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Article

Double Layered Vegetation for Flood Mitigation: A CFD Study on Flow Resistance

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Abstract

This research addresses the use of vegetation as a bio-shield for mitigating flood water flow. Mostly single-layer vegetation is often used; this paper investigates whether double-layered vegetation would be more effective. A numerical model using Computational Fluid Dynamics (CFD) in ANSYS Fluent was explored to simulate water flow through various vegetation setups. The model was built on the Volume of Fluid (VOF) method and was validated against experimental data. The behavior of single- and double-layered rigid vegetation under different vegetal density conditions and flow rates has been investigated in this study. Results demonstrate that an increase in water level upstream, which indicates significant flow resistance, is strongly enhanced by dense and double-layered vegetation. The flow velocity within and directly behind the vegetation zone is strongly reduced. However, the most important finding is the sharp increase in the water speed in the gap regions beside the patches. Generally, double-layered vegetation can slow down the flow and dissipate its energy; hence, it is less likely to be damaged. It is concluded that a vertically double-layered vegetation system is more resilient and efficient in being a bio-shield for mitigating flood impacts on riverbanks and coastal areas than a single layer is. Future work may focus on the optimization of the arrangement of the vegetated patches, considering gaps with inclinations, to better control high-velocity zones for improving the design in real-world applications.

Keywords: Computational fluid dynamics; Double layered vegetation; Volume of fluid method; Flood mitigation; Velocity reduction

1. Introduction

The increasing frequency and intensity of global flood events are part of the growing threats of climate change to infrastructure, ecosystems, and human populations worldwide [1, 2]. In effect, the urgent need for effective and sustainable flood risk mitigation options precipitates. Traditional "hard engineering" methods involve generally expensive, ecologically disruptive measures such as concrete dikes and seawalls, which may fail under extreme conditions [3]. In response, Nature-Based Solutions are gaining prominence for their dual benefits of flood mitigation and ecological restoration, especially through the strategic use of riparian and coastal vegetation, commonly called bio-shields [4]. Vegetation naturally obstructs the flow and increases hydraulic resistance, therefore decreasing the flow velocity of floodwaters and consequently reducing the forces exerted on banks and coastal protection structures [5, 6]. Hydrodynamics of flow through emergent and submerged rigid vegetation have been one of the main areas of interest for years. Most of these studies have focused on the relationship between stem density, height, and stiffness and bulk flow properties such as drag and turbulence [7, 8]. Most of the historical research and models have focused on simple, uniform single-layer vegetation patches to characterize drag coefficients and energy dissipation rates [9].

Thus, with the help of CFD, such complicated interactions of flow and vegetation are investigated more accurately and economically [10]. Numerical models, generally using the VOF method for tracking the air-water interface in complicated free-surface flows over and through vegetation canopies, have been utilized [11, 12]. CFD simulations have successfully validated experimental observations related to high-resolution data on velocity profiles, turbulence kinetic energy dissipation, and water level changes for single-layer setups [13]. While literature indeed supports flow attenuation by single-layer vegetation, its limitation mainly pertains to its resilience and performance under high-flow conditions. A single regular layer may be uprooted or suffer structural damage and might not provide consistent drag over the entire water column at deeper flood stages [14]. Moreover, complicated flow phenomena are introduced by this kind of geometry, such as the jetting with high velocities in the gap regions between patches, which can enhance erosion flanking a patch [15]. This study proposes that a two-tier vegetation setup-a second, usually denser layer just behind the first-can significantly enhance flow resistance and dissipate more energy while strengthening the overall structure more than could be achieved with one layer. The study addresses a specific gap in existing literature since there has not been any detailed CFD analysis quantifying how different density pairs interact with variable discharges to affect the hydraulic performance of such a double-layer setup. In single layer vegetation barrier, trees located at the downstream section are susceptible to damage by high velocity of flood water. Thus, recent researchers have recommended double layered vegetation defense system, schematics have been illustrated in Figure 1.

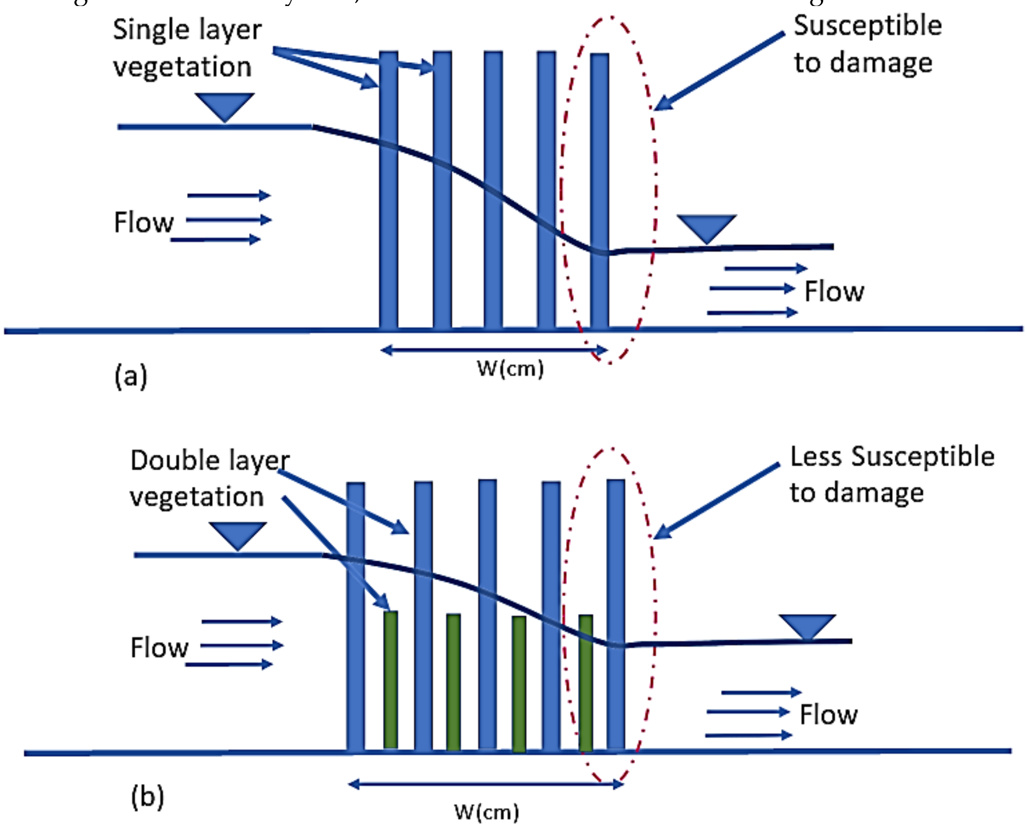


Figure 1. Schematic side view diagram for continuous forest model with (a) Single Layered, and (b) Double layered vegetation.

2. Literature Review

This study concludes that increasing the density of the short vegetation layer in the upstream located vegetation model (UM) increases flow resistance by narrowing the passage of fluid flow, resulting in an increase in backwater rise upstream of the UM and a significant reduction in inundation depth downstream of the DM, resulting in a significant loss of flow energy [16]. In this work the hydrodynamics of submerged flexible vegetation with or without foliage is investigated by using a 3D numerical model. Flexible vegetation is modeled by momentum sink terms, with the velocity-dependent stem height determined by a large deflection analysis which is more accurate than the previously used small deflection analysis. The effect of foliage on flow resistance is expressed in terms of the change in the product of the drag coefficient and the projected area, which is supported by available experimental data. The computed results show that the vertical profiles of the mean horizontal velocity and the vertical Reynolds shear stress are correctly simulated [17]. This research included a comparison of flow structures and energy loss in a single patch of finite length, layered (single or double layer with gaps), and continuous (full width) vegetation models. The results showed that the loss of energy in horizontally layered vegetation models (single and double horizontal layers) was greater in double horizontally layered vegetation layouts [18]. In this study, the experimental data were used to validate a three-dimensional Reynolds stress turbulence model, which was then used to investigate the properties of flow through vertically double-layered and discontinuous vegetation patches that occupy both sides of an open channel with different patch patterns—linear and staggered. The results show that the sheltering impact of vegetation patches reduces flow velocities within the gap zones, which is much larger for the flow through the staggered patch pattern than for the flow through the linear pattern [19]. In this research, a layer of short, submerged trees with varied porosity (Pr= 98%, 95%, 91%, and 79%) was coupled/incorporated and tested with tall emergent trees to improve the efficacy of the coastal forest. Rather than a continuous forest belt, the results showed that the forest in discontinuous placement generated resistance to the flow by significantly raising the backwater increase in the upstream region and reducing the energy of the tsunami current in the downstream region [20]. In this study, a CFD model was used to reproduce steady-state flow in a vegetated channel. The standard volume of fluid (VOF) method was used to track free surface evolution. Turbulence structures were captured using the renormalized groups (RNG) model after performing sensitivity analyses on turbulence models and mesh resolution. The model was validated using experimental data from literature. The results showed that the model could efficiently reproduce the flow velocity in free zones and within the vegetated area [21]. In this study, the mitigation effects of double-layer vegetation were investigated experimentally, paying special attention to the reduction of velocity and fluid force within and behind the vegetation. Experiments were conducted in a flume under a quasi-steady subcritical flow condition with a high inundation depth. The double-layer vegetation produced a large water rise in front of the vegetation and entrained a large amount of air bubbles in the flow behind the vegetation. The double-layer vegetation generated a mild water gradient behind the vegetation which prevented the direct collision between the ground and flowing water. In comparison with single-layer emergent vegetation, the double-layer vegetation reduced the velocity near the ground in front, within, and behind the vegetation by maximums of 18%, 74%, and 33%, respectively [22]. This study performed flume tests to elucidate the mitigation effect of a hybrid defense system comprising an embankment model (EM), followed by different types of single- layer emergent forest models (SLM) or vertical double-layer forest models (DLM). Different types of hydraulic jumps were observed within the defense system, jump position and their characteristics dominated the energy reduction downstream of SLM or DLM. Experimental results showed that this hybrid defense system reduced the flow energy to 30% and 40% of maximum for SLM and DLM, respectively, compared to only the single EM. Moreover, the position of the hydraulic jump was near the EM in the combination of EM and DLMs [23]. In this study, a computational method is used to investigate the flow properties and turbulence characteristics through discontinuous and vertically double layered vegetation patches of finite width in an open channel. A three-dimensional Reynolds stress turbulence model was implemented utilizing FLUENT (ANSYS). After the validation of the numerical model, flow characteristics were investigated against varying vegetation density (*St*/*d* and *S s*/*d*, where *St* =spacing between taller vegetation elements, *d*=diameter of vegetation, *S s*=spacing between smaller vegetation elements) and vegetation patch width. Various profiles and contour plot distributions of mean stream-wise and depth averaged velocities, turbulent kinetic energy and turbulent intensities at specified critical locations and sections simulated by the model are presented in this paper [24]. This paper studies the effects of different types and configurations of double layer vegetation on the flow of open channels. The vegetation is simulated through cylindrical dowels with a diameter of 6.35 mm and heights of 10 and 20 cm, which represent short and tall dowels, respectively. Profiles for instantaneous velocities were obtained by acoustic Doppler velocimetry (ADV) at different locations around vegetation with multiple staggered and linear formations. The experiment covers a wide range of sparse to dense vegetation configurations. Furthermore, different flow depths were selected to simulate fully submerged cases for short vegetation and to capture the inflection of velocity over the mixing region between short and tall dowels [25]. This study predicts how the Free Surface Level (FSL) variations around finite length vegetation affects flow structure by using a numerical simulation. The volume of fluid (VOF) technique with the Reynolds stress model (RSM) was used for simulation. Multizone Hexahedral meshing was adopted to accurately track the free surface level with minimum numerical diffusion at the water– air interface. After the validation, finite length emergent vegetation patches were selected based on the aspect ratio (*AR* = vegetation width-length ratio) under constant subcritical flow conditions for an inland tsunami flow [26].

2.1. Scope of study

This work investigates the hydraulic performance of a double-layer arrangement of rigid vegetation in contrast to single-layer arrangements for various flow rates and plant densities. Using a validated CFD model that utilizes the VOF method within ANSYS Fluent, the increase in upstream water level is quantified, as well as the velocity reduction and energy dissipation within the vegetation area. The most salient part of the discussion concerns the flow in the gaps between patches, where indeed the double layer proved more robust in terms of a substantial increase in discharge capacity and damping effects on floods.

3. Methodology

The methodology for this investigation centers on a CFD approach to modeling the complex hydrodynamics of flow through vertically layered rigid vegetation. All simulations were performed using ANSYS FLUENT, employing the VOF two-phase model to accurately track the air-water free surface as illustrated in Figure 2. The turbulent characteristics of the flow were resolved using the Reynolds Stress Model (RSM), which is suitable for capturing the anisotropy and complexity of the flow structures induced by the vegetation. The computational domain represented a section of a rectangular open channel, with dimensions of 1.5 m in length and 0.7 m in width, and an initial simulated water depth of 4.5 cm. To ensure efficient and accurate computation, a multizone meshing technique was applied. Crucially, the numerical model was subjected to a rigorous validation process against pre-existing experimental data obtained from a laboratory setup at Saitama University, Japan, under sub-critical flow conditions (Fr. no = 0.73). The validation focused on a single-layer, intermediate density vegetation case (G/d = 1.09), comparing the numerical outputs for the longitudinal Free Surface Level (FSL) distribution and the vertical distribution of streamwise velocity at both upstream and downstream locations.

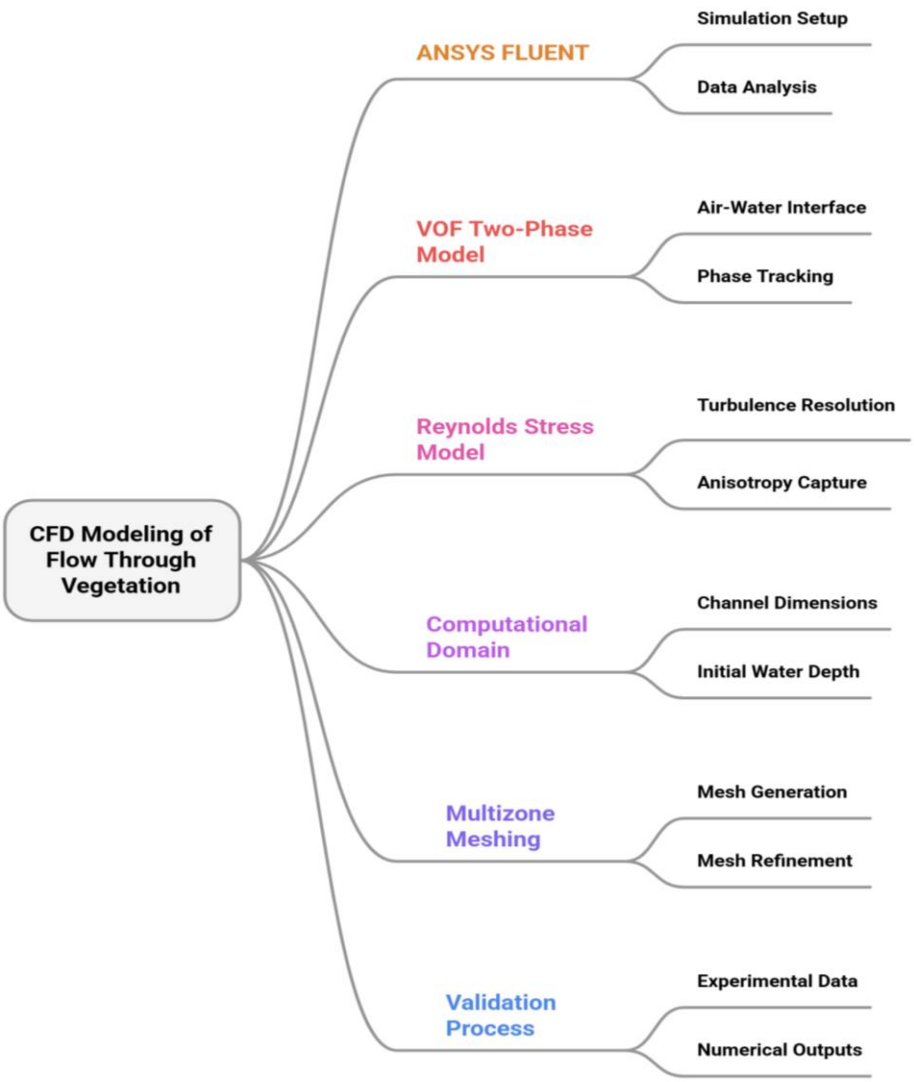


Figure 2. Overview of CFD modeling of flow through vegetation.

Following validation, the study systematically investigated five primary vegetation configurations across three different flow rates. The rigid vegetation was modeled as cylinders with two distinct heights: L1 (10 cm) and L2 (5 cm). The five cases included three single-layer vegetation (SLV) setups: Sparse (G/d=2.125), Intermediate (G/d=1.09), and Dense (G/d=0.25), and two vertically double-layered vegetation (DLV) setups. The DLV configurations paired a Sparse L1 layer (fixed at G/d=2.125) with either a Sparse L2 layer (G/d=1.65) or an Intermediate L2 layer (G/d=0.56).

Each of these five physical setups was simulated under three distinct hydraulic conditions, characterized by initial Froude numbers of 0.5, 0.7, and 0.9, corresponding to initial flow velocities of 0.332, 0.465, and 0.598 m/s, respectively. The output data, including 3D free surface variations, velocity distributions, and turbulence characteristics, were extracted and analyzed both within and immediately downstream of the vegetated zones, with a specific focus on characterizing the flow acceleration in the critical gap regions beside the patches.

4. Results and Discussion

Free surface profiles along channel length taking the longitudinal section (LS1) are shown in Figures 3, 4 & 5. All these profiles are shown in 2-D water-air volume fraction where the blue color is air fraction, and the red color is water fraction. For a sparse single-layered vegetation model, the water surface profile upstream, within vegetation, and downstream has no considerable effect. When the vegetation becomes dense, the backwater rise is more in front of vegetation, and the water surface drawn down is also increased when water passes through vegetation. A hydraulic jump is developed downstream in the sparse vegetation model, but the flow is smoother with a low water profile in the dense vegetation model. Similarly, the backwater rise upstream of vegetation is high in the double-layer vegetation model, but low in the single-layered sparse vegetation model. There is a considerable drop in the water surface profile for double-layered vegetation model and vegetation is also less susceptible to damage downstream of the vegetation model.

(At Fr = 0.5)

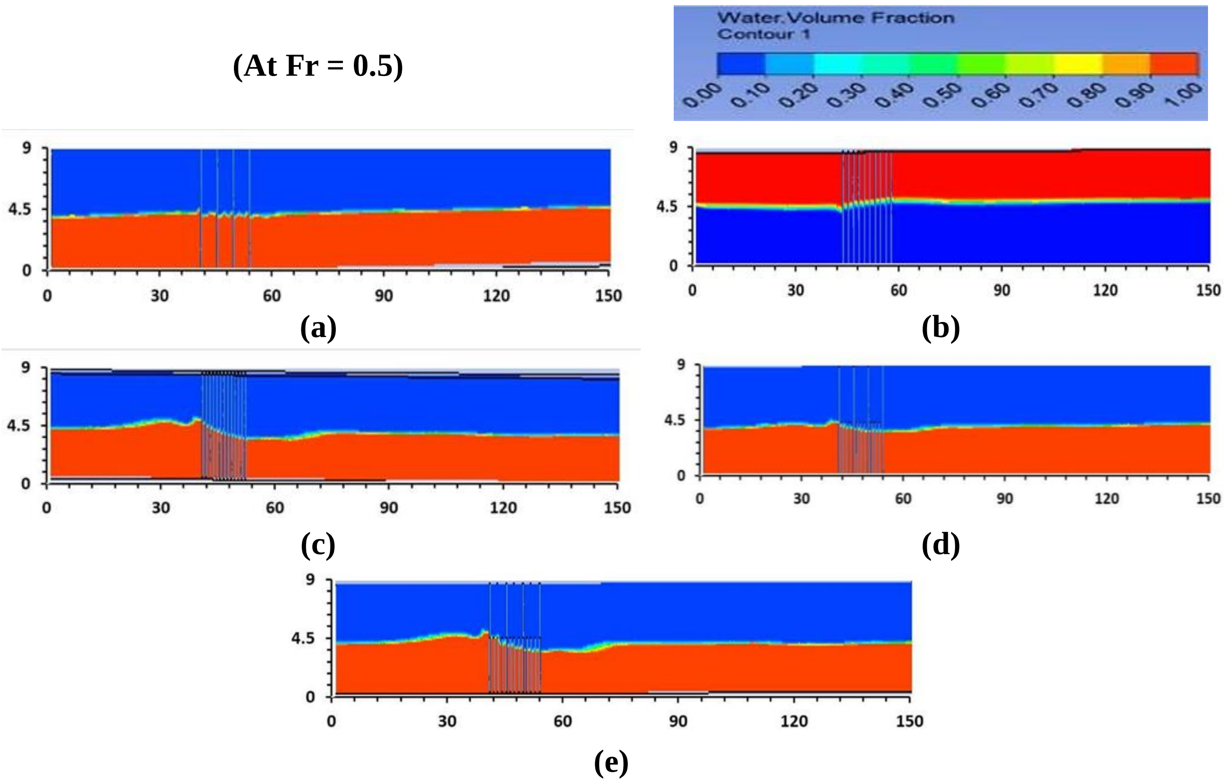
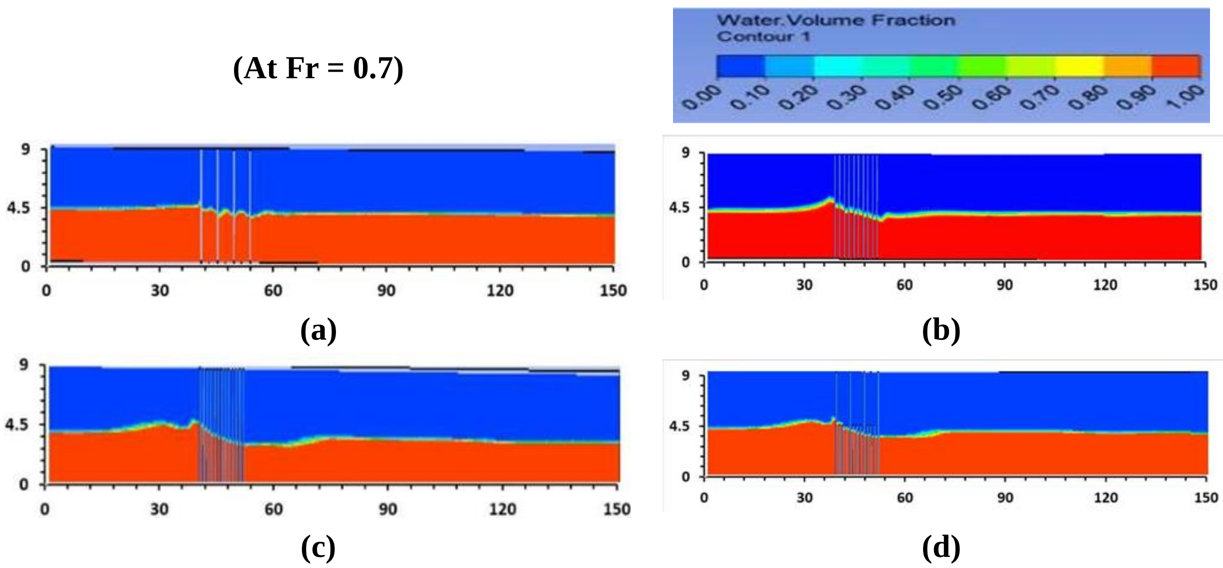
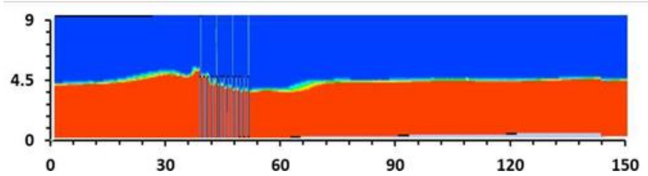


Figure 3. Two-dimensional Water-Air volume Fraction, Case 1 (a); Case 2 (b); Case 3 (c); Case 4 (d) and Case 5 (e).

(At Fr = 0.7)

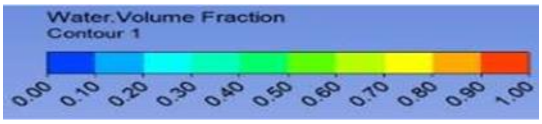


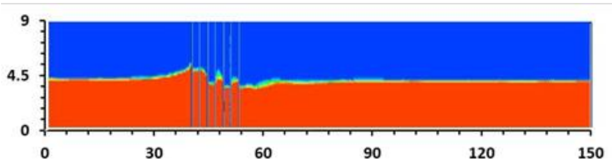


(e)

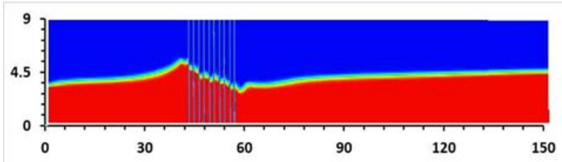
Figure 4. Two-dimensional Water-Air volume Fraction, Case 1 (a); Case 2 (b); Case 3 (c); Case 4 (d) and Case 5 (e).

(At Fr = 0.9)

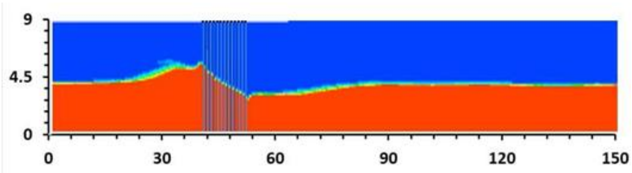




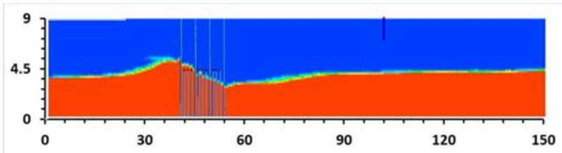
(a)



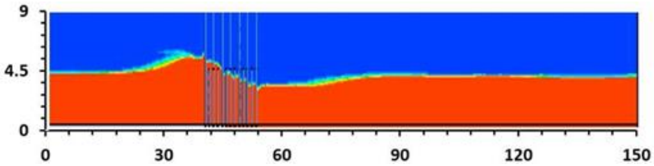
(b)



(c)

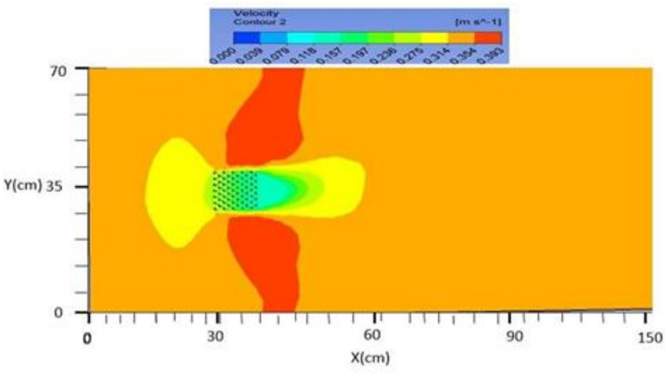


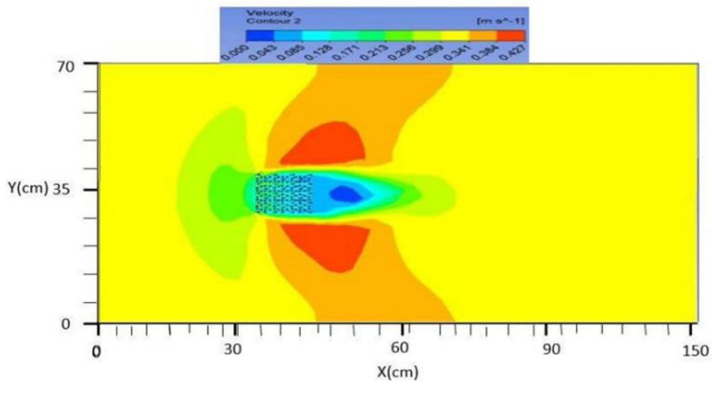
(d)



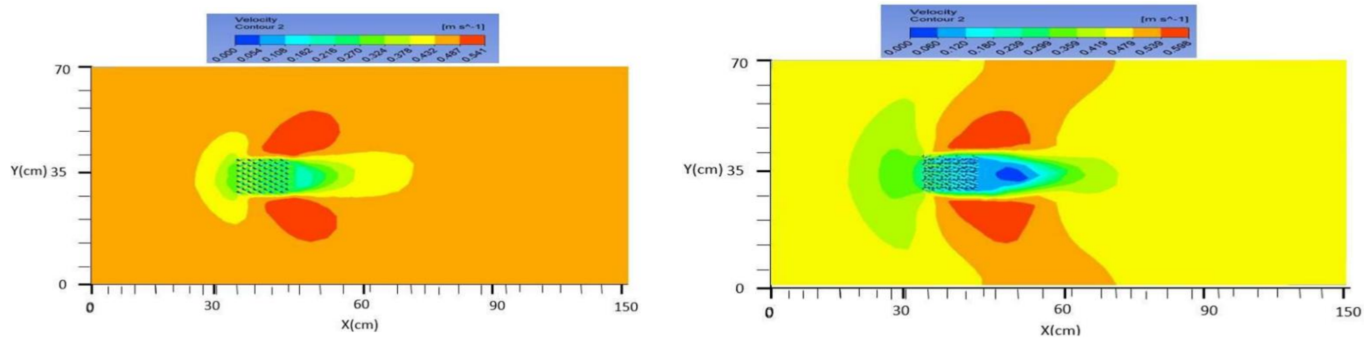
(e)

Figure 5. Two-dimensional Water-Air volume Fraction, Case1 (a); Case 2 (b); Case 3 (c); Case 4 (d) and Case 5 (e).

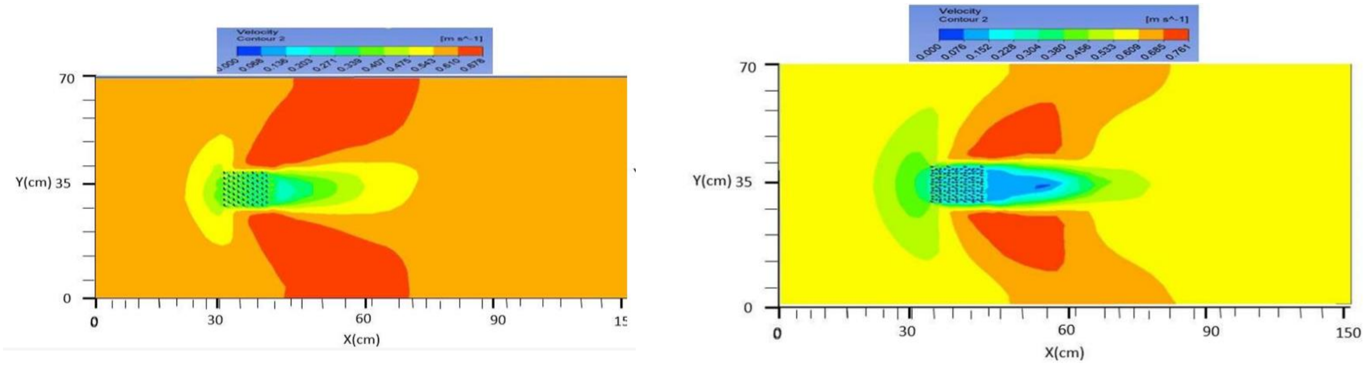




At Fr = 0.5

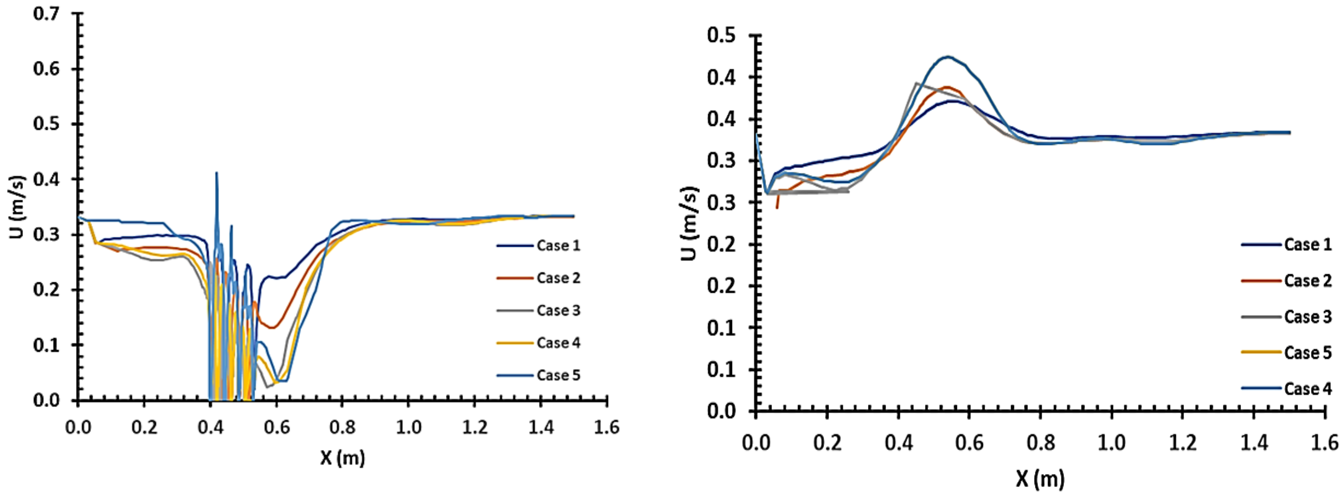


At Fr = 0.7

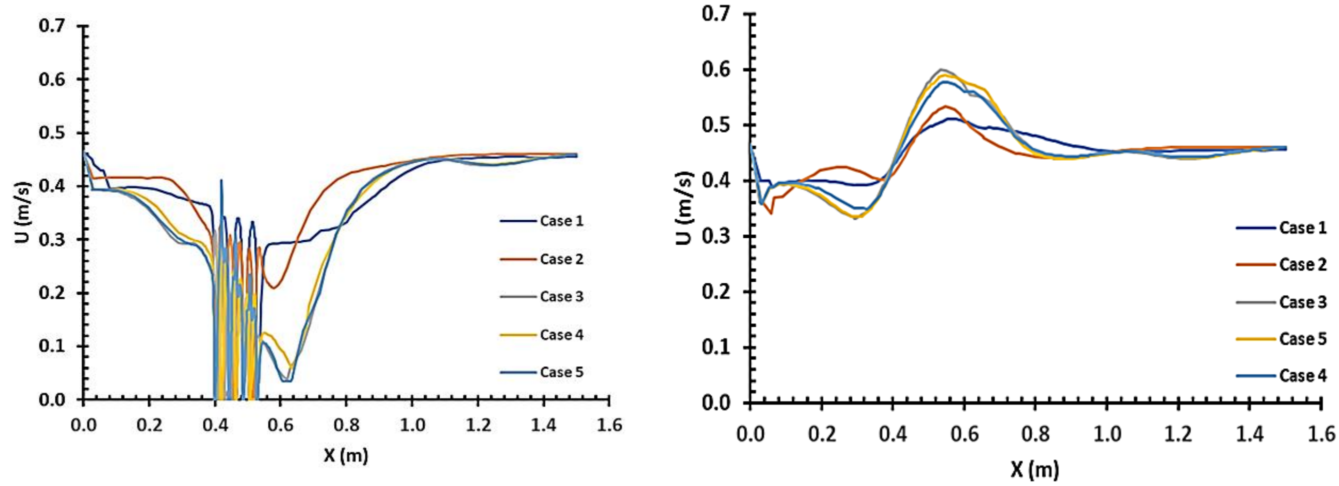


At Fr = 0.9

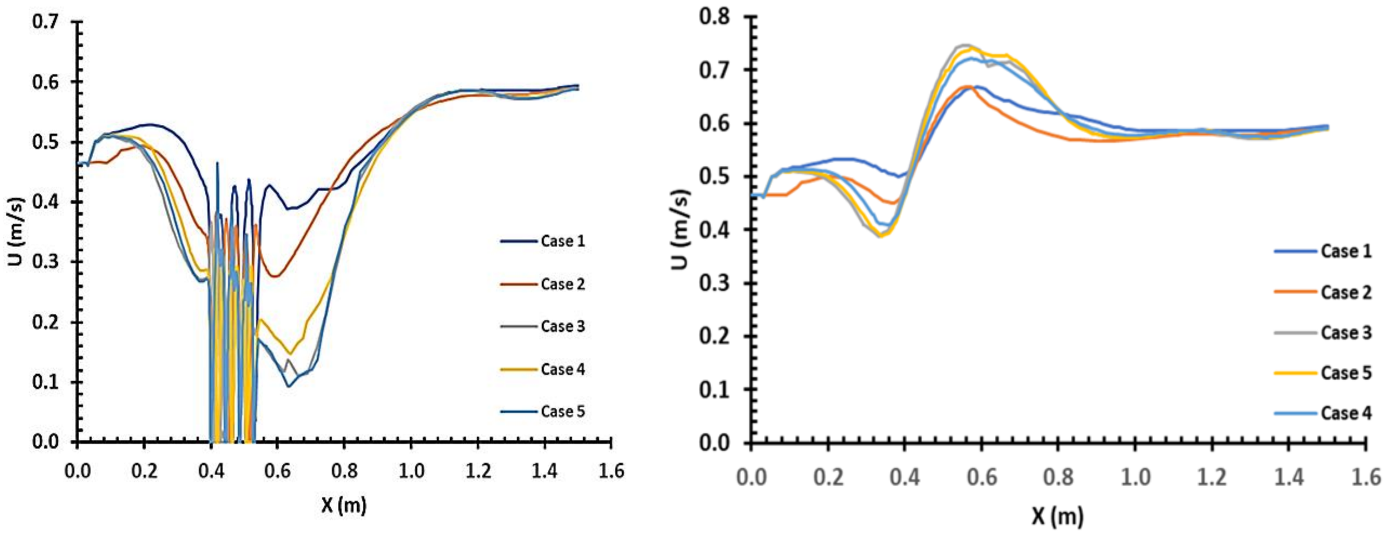
Figure 6. The velocity contours along a horizontal plane at (z=3.5cm). Case (2) & Case (5).



At Fr = 0.5

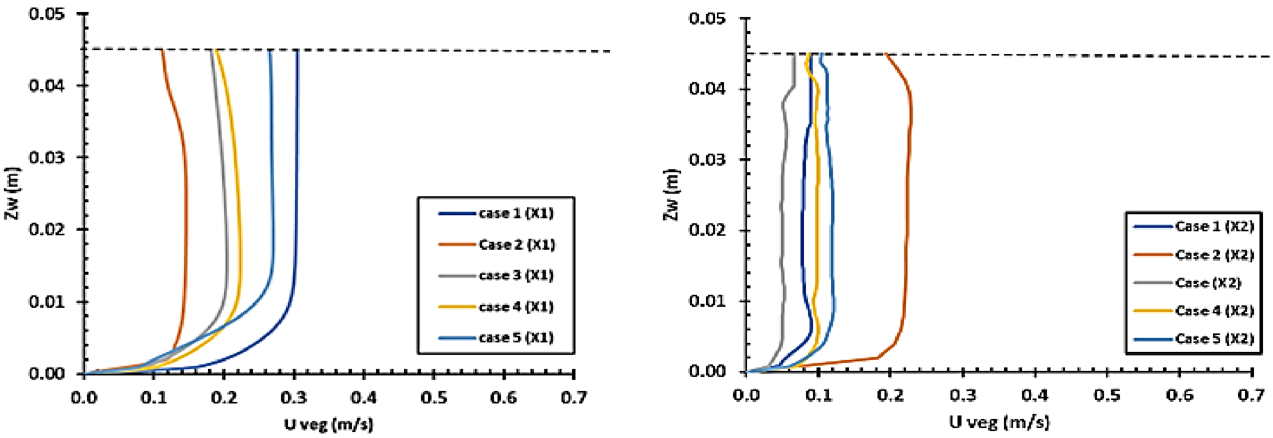


At Fr = 0.7

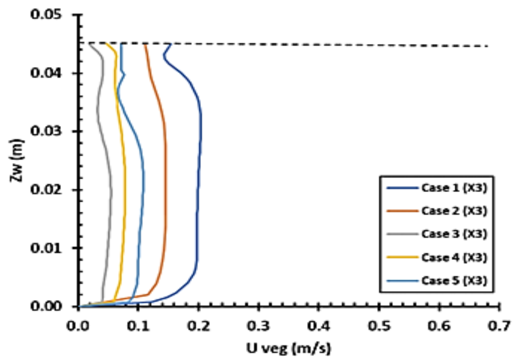


At Fr = 0.9

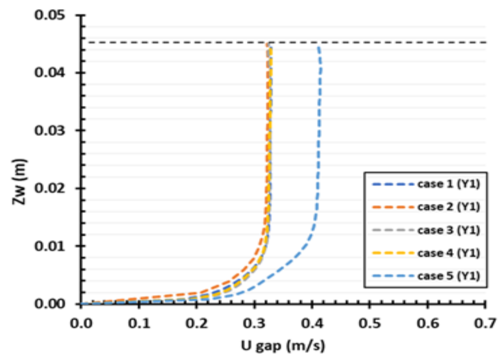
Figure 7. Longitudinal stream wise velocity distributions along LS1 and LS2.



(a) **(b)**



(c)



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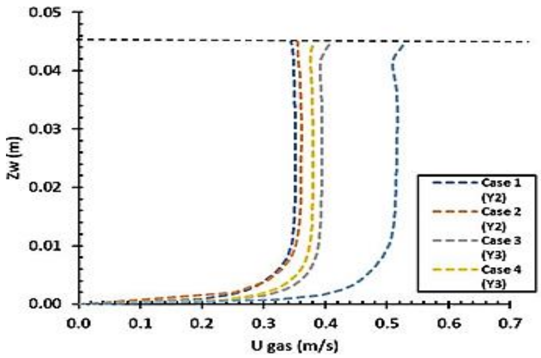

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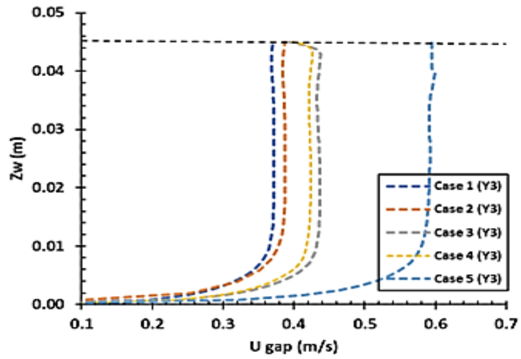
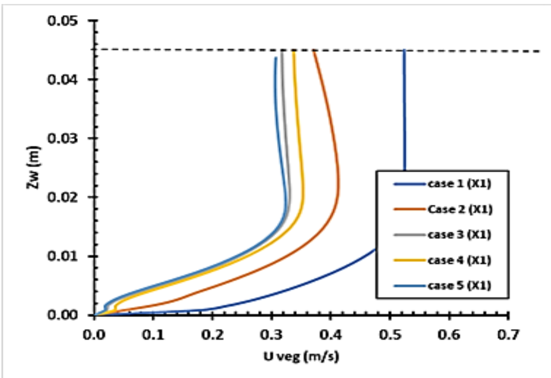
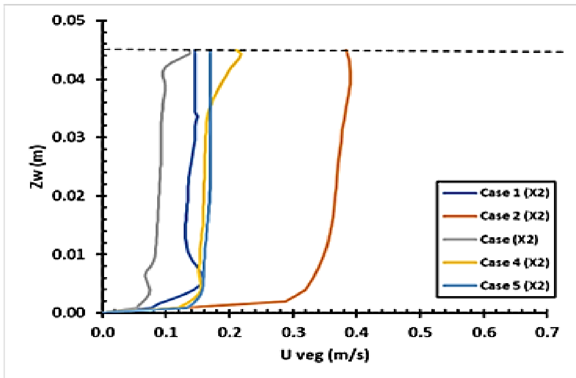


(f)

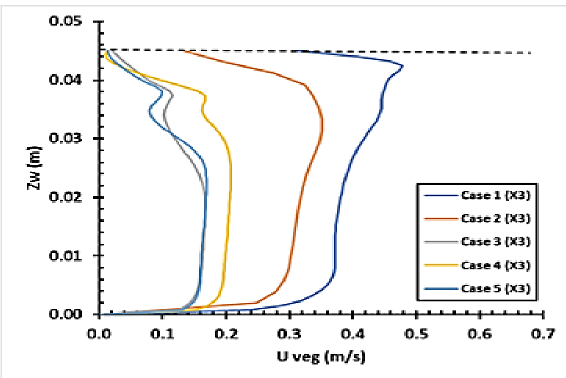
Figure 8. Vertical distributions of streamwise velocities at Fr = 0.5 (a) X_1; (b) X_2; (c) X_3; (d) Y_1; (e) Y_2; (f) Y_3.



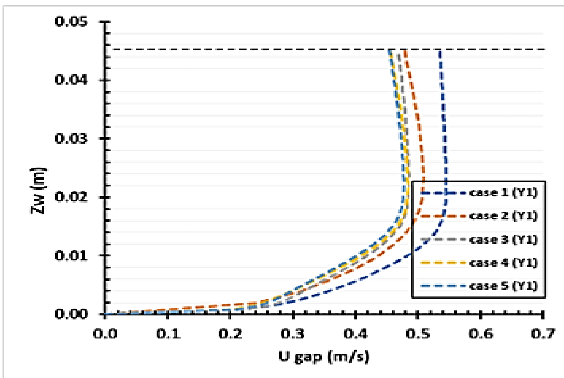
(a)



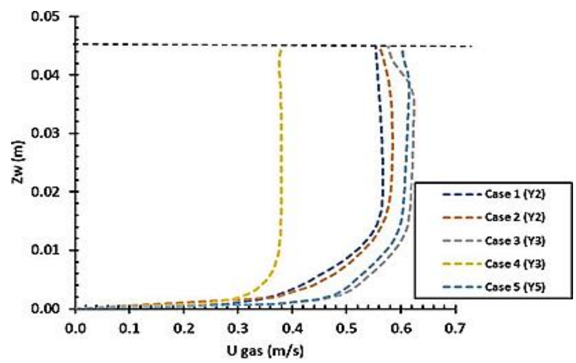
(b)

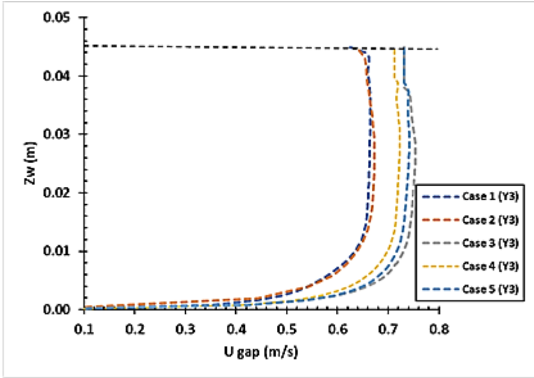


(c)



(d)





(e) **(f)**

Figure 9. Vertical distributions of streamwise velocities at Fr = 0.9 (a) X_1; (b) X_2; (c) X_3; (d) Y_1; (e) Y_2; (f) Y_3.

The maximum decrease in velocity was noticed in dense and double-layered vegetation patches i.e. case (3) case (4) & case (5) at point (x_1) due to the large number of cylinders and high FSL. The results clearly show that dense or double-layered vegetation could efficiently decrease the velocity in front of vegetation as shown in Figures 7 – 9. At point (x_2), located within the vegetation patch, the maximum velocity reduction was observed in dense or double-layered vegetation due to more resistance offered by a greater number of cylinders. Similar, results can be seen at point (x_3), at the end of vegetation. For all cases, the velocity distribution in the vertical direction in the gap regions is also presented in the same figures. Three points are taken in gap regions because gaps on both sides of vegetation cover are symmetrical, so results are identical.

The highest velocity reduction was observed in dense and double-layered vegetation cases that offered more hydraulic resistance against the flow. However, the velocity has critically increased downstream of vegetation gap regions due to the sharp diffraction of flow when it moved through the vegetation. At the downstream of the vegetation zone, the velocity reduction effect is not considerable in the case of spare vegetation, but it is very prominent in dense and double-layered vegetation as shown in Figure 6. It shows that vegetation density can effectively reduce the flow velocity during high floods. The resisting effect of dense vegetation helps to decrease the velocity downstream the vegetation as compared to sparse vegetation.

5. Conclusion

This research aimed to understand the role of vertically single-layered and double vegetation in reducing the flow velocity in front of vegetation, within the vegetation zone, and behind the vegetation using numerical simulations. The numerical models are simulated using ANSYS software and the VOF modeling technique was used to get air-water interaction in the open channel. The dense vegetation model and double-layered vegetation increased the hydraulic resistance (free surface level increased in front of vegetation compared to sparse vegetation and provided more energy reduction. The dense and double-layered vegetation produced a shallow velocity within and downstream due to the large resistance offered by vegetation. However, these models increased the velocity critically in the vegetation gap region downstream compared to the sparse vegetation model. The bed erosion could be reduced due to reduced velocity in front, within vegetation, and at the end of vegetation. So, the double-layered numerical model could be more efficient in decreasing flow velocity in high floods. The double-layered vegetation may have a better- mitigating ability as a bio shield against floods.

5.1. Future Recommendation

These results are beneficial and provide basic information for considering the suitable design of finite-length vegetation based on the Aspect Ratio (AR). Therefore, in the future, more computational research should be conducted to analyze the flow properties against the finite length emergent vegetation, with further varying configurations and with some angled gaps to overcome the high-velocity zone at the edges of the vegetation patch (observed in the wider patch configuration) and other ground conditions.

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References

1. Dehrashid, F. A., Heidari, M., Rahimi, H., Khoshkonesh, A., Yuan, S., Tang, X., ... & Wang, X. (2023). CFD modeling the flow dynamics in an open channel with double-layered vegetation. *Modeling Earth Systems and Environment*, *9*(1), 543-555.
2. Ahmed, N., & Bangalee, Z. I. (2025). Numerical simulation of discontinuously vegetated open channel flow to estimate effects of vegetation condition on flood mitigation. *Journal of Hydraulic Engineering*, *151*(5), 06025007.
3. Rahimi, H. R., Tang, X., & Singh, P. (2020). Experimental and numerical study on impact of double layer vegetation in open channel flows. *Journal of Hydrologic Engineering*, *25*(2), 04019064.
4. Rao, P. L., Prasad, B. S. S., Sharma, A., & Khatua, K. K. (2022). Experimental and numerical analysis of velocity distribution in a compound meandering channel with double layered rigid vegetated flood plains. *Flow Measurement and Instrumentation*, *83*, 102111.
5. Katul, G. G., Poggi, D., & Ridolfi, L. (2011). A flow resistance model for assessing the impact of vegetation on flood routing mechanics. *Water Resources Research*, *47*(8).
6. Şibil, R. (2024). Analysis of open channel flow with various layered vegetation using CFD, considering different near-wall treatment methods. *International Journal of Numerical Methods for Heat & Fluid Flow*, *34*(4), 1780-1810.
7. D'Ippolito, A., Calomino, F., Alfonsi, G., & Lauria, A. (2021). Flow resistance in open channel due to vegetation at reach scale: A review. *Water*, *13*(2), 116.
8. Tang, X., Rahimi, H., Guan, Y., & Wang, Y. (2021). Hydraulic characteristics of open-channel flow with partially-placed double layer rigid vegetation. *Environmental Fluid Mechanics*, *21*(2), 317-342.
9. Abbas, F. M. (2019). Investigating role of vegetation in protection of houses during floods. *Civil Engineering Journal*, *5*(12).
10. Feizbahr, M., Tonekaboni, N., Jiang, G. J., & Chen, H. X. (2021). Optimized vegetation density to dissipate energy of flood flow in open canals. *Mathematical Problems in Engineering*, *2021*(1), 9048808.
11. Woo, H., Ji, U., & Choi, S. U. (2025). Modeling of flow resistance due to vegetation: a state-of-the-art review. *Journal of Korea Water Resources Association*, *58*(3), 193-207.
12. Wilson, C. A. M. E., Stoesser, T., & Bates, P. D. (2005). Modelling of open channel flow through vegetation. *Computational fluid dynamics: Applications in environmental hydraulics*, 395-428.
13. Folkard, A. M. (2011). Vegetated flows in their environmental context: a review. *Proceedings of the Institution of Civil Engineers-Engineering and Computational Mechanics*, *164*(1), 3-24.
14. Qin, Y. (2020). Urban flooding mitigation techniques: A systematic review and future studies. *Water*, *12*(12), 3579.

15. Rowiński, P. M., Västilä, K., Aberle, J., Järvelä, J., & Kalinowska, M. B. (2018). How vegetation can aid in coping with river management challenges: A brief review. *Ecohydrology & Hydrobiology*, *18*(4), 345-354.
16. Tariq, K., Pasha, G. A., Tanaka, N., Ghani, U., & Ahmed, A. (2021). Development of ecosystem-based flood mitigation approach–investigations by experiments and numerical simulation. *Water and Environment Journal*, *35*(2), 685-703.
17. Anjum, N., & Tanaka, N. (2020). Experimental study on flow analysis and energy loss around discontinued vertically layered vegetation. *Environmental fluid mechanics*, *20*(4), 791-817.
18. Anjum, N., & Tanaka, N. (2022). Investigating the effectiveness of discontinuous and layered coastal forest defense system against the inundating tsunami current. *Landscape and Ecological Engineering*, *18*(2), 171-190.
19. Ahmed, N., & Bangalee, Z. I. (2025). Numerical simulation of discontinuously vegetated open channel flow to estimate effects of vegetation condition on flood mitigation. *Journal of Hydraulic Engineering*, *151*(5), 06025007.
20. Li, C. W., & Xie, J. F. (2011). Numerical modeling of free surface flow over submerged and highly flexible vegetation. *Advances in Water Resources*, *34*(4), 468-477.
21. Li, C. W., & Xie, J. F. (2011). Numerical modeling of free surface flow over submerged and highly flexible vegetation. *Advances in Water Resources*, *34*(4), 468-477.
22. Anjum, N., Ghani, U., Ahmed Pasha, G., Latif, A., Sultan, T., & Ali, S. (2018). To investigate the flow structure of discontinuous vegetation patches of two vertically different layers in an open channel. *Water*, *10*(1), 75.
23. Trabucco, A., Zomer, R. J., Bossio, D. A., van Straaten, O., & Verchot, L. V. (2008). Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies. *Agriculture, ecosystems & environment*, *126*(1-2), 81-97.
24. Ghani, U., Anjum, N., Pasha, G. A., & Ahmad, M. (2019). Numerical investigation of the flow characteristics through discontinuous and layered vegetation patches of finite width in an open channel. *Environmental Fluid Mechanics*, *19*(6), 1469-1495.
25. Abbas, F. M. (2019). Investigating role of vegetation in protection of houses during floods. *Civil Engineering Journal*, *5*(12).
26. Abbas, F. M., & Tanaka, N. (2022). Numerical study of flow structures through horizontal double-layered vegetation consisting of combined submergent and emergent vegetations. *Journal of Earthquake and Tsunami*, *16*(01), 2250004.