

Quasi-3D model to simulate flow in straight channels within vegetation patches

Yogi Sahat Maruli Simanjuntak^{1*}, and Tatsuhiko Uchida¹

¹Graduate School of Advanced Science and Engineering, Hiroshima University, 1-4-1 Kagimiya, Highashi-Hiroshima City, Hiroshima 739-8527, Japan

Abstract. Understanding the interaction between flow dynamics and riparian vegetation is essential for effective river management and conservation of the river environment, including the river ecosystem. Numerical simulations have emerged as a valuable tool for this purpose, offering cost-effective and scalable approach. In this paper, we conducted a comparative analysis between the Bottom Velocity Computation (BVC) method for quasi-three-dimensional models, which is the enhanced depth-integrated model with sub-grid three-dimensional model, conventional two-dimensional model, and three-dimensional model to explore the three-dimensional (3D) flow effects induced by the presence of vegetation patches. The vegetation resistance evaluation method for non-equilibrium open channel flows was extended to two dimensions and incorporated into the equations for the BVC models to evaluate the interaction of the vegetation, three-dimensional eddy motion, and turbulence in a depth-integrated model. Our simulations focused on straight channels containing patches of vegetation. The results showed that the velocities within the vegetated areas were observed to decrease, while velocities in non-vegetated areas increased. Moreover, the BVC model showed consistency with experimental data compared to 2DC model. Specifically, the 2DC model tended to overestimate velocities in non-vegetated areas due to its inability to capture momentum transport from non-vegetated areas. This discrepancy highlights the importance of considering 3D flow effects for simulating flows in vegetated areas.

1 Introduction

As the human population has grown, changes in land use have degraded the land and intensified pressure on rivers. Presently, rivers face several environmental challenges, such as the deepening of stream beds, destabilization of banks, and widening of channels. These alterations have profoundly impacted the stability and health of aquatic ecosystems. Riparian vegetation holds promise in addressing these issues and facilitating the restoration of stream stability [1–3]. For example, vegetation plays a pivotal role in attenuating riverbank erosion by reducing bed shear stress [4]. However, it is essential to acknowledge potential adverse effects, such as increased flow resistance which potentially escalates flood hazards [5].

*Corresponding author: d222200@hiroshima-u.ac.jp

Therefore, research on the relationship between water flow and vegetation is crucial for effective river management.

In understanding these interactions, the use of numerical model is crucial as they are more economical and applicable on a larger scale compared to field measurements. However, numerical models have their limitations. For instance, 2DC models, despite their lower computational costs and suitability for large-scale areas, struggle to accurately represent three-dimensional flow effects such as secondary flows on the objective phenomena [6, 7]. This limitation can lead to inaccuracies in predicting velocity distributions, ultimately affecting river management decisions [8]. On the other hand, although advanced models like 3DC models excel in capturing flow characteristics [9, 10], their computational costs make them challenge to apply over large scale areas. Therefore, quasi-3D models, capable of representing 3D flow characteristics but with lower computation costs, emerge as a desirable solution. For example, the Bottom Velocity Computation (BVC) method [11–13] was proposed for quasi-3D models. While the BVC models have demonstrated good performance in many cases, detailed validation against channels with patches of vegetation remains limited. Thus, this study aims to validate the BVC model in a straight channel with patches of vegetation. Additionally, we investigate the influence of three-dimensional flow effects by comparing the BVC model with both 2DC and fully 3DC models.

2 Methods

2.1 Experimental conditions

Experiments on straight channels with patches of vegetation were conducted by Bennet [14] using a tilting recirculating flume measuring 16.5 m in length and 0.6 m in width as depicted in Figure 1. The flow discharge was set constant at $0.0042 \text{ m}^3/\text{s}$. Six patches of vegetation with semi-circular shapes with 0.6 meters diameter were evenly distributed longitudinally with a spacing of 2.4 meters, forming a meandering pattern with a wavelength of 4.8 meters. Vegetation was represented by cylinders having 0.0032 m diameter

Surface velocity was measured in a 6.5-meter-long longitudinal section using particle image velocimetry (PIV). Validation was conducted at 8 sections, namely at $x = 1.32 \text{ m}$, 1.64 m , 2.59 m , 3.89 m , 4.2 m , 4.83 m , 6.12 m , and 6.43 m . Additionally, water depth was measured using a point gauge mounted on a movable carriage that transversed along the flume rails. Water depth measurements were conducted at 2.4-meter-long longitudinal sections. Further details regarding the experiment are provided in Table 1.

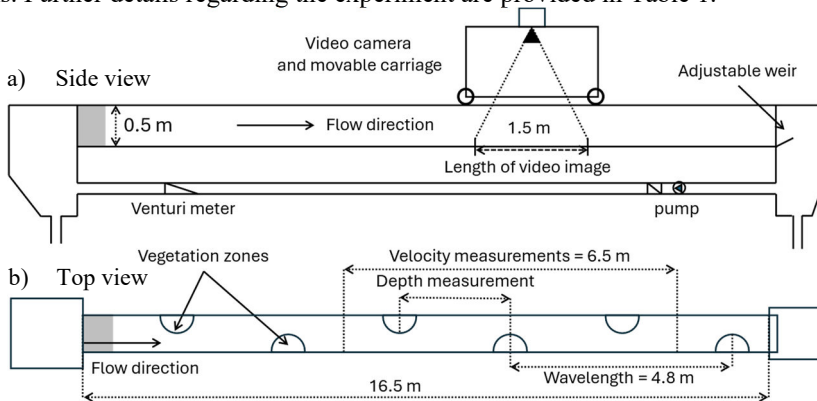


Fig. 1. Vegetation patches configuration of experiment in straight channels. [14].

Table 1. Experimental conditions. [14].

Number of vegetation per zone	Veg. diameter d (mm)	Veg. density a (%)	Flow discharge Q (m ³ /s)	Flow depth H (m)	Channel width B (m)	Slope (-)
113	3.2	0.64 %	0.0042	0.026	0.6	0.0004
1753		9.97 %		0.36		

2.2 Numerical models

For numerical models, the comparison between the BVC models and the 2DC and 3DC models aimed to explore the three-dimensional flow impacts induced by vegetation patches in straight channel. The BVC method was developed by [11, 12, 13], and has found extensive application across different settings for various BVC models. The governing equation of the BVC models employ a general curvilinear coordinate system, as elucidated by Lugina et al. [7].

In the BVC models, vegetation is represented by a drag force term that affects various aspects such as momentum equations, vorticity equations, water surface velocity, and turbulence model production terms. This drag force term of the emergent cylinder for unit control volume extended from one-dimensional form [15] to a multidimensional expression [16], as shown in Equation 1.

$$f_i = Nd \left\{ \frac{C_D |u|^2}{2} - gkd \cdot \frac{u_j}{|u|} \frac{\partial h}{\partial x_j} \right\} \frac{u_i}{|u|} \quad (1)$$

where $N = 1/l_s l_n$, d = vegetation diameter, $|u| = \sqrt{u_i u_i}$, l_s and l_n = distance between vegetation in the streamwise and transverse direction, respectively. The drag force terms for depth-averaged flow (F_i), water surface flow (f_{si}), and bottom flow (f_{bi}) are calculated using the depth-averaged velocity (U_i), the water surface velocity (u_{si}), and the bottom velocity (u_{bi}), respectively, for u_i in equation 1. Drag force coefficient C_D is determined by the base component of the drag force (C_{D0}) and Froude number (Fr) as in Equation 2:

$$\frac{C_D}{C_{D0}} = 1 + \frac{\beta_{cp}}{2} C_{D0} Fr^2 \quad (2)$$

where β_{cp} = the pressure coefficient distribution around the cylinder, C_{D0} = the drag coefficient for free stream (uniform) flows or open channel flows with $Fr \rightarrow 0$ [15].

The BVC method comprises different types of models, including the Simplified Bottom Velocity Computation (SBVC), which further divides into SBVC2, and SBVC3, assuming shallow water conditions, and the General Bottom Velocity Computation (GBVC3) without such assumptions. SBVC2 assumes equilibrium on the water surface, while SBVC3 calculates water surface velocity using the horizontal momentum equation. In contrast, GBVC3 considers non-hydrostatic pressure distribution and vertical velocity variations. Equations utilized in the BVC models are elaborated in Table 2.

On the other hand, the 3DC model employs the interFoam multiphase solver within OpenFoam. Turbulence is addressed using the $k - \omega$ SST approach because it demonstrates good performance in the presence of pressure gradient and flow separation [17]. Similar to the 2DC and BVC models, we assume comparable roughness for the bed wall. Additionally, we integrate the drag force from the model into the momentum equation for interFoam, ensuring consistency with the approaches of the BVC and 2DC models.

For the numerical calculation’s domain, the 2DC, BVC, and 3DC methods employ a computational mesh with identical dimensions in x - y plane, consisting of 451 x 63 nodes. Furthermore, the 3DC method incorporates an additional vertical grid with 40 nodes ($dz = 0.002$ m).

Table 2. Unknown variables and equations for the BVC models.

Unknown variables	Governing equations	2DC	SBVC2	SBVC3	GBVC3
h	DI continuity	O	O	O	O
U_i	DI horizontal momentum	O	O	O	O
u_{bi}	DI definition equations of horizontal vorticity	-	O	O	O
Ω_i	DI vorticity eq.	-	-	O	O
u_{si}	Horizontal momentum equations on water surface	-	-	O	O
dp_b	Double integrated continuity	-	-	-	O
W	DI vertical momentum	-	-	-	O

3 Results

For the vegetation densities of 0.64% and 9.97% (see Table 1), the drag force coefficients (C_{D0}) are adjusted to 1.3 and 3.0, respectively, with $k = 2.1$ and $\beta_{cp} = -0.4$ were chosen to achieve streamwise velocity acting on water surface consistent with the experimental data. The drag force coefficients closely resemble that in the study by Wu and Wang [18]. Figure 2 shows velocity profiles at a density of 0.64%. it is observed that velocity in the vegetation patches and behind vegetation patches are decelerated, while velocity in the non-vegetation patches is accelerated. Furthermore, the flow passes through the vegetation patches without forming vortices in front of the vegetation patches.

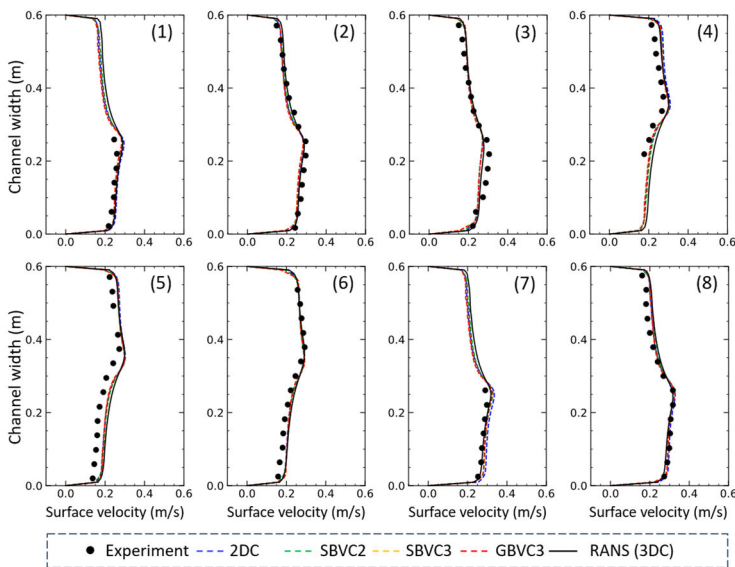


Fig. 2. Distribution of streamwise velocity at the free surface at $a = 0.64\%$.

As a result, there are no significant differences observed among the 2DC, BVC, and 3DC models. All models show strong consistency with the experimental data. A notable difference is observed in the case of vegetation with a density of 9.97% as depicted in Figure 3. The dense vegetation obstructed the flow, leading to a significant reduction in velocity within and behind the vegetation patches. Conversely, velocity in opposite direction experiences acceleration.

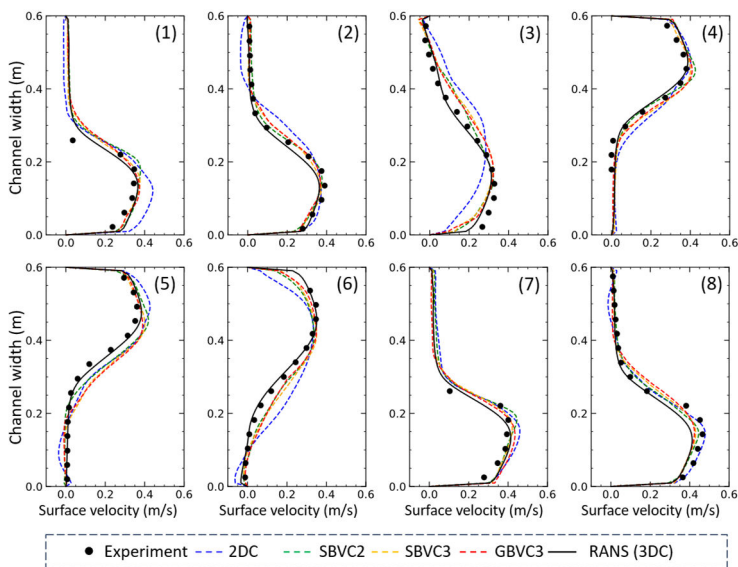


Fig. 3. Streamwise velocity distribution at the free surface at $\alpha = 10\%$.

This condition leads to enhanced 3D flow characteristics due to momentum transport from the vegetated to non-vegetated regions, resulting in discrepancies among the calculation methods. The 3DC model generally captures velocity distribution across all sections. Subsequently, the SBVC2, SBVC3, and GBVC3 models fit well with the experimental data, albeit showing slight overestimation in the interface region. The velocity overestimation is a result of inaccuracies in capturing the 3D flow effect, including the velocity distribution within the dispersion term. Although the BVC model is capable of capturing the 3D flow effect, it appears that there is an overestimation in momentum transport. On the other hand, the velocity distribution from 2DC model is observed to be overestimated in the interface region and in the non-vegetated regions, as it fails to capture the momentum transport phenomena from vegetation to non-vegetated regions, even in the shallow conditions with a water depth of 3.6 cm.

Figure 4 shows the development of vortices in front of the vegetation. In vortices 1, it is evident that 3DC, BVC models exhibit better patterns compared to the 2DC model. Additionally, the location and the size of the vortices from the SBVC3, and GBVC3 models match the experimental data. However, the location of vortices in the 2DC models appears more upstream than the experimental data, and the size of vortices is larger than experimental data. As for vortices 2, it can be observed that both the 2DC, BVC, and 3DC models tend to be more downstream compared to the experimental data. However, it can be said that the SBVC2, SBVC3, and GBVC3 models show better performance than the 2DC model.

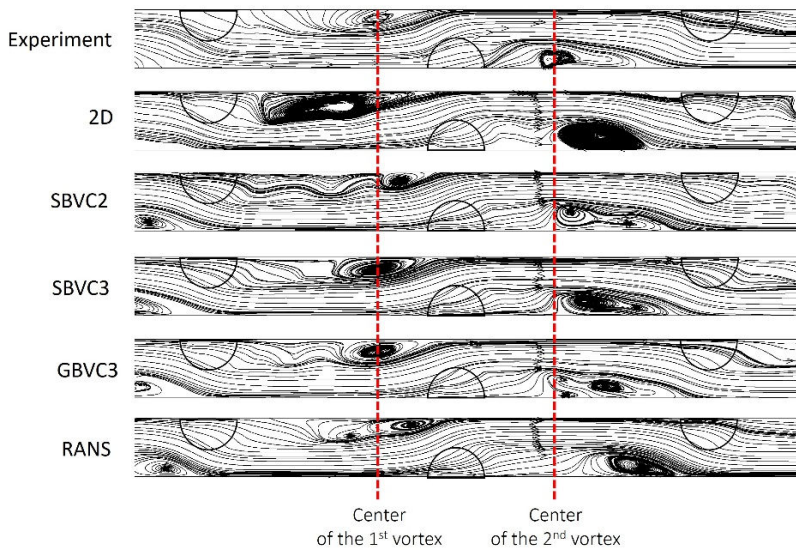


Fig. 4. Streamline velocity at the free surface at $a = 10\%$.

4 Conclusion

Numerical simulations are employed to study the impact of vegetation on flow structure, comparing models such as BVC, 2DC, and 3D models to understand the three-dimensional flow effects. Notably, the BVC models show promising agreement with experimental data and 3DC model regarding capturing velocity distribution and location of vortices. Conversely, the 2DC model tends to overestimate, especially in the non-vegetated areas and at the interface region, since 2DC cannot accurately reproduce the momentum transport between vegetation and non-vegetated areas. The proposed method with BVC models is promising for using riparian vegetation to be an integral part of a sustainable environmental strategy, evaluating the effects of the riparian vegetation on river dynamics, such as the reduction in erosion by stabilizing banks and beds, thereby preventing topsoil loss. Vegetation is also known to act as a natural filter, enhancing water quality by trapping pollutants and sediment that can degrade aquatic ecosystems. Additionally, vegetation fosters biodiversity by creating diverse habitats for both aquatic and terrestrial species, supporting ecological resilience and species adaptation. The integrated evaluation method for these functions these functions are a future challenge for this study.

References

1. Z. Feng, C. Xu, Y. Zuo, X. Luo, L. Wang, H. Chen, X. Xie, D. Yan, T. Liang, Analysis of water quality indexes and their relationships with vegetation using self-organizing map and geographically and temporally weighted regression. *Environmental Research* **216**, 114587 (2023). <https://doi.org/10.1016/j.envres.2022.114587>
2. W. M. Van Dijk, R. Teske, W. I. Van De Lageweg, M. G. Kleinmans, Effects of vegetation distribution on experimental river channel dynamics. *Water Resources Research* **49**, 7558–7574 (2013). <https://doi.org/10.1002/2013WR013574>
3. P. M. Rowiński, K. Västilä, J. Aberle, J. Järvelä, M. B. Kalinowska, How vegetation can aid in coping with river management challenges: A brief review. *Ecohydrology & Hydrobiology* **18**, 345–354 (2018). <https://doi.org/10.1016/j.ecohyd.2018.07.003>

4. A. Vargas-Luna, R. Benifei, L. Solari, M. V. Oorschot, G. Geerling, Effect of vegetation on floods: The case of the River Magra. (2015). <https://doi.org/10.13140/RG.2.1.3057.8004>.
5. T. Tsujimoto, Fluvial processes in streams with vegetation. *Journal of Hydraulic Research* **37**, 789–803 (1999). <https://doi.org/10.1080/00221689909498512>
6. F. P. Lugina, T. Uchida, M. Hatono, Effect of channel meander on flow resistance. *J. JSCE, Ser. B1* **77**, I_865-I_870 (2021). https://doi.org/10.2208/jscejhe.77.2_I_865
7. F. P. Lugina, T. Uchida, Y. Kawahara, Numerical Calculations for Curved Open Channel Flows with Advanced Depth-Integrated Models. *KSCE J Civ Eng* (2024). <https://doi.org/10.1007/s12205-024-1431-7>.
8. H. K. Ghamry, P. M. Steffler, Two-dimensional depth-averaged modeling of flow in curved open channels. *Journal of Hydraulic Research* **43**, 44–55 (2005). <https://doi.org/10.1080/00221680509500110>
9. M. Wang, E. Avital, T. Korakianitis, J. Williams, K. Ai, A numerical study on the influence of curvature ratio and vegetation density on a partially vegetated U-bend channel flow. *Advances in Water Resources* **148**, 103843 (2021). <https://doi.org/10.1016/j.advwatres.2020.103843>
10. T. Fischer-Antze, T. Stoesser, P. Bates, N. R. B. Olsen, 3D numerical modelling of open-channel flow with submerged vegetation. *Journal of Hydraulic Research* **39**, 303–310 (2001). <https://doi.org/10.1080/00221680109499833>
11. T. Uchida, S. Fukuoka, Numerical calculation for bed variation in compound-meandering channel using depth integrated model without assumption of shallow water flow. *Advances in Water Resources* **72**, 45–56 (2014). <https://doi.org/10.1016/j.advwatres.2014.05.002>
12. T. Uchida, S. Fukuoka, Quasi-3D two-phase model for dam-break flow over movable bed based on a non-hydrostatic depth-integrated model with a dynamic rough wall law. *Advances in Water Resources* **129**, 311–327 (2019). <https://doi.org/10.1016/j.advwatres.2017.09.020>
13. T. Uchida, S. Fukuoka, A. (Thanos) N. Papanicolaou, A. G. Tsakiris, Nonhydrostatic Quasi-3D Model Coupled with the Dynamic Rough Wall Law for Simulating Flow over a Rough Bed with Submerged Boulders. *J. Hydraul. Eng.* **142**, 04016054 (2016). [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001198](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001198)
14. S. J. Bennett, T. Pirim, B. D. Barkdoll, Using simulated emergent vegetation to alter stream flow direction within a straight experimental channel. *Geomorphology* **44**, 115–126 (2002). [https://doi.org/10.1016/S0169-555X\(01\)00148-9](https://doi.org/10.1016/S0169-555X(01)00148-9)
15. T. Uchida, T. Ato, D. Kobayashi, M. F. Maghrebi, Y. Kawahara, Hydrodynamic forces on emergent cylinders in non-uniform flow. *Environ Fluid Mech* **22**, 1355–1379 (2022). <https://doi.org/10.1007/s10652-022-09898-7>
16. Y. S. M. Simanjuntak, T. Uchida, T. Inoue, Three-dimensional flow effects to simulate flows in a strongly curved channel with partly emergent rigid vegetation. *Journal of JSCE* **12**, 23–16082 (2024). <https://doi.org/10.2208/journalofjsce.23-16082>
17. F. R. Menter, Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal* **32**, 1598–1605 (1994). <https://doi.org/10.2514/3.12149>
18. W. Wu, S. S. Y. Wang, “A depth-averaged two-dimensional numerical model of flow and sediment transport in open channels with vegetation” in *Water Science and Application*, S. J. Bennett, A. Simon, Eds. (American Geophysical Union, 2004), pp. 253–265. <https://doi.org/10.1029/008WSA18>