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Simulated Study of the interaction between horizontal flow structure and suspended sediment transport in partially vegetated channel

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Introduction

The presence of instream and riparian vegetation significantly affects the flow field of rivers, which in turn impacts sediment transport (Vargas-Luna et al., 2016, Calvani et al., 2023). Few studies, however, have investigated the interaction between horizontal flow structure and suspended sediment transport. Hamidifar (2019) conducted a flume experiment investigating the flow field structure in a half-vegetated channel configuration and found strong horizontal vortices. Other experimental works observed the strong transverse sediment transport process along the interface area between vegetation and open channel (Box et al., 2018; Xu et al., 2022). As for numerical simulations, few studies focus on the reproduction of the physical processes between the partially channel vegetated flow and suspended solids. The present simulation studies mainly focus on the small-scale large eddy simulation model, which has not been applied in practice (Wang et al. 2021). This study focuses on the effect of horizontal viscosity models on the simulation of suspended solid transport in a partly vegetated channel in the most applied Reynolds-averaged Navier-Stokes model. Three viscosity models: the constant model, the Elder model, and the Hybrid viscosity model are applied to reproduce an experimental work selected from the literature.

Methodology

Sharpe's (2003) experimental work on suspended sediment transport in half-vegetated flows is selected for validation in this study. Experiments were conducted in a straight flume made of smooth concrete with 12 m in length, 0.76 m in width and a constant slope. Vegetation was represented as emerged 1 cm-diameters rigid cylinders. The whole vegetated area was set as a staggered pattern covering 11 m in length and 38 cm in width located on the left side of the flume starting from the upstream. Rough Nomad matting was applied at the bottom of the vegetated section to capture sediment deposition. Four 0.306 m-long measurement sections were designed to capture the deposition inside vegetation patterns.

For each case, the upstream discharge remained constant, and a relatively uniform flow was established. The transverse streamwise velocity distribution was measured at the cross-section 7 m from the upstream boundary. Then, the sediment material was fed as a line source with a constant rate of 1.73 g s^{-1} from the water surface via a 0.38 m conveyor belt. The line source was located at the open channel side of the 1 m cross-section from the upstream, with 2 hours input duration.

As for the viscosity models, the Elder model and the Hybrid model are considered. Van Prooijen et al. (2005) proposed that, when the water depth is regarded as the characteristic length scale and friction velocity is regarded as the velocity scale, the eddy viscosity can be calculated by the Elder formulation:

$$\nu_{t,E} = \alpha \sqrt{c_f}\, uh \qquad (1)$$

where α is a constant of the order of 0.1, u is depth averaged velocity and h is the water depth at the calculated location, and bed friction coefficient c_f is calculated as:

$$\frac{1}{\sqrt{c_f}} = \frac{1}{\kappa}\left(\ln\left(\mathrm{Re}\sqrt{c_f}\right) + 1.0\right) \qquad (2)$$

Recently, Truong and Uijttewaal (2022) proposed a hybrid eddy viscosity model considering the impact by the bottom turbulence, the presence of vegetation and the

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occurrence of the large horizontal coherent flow structures in the partially vegetated channel:

$$\nu_{t.H} = \begin{cases} \alpha\sqrt{c_f}\,uh_m + \frac{h_m}{h} h_r^2 \beta^2 \delta^2 \left|\frac{du}{dy}\right| (outside) \\ \alpha\sqrt{c_f}\,uh_m + \frac{1}{8} C_t^{-2} C_d Du + \frac{h_m}{h} h_r^2 \beta^2 \delta^2 \left|\frac{du}{dy}\right| (inside) \end{cases}$$

(3)

In which h_m is mean water depth: $h_m = 0.5*(h_c + h_v)$, which is equal to h in this study , h_c is the water depth in the open channel region; h_v is the water depth inside vegetation region; h_r is the water depth ratio: $h_r = h_v / h_c$, which equal to 1 here; β is a proportionality constant depending on the transition slope, which is 0.0625 in this study; δ is the mixing length, which is 0.28 m calculated based on $y_{5\%}$ and $y_{95\%}$ in this study; C_t is a constant of proportionality which depends on the shape of the streamwise velocity profile; C_D is the drag coefficient of a single stem, both C_t and C_D are equal to 1 theoretically. The 2DH model is established in Delft 3D in this study. The grid size is set as 1cm*1cm, and the time step is set as 0.001 minutes. The upstream boundary conditions are set as constant discharge, and the downstream boundary condition is set as water level. The Baptist approach is used to represent the effects of vegetation. Based on the experimental data, the bottom roughness is set as a manning coefficient of 0.021 in the vegetated area and 0.0145 in the open channel area for the cement mixture bottom. The stable flow condition is first established, and then the sediment is added evenly via 38 subdivided discharge cells at the corresponding cross-sections. Sediment is fed at a very high concentration (45.53kg m^{-3}) with a small discharge (1cm^3 s^{-1}) in each computational cell to neglected the effect of the excess input discharge on the main flow. Sediment transport processes are simulated using the 2DH advection-diffusion equations, in which sediment settling velocity is set as 20 mm/s, which corresponds to a grain size of 0.2 mm.

Preliminary results

For all cases with the three viscosity models, the flow field results are analyzed by comparing the water depth and velocity distribution with measurements to assess the performance of the viscosity models in replicating the flow structure. Preliminary results indicate that, in terms of velocity distribution, vortex development is observed only in the Elder model results (Figure 1b). Conversely, the hybrid model does not exhibit turbulent structures as the transverse hydraulic dynamics is supposed to be represented by the modelled turbulent viscosity (Figure 1a).

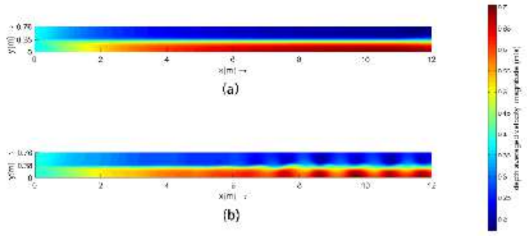

Figure 1 Velocity distribution in Baptist vegetated models in which the horizontal background eddy viscosity is set as (a) Hybrid model;(b) Elder model

Successively, for sediment transport, the final sediment deposition distribution and transverse deposition profiles at each measurement section are analysed and compared with measurement data. Preliminary results indicate that all three viscosity models underestimate sediment deposition, which may be due to the simplified representation of vortex flow structures and also, the simplification of the 2DH model in representing the 3D sediment transport process.

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