Open Channel Flow with Three-Layered Vegetation: Effect on the Velocity Distribution of Flow

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Abstract: Aquatic vegetation is widespread in rivers and influences their hydraulic characteristics. Due to individual differences from a biological point of view, the vegetation of different heights always coexists in nature. The attention on vegetation flow studies has shifted from the previous single-layer vegetation to more complex cases such as double- or triple-layer vegetation. Although only a limited number of studies on two-layer vegetation flow have shown that different vegetation heights have a significant effect on flow structure under partially submerged conditions, the effect of multi-layer vegetation on flow is unclear. In this regard, we conducted a novel experiment with triple-layered vegetation with all vegetation heights (10, 15 and 20 cm) under fully submerged conditions. A micro propeller velocimeter was used to measure the velocity at various locations in the downstream cross-section of the channel, including the positions behind short and tall plastic dowels. The measured results showed that the vertical velocity distribution was strongly influenced by vegetation height and its distribution. The observed data also showed differences in velocity directly behind vegetation and in the area behind the vegetation gap. Typically, the velocity profile has a similar profile, with almost a constant velocity from the bed to the height of about 0.75 of the short vegetation height and then a slight increase to the height of the middle vegetation. Afterwards, the velocity rises fast to the water level, where the reflection can be observed. This novel experiment reveals the effect of multiple layers of vegetation on water flow. It would also contribute to the significance of this vegetation configuration and further research on open channel flow in complex vegetation environments.

1 INTRODUCTION

Vegetation is an essential component of natural river ecosystems, which can be exploited in river engineering to meet hydraulic and ecological requirements (Naiman et al. 1993; Curran & Hession, 2013; Rowiński et al., 2018). Previous experimental and analytical studies have shown that vegetation can affect vertical flow distribution, fluid resistance, Reynolds stress and lateral flow variation in open channels with single-layered vegetation (Follett and Nepf, 2012; Tang et al., 2011; Tang et al., 2013a; Tang et al., 2019a, 2019b; Yang et al., 2020; Box et al. 2021). Recently, several studies have focused on channel flow with double-layered vegetation, which is more complex situation that creates strong vortices in the interaction zone between the vegetation of different heights (Tang et al. 2018; Singh et al., 2019; Rahimi et al., 2020a; Tang et al., 2021b). The velocity distribution in channels with multiple layers of vegetation has received particular attention. Tang et al. (2022) experimentally investigated the effect of partially-submerged triple-layered vegetation on the velocity characteristics of fluids in open channels. The measured velocity profiles showed that the triple-layered vegetation added a significant resistance to the fluid, and the effect of high vegetation on velocity was more significant than that of the short one. Nevertheless, the study by Tang et al. (2022) was based on partially inundated conditions and may not be suitable for some situations, e.g., researchers in freshwater ecosystems have found that reusing inundated vegetation is an advance and feasible approach to clean up water bodies and address eutrophication (Chao et al., 2022). In addition, Tang et al. (2021a) have also found that higher inundation rates lead to increased velocity profile gradients in areas of high and low vegetation interactions.

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Therefore, it is of great importance to understand the effect of multiple layers of vegetation on water flow under fully submerged flow conditions.

In this study, three layers of vegetation, a set of short, medium, and tall dowels, were placed orderly at the bottom of an inclined flume, and the experiment was set to a flow depth of 26 cm with all dowels submerged. Velocities were measured at different locations across the channel using a propeller velocimeter. This research was particularly focusing on the downstream section, since which is the area most hydrological issues occur, such as flooding, water pollution, and eutrophication (Scheumann et al., 2011).

2 EXPERIMENTAL APPARATUS AND SETTING

In order to mimic vegetation of different heights in real water environments, this experiment was conducted at Xi'an Jiaotong Liverpool University (XJTLU) with a rectangular cross-section of 0.4 m wide and 0.5 m high, a water depth of 26 cm, and a bed slope of 0.003 (Tang et al. 2021). A sketch of the flume is shown in Figure 1, which has a 4.3 m long vegetated segment, starting 8.4 m from the entrance to the flume. Three different heights (10, 15, and 20 cm) of round plastic dowels were installed in the vegetated area, with each having a diameter of 6.35 mm. All dowels were arranged linearly, as shown in Figure 2. Each row was a staggered arrangement of short and medium or tall dowels. The spacing between two adjacent dowels was 31.75 mm.

There were 12 measurement points in the downstream area of vegetation, as indicated by the symbol cross (x) in Figure 2. At each location, the flow velocity at 23 points above the bed was measured with a micro propeller velocimeter to obtain the vertical distribution of velocity. The sampling time for velocity measurements was set to 20 seconds twice to ensure the accuracy of velocity. Measurements were made at the downstream section behind the row of the short and tall dowels (10 and 20 cm), respectively. At a flow depth of 26 cm, the discharge of the open channel was 27.15 l/s; thereby all short, middle, and high vegetation was completely submerged.

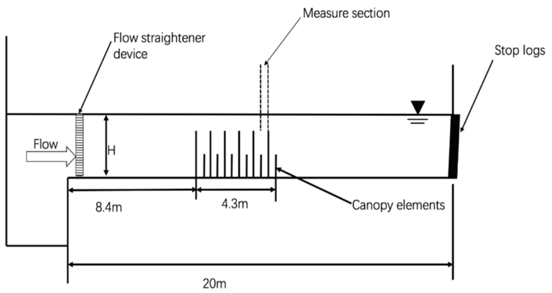

Figure 1: The sketch of the experimental flume.

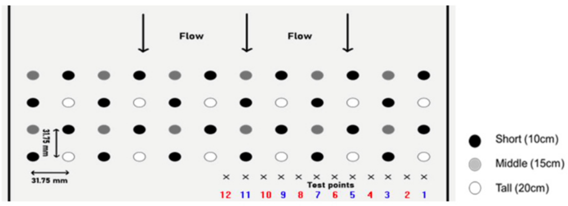

Figure 2: The layout of vegetation array and measurement locations in the downstream zone.

3 RESULTS AND DISCUSSION

3.1 Velocity Profiles Directly Behind Vegetation

Figure 3 presents the velocity results for group A (positions 3, 7 and 11, all behind short vegetation), while Figure 3 illustrates the velocity profiles for group B (positions 1, 5 and 9, all behind tall vegetation). Note that u is the streamwise velocity, u_* is the shear velocity, and h is the height of short vegetation, z is the vertical distance above the bed in all subsequent figures. The velocity profiles demonstrate a distinct vertical variation.

As shown in Figure 3, in the low zone near the bed (layer 1) where z/h is less than or equal to 1, the flow velocity does not change greatly in the vertical direction. It is noted that although there exist certain minor decreases in flow velocity at these locations, the magnitude of the changes is minimal (less than 10%) and can be taken as an allowable margin of error. In the intermediate region (layer 2: $1 < z/h < 1.5$), i.e., the region between the short vegetation and the middle vegetation, the variation of flow velocity is similar for the three positions: the flow velocity gradually increases with height until about z/h = 1.25, which seems to be a velocity inflection point. This S-shaped velocity profile in this region has also been found in studies of double-layered vegetation (Rahimi et al., 2020b; Tang et al., 2021b), indicating a steady slope of the curve at about 0.5 $(u/(u_*))/(z/h)$. In the upper region (including layers 3 and 4), the velocity steadily rises to the water surface starting from a certain distance below the top of the middle vegetation (about z/h = 1.25). Meanwhile, the range of velocity variation was greater, and the rate of change was larger in comparison with the other layers (layers 1 and 2). In general, the velocity profile of group A shows a typical ʃ-shaped curve with a small increase in velocity in the lower layer, followed by a transition at z/h = 1.25 and then a rapid increase up to the water surface, which is consistent with the findings of the other two layers of vegetative flow (Rahimi et al., 2020b; Tang et al., 2021b).

For the velocity profile of Group B (Figure 4), the overall profile does not differ much from that of Group A, but the main difference is in the intermediate layer (layer 2.) The velocity range rate of Group B is larger in layer 2 than that of Group A, indicating that the taller vegetation in Group B seems to penetrate the flow more deeply. In addition, it can be found that in the lower layer (layer 1), the velocity of group A is generally smaller than that of group B with an amplitude of about 29.4%. Moreover, when the height of the middle vegetation is reached, there is a transcendence between the two data sets (2.8 vs 2.25 in velocity).

Finally, when the water surface exceeds the height of the maximum vegetation, the flow velocity of the channel remains the same, about 4.5-5.5 for group A and 3.5-3.8 for Group B; thus, we may draw the following points:

- The vegetation in the water has a decreasing effect on the flow velocity. The higher the depth from the vegetation, the faster the velocity of the water layer. The water layer beyond the vegetation-occupied area shows the free surface flow and is less influenced by vegetation.
- For the velocity profile behind the short vegetation, the velocity beyond the vegetation height rises rapidly (i.e., the velocity starts to rise faster when z/h exceeds 1) and finally reaches a stable value; however, for the velocity behind the tall vegetation, it begins to increasease rapidly after z/h = 2. Finally, the same stable value is reached.

In addition, the side walls of the channel influenced the flow velocity profile. Behind the tall vegetation (group B, Figure 4), the velocity data (z/h<2) show that the fastest velocities are found near the wall (P1) than at other locations (P5 and P9) closer to the centre of the channel. Nevertheless, the velocity in the outer layer (or the free flow, z/h>2) is not influenced by the wall. For the flow velocities in group A (behind short vegetation, Figure 3), the effect of the wall seems to be somewhat different in the upper layers: (a) just below the top of the tall vegetation (z/h=1-1.8), the flow velocities near the side wall (P3) are greater than those near the centre of the channel (P11); (b) However, above the tall vegetation, the flow velocities change in the opposite direction, i.e., the velocities are smaller near the side wall, indicating that the side wall has certain blocking effect. However, velocities away from the wall are less influenced by the wall boundary but are dominated by the vegetation.

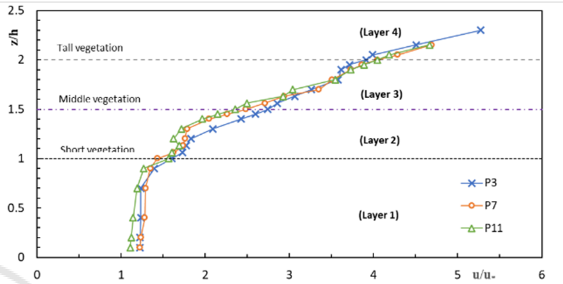

Figure 3: Velocity profiles directly behind the short vegetation (Group A).

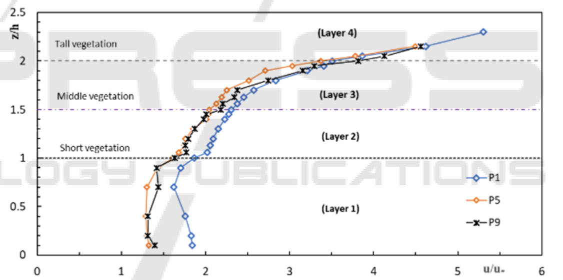

Figure 4: Velocity profiles directly behind the tall vegetation (Group B).

3.2 Velocity Profiles behind the Gap of Vegetation

To better understand the lateral variation of velocity profiles behind vegetation gaps (P2, 4, 6, 8, 10, 12), these positions were divided into two groups. Group C includes P2, P6, P10 (i.e., behind the gap between tall and short vegetation), while group D includes P4, P8, P12 (i.e., behind the gap between short and tall vegetation).

According to Figure 5 (group C), in layer 1 (z/h<1), the velocity profiles of P2, P6 and P10 are almost identical and do not have significant variation. In layer 2 (1<z/h<1.5), the velocity gradually increases with depth, showing a position-independent profile. However, in layer 3 (1.5<z/h<2), the velocity of P6 is significantly greater than the other two positions (P2 and P10), which are nearly identical. In the layer near the water surface (z/h>2), all velocities are close to a single profile. In general, the velocity profile exhibits a ʃ-shape, although the upper end of the curve may have different growth rates, depending on the position. It appears that the growth of velocity is more linear at position (P6) because the sidewall less influences it.

Regarding the flow velocity profile of group D (Figure 6), it generally indicates a similar flow velocity profile to that of group C. However, within the vegetative layer (z/h<2), the flow velocity of P12 (in the centre of the channel) is smaller than that of P4 or P8 (which are identical), due to the effect of the asymmetric distribution of vegetation. Above the tall vegetation (layer 4, z/h>2), the velocity of P12 becomes larger than that of both P4 and P8, and their difference becomes smaller. This result may be due to a certain blocking effect of the sidewalls on P8 and P4 (more as closer to the wall).

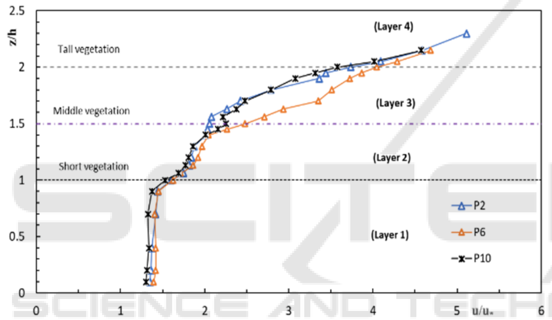

Figure 5: Velocity profiles behind the gap of vegetation (Group C).

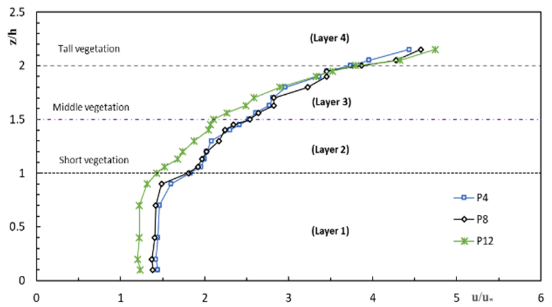

Figure 6: Velocity profiles behind the gap of vegetation (Group D).

To compare the differences in the velocity profiles between the two groups, all data for the 6 positions are shown in Figure 7. It was found that the velocity profiles have a similar trend. In the bottom layer (z/h < 1), the velocity remains almost constant, although P12 (at the centre) has the smallest value. However, in the intermediate layer (1<z/h<1.5), the velocity increases gradually with a similar growth rate, and P12 has the smallest velocity, while P2 (near the sidewall) has the highest velocity. As the flow depth increases, the velocity in the upper layer (z/h > 1.5) increases rapidly until the water surface and approaches a curve.

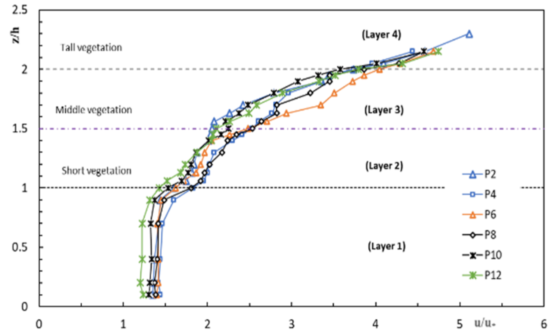

Figure 7: Velocity profiles behind the gap of vegetation for all positions.

In summary, vegetation has a retarding effect on the flow through the gap of vegetation. The flow velocity significantly reflects near the edge of the vegetation, but the velocity is least affected by the vegetation in the flow area above the tall vegetation. When z/h<1, the flow velocity is dominated by the vegetation, resulting in slight vertical variation in velocity because large drag force of vegetation. However, in the vegetated area (1 < z/h < 2), the flow velocity starts to increase gradually (in the densely vegetated area) and then increases rapidly (in the less densely vegetated area). When z/h>2, the free flow area where the velocity changes the most, and finally the velocity reaches a stable value near the free surface. According to Figure 6, the velocity profile of P12 is smaller than the other locations (P4 and P8) when z/h<1.75, between P4 and P8 in the range 1.75<z/h<2, and larger than P4 or P8 when z/H>2. In fact, the velocity profiles of P8 and P4 are almost indistinguishable when z/h<2. At approximately z/h=2.15, the velocity profile of P8 is slightly larger than that of P4 but smaller than that of P12. It indicates that in the area above the tall vegetation (z/h>2), the velocity profile near the wall is smaller than that away from the wall. It can also be seen from Figure 7 that the velocity profile near the wall is greater than that far from the wall when z/h>2.15, while in the upper vegetation layer (z/h>1.5), the water velocity at P6 is greater than at any other location (e.g., P2 and P10).

3.3 Comparison of Velocity Profiles at Various Locations Behind Vegetation

To investigate how vegetation affects the velocity profiles at different locations behind the vegetation, Figure 8 compares the velocity profiles at locations far from the wall (i.e., P6-P10). Since they are positioned at a certain distance from the wall, the effect of the wall can be considered minimal and negligible here.

In the bottom region of the channel (z/h<1), the velocity was affected by the three different heights of vegetation, with a similar pattern of velocity changes: the velocity remained almost constant below the short vegetation (although there were some slight fluctuations, this small difference can be considered as a type of measuring error in the experiment). Furthermore, at about the 0.9*h* height, the velocity starts to increase rapidly to the top of the short vegetation. In terms of flow directly behind and through the vegetation gap, the flow velocity behind the vegetation gap was greater than that directly behind the vegetation, although the difference was small. This result is consistent with the results of other studies (e.g. Rahimi et al., 2020b).

In the flow zone of z/h>1, the velocity has increased rapidly and continued to the water surface. It is inferred that the flow in the intermediate layer (1<z/h<1.5) is more affected by overlaid vegetation (middle and tall), and the increase of velocity is relatively slow. The difference from the previous part is that with the increase of height, the offset of the flow velocity offset directly behind the vegetation gradually decreases or even disappears. For example, the flow velocity at P8 is greater than that at P7, but as the height increases, the velocity at P7 gradually becomes larger than that at P8. Therefore, this phenomenon may be explained as a result of the density of vegetation, which gradually shifts to a regular pattern affected by the wall alone. Furthermore, the flow velocity was greater at P7 (behind short vegetation) than at P9 (after high vegetation). The reason may be that in the upper layer, because P7 is not directly affected by vegetation (height is above the short vegetation), it will have a larger flow velocity than P9, which is directly affected by the middle and tall vegetation. Meanwhile, this also results in the reduction of velocity.

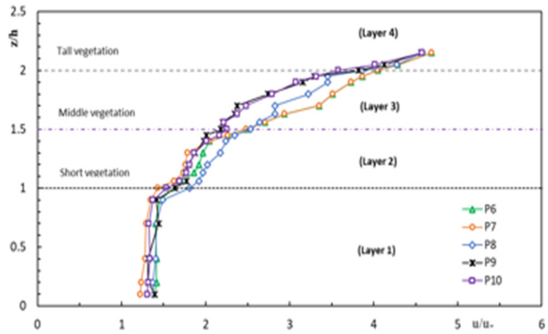

Figure 8: Comparison of velocity profiles at various positions behind the vegetation.

3.4 Comparison of Mean Velocity Profiles at Various Positions Behind Vegetation

In order to reveal the changes of averaged velocity profiles at some typical locations, this section aims to compare the combined effects of a group of vegetation on averaged velocity profiles across a channel section, as shown in Figure 9. BST represents the averaged profile of P1, 5 and 9 (behind the tall after short vegetation). BMS denotes the averaged velocity profile value at P3, P7 and P11 (behind the short after middle vegetation). SM represents the averaged value of velocity profiles at P2, P4, P6, P8, and P10 (behind the gap of tall and short vegetation).

Figure 9 demonstrates significant differences in the averaged velocity profile at some typical locations (BST, BMS and SM): The overall averaged velocity profile is a ‘ ’ type, i.e., the velocity changes small in the bottom region up to 0.9h, and then increases quickly near the top of short vegetation (i.e. z/h =1), where the strong vertical exchange of flow takes place; then the velocity increases gradually in the intermediate region (1<z/h<1.5) and continues fast to the water surface. It was found that when z/h < 1.3, the flow velocity of BMS is smaller than that of BST and SM. Nevertheless, when z/h > 1.3, the flow velocity change of BMS is faster and becomes larger than that of BST and SM. The velocity profiles of BMS, BST and SM are similar in the layer below z/h=1.4, which is the turning point; afterwards, the velocity of BST is accelerated and finally reaches the highest value near the water surface (z/h = 2.2), where the velocity of BMS and SM approaches.

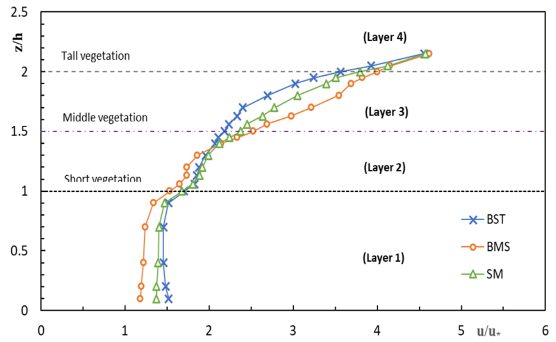

Figure 9: Lateral variation of averaged velocity profiles.

3.5 Lateral Variation of Layer-Averaged Velocity

The layer-averaged and depth-averaged velocities can be obtained from the measured velocity vertical distribution. Figure 10 shows the lateral variation of the layer-averaged and depth-averaged velocities for a half channel. Note that in Figure 10, z/h=Ud denotes the depth-averaged velocity, whereas the others denote the layer-averaged. In general, the velocity at the position directly behind the vegetation (odd-numbered position) is smaller than the velocity at the centre position behind the vegetation gap (even-numbered position). However, for the locations close to the sidewalls (P1 and P2) the velocities do not appear to conform to the above results, indicating the effect of walls. The velocities at the even-numbered locations near the sidewalls are slightly smaller than the velocities at the odd-numbered points. Thus, it may be inferred that the wall has certain influence on the flow velocity. In addition, contrary to the previous results, in the vegetation-covered area (the first to third layer), there is a tendency for the depth-averaged velocity to decrease slightly towards the centre of the channel, although the surface layer (above the tall vegetation) is almost unchanged in the lateral direction.

It is noted that in the middle layer (layer 3, $1.5 < z/h < 2$), i.e., in the area between the middle and tall vegetation, the variation of layered-velocities is particularly complex and fluctuating. Similar to the analysis in the previous sections, the layer-averaged velocities at P3, P7, and P11 are larger than at any other position. This result may be due to the fact that all three locations are directly behind the short vegetation, thus making their flow velocities less influenced by the middle and short vegetation upstream (offset only by the tall vegetation). While at P1, P5, and P9, their layered velocities are considerably influenced by the tall vegetation upstream, thus resulting in smaller flow velocities.

Besides, Figure 11 shows that the averaged layer velocity increased with increasing flow depth, indicating that the lowest velocity was found near the bed (layer 1) and the highest velocity in the upper layer (layer 4). The averaged velocity of each layer is directly related to the vegetation density in the corresponding layer. Layer 1 has the lowest velocity, corresponding to the highest vegetation density, leading to the lowest velocity. Layer 4 behaves as a free-flowing layer (not directly influenced by any height vegetation), leading to the maximum velocity.

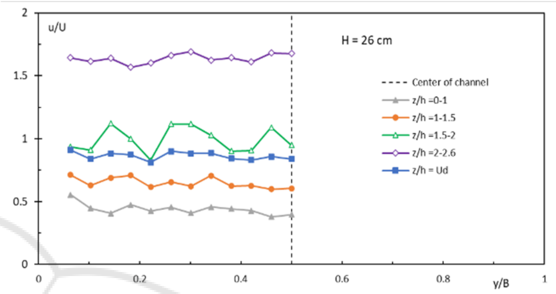

Figure 10: Lateral variation of layer- and depth-averaged velocity.

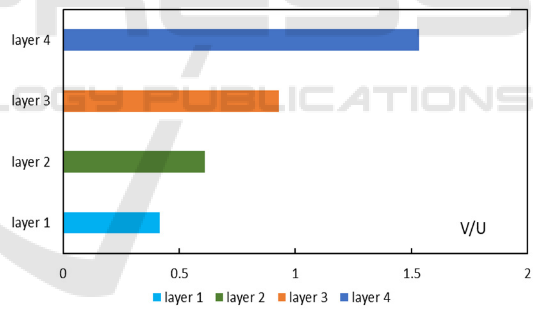

Figure 11: Averaged velocity (V) of each layer for the half channel. Note: U is the cross-sectional mean velocity of the channel.

4 CONCLUSIONS

A novel experiment was conducted to investigate the effect of fully submerged triple-layered vegetation on the flow in an open channel. Detailed flow velocities were measured using micro propeller velocimetry at different locations across a downstream section of the channel. The overall velocity profile has shown that the flow velocity increased with increasing flow depth, which was significantly different from the logarithmic law of velocity in open channels without vegetation. More specifically, flow velocities were relatively small and almost constant near the channel bed up to 0.4 z/h (a position slightly below the top of short vegetation), and then increased consistently to 1.5 z/h (i.e. the height of the middle vegetation). In the region above the middle vegetation, the velocity increased rapidly to the water surface. There are two distinct reflections: the first one is below the short vegetation near 0.4 z/h, and the second occurs close to the top of middle vegetation. Besides, the lateral variation of mean velocity profile is complex, which implies that the open-channel flows with completely submerged multi-layered vegetation are intricate. More experiments or data would be required for further understanding.

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REFERENCES

Box, W., Järvelä, J., Västilä, K, 2021. Flow resistance of floodplain vegetation mixtures for modelling river flows. *Journal of Hydrology*, 601, 126593.

Curran, J., Hession, W. 2013. Vegetative impacts on hydraulics and sediment processes across the fluvial system. *Journal of Hydrology*. 505, 364–376.

Follett, E.M. and Nepf, H.M., 2012. Sediment patterns near a model patch of reedy emergent vegetation. *Geomorphology*, 179, 141-151.

Naiman, R.J. Decamps, H., and Pollock, M. 1993. The role of riparian corridors in maintaining regional biodiversity. *Ecological Application*, 3, 209-212

Rahimi, H.R., Tang, X. and Singh, P., 2020a. Experimental and numerical study on impact of double layer vegetation in open channel flows. *Journal of Hydrologic Engineering*, 25(2), 04019064.

Rahimi, H.R., Tang, X., Singh, P., Li, M. and Alaghmand, S., 2020b. Open channel flow within and above a layered vegetation: Experiments and first-order closure modeling. *Advances in Water Resources,* 137, 103527.

Rowiński, P.M., Västilä, K., Aberle, J., Järvelä, J. and Kalinowska, M.B., 2018. How vegetation can aid in coping with river management challenges: A brief review. *Ecohydrology & Hydrobiology*, 18(4), 345-354.

Scheumann, W., Sagsen, I. and Tereci, E., 2011. Orontes River Basin: Downstream challenges and prospects for cooperation. *Turkey's Water Policy*, 301-312.

Singh, P., Rahimi, H., Tang, X., 2019. Parameterization of the modeling variables in velocity analytical solutions of open-channel flows with double-layered vegetation. *Environmental Fluid Mechanics*, 19(3), 765-784.

Tang, X., Knight, D.W. and Sterling, M., 2011. Analytical model for streamwise velocity in vegetated channels. *Proceedings of the Institution of Civil Engineers-Engineering and Computational Mechanics*, 164(2),91-102.

Tang, X. and Ali, S., 2013. Evaluation of methods for predicting velocity profiles in open channel flows with submerged rigid vegetation. *In Proceedings of the 35th IAHR world congress* (Vol.4, B1, 1744-1755).

Tang, X., 2019a. A mixing - length - scale - based analytical model for predicting velocity profiles of open - channel flows with submerged rigid vegetation. *Water and Environment Journal*, 33(4), 610-619.

Tang, X., 2019b. Evaluating two-layer models for velocity profiles in open-channels with submerged vegetation. *Journal of Geoscience and Environment Protection*, 7(1), 68-80.

Tang, X., Guan, Y., Hu, Y. 2021. Velocity Profile and Lateral Distribution in an Open Channel with Two Distinct Vegetative Zones. In *Proceedings of the 7th International Conference on Water Resource and Environment – WRE*, 240-245, Scitepress.

Tang, X., Guan, Y., Rahimi, H., Singh, P. and Zhang, Y., 2021a. Discharge and velocity variation of flows in open channels partially covered with different layered vegetation. *In E3S Web of Conferences* (Vol. 269, 03001). EDP Sciences.

Tang, X., Rahimi, H., Guan, Y. and Wang, Y., 2021b. Hydraulic characteristics of open-channel flow with partially-placed double layer rigid vegetation. *Environmental Fluid Mechanics,* 21(2), 317-342.

Tang, X., Rahimi, H., Singh, P., Wei, Z., Wang, Y., Zhao, Y., Lu, Q. 2018. Experimental study of open-channel flow with partial double-layered vegetation. In: Proceedings of the 1st International Symposium on Water Resource and Environmental Management (WREM 2018), Nov. 28-29, 2018, Kunming, China. DOI: 10.1051/e3sconf/20198101010.

Tang, X., Zhang, S., Cao, J., Wang, H., Xiao, N. and Guan, Y., 2022. Effect of Multiple Layered Vegetation on the Velocity Distribution of Flow in An Open Channel. *In Proceedings of the 39th IAHR world congress.* 1272-1280, DOI: 10.3850/IAHR-39WC252171192022133.

Yang, F., Huai, W., Zheng, Y. 2020. New dynamic two-layer model for predicting depth-averaged velocity in open channel flows with rigid submerged canopies of different densities. *Advances in Water Resources*, 138(2020), 103553.