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Floodplain flow resistance in case of a sparse mixture of plants at low relative submergences

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ABSTRACT: Vegetation affects flow hydrodynamics and transport processes across various spatial scales and is increasingly put forward as a powerful tool for nature-based solutions (NBS) in river management. Complex mixtures of different plant types at a wide range of densities are common on real floodplains, but such conditions are rarely properly reproduced in experimental investigations. This paper reports on the first results of an ongoing study, with a view on flow resistance associated with low relative submergences ($H/h_v = 1-2$) and low vegetation densities ($LAI = 0.12-0.58$). Such experimental investigations are challenging due to the necessity of a high-accuracy sensor system suited for the bulk scale. A mixture of artificial elements was selected to mimic the behaviour of natural floodplain shrubs and herbaceous vegetation in a laboratory flume. Results suggested that also at very low LAI values the vegetative resistance increased linearly with LAI. An increase of H/h_v from 1 to 2 caused a 25% to 50% reduction in the friction factor for very low to intermediate LAI, respectively. **Keywords:** floodplain vegetation, vegetative flow resistance, nature-based solutions.

1. INTRODUCTION

Riparian vegetation on river floodplains induces hydraulic resistance (Järvelä 2004, Jalonon and Järvelä 2014) and leads to increased water levels and possibly flooding. However, appropriate management of the vegetation as a nature-based solution (NBS) provides means to control the water levels and transport of substances (Rowinski *et al.* 2018). Vegetated floodplains commonly consist of a mixture of vegetation types including herbaceous vegetation with taller bushes and shrubs and woody trees e.g. (Richardson *et al.* 2007). Despite advances in hydraulic modelling (Shields *et al.* 2017, Dalledonne *et al.* 2019, Wang *et al.* 2019), it remains difficult to predict the flow resistance when vegetation is present as a mixture of different types and when its density and coverage vary both in time and space. Accurate predictions require both high spatial and temporal resolution input data and species-specific properties. Vegetation properties such as the stem flexibility or leaf-area to stem-area ratio may vary temporally due to seasonal differences and plant age (Västilä *et al.* 2013, Whittaker *et al.* 2015). For example, the growth of leaves or shedding of leaves is one of the largest contributors to the temporal changes. This can lead to significant structural changes and large differences in vegetation densities (Västilä and Järvelä 2018, Wang *et al.* 2019).

There are two common ways to approach the vegetative flow resistance problem, which are 1) the bulk resistance approach commonly used in practical engineering solutions, and 2) the force concept typically used in numerical or computational fluid dynamic models e.g. (Boothroyd 2015, Västilä and Järvelä 2018). The bulk resistance of a channel can be divided into two main components: 1) boundary resistance f' and 2) vegetative resistance f'' (Yen 2002). Boundary resistance

results from the roughness induced by the channel bed and geometry. Vegetative resistance consist of friction by the foliated woody plants (i.e. bushes, shrubs or trees) and the herbaceous vegetation (i.e. grassy type).

Challenges arise in the prediction of the hydraulic resistance when vegetation densities are very low (Shields *et al.* 2017, Dalledonne *et al.* 2019, Folke *et al.* 2019) and in conditions of low relative submergences where the vegetation is slightly submerged, i.e. its height (h_v) is close to the water depth (H). Despite the previous efforts made (Järvelä 2004, Jalonen *et al.* 2013) a lack of understanding remains in the hydrodynamic behaviour of a mixture of plants in response to variable discharges and water depths. The leaf area index LAI has been shown to be a well-suited measure to describe vegetation density e.g. (Jalonen *et al.* 2013). LAI can be obtained cost-effectively by remote sensing methods with high spatial and temporal resolution over a wide range of scales (i.e. reach to catchment). Nonetheless, this requires insights on the uncertainty of the LAI estimates, especially for the lower and higher-end LAI values.

To predict the vegetative flow resistance of a floodplain, the riparian vegetation is commonly simplified to a case with rigid cylinders e.g. (Boothroyd 2015). However, in reality the floodplain often consists of a combination of herbaceous vegetation and leafless or foliated woody plants. Despite the many previously developed approaches to predict the vegetative flow resistance only a few consider flexible vegetation (Järvelä 2004, Västilä and Järvelä 2014, Whittaker *et al.* 2015). The Darcy-Weisbach friction factor f for a channel with a mixture of submerged foliated vegetation can be determined as (Järvelä 2004, Jalonen *et al.* 2013):

$$f = f' + f'' = f' + 4 C_{D\chi} \text{LAI} (U_m/U_\chi)^\chi \quad (1)$$

where f' is the friction by the channel boundary, $C_{D\chi}$ the species-specific drag coefficient, U_m the mean cross-sectional streamwise velocity, U_χ the reference velocity (usually 0.1 m/s), χ the reconfiguration parameter, and LAI the leaf area index. LAI is defined as the one-sided leaf area per unit bed area ($\text{LAI} = A_L/A_B$) where A_L is the one-sided leaf area and A_B the bed area. Figure 1 illustrates a vegetated setting of a mixture of foliated woody plants and herbaceous vegetation and its parameterisation.

Figure 1. Vegetative resistance components and parameterisation of the foliated woody and herbaceous vegetation in this study. f'' consists of friction by the herbaceous vegetation f_h and the foliated woody plants f_w . The one-sided stem area per unit volume is defined as $a_s = A_s/(A_B h_v)$ and the one-sided leaf area per unit volume defined as $a_L = A_L/(A_B h_v)$ where A_s is the total one-sided stem area, A_L the total one-sided leaf area, A_B the bed area, and h_v the vegetation height. The one-sided area per unit volume of the herbaceous vegetation a_H is estimated from the blade density m ($\#/\text{m}^2$), height h_h and average blade width w_b .

With this study, we aim to improve understanding on the response of the vegetated resistance of a mixture of natural-like flexible vegetation for very low to intermediate LAI (0.12-0.58) over a wide range of bulk flow velocities ($U_m = 0.05$ -1.2 m/s). The specific objectives are to:

- I) Quantify the vegetated flow resistance for very low to intermediate LAI at the bulk scale, made possible by a new high-accuracy sensor system.
- II) Investigate the effect of low relative submergences ($H/h_v \leq 1$ -2) on the bulk flow resistance in terms of the friction factor.

2. METHODS

2.1. Experimental runs and hydraulic conditions

The experiments were conducted at the Aalto Environmental Hydraulics Lab (EHL) using the 20 m long Environmental Hydraulics Flow Channel. The glass-walled working section of the flume is 16 m long, 0.6 m wide and 0.8 deep. In total 52 experiments were conducted to determine the Darcy-Weisbach friction factors f . Forty experiments were conducted with two different vegetation densities, two relative submergences for ten increments of bulk flow velocities (see Table 1). Six experiments were conducted with solely the herbaceous vegetation and six for the empty channel. All experiment were conducted with a horizontal bed slope. The two recirculation modes of the flume allowed for discharges up to 300 l/s. The discharge was measured by an electromagnetic flow-meter (accuracy 0.5%). The tapping at the bed and the false floor located at the middle of the flume allowed for sensor connections through the bottom of the channel, such as pressure sensors or force sensors. The water levels were measured by a set of ten pressure transducers (BD Sensors DMP 331, accuracy of 1 mm, as the primary device; complemented by Huba Control S436, accuracy ± 3 mm). All data were stored at 20 Hz.

Table 1. Experimental conditions: number of runs (#), one-sided stem area per unit volume a_S (m^{-1}), one-sided leaf area per unit volume a_L (m^{-1}), leaf area index LAI, longitudinal and lateral stem spacing S_x and S_y (m), plant density m ($\#/\text{m}^2$), water depth H (m), and relative submergence H/h_v (-).

Experi- ment	# runs	a_S (m^{-1})	a_L (m^{-1})	LAI (-)	S_x (m)	S_y (m)	m ($\#/\text{m}^2$)	H (m)	H/h_v (-)
A1	10	0.01	0.61	0.12	0.5	0.6	3.3	0.19	1.0
A2	10	0.01	0.61	0.12	0.5	0.6	3.3	0.38	2.0
B1	10	0.06	3.07	0.58	0.3	0.2	16.7	0.19	1.0
B2	10	0.06	3.07	0.58	0.3	0.2	16.7	0.38	2.0

2.2. Vegetation properties

Artificial plants consisting of grasses and flexible foliated woody plants were selected to represent similar flexibility and reconfiguration behaviour as natural floodplain plants, as confirmed in prior investigations by (Box *et al.* 2019, Caroppi *et al.* 2019). Five different types of flexible woody plants were fabricated (S3, S4, T3, T4, T7, see Table 2 for details). All plant types were used in the drag force experiments, while the T7 plant was used in the bulk flow resistance experiments.

Table 2. Plant characteristics: type, height h_p (m), one-sided stem area A_S (cm^2), one-sided leaf area A_L (cm^2), number of leaf clusters (#), and leaf-area to stem-area ratio A_L/A_S (-).

Plant type	h_p (m)	A_S (cm^2)	A_L (cm^2)	# of leaf clusters (-)	A_L/A_S (-)
S3	0.15	5.3	150	3	28
S4	0.15	5.3	200	4	38
T3	0.19	7.3	150	3	21
T4	0.19	7.3	200	4	27
T7	0.19	7.3	350	7	48

2.2.1. Mixture of plants

The mixture of vegetation consisted of herbaceous vegetation and flexible foliated woody plants with low LAI. Identical woody plants (T7, see Table 2) with a height h_p of ~ 0.19 m were installed on the flume bed in a rectangular pattern. Each plant contained seven leaf clusters with a one-sided leaf area of 50 cm^2 . The total one-sided leaf area of a plant A_L was 350 cm^2 and the one-sided stem area A_S was $\sim 7.3 \text{ cm}^2$. The one-sided stem a_S and leaf areas a_L per unit volume are shown in Table 1. The leaf area to stem area ratio A_L/A_S was ~ 48 and is assumed to be comparable

to those of natural riparian species (Västilä *et al.* 2013, Västilä and Järvelä 2014). The herbaceous vegetation was on average 20 mm tall and consisted of ~0.4 mm wide flexible blades having a uniform density of ~65 blades/cm². The estimated one-sided area per unit volume of the herbaceous vegetation a_H was approximately 5.2 cm⁻¹.

2.3. Flow resistance measurements

The experiments were conducted under gradually varied flow conditions. The water level differences ΔH ($\Delta H = H_{Up} - H_{Down}$) between upstream (H_{Up}) and downstream (H_{Down}) locations (Fig. 2) over the vegetation were measured by differential pressure sensors (0.1% accuracy). The water surface profile was monitored by the ten pressure sensors with scaled signals spaced every 0.5 m along the length of the vegetated area.

Figure 2. Long view showing the two sections used to measure the friction loss H_f ($H_f = \Delta H + U_{m,Up}^2/2g - U_{m,Down}^2/2g$) between the upstream and downstream measurement location, and the placement of the ten pressure sensors ($P_1, \dots, P_{10}$). Note that the drawn plants are not to scale.

As the determination of the friction factor is very sensitive to the correctness of the water surface (energy) slope used, the measured surface profiles were evaluated statistically to guarantee that the assumption on violated. The Nash-Sutcliffe efficiency (NSE) (Nash and gradually varied flow along the test reach was not Sutcliffe 1970) was used to evaluate how much variability there was between the actual water surface levels and the ideal P3-P8 linearity assumed in computing the bulk flow resistance under non-uniform flow conditions. The NSE was calculated between the fitted points based on the water level measurement and slope obtained from the upstream (P_3) and downstream (P_8) location and the remaining measured pressure levels ($P_1, P_2, P_4-P_7, P_9, P_{10}$). The NSE was calculated as:

$$NSE = 1 - \sum (H_{P3P8fit,i} - H_{P1-P10,i})^2 / \sum (H_{P1-P10,i} - H_{P1-P10,mean})^2 \quad (2)$$

where $H_{P3P8fit}$ is the ideal linear fit of the water level, H_{P1-P10} the measured water levels, i corresponding number $P_{1,\dots,10}$ of the ten pressure sensors with n noting the total number of sensors over the profile.

2.3.1. Gradually varied flow conditions

The friction losses H_f were computed from the measured water levels following the Bernoulli's equation (cf. Fig. 2):

$$z_{Up} + H_{Up} + \frac{\alpha U_{m,Up}^2}{2g} = z_{Down} + H_{Down} + \frac{\alpha U_{m,Down}^2}{2g} + H_f \quad (3)$$

where z is the flume bed elevation, H_{Up} and H_{Down} are the water levels obtained from the scaled pressure measurements for the upstream (P_3) and downstream (P_8) locations, respectively, and α is the velocity distribution coefficient. The total friction factor f of the mixture of vegetation including the boundary resistance was calculated as:

$$f = 8gH/U_m^2 \cdot H_f/dx \quad (4)$$

where g is the gravitational acceleration, H the average water depth, U_m the cross-sectional average velocity and the longitudinal distance between the two measurement locations, H_{Up} and H_{Down} , respectively (Fig. 2). The friction factor for the herbaceous vegetation was computed as $f_h = f - f_w - f'$ where f_w is the friction by the foliated woody plants and f' the boundary friction. The empty flume channel friction factor f' ranged between 0.017-0.023 and was on average 0.02. Throughout all the runs f' was on average about 5% of the total friction, and thus the effect by the walls was assumed to be of minor importance compared to the bulk friction factor.

2.4. Drag force measurements

The forces F (N) acting on a single plant were measured by an in-house built setup of a 5 N force sensor (accuracy 0.025% full scale) located at the false floor of the flume. This setup (shown in Fig. 3) allowed for measurements of the drag forces F (N) acting on the different type of plants placed in an empty flume. Potentially the drag forces on single plants placed within a patch of vegetation can be measured using the same setup.

Figure 3. Flume setup with a 5 N load cell used to measure the drag forces F (N) on a single plant.

3. RESULTS AND DISCUSSION

3.1. Bulk vegetative flow resistance

The bulk friction factors f for the mixture of vegetation are shown in Figure 4. f decreased exponentially with increasing bulk flow velocities up about $U_m = 0.6$ m/s (Fig. 4a). The measurements collected at the lowest and higher bulk flow velocities ($0.1 \leq U_m \leq 0.8$ m/s) were prone to higher levels of uncertainty due to sensor accuracy and presence of surface waves, respectively.

An increase of five times the LAI from 0.12 to 0.58 caused the friction factor to increase about 4 to 5 times. This linearity of f with LAI for very low LAI agrees with previous observations made for higher LAI values e.g. (Jalonen *et al.* 2013) and extends the relationship also to low velocities (see also Västilä and Järvelä 2014). While the difference in f/LAI for the same H/h_v suggest that the flow resistance caused by the herbaceous vegetation complicates this relationship, especially for just submerged conditions or in conditions of very low LAI (Fig. 4b).

Figure 4. Vegetative flow resistance friction factor f (-) (a), and the friction factor f/LAI (-) scaled with LAI as function of the mean bulk flow velocity U_m (m/s) for very low and intermediate LAI (b).

3.2. Effect of relative submergence on the friction factor

Data collected in the present study allows for comparisons between low submergence ($H/h_v = 2$) and just submerged flow conditions at two vegetation densities (Fig. 5). f decreased for increasing relative submergence (H/h_v) of the vegetation mixture. In case of very low LAI, f was almost halved when the relative submergence H/h_v was doubled from 1 to 2 (Fig. 5a). For the intermediate LAI, the effect of relative submergence was less pronounced (Fig. 5b). The friction factor decreased by 25% when the H/h_v was doubled, except at the lowest velocities ($U_m \sim < 0.3$ m/s) (Fig. 5b).

Figure 5. The friction factor f with increasing bulk flow velocity U_m for just submerged ($H/h_v = 1$) vegetation and low relative submergence ($H/h_v = 2$) with very low LAI (a) and intermediate LAI (b). The ratio of friction factors corresponding to the low submergence ($H/h_v = 2$) against the just submerged condition is shown on the right axis.

3.3. Drag exerted by the single plants

Figure 6 shows the drag force F (N) scaled with the one-sided leaf area A_L for the four tested plants (see Table 2) as a function of the mean bulk flow velocity ($U_m = 0.1 - 0.4$ m/s). The increase of F with U_m is notably stronger for the short plants compared to the taller plants. This can be explained by the more profound reconfiguration of the tall plants (T3, T4) compared to the short plants (S3, S4).

Figure 6. Drag forces of single foliated woody plants scaled with the one-sided leaf area F/A_L (N/m²) (Table 2) as function of the mean bulk flow velocity for four different plants of height h_p .

The drag exerted by individual plants placed within a mixture of vegetation (i.e. herbaceous and foliated woody plants) is expected to differ as a result of changes in the vertical plant structure and more complex velocity distributions and turbulence effects (Siniscalchi and Nikora 2012). The current lack of data on F for the higher velocities ($U_m > 0.4$ m/s) and for plants with larger one-sided leaf areas ($A_L > 200$ cm²) limits estimates on the plant characteristic drag coefficients $C_{D\chi}$ and reconfiguration parameter χ . Future experiment are under way for amending and comparing to prior datasets (Västilä and Järvelä 2018, Niewerth *et al.* 2019).

3.4. Contribution of the herbaceous and woody plants on the bulk resistance

The friction factor of the herbaceous vegetation f_h ranged between 0.062 and 0.334 (Table 3). f_h was 1.5 to 2.4 times higher for the just-submerged conditions against the $H/h_v = 2$. The effect of the submergence H/h_v on f_h was at its highest for the low bulk flow velocities ($U_m = 0.1-0.4$ m/s) and decreases for increasing U_m .

Table 3. Vegetative flow resistance of the herbaceous vegetation: flow depth H , bulk flow velocity U_m (m/s), friction head loss H_f (mm), friction factor f_h (-), and Manning's n (s/m^{1/3}).

Experiment	H (m)	U_m (m/s)	H_f (mm)	f_h (-)	n (s/m ^{1/3})
G1_1	0.19	0.1	0.3	0.149	0.047
G1_2	0.19	0.4	6.1	0.192	0.051
G1_3	0.19	1.0	48.2	0.334	0.057
G1_4	0.38	0.1	0.1	0.062	0.033
G1_5	0.38	0.4	2.6	0.118	0.045
G1_6	0.38	1.0	31	0.218	0.051

The computed friction factors (f, f_h, f_w) and the relative share of the friction caused by the herbaceous vegetation f_h/f (%) are shown in Table 4. A decrease in the LAI of the foliated woody plants from 0.58 to 0.12 caused the relative share of f_h to increase with 42%. In all conditions the increase in bulk flow velocity caused the relative share of the friction of the herbaceous vegetation to increase (Table 4) and can be explained by the stronger reconfiguration of the foliated woody plants compared to the herbaceous vegetation.

The relative submergence did not notably affect the f_h/f ratio. However, f_h/f is expected to increase more profoundly with decreasing H/h_v in case of emergent vegetation, while its contribution is expected to remain unchanged for deeply submerged vegetation.

Table 4. Friction factors: leaf area index LAI (-), relative submergence H/h_v (-), mean bulk flow velocity U_m (m/s), bulk friction factor f (-), friction factor of the herbaceous vegetation f_h (-), friction factor of the woody plants f_w (-), and the relative contribution of friction caused by the herbaceous vegetation on the bulk friction f_h/f (%).

Experiment	LAI	H/h_v (m)	U_m (m/s)	f (-)	f_h (-)	f_w (-)	f_h/f (%)
A1_2	0.12	1	0.1	0.67	0.15	0.52	22
A1_5	0.12	1	0.4	0.30	0.19	0.11	63
A1_8	0.12	1	1.0	-	-	-	-
B1_2	0.58	1	0.1	3.28	0.15	3.13	5
B1_5	0.58	1	0.4	0.89	0.19	0.7	21
B1_8	0.58	1	1.0	0.64	0.33	0.31	52

4. CONCLUSIONS

In this paper, the first results of 52 test runs were presented on the vegetative flow resistance of an artificial constructed vegetated channel with a mixture of natural-like vegetation of low vegetation densities. The experimental setup in combination with the use of high-accuracy pressure sensors allowed for deriving the vegetative flow resistance and corresponding friction factors with high accuracy and good reliability. In addition to existing literature, the results showed that also at the very low vegetation densities an increase of 5 times in the LAI caused the vegetative resistance to increase about 4 to 5 times. An increase of relative submergence H/h_v from 1 to 2 caused a 25 to 50% reduction in the friction factor for very low to intermediate LAI, respectively. The relative share of the friction caused by the herbaceous vegetation was 5% and 63% for intermediate and very low LAI, respectively. Experimentation is under way to amend the present dataset, including a broader range of relative submergences and high LAI values.

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