

Article

Spatial Distribution Patterns of Bed Shear Stress in Zones with Alternating Tall and Short Vegetation

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Abstract

Natural floodplain vegetation exhibits heterogeneous patterns in height and density that substantially affect flow and bed stability. Most previous studies have examined flows through uniformly distributed vegetation, resulting in a limited understanding of mixed-height canopies. Consequently, existing methods for estimating bed shear stress remain inadequately validated under such heterogeneous conditions. To bridge this gap, we conducted flume experiments to investigate how the density and height configuration of rigid vegetation affect the spatial distribution of bed shear stress, comparing three commonly used approaches: the Law of the Wall, Reynolds stress, and turbulent kinetic energy (TKE). Results showed strong agreement between TKE and Reynolds stress methods; the Law of the Wall produced larger errors (15–25%) due to log-layer disruption in vegetated zones, limiting its use. Vegetation density dominated bed shear stress: high-density areas reduced mean stress by 17–36%, promoting deposition, whereas tall–short vegetation interfaces increased local stress by 15–26%, elevating scour risk. Flow velocity raised overall stress by 15–25%, while water depth had minimal effect. Sparse vegetation led to patchy stress distributions and higher scour potential, while dense vegetation favored uniform stress and sediment accumulation. These findings clarify bed shear stress mechanisms in heterogeneous vegetation and provide a basis for floodplain restoration and stability management.

Keywords: vegetated flow; flume experiment; bed shear stress; erosion control and sedimentation promotion; turbulent kinetic energy; Reynolds stress

1. Introduction

The river ecosystem is a functionally diverse and complex system, with the floodplain serving as a critical component for maintaining riverine ecological health. As an ecotone connecting terrestrial and aquatic environments, the floodplain plays a vital role in sustaining biodiversity, stabilizing riparian morphology, purifying water, regulating hydrological cycles, and facilitating the exchange of materials and energy [1–3]. By linking distinct ecosystems, floodplains facilitate species migration and interaction, which is essential for maintaining the connectivity and resilience of regional ecosystems and supporting sustainable development. Despite their ecological significance, floodplains worldwide, including alluvial islands and wetlands along major rivers like the Yangtze, face increasing threats from intensive human activities. Floodplain ecosystems are increasingly threatened by urban expansion, agricultural intensification, industrial development, and



Academic Editor: Giuseppe Barbaro

Received: 26 December 2025

Revised: 29 January 2026

Accepted: 5 February 2026

Published: 14 February 2026

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river engineering interventions. These anthropogenic pressures have caused widespread encroachment and fragmentation of floodplain areas, fundamentally altering natural flow regimes and degrading both the structural complexity and ecological functionality of these critical habitats. Historically, such pressures have caused floodplains in many regions to contract or even vanish at an alarming rate, diminishing their natural buffering capacity and substantially increasing the ecological risks to entire watersheds [4].

In this context, the morphological evolution and ecological functions of floodplains are now shaped by the combined influences of natural processes and anthropogenic activities. Hydrological regimes, sediment dynamics, and vegetation all contribute to floodplain morphology and function, with vegetation exerting a particularly strong regulatory effect on flow structure and sediment transport [5–7]. Meanwhile, the impacts of human activity are reshaping these natural dynamics at unprecedented rates and intensities, making floodplain conservation and ecological restoration urgent priorities for advancing watershed sustainability and ecological security.

Bed shear stress is a fundamental hydrodynamic parameter that governs momentum exchange at the water–sediment interface, directly influencing the evolution and stability of fluvial landforms [8]. In floodplain ecosystems, the drag force exerted by vegetation stems and foliage substantially modifies flow structure. Vegetation alters not only the vertical distribution of mean velocity but also significantly impacts turbulent coherent structures and the transport of turbulent kinetic energy. These modifications regulate sediment transport and deposition processes, ultimately shaping floodplain morphology [9–11].

Early investigations primarily focused on the effects of vegetation on vertical mean flow profiles and turbulence characteristics within the canopy layer. With continued research, it has become apparent that vegetation exhibits a characteristic “inhibition–promotion duality” in its influence on bed shear stress. Specifically, the “inhibition” effect refers to how vegetation resistance reduces the near-bed mean flow velocity, thereby decreasing the bed shear stress generated by the mean flow. In contrast, the “promotion” effect refers to how vegetation wakes enhance local turbulence intensity and momentum transport, which may trigger the incipient motion of sediment particles under low-flow conditions [12,13]. This dual mechanism results in a highly heterogeneous spatial distribution of bed shear stress within vegetated zones, establishing it as a core physical process by which vegetation modulates fluvial erosion and deposition dynamics [14–18]. Accurate and direct measurement of bed shear stress is essential for elucidating these physical mechanisms. Park et al., 2021 [19] developed and validated an adjustable shear plate technique that enables direct measurements of bed shear stress across a broad range of Froude numbers, providing a robust basis for the method’s accuracy and applicability. In addition, Aliaga et al., 2024 [20] extended the application of direct measurement techniques to more complex natural systems, confirming the reliability of shear plates for measuring bed shear stress in vegetated flow environments.

Most existing research has concentrated on scenarios with single-height or uniformly distributed vegetation, while few studies have addressed the alternating patterns of tall and short, dense and sparse vegetation that are typical in natural floodplains. In particular, there remains a lack of systematic analysis concerning the effects of rigid vegetation with varying heights on bed shear stress across different spatial arrangements. In reality, variations in vegetation height, density, and arrangement exert significant influence on near-bed momentum dissipation and the distribution of turbulent kinetic energy [21–25]. Specifically, when combinations of vegetation with different heights are present, the disparity in plant height generates strong velocity gradients and shear layers between tall and short stems. This results in localized zones of flow acceleration and intense turbulence at and beneath the vegetation canopy. The structures induced by height differences facilitate the

downward transfer of momentum to the bed, thereby increasing the local bed shear stress and promoting the formation of grooves or scouring. In contrast, in sparsely vegetated areas or regions with abrupt changes in vegetation height, sediment deposition tends to occur, leading to pronounced spatial heterogeneity in patterns of scouring and deposition. These processes have been repeatedly observed and analyzed in previous studies [26,27], highlighting that characterizing sediment dynamics solely with mean flow resistance or homogeneous vegetation parameters often fails to adequately capture the complexity of actual bed evolution. Furthermore, current methods for estimating bed shear stress in vegetated environments still present notable limitations [28,29]. Although direct measurement techniques can provide high accuracy, their application in complex, vegetated flows remains restricted. Indirect estimation approaches based on velocity profiles, Reynolds stress, or turbulent kinetic energy show significant variability in performance depending on vegetation configuration and flow conditions, and lack systematic comparative validation. The sensitivity of these methods to multi-scale turbulent structures, especially in flows with combined tall and short vegetation, remains insufficiently investigated.

To address these gaps, this study employs flume experiments featuring various combinations of rigid vegetation with different heights, as well as a range of flow velocities and vegetation densities. Flow velocity measurements are collected at designated points. Three theoretical and empirical methods, the Law of the Wall, the Reynolds stress method, and the turbulent kinetic energy method, are used to estimate bed shear stress [30,31], to systematically compare their applicability in complex vegetated flows. This investigation focuses on the effects of vegetation height differences and spatial arrangements on the spatial characteristics of bed shear stress distribution, quantify the specific mechanisms by which abrupt changes in vegetation height trigger local enhancements in bed shear stress and thereby regulate sediment scouring and deposition patterns. Beyond theoretical analysis, this study places a strong emphasis on practical utility. The findings aim to provide actionable design principles for river ecological restoration. By offering insights into the strategic arrangement of tall and short vegetation patches, this work guides engineers to actively inhibit erosion or promote sediment deposition in critical areas. These results offer a robust scientific basis for optimizing riverbed stability management and implementing nature-based solutions.

2. Experimental Design

2.1. Experimental Setup and Vegetation Arrangement

The vegetation and water flow experiment is conducted in the Sediment Test Hall of the Zhuankou Experimental Base, Changjiang River Scientific Research Institute, Changjiang Water Resources Commission. This study utilizes a variable-slope open-channel flume to investigate water–sediment dynamics, as illustrated in Figure 1. The flume system comprises an inlet tank, a glass flume, a reservoir, and a return water tank measuring 70 m in length and 140 m³ in volume. The glass flume has an overall length of 60 m, a clear width of 0.8 m, and a height of 0.8 m, with a design discharge of 0.4 m³/s.

Straight cylindrical wooden sticks with heights of 15 cm and 30 cm, and a diameter of 8 mm, were used to simulate rigid floodplain vegetation. To adjust vegetation density and arrangement, custom-made PP plastic perforated plates (1 m × 0.78 m × 8 mm, length × width × thickness) were laid at the flume bottom for fixing the wooden sticks. The plate width was slightly smaller than the flume width (0.8 m), leaving a 1 cm gap on each side. To ensure the plates remained stable under flow action and were easy to remove after experiments, glass glue was used to bond and secure their sides and bottom to the flume base. The plates featured a hole diameter of 8 mm and a hole spacing of 3 cm.

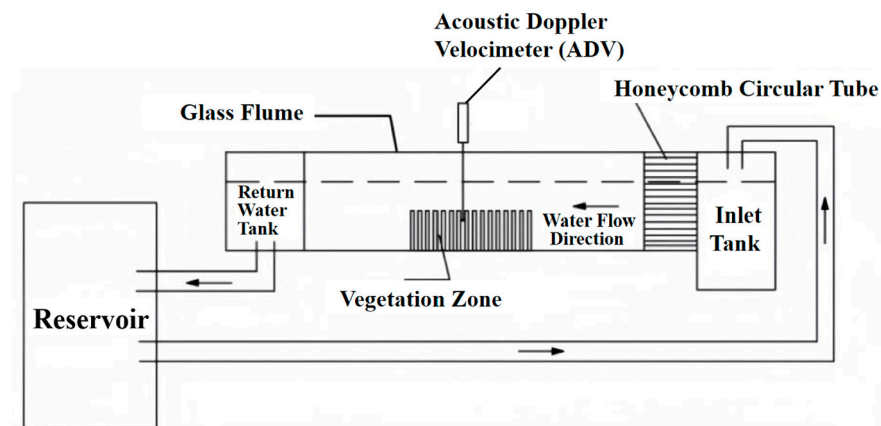


Figure 1. Generalized diagram of experimental setup. Arrows indicate the direction of water flow, and dashed lines represent the measurement positions within the flume. Solid lines denote the piping connections between the reservoir, inlet tank, return water tank, and glass flume.

The test section was located at the midpoint of the flume along the flow direction, with a total length of 10 m and ten PP plastic perforated plates installed. This study set two vegetation densities: low (73.75 stems/m^2) and high (308.75 stems/m^2). Vegetation was distributed as short on the left and tall on the right, with short stems at 15 cm and tall stems at 30 cm. The density of tall and short stems under each configuration was as follows: low density-84.375 tall stems and 63.125 short stems per square meter (stems/m^2); high density-292.5 tall stems and 325 short stems per square meter (stems/m^2). During experiments, based on the target density, the spacing of vegetation was determined using the hole matrix of (26 columns $\times$ 20 rows) the PP plastic perforated plates (8 mm hole diameter, 3 cm hole spacing). The vegetation area is formed by splicing 10 such plates along the flow direction, covering a region of $10 \text{ m} \times 0.78 \text{ m}$. All plants are located in the effective flow area, with no edge-truncated units, as shown in Figure 2.

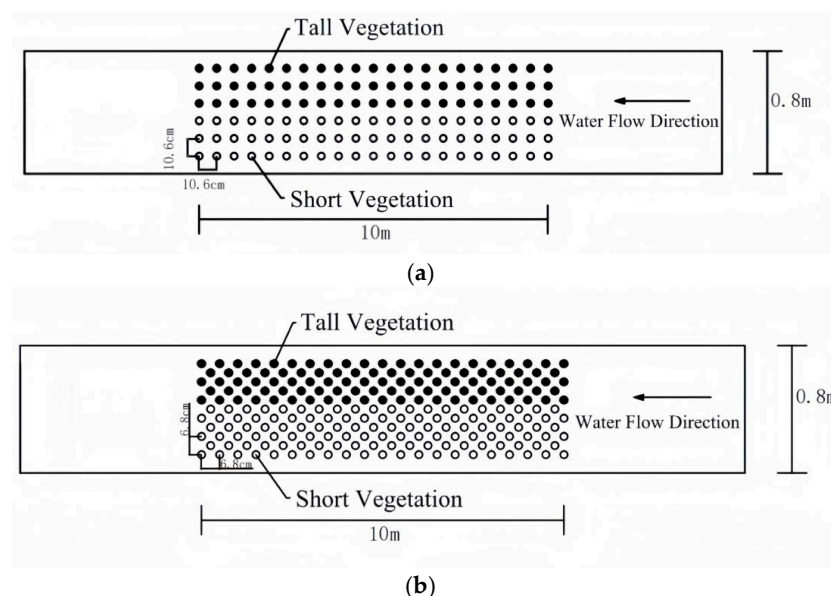


Figure 2. Vegetation arrangement. (a) Low-density vegetation arrangement; (b) High-density vegetation arrangement.

2.2. Experimental Conditions and Measurement Layout

An Acoustic Doppler Velocimeter (ADV) was employed to measure the flow field at designated test points. The sampling frequency was set to 50 Hz, and the sampling duration

at each point was 120 s, providing more than 3000 samples. Flow velocity measurement points were positioned 7 m within the vegetation zone, covering both the longitudinal and transverse directions. For longitudinal velocity measurements, points were established along the $y = 40$ cm line, starting 3 m upstream of the vegetation zone and spaced at 50 cm intervals, extending to 2 m downstream of the vegetation zone. Transverse measurement points were selected at $y = 20$ cm (within the short-stem area), $y = 30$ cm (within the short-stem area), $y = 40$ cm (at the interface of tall and short stems), $y = 50$ cm (within the tall-stem area), and $y = 60$ cm (within the tall-stem area). At each point, vertical velocity profiles were recorded, beginning 1 cm above the flume bed and proceeding at 1 cm intervals up to 3 cm below the water surface. A WEL-II intelligent water level gauge was used to record the water level of the test tank.

Within the vegetation zone, 29 measurement points were arranged for the low-density condition and 23 points for the high-density condition. Five representative groups of measurement points (Groups A, B, C, D, and E) were established for each density scenario. The detailed layout is presented in Figure 3.

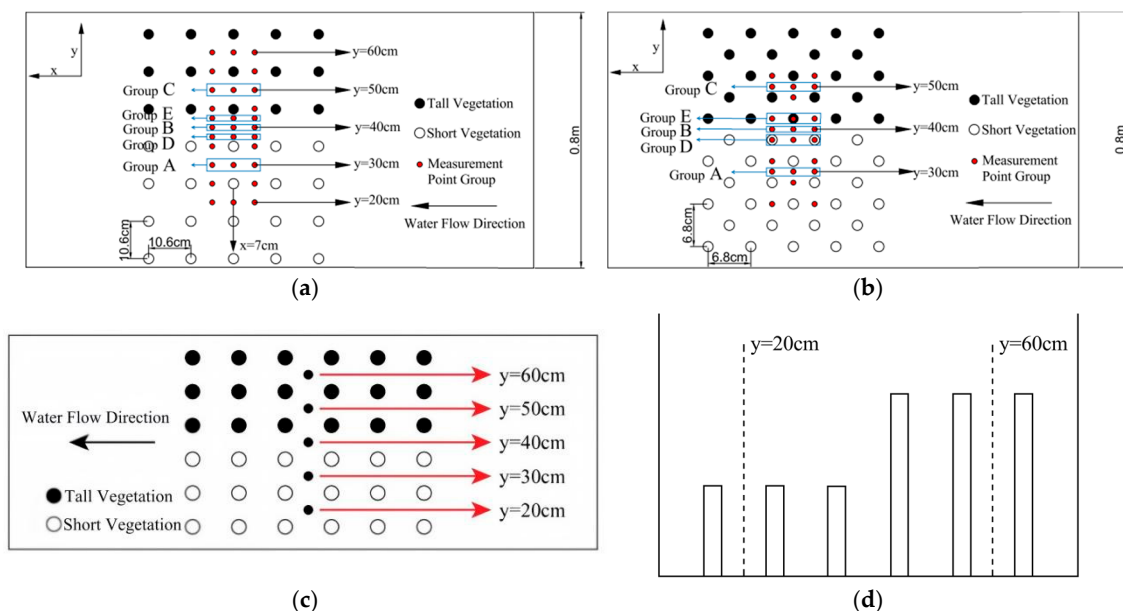


Figure 3. Measurement point layout. (a) Measurement point layout for low-density vegetation; (b) Measurement point layout for high-density vegetation; (c) Plan view of the experimental flume showing the simplified grid arrangement of velocity measurement points relative to the vegetation patch; (d) Transverse cross-sectional view illustrating the vertical distribution of velocity measurement points across the channel width. The blue arrows indicate the arrangement positions of the typical measuring point groups, and the red arrows indicate the positions of the typical measuring point groups in the y -direction.

2.3. Experimental Conditions

With the height of the straight cylindrical wooden rods held constant, we varied vegetation distribution densities and corresponding flow velocity conditions. During the experiments, the inflow discharge was set to 35 L/s, 65 L/s, and 135 L/s, corresponding to target cross-sectional water depths of 0.19 m, 0.24 m, and 0.32 m, respectively, and design flow velocities of 0.23 m/s, 0.34 m/s, and 0.49 m/s. For each scenario, we first established the inflow discharge and then adjusted the tailgate height to achieve the desired cross-sectional velocity. Open-channel flume tests were conducted for the six operational conditions summarized in Table 1.

Table 1. Flume experimental conditions.

Condition	u (m/s)	Q (L/s)	H m	N Stems/m ²
A ₁	0.23	35	0.19	73.75
A ₂	0.23	35	0.19	308.75
B ₁	0.34	65	0.24	73.75
B ₂	0.34	65	0.24	308.75
C ₁	0.49	135	0.32	73.75
C ₂	0.49	135	0.32	308.75

Note: u is the cross-sectional average flow velocity, Q is the flume discharge, H is the cross-sectional water depth, N is the arrangement density of vegetation.

3. Analysis Methods

Currently, wall shear stress estimation methods can be classified into two main categories: direct measurement and theoretical and empirical estimation. These approaches complement and refine each other, and both have seen significant advancements. Direct measurement techniques utilize instruments mounted on channel boundaries, such as the drag plate method developed by Tinoco et al., 2018 [16] and the shear plate method introduced by Pujara et al., 2014 [32]. Theoretical and empirical approaches in hydraulics have proposed various formulas based on hydraulic principles and experimental observations. Since direct measurement of bed shear stress is not feasible under experimental conditions, this study employs three indirect methods, namely the Law of the Wall, the Reynolds stress method, and the turbulent kinetic energy method, to estimate bed shear stress using flow velocity measurements [33,34].

3.1. The Law of the Wall

Von Kármán first proposed the Law of the Wall in 1930, drawing on both theoretical analysis and experimental data. This law relates the velocity gradient near the bed-to-bed shear stress using a logarithmic velocity profile in the near-wall region [30]. Owing to its simplicity and strong correlation with real flow behavior, the Law of the Wall has become a widely used approach for estimating wall shear stress in hydraulic flows over recent decades [35]. In open-channel flume experiments, direct measurements are often compromised by sensor interference and the effects of bed roughness [36–39]. As a result, the indirect method based on the Law of the Wall infers the shear velocity, u_* , and bed shear stress, τ , from the measured vertical velocity distribution at heights between $0.1h$ and $0.3h$ above the bed (where h is the water depth). The application of the Law of the Wall requires three main conditions: the flow must be fully developed and uniform [40], the near-wall turbulent structure must remain stable [30], and velocity measurements must be accurate.

Under smooth bed conditions, the classical formula typically yields errors of less than 5%. For rough beds, corrections are possible by incorporating the equivalent roughness parameter, k_s^+ , which is used to characterize the integrated resistance effect of vegetation arrays on near-wall flow [41]. Within the turbulent layer, the Law of the Wall is expressed as follows:

$$u^+ = \frac{1}{k} \ln z^+ + C^+, \quad (1)$$

u^+ can be expressed as:

$$u^+ = \frac{u}{u_*}, \quad (2)$$

where k is the von Kármán constant, with 0.41, z^+ is the dimensionless wall distance, C^+ is a constant related to relative roughness, u_* is the shear velocity, and the bed shear stress

$\tau = \rho u_*^2$, ρ is the flow density, u is the flow velocity at a certain point parallel to the wall along the flow direction.

Because the present dataset does not include direct measurements of shear velocity, the Law of the Wall can be reformulated as follows [42]:

$$\ln z = k \frac{u}{u_*} + \ln z_e, \quad (3)$$

where z is the height above the bed surface, z_e is the characteristic roughness height.

By performing a linear regression of the data points for $\ln z-u$ within the turbulent layer, the slope yields k/u_* and the intercept corresponds to $\ln z_e$. The bed shear stress can then be determined using the following equation:

$$\tau = \rho u_*^2, \quad (4)$$

To evaluate the applicability of the Law of the Wall under the experimental conditions of this study, time-averaged flow velocity data near the bed were linearly fitted at each measurement point. Profiles with a coefficient of determination $R^2 > 0.85$ were considered valid fits, with an average $R^2 \approx 0.89$. This indicates that the velocity distribution near the bed generally conforms to the logarithmic the Law of the Wall. Figure 4 illustrates the fitting results for point group B under the low-density vegetation condition at an inflow rate of 35 L/s; the observed data points align closely with the fitted line, yielding $R^2 \approx 0.923$. The calculated equivalent roughness height (k_s) is approximately 0.51 mm. It is important to note that, in vegetation simulation experiments, the k_s value represents the overall resistance effect of the vegetation array on the flow, serving as an effective quantification rather than reflecting the physical roughness of the bed material. The ratio of the equivalent sand roughness height k_s to the stem diameter ($D = 8$ mm) yields a relative roughness of $k_s/D \approx 0.064$, which falls within the typical range observed in previous studies of rigid vegetated flows [3,43,44]. This consistency supports the physical plausibility and reliability of our fitted k_s values.

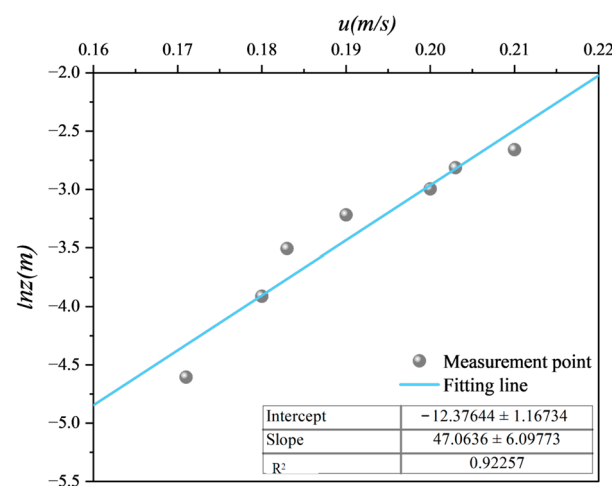


Figure 4. Fitting $\ln z-u$ data using the Law of the Wall: u is the flow velocity of the measuring point parallel to the wall and along the flow direction, z is the height from the measuring point to the bed surface.

3.2. Turbulent Kinetic Energy

Soulsby introduced the turbulent kinetic energy (TKE) method in 1983 [45], which avoids the traditional wall law's dependence on the logarithmic velocity profile. Instead, it directly relates shear stress to the characteristics of turbulent fluctuations, greatly im-

proving its applicability in non-uniform flow fields [46]. Direct numerical simulations have demonstrated that, in the near-wall region, the production term of turbulent kinetic energy dominates the energy balance [47,48]. This dominance accounts for the method's strong robustness over heterogeneous boundaries, such as vegetated beds. Even when the velocity profile deviates from the logarithmic law, the spatial distribution of turbulent kinetic energy remains relatively stable [24]. The TKE method is formulated as follows:

$$k_t = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad (5)$$

$$\tau = k_t c \rho, \quad (6)$$

where k_t is the near-bed turbulent kinetic energy, the terms u' , v' , and w' denote the velocity fluctuations in the streamwise, spanwise, and vertical directions at the measurement location, corresponding to the components along the flow direction, parallel to the wall, and perpendicular to the flow, and normal to the wall, respectively. c is an empirical parameter.

Under smooth or unvegetated bed conditions, the empirical coefficient c in the TKE method is typically set to 0.19 [45]. However, the presence of vegetation fundamentally alters the flow structure. Etminan et al., 2018 [49], using large eddy simulation, systematically investigated bed shear stress within vegetated arrays and demonstrated that, due to the dominant influence of vegetation wake turbulence, the empirical coefficient c in the TKE method decreases significantly from the bare-bed value of 0.19. Under conditions of high vegetation density and elevated Reynolds numbers, c can drop to as low as 0.05. Liu and Zeng, 2017 [50], demonstrated through experiments that the c -value is not constant in the presence of vegetation. Instead, it varies dynamically between 0.09 and 0.21, depending on vegetation density and Reynolds number. This finding further confirms the inadequacy of the traditional c -value for vegetated environments. This finding indicates that directly applying the conventional empirical coefficient in vegetated environments will result in a substantial overestimation of bed shear stress. Therefore, identifying an appropriate empirical coefficient c for the specific vegetation configuration in this study is essential for accurately estimating bed shear stress.

Figure 5 presents radar charts of bed shear stress (τ) at five representative measurement groups under condition A₁, calculated using different empirical coefficients c (0.10, 0.12, 0.14, 0.16, 0.18, 0.20). Each line in the figure represents the bed shear stress corresponding to a specific c value. As shown in Figure 5, bed shear stress exhibits a clear positive correlation with the empirical coefficient; higher c values consistently yield greater bed shear stress across all measurement points. This result highlights that the selection of c has a decisive impact on the calculated bed shear stress.

When $c = 0.10$ or $c = 0.12$, the computed bed shear stress remains relatively low at all measurement locations. Such values may underestimate the actual flow-induced force on the bed, introducing potential safety risks in engineering applications such as riverbed stability analysis or sediment initiation assessment. Conversely, when c reaches 0.16 or higher, the calculated bed shear stress increases substantially, with particularly pronounced effects observed at measurement points B, C, and E. This may lead to an overestimation of bed shear stress. To quantitatively determine the optimal value of c , this study uses the more reliable Reynolds stress extrapolation method (detailed in Section 3.2) as the benchmark [48] and calculates the mean relative error (MRE) between these two methods across different c values. The analysis shows that $c = 0.14$ yields the minimum deviation, with an MRE of approximately 6.7%. In contrast, $c = 0.12$ and $c = 0.16$ produce notably higher errors of 8.1% and 8.9%, respectively. When applying the standard coefficient $c = 0.19$ for conventional open-channel flows, the relative deviation increases significantly to 13.6%, while $c = 0.10$ also results in a substantial deviation of 12.8%. Therefore, statistical

validation confirms that $c = 0.14$ minimizes the computational deviation. Furthermore, although variations in vegetation density and flow conditions may cause minor local fluctuations in the c value [50], the optimal value of $c = 0.14$ remains considerably lower than the typical range of 0.19–0.20 for unvegetated open-channel flows. This reduction occurs because vegetation-generated wakes increase the total turbulent kinetic energy (TKE) without proportionally increasing the Reynolds shear stress, thereby lowering the τ/k ratio. Based on this analysis, this study adopts $c = 0.14$ as the optimal empirical coefficient for the model.

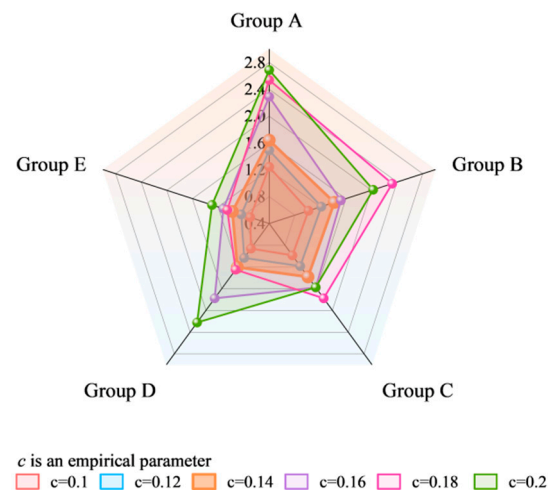


Figure 5. Radar Chart for sensitivity analysis: Comparison of calculated results of bed shear stress (τ) corresponding to different empirical coefficients (c), and the value of c increases from 0.1 to 0.2 with an increment of 0.02.

3.3. Reynolds Stress

According to classical hydraulic theory, the total shear stress at any point within the flow consists of two components: Viscous stress and Reynolds stress. This relationship can be expressed as follows:

$$\tau = \tau_R + \tau_v = -\rho \overline{u'w'} + \rho v \left(\frac{du}{dz} \right) \quad (7)$$

where τ_R is Reynolds stress, τ_v is Viscous stress, u' and w' are the fluctuating velocity components along the flow direction and perpendicular to the wall, respectively, v is the kinematic viscosity.

Near the flow boundary layer, Reynolds stress dominates the momentum transport process. The Reynolds stress method defines Reynolds stress at this point as the wall shear stress.

In fully developed channel or pipe flow, the Reynolds stress, τ_R , is approximately zero ($\tau_R \approx 0$) within the water boundary layer. Consequently, the total shear stress at any point in this region equals the Viscous stress, τ_v . Away from the boundary layer, the Viscous stress becomes negligible ($\tau_v \approx 0$), and the shear stress is dominated by the Reynolds stress. Theoretically, the total shear stress varies linearly with the distance from the wall [30]. Based on this linear relationship, the Reynolds stress measured at a given height above the bed can be extrapolated to estimate the bed shear stress. This technique is known as the Reynolds stress extrapolation method [51].

The Reynolds stress extrapolation method effectively circumvents the uncertainties associated with near-bed turbulence measurements by extrapolating the linear stress distribution from regions farther from the bed to the bed surface. This approach provides reliable

references in complex flow scenarios, such as vegetated flows. Dong et al., 2017, [29] systematically compared seven shear stress estimation methods and highlighted that the turbulent kinetic energy extrapolation method and the Reynolds stress extrapolation method yield the highest reliability and accuracy, with mean relative errors of 3.2% and 5.2%, respectively. Therefore, when direct measurement of true bed shear stress is not feasible, the results from the Reynolds stress extrapolation method can serve as a benchmark for evaluating the suitability of the Reynolds stress method.

As shown in Figure 6, this study applied both the Reynolds stress extrapolation method and the direct Reynolds stress method to measurement points A, B, and C under condition A1. The results indicate that the average relative deviation in bed shear stress estimates between the two methods is 9.7%. According to established error assessment criteria in the literature [29], a relative error of less than 10% between methods is considered to indicate good consistency. Additionally, it is important to note that Reynolds stress typically exhibits a peak in the near-wall region. The extrapolation method effectively estimates the wall value by extending the linear portion, whereas the direct method relies on measurements near the boundary layer. If the selected measurement point does not coincide with the peak value, bias may be introduced. Furthermore, local flow non-uniformities and measurement limitations can also contribute to estimation errors. Although the extrapolation method generally offers higher accuracy, the direct Reynolds stress method remains valuable in practical applications due to its relative simplicity under certain conditions.

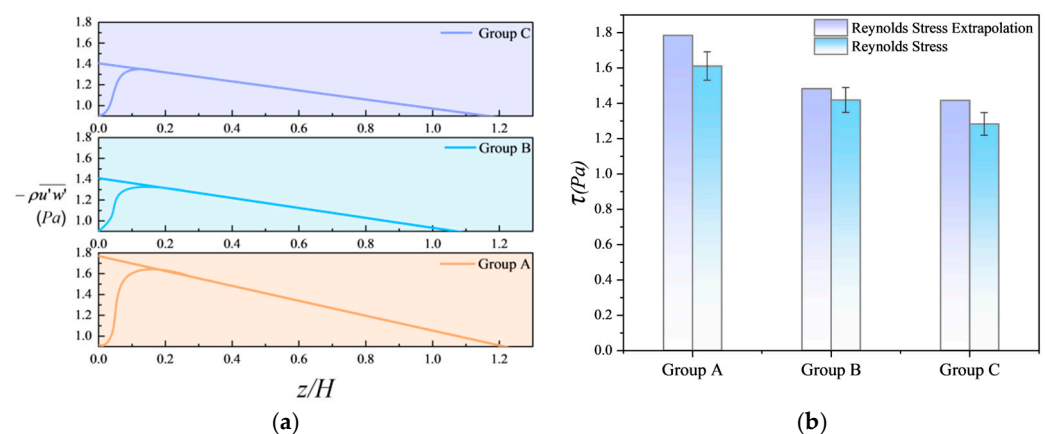


Figure 6. Comparison of bed shear stress estimation methods. (a) Bed shear stress estimated using the Reynolds stress extrapolation method (z is distance from bed, H is water depth); (b) Comparison between the Reynolds stress method and the extrapolation method. Vertical axes in both panels represent bed shear stress (Pa). Orange represents the bed shear stress values of measuring point group A, blue for group B, and purple for group C, and all estimated via the Reynolds stress extrapolation method under A1 working condition.

4. Results and Analysis

In this study, velocity measurements were performed at the central cross-section of the vegetated area (refer to the schematic diagram for measurement point locations). Five representative groups of measurement points were positioned at the interface between tall and short vegetation, while additional control groups were established within the short and tall vegetation zones, respectively. In the subsequent analysis, the ordinate denotes τ , representing bed shear stress.

4.1. Comparative Analysis of Calculation Methods

Using the experimental data from Measurement Point Group B, this study calculates bed shear stress with the three previously described methods. The objective is to system-

atically compare and assess the results and associated errors of each method, using the turbulent kinetic energy approach as the reference. Drawing on both the experimental findings and relevant literature, the study will identify the method that is most appropriate for investigating vegetated flow conditions.

The results in Table 2 and Figure 7 indicate that estimates of bed shear stress in complex vegetated flow fields vary considerably depending on the calculation method. Both Reynolds stress method and the turbulent kinetic energy method produce lower values than the Law of the Wall, with a high degree of agreement between the former two approaches, while the Law of the Wall consistently generates larger errors. These discrepancies arise from differences in how each method's underlying physical assumptions align with the actual characteristics of vegetated flows.

Table 2. Relative error of bed shear stress estimated by the Law of the Wall and Reynolds stress.

Density	Relative Error (%)	
	the Law of the Wall	Reynolds Stress
Low-Density N_1	16.5	−9.8
High-Density N_2	24.3	−14.4

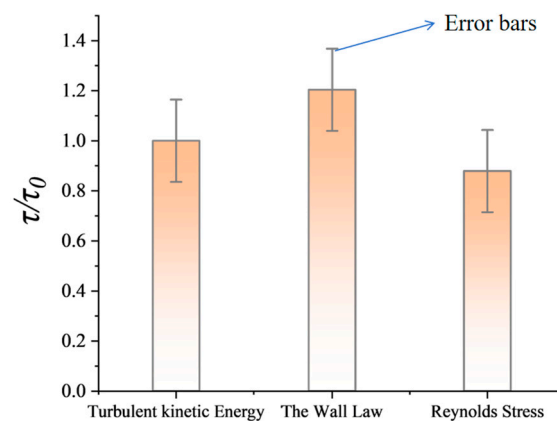


Figure 7. τ/τ_0 and standard deviation for three estimation methods. The blue arrows refer to the error bars, representing the standard deviation of the measured values.

The Reynolds stress method systematically underestimates bed shear stress, primarily due to enhanced turbulent anisotropy in the lower and middle regions of the vegetation canopy. Vegetation obstructs vertical momentum exchange, which limits the effectiveness of calculating shear stress using only a single Reynolds stress component. In contrast, the Law of the Wall tends to significantly overestimate bed shear stress. Its principal limitation lies in the fact that vegetation disrupts the uniform boundary conditions near the wall, causing velocity profiles to deviate substantially from the classical logarithmic law. Applying the Law of the Wall under these circumstances inevitably leads to considerable errors. Moreover, higher vegetation density further disturbs the standard boundary layer structure, amplifying errors in this method and highlighting its limited accuracy and applicability for vegetated flows.

The turbulent kinetic energy method estimates bed shear stress indirectly by considering the local spatial equilibrium of turbulent kinetic energy. Its theoretical framework emphasizes the generation and dissipation of flow energy, a process that remains valid even in the presence of strong turbulence induced by vegetation. As a result, although this method yields trends similar to Reynolds stress approach, its physical basis is more adaptable to the turbulent anisotropy created by vegetation, making it more robust and reliable

in complex flow environments. This conclusion is supported by previous research [40,41]. Based on the above analysis of methodological principles and sources of error, this study selects the turbulent kinetic energy method for calculating bed shear stress.

4.2. Lateral Distribution of Bed Shear Stress Under Different Conditions

Experimental data were selected from five measurement point groups under two vegetation distribution densities: Group A (between short vegetation stands), Group B (alternating tall and short vegetation), Group C (between tall vegetation stands), Group D (alternating tall and short vegetation, adjacent to short vegetation), and Group E (alternating tall and short vegetation, adjacent to tall vegetation). Each group consists of three measurement points. The data were calculated, analyzed, and plotted, with the turbulent kinetic energy method taken as an example in this study. When the inflow rate is set at 35 L/s, the short rigid vegetation becomes fully submerged, while the tall rigid vegetation remains emergent.

As illustrated in Figure 8, under the low-density condition ($N_1 = 73.75$ stems/m²), the sparse arrangement of vegetation offers minimal resistance, resulting in weaker flow disturbance and comparatively higher bed shear stress values. In contrast, under the high-density condition ($N_2 = 308.75$ stems/m²), the increased vegetation density significantly enhances flow resistance, with the canopy imposing a more substantial blocking effect. Most of the momentum dissipates at the canopy top and is not efficiently transferred to the near-bed region. Consequently, high-density vegetation further reduces bed shear, resulting in lower bed shear stress values compared to the low-density scenario.

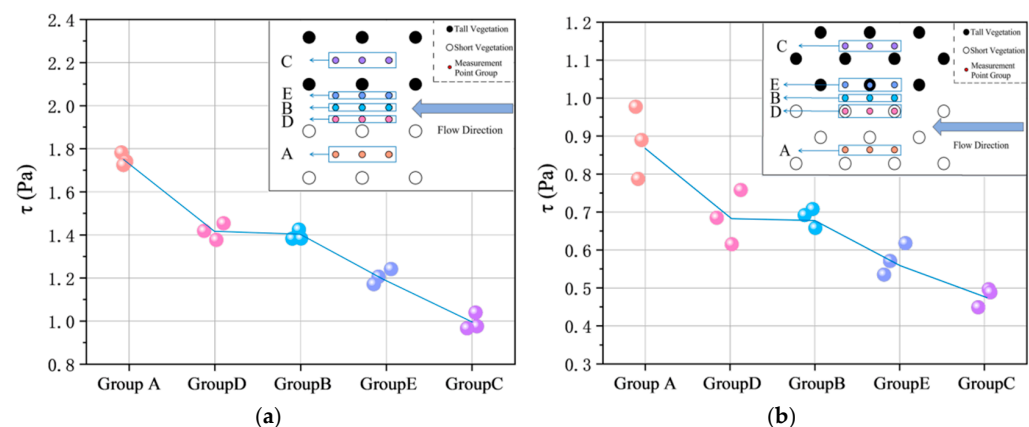


Figure 8. Comparison of lateral bed shear stress distribution at a flow rate of 35 L/s. (a) the low-density N_1 ; (b) the high-density N_2 . Data points represent measurement results from five sampling location groups: Group A (orange), Group B (blue), Group C (purple), Group D (pink), and Group E (blue-purple). Each group contains three measurement points. The inset shows the spatial arrangement of vegetation and measurement point groups, where solid black circles indicate tall vegetation, open white circles indicate short vegetation, red dots indicate measurement points, and blue arrows indicate the flow direction of water. Blue lines represent the variation trend of bed shear stress along the transverse profile.

The bed shear stress values of Measurement Group A are higher than those of other groups, attributed to the short-stemmed vegetation being in a submerged condition. Flow can overtop the canopy, allowing the mainstream to more easily divert and penetrate this area. A strong shear layer forms at the top of the canopy, generating large-scale coherent vortex structures. These vortices undergo periodic sweeps, effectively transporting high momentum from the upper flow downward to the bed surface. This downward momentum transport mechanism sustains elevated near-bed flow velocities and intense turbulent activity within the submerged canopy, leading to enhanced momentum dissipation at

the bed and consequently higher shear stress values. In contrast, Measurement Group C exhibits relatively low bed shear stress values overall. This is because the vegetation stems protruding above the water surface strongly obstruct the flow. As the flow approaches the water surface, it is forced to sharply change direction and predominantly bypass the canopy from both sides. The flow characteristics around such emergent vegetation resemble a “typical rigid canopy mixing layer,” where energy dissipation primarily occurs within the shear layer at the canopy top. Since the dominant vortex motion is confined above the canopy, it severely hinders the effective transfer of momentum into the canopy interior and to the bed surface, resulting in a significant reduction in bed shear stress [52].

Groups B, D, and E are positioned at the interface between short and tall vegetation. These measurement points are simultaneously influenced by the sheltering effect of the tall vegetation canopy and the wake generated by the short vegetation, resulting in transitional characteristics. Their bed shear stress values fall between those of Groups A and C. Group D, located on the alternating tall–short vegetation zone adjacent to the short vegetation, behaves more like a low-resistance channel. Although the shear layer at the top of short vegetation generates turbulence, the overall reduction in flow velocity limits the intensity of turbulence production. This phenomenon aligns with the condition described by Nepf (2012) [3], where canopy drag exceeds shear production and suppresses vertical turbulent exchange. Group E, located adjacent to tall vegetation, corresponds to a high-drag region. In contrast, Group B—situated at the interface between short and tall vegetation—experiences a sharp velocity gradient that fosters a strong shear layer. Such shear layers are prone to shear-layer instability, a well-documented process in stratified and heterogeneous flows. Kelvin–Helmholtz (K–H) instability represents one possible mechanism through which these instabilities manifest, leading to coherent vortical structures that enhance downward momentum transfer and elevate bed shear stress. The observed stress peak in Group B is therefore consistent with the turbulence dynamics associated with such interfacial instabilities, as discussed in the review by Li et al. (2023) [25]. Overall, these findings demonstrate that the spatial configuration and density of vegetation jointly influence the energy distribution and turbulent structure within the flow, ultimately determining the lateral distribution pattern of bed shear stress.

When the inflow rate is 65 L/s, the short rigid vegetation is fully submerged, while the tall rigid vegetation becomes partially submerged. A comparison between Figures 8 and 9 shows that the lateral distribution pattern of bed shear stress at this flow rate closely resembles that observed at 35 L/s. This consistency indicates that, under similar vegetation submergence conditions, the distribution pattern remains inherently stable. The spatial arrangement and height of the vegetation establish fixed boundaries for the flow field, resulting in a relatively stable resistance configuration that preserves the lateral distribution of bed shear stress magnitudes. Although the overall distribution remains similar, increasing the flow rate from 35 L/s to 65 L/s enhances the flow’s kinetic energy, which in turn increases the absolute values of bed shear stress.

The observed similarity in the lateral distribution of bed shear stress at both flow rates suggests that vegetation configuration is the primary factor governing shear stress distribution. In contrast, variations in flow rate predominantly affect the magnitude, rather than the lateral pattern, of bed shear stress. This regularity highlights the dominant role of vegetation in controlling bottom boundary layer dynamics under partially submerged conditions, mainly through its influence on turbulent structures and the redistribution of momentum.

When the inflow rate reaches 135 L/s, both the short and tall rigid vegetation become fully submerged. As shown in Figure 10, under these conditions, the lateral distribution of bed shear stress initially increases and then decreases, with the maximum value occurring

at the interface between short and tall vegetation. Complete submergence by the flow depth intensifies the shear force and creates a pronounced gradient from the top of the short vegetation to the top of the tall vegetation. As a result, bed shear stress at $y = 40$ cm exceeds that at $y = 30$ cm.

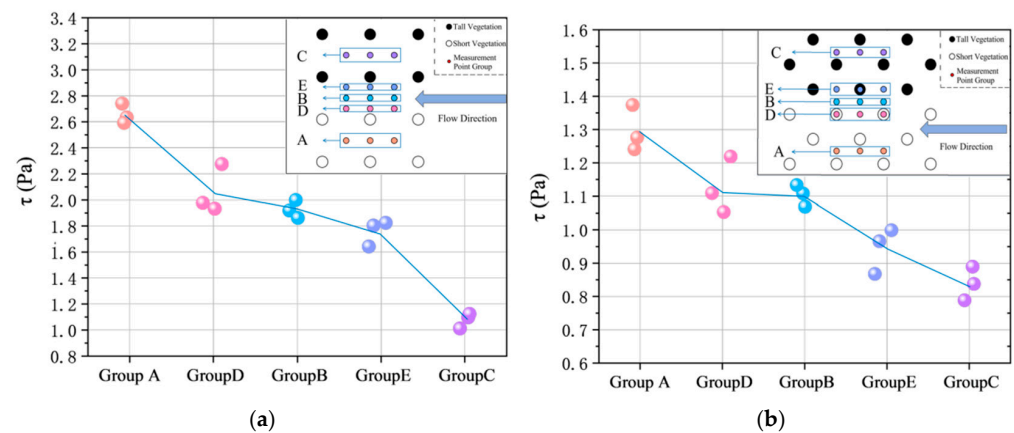


Figure 9. Comparison of lateral bed shear stress distribution at a flow rate of 65 L/s. (a) the low-density N_1 ; (b) the high-density N_2 . Data points represent measurement results from five sampling location groups: Group A (orange), Group B (blue), Group C (purple), Group D (pink), and Group E (blue-purple). Each group contains three measurement points. The inset shows the spatial arrangement of vegetation and measurement point groups, where solid black circles indicate tall vegetation, open white circles indicate short vegetation, red dots indicate measurement points, and blue arrows indicate the flow direction of water. Blue lines represent the variation trend of bed shear stress along the transverse profile.

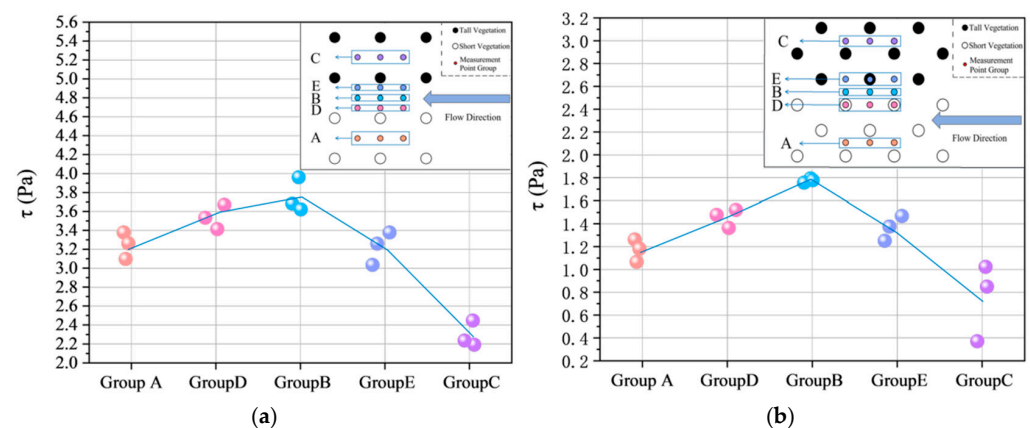


Figure 10. Comparison of lateral bed shear stress distribution at a flow rate of 135 L/s. (a) the low-density N_1 ; (b) the high-density N_2 . Data points represent measurement results from five sampling location groups: Group A (orange), Group B (blue), Group C (purple), Group D (pink), and Group E (blue-purple). Each group contains three measurement points. The inset shows the spatial arrangement of vegetation and measurement point groups, where solid black circles indicate tall vegetation, open white circles indicate short vegetation, red dots indicate measurement points, and blue arrows indicate the flow direction of water. Blue lines represent the variation trend of bed shear stress along the transverse profile.

Further analysis indicates that the lateral distribution of bed shear stress is primarily controlled by the configuration of the vegetation, while changes in flow rate mainly influence its absolute magnitude. At lower flow rates (35 L/s and 65 L/s), the tall vegetation is unsubmerged or only partially submerged. The strong shear layer formed at the top of the canopy produces large-scale turbulence, but the shading effect of the canopy causes

significant dissipation of flow energy within the mid-canopy region, resulting in a marked reduction in bed shear stress in high-density vegetation zones. In areas with alternating vegetation, shear stress displays transitional characteristics.

At higher flow rates (135 L/s), when all vegetation is fully submerged, the canopy's shading effect diminishes. The flow can pass through the uppermost layer of vegetation and develop a strong turbulent dissipation layer. The region at the boundary between tall and short vegetation then exhibits a steep horizontal velocity gradient. According to established turbulence theory [13], such shear layers are prone to triggering Kelvin–Helmholtz (K–H) instability and generating coherent vortex structures. Although direct vorticity measurements were not performed in this study, the peak bed shear stress observed in this region aligns well with the mechanism of secondary currents and vortex-driven transport described in the literature—where these turbulent structures effectively transport high-momentum fluid from the overflow layer down to the bed. This finding highlights the intrinsic mechanism by which vegetation configuration governs bottom boundary layer dynamics through the alteration of turbulence structures and energy distribution paths.

4.3. Spatial Characteristics of Bed Shear Stress Distribution

Figure 11 displays spatial contour maps of bed shear stress distribution on vegetated beds under two different vegetation densities. Under low-density vegetation conditions ($N_1 = 73.75$ stems/m²), the spatial distribution of bed shear stress remains relatively uniform. The large spacing between vegetation elements results in weak obstruction to the flow, so the maximum bed shear stress typically occurs on either side of the vegetation (in flow-constricted zones), while the wake regions and areas upstream of the vegetation exhibit markedly reduced or even negative bed shear stress. In contrast, at high-density vegetation conditions ($N_2 = 308.75$ stems/m²), the distribution of bed shear stress displays much greater spatial variability. Dense vegetation exerts stronger blockage and disruption on the flow, leading to more pervasive and intense energy dissipation. The concentrated arrangement of vegetation promotes more uniform flow and more effective redistribution of turbulent energy, thereby reducing local fluctuations in bed shear stress.

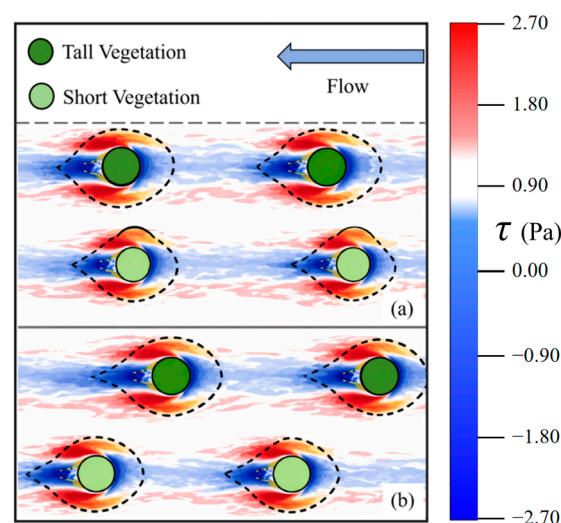


Figure 11. Spatial distribution contour maps of bed shear stress under different densities. (a) bed shear stress (τ) contour map for low-density N_1 ; (b) bed shear stress (τ) contour map for high-density N_2 ; Select the working condition with a flow rate of 35 L/S, and compare the spatial distribution of bed shear stress under the two densities. The dashed black contours denote the flow separation zones or wake boundaries around vegetation elements, highlighting the extent of hydrodynamic disturbance.

Figure 11 clearly illustrates a key hydraulic phenomenon. Bed shear stress in vegetated flows is not distributed uniformly, but rather forms high-stress zones surrounding vegetation elements, with low-stress regions in their wakes and upstream areas. This spatial variability is primarily driven by flow separation, wake turbulence, and channeling effects induced by the vegetation. In the flow-constricted regions adjacent to vegetation stems, accelerated flow and lateral compression create localized high-velocity shear bands. The resulting steep velocity gradients and intense turbulent activity sharply increase bed shear stress and promote localized scouring. Simultaneously, in regions upstream of vegetation and within the wake, flow separation and the development of secondary structures such as horseshoe vortices and wake eddies can generate shear in the direction opposite to the main flow, even producing zones of negative shear stress. Such conditions may induce upward flow near the bed or environments conducive to sediment deposition.

These observations highlight that vegetation does not merely dissipate flow energy uniformly, but fundamentally redistributes flow energy and reshapes its spatial pattern. The pronounced heterogeneity in bed shear stress distribution directly reflects the critical role of secondary flow structures, such as horseshoe vortices and wake eddies, in driving localized scouring and deposition, and in generating the patchy geomorphic features observed in vegetated beds.

According to classical sediment transport theory, the local evolution of erosion and deposition is fundamentally the result of dynamic equilibrium between local hydrodynamic forces and sediment conditions [51]. The core criterion in this process is the relationship between local bed shear stress and a reference threshold. When local hydrodynamic forces substantially exceed this threshold, the drag force exerted by the flow is sufficient to overcome the gravitational and frictional forces of sediment particles, initiating sediment entrainment and transport, and resulting in scour. Conversely, when local hydrodynamic conditions fall well below the threshold, the flow's capacity to carry sediment is limited, leading to the deposition of suspended particles and the formation of depositional zones. The essence of localized erosion and deposition lies in the spatial redistribution of flow energy [52]. The dimensionless parameter τ_{local}/τ_{avg} effectively quantifies the relative concentration of the erosional or depositional driving forces. Where τ_{local} is the local bed shear stress, τ_{avg} is the spatial average of bed shear stress within the vegetated zone. Areas where this ratio exceeds one are identified as potential high-risk scour zones; the higher the value, the stronger the local shear action on the bed, and the greater both the likelihood and anticipated magnitude of scouring. Conversely, regions with ratios below one indicate locally reduced hydrodynamic force, favoring sediment deposition and thus representing potential depositional zones. This approach not only circumvents the complexities associated with determining the critical shear stress for sediment incipient motion but also simplifies the analysis. More importantly, as a relative metric, τ_{local}/τ_{avg} is particularly well-suited for spatial comparisons within a single study area, enabling a clear identification of the alternating pattern of high-risk scour zones and stable depositional zones.

Further analysis reveals that vegetation density plays a pivotal role in regulating both hydrodynamic distribution and the resulting patterns of erosion and deposition. Vegetation density modifies flow structure and thus governs the spatial distribution, discreteness, and continuity of areas with elevated τ_{local}/τ_{avg} . Under low-density conditions (N_1), the flow readily develops concentrated, isolated high-velocity channels, leading to pronounced and spatially discrete increases in local hydrodynamic force and a heightened risk of scour. In contrast, under high-density conditions (N_2), the obstructive and disruptive effects of vegetation on the flow are intensified, resulting in greater dissipation and homogenization of flow energy. This results in a more uniform distribution of bed shear stress, promoting overall bed stability.

5. Discussion

5.1. Comparison of Estimation Methods

The results confirm that the turbulent kinetic energy (TKE) method represents the most robust approach for estimating bed shear stress in vegetated flows (Figure 7), consistent with previous findings [24,47,48]. The law of the wall yields estimates with excessive errors because vegetation disrupts the logarithmic velocity profile, a limitation frequently noted in the hydraulics literature [36–39]. The Reynolds stress method systematically underestimates bed shear stress due to the strong anisotropy of turbulence within the canopy, highlighting the necessity of considering the complete turbulent kinetic energy budget in complex canopy environments.

5.2. Physical Mechanisms of Stress Distribution

The spatial heterogeneity of bed shear stress fundamentally reflects vegetation configuration's regulation of turbulence structure, manifesting the typical "inhibition-promotion duality" [14–18]. First, abrupt canopy height transitions induce strong horizontal velocity shear, triggering Kelvin–Helmholtz instability and forming vertical mixing layers with coherent vortex structures. These structures effectively promote momentum transport from the canopy top to the near-bed region, thereby creating local shear stress "hotspots" downstream of the interface (e.g., Groups B and D) that significantly elevate scour risk. Second, vegetation density controls the energy partitioning pathway by modulating wake interaction intensity. Under low-density conditions (N_1), flow forms discrete high-velocity channels between stems, resulting in concentrated shear stress with high spatial variability. In contrast, under high-density conditions (N_2), dense vegetation enhances wake interference, promoting the conversion of mean flow energy to turbulent kinetic energy (TKE), which subsequently dissipates rapidly [49,50]. This produces a sheltering effect that homogenizes the near-bed flow field, substantially reducing both the magnitude and variability of shear stress.

Based on classical sediment transport mechanics, local riverbed erosion and deposition fundamentally result from the dynamic equilibrium between local hydrodynamic conditions and sediment properties [53]. The core criterion for this process lies in the relative relationship between local bed shear stress and a reference threshold. When local hydrodynamic conditions significantly exceed this threshold, the drag force exerted by the flow overcomes the gravitational and frictional forces on sediment particles, initiating sediment entrainment and transport that leads to scour. Conversely, when local hydrodynamic conditions fall significantly below this threshold, the flow's sediment-carrying capacity becomes insufficient, causing suspended sediment to settle and form deposits. Local scour and deposition essentially result from the spatial redistribution of flow energy [54]. The dimensionless parameter τ_{local}/τ_{avg} appropriately quantifies the relative concentration of scour or deposition potential, where τ_{local} represents the local bed shear stress and τ_{avg} represents the spatially averaged bed shear stress within the vegetated area. Regions where this ratio exceeds unity are considered potential scour risk zones; higher ratios indicate stronger local flow shear on the bed, with greater likelihood and expected magnitude of scour. Correspondingly, regions where this ratio falls below unity indicate local hydrodynamic conditions below the average level, where sediment more readily settles, representing potential deposition zones. This approach not only avoids the complexity of determining the critical shear stress for sediment incipient motion, thereby simplifying the analysis, but more importantly, τ_{local}/τ_{avg} as a relative metric proves more suitable for spatial comparisons within the same study area, clearly identifying the complex pattern of alternating high-risk scour zones and stable deposition zones.

5.3. Ecological Implications

Mixed-height vegetation not only reduces bed shear stress but also spatially redistributes it, with tall–short vegetation interfaces serving as predictable zones of stress enhancement. These findings provide directly actionable guidance for floodplain and vegetated bank management: high-density planting can suppress and homogenize bed shear stress at the patch scale, while transition zones between different vegetation heights should be treated as critical design areas, requiring scour protection measures or gradual vegetation height transitions to mitigate local scour risk.

5.4. Limitations

Although this study provides insights into bed shear stress in mixed-height vegetation, several limitations remain. First, this study uses uniformly distributed rigid vegetation represented by cylindrical wooden dowels. This differs significantly from natural floodplain vegetation, which typically exhibits flexible characteristics, complex morphology, and random spatial distribution. Specifically, natural floodplain vegetation such as reeds and shrubs possesses flexible properties that induce streamlining effects and monami phenomena, thereby altering turbulence structure [21].

Second, the experimental flume features a straight channel with a rectangular cross-section, whereas natural floodplains are rarely straight, often exhibiting meandering patterns, and their flow cross-sections are typically irregular rather than rectangular.

Third, this study focuses on relative differences among vegetation configurations and therefore does not include an unvegetated control case. While this precludes direct quantification of vegetation's absolute contribution to shear stress, given that smooth-bed open-channel flow characteristics have been thoroughly characterized in classical studies [40,53], this study concentrates on more complex non-uniform vegetation scenarios to reveal local stress enhancement phenomena induced by height heterogeneity.

Fourth, the lateral vegetation arrangement employs only one idealized configuration (short vegetation on the left side and tall vegetation on the right side along the flow direction). Although this design effectively isolates the influence of abrupt vegetation height transitions as a key factor, natural floodplains commonly exhibit patchy, staggered, or randomly distributed vegetation patterns. Therefore, the current findings primarily apply to interface regions with distinct height gradients, and extrapolation to more complex spatial configurations requires caution.

Fifth, regarding vegetation height configuration, this study adopts a fixed height combination (15 cm/30 cm, ratio of 1:2). This setup effectively reveals the fundamental mechanisms of shear layer formation and interface stress redistribution induced by abrupt vegetation height transitions. However, the quantitative effects of different height ratios (e.g., 1:3 or 1:5) on turbulence intensity and bed shear stress have not been systematically examined. Given that shear layer dynamics may intensify nonlinearly with increasing height differences, future work needs to conduct height ratio sensitivity analyses to develop parameterized models applicable to broader vegetation heterogeneity scenarios.

Furthermore, although the width-to-depth ratio of the experimental flume ($B/h \approx 2.5\text{--}4.2$) is smaller than that of natural rivers and may introduce some sidewall friction effects, vegetation drag dominates in this study, with magnitudes far exceeding sidewall friction forces [50]. More importantly, all ADV measurement points are located in the central region of the vegetated area, within the main flow core. According to the classical study by Nezu and Rodi in 1986 [55], in open channels with width-to-depth ratios greater than 2, sidewall contributions to bed shear stress typically remain below 5% and can be safely neglected in the central region. Therefore, the observed spatial heterogeneity of shear stress primarily results from vegetation configuration itself rather than boundary

interference. Nevertheless, caution remains necessary when extrapolating flume results to wide and shallow natural floodplains, considering scale effects and boundary condition differences.

Finally, this study establishes only two vegetation density levels, whereas natural vegetation density exhibits seasonal variability, and only considers rigid vegetation combinations. In reality, floodplains commonly consist of interspersed rigid and flexible vegetation with diverse density and flexibility combinations. Meanwhile, the experiments cover only three discharge conditions (35, 65, 135 L/s), which, although encompassing the critical hydraulic states from emergent to fully submerged conditions, do not extend to higher or lower velocity ranges. Notably, at each measurement point, the Acoustic Doppler Velocimeter (ADV) sampled at 50 Hz for 120 s, yielding over 3000 instantaneous samples per point, ensuring good statistical stability.

In future research, experiments can not only employ curved flumes with more naturalistic cross-sectional geometries but also establish more diverse vegetation conditions, including interspersed rigid and flexible vegetation under different height combinations, multiple spatial patterns (e.g., patchy, random distributions), and broader density and discharge ranges to better simulate natural scenarios. By advancing toward research models that more closely approximate natural conditions, we can more thoroughly reveal the underlying mechanisms and enhance the practical guidance value of theoretical findings for floodplain ecological restoration and flood management.

6. Conclusions

This study quantified how heterogeneous floodplain-like vegetation, configured as laterally adjacent tall (30 cm) and short (15 cm) rigid canopies with contrasting densities, controls the spatial variability of bed shear stress in open-channel flow. Flume experiments were conducted under three discharges (35, 65, and 135 L/s), and high-resolution velocity profiles were measured using an ADV. Bed shear stress was then estimated using three commonly adopted indirect approaches (the Law of the Wall, Reynolds stress, and turbulent kinetic energy), enabling both a methodological evaluation and a mechanistic interpretation of shear stress heterogeneity in mixed-height vegetated flows.

From a methodological perspective, the turbulent kinetic energy (TKE) method demonstrates the most robust performance across all tested vegetation configurations, yielding the smallest errors. We recommend adopting a modified coefficient $c = 0.14$ to reflect vegetation-modified turbulence. The log-law method systematically overestimates shear stress by 16–25% due to logarithmic profile breakdown, while the Reynolds stress method underestimates by 10–14% due to turbulence anisotropy.

Vegetation density serves as the primary controlling factor affecting both the magnitude and uniformity of bed shear stress. Increasing vegetation density from 73.75 stems/m² to 308.75 stems/m² significantly reduces mean bed shear stress by approximately 17–36%. High-density configurations effectively homogenize the flow field and produce a sheltering effect that stabilizes the bed. In practical engineering, for floodplain restoration projects aimed at promoting sediment deposition, a vegetation planting density threshold approaching 300 stems/m² is recommended to achieve shear stress reductions exceeding 30%, rather than relying on sparse planting combined with other measures.

The tall–short vegetation interface represents a critical zone where local bed shear stress increases significantly by 15–26%. The sustained horizontal velocity gradient in this region promotes shear layer dynamics and enhances downward momentum transfer, elevating local scour risk. In riverbank designs employing mixed-height vegetation, transition zones between different plant heights must be treated as high-risk areas. These interfaces require reinforcement measures (e.g., gravel coverage or gradual height transitions) to

withstand the expected hydrodynamic surge of approximately 25% and effectively mitigate local scour.

Vegetation pattern determines the spatial distribution of bed shear stress, while flow velocity primarily regulates its magnitude. Increasing flow velocity from 0.23 m/s to 0.49 m/s elevates overall bed shear stress by 15–25%, whereas water depth exerts a relatively minor influence. When assessing riverbed stability and calculating hydraulic loading on vegetated floodplains, flow velocity extremes should take priority over water depth variations.

Author Contributions: Conceptualization, Y.L., J.W. and X.L.; data curation, Y.L.; methodology, Y.L. and X.L.; software, Y.L.; writing—original draft preparation, Y.L.; writing—review and editing, J.W. and X.L.; visualization, Y.L. and L.Y.; validation, Y.L., J.W. and L.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was mainly supported by the National Natural Science Foundation of China (Grant nos. 12302508 and 52320105006). The data that support the findings of this study are available on request from the corresponding author.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TKE Turbulent kinetic energy

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