (Järvelä 2004). There have been some studies on the drag force of flexible vegetation, and it is believed that the drag force of flexible vegetation is generally less than that of rigid vegetation (Aberle & Järvelä 2013). Chapman *et al.* (2015) gave the drag force coefficient formula of flexible vegetation. There are also some studies on the deformation of flexible vegetation. It is determined that the deformation of flexible vegetation is related to the elastic modulus and the leaf area index of vegetation (Luhar & Nepf 2011). This should be considered in the simulation of multi-layer flexible vegetation flow.

This model can be effectively applied to the prediction of vertical velocity distribution in rivers covered by rigid vegetation. At the same time, the lattice Boltzmann method, as a method that can adapt to complex boundary conditions, is suitable for combining with the pollutant transport equation, so that the results of this paper can be more widely used in the simulation of river water quality environment in the future (Prestininzi *et al.* 2016; Chen *et al.* 2018; Wang *et al.* 2018).

CONCLUSIONS

A numerical model based on the lattice Boltzmann method is proposed to predict the vertical distribution velocity in two-layer rigid vegetation. Compared with the analytical solution, laboratory measurement and field investigation, the numerical model is more suitable for the prediction of velocity under complex and multi-layer conditions of rivers. The numerical prediction of the average velocity is compared with the experimental data, including emergent vegetation, submerged vegetation, emergent double-layer vegetation, and submerged double-layer vegetation. The good consistency shows that the numerical model is effective for open-channel flows with different rigid vegetation conditions. At the same time, more outdoor experiments should be carried out to verify the model, and the pollutant transport module should be added to solve the problem of predicting river pollution.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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