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Determination of flow resistance of vegetated channel banks and floodplains

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ABSTRACT: Flow resistance due to vegetation may greatly affect the conveyance of a channel, and thus evaluating the resistance is a critical task in river engineering and restoration. Therefore, flow resistance of natural willows and sedges was studied in a laboratory flume. The aim was to investigate, how type, density and combination of vegetation, flow depth and velocity influence vegetal drag or friction losses. Friction factors, f, and vegetal drag coefficients, C'_d, were determined for a selection of 170 test runs. The results showed large variations with depth of flow, velocity, Reynolds number and vegetal characteristics. E.g. the vegetal drag coefficient for the leafy willows was three to seven times that of the leafless willows. The experimental drag coefficients for the leafless willows were compared to the values predicted by four methods, which were developed based on theory and experiments on rigid cylinders.

1 INTRODUCTION

Ecological and aesthetic values are of great importance in modern river management, and herein natural riverbank and floodplain vegetation has a major role to play. Recently, river restoration has become a common practise in several countries (e.g. Brookes & Shields 1996). In addition, 'softer' alternatives to earlier engineering solutions such as bioengineering are increasingly favoured. Thus, assessing the flow resistance caused by vegetation is a critical task in this development.

For large part research on vegetal resistance has focused on rigid and cylindrical roughness or grass linings in irrigation and flood channels. Less is known about the effects of plant shape and flexibility and alternating flow depth. The aim of this paper is to study flow resistance of partially and fully submerged natural vegetation. For this purpose living willows and sedges were investigated in a flume. In the first phase emphasis is put on analysing flow through the leafless willows. In the second phase the effect of leaves will be assessed.

The experimental results of the friction factor and the vegetal drag coefficient show large variations with the Reynolds number, depth of flow, flow velocity, and vegetal characteristics. Experimental data are used to test the applicability of four methods, which were developed based on experiments and theory on cylindrical elements, to estimate the drag coefficient and friction factor for leafless willows.

2 LITERATURE REVIEW

Li & Shen (1973) studied effects of tall non-submerged vegetation on flow resistance by investigating the wake caused by various cylinder set-ups. Experimental results indicated that different patterns or groupings of cylinders significantly affected flow rates. Petryk and Bosmajian (1975) presented a model to estimate Manning's n as a function of hydraulic radius and vegetation density for unsubmerged rigid vegetation. For non-submerged vegetation Lindner (1982) extended the work of Li & Shen (1973) resulting in a method to compute the drag coefficient, C_d, for a single plant in a group, and further the friction factor for the vegetation, f_p. The method to quantify f_p utilised, in addition to C_d, readily measurable physical properties: longitudinal and lateral distances between the plants, and the plant diameter. A further development was to determine C_d through an iterative process including empirical relationships from experiments on rigid cylinders (Pasche 1984, Pasche & Rouvé 1985). Mertens (1989) and Nuding (1991) simplified Lindner's approach assuming that a constant C_d value of 1.5 is valid for most practical cases. However, to relate the projected plant area more closely with the actual dimensions of the plant, Nuding (1991) suggested a simple method to account for the branches separately from the main stem. All these methods basically treat plants as cylinders.

Kouwen & Unny (1973) developed a method to estimate the roughness for flow over submerged and flexible grass, which was simulated using plastic strips. They concluded that the friction factor was a function of the relative roughness for the erect and waving regimes, and appeared to be a function of the Reynolds number for the prone roughness. Kouwen & Fathi-Moghadam (2000) used coniferous tree saplings in flume experiments and large coniferous trees in air experiments to demonstrate that the friction factor varied greatly with the mean flow velocity due to bending of the vegetation and with flow depth caused by an increase in the submerged momentum absorbing area. The results indicated good correlation of the friction factor with the flow velocity. In like manner, Oplatka's (1998) experiments on flow resistance of tall flexible willows in a towing tank showed that with increasing flow velocity the projected plant area perpendicular to flow rapidly decreased. For example, at the velocity of 1 m/s, the projected area was only about 1/4 of the initial value with no flow.

Wu et al. (1999) conducted experiments on simulated vegetation under uniform flow conditions and proposed a simplified model to estimate the vegetal drag coefficient, C'_d, for submerged and non-submerged vegetation. The regression analysis indicated that the important factors were the Reynolds number, slope, and height of vegetation. The exponent of the Reynolds number was defined as the vegetative characteristic number. Under the same Reynolds number, C'_d was greater for the steeper slope. Further, it was shown that Manning's n for the unsubmerged vegetation was independent of the slope.

Freeman et al. (2000) reported a methodology to determine flow resistance coefficients in cases of submerged and partially submerged shrubs and woody vegetation. Extensive flume experiments were conducted for 20 natural plant species with both homogenous and mixed plant spacings. Plants were studied with and without leaves, but a density measure such as leaf area index (LAI) was not recorded. Separate empirical regression equations were developed for the submerged and partially submerged cases with two formulations of the resistance coefficient: Manning's n, and the ratio of shear velocity to mean velocity v^*/v, where by definition $v^* = (gRS)^{1/2}$. According to Equation 1, v^*/v is actually the square root of $f/8$. The critical parameter in the regression equations is the plant stiffness modulus, which can be estimated from the ratio of the undeflected plant height to the plant diameter, though field measurements are recommended.

3 THEORETICAL CONSIDERATIONS

3.1 *Friction factor of vegetation*

The advantage of using the Darcy-Weisbach friction factor lies in its sound theoretical basis. As opposed to Manning's n or Chezy's C the friction factor is a dimensionless parameter. However, the Manning's formula is widely used in engineering practise. For open-channel flow the friction factor is defined in hydraulics textbooks as

$$f = 8gRS / v^2 \tag{1}$$

where g = gravitational acceleration; R = hydraulic radius; S = energy slope; and v = average velocity over the cross-section.

Several researchers have used the additive property of the friction factor to determine the total friction factor for vegetated channel parts as a sum of the channel boundary friction factor, f_b, and vegetal friction factor, f_p. In densely vegetated channels f_b is usually small and may be omitted. The challenge is the determination of the parameter f_p. One approach is to use equations such as (Lindner 1982)

$$f_p = \frac{4d_p h}{a_x a_y} C_d \tag{2}$$

where h = flow depth; d_p = diameter of the plant; a_x longitudinal distance between the plants; a_y = lateral distance between the plants; and C_d = drag coefficient. This type of formulation was originally developed for rigid cylinders simulating tall trees, but the use has been extended for other types of vegetation. However, for natural plants the determination of the projected area and the drag coefficient is difficult as these two parameters are coupled. With increasing flow velocity plants will bend and streamline, which will decrease the projected area and alter the drag coefficient. The vegetal drag is discussed in the next section.

3.2 *Vegetal drag coefficient*

In fluid mechanics the drag force, which acts on a surface area A_p measured perpendicular to the direction of the flow, may be defined as

$$F_d = \frac{1}{2} \rho C_d A_p v^2 \tag{3}$$

where ρ = density of the fluid; C_d = drag coefficient; A_p = projected area; and v = average velocity. The drag coefficient sums up pressure and friction drag. The pressure or form drag is caused by the difference between the high pressure upstream and low pressure downstream of an element. The friction or surface drag is caused by the shear stress acting over the surface of an element. According to standard fluid mechanics texts the ratio of form drag to surface drag depends on the shape of the element and the flow condition. In fully turbulent flow with a thin boundary layer, the pressure drag will drop substantially compared to laminar flow, caused by flow separation. Furthermore, streamlining will sharply reduce the pressure drag.

To estimate the drag force on the unsubmerged willows in this study, the force balance for uniform flow is extended for gradually varied flow by applying the momentum principle. The gravitational force is defined as $F_g = \rho g(AL)S$, where S = energy slope; A = average cross-sectional area; and L = length of the channel reach. Assuming that the drag force exerted on the boundaries of a densely vegetated channel is not significant compared to the drag force on vegetal elements, implies that $F_d = F_g$. Defining a vegetal area coefficient, $\lambda = A_p/(AL)$, and a vegetal drag coefficient, $C'_d = \lambda C_d$, and solving for C'_d yields (cf. Kadlec 1990, Wu et al. 1999)

$$C'_d = \frac{2gS}{v^2} \tag{4}$$

C'_d is a bulk drag coefficient, which is a lumped parameter based on the total frontal area of vegetation in the channel reach L, i.e. projected plant area per unit volume. The disadvantage of this formulation is that the vegetal drag coefficient has a unit of 1/m. This drawback is because of the difficulties in defining the projected area for natural vegetation. It should be noted that there are other alternatives to define the reference area (e.g. wetted area, plan area), which can significantly influence the computed drag coefficient.

Combining Equation 4 with Darcy-Weisbach equation (1) gives

$$C'_d = f/4R \tag{5}$$

4 LABORATORY INVESTIGATIONS

4.1 *Experiments*

Experiments were conducted in a 50 m long, 1.1 m wide and 1.3 m deep glass-walled flume, which has a fixed horizontal bed. The six-meter long test area was located in the midway of the flume. At the downstream end of the flume there was an over-flow weir to adjust the desired flow depth. Water stage and head loss along the test section was measured utilising pressure transducers. Measurements were averaged over a 60 s period.

A set of six discharges (Q = 40, 70, 100, 143, 201, 292 l/s) and seven flow depths at the approach to the test area, herein called the entrance flow depth (h_0 = 25, 30, 40, 50, 60, 70, 80 cm), was established for the study. For each test series 18 to 23 h_0-Q combinations were investigated. The experiments were started with slender tufted-sedges. Thereafter, willows were installed in the flume without roots in

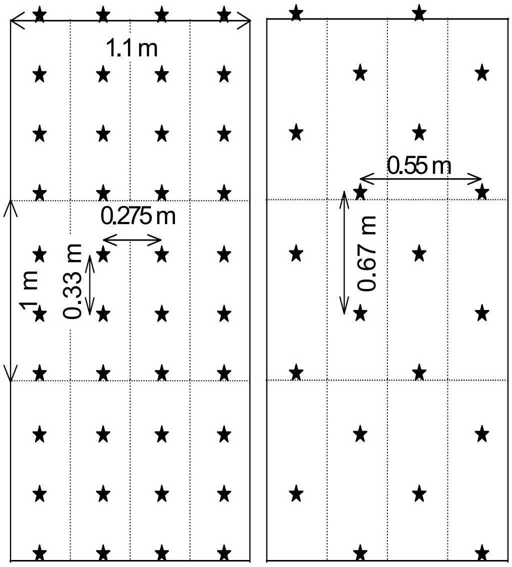

Figure 1. Spacing of the willows in the pattern Pa (left) and Pf (right). Only half of the 6 m long test reach is shown (not to scale).

two different patterns (Fig. 1) with the sedges. The willows were investigated first with leaves and in the next phase without leaves. In the last phase the sedges were removed, and the leafless willows on bare bottom soil were investigated.

The willows averaged 70 cm in length and 8.6 mm in diameter at 10 cm height from the bottom. Based on small sampling the leaf area of the willows per square meter of the bottom was estimated to be 3.2 m^2. The sedges were planted in small pots in a staggered pattern averaging 512 stems/m^2. In each plant pot there were several stems of 3 mm in average diameter. Maximum stem length was kept at 35 cm by cutting. The experiments are described in detail in Järvelä (in press).

4.2 *Data processing*

In all the experiments the flow was gradually varied. Friction losses, H_f, were computed from the flume data using Bernoulli's equation

$$\alpha \frac{v_1^2}{2g} + h_1 = \alpha \frac{v_2^2}{2g} + h_2 + H_f \tag{6}$$

where α = velocity distribution coefficient, and subscripts 1 and 2 refer to upstream and downstream sections, respectively. Further, by means of Equation 1 with $S = H_f/L$, friction factors were computed for each test run. A constant f_b value of 0.055 for the

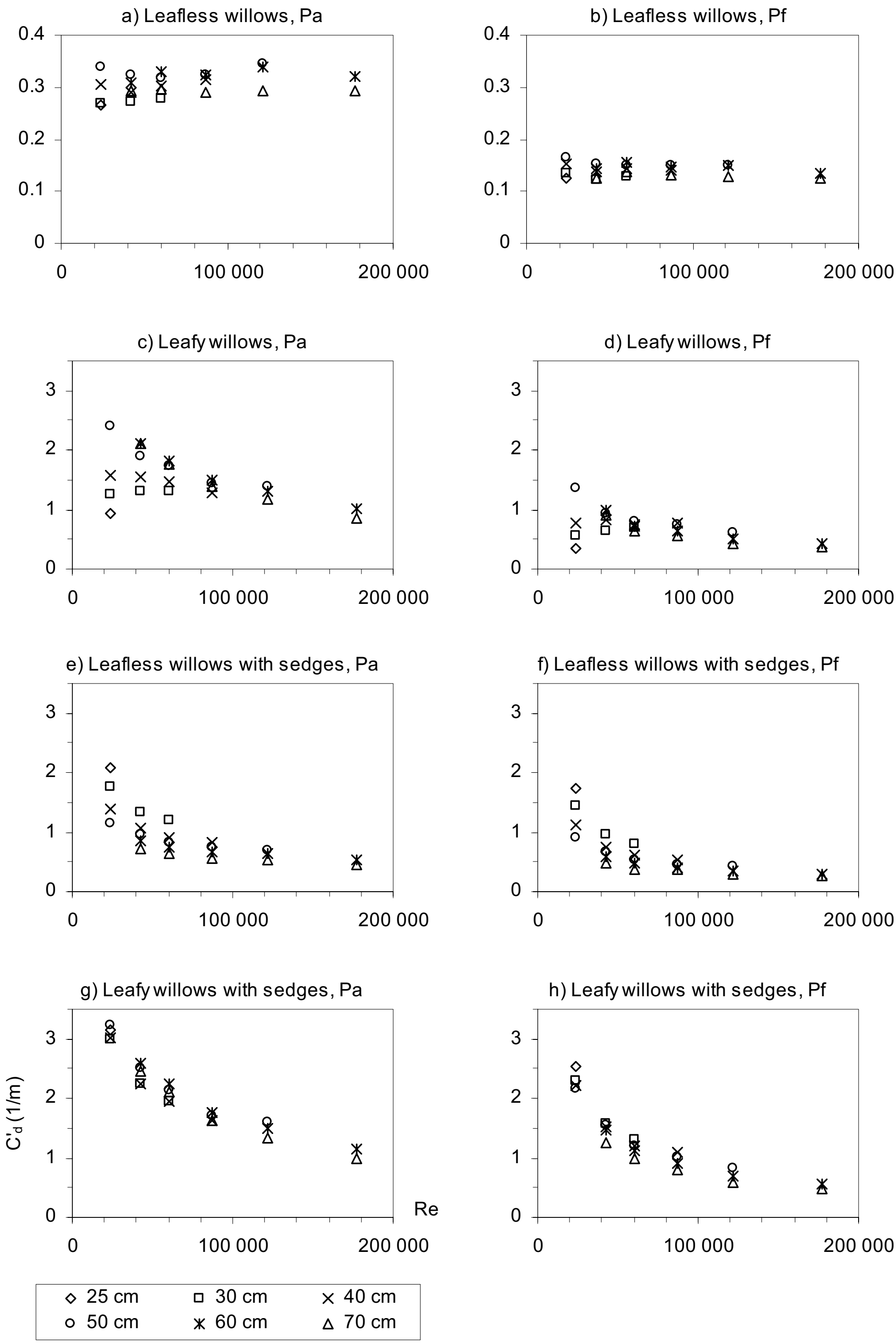

Figure 2. Vegetal drag coefficient as a function of the corresponding depth Reynolds number. Data are classified according to the flow depth, h_0. Willow patterns Pa and Pf described in Figure 1. Note vertical scale.

flume with no vegetation was subtracted to obtain the friction factor of the vegetation. In Equations 1 and 5 the hydraulic radius was replaced with the flow depth. Friction factors for the leafy willows were derived by using the superposition principle. The friction factors for the series with sedges only were subtracted from the corresponding values for the series with leafy willows and sedges combined. Vegetal drag coefficients, C'_d, were derived from Equation 4 or 5. In addition, for the leafless willows dimensionless drag coefficients, C_d, were determined using measured frontal area.

For leafless willows the projected stem and branch area against the flow was determined by means of digital imaging. Greyscale images of the willows were produced against a white board, and the images were transformed into black and white. The projected area was derived by counting the black pixels at 10 cm increments from the bottom. Professional image editing software was utilised to adjust a threshold level for the black pixels. A sample of willow stems with known diameters and geometrically well-defined dark plastic and steel bars was used as a reference for adjusting the correct threshold level. This approach is expected give to the projected area within ~5% error margin, which is much less than the area variation between the individual willows in the canopy.

4.3 *Experimental results*

For this paper data for 170 test runs were selected. In all the test runs the willows were erect with minor bending in a few experiments resulting in a 5-10 cm reduction in the height of the tips. More important than the bending of the main stems appeared to be the streamlining of small branches and leaves at higher velocities. Bending of the sedges was dependent on the velocity and depth showing a wide range of the deflected height. At low velocities the sedges formed roughly an erect layer, but at higher velocities a 12-15 cm thick waving layer was produced.

The range of the depth Reynolds number (= vh/ν) was 24200-177000, indicating that all the test runs were above the laminar-flow range. The Froude numbers were 0.25 at the maximum. The average flow velocity (= Q/A) varied between 7.2 and 46.8 cm/s. The energy slope ranged between 0.0001 and 0.0127. The overall maximum values for the friction factor were obtained when the Reynolds number or the flow velocity were at their lowest, and the vegetation was just submerged or ~10 cm before full submergence.

The friction factor and the vegetal drag coefficient were examined by plotting the parameters against the corresponding Reynolds number, flow velocity, flow depth, and relative submergence or relative roughness. In Fig. 2 the vegetal drag coefficient is plotted against the depth Reynolds number for ease of comparison.

5 FLOW RESISTANCE OF NATURAL VEGETATION: ANALYSIS OF EXPERIMENTAL RESULTS

5.1 *Leafless willows*

5.1.1 *Projected area and characteristic diameter*

Lateral and longitudinal distances between willow bushes are reasonably easy to define both under laboratory and field conditions. On the contrary, the projected area or the momentum absorbing area (MAA) is difficult to determine as bushes even in a leafless situation exhibit a complex three-dimensional structure. A brief compilation of various approaches is presented by Fischenich & Dudley (2000). The projected area of the leafless willows used in the present study appeared to increase fairly linearly with the increasing flow depth excluding the base and tip regions of the plant (Fig. 3). The graphs agree well with the visual observations of the plants. A linear relationship between the area and depth was formulated with a R^2 value of 98%.

Applying the linear relationship, the average projected willow area and the characteristic diameter, $d_r = A_p/h$, were computed for each test run. Herein the characteristic diameter interprets the willow bush as an imaginary rigid object, and may be used to characterise d_p in Equation 2. However, in reality willow bushes are porous objects with overlapping branches. For the present study, roughly 1/3 of the total projected area of a willow was contributed by the main stem. The characteristic diameter was approximately doubled to the stem diameter at the base of the willow. Lindner (1982) found that the characteristic diameter was usually two to three times the stem diameter for wheat, sorghum and cotton.

5.1.2 *Drag coefficient and friction factor*

Drag coefficients for the leafless willows were computed for 46 test runs. The average drag coefficients with standard deviations in parentheses for the wil-

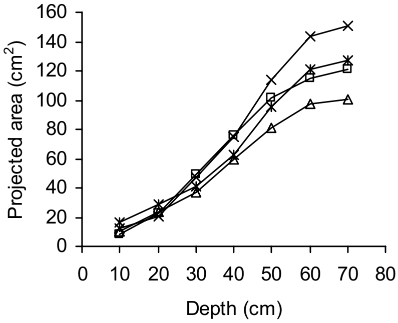

Figure 3. Four examples of the dependence between the projected area of the leafless willows and the flow depth.

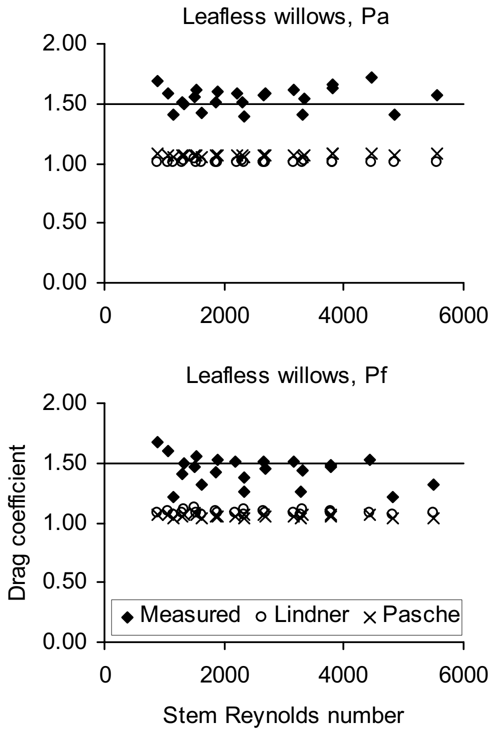

Figure 4. Measured and predicted drag coefficient vs. the Reynolds number based on the characteristic diameter. Constant line of C_d = 1.5 used in Mertens' and Nuding's methods is shown for reference.

low patterns Pa and Pf were 1.55 (0.10) and 1.43 (0.12), respectively. The coefficients include the effect of the other willows, i.e. are dependent on the willow pattern and density. Drag on single willows (in idealised 2-D flow) was not studied.

The obtained values of the drag coefficients did not show any distinct dependence on the Reynolds number, either defined based on the characteristic willow diameter (Fig. 4) or the flow depth. Nor did doubling of the willow density have any significant effect on the drag coefficient. For comparison, Klaassen & Zwaard (1974) reported a mean drag coefficient of 1.5 for small branched fruit trees, but deviation of the data was much greater.

The experimental data were used to test the applicability of the computational methods by Lindner (1982), Pasche (1984), Mertens (1989), and Nuding (1991) in case of leafless willows. These methods were developed for determining drag coefficient and friction factor based on theory and experiments on cylindrical objects. However, in Nuding's method branches are taken into consideration separately from the main stem. The key requirement of the successful application of all these methods is the correct determination of the drag coefficient and the diameter of the plant.

Drag coefficients for the investigated willows were computed using Lindner's (1982) simplified method and Pasche's (1984) method. For the computational details, the reader can refer to the original publications or Rouvé (1987) as the relatively lengthy procedures cannot be repeated here. The vegetation density, $\omega = d_p/(a_x a_y)$ in Equation 2, was redefined based on the characteristic diameter of the plant, d_r. The drag coefficient of a single cylinder in an idealised two-dimensional flow, $C_{d\infty}$, is needed as a base value and is evaluated from the stem Reynolds number. According to standard texts its value usually is 1.0 or 1.2 for the present Reynolds number range. Both methods underestimated the measured drag coefficient (Fig. 4).

To gain a better understanding how the lateral distribution of the plants affects the computation in Lindner's and Pasches's methods, the values of d_r and a_y were altered maintaining the measured projected area constant. It was observed that redistributing the projected area of a single willow evenly in two to three imaginary adjacent cylinders appeared to give a reasonable estimate of the drag coefficient. The ratio of the characteristic diameter to the stem diameter was determined to be in the range of two to three (see previous section). Further investigations revealed that Lindner's method was fairly insensitive to the chosen value of $C_{d\infty}$, but in Pasche's method it was an important parameter. Pasche's method may be able to estimate the drag coefficient for various willow spacings if $C_{d\infty}$ is determined for a single willow instead of an ideal cylinder. However, the present data do not allow a thorough testing of this hypothesis.

5.2 *Leafy willows and sedges*

The presence of leaves makes the determination of drag coefficient and friction factor complex. Vogel (1994) thoroughly discusses the topic and points out that the major contributor to the drag of most trees is the drag of the leaves, whether broad or needlelike. He performed experiments on individual leaves and clusters of leaves and found that reconfiguring or reshaping of the leaves was a critical process in generating drag. Figures 2a-d depict the importance of leaves on willows in contributing to the vegetal drag.

For the leafy willows and the combinations of sedges and willows, the vegetal drag coefficient is dependent on the Reynolds number, but there is distinct variation between the test series (Figs 2c-h). However, all these series show a decreasing trend with increasing Reynolds number. The vegetal drag coefficient for leafy willows appears to be three to seven times that of the leafless willows for both willow patterns. When the number of the leafy willows

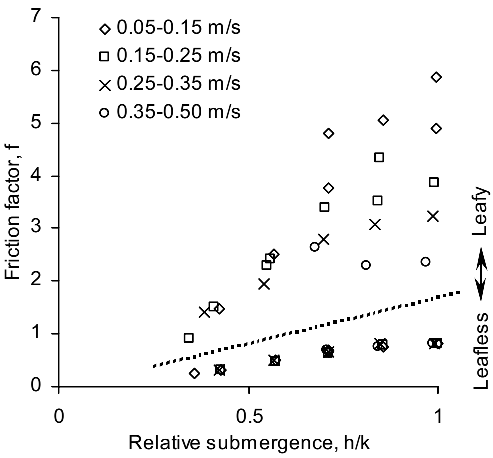

Figure 5. Presence of leaves affects significantly the flow resistance. Friction factor vs. the relative submergence for leafy and leafless willows (pattern Pa). The dashed line separates the leafless and leafy cases.

doubles, the vegetal drag coefficient in average slightly more than doubles for comparable flow conditions (Figs 2c-d). However, the flow depth seems to affect the ratio.

The results indicate that the resistance caused by leaves is strongly dependent on the flow velocity (Fig. 5). During the flume experiments it was observed that when the willows were exposed to higher velocities the leaves rolled or reconfigured into cones and cylinders. This process of streamlining did reduce both the frontal area and the wetted area. Very little fluttering of the leaves was observed. However, there was considerable variation in the behaviour.

6 CONCLUSIONS

This paper presents an analysis of experiments on flow resistance of natural floodplain plants. Resistance caused by willows and sedges was investigated in a laboratory flume. Flow depths were altered such that the willows were partially or just submerged while the sedges were mostly fully submerged. Friction factors, f, and vegetal drag coefficients, C'_d (a bulk parameter), were calculated from the measurements. Drag coefficients, C_d, were also determined for leafless willows.

The projected area of the leafless willows was determined by means of digital imaging, with an expected accuracy of ~5%. The projected area increased approximately linearly with the willow height, excluding the base and tip regions of the plants. The ratio of the characteristic diameter to the measured stem diameter at the base of the willow appeared to be roughly two.

The experimentally attained values of f and C'_d showed large variations with the Reynolds number, depth of flow, flow velocity, and vegetal characteristics. For leafless willows the vegetal drag coefficient was fairly independent of the Reynolds number. All the other test series exhibited a decreasing trend. The vegetal drag coefficient for the leafy willows was found to be three to seven times that of the leafless willows. When the number of the leafy willows was doubled, the vegetal drag coefficient in average approximately doubled for comparable flow conditions.

The average measured drag coefficient, C_d, for the leafless willows was 1.5. The measured coefficients were compared against the values predicted by four methods, which were derived based on theory and experiments on rigid cylinders. The methods of Lindner (1982) and Pasche (1984) produced underestimations in the case of willow bushes, as these methods were originally developed for single-stem trees. However, both methods have a rational theoretical basis, and potentially the methods may be modified to compute the drag coefficient at least for leafless bushes. Mertens (1989) and Nuding (1991) suggest a constant value of 1.5 for most practical river engineering cases. This assumption in general cannot be justified despite its success in the present case.

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