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Effect of submerged vegetation on solute transport in an open channel using large eddy simulation

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ABSTRACT

Existence of vegetation plays a significant effect on the flow velocity distributions, turbulence structures and solute mixing in an open channel. This paper has implemented a 3D large eddy simulation model for the flow and scalar transport in the open channel with vegetation. The model can produce a typical turbulence characteristics and concentration distribution with vegetation. The scalar transport mechanism is quantitatively explained by the turbulent Schmidt number, Reynolds flux, coherent structures and quadrant conditional analysis. A dominance of ejection-sweeping events occurs in the process of the momentum and scalar flux transport. The spectral analysis is used to identify the Kelvin–Helmholtz frequency. The turbulence characteristics of the length scale of vortexes, Kelvin–Helmholtz frequency and Reynolds stress etc. are analyzed with the vegetation density. The model quantitatively predicts the trend of decreasing in the concentration distribution along the flow direction with the increasing of vegetation density.

1. Introduction

Vegetation plays a significant role in the sustainable development in streams and rivers, and it has important effects on the flow characteristics such as the velocity distributions, turbulence structures and the process of solute mixing (Tsujimoto, 1999; Nepf and Ghisalberti, 2008; Okamoto and Nezu, 2010). As a result, it is important for environmental or ecological engineers to investigate the hydrodynamic characteristics and process of solute transport through submerged vegetation.

Effects of vegetation on the flow characteristics have been studied by a lot of laboratory flume experiment works (e.g. Carollo et al., 2002; Järvelä, 2002; Huthoff et al., 2007; Poggi et al., 2004). The mean velocity distribution within submerged vegetation does not follow the universal logarithmic law. Moreover, the peak value of the Reynolds stress occurs at the canopy edge and decreases linearly above the canopy to a value of zero at the free surface. In a study involving the submerged vegetation study, Nezu and Sanjou (2008) found that the entire vertical velocity distribution can be divided into three layers: emergent zone, mixing-layer zone and log-law zone (e.g. Neary, 2003; Huai et al., 2009). The authors divided the zone from the river bed to the 90% of the maximum value of the stress as the emergent zone, in which turbulence is dominated by stem-scale turbulence. They defined the whole range from the elevation of the mean velocity starting to obey the log-law to the water surface as the log-law zone. The region between the emergent and log-law zone is the mixing-layer zone, in which turbulence is governed by the KH vortices. The difference in drag magnitude between the non-vegetated and vegetated zones leads to Kelvin–Helmholtz (KH) vortices occurring at the interface between the non-vegetated and vegetated zones. The KH vortices can promote the mass and momentum transport between the within and over canopies (Raupach et al., 1996; Nepf, 1999; Nepf and Vivoni, 2000). The KH instabilities have significant effects on the large-scale turbulence structures and the momentum transfer between the non-vegetated and vegetated regimes. The large-scale turbulence structure dominates the turbulent diffusion in the mixing-layer zone and the turbulent diffusion coefficient is not unity (Ghisalberti and Nepf, 2005).

The above works provide physical insight of the flow phenomenon with vegetation. However, many numerical models have been recently developed for free surface flows with vegetation. For examples, Li and Yan (2007) and Busari and Li (2015) employed the resistance model with the Spalart–Allmaras models (Spalart et al., 1997), in which the presence of vegetation is obtained in the turbulence model by introducing the drag-related source terms, to simulate the interactions between the flows and vegetation. The two-equation resistance models based on the Reynolds-averaged Navier–Stokes (RANS) models was proposed and validated (e.g. Shimizu and Tsujimoto, 1994; Lopez and Garcia, 1998; Leu et al., 2008). The anisotropic Reynolds stress models (RSM) for flows with vegetation were developed by Naot et al. (1996) and Choi and Kang (2004). Moreover, a large eddy simulation, which not only predicts

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the time-averaged velocity fields but also can give instantaneous velocity fields and resolved turbulence structures, has been used for analyzing the instantaneous monument transferring process at the interface between the vegetated and non-vegetated region (Su and Li, 2002; Cui and Neary, 2008; Li and Xie, 2011; Lu and Dai, 2016a).

In addition, the presence of vegetation can alter the flow of streams and rivers by affecting the bed shear stress, sediment concentration and water quality and so on (Schultz, 2002; Nepf et al., 1997). The vegetation can also affect the solute diffusion due to the blocking of vegetation resulting in the mechanical dispersion phenomenon (Nepf, 2012). The mathematical models considering the mechanical dispersion were recently developed by Zhang et al. (2010), Poggi et al. (2006) and Lu and Dai (2016b). Moreover, a series of scalar flux models were proposed by Kang and Choi (2009). The authors investigated the averaged concentration profiles deviating from the Gaussian distribution in a submerged vegetation study. Okamoto and Nezu (2010) employed a LES model to find that the vertical turbulent exchange contributes largely to the scalar transport in the mixing layer zone.

Although extensive research works mentioned above on the flow characteristics in a vegetated channel and a few studies on the solute mixing process in an open channel with vegetation have been investigated, the process of the solute transport within the vegetation has not been fully investigated. In the present work, a large eddy simulation model was used to study the effects of vegetation on the solute transport in an open vegetated channel. Therefore, the flow and solute concentration characteristics were investigated. The effects of submerged vegetation on the concentration transport were analyzed. The quadrant and spectral analyses were used to understand the flow structure and solute transport mechanics.

2. Governing equations

The basic equations consist of the filtered continuity equation, N-S equations including additional drag terms produced by vegetation which is evaluated as an internal source of resistant drag force per unit fluid mass, and the concentration transport equation. The governing equations for incompressible fluid flow in the Cartesian coordinate can be written in following (Lu and Dai, 2016b):

$$\frac{\partial}{\partial x_i}(\overline{u_i}) = 0, \tag{1}$$

$$\frac{\partial(\overline{u_i})}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u_i}\,\overline{u_j}) = g_i - \frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\upsilon\frac{\partial \overline{u_i}}{\partial x_j} - \tau_{ij}\right) - \frac{1}{\rho}F_i, \tag{2}$$

$$\frac{\partial \overline{C}}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u_j}\overline{C}) = \frac{\partial}{\partial x_j}\left(D_t\frac{\partial \overline{C}}{\partial x_j}\right) + S_c, \tag{3}$$

where $\overline{u_i}$ are the filtered velocity components in the Cartesian coordinate, x_i are the Cartesian coordinate, t is the time, g_i are the gravity force components, p is the pressure, ρ is the density of fluid, υ is the molecular viscosity, F_i are the resistance force components per unit volume induced by vegetation in the x, y and z directions, respectively. $\overline{C}$ is the concentration, D_t is the diffusion coefficient and S_c is the source term . The sub-grid stresses τ_{ij} can be written as:

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\upsilon_t\overline{S_{ij}},\ \overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) \tag{4}$$

Here, the eddy viscosity within vegetation was modeled by the maximum value of the sub-grid scale viscosity (υ_{smg}) and the eddy viscosity generated by the stems (υ_{veg}), which was proposed by Lu and Dai (2016a).

$$\begin{aligned}\upsilon_t &= \max(\upsilon_{veg}, \upsilon_{smg}) \\ &= \max\left(\frac{1}{2}C_u\left(C_d DN(\overline{u_i})^2\sqrt{\overline{u_j}\,\overline{u_j}}\right)^{1/2}\min(D, S),\ (C_s\Delta)^2|S|\right),\end{aligned} \tag{5}$$

where C_d is the drag coefficient of stem, D is the vegetation stem diameter or width normal to the flow direction, N is the number density and C_s is the Smargorinky constant. $\Delta = (\Delta x\Delta y\Delta z)^{1/3}$, $|S| = (2\overline{S}_{ij}\overline{S}_{ij})^{1/2}$, C_u=0.09.

The diffusion coefficient D_t within vegetation considering the mechanical dispersion (Lu and Dai, 2016b) is given as:

$$D_t = \left(\nu + \frac{\beta^2}{2}N\,\overline{u_m}\,D^3 + \upsilon_t\right)/S_t, \tag{6}$$

where $\beta = \sqrt{2}$, S_t =1 is the turbulent Schmidt number and $\overline{u_m}$ is the absolute velocity within vegetation. The first and second terms of right hand in the Eq. (6) are the modular and mechanical diffusion terms, respectively. The third term of right hand in the Eq. (6) is the turbulent diffusion, which could be replaced by the Eq. (5).

The average force per unit volume within the vegetation domain is given as follows:

$$F_i = \frac{1}{2}C_d\rho DN\,\overline{u_i}\,\sqrt{\overline{u_j}\,\overline{u_j}} = \frac{1}{2}C_d\rho\alpha\,\overline{u_i}\sqrt{\overline{u_j}\,\overline{u_j}}, \tag{7}$$

where α is the vegetation density.

3. Numerical methods and boundary conditions

Since the free surface elevation varies with time, and the bottom is uneven for hydrodynamic flows, it is difficult to discretize the domain along the vertical direction. To solve the uneven physical domain, the governing equations are first transformed into the vertical σ -coordinate. The splitting operator approach is then implemented to numerically solve the governing equations (Lu and Dai, 2016a). At each time interval the N-S equations are solved in three steps: advection, diffusion (source/sink) and pressure propagation steps, and the concentration transport equation is solved in two steps: advection and diffusion steps. The combination of Lax–Wendroff method and quadratic backward characteristic method on non-uniform grids is used to solve the advection equations. The central difference scheme in space is used to solve the diffusion and pressure propagation equations. A bi-conjugate gradient stabilized method (BI-CGSTAB) is used in this paper to solve the Poisson equation (Lu et al., 2010).

For solving the governing equations, boundary conditions must be specified. Different boundary conditions are usually used in free surface flow problems. At the free surface the dynamic and kinematic condition is applied, which is written as:

$$\frac{\partial\eta}{\partial t} = \overline{u}_3 - \overline{u}_1\frac{\partial\eta}{\partial x} - \overline{u}_2\frac{\partial\eta}{\partial y}, \tag{8}$$

in which η is the surface elevation.

At the inflow boundary, the convective boundary condition for the surface elevation is imposed, and the mean velocity components are specified, and the fluctuating velocity proposed by Jarrin et al. (2006) is used.

$$\frac{\partial\eta}{\partial t} = -U_c\frac{\partial\eta}{\partial x},\ \overline{u_i} = U_i + u_i', \tag{9}$$

where $U_c = \sqrt{gh}$, U_i is the mean velocity components. The fluctuating velocity components u_i' is generated by the synthetic eddy method of Jarrin et al. (2006). The synthetic eddy method based on the characterization of turbulence as a series of coherent eddies which has been implemented in our previous research (Lu and Dai, 2016a), is used here.