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Modelling open-channel flow with rigid vegetation based on two-dimensional shallow water equations using the lattice Boltzmann method

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ABSTRACT

A two-dimensional lattice Boltzmann model with a D2Q9 lattice arrangement is developed to simulate the flow-vegetation interactions in an open channel. The rigid vegetation is modelled as vertical cylinders. A formula of drag force induced by the rigid vegetation is included in the momentum equations as a sink term. The large eddy simulation technique is adopted to simulate turbulent flows. External forces, such as bed friction and drag force, are discretised with a centred scheme. The mixed scheme of no-slip and slip boundary conditions is considered to correctly describe the interaction between the fluid and the boundary wall. The proposed lattice Boltzmann model was used to simulate two experimental results in partially vegetated channels. The results show that the presented model can simulate the vegetated channel flows correctly.

1. Introduction

Vegetation growing on open channels, floodplains and coasts are responsible for ecological and hydraulic effects and biological processes in river and coastal systems. Vegetation can increase bed roughness, reduce flow velocity and channel conveyance capacity (Nepf, 1999; Wu et al., 1999; Devi and Kumar, 2016). Also, vegetation is an important driver of river ecosystem change, and it is a sensitive and key environmental factor in the river ecosystem. Thus, vegetation plays an important role in stabilising the shoreline, mitigating fluvial flood risk and increasing the ecological value for ecological engineering and restoration.

In recent years, a considerable amount of research has been devoted to study flow-vegetation interactions; such research includes laboratory experiments, field measurements, analytical solutions and numerical models. An analytical model for hydraulic roughness with submerged vegetation was presented by Klopstra et al. (1996) by dividing the water body for open channel flow into vegetation layer and surface free water layer. Through a laboratory study, Stone and Shen (2002) showed that flow resistance varies with flow depth, stem concentration, stem length and stem diameter. Huai et al. (2009) proposed a three-layer model for the vertical velocity profile with rigid vegetation in open channel flows, and the flow body was distributed into an upper non-vegetated layer, an outer layer and a bottom layer within vegetation. Complex flow-vegetation interactions have been simulated with various numerical models, in which a formula of drag force induced by the rigid vegetation is included in the momentum equations as a sink term. The commonly used numerical approaches include the finite volume scheme based on the Boussinesq wave equations (Augustin et al., 2009; Huang et al., 2011; Kuiry et al. 2011). Reza and Wu (2014) presented a three-dimensional model for solving Reynolds-averaged Navier–Stokes equations by using the finite volume method. The depth-averaged two-dimensional model is another popular method (Struve et al., 2003; Wu and Marsooli, 2012; Guan and Liang, 2017). Weissteiner et al. (2015) studied the spatial–structural properties of woody riparian vegetation under hydrodynamic loading with 3D tree models.

New alternatives are always sought to simulate flows considering the effect of vegetation. The lattice Boltzmann method (LBM) is a relatively new discrete numerical approach that has elicited increasing attention recently. Unlike conventional numerical methods, the LBM describes macroscopical fluid flows from microscopic flow behaviour through particle distribution functions. The advantages of the LBM, such as simplicity, efficiency and easy treatment of boundary conditions, in simulating fluid flows have been demon-

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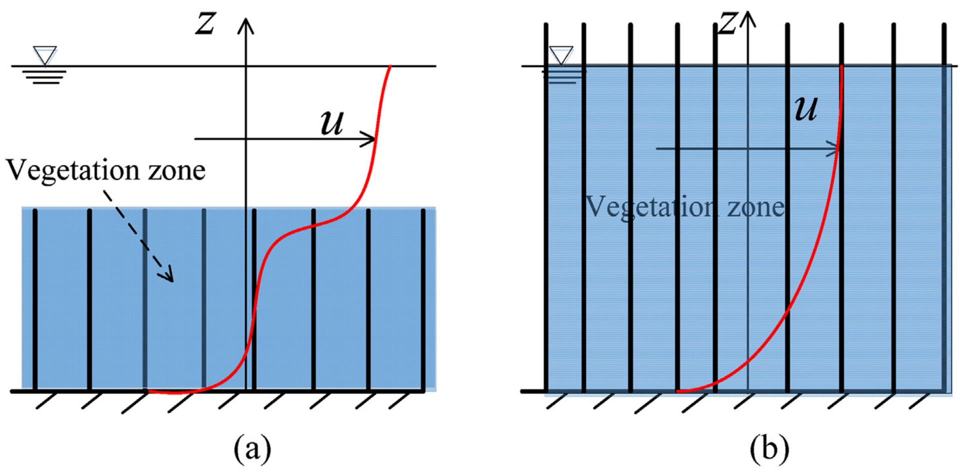

Fig. 1. Sketch of flow over vegetation: (a) flow over submerged vegetation; (b) flow over unsubmerged vegetation.

strated (Zhou, 2004; Li and Huang, 2008; Fernandino et al. 2009). Without considering the bed slope, Jiménez-Hornero et al. (2007) developed a two-dimensional lattice model to describe the influence of vegetation on the turbulent flow by using a semi-slip boundary condition. Considering the vegetation as solid boundaries in flows, Gac (2014) presented a three-dimensional lattice model and computed the vertical velocity profile in an open channel flow.

This paper aims to develop a lattice Boltzmann model on the basis of two-dimensional shallow water equations to simulate the flow-vegetation interactions in open channels with large eddy simulation (LES) technique. The rigid vegetation is treated as vertical cylinders. The drag force caused by the vegetation is considered. A mixed scheme of no-slip and slip boundary conditions is introduced. To validate the proposed model, two laboratory cases are applied by comparing the numerical predictions with experimental results.

The rest of this paper is organised as follows: Section 2 presents the governing equations and the LBM. Section 3 presents an evaluation of the scheme's performance in two laboratory cases. Section 4 provides the conclusions.

2. Mathematical formulas

2.1. Governing equations

The natural flow through vegetation is usually unsteady and turbulent. In practice, the time- and space-averaged characteristic is mostly considered (Liang and Marche, 2009; Hou et al., 2013). The two dimensional shallow water equations can be derived through an in-depth integration of the Reynolds-averaged Navier–Stokes equations. Considering the flow-vegetation interactions, the nonlinear shallow water equations can be written in a tensor form as follows:

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

$$\frac{\partial (hu_i)}{\partial t} + \frac{\partial (hu_i u_j)}{\partial x_j} + gh\frac{\partial h}{\partial x_i} = (\nu + \nu_e)\frac{\partial^2 (hu_i)}{\partial x_j x_j} - gh\frac{\partial z_b}{\partial x_i} - S_{bi} - S_{vi} \tag{2}$$

where the Einstein summation convention over Latin indices is used; h is the water depth; t denotes the time; u_i is the depth-averaged velocity; ν and ν_e stand for the kinematic and eddy viscosity, respectively; z_b is the bed elevation above datum; S_{vi} is the drag force term caused by the rigid vegetation; and S_{bi} is the bed shear stress term in i direction and is expressed as a Manning formula

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

where n is the Manning's coefficient.

2.2. Drag force caused by rigid vegetation

For the rigid vegetation, a common approach is to treat it as vertical cylinders (Bennett et al., 2008; Guan and Liang, 2017; Wu and Marsooli, 2012). For the submerged vegetation, the velocity in the plant layer is smaller than that in the upper water layer due to the effect of drag force (Fig. 1a). In case of unsubmerged vegetation, the magnitude of velocity in the entire water-vegetation body is significantly affected (Fig. 1b). The drag force can be expressed as (Morison et al., 1950)

$$S_{vi} = \frac{1}{2}\lambda C_d h u_{vi} \sqrt{u_{vj} u_{vj}} \tag{4}$$

where C_d is the drag force coefficient and usually in the range of 0.8 and 3.5; u_{vi} denotes the apparent velocity on the vegetation elements in the i direction; and λ is the projected area of vegetation normal to the streamwise and given by

$$\lambda = \frac{4\alpha_v c}{\pi d_v} \tag{5}$$

where α_v is a vegetation element shape factor; c is the vegetation density in vegetation zones; and d_v represents the diameter of vegetation element. The drag coefficient C_d can be selected as a constant in the range of 0.7 and 3.5 (García et al., 2004; Wu et al., 2005; López and García, 2001). For unsubmerged vegetation, the apparent flow velocity on the vegetation u_{vi} in Eq. (4) is equal to the depth-averaged velocity u_i in Eq. (2). For submerged vegetation, u_{vi} is the averaged velocity in the vegetation layer. Stone and Shen (2002) presented a solution for u_{vi} in case of submerged vegetation

$$u_{vi} = \eta_v u_i (\frac{h_v}{h})^{1/2} \tag{6}$$

where η_v is a coefficient and is defined as 1.0 in this paper, and h_v is the vegetation height.

2.3. Lattice boltzmann method

In this paper, we consider the LBM to solve the two-dimensional nonlinear shallow water equations with turbulence considering the effect of rigid vegetation. The D2Q9 (shown in Fig. 2) lattice pattern