

Document Version

Final published version

Licence

Dutch Copyright Act (Article 25fa)

Citation (APA)

Liu, J., Bregoli, F., Uijttewaal, W., Crosato, A., & Calvani, G. (2025). Reproducing Suspended Sediment Transport in Half-Channel Vegetated Flow Using 2D Horizontal Eddy Viscosity Models. In A. Wing-Keung Law, & J. W. Er (Eds.), *Book of Extended Abstracts of the 41st IAHR World Congress, 2025* (pp. 1941-1945). (Proceedings of the IAHR World Congress). IAHR. <https://www.iahr.org/library/infor?pid=37722>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

In case the licence states “Dutch Copyright Act (Article 25fa)”, this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

REPRODUCING SUSPENDED SEDIMENT TRANSPORT IN HALF-CHANNEL VEGETATED FLOW USING 2D HORIZONTAL EDDY VISCOSITY MODELS

Jiaqi Liu¹, Francesco Bregoli², Wim Uijttewaal³, Alessandra Crosato⁴, Giulio Calvani⁵

^{1,2,4} Department of Water Resources and Ecosystems, IHE Delft Institute for Water Education, Delft, the Netherlands

email: j.liu@un-ihe.org

email: f.bregoli@un-ihe.org

email: a.crosato@un-ihe.org

^{1,3} Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands

email: W.S.J.Uijttewaal@tudelft.nl

⁵ School of Architecture, Civil and Environmental Engineering, Lausanne University of Applied Sciences, Lausanne Switzerland

email: giulio.calvani@epfl.ch

ABSTRACT

In river systems, transported suspended sediment interacts with in-channel and riparian vegetation. The involved physical processes are complex and still poorly reproduced by numerical models. This study compares the performance of background horizontal eddy viscosity models in reproducing flow fields and suspended sediment transport processes inside partially vegetated flows. Particularly, we selected an experiment with a partly-vegetated flume which we numerically replicated with the Delft 3D-2DH model. We applied three existing horizontal eddy viscosity approaches: constant value, Elder model and hybrid model. Besides, we represented the vegetation by using Baptist formulation. The results show that the Elder viscosity model reproduces the explicit development of vortices along the flume, while all three viscosity models show an underestimate of the sediment deposition in the vegetated area and an overestimation of sediment deposition in the non-vegetated area. Further investigation is needed to reproduce the experimental introduction of the sediment and to link transversal suspended sediment dynamics with the resolved dynamics in numerical models.

Keywords: Suspended sediment transport; Partially-vegetated channel; Delft 3D; Hybrid horizontal eddy viscosity; Modelling.

1. Introduction

In river systems, vegetation is present in floodplains, riparian areas, in river bars as well as in wetlands. Here, the vegetation interacts with water and sediment in complex non-linear processes that are still matter of investigation. The riverine vegetation has been reproduced in laboratory experiments with fully or partially vegetated channels (e.g.: Sharp 2003; Vargas-Luna et al., 2016; Hamidifar, 2019; Calvani et al., 2023). Previous experimental studies have found that the presence of vegetation increases the gradient of the stream-wise velocity at the interface area between the open flow and the vegetated area and creates strong vortices and large coherent structures in the horizontal plane (LHCS) which dominate the momentum transfer and the intensity of transverse fluctuations (Ervine et al., 2000; White & Nepf, 2008; Zong & Nepf, 2011; Villota et al., 2023). This flow field has been found to lead to strong transverse suspended solids transport, which influences the deposition distribution and then the local morphology development (Box et al., 2018; Xu et al., 2022). Specifically, Truong and Uijttewaal (2019) proposed a hybrid viscosity model that contains several significant factors that would contribute to the transverse momentum exchange.

Numerical simulation has been widely applied to reproduce detailed flow field structure and to predict the development of flow and morphology in rivers (e.g.: Su & Li, 2002; Wang et al. (2021); Particularly, in order to improve the performance of the 2DH RANS models in simulating the flow field in a partially vegetated river, Truong et al. (2022) implemented different horizontal eddy viscosity models in a 2DH vegetated compound channel. Results showed that a hybrid model accounting for both 3D and quasi-2D turbulence can provide improved velocity and transverse shear stress distribution results.

Based on the findings of Truong et al. (2022), this study focuses on whether the horizontal eddy viscosity models can also perform well in simulating the suspended sediment transport and deposition. A previous flume experiment (Sharpe 2003) will be reproduced in Delft3D-2DH, where the vegetation is assumed as rigid cylinder patterns with different densities. Three horizontal eddy viscosity models and two available vegetation modeling approaches will be considered. Flow field and sediment transport results under different eddy viscosity models and different vegetated modeling approaches will be compared and discussed.

2. Methodology

2.1. Selected experimental work

For this study, we selected the Sharp's (2003) half-vegetated channel experiment which were conducted in a straight 12 m long and 0.76 m wide laboratory flume with a constant slope of 0.002134 m/m. The flume bottom was made of smooth concrete. Emergent vegetation was represented by rigid wooden cylinders with a diameter of 1 cm. The vegetation section was set in a staggered pattern of 11 m length and 38cm width at the left side of the flume. The bottom of the vegetated area was covered by a rough Nomad matting to capture sediment deposits, which led to a higher bed roughness than the concrete bottom of the open channel section. Sediment, fine silica sand with density of 2650kg/m³ and D₅₀ = 0.2mm, is fed as a line source on the water surface by a conveyor belt having 0.38 m width with a constant rate of 1.73 g s⁻¹. The sediment input is located at the open-channel side 1m upstream of the commencement of the half-vegetated channel. Flow velocities are measured along 7 m distance from upstream, and sediment deposition is measured along four transversal sections at 2.64, 3.87, 5.10 and 6.32 m distance downstream of the sediment feeder. Five test cases are conducted with different vegetation and flow conditions (Table 1). For each case, the upstream discharge remains constant, and a relatively uniform flow is established first by adjusting the weir at the flume outlet. The total time of the experiment is about 2 hours each.

Table 1 Experimental set up of Sharp (2003)

Case	Density (stem/m ²)	Flow Depth (m)	Discharge(m ³ /s)	Bed slope
B1	312	0.143	0.0348	0.002134
B2	194	0.15	0.0409	0.002134
B3	104	0.142	0.0422	0.002134
B4	194	0.174	0.0475	0.002134
B5	194	0.106	0.0282	0.002134

2.2. Model set up

The B3 case is selected and reproduced in Delft3D. The model domain covers the entire flume. The grid cell size is 1cm in longitudinal and transverse directions, the same as the vegetation stem diameter. The time step is 0.001 minutes to balance the result's accuracy and the required Courant number for Delft 3D. The upstream boundary conditions are set as discharge, and the downstream boundary condition is set as water level. Based on the experimental observation, the bottom roughness is set as a manning coefficient of 0.021 s m^{-1/3} in the vegetated area and 0.0145 s m^{-1/3} in the open channel area for the cement material. To establish an initial uniform flow conditions, the model first runs for 10 minutes without sediment input. Successively, the sediment is introduced at the corresponding cross-section with a very high concentration (45.53 kg m⁻³) and a small discharge (1 cm³ s⁻¹) in each of the 38 cells. Suspended sediment transport processes are simulated using the 2DH advection-diffusion equations, in which sediment settling velocity is set as 10mm/s and the critical erosion shear stress is set as 0.5 pa/m². Note that the in the depth averaged model the sediment is present in the whole water column from the beginning. This in contrast to the experiment where it is introduced at the surface.

2.3. Horizontal eddy Viscosity models

In Delft 3D, the background horizontal eddy viscosity in the closure model is usually assumed a constant in space and time , with a value that depends on the grid size (Deltares, 2018). Additionally, in this study, two

other space-varying and time-constant horizontal eddy viscosity models of half-vegetated configuration are employed: the Elder model and the Hybrid model.

Considering the water depth as the length scale and friction velocity as the velocity scale, Elder model describes the horizontal eddy viscosity that is generated from the bottom turbulence (van Prooijen et al. 2005):

$$v_{t,E} = \alpha \sqrt{c_f} u h \quad (1)$$

in which u is depth averaged velocity and h is the water depth at the calculated location, and bed friction coefficient c_f is calculated as:

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

$\text{Re} = uh/\nu$ is the Reynolds number; ν is the kinematic viscosity of the fluid, which is $10^{-6} \text{ m}^2 \text{ s}^{-1}$; α is a constant of the order of 0.1; κ is the von Karman constant, which is 0.4.

Based on their experimental study, Truong and Uijtewaal (2022) proposed a hybrid eddy viscosity model that contains a bottom turbulence term and the contribution due to the presence of vegetation as well as large horizontal coherent flow structures that emerge in the shear layer:

$$v_{t,H} = \begin{cases} \alpha \sqrt{c_f} u h + \frac{h_m}{h} h_r^2 \beta^2 \delta^2 \left| \frac{du}{dy} \right| & (\text{outside_vegetation}) \\ \alpha \sqrt{c_f} u h + \frac{1}{8} C_t^{-2} C_d D u + \frac{h_m}{h} h_r^2 \beta^2 \delta^2 \left| \frac{du}{dy} \right| & (\text{inside_vegetation}) \end{cases} \quad (3)$$

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 (Truong 2022); δ is the mixing length, calculated based on $y_{5\%}$ and $y_{95\%}$, which is 0.28m in this study; C_t is a constant proportionality 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.

In this study, the distribution of horizontal eddy viscosity is calculated based on the measured velocity profile. The constant value is determined as the average value of the Hybrid viscosity profile, so the transverse distribution of three models are shown as Figure 1 (The vegetation is located on the left side).

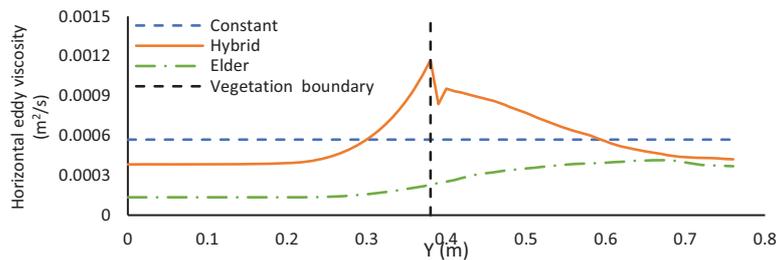


Figure 1 Background eddy viscosity models prescribed in the 2DH model

2.4. Vegetated modelling approaches

Three vegetated modeling approaches have been applied in Delft 3D: the Baptist approach, in which the vegetation is represented as an extra roughness on the bottom; the Drag Force approach, in which the vegetation is represented as an extra force acting on the momentum transport equation; and the Single Stem approach, in which the physical existence of rigid vegetation is represented by the Dry Point function in Delft 3D. Here, we used the Baptist approach, while the drag force and single stem approaches will be investigated in a later stage.

3. Results Analysis

3.1. Flow field

The transverse velocity profile at the measured cross section (7m) using the Baptist approach are shown together with experimental data in Figure 2. Simulated results show underestimation of the velocity at the interface area combined with a steeper gradient in the mixing layer. Neglecting the side-wall effect, the simulated cases also show an overestimation of the velocity near the wall on open channel side.

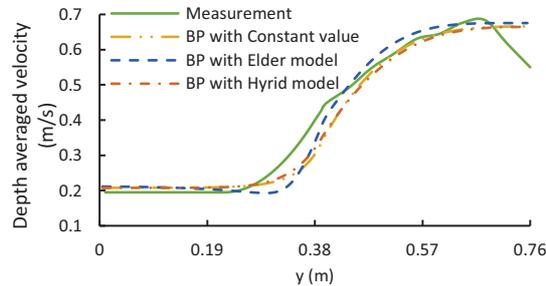


Figure 2 Comparison of measurement and simulated results of transverse depth averaged velocity profile on 7m cross-section in model with Baptist approach

The vorticity distribution of the models with the Baptist approach is shown in Figure 3. It can be seen that only with the Elder model the development of vortices in the shear layer is found. Specifically, the vortices are growing after several meters' adjustment length. Similar phenomena have also been observed in other experimental and numerical work. A theoretical model has been proposed by Rominger and Nepf (2011) to calculate the flow adjustment length. In this study, the calculated adjustment length is between 4.16 and 5.05m, which is consistent with the simulated results. The Elder model's performance is a consequence of the viscosity formulation. A lower defined background eddy viscosity leads to shear instabilities that are resolved on the grid accounting for the total shear stress, whereas the higher viscosity in the hybrid and constant viscosity models suppress these instabilities and the momentum transfer is realised by the enhanced viscosity only.

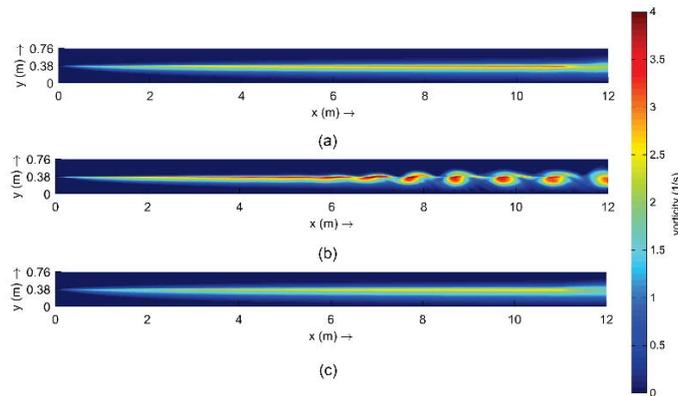


Figure 3 vorticity distribution in Baptist vegetated models in which the horizontal background eddy viscosity is set as (a) constant value;(b) Elder model and (c) Hybrid model

3.2. Sediment deposition

The final deposition weight in cross-sections B, C and D are measured in the B3 case. The deposition results about Baptist approach are listed in Table 2. Compared with experimental data, all simulated cases show underestimation. The highest underestimation appears in the Elder model, which is 87%, even for the best performed Hybrid model, the relative error still reaches to 55%. Besides, the deposition weight in Hybrid and Constant model decrease from upstream to downstream in experiments, which is contrary to the trend in the experimental measurement. Only the Elder model shows the increasing deposition trend.

Table 2 Deposition weight in each measurement section and results from Baptist approach cases

Cases		Deposition Weight (g)			Relative error
		B section	C section	D section	
Measurement		42.86	44.6	47.26	
Baptist	Constant value	13.55	12.94	12.08	-0.71
	Elder model	3.27	3.85	10.35	-0.87
	Hybrid model	21.81	20.22	18.36	-0.55

The reason for the discrepancy may be due to the difference of sediment feeding process between experimental work and the setting in the 2DH model. In the experimental work, the sediment is introduced as a line source from the water surface, and the vertical and horizontal mixing and dispersion process should first evolve before it reaches the bottom. However, in 2DH model, although the sediment is added via a line of cells at the corresponding cross section, the sediment should be considered as uniformly distributed over the water depth from the beginning. The lack of vertical dispersion and mixing process makes the sediment to be transported and deposited in the open channel section further upstream in the flume and won't have much chance to be transferred transversely into the vegetation section as the concentration has decreased already significantly.

4. Conclusion

This study compared the performance of the combination of two modelling approaches and three horizontal eddy viscosity models in reproducing the flow field and the suspended sediment transport in the 2DH half-vegetated channel model. Among the three horizontal eddy viscosity models, the Elder model reproduces the development of horizontal vortex structures because of its low viscosity values. All three viscosity models underestimate the sediment deposition inside the vegetation. The reason could be the difference in sediment input processes between the experimental setting and the 2DH model. Considering such difference, detailed physical processes about how suspended sediment transport transversely in the 2DH model should be further explored.

Acknowledgements

The authors would like to thank Dr Richard Sharpe from Griffith University, Australia, for his support on the experimental data and Dr Truong Hong Son, from Thuyloi University, Vietnam, for providing insight on the viscosity models.

References

- Bebina Devi, T., Sharma, A., & Kumar, B. (2019). Flow characteristics in a partly vegetated channel with emergent vegetation and seepage. *Ecology and Hydrobiology*, 19(1), 93–108.
- Box, W., Västilä, K., & Järvelä, J. (2018). Transport and deposition of fine sediment in a channel partly covered by flexible vegetation. *E3S Web of Conferences*, 40, 1–8.
- Calvani, G., Francalanci, S., & Solari, L. (2023). Insights Into the Dynamics of Vegetated Alternate Bars by Means of Flume Experiments. *Water Resources Research*, 59(3).
- Deltares. (2018). 3D/2D modelling suite for integral water solutions: Hydro-Morphodynamics. Delft.
- Ervine, D. A., K. Babaeyan-Koopaei, & Sellin, R. H. J. (2000). Two-dimensional solution for straight and meandering overbank flows. *Journal of Hydraulic Engineering*, 126(September), 653–669.
- Hossein Hamidifar. (2019). Influence of Rigid Emerged Vegetation in a Channel Bend on Bed Topography and Flow Velocity Field : Rominger, J. T., & Nepf, H. M. (2011). Flow adjustment and interior flow associated with a rectangular porous obstruction. *Journal of Fluid Mechanics*, 680(October), 636–659.
- Sharpe, R. (2003). Suspended sediment transport through non-submerged reeds. University of the Witwatersrand, 5-18 pp.
- Truong, H. S. (2022). Hydrodynamics of Vegetated Compound Channels Model. In TU Delft University, 99 pp.
- Truong, S. H., & Uijttewaai, W. S. J. (2019). Transverse Momentum Exchange Induced by Large Coherent Structures in a Vegetated Compound Channel. *Water Resources Research*, 55(1), 589–612.
- Unigarro Villota, S., Ghisalberti, M., Philip, J., & Branson, P. (2023). Characterizing the Three-Dimensional Flow in Partially Vegetated Channels. *Water Resources Research*, 59(1), 1–26.
- van Prooijen, B. C., Battjes, J. A., & Uijttewaai, W. S. J. (2005). Momentum Exchange in Straight Uniform Compound Channel Flow. *Journal of Hydraulic Engineering*, 131(3), 175–183.
- Wang, M., Avital, E., Chen, Q., Williams, J., Mi, S., & Xie, Q. (2021). A numerical study on suspended sediment transport in a partially vegetated channel flow. *Journal of Hydrology*, 599(April), 126335.
- White, B. L., Nepf, H. M. (2008). A vortex-based model of velocity and shear stress in a partially vegetated shallow channel. *Water Resources Research*, 44(1), 1–15.
- Xiaohui, S., Li, C. W. (2002). Large eddy simulation of free surface turbulent flow in partly vegetated open channels. *International Journal for Numerical Methods in Fluids*, 39(10), 919–937.
- Xu, Y., Li, D., & Nepf, H. (2022). Sediment Pickup Rate in Bare and Vegetated Channels. *Geophysical Research Letters*, 49(21), 1–11.
- Zong, L., Nepf, H. (2011). Spatial distribution of deposition within a patch of vegetation. *Water Resources Research*, 47(3), 1–12.