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Determination of flow resistance caused by non-submerged woody vegetation

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ABSTRACT

This paper investigates the determination of flow resistance caused by stiff and flexible woody vegetation. A new procedure has been developed which allows the determination of friction factor f or Manning's n using measurable characteristics of vegetation and flow. The procedure is capable of predicting flow resistance due to: (1) leafless bushes or trees and (2) leafy bushes or trees. The application of the procedure is limited to non-submerged flow ($h \leq H$) and relatively low velocity ($U \lesssim 1$ m/s), which are typical conditions in low-gradient stream valleys, floodplains and wetlands. The procedure is novel in that it uses sound hydraulic principles and methods that are available but incorporates some adjustments based on the knowledge on mechanical design of trees and deformation of foliage in a flow. The procedure is able to account for the natural branched structure in determining area or volume of a woody plant. This makes the prediction of resistance caused by plants more accurate than if they were treated as arbitrary cylinders. The accuracy of the approach to estimate f and U was somewhat better for the leafless condition (mean error of f was -5% to $+4\%$) compared to the leafy condition (mean error of f was -9% to -3%). The presented procedure is intended as a practical tool for estimating the relationship between plant characteristics and flow resistance for flows over floodplains and wetlands growing woody vegetation.

Keywords: Hydraulics; flow resistance; roughness; vegetation; rivers; floodplains; wetlands.

1 Introduction

A reliable estimate of flow resistance and conveyance capacity is desirable in river and wetland management. Natural floodplains and wetlands typically grow grasses, bushes and trees. It has been generally agreed that vegetation increases flow resistance, changes backwater profiles, and modifies sediment transport and deposition (Yen, 2002). The contribution of different vegetative roughness types to the total flow resistance depends strongly on the type and combination of the vegetation and exhibits considerable variability in time and space (Järvelä, 2002a). This can be illustrated by the following two examples considering a floodplain growing dense willows and grasses. First, in the midst of a growing season, leaves on willows are likely to dominate the total drag, and bottom grasses may be only a minor source of flow resistance. Second, in winter, when the willows are leafless, the bottom grasses may contribute more than the willow stems to the total flow resistance. Nevertheless, a considerable number of flow resistance formulas or models has been developed treating vegetation simply as static rigid cylinders and/or bottom roughness. Obviously, branched and leafy flexible plants are far from this simplification.

The need to evaluate flow resistance caused by vegetation has spurred a multitude of studies. Conventional approaches typically use reference publications (e.g. Chow, 1959; Barnes, 1967; Coon, 1998; Hicks and Mason, 1999) for selecting a roughness coefficient, which groups all sources of flow resistance, including vegetation, into Manning's coefficient n. A significant amount of research has been carried out in developing resistance laws for channels with stiff vegetation (e.g. Petryk and Bosmajian, 1975; Pasche and Rouvé, 1985), flexible vegetation (e.g. SCS, 1954; Kouwen and Unny, 1973; Kouwen and Fathi-Moghadam, 2000), and various combinations (e.g. Freeman *et al.*, 2000; Järvelä, 2002a). Recently, several studies have focused on velocity profiles and turbulent characteristics of vegetated channels (e.g. Shimizu and Tsujimoto, 1994; Naot *et al.*, 1996; Nepf, 1999; López and García, 2001).

The purpose of this paper is to investigate the determination of the flow resistance caused by: (1) leafless bushes or trees and (2) leafy bushes or trees. The paper presents a practice-oriented procedure for determining friction factor f or Manning's n. Emphasis is put on assessing the difference between complex natural and simple artificial plants, as it is expected that simple cylinder-based drag coefficient models offer limited applicability in treating branched vegetation, even without leaves. The research is limited to the case of relatively low velocities and flow depths less than the height of vegetation. Such conditions are often found in low-gradient stream valleys, floodplains and wetlands.

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2 Previous research

2.1 *Theoretical considerations*

In fluid mechanics, the drag F_d, which acts on a reference area A_p (typically projected area), may be defined as

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

where ρ = density of the fluid, C_d = drag coefficient, A_p = reference (projected) area, and U = average velocity. 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. Therefore, Vogel (1994) regarded Eq. (1) as only a definitional equation that converts drag to drag coefficient and vice versa. Furthermore, he stated that no published figure for drag coefficient is of any value unless the reference area is indicated. Defining the reference area or the momentum absorbing area (MAA) for natural vegetation is difficult. Among others, Wu *et al.* (1999) coupled the drag coefficient with the reference area into a bulk drag coefficient C_d', which is a lumped parameter based on the total frontal area of vegetation in a channel reach L, i.e. projected plant area per unit volume. The disadvantage of this formulation is that the vegetal drag coefficientC_d' has a unit of 1/m.

To estimate flow resistance caused by natural vegetation, the force balance for uniform flow can be extended for gradually varied flow by applying the momentum principle. The gravitational force is defined as $F_g = \rho g(A_b h)S$, where S = energy slope, A_b = bottom area, and h = flow depth. Assuming that the drag exerted on the boundaries of a densely vegetated channel is not significant compared to the drag on vegetal elements implies that $F_d = F_g$. By equating Eq. (1) to the gravitational force and using the definitions $u_* = (ghS)^{1/2}$ and $U/u_* = (8/f)^{1/2}$ the friction factor can be formulated as

$$f = 4C_d\frac{A_p}{A_b} \tag{2}$$

In the next two sections, methods that are currently available to determine flow resistance caused by stiff and flexible roughness, respectively, are reviewed in detail. Emphasis is placed on approaches that are based on Eqs. (1)–(2).

2.2 *Stiff roughness: leafless bushes and trees*

A majority of research on vegetative flow resistance is based on theory and experiments with rigid cylindrical elements. Petryk and Bosmajian (1975) presented a model to estimate Manning's n as a function of hydraulic radius and vegetation density for non-submerged rigid vegetation. Li and Shen (1973) modelled flow resistance of tall non-submerged vegetation including wake effects caused by various cylinder set-ups. This wake correction approach was incorporated into the methods of Thompson and Roberson (1976) and Jordanova and James (2003). Li and Shen (1973) identified four factors that need to be considered in determining the drag coefficient: (1) the effects of open-channel turbulence; (2) the effect of non-uniform velocity profile; (3) the free surface effects; and (4) the effect of blockage. Lindner (1982) concluded that, in densely vegetated channels, the first two of these are of minor importance and can be neglected. Lindner (1982) extended the work of Li and 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 vegetation. Based on experimental studies with cylindrical elements, an empirical formulation was derived as

$$C_d = \left(1 + 1.9\frac{d}{a_y}C_{d\infty}\right)\left(0.2025\left(\frac{a_x}{d}\right)^{0.46}C_{d\infty}\right) + \left(\frac{2a_y}{a_y - d} - 2\right) \tag{3}$$

where $C_{d\infty}$ is the drag coefficient of a single cylinder in an ideal 2-D flow, d is the diameter of the element, and a_x and a_y are the longitudinal and lateral distances, respectively, between the cylinders. The two terms in RHS of Eq. (3) represent the blockage and free surface effects, respectively. The experiments were conducted using a vegetation density of 50 elements per m^2 produced with PVC cylinders of 10 mm in diameter and 150 mm in height. Standard fluid mechanics texts report $C_{d\infty}$ values of 1.0 to 1.2 for the typical range of the Reynolds number. Lindner's (1982) method for computing f uses, in addition to C_d, readily measurable physical properties: longitudinal and lateral distances between the plants, and the plant diameter

$$f = \frac{4dh}{a_x a_y}C_d \tag{4}$$

Based on Lindner's approach and further experimental work, Pasche and Rouvé (1985) presented a semi-empirical iterative process to determine C_d. 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. Klaassen and Zwaard (1974) reported a mean drag coefficient of 1.5 for small, branched fruit trees. Järvelä (2002b) presented average drag coefficients for two different willow patterns equal to 1.55 and 1.43, respectively. DVWK (1991) recommends $C_d = 1.5$ for practical computations, which is well in line with the reported experimental values. Recently, Stoesser *et al.* (2003) used the approach in Eq. (4) at reach scale with good success for the numerical modelling a heterogeneously vegetated floodplain.

2.3 *Flexible roughness: leafy bushes and trees*

A considerable number of flow resistance formulas or models has been developed treating plants simply as rigid cylinders. Branched and leafy flexible plants are far from this simplification. Because of a lack of information and despite very poor results, the effects of flexibility and depth on resistance for non-submerged vegetation are universally ignored in practice and in theoretical analysis (Fathi-Moghadam and Kouwen, 1997). Several researchers have used the stiffness of vegetation as a primary independent parameter to relate flow resistance to vegetation characteristics. Kouwen and Li (1980) related the flexural rigidity of vegetation per unit area (MEI) to the deflected plant height, and further, the flow resistance. Tsujimoto *et al.* (1996) and

Kutija and Hong (1996) coupled a numerical model with a model describing bending of vegetation using cantilever beam theory.

Fathi-Moghadam and Kouwen (1997) concluded that for non-submerged cases, the vegetation density is always a dominant parameter regardless of tree species or foliage shape and distribution. Vogel (1994) stated that the major contributor to the drag of most trees is the drag of the leaves, whether broad or needle-like. He found that reconfiguring or reshaping of the leaves was a critical process in generating drag. According to Eq. (1), the drag of a rigid element is expected to increase with the velocity squared. The experimental work by Fathi-Moghadam (1996), Werth (1997), Oplatka (1998), Freeman *et al.* (2000), and Järvelä (2002a) showed that this relationship does not hold for flexible trees and bushes. In Järvelä's (2002b) experiments on willows, for example, the vegetal drag coefficient for leafy willows was three to seven times that of the leafless willows depending primarily on flow velocity. Kouwen and 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 proposed model for estimating the friction factor for non-submerged roughness was

$$f = 4.06 \left(\frac{U}{\sqrt{\xi E/\rho}} \right)^{-0.46} \left(\frac{h}{H} \right) \tag{5}$$

where ξE is a species-specific vegetation index, which accounts for the effects of shape, flexibility, and biomass. The determination of ξE requires measuring of the natural frequency of a tree. This is very difficult to perform in the field, and therefore the method has limited practical applicability until values of ξE become available for typical species of bushes and trees.

3 Development and testing of a procedure

3.1 General approach and data requirements

To estimate flow resistance caused by vegetation, an equation or set of equations that will relate resistance to readily defined, measurable characteristics of the vegetation and the flow is desirable. The equation(s) should be based on physical laws and be dimensionally homogeneous. Many of the hydraulic design methods used currently rely on the professional judgment of an experienced engineer, e.g. in selecting a roughness coefficient. Theoretical or semi-empirical approaches should provide a better general understanding of the variation of flow resistance.

From a practical point of view, a suitable approach should be transparent and straightforward enough to be applied by a practising engineer. However, no approach can deliver reliable results if the physical reality is excessively simplified or if the source data is of low quality. Gathering field data for natural vegetation is far more complicated and time-consuming than describing the properties of simulated vegetation in laboratory conditions. Therefore, a preferable approach uses clearly defined variables, which can be easily and objectively determined. In the next two sections, a procedure is developed for determining flow resistance caused by leafless and leafy woody vegetation, respectively. To support this work, data published earlier by the writer and others are used and reanalysed.

3.2 Flow resistance due to leafless woody vegetation

Bushes and trees are porous objects with a complex three-dimensional structure. Lateral and longitudinal distances between the bushes are reasonably easy to define under both laboratory and field conditions. In contrast, the projected area and the momentum absorbing area (MAA) are difficult to determine in the field. From the viewpoint of determining flow resistance, an important question is how to characterise a natural bush or a tree in terms of geometry (typically projected area or volume). Järvelä (2002b), for example, found for the studied species of willows that the projected area of the willows appeared to increase linearly ($R^2 = 98\%$) with the increasing flow depth excluding the base and tip zones of the plant. Branches contributed approximately 2/3 to the total leafless projected area. Before Eq. (4) can be used for practical purposes, a suitable approach for the estimation of an effective diameter (or A_p) and C_d is needed. Herein, a simple approach that is reasonable for field applications is desirable. For further development, it is hypothesized that a leafless bush is an assemblage of rigid cylinders. First, the estimation of C_d is discussed. Second, a method is developed to characterise a bush by reducing it to a single imaginary element taking advantage of the knowledge on mechanical design of trees. Finally, based on Eq. (4), a new computational procedure for determining f is suggested.

3.2.1 Estimation of C_d

Järvelä (2002b) showed that Eq. (3) significantly underestimated the drag coefficient of the studied willow patterns. With the same experimental data, additional calculations were performed to compute C_d of an individual willow by replacing d and a_x with an average branch diameter and an average distance between the branches, respectively. These simple tests showed that the method again significantly underestimated the measured drag coefficient of the assemblage. The detailed results are not shown here. Obviously, the complex three-dimensional plant structure with randomly orientated branches is not accounted for by the method. Neither is it feasible to compute the drag for all the individual branches. As Eq. (3) appears not to be suitable for determining C_d, it is necessary to rely on experimental data until better alternatives become available. Fathi-Moghadam (1996) and Järvelä (2002a) have shown that the pattern and distribution of trees and bushes do not have a significant effect on the friction factor, i.e. C_d should be practically constant for a given Re range. Based on the research reported in Section 2.2, it is assumed that $C_d = 1.5$ can be used as a base value in Eq. (4), which is analogous to the typically made assumption of $C_d = 1.0$ for cylinders. This introduces uncertainty in the computations, but in practice the error may be masked over by the uncertainty in determining d or A_p, which is discussed next.

3.2.2 *Estimation of d or A_p*

In the following, a rational method for determining the projected area of woody leafless plants is developed. McMahon and Kronauer (1976) applied the Strahler (1952) stream ordering scheme to trees to gain a better understanding of the mechanical design of trees. The ordering system begins from the smallest branches towards the base of the trunk and involves the following rules: (1) fingertip branches are designated order 1; (2) the junction of two branches of order m forms a branch segment of order $m+1$; and (3) the junction of two branches of unequal order creates a segment having an order equal to that of the higher order branch (Figure 1). McMahon and Kronauer (1976) showed that the branching pattern within any tree species is approximately stationary, which means that the structure is self-similar, and any patch of the structure is a model of the entire tree. They concluded that the principle of mechanical design is the maintenance of elastic similarity. For elastically similar beams, the diameters proved to be proportional to the 3/2 power of their length (McMahon, 1975). The findings can be formulated to the following three equations of branching, diameter, and length ratio, respectively:

$$R_B = \frac{N_m}{N_{m+1}} \tag{6}$$

$$R_D = \frac{d_{m+1}}{d_m} \tag{7}$$

$$R_L = \frac{L_{m+1}}{L_m} \approx R_D^{2/3} \tag{8}$$

where N is the number of segments in a particular order, d is the average diameter within an order, and L is the average length within an order. R_B describes how many branches of order m a bigger branch of order $m + 1$ supports. Similarly, R_D and R_L describe the corresponding differences in branch thickness and length, respectively. The equations are based on the geomorphic laws of drainage network composition by Horton (1945) and Schumm (1956). McMahon and Kronauer (1976) presented values of R_B and R_D for various species of trees (Table 1). McMahon (1975) reported that the diameter ratio is about half the branching ratio for several species of trees.

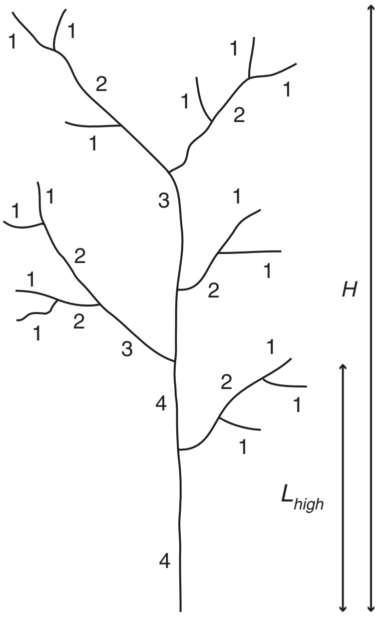

Figure 1 The principle of the Strahler ordering scheme applied to a woody plant.

Table 1 Values of R_B and R_D for different species of woody vegetation. The total height of the specimens was in the range 1.5–5.4 m (McMahon and Kronauer, 1976).

Species	R_B	R_D
White oak	4.24	1.86
Poplar	4.22	1.86
Pin cherry	5.18	2.05
White pine	4.44	2.04

Next, a method is developed to compute the projected area of a branched plant as a function of depth, $A_p(h)$. Eqs. (6)–(8) as such are insufficient to reproduce a plant. The average diameter of branches of order one, $d_{\min}$, is needed as an additional input parameter. It is a biological, species-specific parameter representing the minimum branch diameter that a plant can have. The four parameters R_B, R_D, R_L and $d_{\min}$ are called the plant structure parameters. A further three parameters are needed to describe a particular plant individual: the average diameter d_{high} of the highest order (trunk), the plant height H, and the length of the highest order L_{high} (Figure 1). These three parameters can be easily determined in the field. Finally, to solve the above set of equations, the number of segments in the highest order, $N_{m,\text{high}}$, needs to be assigned. If a plant has only one stem rising from the ground, $N_{m,\text{high}}$ is equal to one. The computational procedure is as follows:

(1) Estimate the plant structure parameters R_B, R_D, R_L and $d_{\min}$ from literature or field measurements
(2) Determine d_{high}, H and L_{high} in the field
(3) Assign a value for $N_{m,\text{high}}$ (typically $N_{m,\text{high}} = 1$)
(4) Use Eqs. (6)–(8) to compute N_m and L_m for each order beginning with the highest order (trunk); the highest order number M is unknown in the beginning
(5) Repeat step 4 for subsequent orders until $d_m < d_{\min}$; M is delivered as a result
(6) Multiply N_m, L_m and d_m for each order to get the projected area of each order and sum up sub-areas to obtain the total projected area $A_{p,\text{tot}}$
(7) To determine the projected area as a function of the plant height, assume that the total projected area is linearly distributed over the height (Järvelä, 2002b)

$$A_p(h) = \frac{h}{H} A_{p,\text{tot}} \quad \text{for } 0 \leq h \leq H \tag{9}$$

If a particular height-area function is known, Eq. (9) should be modified accordingly. However, the error introduced by making the linearity assumption is expected to be small, at least for the studied willows (Järvelä, 2002b). A characteristic diameter is here defined as a function of depth as $d_r(h) = A_p(h)/h$. Finally, the friction factor can be computed by modifying the diameter definition in Eq. (4) as

$$f = \frac{4d_r h}{a_x a_y} C_d \tag{10}$$

where a_x and a_y are the mean longitudinal and lateral distances, respectively, between the plants. The advantage of Eq. (10) is that it is based on the physical laws (conservation of momentum) and characteristics of vegetation. Additionally, when a better method becomes available to determine C_d, it will directly improve the reliability of the approach. It is worth noting also that the approach can be easily used to compute the area and volume of vegetation. This is useful if other definitions of C_d are used.

3.3 Flow resistance due to leafy woody vegetation

According to the research reported in Section 2.3, the fundamental properties to be considered in establishing a resistance equation are (1) density of vegetation, and (2) deformation of plants in a flow. Considering that the major contributor to the drag of most trees is the drag of the leaves suggests that the leaf area index (LAI) is a key parameter in determining the density effects on f. Conventionally LAI refers to the ratio of the area of the upper side of the leaves in a canopy projected onto a flat surface to the area of the surface under the canopy. This definition of LAI as the one-sided area of foliage per unit area of ground or A_l/A_b was adopted for this study. Fathi-Moghadam and Kouwen (1997) propose a linear relationship between LAI ($\propto$ MAA) and the friction factor. Järvelä's (2002a) experiments confirmed this relationship for the willows used in the study. For further development, it is assumed that this relationship is reasonable for practical applications. Thus, substituting the reference area A_p with the leaf area A_l in Eq. (2) and introducing a dimensionless vegetation parameter α yields

$$f = 4C_{d\chi} \frac{A_l}{A_b} \alpha \tag{11}$$

where $C_{d\chi}$ is a species-specific drag coefficient and α accounts for the deformation effects of plants in a flow. Fathi-Moghadam (1996) and Järvelä (2002a) reported for the studied coniferous and deciduous plant species that the friction factor was a power function of flow velocity. Based on these experimental data, α can be expressed as a function of velocity as

$$\alpha = \left(\frac{U}{U_\chi}\right)^\chi \tag{12}$$

where the parameter χ is unique for a particular species. U_χ is used to normalize the relationship and is equal to the lowest velocity used in determining χ, i.e. typically $\alpha \approx 1$, when flow velocity is only a few cm/s. Inserting the definition of α and LAI into Eq. (11) gives for the just-submerged case

$$f = 4C_{d\chi}\mathrm{LAI}\left(\frac{U}{U_\chi}\right)^\chi \tag{13}$$

Equation (13) is closely related to Eq. (5). The primary difference is that the parameters $C_{d\chi}$ and LAI are used to describe the vegetation properties instead of the vegetation index ξE, which is difficult to determine. For simplicity, it can be assumed that canopies have a uniform distribution of LAI over the height of vegetation (Kouwen and Fathi-Moghadam, 2000). Thus, Eq. (13) may be applied to partial submergence by taking into account the linear increase of LAI over the vegetation height as

$$f = 4C_{d\chi}\mathrm{LAI}\left(\frac{U}{U_\chi}\right)^\chi \frac{h}{H} \tag{14}$$

Equation (14) can be used to estimate the friction factor for flow inside leafy woody vegetation on floodplains and wetlands, where $h/H \leq 1$ and $U \geq U_\chi$. Values of χ and $C_{d\chi}$ are presented for different plant species in Table 2. For the compilation of the table, previously published data were reanalysed to obtain values for the parameters $C_{d\chi}$, χ and U_χ. Firstly, f, χ, U_χ and LAI were derived, and secondly, values of $C_{d\chi}$ were back calculated from these data. The maximum acceptable value of U depends on the conditions in determining χ. For the willows in Järvelä (2002a) and the coniferous trees in Fathi-Moghadam (1996), the maximum U values were approximately 0.5 m/s and 1.5 m/s, respectively. The minimum acceptable value of LAI is set by the condition that leaves must dominate the total resistance, but further research is needed to establish the exact limits of application. The computational procedure runs as follows:

(1) Estimate parameters χ, $C_{d\chi}$ and U_χ from literature values (Table 2) or compute by Eq. (13) from field data if available
(2) Determine LAI by field measurements or use literature values
(3) Select a design discharge or depth
(4) Solve Eq. (14) iteratively on condition that the principle of conservation of momentum is satisfied (for details refer to the test computations in Section 3.4).

In general, the use of LAI as a density measure offers notable advantages. LAI is a measure widely used in silvicultural, agricultural, and hydrological sciences, and thus there is a good knowledge base available for different vegetative conditions. LAI can be measured by ground-based equipment in the field or by using remote sensing techniques (e.g. Welles, 1990; Smolander and Stenberg, 1996; Welles and Cohen, 1996; Rautiainen *et al.*, 2003; Stenberg *et al.*, 2003). The increased availability of high-resolution satellite data makes the analysis of large floodplains possible (e.g. Szoszkiewicz *et al.*, 2003).

Table 2 Values of $C_{d\chi}$ for different plant species determined by reanalysing published data. Data on χ, U_χ and LAI derived from the indicated sources.

Species	$C_{d\chi}$	χ	U_χ (m/s)	LAI	Data source
Cedar	0.56	−0.55	0.1	1.42	Fathi-Moghadam, 1996
Spruce	0.57	−0.39	0.1	1.31	Fathi-Moghadam, 1996
White Pine	0.69	−0.50	0.1	1.14	Fathi-Moghadam, 1996
Austrian Pine	0.45	−0.38	0.1	1.61	Fathi-Moghadam, 1996
Willow	0.43	−0.57	0.1	3.2	Järvelä, 2002a; series S3Pa

3.4 Testing the procedure

In this section, the procedure is evaluated by estimating f, U, and h or q for leafless and leafy willows in three separate tests. Predicted values were compared against measured data taken from Järvelä (2002a,b; series group S3*). The data selected for the comparison were not used in determining the parameters in the procedure. The studied willow species (goat willow, *Salix caprea*) is found throughout Europe. The willows were investigated in a flume in two different patterns (Pa and Pf) having different vegetation densities. The willows averaged 70 cm in length and 8.6 mm in diameter at a height of 10 cm from the bottom. The plants were investigated first with leaves and in the next phase without leaves. The leaf area index (LAI) corresponding the patterns Pa and Pf was 3.2 and 1.6, respectively. For both patterns, 19–23 different U–h combinations were investigated. The experiments are described in detail in Järvelä (2002a). In the leafless case, all the parameters in the procedure were independent of the test data. In the leafy case, data for series S3Pf having LAI, U and h as independent variables were used to test the procedure as data for series S3Pa were used to determine the parameters in the procedure.

In the case of the leafless willows, testing follows the steps presented in Section 3.2.2. Values for the plant structure parameters R_B and R_D were taken from the poplar data (Table 1) as measured data were not available for the willows. R_L was computed from R_D using Eq. (8). Values for $d_{\min}$, d_{high}, H and L_{high} were estimated from the plant specimens. The number of segments in the highest order, $N_{m,\text{high}}$, was one. The values of the parameters are collected in Table 3. The resulting number of orders M was computed to three. The estimated projected area was 0.0123 m^2, which was 2% smaller than the average measured value of 0.0125 m^2.

Table 3 Parameter values used in computing the projected area for the leafless willows.

Parameter	Value
R_B	4.22
R_D	1.86
R_L	1.51
$d_{\min}$	0.002 m
d_{high}	0.0086 m
H	0.7 m
L_{high}	0.3 m
$N_{m,\text{high}}$	1

Based on the above data, f, U and q were estimated for the two willow patterns, Pa and Pf. The distances a_x and a_y between the plants were 0.33 m and 0.28 m, respectively, for the pattern Pa. The distances for the pattern Pf were 0.46 m and 0.39 m, respectively. Values for f, U and q were computed at 0.1-m depth increments up to H. The predicted and measured values are presented for both patterns in Figure 2; measured data were available for the comparison in the depth range of 0.3–0.7 m, which is equal to the relative submergence range of 0.4–1.0. The mean error of f was -5% and $+4\%$ for the patterns Pa and Pf, respectively. The maximum error ranged between -16% and $+18\%$. For both patterns, the mean error of q was 8% with a standard deviation of less than 4%. Considering the natural variability of the plants, the error values are reasonable. The values for both R_B and R_D for the various species presented by McMahon and Kronauer (1976) were mostly within 10% of the corresponding average value. Sensitivity of the procedure on the selection of the plant structure parameters was investigated by deviating R_B and $R_D \pm 10\%$. The sensitivity analysis revealed that a $\pm 10\%$ change in R_B resulted in a $+13/-12\%$ change in f, respectively. Similarly, a $\pm 10\%$ change in R_D yielded a $+26/-18\%$ change in f, respectively. The procedure was more sensitive to R_D than R_B, since R_D affects also the value of R_L. In the next phase, the performance of the procedure was evaluated using the efficiency as proposed by Nash and Sutcliffe (1970). The efficiency (R_{eff}) is a dimensionless transformation of the sum of squared errors and is defined for a parameter x as $\text{R}_{\text{eff}} = 1 - \sum(x_{\text{mes},i} - x_{\text{pred},i})^2 / \sum(x_{\text{mes},i} - x_{\text{mes,mean}})^2$ where the subscripts mes, i; pred, i and mes, mean refer to the ith measurement, the ith prediction and the mean of the measurements, respectively. R_{eff} values were computed for both patterns separately revealing efficiencies, which indicated good performance (Figure 2).

Next, the procedure was tested with leafy willows in two typical design situations: (1) friction factor, average velocity and unit discharge were estimated for a given depth, and (2) a design discharge was given, and f, U and h were estimated. Slope can be assumed to be known; typically for uniform flow, it is equal to the bottom slope. In this test, energy slope was used as the flow was non-uniform in the experiments. Cross-section was considered

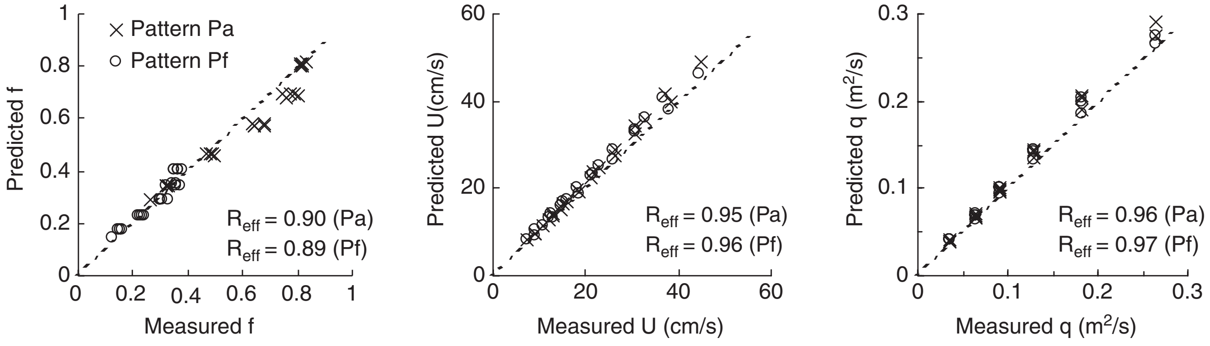

Figure 2 Predicted and measured friction factors, velocities and unit discharges for two patterns of leafless willows. See text for the definition of the efficiency R_{eff}. The dashed line denotes the perfect agreement.

wide so that $R = h$. The dataset selected for the test consisted of 19 test runs with the relative submergence ranging from 0.4 to 1.0. The willow stand was 0.7 m high and had a LAI value of 1.6. Values for χ and $C_{d\chi}$ equal to -0.57 and 0.43, respectively, were taken from Table 2. Testing follows the steps presented in Section 3.3. The problem was solved iteratively in a spreadsheet.

For the first design situation, Eq. (14) was applied inserting an initial estimate for U. From the resulting f, a new velocity estimate was computed using the Darcy–Weisbach equation. Iteration was continued until the velocity did not change. The predicted values for f, U and q are compared with the measured data in Figure 3. The mean error of f and q was -3% and -6% with a standard deviation of 28% and 16%, respectively. The largest individual discrepancy of f and q was 49% and 38%, respectively. Goodness of the fit between the measured and predicted parameters was quantified by computing $\mathrm{R_{eff}}$ values as in the case of the leafless willows. The estimation of the unit discharge yielded good results showing a $\mathrm{R_{eff}}$ value of 0.87 (Figure 3, right).

For the second design situation, Eq. (14) was applied inserting initial estimates for h and U computed from the design discharge. From the resulting f, a new velocity estimate was computed using the Darcy–Weisbach equation. Iteration was continued by varying h until the computed discharge was equal to the design discharge on condition that $h \leq H$. The predicted values for f, U and h are compared with the measured data in Figure 4. Statistical analysis was conducted similarly to the previous test. The mean error in estimating f was -9% with scatter slightly greater (standard deviation 32%) compared to the previous test (Figure 4, left). The mean error of U was -6% with a standard deviation of 14%. The largest individual discrepancy of f and U was 61% and 37% , respectively. The estimation of the U and h gave reasonable results with $\mathrm{R_{eff}}$ values of 0.80 and 0.87, respectively (Figure 4).

The difference in the plots for friction factors (Figures 3 and 4, left) was caused by the applied test approach. In design situation 1, h was defined and U was estimated. In design situation 2, both h and U were unknown. In addition, in the latter case, h was limited so that its value did not exceed the vegetation height (just-submerged flow). Thus, it was evident that the plots for f were not exactly identical. In design situation 2, the predicted f values were slightly but systematically smaller than in design situation 1, and therefore, $\mathrm{R_{eff}}$ was smaller in the latter situation. Friction factors were underestimated for the lower flow depths in both design situation 1 and 2. For the partially submerged leafy willows, the errors in the predicted f values resulted mainly from the vertical distribution of the momentum absorbing area, which deviated from the assumed linearity relationship. Furthermore, at lower depths, the relative effect of the stems increased compared to the leaves. However, the resulting errors did not severely affect the performance of the procedure to estimate h, U and q (Figures 3 and 4).

3.5 *Using the procedure: capability and limitations*

The proposed procedure can be applied to estimate the flow resistance for any canopy height, density, and any relative submergence ($h/H \leq 1$) where total resistance is dominated by

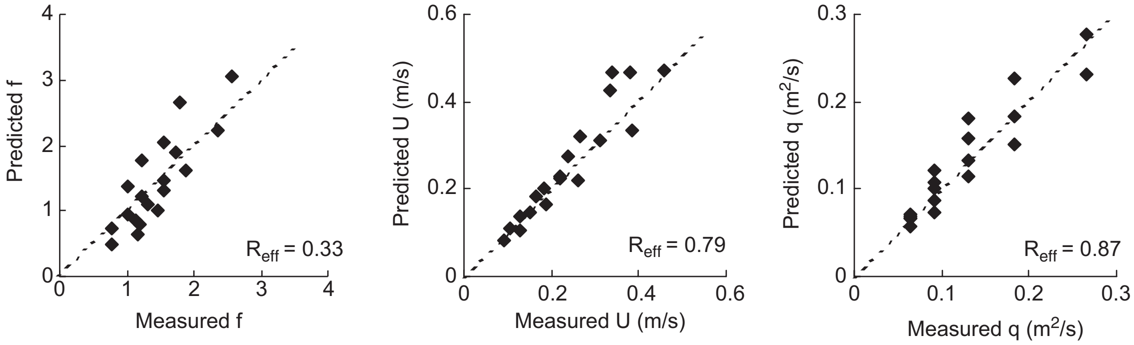

Figure 3 Design situation 1: Predicted and measured friction factors (left), mean velocities (mid) and unit discharges (right) for leafy willows. See text for the definition of the efficiency $\mathrm{R_{eff}}$. The dashed line denotes the perfect agreement.

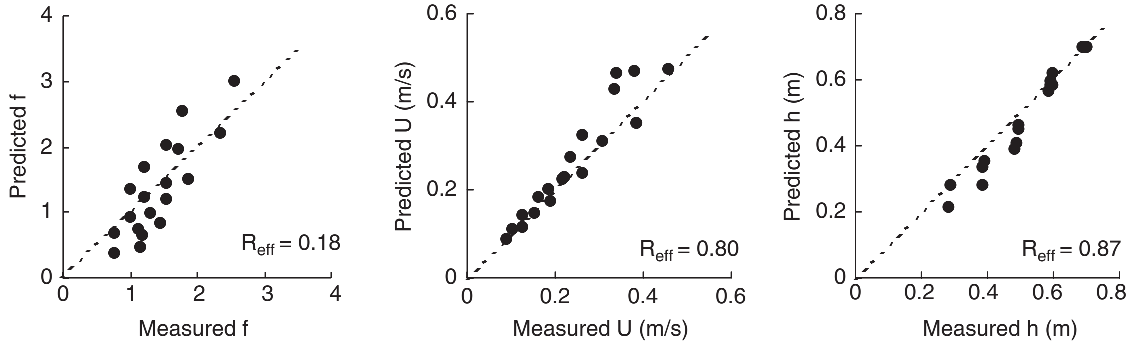

Figure 4 Design situation 2: Predicted and measured friction factors (left), mean velocities (mid) and flow depths (right) for leafy willows. The dashed line denotes the perfect agreement.

vegetation rather than channel boundary roughness. The application of the procedure is limited to non-submerged flow, i.e. flow-through vegetation. The procedure is able to predict flow resistance caused by woody vegetation of different flexibility. The study is limited to the condition of relatively low velocity ($U \lesssim 1$ m/s, transitional to turbulent flow), which is often the case in low-gradient stream valleys and wetlands. The range of conditions for which the empirically calibrated vegetation parameters employed in the analysis of leafy vegetation are valid is presented in the text following Eq. (14).

Practical application of the procedure is relatively straightforward. At the first stage, a distinction must be made between the leafless and leafy condition presented in Sections 3.2 and 3.3, respectively. All steps in the procedure can be conveniently computed by means of a spreadsheet requiring no special programming skills. To compile the required source data, field studies are recommended whenever possible. If this is not feasible, the parameters may be estimated using available datasets and literature. If a specific relationship between $A_p(h)$ and h/H for the leafless case or LAI and h/H for the leafy case is known, the procedure can be easily adjusted to account for any nonlinearity relationship between the parameters. Determination of the total flow resistance for various plant combinations or aggregates can be based on the additive property of drags or friction factors (Einstein and Banks, 1950). Additionally, this property can be used to include the resistance caused channel boundaries. Particularly in the case of leafless woody vegetation, bottom roughness (e.g. grasses) may contribute significantly to the total flow resistance. Significant practical and theoretical research is available on grassy vegetation (e.g. SCS, 1954; Temple *et al.*, 1987; Kouwen, 1992).

4 Conclusion

The presented procedure is a practical tool for estimating the relationship between plant characteristics and flow resistance for flows over floodplains and wetlands growing natural woody vegetation. A major advantage of this procedure over the old methods is its ability to estimate flow resistance of woody vegetation both in leafless (Eq. (10)) and leafy (Eq. (14)) condition. This is highly relevant, for example, in evaluating the effects of winter and summer floods.

Leafless vegetation is characterised by a bulk drag coefficient and a characteristic diameter computed from the projected area. The projected area is derived utilising theory on mechanical design of trees. The approach uses measurable parameters of vegetation while taking into account the natural branched structure of woody plants. Leafy vegetation is characterized by a vegetation parameter χ, leaf area index (LAI), and the new species-specific drag coefficient $C_{d\chi}$. The vegetation parameter accounts for the effects of plant deformation (flexibility and shape) in a flow, and is unique for a particular species. LAI has been shown to be a useful measure to take into consideration the effects of the density of vegetation.

The procedure was evaluated by comparing predicted and measured friction factors for leafless and leafy willows. The largest individual discrepancies of f were 18% and 61% for the leafless and leafy cases, respectively, while the mean errors ranged between −9% and 4%. In both the leafless and the leafy case, the procedure will deliver the most accurate results when the flow depth is close to the vegetation height. If proper plant structure parameters are available, estimates for the leafless condition are expected to be more accurate compared to the leafy condition. However, in the case of leafless vegetation, the procedure relies on the knowledge of the mechanical design of natural trees (McMahon and Kronauer, 1976). Maintained trees and bushes differ in structure and shape from natural ones. Before the procedure can be used for such vegetation, the plant structure parameters should be studied for typical maintained bushes and trees.

The benefit of the procedure is that it is based on the physical laws and characteristics of vegetation. The procedure can be improved, firstly, by studying the plant structure parameters and drag coefficients for further species of trees and bushes, and secondly, by investigating the vertical distribution of the projected area and the leaf area. Additionally, when a better method becomes available to determine C_d or $C_{d\chi}$, it will directly improve the reliability of the procedure. A future development will be the coupling of the procedure with a LAI model (e.g. leaf growth related to effective temperature sum or degree-days) to gain better estimates of temporal change in flow resistance.

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Notations

A_b = bottom area
A_l = leaf area
A_p = projected area
$A_{p,\mathrm{tot}}$ = total projected area
a_x, a_y = longitudinal, lateral distance between the plants
C_d = drag coefficient
C'_d = vegetal drag coefficient
$C_{d\infty}$ = drag coefficient of a single cylinder in ideal 2-D flow
$C_{d\chi}$ = drag coefficient of a leafy bush or tree
d = diameter of an element
d_{high} = average diameter of the highest order (trunk)
d_m = average diameter of branches of order m
$d_{\min}$ = average diameter of branches of order 1
d_r = characteristic diameter
E = modulus of elasticity

f = Darcy–Weisbach friction factor
F_d = drag
F_g = gravitational force
g = gravitational acceleration
h = flow depth (bottom to free surface)
H = plant height
I = moment of inertia
L = length of the channel reach
L_m = average length of branches of order m
L_{high} = length of the highest order
LAI = leaf area index
m = Strahler order number
M = highest Strahler order number
MEI = flexural rigidity per unit area
N_m = number of segments in order m
$N_{m,\text{high}}$ = number of segments in the highest order
n = Manning's resistance coefficient
Q = discharge
q = discharge per unit width
R = hydraulic radius
R_B = branching ratio
R_D = diameter ratio
R_L = length ratio
Re = Reynolds number ($= Uh/\nu$)
S = bottom or energy slope for uniform and non-uniform flows, respectively
U = mean cross-sectional velocity
U_χ = lowest velocity used in determining χ
u_* = shear velocity
α = vegetation parameter
χ = vegetation parameter
ν = kinematic viscosity
ρ = fluid density
ξE = vegetation index

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