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OPEN-CHANNEL FLOW OVER LONGITUDINAL ROUGHNESS TRANSITION FROM HIGHLY-SUBMERGED TO EMERGENT VEGETATION

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ABSTRACT

The understanding of vegetated flows is of primary importance since a new trend in river management consists in restoring rivers and floodplains to their natural form. The present laboratory study focuses on the particular case of a floodplain with a longitudinal roughness step change from highly-submerged dense meadow to emergent rigid stems set on the dense meadow (representing a wood), and vice versa. First, it was found that the flow depth solely varies upstream from the roughness change (but the flume is too short to observe the uniform flow depth at the upstream end of the flume). In this region, the vertical profiles of mean velocity, Reynolds stress and turbulent intensities are self-similar, when the mean streamwise velocity is normalized by the bulk velocity and the turbulent quantities by the shear velocity. Downstream from the roughness step change, the mean flow and turbulent quantities are spatially evolving over longitudinal distances that are about 35 to 50 times the water depth. Second, a simple 1D model is found to accurately predict the longitudinal profile of water depth through the two types of roughness transitions (from meadow to rigid stems and vice versa). Bed-roughness is modelled by Manning's formula and the drag caused by the stems is modelled by a volume force with constant drag coefficient and constant frontal surface per unit area. Results of this model show that the convergence length upstream of the roughness step change, that is necessary to reach the uniform water depth of the upstream roughness, scales with the uniform water depth of the upstream roughness H_{up} and can be estimated in the present case as 2000 H_{up}.

Keywords: Vegetation, roughness transition, laboratory study, floodplain, open-channel flow

1. INTRODUCTION

The presence of vegetation on floodplains can drastically reduce the river conveyance during flood events; but floodplain vegetation plays an important ecological role for rivers in terms of water quality, biodiversity of fauna and flora.

The influence of vegetation on river flows has been studied extensively over the last twenty years: submerged/emergent, rigid/flexible vegetation, with a uniform or patch-wise distribution. The present study examines flows over step change in roughness. These flows were widely investigated for atmospheric applications (Townsend 1966, Antonia and Luxton 1971, Pendergrass and Arya 1984, Cheng and Castro 2002) but scarcely studied in the case of hydraulic flows (Chen and Chiew 2003). All these works consider step changes between two bed roughnesses. In contrast, the present study focuses on the longitudinal transition between two different types of vegetation: submerged dense vegetation representing a meadow, and emergent rigid stems standing for a wood. Uniform flow through emergent rigid stems is characterized by a large flow field heterogeneity in the horizontal plane and by constant velocity and turbulent quantities over the flow depth, except very close to the bed where bed roughness can have an influence (Liu *et al.* 2008, Martino, Paterson and Piva 2012). Uniform flow over bed roughness can be well modelled with the logarithmic law using the equivalent sand roughness and the zero plane displacement (Raupach, Antonia and Rajagopalan 1991, Nikora *et al.* 2001). The present laboratory study aims at investigating how the vertical profiles of mean flow and turbulent quantities observed for a uniform bed roughness are altered by a step change in the roughness type, namely from a bed-induced roughness to emergent macro-roughness. First, the experimental methodology and setup are exposed. Second, we experimentally describe two roughness transitions (meadow-to-wood and wood-to-meadow). In particular, water depth profiles, vertical profiles of mean velocity, Reynolds stress and turbulent kinetic energy (TKE) are analyzed. Lastly, a 1-D model is used to compute the water depth throughout the longitudinal roughness transition.

2. EXPERIMENTAL SETUP AND METHODOLOGY

The experiments were performed in an 18-m long and 3-m wide glassed-wall flume, located in the Hydraulics and Hydromorphology Laboratory of Irstea Lyon-Villeurbanne, France. The bottom slope S_0 is 1.05 mm/m. For the purpose of this study, the width of the channel was reduced to 1 m with a Plexiglas wall (see Figure 1, middle). A commercial plastic grass was used to model the highly submerged meadow. The blades are 5-mm long and very dense, so that flow velocity within the canopy can be neglected. The wood is modelled with wooden cylindrical stems that are distributed uniformly in staggered rows. The stem diameter is D = 10 mm and the stem density is N = 81 stems/m^2. The stems stand on the plastic grass, an original flow configuration in comparison with previous physical models of flow throughout rigid vegetation. The combination of bed roughness and emergent roughness remains quite unexplored in the literature, but it seems to us that this is of interest when comparing to field measurements.

First, the vertical distribution of mean velocity and turbulent quantities was investigated for each roughness type (meadow and wood) under uniform flow conditions. Second, we studied the transition from a meadow to a wood (for discharge Q = 15 L.s^{-1}) and from a wood to a meadow (for discharge Q = 15 and 50 L.s^{-1}).

Figure 1: Left: Flow through staggered arrays of emergent rigid stems representing a wood; Middle: view from upstream of a meadow-to-wood transition; Right: position of measurement (a) within the array of stems.

Water depths were measured with an ultrasonic sensor (UNDK20I69, Baumer) with an accuracy of +/- 0.5 mm. Mean velocity and turbulent fluctuations were recorded using a side-looking ADV probe (Vectrino Plus, Nortek). The ADV raw data were filtered with the free software WinADV, which uses the despiking concept exposed by Goring and Nikora (2002). During ADV measurements, the flow was seeded with micro-bubbles generated by an iron anode (wire) set on the bottom of the flume about three meters upstream of the measurement point. The accuracy of the ADV sensor was 0.5 % of the measured value of mean velocity. Some velocity profiles were measured using 2D-PIV (LaVision Laser system). The discharge was regulated and measured by an electromagnetic flowmeter.

All vertical profiles measured in the wood were located at the same position in the elementary pattern of the stem field, i.e. at position (a) in Figure 1 (right). In all figures, the position along the longitudinal x-axis is measured from the location of the step change in roughness (x = 0); the z-axis is the vertical direction. If not specified, all velocity, Reynolds stress and TKE profiles were obtained with ADV.

For the roughness transitions, the position of the roughness step change is located at mid-length of the flume (e.g. for the first transition, a 9-m-long meadow followed by 9-m-long wood, see Figure 1, middle). The roughness of the upstream half of the flume is called “upstream roughness” and the roughness of the downstream half of the flume is called “downstream roughness”.

For each transition, the downstream boundary condition (weir level) is chosen as the downstream boundary condition of the uniform flow over the downstream roughness. This is justified by the fact that immediately downstream from the step change, the flow depth equals to the uniform flow depth related to the downstream roughness (see section 3).

3. EXPERIMENTAL RESULTS

The uniform water depth for the meadow is H_M = 55 mm for discharge Q = 15 L.s^{-1} and H_M = 116.5 mm for discharge Q = 50 L.s^{-1}. The uniform water depth for the wood is H_W = 113 mm for discharge Q = 15 L.s^{-1}. Figure 2 shows the water depth profile along the flume for the transition meadow-to-wood for discharge Q = 15 L.s^{-1} (Figure 2.a), the transition wood-to-meadow for discharge Q = 15 L.s^{-1} (Figure 2.b) and the transition wood-to-meadow for discharge Q = 50 L.s^{-1} (Figure 2.c). The uniform water depth of the downstream roughness is also represented (solid lines), as a reference.

As the flow is subcritical for each flow configuration, the water profile is essentially driven by the downstream weir. In the downstream half of the flume, from x = 0 to x = 9 m, the flow depth is very close to the uniform flow depth related to the downstream roughness (within the measurement uncertainty). In the upstream part, the flume is too short to observe the uniform depth associated with the upstream roughness at the upstream end of the flume. For the same discharge (Q = 15

L.s^{-1}), the variation in water depth for the wood-to-meadow transition is larger than for the symmetrical one, with a water depth gradient about twice larger.

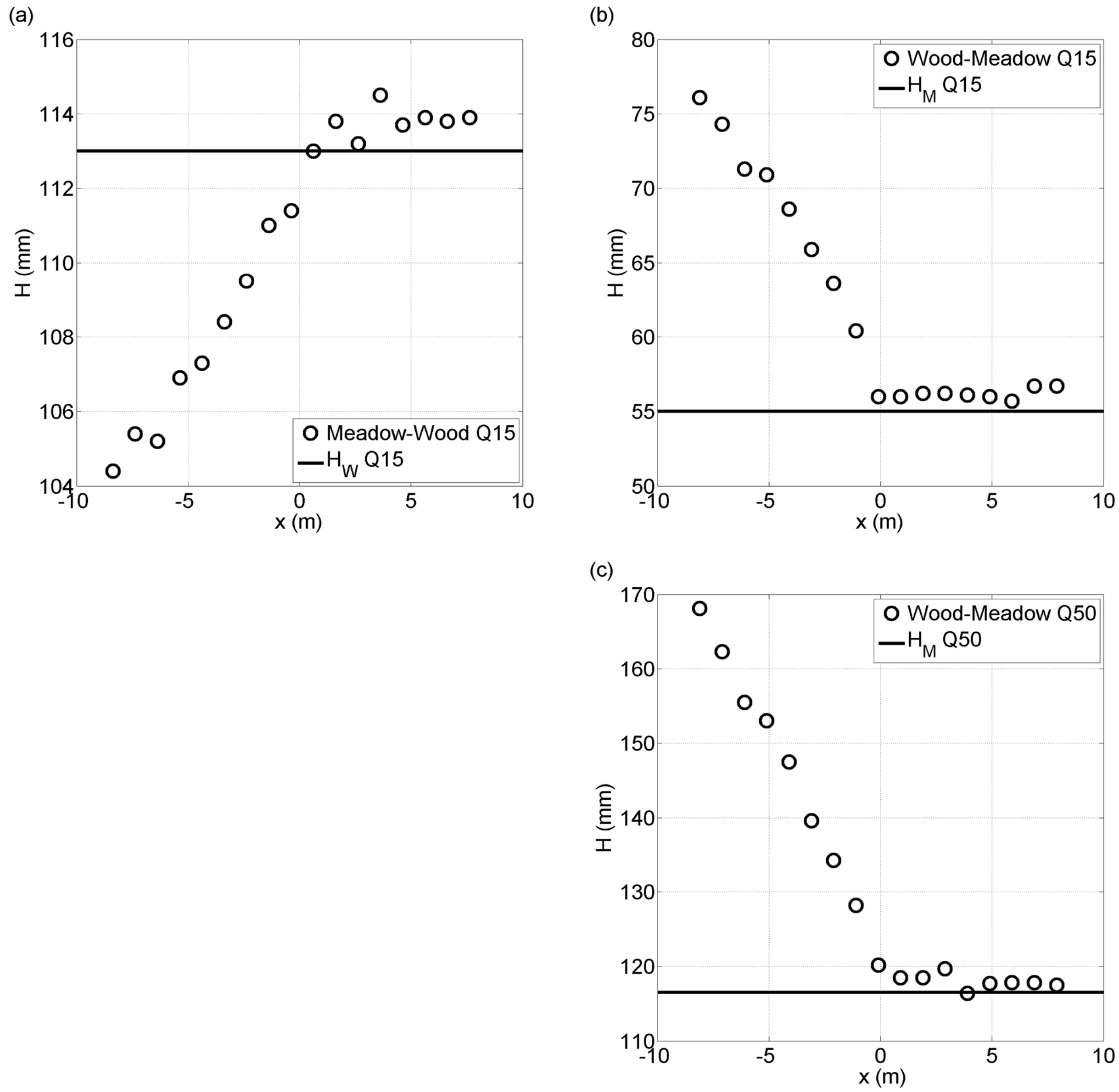

Figure 2: Water depth throughout the meadow-to-wood transition *Q* = 15 L.s^{-1} (a) and throughout the wood-to-meadow transition *Q* = 15 L.s^{-1} (b) and *Q* = 50 L.s^{-1} (c). The solid line is the uniform flow depth of the downstream roughness.

In the following we describe successively the longitudinal development of the vertical distributions of mean velocity and turbulent quantities throughout the two roughness transitions (meadow-to-wood and wood-to-meadow). For this latter, only the data for *Q* = 50 L.s^{-1} are shown.

3.1 Meadow-to-wood transition

The longitudinal development for Q = 15 L.s^{-1} of the vertical distribution of mean velocity, Reynolds stress and TKE are shown in Figure 3, Figure 4 and Figure 5, respectively. The uniform flow profiles for meadow or wood (markers ‘+’, blue) are also shown in each figure, as a reference. These reference profiles were measured under uniform flow conditions for discharge *Q* = 15 L.s^{-1} (wood) or *Q* = 50 L.s^{-1} (meadow). A preliminary study showed that the profiles are self-similar for both discharges.
The velocity is normalized by the bulk velocity $U_Q = Q/(BH)$, *B* being the channel width and *H* the water depth. The uniform profile over the meadow can be considered as the velocity profile infinitely upstream of the roughness step change. After normalization, the profiles upstream of the transition (Figure 3.a) fairly collapse. This self-similarity indicates that the velocity variations are inversely proportional to the water depth (*Q* and *B* being constant). Previous studies (Song and Graf 1994, Kironoto and Graf 1995) have shown that decelerating profiles are more spread out compared to the uniform one. Here the deceleration is too small to observe this deformation.

In contrast, downstream of the roughness step change (Figure 3.b), the velocity profiles are not self-similar. The shape of the profile progressively evolves. About four meters downstream from the roughness step change, the velocity profile has reached the uniform profile of the new roughness type (blue '+'), by mass and momentum transfers over the water column.

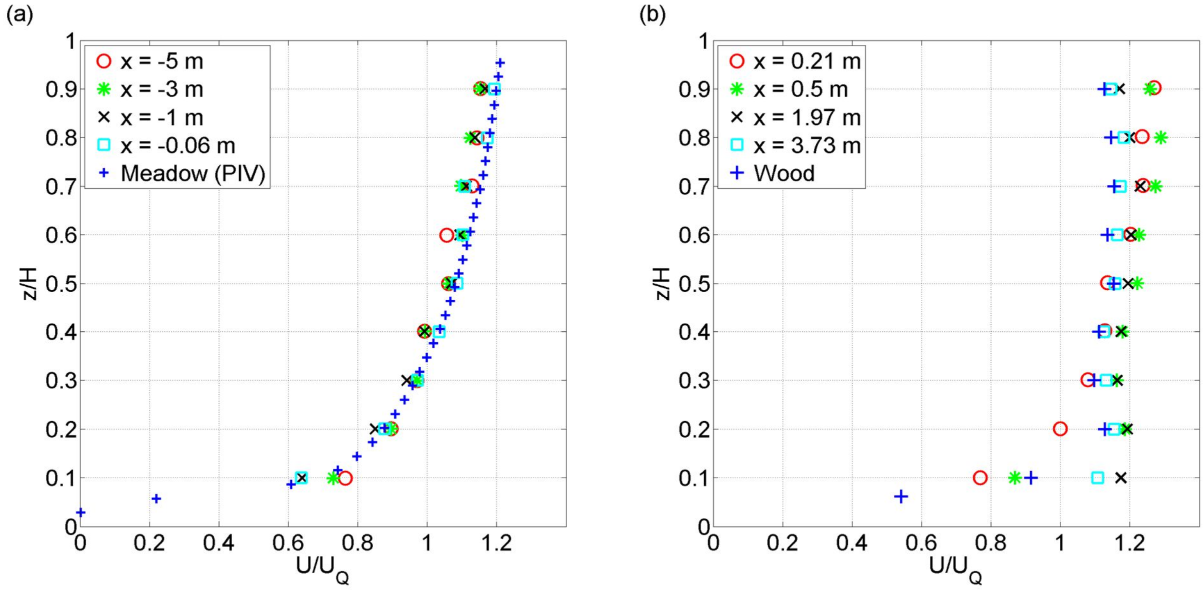

Figure 3: Vertical profiles of the streamwise mean velocity upstream (a) and downstream (b) from the meadow-to-wood transition.

The Reynolds stress and the TKE are normalized using the equivalent shear velocity $U^*_{eq} = (gHS_f)^{1/2}$ where S_f is the equivalent slope, determined using the Manning equation $S_f = n^2 U_Q^2 / H^{4/3}$, where n is the Manning coefficient corresponding to the meadow roughness. Upstream from the transition (Figure 4.a), the distribution of the Reynolds stress follows the linear law related to flow uniformity. Similarly to the velocity, the effect of the deceleration is not significant and does not result in a convex shape of the Reynolds stress profile (Yang and Lee 2007). In Figure 5.a, the TKE normalized profiles collapse together and with the uniform profile.
Downstream of the transition (Figure 4.b and Figure 5.b), a longitudinal distance of about 4 meters is required so that velocity, Reynolds stress and TKE reach the equilibrium. Perfect agreement between the last profile (x = 3.73 m) and the uniform profile is not reached but we can expect convergence around 4 meters.

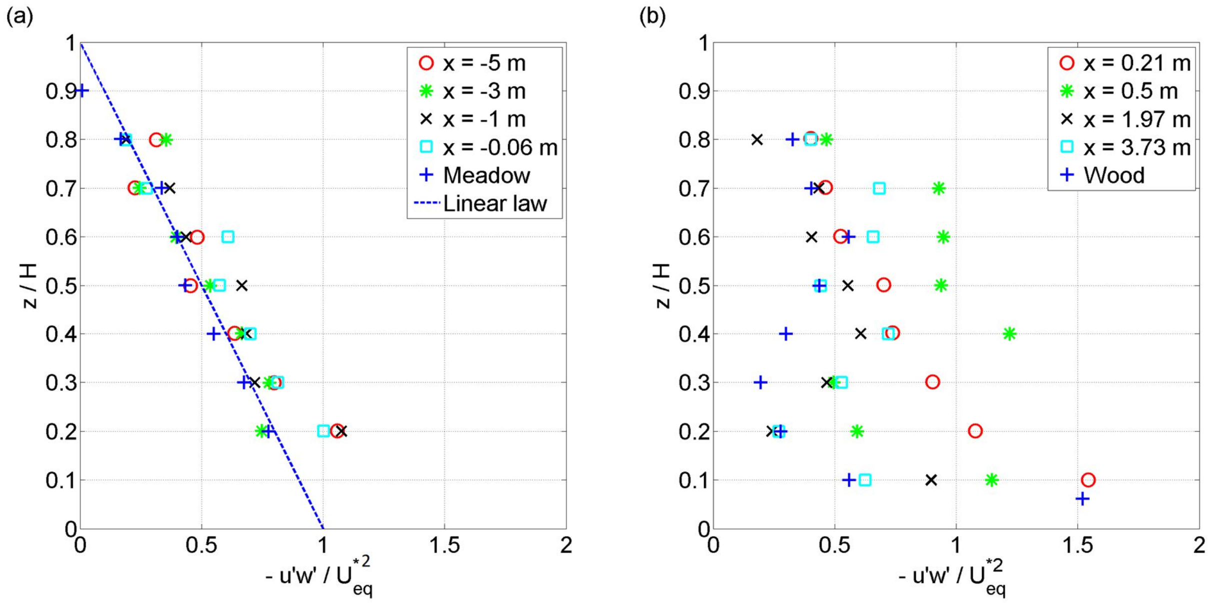

Figure 4: Vertical profiles of the Reynolds stress upstream (a) and downstream (b) from the meadow-to-wood transition.

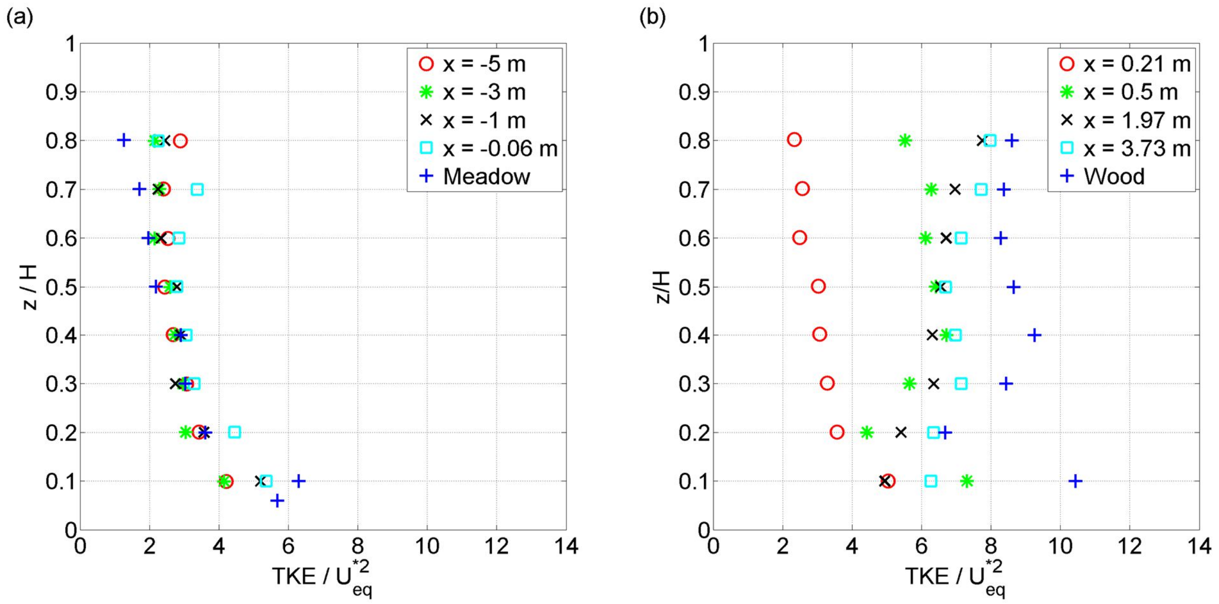

Figure 5: Vertical profiles of the turbulent kinetic energy upstream (a) and downstream (b) from the meadow-to-wood transition.

3.2 Wood-to-meadow transition

The longitudinal development of the vertical distribution of mean velocity, Reynolds stress and TKE for Q = 50 L.s^{-1} are shown in Figure 6, Figure 7 and Figure 8, respectively.

Similarly to the precedent transition, when the velocity is normalized by the bulk velocity U_Q, all velocity profiles upstream of the roughness change are superposed together and with the uniform flow profile over the upstream roughness (Figure 6.a). Downstream of the transition the velocity profile adapts to the new roughness type over a distance shorter than 5 m. For the discharge Q = 15 L.s^{-1} an adaptation length of 3 m was observed. An adaptation length of the same order of magnitude was observed for the meadow-to-wood transition.

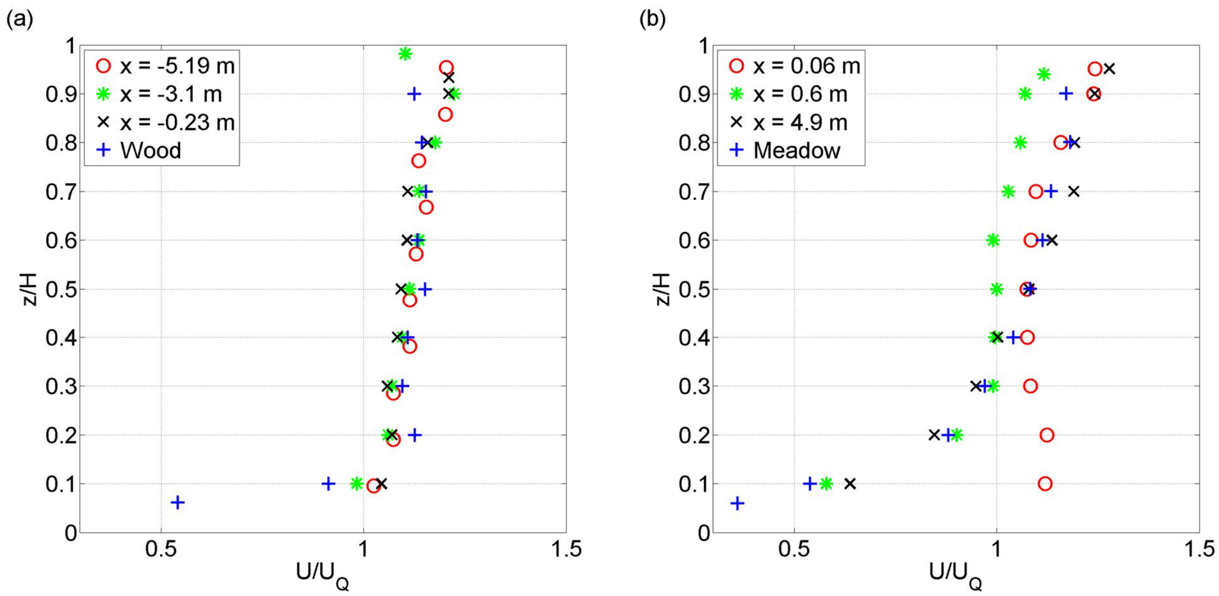

Figure 6: Vertical profiles of the streamwise mean velocity upstream (a) and downstream (b) from the wood-to-meadow transition.

The weak values of Reynolds stress upstream from the transition are quite dispersive (Figure 7.a), but non dimensional stresses are the same order of magnitude. For the station x = - 0.23 m, although being very close to the transition, the Reynolds stress profile follows quite perfectly the S-shape of the uniform profile, showing that the presence of the roughness transition has no effect on the upstream profiles. The normalization of the TKE by the shear velocity leads to self-similar profiles upstream of the roughness change (Figure 8.a) but the normalized uniform profile is quite higher.

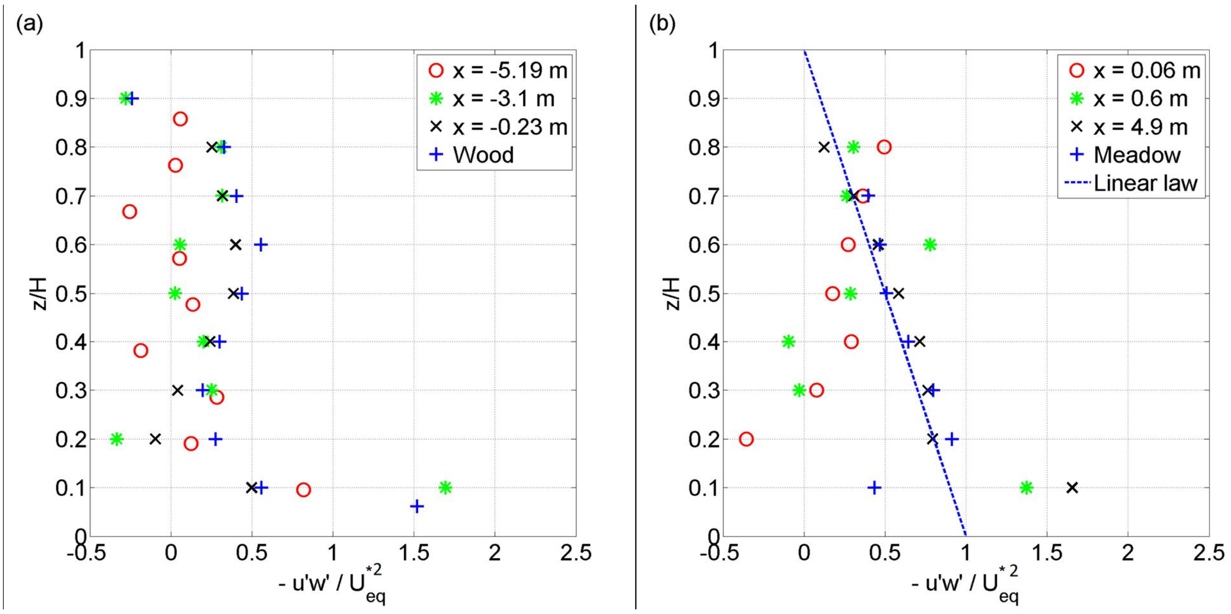

Figure 7: Vertical profiles of the Reynolds stresses downstream from the wood-to-meadow transition.

Five meters downstream from the roughness change (Figure 7.b and Figure 8.b), equilibrium is reached for mean velocity, Reynolds stresses and TKE (uniform profiles over the meadow).

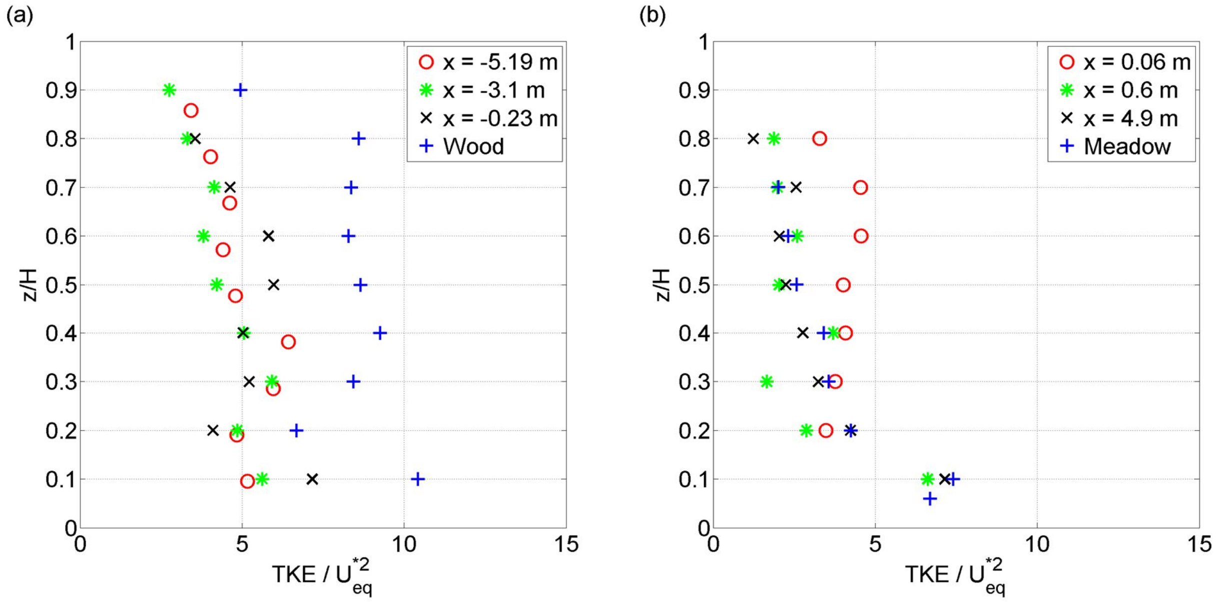

Figure 8: Vertical profiles of the turbulent kinetic energy upstream (a) and downstream (b) from the wood-to-meadow transition.

4. 1D MODEL

In this section, the ability of a simple 1D modelling to predict the variation in flow depth throughout the roughness transition is estimated. The modelling is based on the classical approaches accounting for bed-induced roughness and drag forces.

4.1 Equations

According to Nepf (1999), the volume force exerted by an array of stems can be expressed as :

$$F_s = -\frac{1}{2}\rho C_D a U^2, \tag{1}$$

where C_D is the drag coefficient related to each stem and a is the frontal surface per unit volume, with $a = ND$, where *N* is the stem density and *D* the stem diameter.

Including this volume drag force to the common 1D-Saint-Venant equation – see for example Kironoto and Graf (1995) – yields:

$$\frac{\partial H}{\partial x}\left(1 - \frac{Q^2}{gB^2H^3}\right) = S_0 - \frac{\tau_b}{\rho g H} - \frac{a C_D Q^2}{2gH^2B^2}. \tag{2}$$

In order to evaluate the bed friction τ_b we use the Manning coefficient *n*, constant in the present study as the flows are fully rough turbulent. Assuming that Manning's formula for gradually varied flows is still valid in the presence of rigid stems set on the meadow, the bed friction can be estimated as:

$$\tau_b = \frac{\rho g n^2 U_Q^2}{H^{1/3}}. \quad (3)$$

The combination of equation (2) and (3) gives:

$$\frac{\partial H}{\partial x}\left(1 - \frac{Q^2}{gB^2H^3}\right) = J - \frac{n^2Q^2}{H^{\frac{10}{3}}B^2} - \frac{aC_DQ^2}{2gH^2B^2}. \quad (4)$$

4.2 Results

Six flows were modelled using equation (4): three meadow-to-wood transitions, with discharges *Q* = 7, 15 and 21 $L.s^{-1}$ and three wood-to-meadow transitions, with discharges *Q* = 7, 15 and 50 $L.s^{-1}$. The water depth of each transition flow was previously experimentally measured in the flume (Figure 9). The initial condition for the computation was the water depth value at the most downstream measurement point. In the legend of Figure 9, 'M-W' stands for meadow-to-wood transition, 'W-M' stands for wood-to-meadow transition and the number after 'Q' indicates the discharge in $L.s^{-1}$. The model reproduces quite well the water depth measured (maximal relative error 5 %). The downstream boundary condition is not exactly the uniform water depth of the downstream roughness, so that for some cases, the modelling in the downstream reach is not a constant water depth profile.

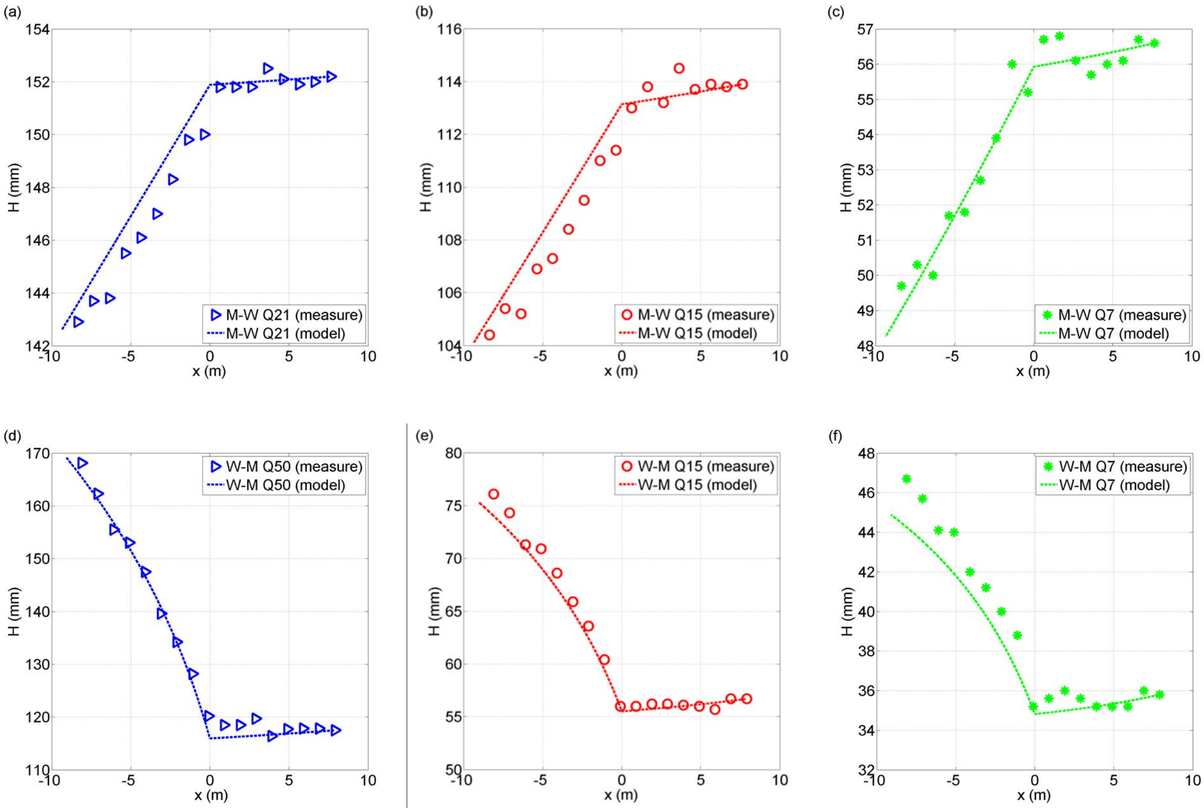

Figure 9: Water depth for transition meadow-to-wood (M-W) [(a): Q = 21 $L.s^{-1}$; (b): Q = 15 $L.s^{-1}$; (c): Q = 7 $L.s^{-1}$] and wood-to-meadow (W-M) [(d): Q = 50 $L.s^{-1}$; (e): Q = 15 $L.s^{-1}$; (f): Q = 7 $L.s^{-1}$].

As the uniform water depth of the upstream roughness is not reached at the upstream end of the channel, the model was used to extrapolate the water depth further upstream. The results are shown in Figure 10. In order to have the same reference of water depth downstream, the uniform water depth of the downstream roughness has been subtracted from the local water depth. We can observe that the water depth remains non-uniform over large distances. For a fixed discharge, the distance L_e to reach equilibrium is higher for the wood-to-meadow transition than for the meadow-to-wood transition.

The water depth profile upstream of the transition meadow-to-wood is a M1-type backwater curve (Graf 2000). Indeed, the downstream tangent at *x* = 0 m corresponds to the slope of the flume (S_0 = 1.05 mm/m). The water free-surface in this part of the flume is horizontal. The backwater curve of the wood-to-meadow transition is of M2-type.

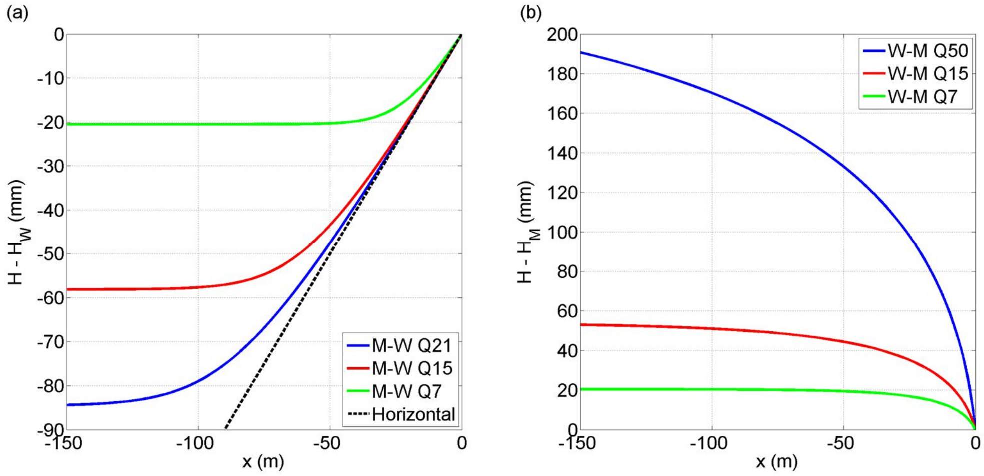

Figure 10: Water depth (modelled) upstream from a roughness transition meadow-to-wood (a) and wood-to-meadow (b).

In Figure 11, all six transitions are represented in the non-dimensional form

$$\xi = \frac{H - H_{up}}{H_{dw} - H_{up}}, \qquad (5)$$

where H_{up} is the upstream uniform water depth and H_{dw} is the downstream uniform water depth. This representation clearly shows that, for a fixed discharge (see Q = 7 and 15 L.s^{-1}) the initial water depth gradient is higher for the wood-to-meadow transition, but the distance to reach equilibrium is larger.

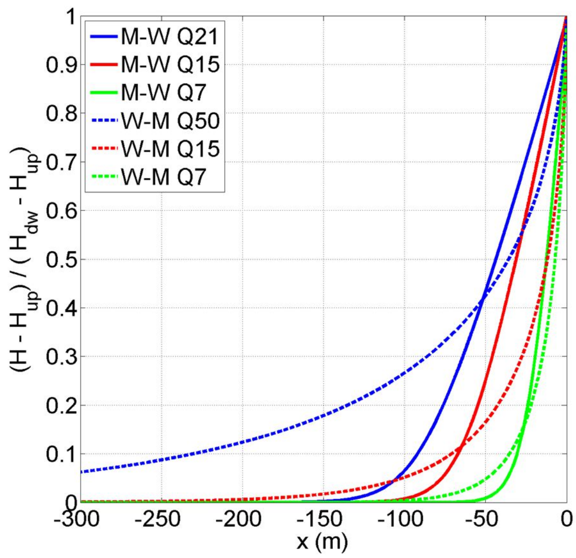

Figure 11: Dimensionless representation of calculated water depth throughout six roughness transitions.

The distances L_e to reach equilibrium of the six transitions are reported in Table 1. This distance is normalized by the absolute value of the difference between upstream and downstream uniform water depths, by the upstream uniform water depth and by the downstream uniform water depth, respectively. It appears that the distance L_e scales with the upstream water depth H_{up} with $L_C/H_{up} \approx 2000 - 2500$.

Table 1: Distance to reach equilibrium upstream from the roughness change for the six roughness transition.

	Q (L.s^{-1})	L_e (m)	L_e / (H_W-H_M)	L_e / H_{up}	L_e / H_{dw}
Meadow-to-Wood	21	170	2000	2537	1118
	15	120	2069	2182	1062
	7	70	3333	2059	1273
Wood-to-Meadow	50	840	3597	2400	7210
	15	300	5172	2655	5455
	7	130	6190	2364	3824

5. CONCLUSIONS

A longitudinal roughness transition from a bed-induced roughness (highly-submerged dense meadow) to emergent macro-roughness (rigid stems), or vice versa, was experimentally investigated. With both transitions (meadow-to-wood, and wood-to-meadow), the water depth varies upstream from the change in roughness, but is constant downstream. What is outstanding is that: (i) vertical profiles of mean velocity scaled by the bulk velocity, and vertical profiles of turbulent quantities scaled by the shear velocity are constant where the flow depth varies (upstream reach); (ii) the same vertical profiles are developing where flow depth is constant (downstream reach). As a result, the presence of the roughness change has no effect on the vertical distributions of mean flow and turbulence along the upstream reach, even immediately upstream from the roughness change.

Downstream from the roughness change, the transfers of mass and momentum over the water column occur on longitudinal distances ranging from 35 to 50 times the flow depth.

The water surface profile was simulated with a simple 1D model based on Manning's formula and on a volume drag force. Whatever the total flow rate, and for both transitions, simulations are in very good agreement with the measurements. In addition, the simulations show that, upstream from the change in roughness, a longitudinal distance of about 2000-2500 times the upstream uniform water depth is required to reach equilibrium.

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