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Floodplain Transition Zone Hydrodynamics: The Role of Riparian and Floodplain Vegetation in Compound Channel Flows

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ABSTRACT

During floods, many rivers exhibit a compound channel configuration, resulting in significant interactions between the flows in the main channel and the floodplains. Due to its water and nutrient-rich soils, floodplains are often covered by shallow vegetation and riparian woodland at the interface of the floodplain and the main channel. Owing to the numerous overtopping scenarios, compound channels are viable in both urban and natural watercourses having floodplains with riparian shrubs, in-line woodland and transplanted trees with different arrangements dictated by shading, species, spacing and occupation of the floodplains. This study investigates the influence of submerged floodplains and combinations of riparian grass, woodlands and shrubs on flow resistance and structure. An experimental campaign was conducted, generating 11 uniform compound channel flows under four different configurations: (i) without vegetation, (ii) with synthetic grass in the floodplains, (iii) with synthetic grass in the floodplains and rods at the floodplain edge and (iv) with synthetic grass in the floodplains and artificial shrubs at the floodplain edge. Primarily, flow mechanisms and turbulence characteristics for three uniform flow depths are analyzed using acoustic Doppler velocity measurements. Then, the increase in flow resistance and reduction of compound channel conveyance capacity were analyzed for individual cases. The synthetic grass in the floodplains minimally influenced the cross-sectional distribution of streamwise velocity, turbulence intensities and lateral shear. On the other hand, riparian vegetation significantly affected these distributions by impeding lateral shear spreading. The effects of vegetation on flow structure were enhanced by foliage on vegetation elements. Additionally, the study examined coherent two-dimensional large structures and secondary currents, revealing that riparian vegetation is critical in altering flow patterns. These findings provide valuable insights into the complex interactions between vegetation and flow dynamics in compound channels.

1 | Introduction

Riparian vegetation zones are distinct in species, composition, structure and extent. These riparian zones work together to

determine run-off at natural and urban watercourses, ecosystem connectivity, riverbank strength, pollution reduction and water quality (Figure 1). Their connections to agronomics, recreation and amenities, fishing and flood control provide

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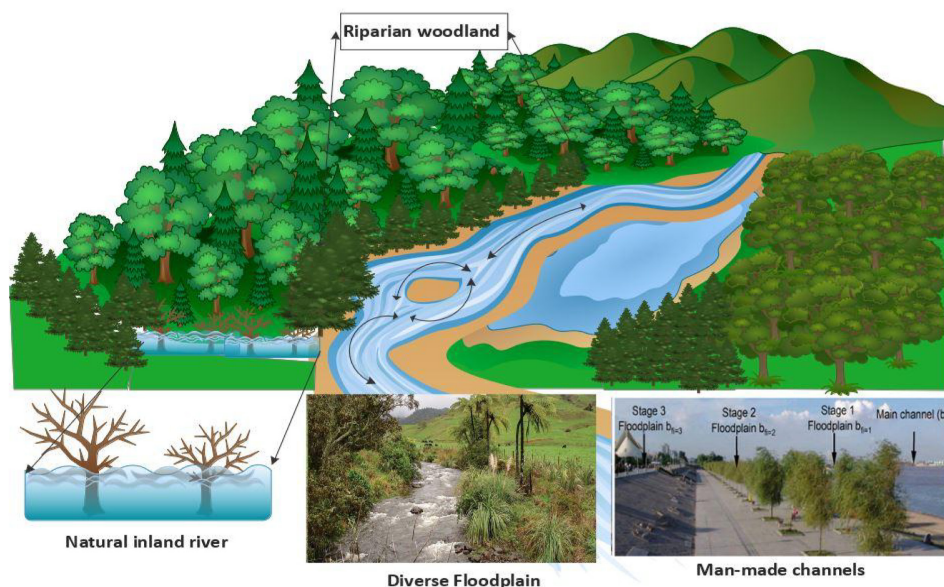


FIGURE 1 | Pictorial depiction of the range of the riparian woodland in nature and urban watercourses.

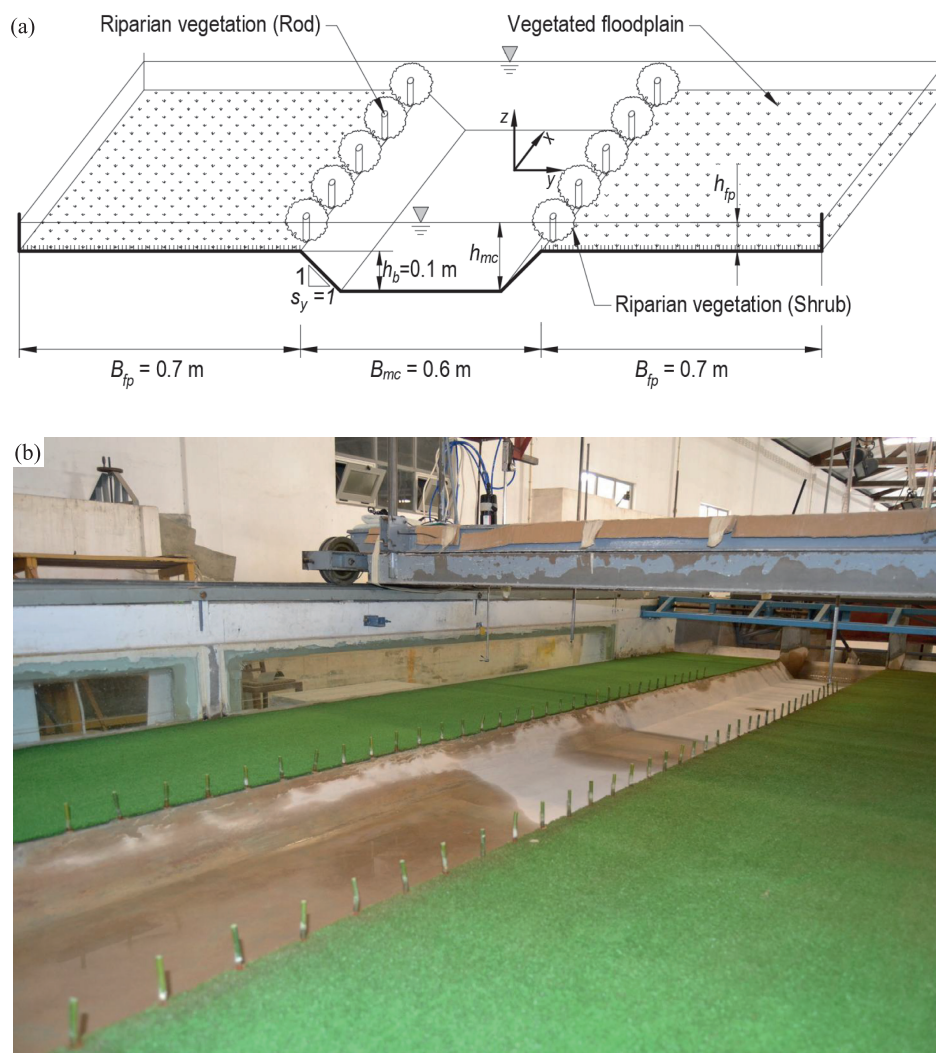


FIGURE 2 | (a) Schematic representation of the compound channel, (b, c) photograph of the compound channel with vegetated floodplains (b) with rods and (c) with shrubs at the interface and (d) cross-sectional and (e) plan view measurement meshes.

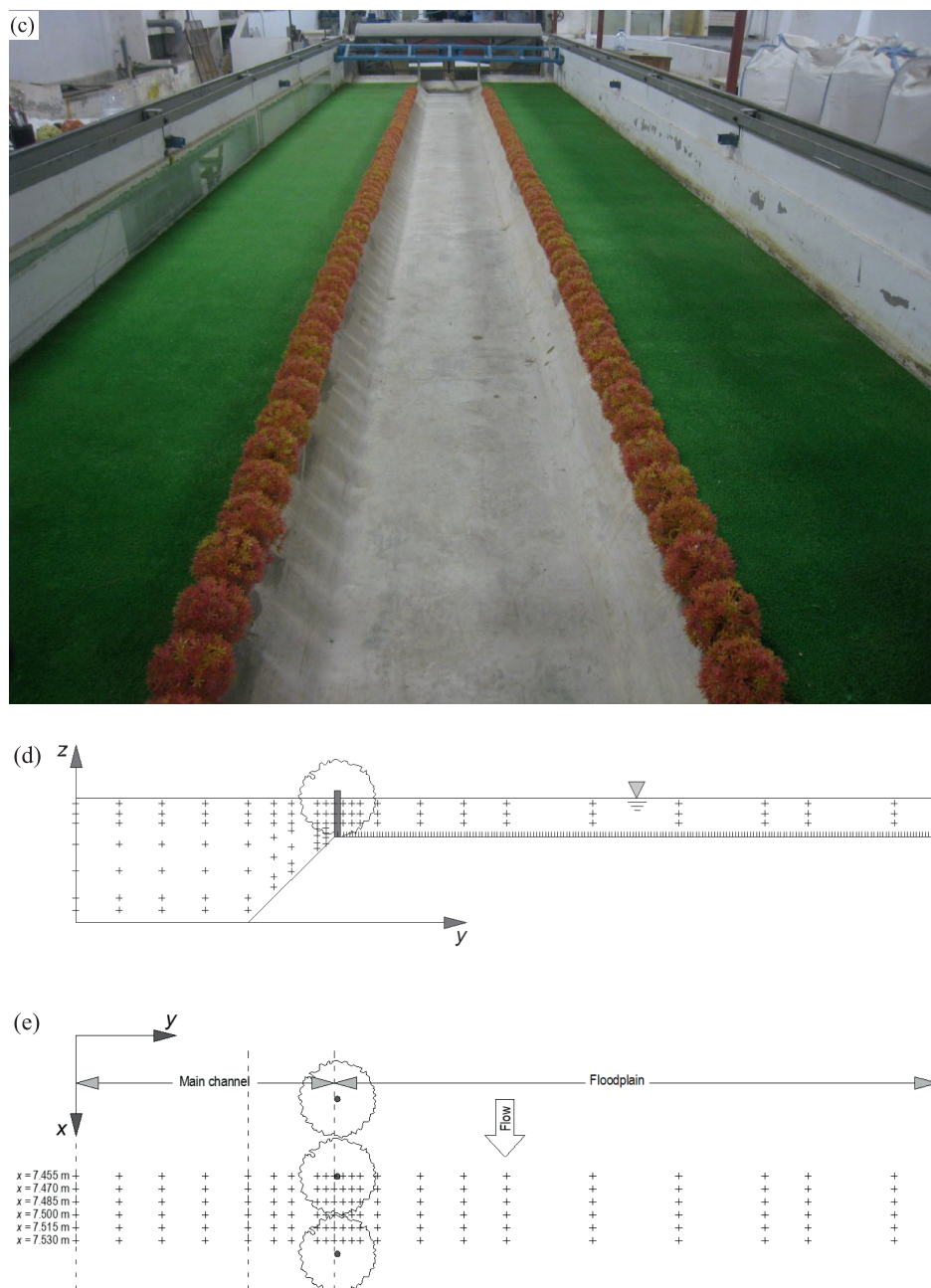


FIGURE 2 | (Continued)

an additional perspective for managing riparian vegetation along riverbanks (SEPA 2008; River Restoration Centre 2002). Riparian forests are important in sustainable biodiversity, floodplain flow resistance, pollutant filtering and bank stability. The riparian woodlands are characterized as a combination of shallow vegetation like grass, trees and shrubs, which can either be composed of native species or transplanted trees in floodplains of urban watercourses. Transplantation is a term used to describe the replantation of trees from one location to another through a machine or manually (Guidelines on Tree Transplanting 2014; Singh et al. 2024). It is generally necessary to follow guidelines regarding shade, tree species, species grouping, distance and layouts when planting trees and bushes on the channel's bank. By evaporative cooling and evaporation, stream shading can affect refuge wildlife from climate change and inhibit the establishment of aquatic plants

in the shaded area (Stromberg et al. 2013). In the same way, the planting scheme of riparian woodland can resolve the issues of weed growth, imbalance of the wildlife environment, overgrazing and carbon capture through photosynthesis (Marks et al. 2020). Additionally, by using flow resistance modelling during high flow events, such as floods, and seasonal variability modelling of droughts, riparian woodland planting schemes can be used to concentrate on stabilizing river or artificial channel banks (Palmer et al. 2008), controlling infrastructure damage (Rood, Pan, et al. 2008) and adapting to climate change (Capon et al. 2013; Perry et al. 2015). Stutter et al. (2019) state that riparian buffers are among the most popular global management strategies to shield surface waterways from diffuse agricultural contamination. Besides that, there is a lack of studies on the hydrodynamics of the river and floodplains interaction with combinations of riparian grass,

TABLE 1 | Flow conditions of the experiments under uniform flow with vertical elements in the floodplain edge.

Test reference	h_{mc} (m)	h_r (—)	Q_{mc} (L·s ^{−1})	Q_{fp} (L·s ^{−1})	Re_{mc} (×10 ^{−5})	Re_{fp} (×10 ^{−5})	Fr_{mc} (—)	Fr_{fp} (—)	Compound channel representation
Unvegetated floodplains (‘s’)									
hr015s	0.1172	0.15	38.8	6.0	2.25	0.17	0.69	0.61	
hr020s	0.1220	0.19	42.2	11.2	2.45	0.31	0.70	0.78	
hr030s	0.1402	0.30	54.2	26.4	3.17	0.66	0.70	0.76	
Vegetated floodplains (‘r’)									
hr015r	0.1192	0.15	35.1	3.7	2.04	0.10	0.61	0.32	
hr020r	0.1284	0.21	39.3	7.3	2.28	0.20	0.60	0.36	
hr030r	0.145	0.31	42.3	16.6	2.45	0.44	0.52	0.41	
Vegetated floodplains and rods as riparian vegetation (‘rr’)									
hr020rr	0.1264	0.20	38.3	5.0	2.83	0.14	0.17	0.09	
hr030rr	0.1419	0.30	41.3	14.9	3.05	0.40	0.15	0.13	
Vegetated floodplains and shrubs as riparian vegetation (‘rs’)									
hr015rs	0.1173	0.15	34.9	1.6	2.58	0.05	0.18	0.05	
hr020rs	0.1244	0.20	36.1	3.8	2.67	0.11	0.17	0.07	
hr030rs	0.1428	0.30	39.3	11.7	2.90	0.32	0.14	0.10	

woodland, and shrubs during high flow events like flooding. To ascertain the following gap, one can see that the review of the riparian research with the overlapping research themes mainly focuses on habitat, conservation, restoration and climate change in the past half-decade (Rood, Scott, et al. 2020). Research in this field still emphasizes the significance of incorporating ecological factors into river management, emphasizing that aquatic ecosystem health is inextricably linked to the larger landscape and vegetative cover. Improved river management and ecological restoration techniques will result from a better knowledge of the interactions between vegetation and hydrodynamic processes (e.g., McBride et al. 2007; Naiman et al. 1998). Conclusively, floodplains with combinations of riparian vegetation like grassland biomes and in-line woodland with and without shrub configurations near riverbanks need critical hydrodynamic studies to understand flow behaviour around different types of submerged and emergent vegetation elements.

The influence of the vegetation in the flow is related to the vegetation elements type, namely, if they are rigid or flexible, submerged or partly submerged and with or without foliage (Pasche and Rouvé 1985). In floodplains, grass is a common type of vegetation (Arcement and Schneider 1989), whereas the woody strata of the riparian vegetation may change worldwide, according to the climate region. For instance, Mediterranean climates are dominated by ash, alder, black poplar and willows (Ferreira et al. 2005). Without foliage, riparian vegetation can be modelled as vertical rods, where drag forces are influenced by rod density and arrangement (Tanino and Nepf 2008; Asif et al. 2020; Tang, Guan, et al. 2021; Tang, Singh, et al. 2024). Vegetation

with foliage, however, significantly increases flow resistance and modifies turbulence (Yagci et al. 2010; James et al. 2008). Experimental studies have explored vegetation impacts on flow dynamics. Hopkinson and Wynn (2009) observed that trees and shrubs along single-channel banks increased turbulent kinetic energy near the toe of the bank. Sun and Shiono (2009) investigated 9-mm-diameter rods at floodplain edges, finding reduced streamwise velocity and boundary shear stress, with variations depending on rod spacing. Similarly, Sanjou and Nezu (2011) studied 2-cm rods in rectangular compound channels, noting decelerated flow in rod-occupied regions and large-scale vortices affecting the main channel and floodplain flows. While many studies focus on rigid rods (Kumar and Sharma 2022; Rahimi et al. 2020; Pasha et al. 2023; Anjum et al. 2025), fewer experiments address vegetation with foliage in compound channels despite its critical impact on flow resistance and turbulence (Järvelä 2004; Yagci et al. 2010; Boothroyd et al. 2018; Wang et al. 2022). Even fewer or no studies have considered the combination of grass, in-line shrubs and trees on the floodplains. This knowledge gap motivated the following study. This aspect is essential for understanding flow behaviour, such as flow structure and resistance, due to the complex combination of riparian vegetation on the floodplains and the main channel interface.

The velocity gradient between the main channel and floodplain flows in compound channels generates a flow structure significantly more complex than in single channels (Knight and Shiono 1996). Pioneering research identified momentum transfer between the main channel and floodplain flows as a key distinguishing feature. Vertical and horizontal vortices interact in such systems, complicating flow discharge predictions compared to

single channels (Bousmar et al. 2005). The presence of vegetation across floodplains or at the interface between the main channel and floodplain (the so-called riparian vegetation) is driven by access to water and nutrients and frequent inundation. During over-bank flow, vegetation affects hydrodynamics by slowing flow in vegetated zones, deflecting it towards non-vegetated areas and reducing overall channel conveyance (Nepf 1999; Czarnomski et al. 2012). As a biofilter, riparian vegetation contributes to water storage and infiltration (Naiman and Décamps 1997). Its structural complexity and high species diversity influence the hydrodynamic flow field (McBride et al. 2007) and enhance riverbank stability (Esfahani and Keshavarzi 2010). The flow resistance around the vegetation zone is proportional to the shear layer induced in the riverine flow (Kim et al. 2018). The free shear layer formed at the main channel–floodplain interface, in interaction with vegetation, controls the resistance as water is exchanged between the main channel and the vegetated floodplain (Sun and Shiono 2009). Due to the macro-roughness effects of vegetation, secondary currents play a crucial role in shaping this interfacial zone in compound open-channel flows. Additionally, coherent structures (i.e., organized turbulent motions) develop across the vegetated interface and influence the transverse momentum exchange between the main channel and floodplain. These structures are closely linked to the development of Kelvin–Helmholtz (K–H) instabilities, which arise from velocity gradients between vegetated and non-vegetated regions. Proust et al. (2017) found that the velocity difference and reduction in discharge around the compound channel section are also heightened by the extension of the Kelvin–Helmholtz instability, which is determined by penetration length (δ). This might further contribute to the reduction of discharge (Huai et al. 2015). Rominger and Nepf (2011) also identified that the penetration length is the function of the drag length scale ($(c_d a)^{-1}$) where c_d denotes the vegetative drag coefficient, and a is the frontal area fraction. The following phenomenon has been well studied in the literature for emergent patch vegetation (Liu et al. 2020; C. Yan et al. 2020; Iqbal et al. 2024), rigid emergent vegetation near the side wall of the open channel (Koken and Constantinescu 2021) and partially covered submerged vegetation (X. F. Yan et al. 2022). Despite this, little is known about the effect of in-line riparian woodland configurations on flow resistance and structure in compound open channels, which are viable in real-time scenarios.

This study investigates the influence of floodplain and riparian vegetation on flow dynamics within a symmetric trapezoidal compound channel, utilizing velocimetry measurements. The experimental set-up encompasses four distinct configurations: (i) absence of vegetation, (ii) floodplains with synthetic grass, (iii) floodplains with synthetic grass and rods at the edge and (iv) floodplains with synthetic grass and shrubs at the edge. Based on the work started in Fernandes et al. (2018), the primary objective is to discern how these varying vegetation arrangements affect flow discharge distribution, time-averaged streamwise velocity profiles, velocity fluctuations, turbulence intensities and lateral shear stresses at the interface between the main channel and the floodplain. Understanding these effects is crucial for enhancing river engineering practices, flood management strategies and ecological restoration efforts.

The rationale behind this investigation derives from the recognition that vegetation significantly alters hydraulic characteristics

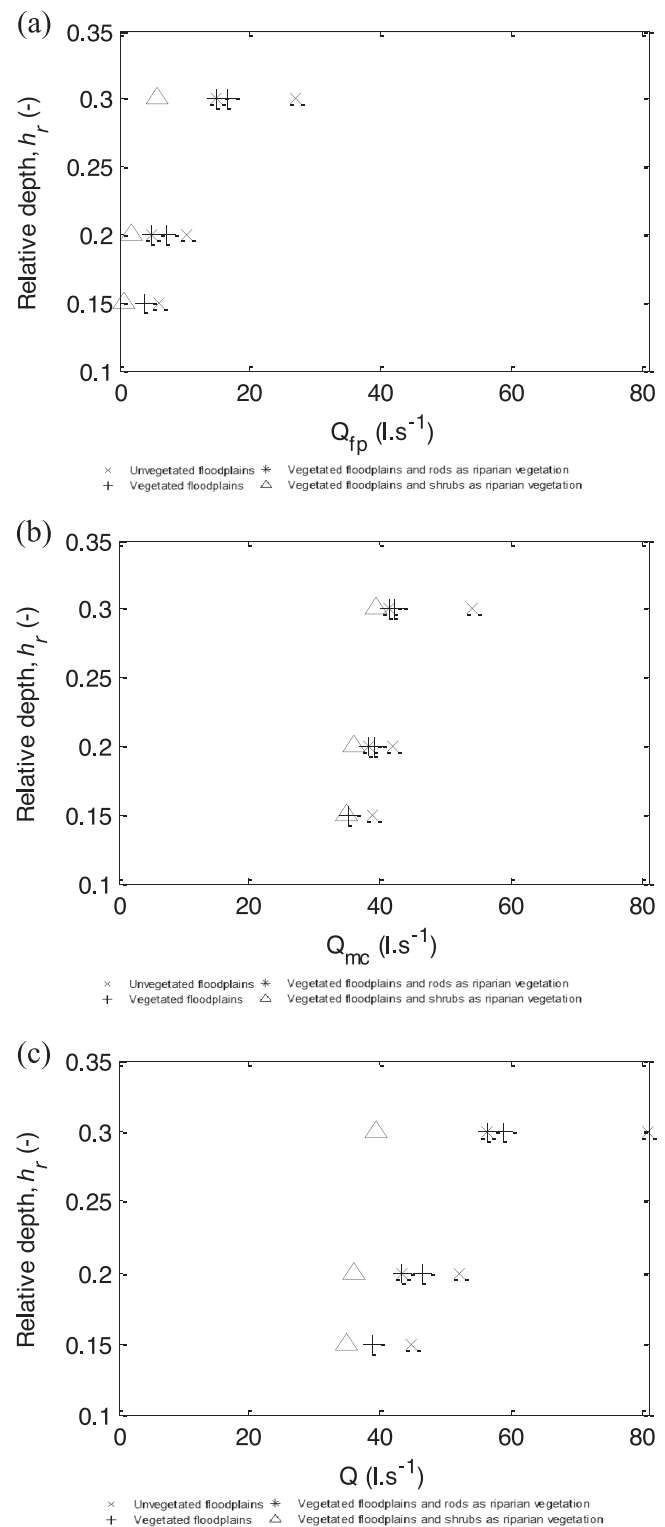


FIGURE 3 | Stage-discharge curve for the (a) floodplain, (b) main channel and (c) whole compound channel.

in compound channels. Vegetation elements, depending on their type and placement, can modify flow resistance, induce turbulence and influence momentum exchange across channel interfaces. Moreover, the effects of the existence or inexistence of foliage in the riparian vegetation can also modify the flow hydrodynamics during high-flow events. By examining

TABLE 2 | Variations in the flow discharges (in percentage).

h_r (—)	Vegetated floodplains			Vegetated floodplains and rods			Vegetated floodplains and shrubs		
	ΔQ_{mc}^r	ΔQ_{fp}^r	ΔQ^r	ΔQ_{mc}^{rr}	ΔQ_{fp}^{rr}	ΔQ^{rr}	ΔQ_{mc}^{rs}	ΔQ_{fp}^{rs}	ΔQ^{rs}
0.15	−9.5	−38.3	−13.4	—	—	—	−10.1	−73.3	−18.5
0.2	−6.9	−34.8	−12.7	−9.2	−55.4	−18.9	−14.5	−66.1	−25.3
0.3	−22.0	−37.1	−26.9	−23.8	−43.6	−30.3	−27.5	−55.7	−36.7

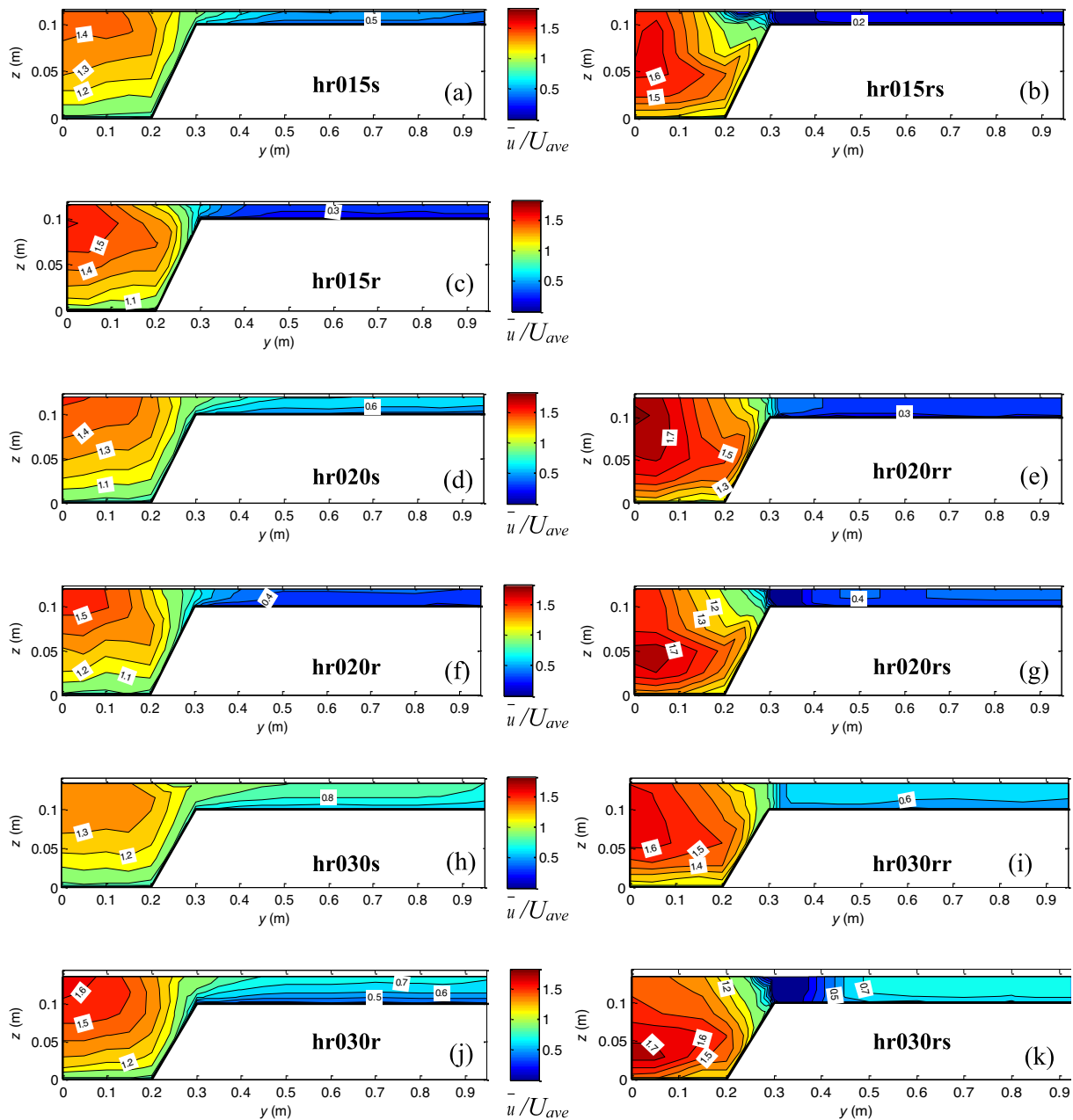


FIGURE 4 | Distribution of the streamwise velocity $\bar{u}$, scaled by the cross-section averaged streamwise velocity, U_{ave} .

configurations with and without vegetation, and with different types of riparian vegetation (rods and shrubs), the study aims to elucidate the mechanisms by which vegetation impacts flow

structures. Insights gained from this research will contribute to the development of more accurate predictive models for flow behaviour in vegetated channels, thereby informing the design

and management of riverine systems. Such complex flows can also be validated and quantitatively modelled using the provided experimental data.

2 | Experimental Set-Up

Experiments were conducted on a 10-m-long and 2-m-wide compound channel in the National Laboratory for Civil Engineering. Figure 2a–c illustrates a schematic overview of the compound channel and the main geometric characteristics. The symmetrical cross-section includes a central trapezoidal main channel (0.1 m bank full height, 0.4 m bottom width, 0.6 m bank full width, with a side slope of 45°) and two 0.7-m-wide lateral floodplains. The lateral walls and the original bed were made of polished concrete. The channel had a slope of 0.0011 m/m.

By the recommendations of Bousmar et al. (2005), separated inlets for the main channel and for the floodplains featured the independent feed of these subsections (main channel and respective adjacent floodplains), which allowed the reduction of the length to establish a uniform flow. The flow rate was controlled by a valve and monitored by an electromagnetic flow meter (uncertainty of 0.3 L/s). At the far end of the flume, three independent tailgates (one per subsection) were used to adjust the water level in the flume.

The experiments comprise the four conditions presented herein (cf. Figure 2):

- *Unvegetated floodplains* (identified in the results with the subscript 's'): the original bottom is polished concrete in the main channel and the floodplains.
- *Vegetated floodplains* ('r'): floodplains covered by 5-mm-high synthetic grass.
- *Vegetated floodplains and rods as riparian vegetation* ('rr'): same as previous but with 6-mm diameter and 45-mm-high vertical rods, each 90 mm in the interfaces between the main channel and floodplains.
- *Vegetated floodplains and shrubs as riparian vegetation* ('rs'): same as previous but with a highly dense foliage crown with a spherical shape located radially around the centre on top of the vertical rods.

Manning-Strickler coefficient, n , and the equivalent sand roughness, k_s , were evaluated through preliminary single-channel experiments. For the polished concrete, $n = 0.0092 \text{ m}^{-1/3}\text{s}$, and $k_s = 0.15 \text{ mm}$; for the synthetic grass, $n = 0.0172 \text{ m}^{-1/3}\text{s}$, and $k_s = 6.8 \text{ mm}$ (see Fernandes et al. 2025).

Despite the flexibility of the branches of the vegetation elements with foliage, the shape of the foliage remained practically unchanged during the tests. The chosen vegetation elements, synthetic grass, rods and shrubs, were selected to represent typical riparian vegetation structures with varying stiffness and complexity. Despite some flexibility, the foliage shape remained nearly constant during testing, with approximately 6–8 branches per cm^3 , consistent with a high degree of ramification observed in natural riparian shrubs (Dittrich et al. 1999). The

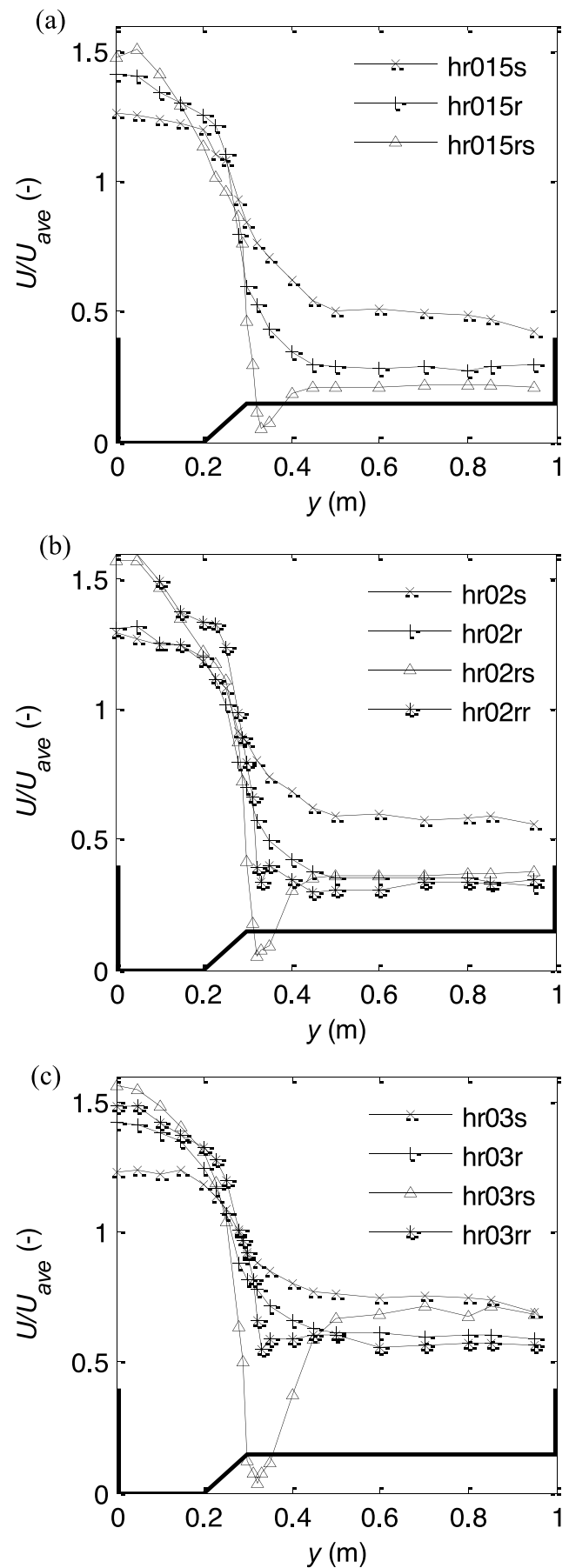


FIGURE 5 | Depth-averaged streamwise velocity U , scaled by the cross-section averaged streamwise velocity U_{ave} .

density effects on the friction factor may be determined by the so-called leaf area index (LAI), which is defined as the ratio of the area of the upper side of the leaves in a canopy projected onto a flat surface to the area of the surface under the canopy (Chen and Black 1992; Järvelä 2004). For the vegetation element that mimics shrubs in the present study, $LAI = 2.5$ corresponds to typical riparian vegetation values (e.g., Nagler et al. 2004).

The arrangement of the vegetation elements in the compound channel, defined by a spacing ratio, L/D , where L is the spacing between two consecutive rods with a diameter D , may be used to describe different flow structures. In the present work, $L/D = 15$, which aligns with the few studies concerning the riparian vegetation structure. Landcare Notes (1998) reported typical values of spacing ratios, L/D , between 8 and 16. Shiono et al. (2009) found values of L/D around 12–16 for the three rivers in Japan. Terrier (2010) presented typical values of L/D between 12 and 18 on the River Thames and approximately equal to 10 on the River Rhone. According to Esfahani and Keshavarzi (2010), a tree cultivation spacing of 10 times the grown tree diameter is normally recommended.

Figure 2a presents the reference frame. The longitudinal direction is defined by the x -axis, starting at the inlet cross-section, where $x = 0$. The y -axis refers to the lateral distance to the centre of the main channel, and the vertical direction is defined locally by the z -axis, starting at the bottom of the main channel

and moving to each x position. Figure 2b,c depicts the pictorial representation of the vegetated floodplains and rods as riparian vegetation (' rr ') and vegetated floodplains and shrubs as riparian vegetation (' rs '), respectively.

After the verification of the symmetry of the flow conditions, only half of the cross-section was investigated. The measuring mesh comprises 102 points distributed by 22 verticals (cf. Figure 2d), each with three vertical positions in the floodplain (between $0.4h_{fp}$ and $0.8h_{fp}$, where h_{fp} is the floodplain water depth) and seven vertical positions in the main channel (between $0.10h_{mc}$ and $h_b + 0.8h_{fp}$, where h_{mc} is the water depth in the main channel).

The measurements were made at $x = 7.5$ m (i.e., 7.5 m downstream of the inlet), where the boundary and mixing layers are fully developed (Fernandes et al. 2025). This cross-section is halfway between two consecutive artificial vegetation elements. For the description of the flow in the flow cases with riparian vegetation, the measurements were also conducted in five more cross sections $x = 7.455, 7.470, 7.485, 7.515$, and 7.530 m (see Figure 2e). Velocity measurements were performed with a 3d side-looking Vectrino ADV. The sampling rate was 100 Hz, and the acquisition time was 3 min at each measurement position. For the calculation of the power spectral density (Section 4.5), the acquisition time was increased to 10 min. The velocity time series were despiked using the 3d phase space method proposed in Goring and Nikora (2002). Only correlations higher than 70% were considered.

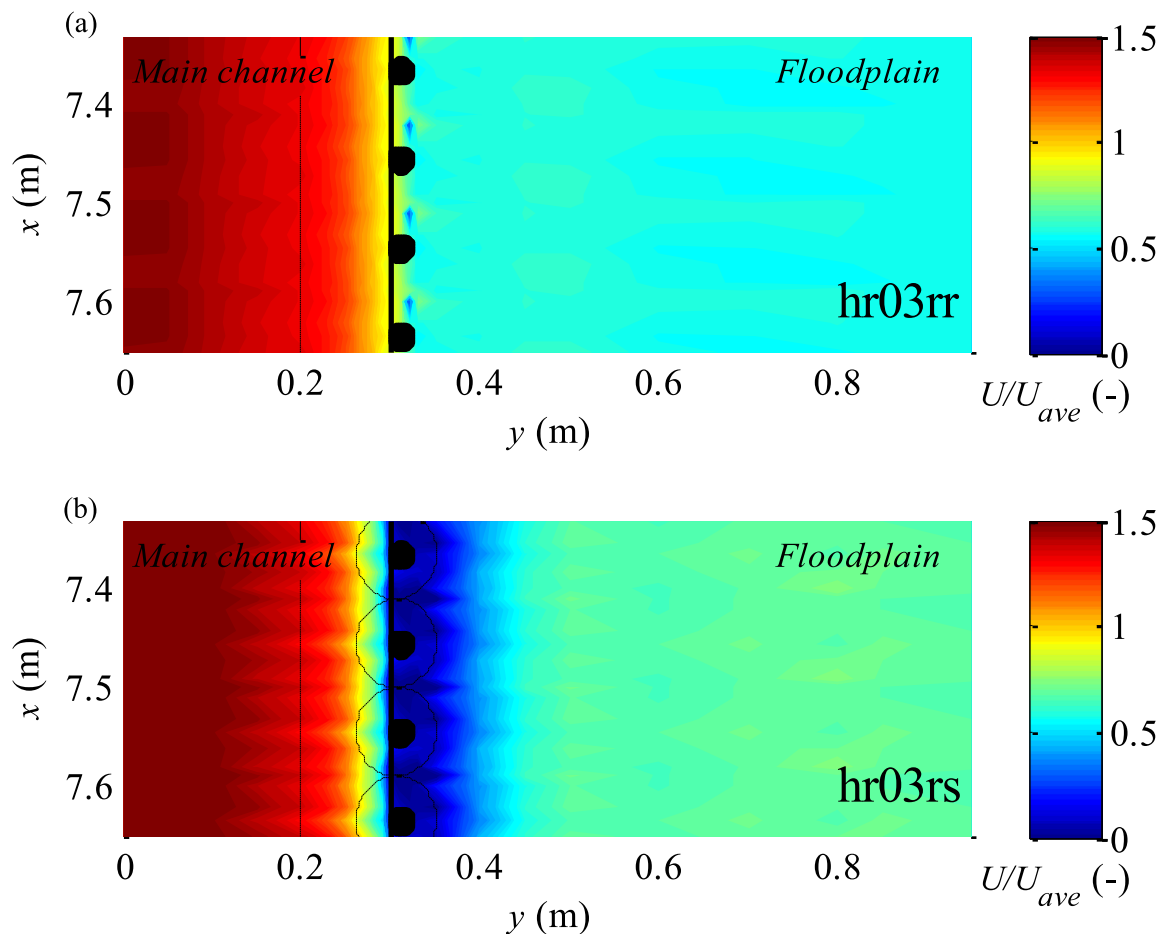


FIGURE 6 | Planview of the depth-averaged streamwise velocity around the riparian vegetation element, for $h_r = 0.3$ (note: measurements were made between $x = 7.455$ and 7.530 m; therefore, all values outside this range are a mirror replication of the measured values).

To align the ADV probe with the longitudinal direction, the pitch angle was slightly modified to obtain a depth-averaged spanwise velocity, V , equal to 0 near the lateral wall in the floodplain. In cases where a slight misalignment remained, a second correction was carried out during the post-processing by minimizing V both in the centre of the main channel and near the floodplain sidewall. This correction was considered when computing the local time-averaged velocity and the velocity fluctuations (cf. Roy et al. 1996).

3 | Flow Conditions

Eleven uniform flow tests were calibrated in the channel through an iterative procedure to achieve constant flow depths and subsection flow discharge distributions in the longitudinal direction. The most important variables of the tests are listed in Table 1, where Q_{mc} and Q_{fp} stand for the flow discharges in the main channel and the floodplains, respectively. The relative depth, h_r , represents the ratio between the floodplain (h_{fp}) and the main channel (h_{mc}) flow depths. The reference of each test is: 'hr' + 'relative depth in percentage' + 's' or 'r' for unvegetated (smooth) or vegetated (rough) floodplains, respectively. For tests with riparian vegetation at the

interface, 's' or 'r' were added to the flow reference (for shrubs or rods, respectively).

Table 1 also presents the Froude number, $Fr_i = U_i / \sqrt{gR_i}$, and the Reynolds number, $Re_i = 4U_iR_i / \nu$, of each subsection flow, where U_i and R_i are, respectively, the averaged velocity, the hydraulic radius, and ν is the kinematic viscosity. The values of Re_i are markedly higher in the main channel than in the floodplain. The flow is subcritical ($Fr < 1$) for all flow cases.

Relative depths 0.15, 0.20 and 0.30 were tested for flow conditions of (a) *Unvegetated floodplains* (test references hr015s, hr020s and hr030s), (b) *Vegetated floodplains* (hr015r, hr020r and hr030r), (c) *Vegetated floodplains and rods as riparian vegetation* (hr020rr and hr030rr, only relative depths 0.2 and 0.3 were tested) and (d) *Vegetated floodplains and shrubs as riparian vegetation* (hr015rs, hr020rs and hr030rs).

The values of Re_i are markedly higher in the main channel than in the floodplain, but in both subsections, they are high enough to neglect viscosity effects. In all cases, the flow remains subcritical ($Fr < 1$), but backwater effects were not observed at the measuring cross sections. Since Fr values are low, the free-surface deformation is small, and its effect is negligible.

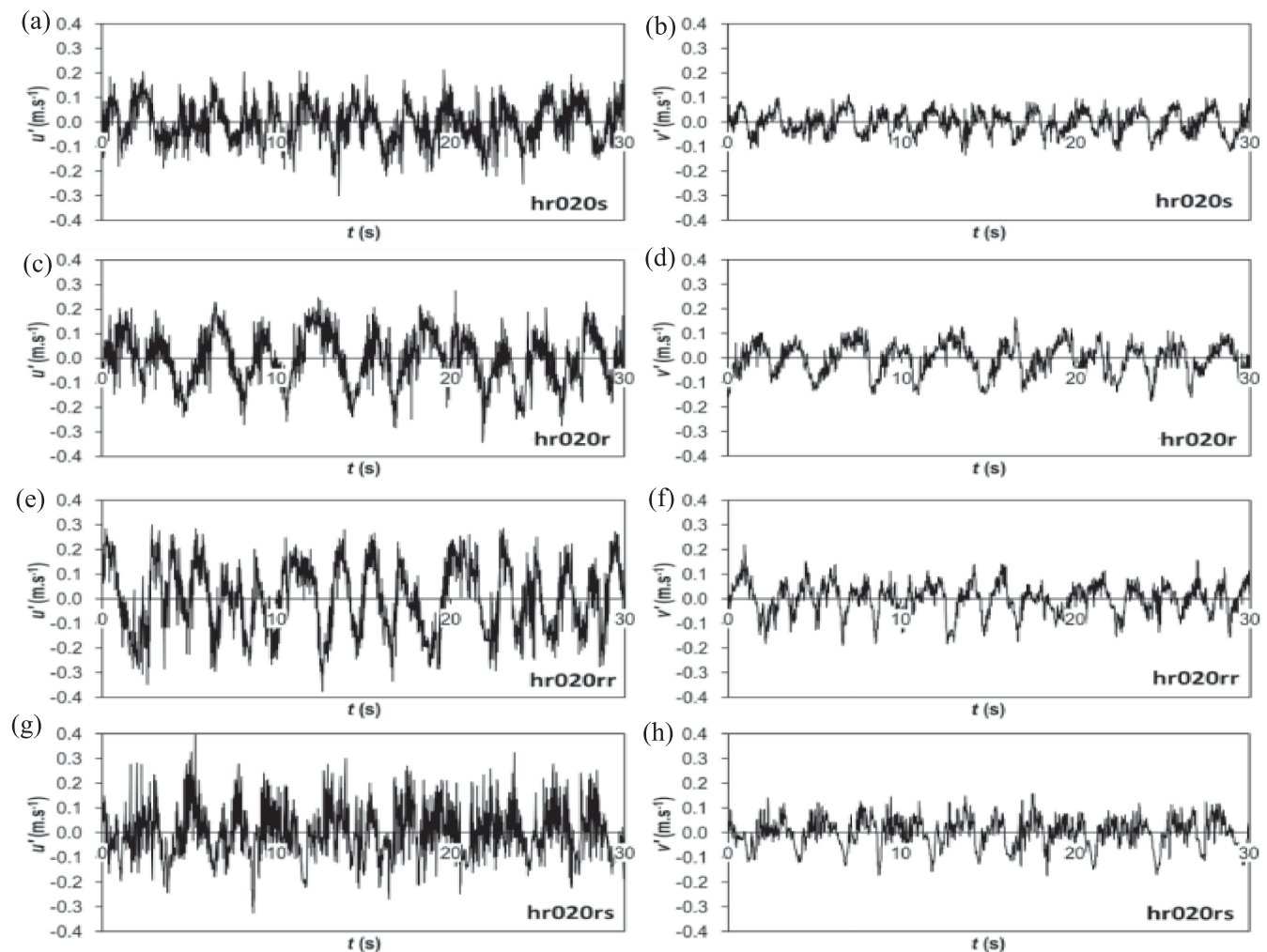


FIGURE 7 | Time series of the (a, c, e and g) streamwise and (b, d, f and h) spanwise velocity fluctuations at 40% of the water depth in the interface between the main channel and the floodplains (flow cases with relative depth 0.2).

The roughness effects in the turbulent structure flow in the wall region may be distinguished according to the boundary Reynolds number defined as $\frac{u_* k_s}{\nu}$, where u_* is the average friction velocity. For the polished concrete floodplain, $\frac{u_* k_s}{\nu}$ is equal to 4.6, which lies in the range of a hydraulically smooth boundary ($\frac{u_* k_s}{\nu} < 5$). For the synthetic grass, $\frac{u_* k_s}{\nu} = 178$, corresponding to a hydraulically rough boundary ($\frac{u_* k_s}{\nu} > 70$).

4 | Results and Discussion

4.1 | Channel Conveyance

The stage-discharge curves in Figure 3 show how the total and subsection flow discharges of the compound channel are influenced by the presence of vegetation on the floodplain and riparian vegetation at the floodplain edge. The variation of the flow discharge in relation to the discharge of unvegetated floodplains, $\Delta Q = (Q - Q_s)/Q_s$ in the main channel, floodplain and whole compound channel, ΔQ_{fp} , ΔQ_{mc} and ΔQ , respectively, is presented in Table 2. Table 2 is split into three parts, corresponding to the variations due to the synthetic grass in the floodplains and due to the presence of the rods and shrubs at the floodplain edge. For a given relative depth, subsection and total conveyance are affected by floodplain vegetation.

Comparing flow cases without riparian vegetation, a reduction in the total discharge between 13.4% and 26.9% is observed for vegetated floodplains. The reduction in the floodplain discharge falls in the range of 34.8%–38.3%. Even if the main channel remains unchanged, a reduction between 9.5% and 22% is observed in the discharge for this subsection. For the studied water depths, the decrease in the compound channel discharge due to the riparian vegetation is between 4.6% and 7.1% for rods and between 5.9% and 14.4% for shrubs when compared with the experiments with synthetic grass in the floodplain and without artificial vegetation in the floodplain edge. That overall reduction is mainly due to a reduction in the floodplain discharge.

Compared to an independent single channel with the same geometry, the floodplain subsection discharge increases due to the influence of the faster discharge in the main channel (e.g., Wormleaton and Merrett 1990). This influence is enhanced when the roughness in the floodplain is higher than on the main channel (Table 2). For the flow cases with riparian vegetation, this effect seems to be reduced due to a blocking effect of the elements in the interface between the main channel and the floodplain (refer to Figure 3c). Following the results obtained in a single channel by James et al. (2008), the drag force due to the existence of foliage is significantly greater than for simple and unfoliated rods.

4.2 | Time Average Streamwise Velocity

The cross-sectional distributions of the time-averaged streamwise velocity, $\bar{u}$, scaled by the averaged cross-section streamwise velocity, U_{ave} , are shown in Figure 4a–k for all flow cases at the cross-section $x = 7.5$ m (for the flow cases with riparian vegetation, that cross-section corresponds to the middle cross-section

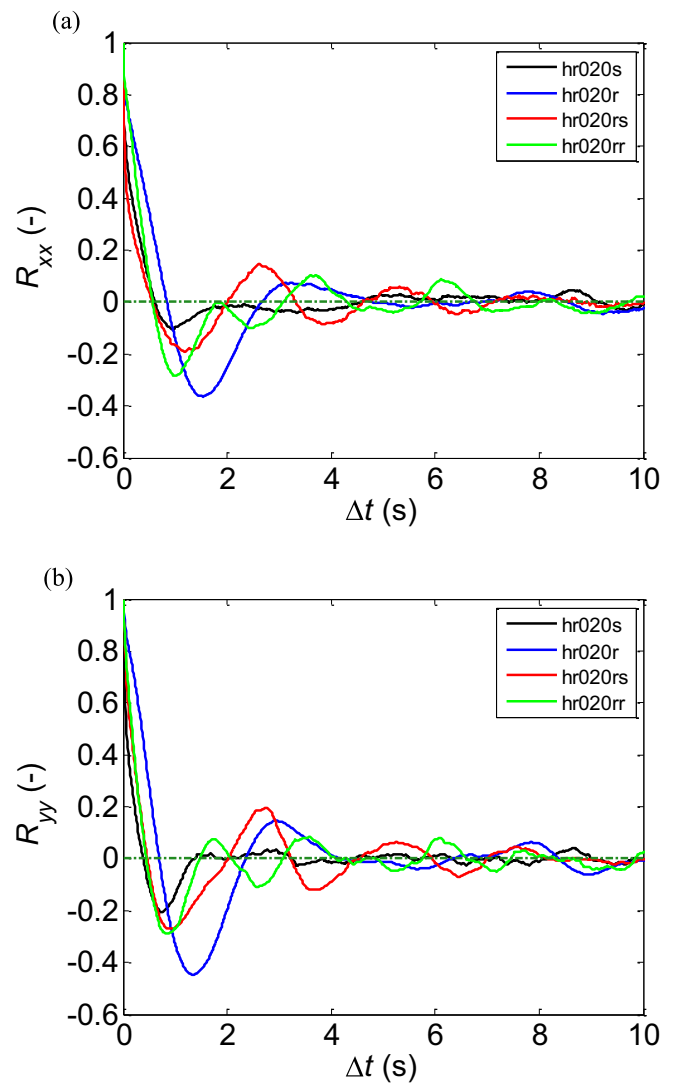


FIGURE 8 | Autocorrelation functions for flow cases with relative depths at 40% of the water depth in the interface: (a) streamwise velocity fluctuations and (b) spanwise velocity fluctuations.

between two consecutive vegetation elements). Figure 5a–c presents each flow case's lateral distribution of the scaled depth-averaged streamwise velocity, U/U_{ave} .

The cross-sectional distribution of the scaled time-averaged streamwise velocity for smooth and rough (synthetic grass) floodplain cases without riparian vegetation is rather similar (cf. Figure 4a,c,d,f,h,j). In both cases, the depth-averaged streamwise velocity can be described by a monotonic function decreasing from the centre of the channel to the end of the floodplain (Figure 5). The lateral gradient of the time-averaged streamwise velocity is mainly observed near the interface where the existence of an inflection point (Rayleigh's criterion, see, e.g., Huerre and Rossi 1998) suggests the generation of horizontal vortices (e.g., Nezu et al. 1999; Sanjou et al. 2010); similarly to the findings of Yang et al. (2007) and Hopkinson and Wynn (2009), the depth-averaged velocity increases in the main channel for vegetated floodplains.

The most noticeable systematic difference between compound channels with and without vegetation in the floodplains is the

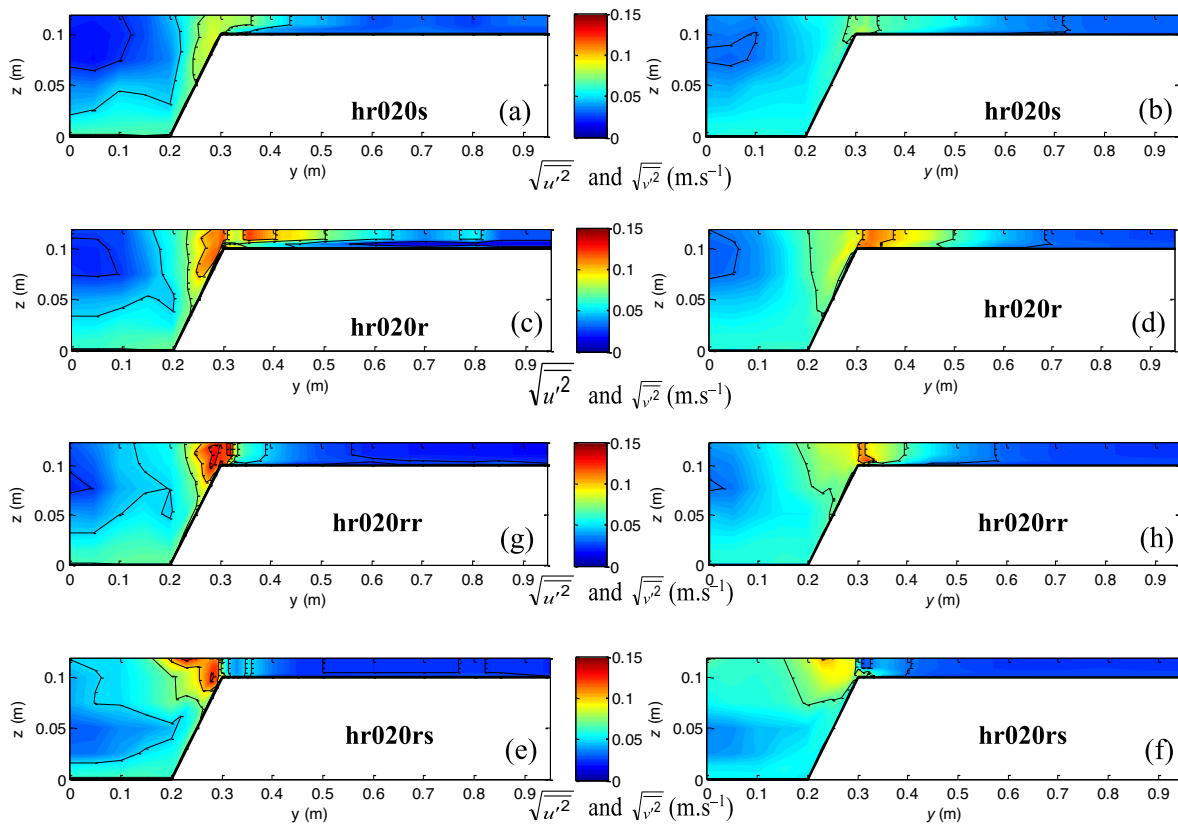


FIGURE 9 | Distribution of the turbulence intensities: (a, c, e and g) streamwise and (b, d, f and h) spanwise directions.

increase of the velocity gradient between the main channel and floodplain flows in the rough floodplains. This difference is a consequence of the increase in flow resistance observed for all water depths.

Near the interface between the main channel and the floodplains, the patterns of the streamwise velocity distributions are deeply influenced by rods and shrubs (Figure 4e,g,i,k). The depth-averaged streamwise velocity with rods in the interface does not follow a monotonic function; instead, it presents a flat step in the floodplain. With shrubs at the interface, the link between the flows in the main channel and floodplain seems to be broken, and a valley in the depth-averaged streamwise velocity is observed, with streamwise velocities close to zero in the interface (see Figure 5a–c). Nevertheless, in regions far from the interface, riparian vegetation does not influence the depth-average velocity much. In those regions, the difference between the main channel and the floodplain velocity is roughly the same for the three flow cases with synthetic grass in the floodplains.

In flow cases with riparian vegetation, the streamwise velocity pattern in the main channel is characterized by a bulge in the isovels, extending from the interface towards the centre of the channel (see hr03rr and hr03rs in Figure 4i,k). Although a similar effect is observed in cases without riparian vegetation (hr03s and hr03r), it is less pronounced. In these latter cases, as Sun and Shiono (2009) noted for rods at the interface, the region of maximum velocity is not found near the surface of the main channel flow but shifts towards the bottom. This effect is most

noticeable in the presence of shrubs, which influence the entire main channel flow, where the velocity isovels exhibit an upward concavity (Figure 4b,e,i).

The plan view of the depth-averaged streamwise velocity shown in Figure 6a,b for $h_r = 0.3$ with rods and shrubs helps to clarify this. It illustrates that riparian vegetation generates turbulent structures that detach from the vegetation elements, disturbing the flow in both the main channel and the floodplain (see lighter regions that penetrate both the main channel and the floodplain). This effect is more pronounced in the shrubs case (hr03rs i.e., Figure 6b), where the disturbances extend further into the main channel and the floodplain (Figure 6b). While several studies (e.g., Sanjou et al. 2010) have focused on the secondary currents enhanced by riparian vegetation, the results in Figure 6a,b highlight the significant role of vertically oriented turbulent structures created by the interaction between the flow and vegetation elements.

4.3 | Velocity Fluctuations and Turbulence Intensities

The distributions of the streamwise and spanwise velocity fluctuations v' , respectively, at the floodplain edge at 40% of the floodplain flow were studied for each tested flow. Typical time records for $h_r = 0.2$ are presented in Figure 7a–h (truncated at 30s).

The periodic behaviour of the streamwise velocities is observed. The spanwise velocity fluctuation corresponds with the

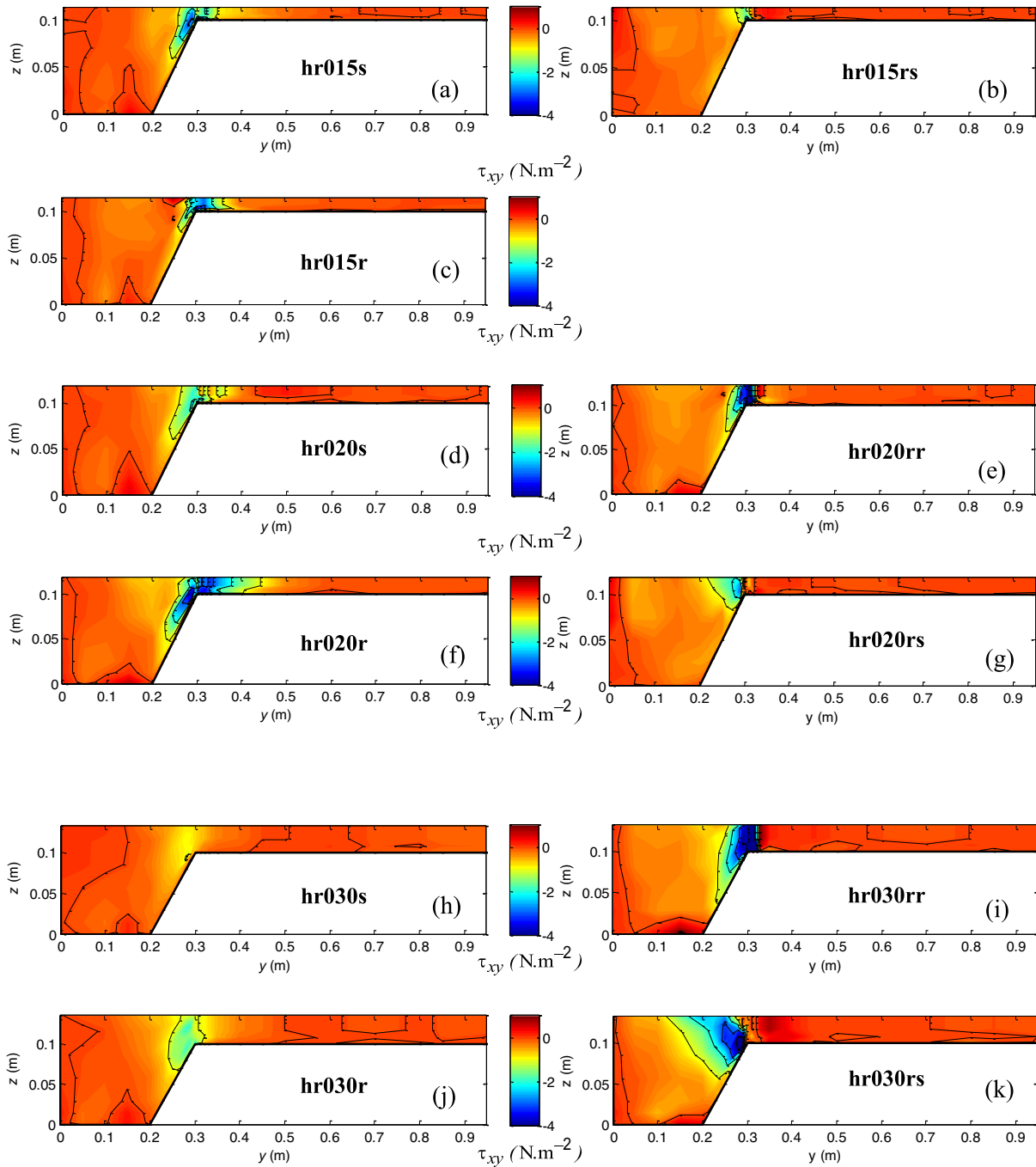


FIGURE 10 | Cross-sectional distribution of the lateral shear stresses for three test cases: (a–c) hr015, (d–g) hr020 and (h–k) hr030.

streamwise velocity fluctuation, displaying peaks in similar instants. Periods of accelerating and decelerating flow may be observed. A large-scale motion with small-scale fluctuations induces this behaviour, superposed on it. According to Van Prooijen et al. (2005), this latter source of turbulence is due to the bottom. The periodic behaviour of streamwise and spanwise velocity fluctuations is also present for flow cases with rods and shrubs in the floodplain edge (Figure 7e–h). Due to the foliage, the small-scale fluctuations are stronger in the flow cases with shrubs.

The coherent structures in the mixing layer between the main channel and the floodplain flows may be recognized by the correlation between the velocity fluctuations over a given time

span. The autocorrelation function of the streamwise velocity fluctuations, R_{xx} , is given in Equation (1) as

$$R_{xx} = \frac{\overline{u'(t)u'(t+\Delta t)}}{\overline{u'(t)u'(t)}} \quad (1)$$

where Δt is the time span. The autocorrelation function of the spanwise fluctuations, R_{yy} , is obtained by replacing u' by v' . The autocorrelation functions for the streamwise and spanwise velocity fluctuations at a point of the floodplain edge at 40% of the water depth are presented in Figure 8a,b for $h_r = 0.2$.

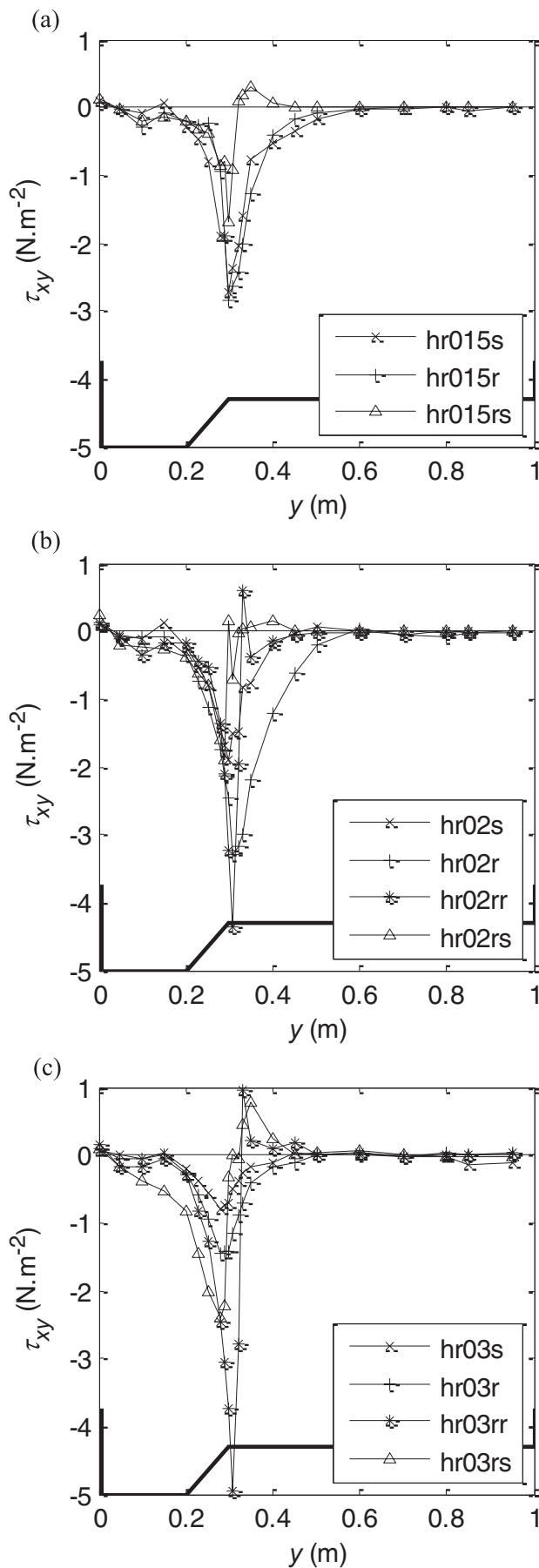


FIGURE 11 | Depth-averaged lateral shear stresses for different depth ratios (a) hr015, (b) hr02 and (c) hr03.

The modulation of the autocorrelation function of streamwise and spanwise velocity fluctuations observed in Figure 8a,b expresses the large coherent structures at the interface. It is obvious that the synthetic grass in the floodplains (hr20r) enhances the formation of structures with a lower frequency and higher amplitude than the smooth case. Coherent structures will be further analysed in Section 4.5.

Turbulence intensities, given as $\sqrt{u'^2}$ and $\sqrt{v'^2}$ for streamwise and spanwise directions, respectively, are shown in Figure 9a–h for $h_r = 0.2$. The turbulence intensities in streamwise and spanwise directions increase near the interface between the main channel and the floodplains for all flow cases. The distribution of the turbulence intensities is strongly affected by both floodplain and riparian vegetation.

Comparing the flow cases with and without vegetation in the floodplain, it can be concluded that the synthetic grass doubles the turbulence intensities near the interface (Figure 9c,d). For vegetated floodplains, high values of turbulence intensities extend laterally from the interface into the floodplain and the main channel. Similar distributions of turbulence intensities are observed for rods and shrubs in the floodplain edge (Figure 9e–h). The same increase in the turbulence intensities is observed with riparian vegetation. The lateral spreading of that region into the floodplain is blocked in the experiments with shrubs. The results obtained for the other relative depths were consistent with the conclusions drawn for $h_r = 0.2$.

4.4 | Lateral Shear Stress

The cross-sectional distribution of lateral shear stresses, $\tau_{xy} = \rho u'v'$, is shown in Figure 10a–k for all flow cases, and their depth-averaged values are presented in Figure 11a–c. These results were obtained by averaging three measurements per vertical of lateral shear stress in the floodplain and seven measurements per vertical in the main channel. For all flow cases, the highest shear region is located near the interface between the flows in the main channel and the floodplain. Far from that location, τ_{xy} becomes negligible. The maximum lateral shear and the shear-layer width decrease as the relative depth increases in the absence of vegetation.

When compared with smooth floodplains, the presence of synthetic grass in the floodplain does not appreciably change the cross-sectional distribution of the lateral shear stress, but it increases the magnitude of lateral shear close to the floodplain edge, in line with the findings of Juez et al. (2019). In the absence of riparian vegetation, a significant vertical and lateral spreading of the shear region towards the main channel side slope is observed for small relative depths in the main channel (Figure 10a,c). The shear region also extends laterally towards the floodplain.

The distribution of the lateral shear stresses is deeply affected by the presence of riparian vegetation. Two common features are observed for both rods (rr) and shrubs (rs): (i) The lateral shear stress in the interface increases (see Figure 10b,e,g,i,k), and (ii) the wake structure generated by the vegetation

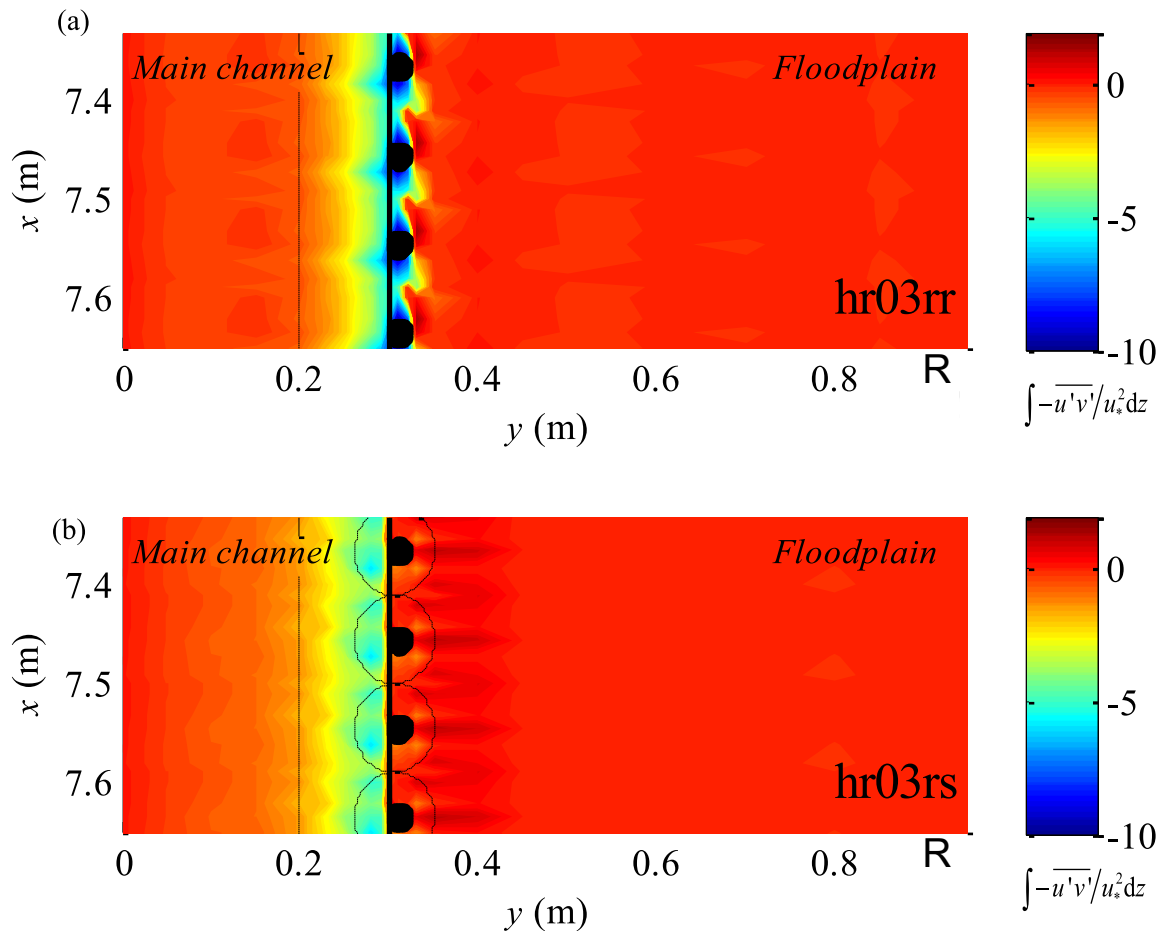


FIGURE 12 | Planview of the depth-averaged lateral shear stress $\int -\frac{u'v'}{u_*^2} dz$ around the riparian vegetation element (note: measurements were made between $x = 7.455$ and 7.530 ; therefore, all values outside this range are a mirror replication of the measured values).

elements originates positive lateral shear stress on the floodplain side since the flow velocity in the latter is higher than the one in the near region of the vegetation elements (see Figure 4). For rods (*rr*), the spreading of the shear region towards the main channel is similar to what happens without the riparian vegetation (Figure 10e,i). As mentioned, different patterns are observed for shrubs (*rs*) in which the spreading is stronger towards the main channel.

With riparian vegetation, two different peaks are observed: one with a negative sign between the vegetation element and the main channel flow and another positive between the vegetation element and the floodplain (Figure 11). At some point between the two, the lateral shear stress is zero, suggesting that the vegetation suppresses the momentum exchange between the main channel and the floodplain flow. Similar results were found by Sanjou and Nezu (2011). This means that the lateral shear stress is not due to the interaction between the main channel and floodplain flows but rather a consequence of the interaction of the wake structure generated by riparian vegetation and the flow in each subsection. This can be better observed by looking at the plan view of the depth-averaged lateral shear stress presented in Figure 12 for $h_r = 0.3$. Both the main channel and the floodplain show perturbations arising from the vegetation elements due to the wake structure created on both sides of those elements. As already seen in the depth-averaged streamwise velocity (see Figure 6), the

influence of the shrubs (*rs*) extends more laterally into those two sub-sections, although the rods (*rr*) present higher local absolute values of the shear stress, as also seen in Figure 10.

4.5 | Coherent 2D Structures

Figure 8 presents the autocorrelation functions for $h_r = 0.2$ for a point in the interface at a fixed downstream distance $x = 7.5$ m and an elevation $z = h_b + 0.4 h_r$. Figure 13a,b presents the same data for $h_r = 0.3$, and Figure 13c,d presents the power spectra density as a function of the wavenumber k by S_{xx} and S_{yy} for the streamwise and spanwise velocity fluctuations, respectively.

The autocorrelation results reveal distinct differences across the four flow cases. In the case of a smooth floodplain, the modulation of the autocorrelation functions for the fluctuating velocities is almost negligible, suggesting that large coherent structures are almost absent (see Figures 8a,b and 13a,b). This observation is further supported by the power spectral density analysis of the streamwise velocity fluctuations, where only a small peak is observed in the spanwise direction (Figure 13c,d).

In contrast, flow cases with synthetic grass in the floodplains, both with and without riparian vegetation, show a clear

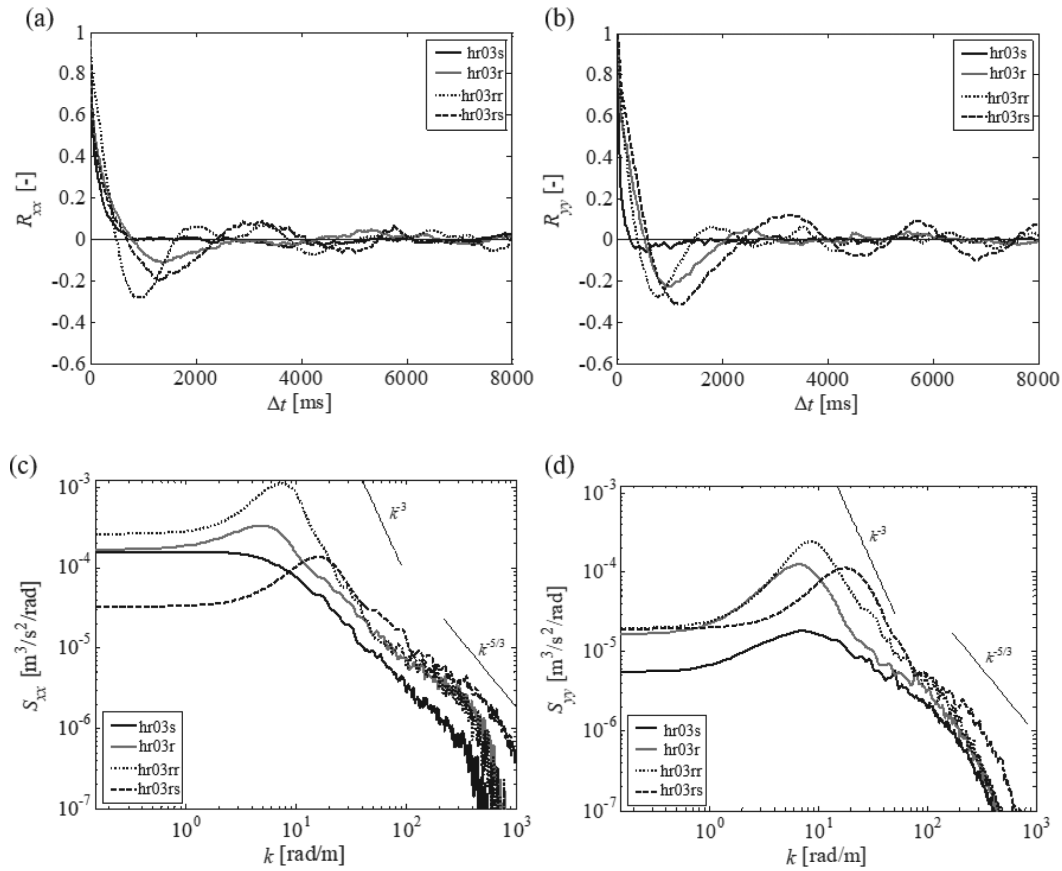


FIGURE 13 | Autocorrelation (a, b) and power spectral density (c, d) in the interface between the main channel and the floodplain at a fixed downstream distance $x = 7.5$ m and an elevation $z = h_b + 0.4 h_f$.

modulation of the autocorrelation functions, accompanied by a prominent peak in the power spectral density for streamwise and spanwise velocity fluctuations. A slope of k^{-3} follows these peaks at higher wavenumbers, which indicates the development of large two-dimensional structures. Interestingly, the peak in the power spectra is not identical across all flow cases, suggesting the presence of vortices with different length scales. Specifically, the flow case with shrubs at the interface shows the smallest length scale structures (Figure 13c).

For flow cases *rr* and *rs*, Figure 14 presents these functions for $h_r = 0.3$ and for several downstream distances for points with a high absolute value of lateral shear stress and at an elevation $z = h_b + 0.4 h_f$. Observing the autocorrelation presented in Figure 14a,b, it can be concluded that the rod cases (*rr*) create large turbulent structures that have a higher correlation than the shrub cases (see the neat negative peaks). However, the autocorrelation rapidly decays in the transverse direction for rod cases (Figure 14b). The power spectral density (Figure 14c,d) shows a clear peak, which is higher for the rod cases in the streamwise direction. The rod cases also present the peak at a higher wavenumber, meaning that vortices are being shed at a higher frequency than the shrub cases.

The turbulent energy is higher streamwise for the rod cases than in the transverse direction, while the shrub cases have approximately the same magnitude. Moreover, comparing the results on both sides of the vegetation elements (i.e., main channel $y <$

0.3 m and floodplain $y > 0.3$ m), it is clear that shrubs equally affect the flow on both sides, while rods extend their influence in the transverse direction more into the floodplain side than into the main channel.

5 | Conclusions

In the present paper, the effects of the vegetation in compound channel flows were experimentally evaluated. Floodplains that were (i) unvegetated, (ii) vegetated, (iii) a combination of vegetated and rods as riparian vegetation and (iv) a combination of vegetated and shrubs as riparian vegetation were the four criteria that were taken into consideration. For every situation, the turbulent structure and velocity distribution of compound channel flows were described. The results suggest that during floodplain inundation, the floodplain and the riparian vegetation strongly influence channel conveyance and flow structure.

The major findings are summarized as follows:

- The presence of synthetic grass in the floodplain reduces the channel conveyance. That reduction is due not only to floodplain conveyance reduction but also to the reduction of the main channel conveyance. Riparian vegetation also affects channel conveyance, but the reduction is almost due to the reduction of floodplain conveyance.

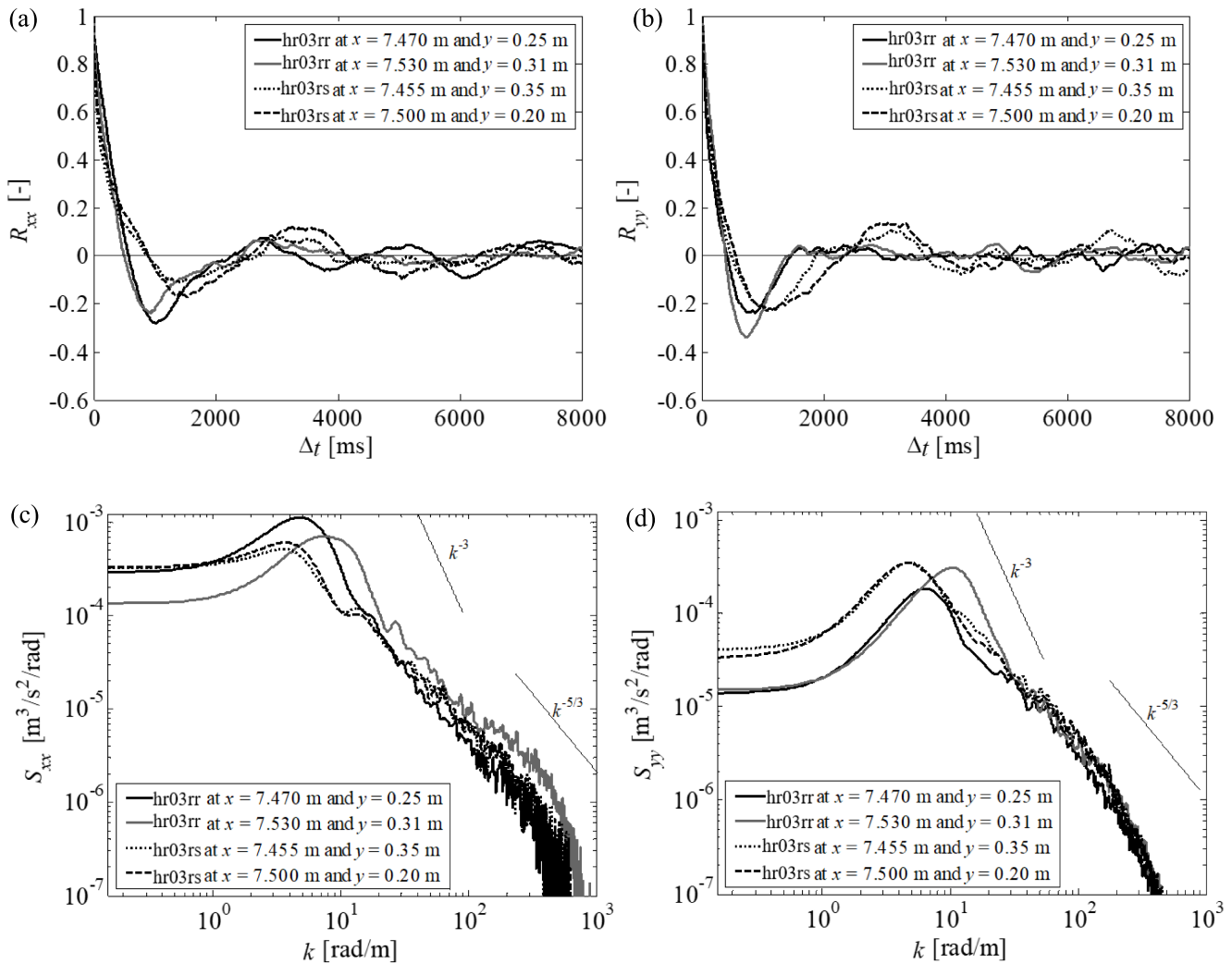


FIGURE 14 | Autocorrelation (a, b) and power spectra density (c, d) in the interface between the main channel and the floodplain at several distances, x , and at an elevation $z = h_b + 0.4 h_f$.

- The streamwise velocity patterns for flow cases without riparian vegetation are similar. An increase in the velocity gradient between the main channel and the floodplain flows is observed for compound channels with vegetated floodplains. This increase in the velocity gradient results in a rise in lateral shear stress. Increasing the relative depth reduces the velocity gradient in both cases, with and without vegetation in the floodplains.
- Compared with the case without riparian vegetation, the presence of rods and shrubs in the floodplain edge results in a different streamwise velocity pattern. In the main channel, the maximum velocity region moves towards the bottom. The influence of the shrubs is felt in the whole main channel. For small relative depths, the presence of riparian vegetation results in a concavity upwards in the velocity isovels.
- When the floodplains are covered by synthetic grass, the turbulence intensities and the lateral shear stress are enhanced for all water depths. In these flow cases, the shear region extends laterally towards the main channel and the floodplain.

- On the contrary, lateral shear stress increases with the relative depth in the flow cases with riparian vegetation. That vegetation blocks the spreading of the shear region into the floodplain.

The findings of this study offer valuable insights for the practical management of riverine systems, especially in flood-prone urban and natural environments. By experimentally analysing the influence of various floodplain vegetation configurations—including synthetic grass, rods and shrubs—the study highlights how different types of riparian vegetation significantly alter flow structure, velocity distribution and lateral shear stress in compound channels. These results underline the critical role of riparian zones in modifying channel conveyance during flood events, which has direct implications for flood risk mitigation, eco-hydraulic design, and restoration planning. The observed effects of vegetation on turbulence and flow separation emphasize the need to accurately represent canopy roughness in both flume experiments and numerical models. As proposed by Czarnomski et al. (2012) for experiments in a single channel, the differences found between the distributions of velocity and lateral shear with rods

and shrubs in the interface point out the importance of including foliage or equivalent canopy roughness in both flume and numerical experiments.

This study also highlights that both vegetation structure (1/D ratio) and vegetation properties critically influence flow resistance during different flow conditions. The results emphasize the importance of designing in-line riparian vegetation corridors along floodplains to improve flood resilience, enhance pollutant attenuation, and stabilize riverbanks. Implementing multiple vegetative buffer strips of native trees on different channel stages can effectively mitigate flooding, erosion and contaminant spread while supporting biodiversity and recreational functions.

Furthermore, water resource managers can leverage this knowledge to better assess and manage vegetated floodplains and riparian buffers to reduce the impact of floods and preserve channel morphology. Furthermore, the experimental framework established here lays a foundation for future modelling efforts, including simulations of bedload transport and pollutant dispersion (e.g., microplastics), particularly in systems with complex vegetation patterns. Incorporating approaches such as wall-modelled large eddy simulations (WMLES) and porous media modelling can enhance predictive capabilities in such dynamic shallow-flow environments.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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