Vertical flow structure in flows over rough beds and through sparse arrays of rigid emergent vegetation

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Introduction

Vegetation is an essential component of natural rivers, and its interplay with flow and morphodynamic processes is considered beneficial for aquatic life by enhancing habitat heterogeneity. However, the combined impact of vegetation and bed roughness still needs better characterization in the flow region close to the bed. The present work aims to investigate the effect of array density on the vertical flow structure in rough-bed flows through rigid emergent vegetation simulated using rigid cylinders elements, with focus on the near-bed region.

Methods

Experiments were carried out in a 32-m long, 0.4-m depth, and 0.6-m wide tilting flume at the Leichtweiß-Institute for Hydraulic Engineering (Fig. 1). The bed was covered with a fixed layer of fine gravel ($\boldsymbol{d_{50}}$ = 6.46 mm). The emergent vegetation was represented by rigid cylinders (1 cm diameter) in a 14.7-m long staggered array. Experiments were carried out with two array densities (6.25 and 25 stems/m^2, respectively) and without vegetation (reference run) with a discharge $\boldsymbol{Q}$ of 0.05 m^3/s and a bed slope $\boldsymbol{S_b}$ of 0.35 %. The spatially averaged flow depth $\langle \boldsymbol{h} \rangle$ and water surface slope $\boldsymbol{S_w}$ were measured through 12 piezometers located between 12 and 18 m from the flume inlet. For the runs with vegetation, higher water depths were required to ensure quasi-uniform flow ($\boldsymbol{S_w = S_b}$) due to drag exerted by the cylinders.

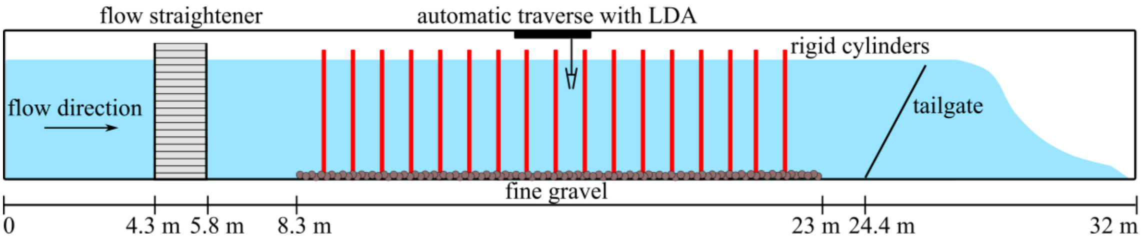

Fig. 1. Schematic representation of the experimental setup (not to scale).

Velocity measurements were made with a 3D Laser Doppler Anemometer (LDA) in 10 planes parallel to the bed for relative elevations $\boldsymbol{z/\langle h \rangle}$ between 0.015 and 0.8. Each plane consisted of 35 times series. Due to the spatial heterogeneity of vegetated flows, velocities were double-averaged (time and space) to provide a proper characterization of the vertical distribution of the flow field. The flow field was assessed through the changes in dimensionless streamwise velocity $\langle \overline{\boldsymbol{u}} \rangle / \boldsymbol{U}$, turbulent kinetic energy $\langle \boldsymbol{k_t} \rangle / \boldsymbol{U^2}$; $\langle \boldsymbol{k_t} \rangle \equiv \langle \overline{\boldsymbol{u'^2}} + \overline{\boldsymbol{v'^2}} + \overline{\boldsymbol{w'^2}} \rangle / \mathbf{2}$, Reynolds shear stress $-\langle \overline{\boldsymbol{u'w'}} \rangle / \boldsymbol{U^2}$, and dispersive shear stress $-\langle \widetilde{\boldsymbol{u}}\widetilde{\boldsymbol{w}} \rangle / \boldsymbol{U^2}$, with bulk velocity $\boldsymbol{U}$ (=$\boldsymbol{Q/(\langle h \rangle B)}$; $\boldsymbol{B}$ = channel width) as normalization variable. Overbars and brackets denote temporal and spatial averaging, $\boldsymbol{\theta'}$ and $\widetilde{\boldsymbol{\theta}}$ denote fluctuation from temporal and spatial mean values, and $\boldsymbol{u}$, $\boldsymbol{v}$, and $\boldsymbol{w}$ are the streamwise, spanwise and vertical velocity components.

Results

The vertical profiles of the dimensionless flow parameters presented in Fig. 2 show that, for the runs with vegetation, there is a clear distinction between a near-bed and the intermediate flow layer. The near-bed layer corresponds to the layer close to the bed that is characterized by a strong vertical gradient of all flow parameters due to resistance exerted by the bed roughness, whereas the intermediate flow layer is characterized by lower vertical gradients due to vertically uniform cylinders (Conde-Frias et al., 2023; Penna et al., 2020), contrasting with a continuous gradient of the reference run. The data show that for the vegetated runs, there is a logarithmic shape of the vertical distribution of $\langle \bar{u} \rangle$ close to the bed, whereas for higher elevations it tends to be vertically uniform (Fig. 2a). Regarding $\langle k_t \rangle$ (Fig. 2b) it is observed that, at the intermediate layer, the turbulent kinetic energy increases with array density which can be attributed to cylinder wakes. However, very close to the bed, all runs are characterized by similar $\langle k_t \rangle / U^2$ values, suggesting that the bed roughness governs the near-bed turbulence in agreement with Penna et al. (2020) experiments with variable grain size and constant array density. A similar behavior is observed for $-\langle \overline{u'w'} \rangle$ (Fig. 2c), and $-\langle \tilde{u}\tilde{w} \rangle$ (Fig. 2d) with a similar peak close to the bed for all the runs. Therefore, our data suggest that, although the flow profile is significantly affected by the presence of vegetation, there is a layer close to the bed (near-bed layer) where the flow field is very similar to the flow without vegetation, i.e. that the bed roughness governs the near-bed flow structure.

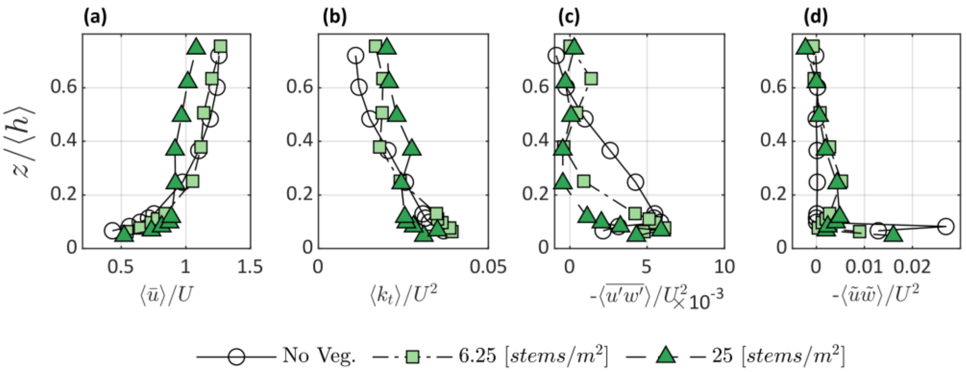

Fig. 2. Impact of array density over the vertical structure of dimensionless streamwise velocity (a), turbulent kinetic energy (b), Reynolds stresses (c), and dispersive stresses (d).

Conclusions

The impact of array density on the vertical flow structure of vegetated flows with a rough bed is presented. The results show a clear difference in the flow field between the intermediate and the near-bed layer, where the latest seems governed by the bed roughness. Therefore, our data highlights the interaction between bed roughness and vegetation on near-bed flow.

Acknowledgements

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References

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