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Hydraulic Effects of Coverage Width of Double-Layer Vegetation on Open-Channel Flows: Experimental Study

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Abstract

Aquatic vegetation is an essential component of both urban and rural ecosystems. Investigating the effect of aquatic vegetation on water flow is an important topic in hydraulics since it affects hydraulic characteristics that provide rivers with many functions. Due to the complexity of the effect, previous researchers have explored the submergence, density, and arrangement of aquatic vegetation and established some models for predicting the velocity distribution of flow with vegetation. However, natural rivers have more complex aquatic vegetation conditions: the shallow region grows more vegetation, while the deep region has less vegetation. The change of vegetation cover in a channel can result in significant differences in the effect of aquatic vegetation on water flow. Still, such influence has not been fully understood in previous studies. This paper explores the impact of the coverage width of double-layer aquatic vegetation on the river flow. The experiments were conducted to understand the impact of different vegetation widths on the velocity and discharge distribution. The dowels of two heights were used to simulate aquatic rigid vegetation and lay partially on the bed of a water flume. The width of vegetation coverage was set at 50% to simulate different vegetation in a natural river. The mixed vegetation's flow depth was set under partial and full submergence conditions. The velocity at different positions was measured using a micro propeller meter, which enables the calculation of the discharge in different flow regions for comparison. The results of the experiments show that aquatic vegetation affects the velocity distribution and discharge in many aspects. In 50% covered conditions, the average velocity in vegetated zones is one-third of that in the free flow zone, and the vegetated zone discharge is about one-quarter of the whole flow discharge. These findings provide a base for establishing analytical models to predict velocity distributions in different vegetation coverages in a river channel.

Keywords

Aquatic Vegetation, Depth-Averaged Velocity, Mixed Vegetation, Velocity, Open-Channel

1. Introduction

Aquatic vegetation is widely distributed in both natural and urban ecosystems. The influence of aquatic vegetation on ecological and flow processes is becoming increasingly significant in river flood risk and aquatic environmental management. On the one hand, aquatic vegetation can effectively enhance species richness (Dong et al., 2022), because its resistance to water flow can provide a stable aquatic environment. On the other hand, aquatic vegetation can effectively reduce the excessive growth of algae and prevent water blooms (Scheffer et al., 2001). Thus, aquatic vegetation is often used in ecological restoration projects. Besides, aquatic vegetation can also reduce losses caused by soil erosion and flooding because of its protective function (Guo et al., 2022).

Vegetation often has various cover ranges, heights, or other characteristics, and its interaction with water flow can be vital and complex. Previous studies have explored some of these influencing factors. The research on simulated aquatic vegetation is based on single-layer vegetation. Research on vegetated flow covers a wide range of flow characteristics. The aquatic vegetation affects the flow structure in different aspects, such as velocity, discharge, boundary layer, Reynold stress, and turbulence intensity (Nepf & Vivoni, 2000; Tang et al., 2021). Some researchers (e.g. Ghisalberti & Nepf, 2004) have conducted experiments in a water flume with circular wooden cylinders to measure the shear layers generated by submerged vegetation, showing that single-layered vegetation will inhibit the growth of shear layers. As research into the impact mechanism of single-layered vegetation deepened, researchers have also studied the flow through more complex vegetation. Multi-layered vegetation has shown a more complex effect on river flows, and the influence factors are also diverse. The vertical velocity profile of the flow in double-layered vegetation conditions has been measured (Huai et al., 2014; Rahimi et al., 2020; Tang et al., 2024), showing a typical ‘S-type’ velocity profile. In their experiments, the arrangements of aquatic vegetation were changed, and parameters were measured for different vegetation heights in parallel and staggered arrangements. Recently, Barman et al. (2024) explored the effect of the vegetation’s distribution pattern (homogeneous and heterogeneous) and applied the quadrant analysis of different distributions. The results showed that the flow characteristics near the interface between the vegetated and free-flow zones are significantly enhanced as the vegetation emergence increases.

Previous studies mainly focus on the impact of vegetation arrangement on the flow, but relatively little attention has been paid to the ratio of vegetation coverage. Some researchers have explored patchy vegetation; Bae et al. (2024) simulated the aquatic vegetation in patch form and found that the area or volume fraction of vegetation occupation can be used to measure the blockage coefficient of vegetation on water flow. This study aims to fill the knowledge gap by conducting an experimental investigation and analysis of the impact of aquatic vegetation with 50% coverage width on flow. In the experiment, the velocity at different positions was measured, which enabled the velocity distribution to be obtained, thereby obtaining flow rates in different zones.

2. Experimental Setting

The experiment apparatus and the velocity measuring meter are shown in **Figure 1**. The experiment was conducted in the tilting 40 cm wide flume in XJTLU (Xi'an Jiaotong-Liverpool University). The bed slope of the flume was fixed at 0.003, and the total length of the channel was 20 m. The inlet pump and tailgate control the water depth, while the volume flow rate is measured with the electromagnetic flowmeter. The coverage width of the dowels (representing rigid vegetation) in the flume bed was set at 50% coverage. A micro propeller current meter was used to measure the velocity at different locations in a cross-section.

The vegetation area was located 8.0 m away from the entrance, consisting of 7.0 m in length, and the measurement position was set at 10.0 m away from the entrance. This length setting can ensure quasi-unform flow through observed vegetation areas. The water flow depth was set at 8.5 cm (partially submerged) and 11.5 cm (fully submerged). Thus, we can compare the effects of double-layered vegetation on flow under partially submerged and fully submerged conditions.

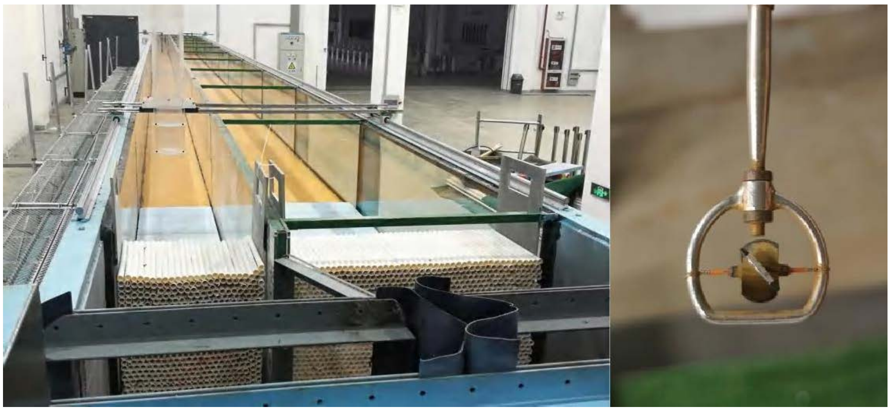

Figure 1. Flume and propeller current meter.

The specific arrangement of the simulated vegetation (dowels) is shown in **Figure 2**, where the short vegetation is 5 cm in height while the tall vegetation is 10 cm high. The distance between the two dowels is 3.07 cm. The symbol x represents the location of the measurement points. In vegetation areas, the arrangement of measurement points is relatively dense due to the large changes in flow velocity. Measurement points are taken directly behind each dowel and the center behind the gap of two dowels. In addition, more dense measurements are taken near the transition region between the vegetation and free-flow zones where the large velocity variation exists.

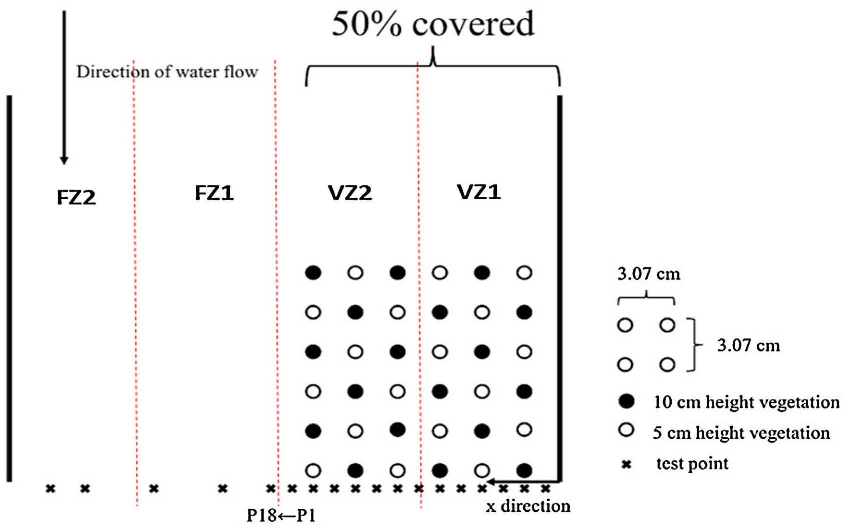

Figure 2. The experimental settings.

3. Results

The measured velocity distribution and flow discharge in 50% covered condition are introduced in this section. u is the layer-average velocity at the measurement position, which is calculated using the measured velocity within a given layer or depth. This velocity is normalized by U, the overall velocity of a cross-section, to eliminate the influence of the local boundary. For the convenience of comparing flow velocities at different depths, the water flow is divided into two layers: layer 1 (near the bed) and layer 2 (near the water surface). Layer 1 refers to the water layer below 5 cm, while Layer 2 refers to the water layer above 5 cm. The flume is evenly divided into four areas from right to left, namely vegetation zone 1 (VZ1), vegetation zone 2 (VZ2), free flow zone 1 (FZ1), and free flow zone 2 (FZ2), which have equal width, i.e. one-quarter of the channel width B).

From **Figure 3** and **Figure 4**, it can be seen that the lateral change of layer-average velocity is relatively consistent for the two submergence conditions in the 50% vegetation coverage channel. As y/B increases, the velocity decreases first near the wall, remains almost constant in the vegetation zones and then increases near the interface boundary (y/B = 0.5) between the vegetated zone and flow zone. In general, velocity in the free flow zone (y/B>0.5) is much larger than that in the vegetated zone (y/B<0.5), and a large velocity gradient occurs in the interface, indicating a strong momentum exchange. The decreases near the interface and wall in the free flow zones reflect the effect of the resistance of vegetation and the side wall. Close examination shows that the velocity in the lower layer (layer 1) is smaller than that in the upper layer (Layer 2), which corresponds to the large resistance (Layer 1) and relatively small resistance of flow (Layer 2) due to different density of vegetation: more dense of vegetation in the lower layer than in the upper layer. Moreover, the large differences in layer-average velocity between two water layers are enhanced under high-depth conditions. This finding is consistent with the results of other researchers by Tang et al. (2024).

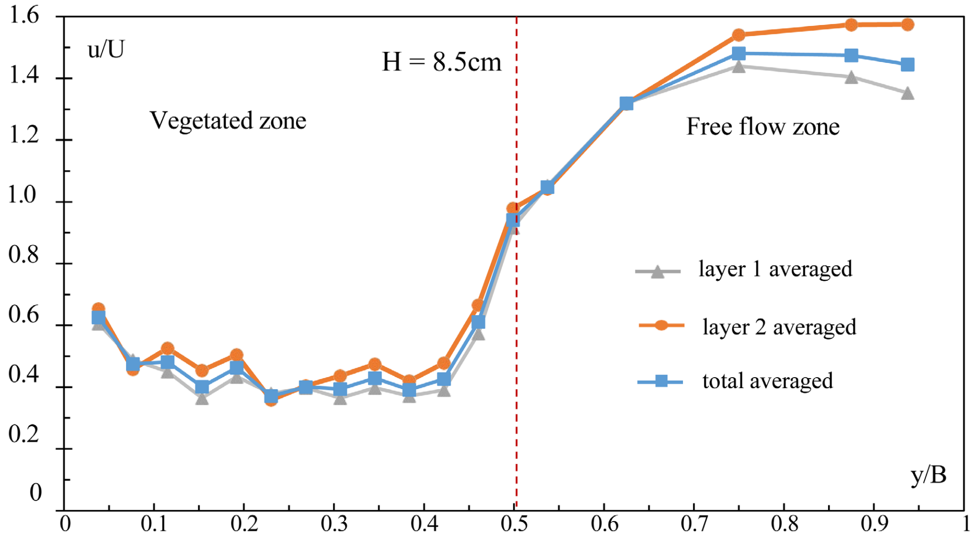

Figure 3. Layer-averaged velocity distribution in 8.5 cm depth condition.

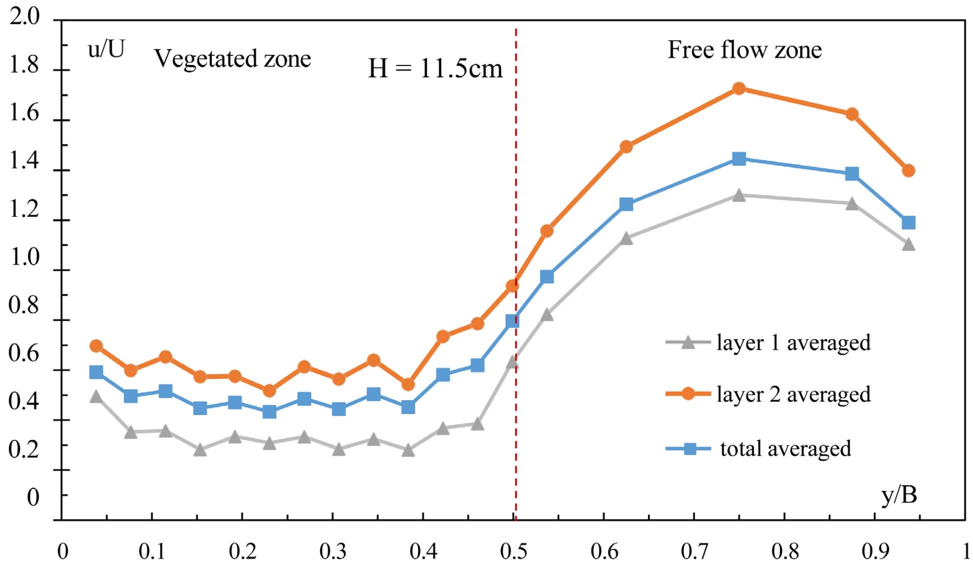

Figure 4. Layer-averaged velocity distribution in 11.5 cm depth condition.

From **Figure 5** and **Figure 6**, it can be seen that the resistance to water flow is more intuitively manifested through the difference in flow discharge. The flow discharge percentage in vegetation zones is almost one-third of that in free-flow zones for both flow depths in the study, although the discharge percentage in the vegetated zone is slightly higher (2 percent more) in the higher flow condition (H

= 11.5 cm) than that in the lower flow conditions, implying that the influence of the boundary layer effect on the wall surface is not dominant compared to vegetation.

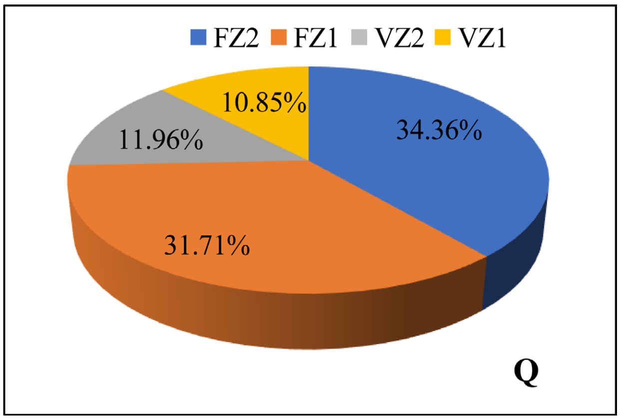

Figure 5. Flow discharge in different zones in 8.5 cm depth condition.

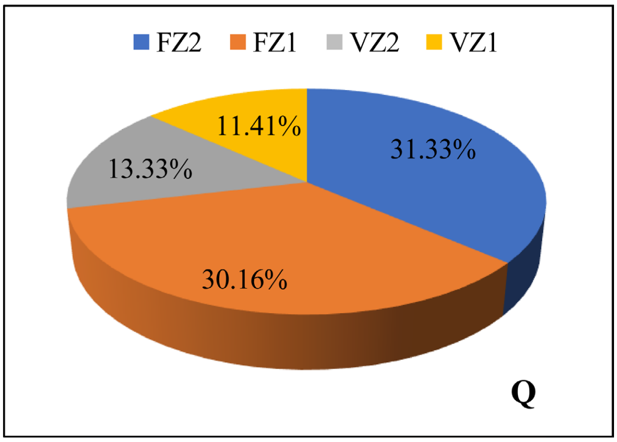

Figure 6. Flow discharge in different zones in 11.5 cm depth condition.

4. Conclusion

The following points may be drawn based on the observed velocity and zonal discharge in a channel covered with 50% vegetation.

The lateral variation of layer-average velocity is similar given different depths of flow depth, but the velocity difference between water layers increases as the flow rate increases, i.e. in deep flow conditions. The average velocity of the upper layer flow is higher than that of the lower layer water flow, which becomes more pronounced as the water depth increases because the upper layer water flow has less resistance of vegetation (i.e. relatively small density of vegetation in the upper layer). This indicates the predominant resistance effect of vegetation in the lower layer.

The flow discharge in the free flow zone is almost three times that of the vegetation zone even though each zone has the same width, indicating a significant retarding effect of vegetation. The difference in zonal discharge between vegetated and non-vegetated zones becomes slightly larger as the water depth increases, which indicates the obstructive effect of aquatic vegetation, especially emergent plants, on water flow. This finding would be helpful in river restoration and management by applying vegetation.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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