

Feedbacks of flow fields and sediment deposition to discontinuous vegetation patches: impacts of density and characteristic length of patches

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Abstract: The discontinuous instream plants, which have progressively emerged as potentially advantageous eco-morphologic engineers capable of changing hydraulics, enhancing ecosystem resilience, and influencing sediment deposition, usually grow seasonally. Thus, understanding the feedback of flow fields and sediment deposition to the density and length of vegetation patches is essential in exploring the geomorphic role of vegetation due to its seasonal evolution in natural rivers. In this study, we conducted flume experiments to clarify the interaction mechanisms between the hydraulics and suspended sediment deposition in discontinuous emergent vegetation patches. Results validated with field data demonstrate that discontinuous vegetation patches modify flow velocity and turbulence, significantly influencing sediment deposition along the streamwise direction. Within the vegetation region, represented by L_i , the enhanced turbulence and flow velocity induced by emergent vegetation were found to reduce sedimentation, while sediment deposition increased in interval regions. The sediment deposition pattern with the different lengths of patches (L_v) reveals the expansive effects of upstream patch on the downstream interval regions with different vegetation densities. When $L_i/L_v > 1$, the interval is sufficiently long to extend turbulent eddies that originated from upstream dense vegetation patches, which restricts sediment deposition and leads to the decreased deposition of suspended sediment compared to the scenario without vegetation. However, this effect recedes with the increase in interval length. Conversely, the sparse vegetation patch enhances the total deposition magnitude when the velocity in the interval zones is small. When $L_i/L_v < 1$, the decreased sediment deposition is observed in both dense and sparse vegetation scenarios.

Keywords: Discontinuous vegetation patches; Turbulence; Velocity distribution; Sediment deposition.

1 INTRODUCTION

Aquatic vegetation plays an essential role in river ecosystems by modulating flow variability in the active channel (Schwarz et al., 2018), enhancing the ecosystem resilience (Kohler et al., 2017; Tang et al., 2022), and enriching the biodiversity (Allen et al., 2018). Vegetation affects the structure of flow fields, such as velocity and turbulence, which changes the discharge capacity and mass transport (Huai et al., 2019; Yang et al., 2023). Previously, the instream vegetation was regarded as a nuisance for the river due to the decreased flow carrying capacity induced by the vegetation drags (López and García, 2001). Nevertheless, the usage of vegetation has progressively become a main method to manage rivers in recent decades, which reflects the practical value of aquatic vegetation in ecological engineering and restoration of rivers. On the one hand, vegetation promotes biodiversity by providing habitat and food for aquatic life (Hori et al., 2009).

On the other hand, the effects of vegetation on the flow rate and turbulence play a significant role in flood risks, river restoration, and river-bed morphology (Huai et al., 2021; Wang et al., 2024). The hydraulic features of flows with vegetation in open channels have been widely studied, which revealed the general velocity profile and flow rate characteristics (Wang et al., 2019). Due to the seasonal growth and temporal changes, vegetation usually colonizes in communities on rivers, as shown in Fig. 1, which are usually called vegetation patches (Anjum and Tanaka, 2020a; Zhao and Huai, 2016).

1.1 Hydrodynamic features of flow fields with vegetation patches

Flow fields with partly distributed vegetation have been considerably explored in terms of flow velocity profile, the shear layer at the junction between vegetation and non-vegetation regions, and features of turbulent eddies (Unigarro Villota et al., 2023; Peng et al., 2024). Discontinuous vegetation communities are more common in natural river channels due to seasonal growth and temporal changes (Cotton et al., 2006; Ma et al., 2022). Aquatic vegetation spontaneously develops spatial inhomogeneity and self-organizes to grow with vegetation patches with the limitation of oxygen and nutrients (Carbonari et al., 2022; Schoelynck et al., 2012). While most existing studies have focused on continuous vegetation profiles, a few have focused on the single vegetation patch (Liu et al., 2021). Several studies have started to explore the features of flow fields with the effects of longitudinal discontinuous vegetation patches (Anjum



Fig. 1. Vegetation patches in natural rivers. Subfigure (b) comes from Xu et al., (2020).

and Tanaka, 2020b; Ghani et al., 2019). For example, Anjum and Tanaka (2020b) investigated the turbulent flow behavior through partially distributed discontinuous vegetation by conducting experiments. They emphasized that the flow velocity, turbulent kinetic energy, and turbulent intensity reduce significantly within the gaps between patches due to the blockage effect and sheltering offered by the vegetation patches. This finding indicates a positive flow response towards aquatic life and sediment deposition. Ghani et al. (2019) numerically studied flows around circular and staggered vegetation patches, demonstrating that the distribution pattern and vegetation density play crucial roles in influencing flow velocity and turbulence within the different regions of the channel. However, the effects of discontinuity of vegetation patches, represented by the length of interval region and density of discontinuous vegetation patches, on flow fields remains poorly understood.

These studies collectively highlight the importance of vegetation patterning in influencing hydrodynamic conditions, yet they also reveal significant gaps in understanding the specific effects of discontinuous vegetation on flow characteristics. The current study aims to improve its understanding by examining how variations in the interval lengths and patch densities of discontinuous vegetation affect the flow fields and sediment transport in river channels.

1.2 Potential relation between vegetation growth and deposition processes

The spatial distribution of vegetation is complicated due to the effects of multiple factors, including climate, topography, flow characteristics, and sediment motion processes (Kyuka et al., 2021). Schnauder and Moggridge (2009) emphasized that, after a flood, vegetation in the deposition region develops well because the amount of seeds or fragments deposit along the river with the water retreat. Moreover, vegetation colonization changes the spatial variation in sediment, which reshapes the river morphology, and in turn, impacts the vegetation growth patterns (Gao et al., 2023). Besides, a complicated intertwined relationship exists among flow, sediment, and vegetation; this relation impacts the bio-geomorphic processes at the patch scale, which have a large-scale geomorphologic impact (Gurnell, 2014). Thus, in a sense, the spatial profile of sediments around the patch are considered the signature of vegetation evolution.

Many studies have investigated the positive or negative feedbacks of sediment deposition to vegetation growth through field observation, numerical simulation, and experiments. For example, a 12-year (from 1989 to 2001) study of aerial photographs of the Westerchelde estuary showed that vegetation evolves from individual patches to extensive areas; the vegetation-flow interaction occurs as vegetation acts as erosion agents by concentrating the flow at the patch edges and inducing erosion (Temmerman et al., 2007). Kleeberg et al., (2010) observed the seasonal dynamics of matter deposition around a representative patch in the lowland River Spree, NE Germany, and pointed out that the entrainment rate of particles is significantly higher inside the plant patch than outside, and submerged vegetation is more related to modifying the resuspension than to the retention of nutrients downstream. Numerical simulations were also conducted by Zhu et al., (2020) and Dang et al., (2023) to explore vegetation evolution with the effects of flow and sediment deposition. They concluded that flow velocity, which is closely related to sediment movements, is a crucial parameter that indicates the suitable condition for vegetation growth. The study of Yamasaki et al., (2019) also showed that the growth of vegetation is impacted by the initial

vegetation coverage and flow velocity. They emphasized that the pattern of the final vegetation coverage is not dependent on either the initial coverage or on the specific profile of vegetation but depends on the critical velocity for vegetation growth.

1.3 Influence of vegetation patches on the sediment deposition

We have introduced the feedback of vegetation growth to sediment deposition processes in above section. In turn, aquatic vegetation also influences sedimentation spatial patterns in channels. On the one hand, aquatic vegetation typically accelerates velocity around vegetation and enhances turbulence intensity (Kitsikoudis et al., 2016), which weakens sediment accumulation creating sediment erosion zones and inhibits expansion of the patch, i.e., negative feedback (Kim et al., 2015, Tranmer et al., 2024). Conversely, the presence of vegetation constitutes positive feedback through dampening flow velocity and sediment transport capacity due to the additional resistance and impediment to flows, which promotes sediment deposition (Yang et al., 2021, Yang and Nepf, 2019, Zhang et al., 2020). Therefore, comprehending the impact mechanism of aquatic vegetation on sediment deposition is imperative for accurately predicting retention or erosion dynamics.

The presence of vegetation significantly changes the turbulence intensity, bottom shear stress, velocity distribution, and momentum exchange; thus, the sediment deposition pattern changes considerably with the variation in vegetation patch arrangements (Huai et al. 2021). In recent years, several studies have focused on sediment deposition in the channel with discontinuous vegetation patches instead of a single patch. Yagci and Strom (2022) experimentally studied the sediment deposition processes in a channel with discontinuous circular vegetation patches. They pointed that vegetation patches locally increase the resistance, which generates a backwater condition upstream of the patch and high-water surface slopes within the patch. This phenomenon enhances the deposition of suspended sediment upstream of the patch and reduces the deposition within the patch. Yagci et al. (2024) further explored the deposition and scour processes in the wake region of different vegetation patches and found that as the patch expands, the steady-wake region becomes shorter, turbulence diminishes, lateral shear stress enhances, and deposition occurs far from the patch. Moreover, they pointed out that the length and density of patches may restrict further expansion of vegetation due to the change in hydrodynamic consequences.

1.4 Objectives of this study

According to above introduction, the interplays between discontinuous vegetation patches and sediment deposition are not only crucial for sedimentation spatial patterns but also dominate the vegetation growth. However, research focused on sediment deposition in channels with discontinuous vegetation patches is limited. Particularly, variations in the density and length of vegetation patches are typical features of seasonal variations. However, a knowledge gap exists on the influence of the length and density of discontinuous vegetation patches on the flow and sediment deposition patterns. The variation in flow velocity and turbulence induced by the vegetation patches is impacted by the vegetation density and patch length (Xu et al. 2020). The effect of these characteristic factors of vegetation patches on sediment deposition is unclear, impeding the application efficiency of vegetation in ecological engineering. With this motivation, we conducted experiments to investigate

the hydraulic features of flow fields and sediment deposition patterns with varying vegetation density and patches length. As an initial and explorative study, we investigated the bank-wide emergent discontinuous vegetation patches to clarify the feedback of flow fields and sediment deposition to the discontinuous vegetation patches.

2 EXPERIMENTAL METHODS

The experiments were conducted in a hydraulic recirculating glass flume with a length of 6 m, a width of 0.3 m, and a depth of 0.3 m. As shown in Fig. 2 (a), the flow was recirculated by a pump fixed under the storage tank and the discharge was measured with an electromagnetic flow meter.

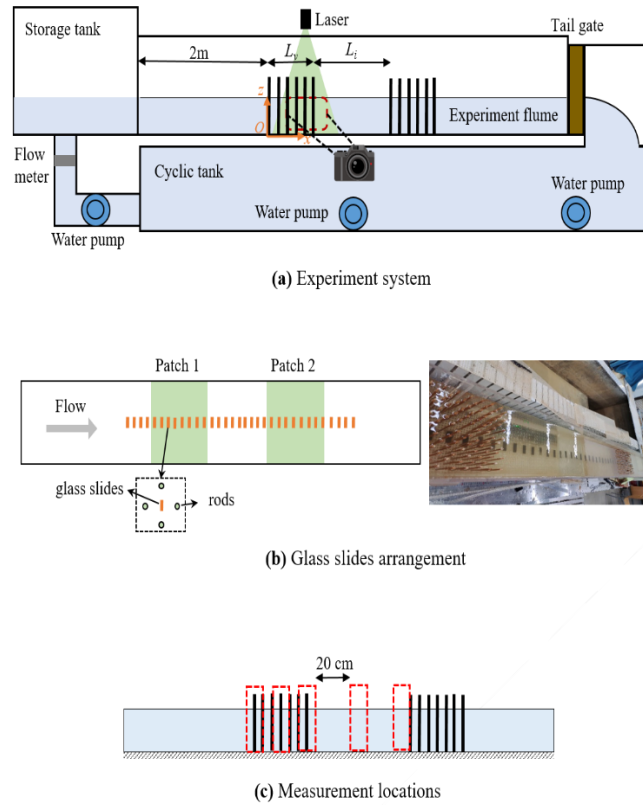


Fig. 2. (a) Experiment system including PIV measurement system, recirculating glass flume, three water pumps, and vegetation patches; (b) Glass slides were fixed along the centerline of flume to collect deposited sediment; (c) Locations of velocity captured by PIV during experiments, represented by red dotted boxes.

A 50 cm-long current rectifier was placed at the inlet 2 m ahead of the first patch to mainly shorten the adjustment distance. We note that in field conditions, the representative diameter of the stems for natural canopies can vary from ~ 0.003 m to ~ 0.02 m (Fonseca et al., 2007; Hansen et al., 2012). Therefore, in the study, rigid rods with a diameter of 5 mm were arranged in a staggered pattern within acrylic boards to imitate the aquatic vegetation. Fig. 2(b) shows that two emergent vegetation patches were placed in a glass tank with different ratios $R_{iv} = L_v/L_i$, where L_v and L_i are the length of the vegetation patch and interval regions, respectively. In the present experiments, five R_{iv} and two vegetation densities were studied. Table 1 lists the mainly parameters adopted in experiments. $1x$ is the distance of the adjacent stems. Where $a_v = nd_v$ is the front area density of vegetation, where n is the number of stems per unit area and d_v is the diameter of rigid stems. H is the water depth,

which was controlled by adjusting the height of tail gate. A total of 11 cases were considered, including a condition without vegetation, i.e., case N .

The coordinate system was defined as $x=0$ at the leading edge of the first vegetation patch (streamwise, positive downstream), $y=0$ at the center of the channel (lateral, positive to the right looking downstream), and $z=0$ at the bottom of the flume (vertical, positive upward). Simultaneous velocity was measured by particle image velocimetry (PIV) system in the x - z plane at $y=0$, with a sampling frequency of 100 Hz. The images acquired by the camera were in 8-bit grayscale with a resolution of 2560×1600 pixels. The interrogation windows in post-processing procedure were 64×64 pixels. Only the velocity in x - z plane was observed in this study due to the immovable installation of the laser device and camera, as shown in Fig. 2 (a). Actually, the stem-scale vortices induced by vegetation stems is typically three-dimension, which indicates that the transverse features of wake vortices would be lost in observed two-dimension (the vertical plane) results. This is the inert deficiency of the measurement. However, velocity, Reynolds stresses and turbulence intensity in the vertical plane could still provide insights into the flow features, even though the precise vortex structures were not examined in the study. Due to the barrier of rods and the limited frame of the camera, the velocity has to be measured separately. Fig. 2 (c) shows the locations of velocity measurements. Several typical cross sections within the patch, including the leading, center, and ending of the first patch were observed to find the flow features in the transition regime. Additionally, the velocity was measured per 25 cm in the interval region to examine the development of velocity.

The study also conducted experiments on sediment deposition with the effects of discontinuous vegetation patches. Given that the suspended sediment particles significantly affect the usage of PIV, instantaneous velocity was first measured with clear water. Then, sediment deposition was measured with sandy flows with the same hydraulic conditions as the above velocity measurement experiments. Plastic sands with a density of 1.05 g/cm^3 and a diameter range of $0.10\text{--}0.49 \text{ mm}$ (median diameter $d_{50} = 0.238 \text{ mm}$) were used in the study. The settling velocity (0.0108 cm/s) was estimated from Zhang and Xie (1989) as follows:

$$\omega = \sqrt{\left(13.95 \frac{v}{d_{50}}\right)^2 + 1.09 \frac{\gamma_s - \gamma_f}{\gamma_f} g d_{50}} - 13.95 \frac{v}{d_{50}} \quad (1)$$

where v is the kinematic viscosity of fluids, g is the acceleration of gravity, γ_i and γ_f are the bulk density of sediment and water, respectively. The friction velocity $u = \sqrt{C_f U_0}$ ranges from 1.15 cm/s to 1.23 cm/s using the bed friction coefficient $C_f = 0.004$ estimated from velocity profile measured over the bare acrylic boards. Thus, the ratio (ω_s/u^*) ranges from 0.008 to 0.009 , which is included in the range of suspended sediment in aquatic environments, that is 0.002 to 0.3 (Ortiz et al., 2013). During experiments, the inlet suspended sediment concentration should be kept stable throughout the experiment. Two methods contribute to a stable inlet suspended sediment concentration. First, 2000 g of plastic sediment, which was much larger than deposited sediments (in the order of $O(10) \text{ g}$), was added into the cyclic flume before the experiments began. Besides, the two water pumps were immersed in the bottom circular tank to avoid sediment deposited due to the low flow velocity.

Before deposition experiments, glass slides ($2.5 \text{ cm} \times 5 \text{ cm} \times 0.1 \text{ cm}$) were weighed and placed longitudinally in the center line

of the channels in 6 cm intervals, with four upstream of the first patches and four downstream of the second patch, as shown in Fig. 2 (b) and (c). Subsequently, two water pumps within the recirculating flume was activated to thoroughly mix the sediment within the flume, and the process lasted for 30 minutes.

Thereafter, the mixed sediment-laden water entered into the experimental flume from the inlet and returned to the recirculating flume from the outlet. Flow rate was adjusted to the predetermined experimental value.

Table 1. Experimental hydraulic parameters and vegetation features.

Cases		$l_v(\text{cm})$	$\alpha_v(\text{m}^{-1})$	$L_i(\text{m})$	$L_v(\text{m})$	R_{iv}	$H(\text{cm})$	$Q_0(\text{m}^3/\text{h})$	$U_0(\text{m/s})$
Dense	A1	4	6.25	0.5	1.0	0.5	18.6	7.1	0.036
	A2	4	6.25	0.5	0.5	1	18.4	6.9	0.034
	A3	4	6.25	1.0	0.5	2	18.6	6.7	0.034
	A4	4	6.25	1.3	0.5	2.6	18.1	6.5	0.033
	A5	4	6.25	1.5	0.5	3.0	18.3	6.8	0.034
Sparse	B1	6	2.78	0.5	1.0	0.5	18.3	7.3	0.037
	B2	6	2.78	0.5	0.5	1	18.2	7.5	0.038
	B3	6	2.78	1.0	0.5	2	18.2	6.8	0.035
	B4	6	2.78	1.3	0.5	2.6	18.3	7.1	0.036
	B5	6	2.78	1.5	0.5	3.0	18.1	7.4	0.038
No canopy	N	0	0	0	0	/	18.5	7.0	0.035

After the flow became stable (approximately 30 minutes), the suspended sediment concentration, flow velocity, water depth, and other parameters were measured at the leading of the first vegetation patch. To ensure the stable state of sediment concentration along the streamwise direction with the abovementioned struggles, we measured the suspended sediment concentration at three locations in front of the first vegetation patch (upstream), in the middle of the interval region (midstream), and after the second vegetation patch (downstream), respectively. We sampled one-liter sandy water, including suspended sediment and water, at three locations respectively, then left it to settle and separated before drying within oven. The weight of sediment was derived from the difference between empty bottle and bottle with sands. To ensure the reliability of the measurement method, all measurements were repeated three times at every positions along the water depth direction. The depth-averaged suspended sediment concentrations were obtained from the three values at corresponding position. As listed in Table 2, $\overline{C}_1$, $\overline{C}_2$, and $\overline{C}_3$, and represent depth-averaged suspended sediment concentration in front of the first patch, in the middle of the interval, and after the second patch, respectively. $\overline{C}$ is the mean suspended sediment concentration of three characteristic positions. The small relative

variation in suspended sediment, $RV = \frac{\overline{C}_1 - \overline{C}_3}{\overline{C}_1} \times 100\%$, was observed, as shown in the last column. It means that the suspended sediment concentration slightly changes along the streamwise direction. Therefore, $\overline{C}$ was regarded as the mean suspended sediment concentration at the corresponding scenarios.

The experiment lasted for 10 hours when no obviously sediment deposition variation occurs on the glass slides. The pump rate was decreased slowly to zero and water was gradually drained from the experimental flume over 30 minutes to minimize potential impacts of drainage on sediment deposition. After the experiments, the glass slides with deposited sediments were left undisturbed in the flume over 12 hours. Then, they were moved to the drying oven. Finally, the sediment deposition on each glass plate was weighed. The net deposition was calculated from the weight difference with and without deposited sediment of glass slides. The sedimentation experiments were repeated three times for all scenarios to make sure the stability of results. A comparison experiment was conducted without vegetation to ascertain the influence of the inflow and outflow processes on the measured sediment depositions. In this experiment, the water flow was immediately slowly drained after reaching a stable state, and the sediment deposition was recorded.

Table 2. Suspended sediment concentration conditions in experiments.

Cases		$\overline{C}_1$ (mg/L)	$\overline{C}_2$ (mg/L)	$\overline{C}_3$ (mg/L)	$\overline{C}$ (mg/L)	RV (%)
Dense	A1	77	67	65	69.7	15.6
	A2	75	68	67	70.0	10.7
	A3	75	66	64	68.3	14.7
	A4	70	68	67	68.3	4.3
	A5	80	72	68	73.3	15.0
Sparse	B1	78	69	66	71.0	15.4
	B2	73	67	67	69.0	8.2
	B3	79	62	65	68.7	17.7
	B4	79	65	63	69.0	20.3
	B5	75	68	67	70.0	10.7
No canopy	N	76	70	69	71.7	9.2

The total sediment deposition during the inflow and outflow processes (0.44 g) was significantly lower than the total sediment

deposition measured during the whole experiment (44.55 g), accounting for approximately 0.9% of the total deposition.

Therefore, this process had a negligible impact on the experimental results.

3 RESULTS

3.1 Mean flow velocity and turbulence features

Firstly, we focused on the vertical profile of longitudinal velocity to examine the longitudinal velocity development within the patch and the interval region. Taking scenarios A1~A5 as examples, the time-averaged longitudinal velocity features are showed in Fig. 3. The velocity nearly keeps a constant along the water depth with slight fluctuations within the first vegetation

patch, i.e. $x < 1$ m. The vertical velocity approximates to a constant in the interval region, which is different from the logarithmic profile of velocity in the open channel without vegetation (Huai et al., 2019b). The resistance induced by the bottom boundary leads to a slightly decreased velocity near the bed region. The deviation in the interval zones shows that the presence of discontinuous vegetation patches makes the flow velocity within patches and interval regions approximate to a constant. The results emphasize the sustainable impacts of the upstream vegetation patch on the flow field in the subsequent interval region. Additionally, Fig. 3 also shows that the velocity within the vegetation patch is obviously larger than velocity in the interval region.

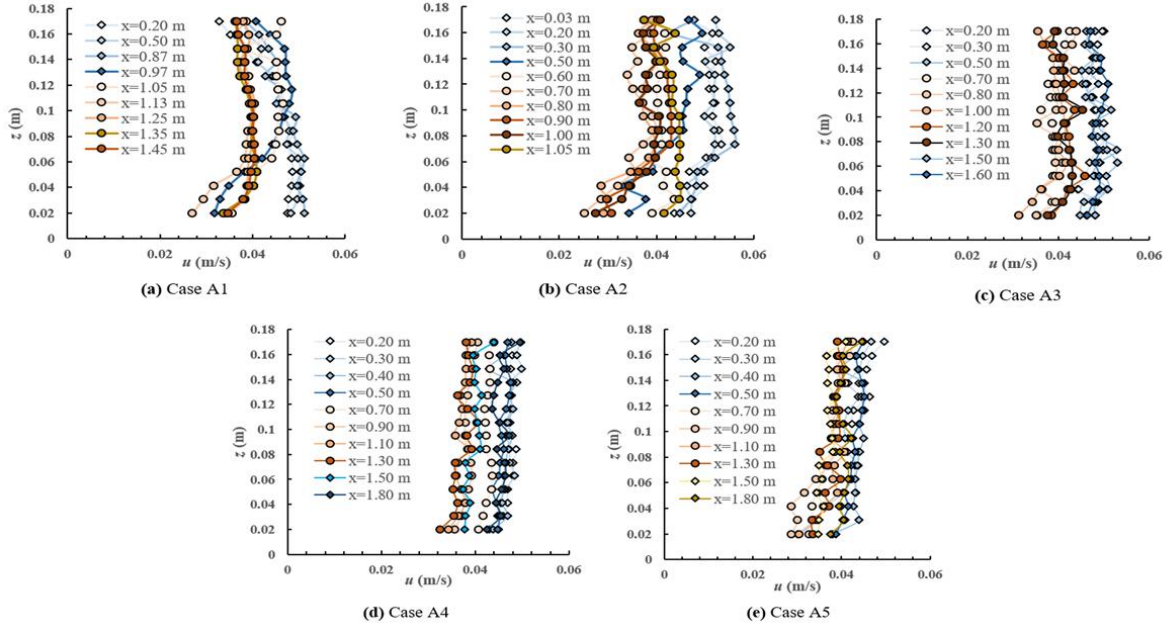


Fig. 3. Vertical profile of streamwise velocity along the longitudinal direction. The blue diamond represents the velocity measured in the patch regime, and the orange circle is the velocity observed in the interval region.

The depth-averaged velocity, U_H , was illustrated in Fig. 4 to show the longitudinal variations of flow velocity. The gray squares represent the regions of vegetation, and the dotted lines indicate the depth-averaged velocity in the flow without vegetation, represented by U_0 . The results show the adjustment effects of discontinuous vegetation patches to velocity. Specifically, depth-averaged velocities within vegetation patches are larger than that within the interval region, which are contributed by the drag force induced by vegetation stems. The presence of river-width emergent vegetation reduces the flow area, leading to increased velocity within patches. Besides, the velocity was measured along the path of rods where the preferential flow occurs compared to the stem wake and vortex street regimes. Therefore, U_H within the patch is larger than U_0 , while velocity at the interval region always decreases and approximates to U_0 . This kind of variation in velocity at different regimes will impact sediment movements. Additionally, the flow velocity in dense vegetation, i.e. cases A, is larger than that in sparse vegetation, i.e. cases B, owing to the higher fraction of vegetation. It should be noted that the velocity at the centerline of the flume was measured in present study and the effect of side walls was ignored in the study. The drag forces generated by the river-wide vegetation is stronger than the friction of side walls. As a result, present analysis based on the velocity observed in the centerline of the flume is credible.

Fig. 5 and Fig. 6 show the vertical profile of Reynolds stresses at different positions, respectively, to present the features of

Reynolds stresses. For convenience, the first rows of Fig. 5 and 6 show the Reynolds stresses within the vegetation region, while the second rows are Reynolds stresses in the interval region. Large Reynolds stresses are always observed near the water surface, which possibly result from the less reliable observations of velocity near the water surface due to the absence of tracking particles in the interrogation windows there (Park et al. 2015). It should be noted that the intermittent appearance of the water surface and reflections make it challenging to accurately measure velocity near water surfaces with PIV. As a result, the large Reynolds stresses observed in patch regions likely reflect stronger fluctuations in the water surface induced by vegetation compared to the more stable conditions in interval regions. The Reynolds stresses fluctuates along the water depth direction within the first patch region, that is, x ranges from 0 m to 1.0 m. The magnitude descends with the distance to the interval regions (i.e., x ranges from 1.0 m to 1.50 m), where τ is nearly close to the zero, but it rises again within the second vegetation patch, i.e. $x = 1.75$ m in the figure. The same phenomenon was also observed in case B2 with a shorter vegetation patch, as shown in Fig. 6. The results show that Reynolds stresses approximate to zero within the interval region with the effects of both short and long vegetation patches. Associating with the vertical velocity profiles (Fig. 3), the results indicates that the presence of vegetation leads to the stronger Reynolds stresses fluctuations at the vegetation region compared to that in the interval region even although velocities in both

regimes are close to constant. The stem-scale turbulence vortices induced by vegetation may result in the variation. The intensity of the vertical mass exchange is expected to change considerably at

different characteristic regions, which is also adjusted by the length of vegetation patches.

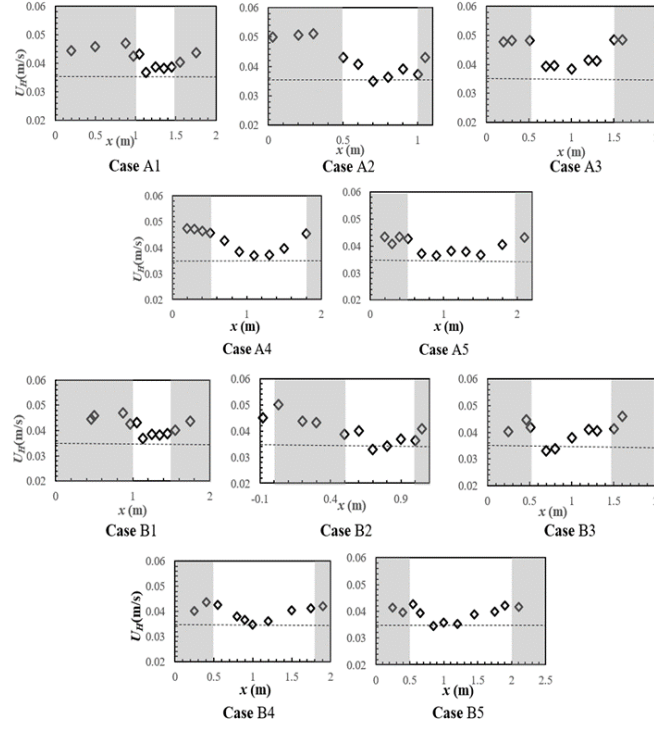


Fig. 4. Depth-averaged velocity of different cases along the streamwise direction.

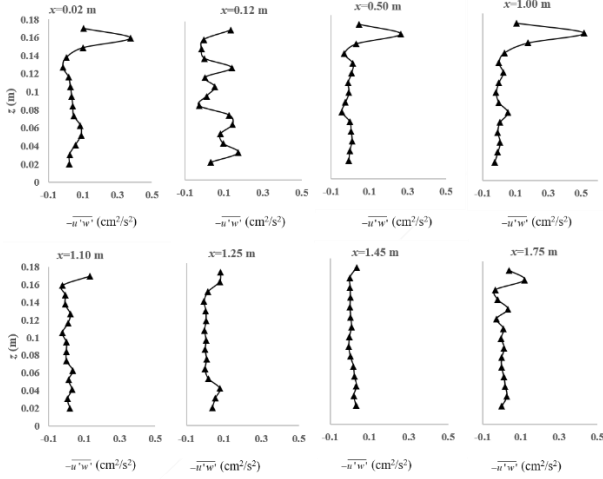


Fig. 5. Vertical profiles of Reynolds stresses at different positions of case B1, where the length of the first patch $L_v = 1.0$ m.

The turbulence intensity is usually represented by parameter $TI = u_{rms}/\bar{u}$, where $\bar{u}$ is the time-averaged velocity, and $u_{rms} = \sqrt{\overline{u'^2}}$ is the root mean square deviation value of a turbulent velocity u' . Fig. 7 illustrates the normalized turbulence intensity $u_{rms}/\bar{u}$ at the vegetation and interval regions for sparse (case B3) and dense vegetation (case A3) to elucidate turbulence evolution downstream of the vegetation patch. The intervals of the two cases are relatively longer than the forward patch, with $L_v = 0.5$ m and $L_i = 1.0$ m. The normalized turbulent intensity for case B3 (sparse vegetation) remains stable at around 0.1 in both vegetation and interval zones, and it keeps nearly constant along the water depth. In contrast, turbulent intensity for the dense vegetation case is always larger than that for sparse vegetation,

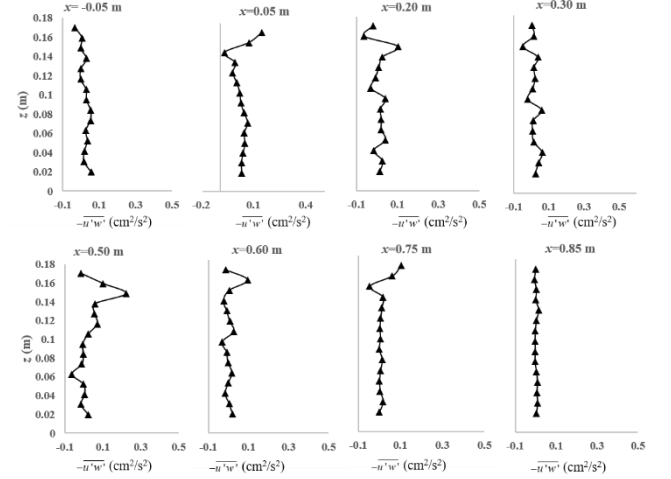


Fig. 6. Vertical profiles of Reynolds stresses at different positions of case B2, where the length of the first patch $L_v = 0.5$ m

indicating that dense vegetation enhances turbulence. Furthermore, turbulence eddies generated in the first vegetation patch region extend into the downstream interval region, promoting the turbulence intensity there. Notably, turbulence intensity near the bottom boundary within the interval region is large, likely due to bed friction and strong turbulent eddies originating from upstream vegetation stems. In a word, turbulence enhancement caused by dense vegetation patch extends further into the interval region compared to sparse vegetation, which may result in different sedimentation patterns in channels with dense and sparse vegetation discontinuous patches. These results are crucial for understanding sediment

particle movement in different regions, which will be analyzed in the following section.

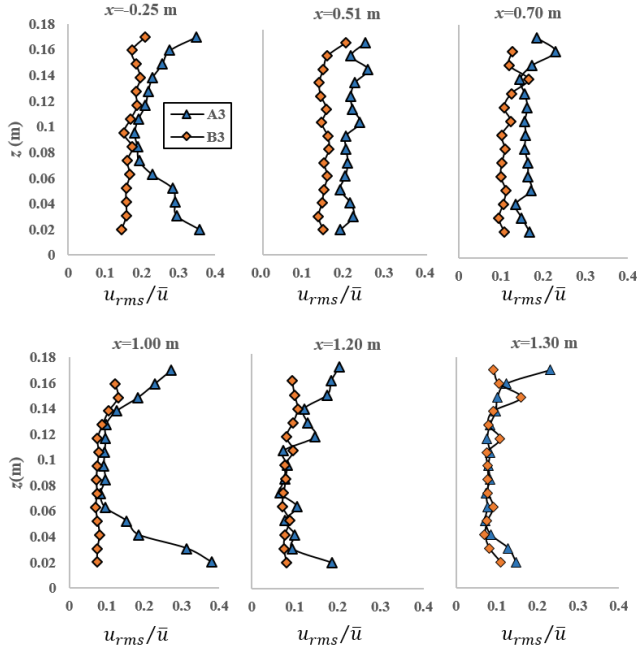


Fig. 7. Turbulence intensity of cases A3 and B3.

3.2 Sediment deposition pattern

We have stated the typical spatial features of flow fields, including velocity profiles and turbulence intensity, in channels with discontinuous vegetation patches with different lengths and densities. This section further explores the physical mechanism of particles movements with the influence of this kind of flow fields. We will analyze the spatial patterns of sediment deposition at the vegetation and interval regions and find the feedback of sediment deposition to the variation of flow fields and vegetation patches.

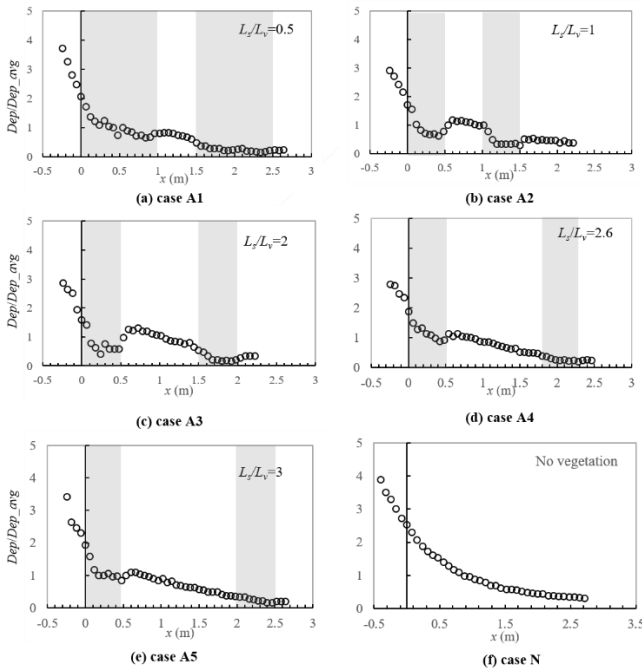


Fig. 8. Sediment deposition along the streamwise direction with the dense discontinuous vegetation patches.

Sediment deposition Dep was derived from the ratio of the local mass of deposited sediment collected by slides to slide areas. The averaged deposition of the channel was used to normalized deposition. Fig. 8 depicts sediment deposition patterns for cases with dense vegetation patches along the streamwise direction, and Figure 9 presents those for sparse vegetation scenarios.

In both figures, gray squares represent the regions with vegetation. The sediment deposition in the bare channel are showed in both figures, i.e. subgraph (f), to evaluate the effects of vegetation. The results indicate that sediment deposition without effects of vegetation significantly descent with the longitudinal positions at $x < 1$ m, after which sediment deposition decreases slightly and then stabilizes. Discontinuous vegetation patches significantly alter sediment deposition pattern. Specifically, when sandy flow goes through vegetation areas, the sediment deposition movement is significantly restricted due to the strong wake vortices generated by vegetation stems and the larger flow velocity. In contrast, sediment deposition in the interval region is obviously larger than that in the vegetation region. The sediment deposition pattern is generated by the relative larger velocity and turbulence intensity in the vegetation region compared to the interval region.

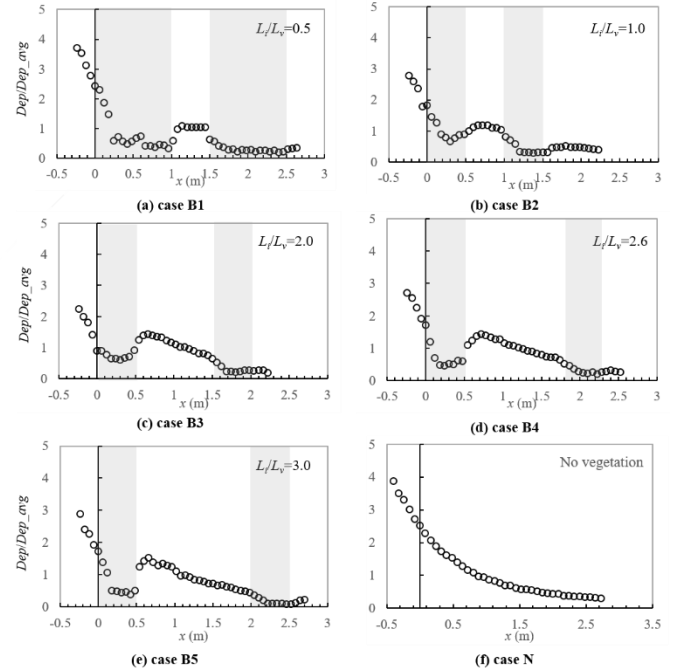


Fig. 9. Sediment deposition along the streamwise direction with the sparse discontinuous vegetation patches.

Fig. 8 and 9 also demonstrate that sediment deposition magnitude and patterns are closely related to the ratio parameter R_{iv} and vegetation density. Both figures illustrate that when the interval is relatively short compared to the vegetation length ($R_{iv} = 0.5$), sediment deposition is minimal in both vegetation and interval areas, although deposition in the interval area is slightly larger than in the vegetated area. This indicates a limited impact of discontinuous vegetation patches at this condition, which resembles that of a continuous long vegetation patch. As R_{iv} increases, sediment deposition notably rises due to the decreased flow velocity and turbulence intensity in the interval region. However, sediment deposition patterns in the channel with discontinuous vegetation patches with different densities vary in accordance with R_{iv} alterations. For sparse vegetation patches, turbulent intensity and flow velocity behind the first patch quickly recover to a relatively lower state, leading to a significant increase

in sediment deposition with the rise in R_{iv} , as shown in Fig. 9. In addition, the influence of the first patch on flow fields in interval regions gradually recedes with the distance to the patch, resulting in decreased sediment deposition in the interval area. This pattern resembles that of sediment deposition without vegetation. However, for dense vegetation patches, the enhanced turbulent intensity extends into interval regions, as depicted in Fig. 7, and turbulent eddies near the bottom, generated by the drag force of vegetation stems and boundary, develop in the interval region. Consequently, sediment deposition is restricted by the enhanced turbulence, which leads to notably lower sedimentation in interval regions of dense vegetation patches compared to the sparse vegetation scenarios.

3.3 Feedbacks of sedimentation to vegetation density and length

We further explore the impact of the vegetation density on sediment deposition motions, which could be quantified by several parameters (Xu et al. 2022). The ratio of deposition rate M_d to the upstream sediment supply C_0 represents the sediment retention by vegetation patches, and it is called retention efficiency (RE):

$$RE = \frac{M_d}{C_0} \times 100\% \quad (2)$$

where deposition rate is derived from $M_d = \frac{M}{T}$ (M is the total sediment deposition masses in the range from $x=0$ m to 2.5 m during the experiment period, 10 hours).

To compare between different cases, the deposition rate is normalized by the deposition rate in the scenario without vegetation M_0 , and the ratio is called the relative deposition (RD):

$$RD = M_d / M_0 \quad (3)$$

In the present study, the total mass of deposition without vegetation is taken as the criterion to evaluate whether the presence of vegetation restricted or promoted the sediment deposition. If the total deposition is larger than the sediment deposition in the bared channel, that is, $RD > 1$, the presence of vegetation patches promotes the sedimentation.

Table 3 lists the total deposition, retention efficiency, and relative deposition for all cases, while Fig. 10 illustrates the retention efficiency and relative deposition for experiments with dense and sparse vegetation patches. The results show that the retention efficiencies are smaller than 2% across all scenarios, suggesting that deposition constitutes only a small fraction of the sediment supply. Consequently, deposition in this study is primarily influenced by vegetation and hydraulic features, rather than sediment supplies. Fig. 10 reveals that the impact of vegetation on sediment deposition is closely related to the length of the vegetation patch. When $L_i/L_v < 1$, the decreased deposition relative to bare channels was observed in channels with both dense and sparse vegetation patches. This indicates that the short, discontinuous vegetation patches ($L_i/L_v < 1$) lead to sediment erosion in the bed. Conversely, for conditions of $L_i/L_v > 1$, vegetation density plays a significant role in sediment deposition and erosion. Fig. 10 shows that dense vegetation inhibits sediment deposition within the study area compared to the scenario without vegetation, i.e. $RD < 1$, while sparse vegetation promotes sediment deposition, i.e. $RD > 1$. The disparity in sediment deposition primarily arises from the interval area. The large velocity and extensive turbulence from upstream dense vegetation patches reduce the deposition of suspended sediment, whereas the smaller velocity and relative weaker turbulence induced by sparse vegetation promote sedimentation. These findings suggest that modifying the vegetation density and spacing characteristics, represented by the parameter R_{iv} , of discontinuous vegetation patches can modulate sediment deposition patterns within the interval area.

Table 3. Several quantified parameters of sedimentation in the experiments.

Cases	Dense vegetation					Sparse vegetation					N
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	
$M(g)$	30.4	38.2	32.6	31.2	27.2	29.2	40.2	48.0	67.0	61.7	37.1
$RE(\%)$	0.56	0.74	0.65	0.69	0.50	0.51	0.74	0.89	1.19	1.11	0.70
RD	0.82	1.03	0.88	0.84	0.73	0.79	1.09	1.29	1.81	1.67	/

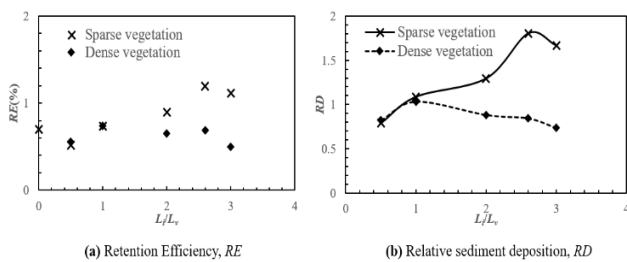


Fig. 10. Variation in the retention efficiency and the relative sediment deposition against L_i/L_v .

4 DISCUSSIONS ABOUT UNCERTAINTIES IN THE EXPERIMENTAL RESULTS

In the study, we conducted a simplified physical experiment to understand effects of instream discontinuous vegetation on hydraulic and sedimentation traits along flume. Although the experimental setup was particularly aimed to understand this influence of instream plants, how to popularize present flume-scale results to the reach-scale application in practice is still uncertain. Therefore, we validate the experimental results with the field data observed in Cubits Gap sub-delta, MRD, from Beltran-Burgos (Beltran-Burgos, 2021) to eliminate the uncertainties of

experimental results. The dimensionless parameter of vegetation coverage V_c , defined as the fraction of surface area of plants, is most common reach-scale parameter used to describe instream plants. As a result, the vegetation coverage, representing the fraction of patch-scale plants rather than the stem-scale, was usually derived from the GIS analysis and field observations. From this aspect, $V_c = \frac{L_v}{L_v + L_i} \times 100\%$ could be derived in present study.

Additionally, leaf area index (LAI, surface area per bed area) is another feature parameter used to describe the density of aquatic plants in practice. LAI is reasonably estimated from plant frontal area per bed area a_v , such that $LAI = a_v h_v$, according to the empirical relation between vertical gap fraction and leaf area index (Zhao et al. 2012). The relation was also adopted and used in Xu et al. (2020). Associating above two characteristic parameters of plants and sediment deposition rate Q_s , it is available to compare the experimental results with field observations. These parameters are listed in Table 4. It should be noted that the field sedimentation rate was averaged sedimentation of six stations at the marsh patch region for one- to two-month collection, see Table 19 in reference of Beltran-Burgos (2021).

Fig. 11(a) was drone photo of field sites taken in June 2019 in Cubits Gap sub-delta, MRD, corresponding to vegetation coverage V_c of 66%, and Fig. 11(b) was taken in July 2019 with $V_c=20\%$. There are the main channel and the marsh region in the filed observation site, but present experiments focused on the marsh region not including the main channel. However, the main parameters of vegetation and dynamics are similar. For example, velocity of fields ranges from 0.02 m/s to 0.13 m/s when the velocity of present study is around 0.035 m/s, and suspended sediment concentration was 16 to 186 mg/L in the delta and around 70 mg/L. The vegetation coverage and LAI both fall into the similar order, shown as Table 4.

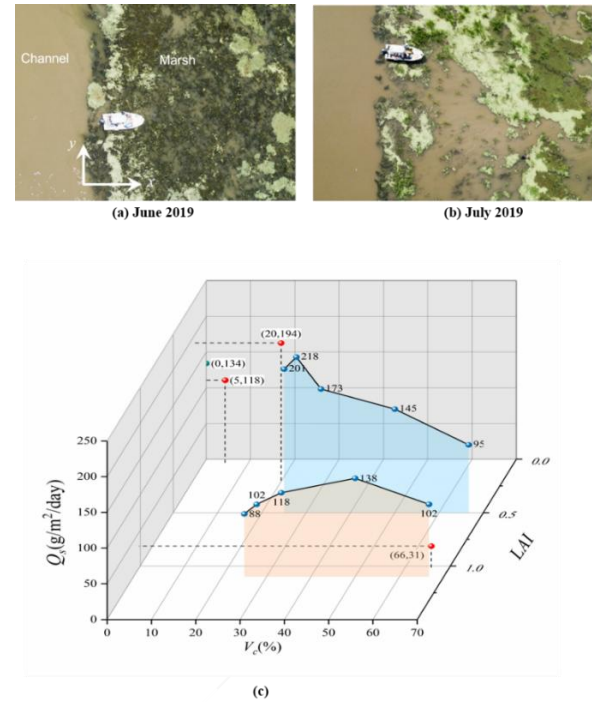


Fig. 11. Marsh with aquatic emergent plants and sediment deposition rate observed and experimentally measured. (a) Scenario with aquatic vegetation in Cubits Gap sub-delta, MRD, taken in June 2019, with $V_c=66\%$; (b) the same location, but taken in July 2019 with $V_c=20\%$. Both figures come from Beltran-Burgos (2021). (c) Comparison experimental results with observed data.

Table 4. Sediment deposition rate derived from experiments and observed in Cubits Gap sub-delta (Beltran-Burgos, 2021).

Descriptions		LAI	V_c (%)	Q_s (g/m ² /day)
Experiments	A1	1.13	67	102
	A2	1.13	50	138
	A3	1.13	33	118
	A4	1.13	28	102
	A5	1.13	25	89
	B1	0.50	67	95
	B2	0.50	50	145
	B3	0.50	33	173
	B4	0.50	28	218
	B5	0.50	25	201
Field data	N	0	0	124
	4/1/2019	0.05	5	118
	6/3/2019	1.02	66	31
	7/1/2019	0.21	20	194

Present experiments thus could be thought as a simplified estimation regarding to the vegetation marsh region. In Fig. 11(c), the sediment deposition observed on March 6, 2019, are almost within the range of experimental deposition rate of cases B, indicating a strong similarity between results obtained at flume- and reach-scales. Furthermore, at April 1 and July 1, 2019, the vegetation coverage in the marsh area was recorded at low values of 5% and 20%, respectively. The sediment deposition values measured at these periods were 118 g/m²/day and 194 g/m²/day, which are closely aligned with the value of 124 g/m²/day obtained under no-vegetation conditions in the current experiment. This close correspondence highlights the consistency of sediment deposition results across varying vegetation conditions. The field conditions are subject to considerable

variability, such as the sediment supply changes a lot during observation period but nearly keeps constant during in experiments, and the number of measurement sites is limited. These are all the potential reasons for deposition deviations. In spite of these variations, the observed results demonstrate a high degree of reliability and support the validity of the experimental findings. The results also emphasize that the vegetation coverage, featured by the ratio of patches and interval regions in the experiments, and vegetation density significantly impact the sedimentation in the flow with aquatic plants. Therefore, understanding the interaction between flow, vegetation, and sedimentation would improve the restoration and management of marshes and rivers.

5 CONCLUSION

This study was conducted to explore the impacts of vegetation density and vegetation patch length on flow fields and sediment deposition pattern in the channel with discontinuous vegetation. The flume experiments were conducted to measure the velocity within both vegetation patch and the interval regions. Sediment deposition along the streamwise direction was separately observed in flows with suspended sediment loaded under the same hydrodynamic conditions as velocity-observation experiments. The main variables of experiments, i.e. interested impact factors, were vegetation density α_v and the ratio of interval length to patch length L_i/L_v .

The experimental results showed a typical velocity profile along the streamwise direction, that is, a relatively large velocity in the vegetation patch regions while a small velocity in the interval regions. The adjustment effects of upstream vegetation patch on the velocity profile extended into the interval region, resulting in a vertical constant velocity profile instead of logarithmic distribution in the open channel flow without vegetation.

The study also found a positive correlation between vegetation density and turbulence enhancement, that is, dense vegetation conditions consistently exhibited higher turbulent intensity than sparse vegetation. Additionally, turbulent eddies generated within the upstream vegetation patch extended downstream, increasing turbulence intensity within the interval region. These findings emphasize the significant influence of dense vegetation patches on turbulence propagation over longer distances within the interval region, in contrast to the minimal effect observed in sparse vegetation. These insights are crucial for understanding sediment particle movement across different regions in a channel with discontinuous vegetation.

Significantly less sediment was deposited in the vegetation region, where velocity is greatly promoted by the presence of vegetation, compared to the interval region in all experimental cases. The sediment deposition pattern, influenced by the relative length of patches L_i/L_v , reveals the expansive effects of upstream patches on downstream interval regions under varying vegetation densities. When $L_i/L_v > 1$, suspended sediment deposition is restricted by dense discontinuous vegetation. The total mass of deposition deduces with the rise in L_i/L_v , while the sparse vegetation promotes the deposition of suspended sediment. The phenomenon is primarily due to the enhanced turbulent eddies originating from upstream dense vegetation, which extend into the interval region in the scenario with long interval regions, reducing sediment deposition. Conversely, when $L_i/L_v < 1$, reduced sediment deposition is observed in both dense and sparse vegetation scenarios.

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