

Flow resistance due to shrubs and woody vegetation

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ABSTRACT

In this paper, a theoretical open channel flow resistance equation was verified using flow depth and discharge measurements carried out by Freeman et al. in a large channel, 2.44 m wide, for ten different types of uniform-sized plants (shrubs and woody vegetation). The plants, which are broadleaf deciduous vegetation commonly found in floodplains and riparian zones, were placed in staggered rows inside the channel whose bed was constructed to accept plants with their root systems. For each species, the available measurements were carried out by Freeman et al. with plants having different values of plant density, height, and bending stiffness. The available literature database (87 measurements) was divided into two groups which were separately used to calibrate and test the theoretical approach. In particular, 46 measurements were used to calibrate the relationship between the scale factor Γ of the velocity profile, the Froude number, and the channel slope. This relationship was calibrated using the entire available dataset or varying the scaling coefficient a with the investigated vegetation type. The measured values of the Darcy-Weisbach friction factor, obtained by the measured flow velocity, water depth and slope values, were compared with those calculated by the theoretical flow resistance law, coupled with the relationship for estimating the Γ function having a scaling coefficient different for each investigated vegetation type. This comparison allowed to demonstrate that an accurate estimate of the Darcy-Weisbach friction factor (errors less than or equal to $\pm 10\%$ for 87% of the investigated cases) can be obtained. However, for the investigated vegetation species, that are characterized by a large range of bending stiffness, also a mean value of the scaling coefficient a equal to 0.3283 allows an accurate estimate of the Darcy-Weisbach friction factor.

1. Introduction

Discharge measurement is a consistent objective of hydrometry which can be performed applying different methods. For instance, a common method of discharge measurements applied for rivers is the slope-area method. The latter allows for calculating the discharge using Manning or Darcy-Weisbach equation combined with the measurements of bed slope, cross-section area, hydraulic radius, and an estimate of the channel boundary roughness.

Modeling flow resistance in vegetated channels is useful to estimate the risk of flooding and to plan scientifically-driven flood mitigation strategies [1]. During a flood event, vegetation, having a branch structure and leaves, is able to reduce mean flow velocity and channel conveyance capacity and to increase water depths [2]. Vegetation influences the morphological processes controlling river channel evolution and reduces flow velocity and shear stress affecting sediment deposition [3,4]. Riparian vegetation also has a relevant role in

landscape stability and reduces pollutant loads of flows entering waterways [5].

Estimating friction factors for open-channel flows is a challenging topic useful for bioengineering practices and programming the management of riparian vegetation in rivers [6].

Notwithstanding flow resistance of vegetated channels is a well-studied problem, the obtained results are characterized by applicability limits due to the biodiversity of vegetation and, therefore, to the different hydraulic behavior depending on the mechanical behavior [7]. Flexible grass-like vegetation, for which a widespread literature is available [4,8–14], is commonly completely submerged as its height h_s is small in comparison with the flow depth h [8]. The hydraulic behavior varies if the elements are emergent, for $h < h_s$, or completely submerged ($h > h_s$). Grass-like vegetation elements are generally submerged and assume a different configuration (erect, waving, prone) [4,8] related to the vegetation bending stiffness and the hydrodynamic flow action. Kouwen's method is the most applied for the case of grass-like vegetated

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channels and states that the Darcy-Weisbach friction factor f increases with the stem density as the used stem density M values (7.5–50 stems dm^{-2}) were less than the threshold value, M^* , for which the quasi-smooth skimming flow regime occurs [15]. Carollo et al. [12,13,16,17] carried out some laboratory experiments using three grass vegetation species (*Lolium perenne*, *Festuca rubra*, and *Poa pratensis*) characterized by four stem density values M (280, 310, 337, and 440 stems dm^{-2}). The measurements ($280 \leq M \leq 440$ stems dm^{-2}) of Carollo et al. [12] joined with those of Kouwen et al. [8] ($M = 50$ stems dm^{-2}), Wilson and Horritt [18] ($M = 25$ stems dm^{-2}), and Raffaelli et al. [19] ($10.2 \leq M \leq 20.4$ stems dm^{-2}) demonstrated that for low stem density values ($M \leq 50$ stems dm^{-2}) f increases with M while for high values of M the quasi-smooth (skimming) flow regime [20] occurs and the invariance of the friction factor with the stem density is expected [15].

Riparian vegetation is frequently composed of rigid, erect, and non-submerged elements and the application of the results obtained for grass-like vegetation [12,18,19] is quite limited. The hydraulic behavior of rigid and non-submerged vegetation was generally studied by flume investigations with artificial elements similar to natural plants [21,22] and with real plants or tiny portions of green vegetation [23,24]. The experimental runs were rarely carried out using fully developed vegetation in real flow conditions [24,25]. Järvelä [26] observed that the Darcy-Weisbach friction factor was mostly dependent on the relative roughness, the flow velocity, or the flow depth depending on the examined condition (submerged and unsubmerged). Järvelä [27] also developed a method to determine the Darcy-Weisbach friction factor f caused by stiff and flexible woody vegetation (leafless or leafy bushes or trees). The applicability of the proposed method is limited to non-submerged flow and relatively low flow velocity (≤ 1 m s^{-1}), which are typical conditions in low-gradient stream valleys, floodplains, and wetlands. The accuracy of the approach to estimate f gave better results for the leafless condition as compared to the leafy one.

Rhee et al. [23] carried out some experiments in two large laboratory flumes to investigate the flow resistance of three different vegetation species typical of the Korean region (*Zoysia matrella* (Korean zoysia), *Pennisetum alopecuroides* (L.) Spreng. (Korean native vegetation) and *Phragmites communis* Trin. (Korean reed)). For each vegetation species, the experiments allowed to obtain the ‘ n - VR ’ retardance curves, in which n is the Manning’s coefficient, V is the mean flow velocity, and R is the hydraulic radius. The experimental runs were carried out by a “green” vegetation state, in which the tested vegetation was fully green and in an active growing state, and in a “dormant” state in which vegetation was inactive and started to be wilted or dead. Rhee et al. [23] concluded that the friction factor of *dormant* vegetation is usually smaller than those of the *green* state and the largest hydraulic resistance corresponds to a flow affected by both leaves and stems.

Shi et al. [28] found an inverse relationship, independent of vegetation (*Hydrilla verticillata*) density (stems m^{-2}), between the Manning’s roughness coefficient n and the depth-averaged flow velocity.

Errico et al. [14,29] carried out field investigations to study the effect of the vegetation distribution in drainage channels colonized by *Phragmites australis*. The impact of vegetation and different management scenarios (full-vegetated in natural conditions, bank removal or cutting the vegetation in the central part of the channel, extensive cutting of vegetation) on flow resistance, flow velocity distribution, and flow turbulence was investigated. These investigations allowed to conclude that (i) the increase of flow velocity determines a plant reconfiguration due to drag effects which reduces flow resistance, (ii) the preservation of an undisturbed vegetation buffer on a bank gives hydraulic conditions similar to that of a total cutting of vegetation, and (iii) clearing the vegetation in the central part of the channel increases the channel conveyance to values similar to those obtained by a total cutting of the vegetation.

Small-scale experiments carried out by laboratory flumes allow to detect the interaction between vegetation and flow under controlled conditions. However, these laboratory investigations could be

characterized by scaling problems related to vegetation properties and flow hydraulics and their results should be carefully generalized to natural large-scale conditions. Full-scale experiments allow to investigate the actual interaction between vegetation (stiffness, stem concentration, branching, foliation) and flow characteristics occurring in field conditions [30,31]. Freeman et al. [25] used a large flume to measure in situ flow resistance and obtained power flow resistance equations for submerged and partially submerged conditions. Recently Chiaradia et al. [31] used a full-scale channel to investigate the flow resistance law for three species of shrubs (*Alnus glutinosa* L., *Salix alba* L. and *Salix caprea* L.). These Authors detected a shrub-vegetation behavior due to the plant-flow interaction, which was not previously captured by small-scale experiments. For low values of the product VR the riparian vegetation behaves as a rigid body and, as a consequence, flow resistance increases with VR . For increasing VR values a new hydraulic behavior is detected: the flow resistance decreases as a result of stem and branch bending and/or leaf-branch compaction. No functional relationship between vegetation Manning’s coefficient and variables representative of flow and plant characteristics was obtained.

Currently, flow resistance in open channels is estimated by well-known hydraulic equations such as Manning’s and Chezy’s [15,32,33]. The developed review analysis showed that the resistance coefficient for vegetated channels is expressed by Manning n or Darcy-Weisbach f for which the following relationship can be provided [34]:

$$\sqrt{\frac{8}{f}} = \frac{V}{u_*} = \frac{R^{1/6}}{\sqrt{g} n} \quad (1)$$

in which V is the cross-section average velocity, $u_* = \sqrt{g R s}$ is the shear velocity, g is the acceleration due to gravity and s is the channel slope.

To the best of our knowledge, Manning’s n has been generally used to analyze measurements carried out in vegetated waterways, while theoretical analyses were developed using f [8–12].

From a theoretical point of view, the flow-resistance law can be obtained by the integration of a known flow-velocity distribution in the cross-section law [35–37]. In previous papers, a power-velocity distribution, deduced by dimensional analysis and the self-similarity theory, was integrated to obtain the Darcy-Weisbach friction factor [36,38]. The applicability of this flow resistance equation was tested for gravel-bed rivers [38], rill flows [39] and overland flows [40]. Ferro [4] calibrated and tested a theoretical flow resistance law using available small-scale laboratory measurements carried out with grass-like vegetation by Kouwen et al. [8], Wilson and Horritt [18], Raffaelli et al. [19] and Carollo et al. [12]. Nicosia et al. [41] calibrated and tested the theoretical flow resistance law proposed by Ferro [4] using the measurements by Chiaradia et al. [31]. The developed analysis demonstrated that the theoretical flow resistance law coupled with the relationship for estimating the velocity profile parameter, having a scaling factor different for each investigated vegetation type, allows the best estimate of the Darcy-Weisbach friction factor (estimate errors less than or equal to 20% for 82.6% of the cases).

A significant research need is to solve the lack of approaches to estimate flow resistance for vegetated channels characterized by rigid vegetation, such as that made by woody vegetation and shrubs. The greatest limit of the few studies available in the literature is represented by the small number of flow velocity and resistance measurements performed for full-scale channels characterized by woody vegetation and shrubs. Moreover, these studies present the results in terms of Darcy-Weisbach friction factor f or Manning’s n following empirical approaches. While, a theoretical approach, capable overcoming the gap between the flow velocity distribution and the flow resistance law, could be a major tool for studying hydraulics of flows in vegetated channels. For these reasons, in this paper, the theoretical approach by Ferro [4] was tested by measurements carried out by Freeman et al. [25] in a

large-scale flume with shrub and woody vegetation. In particular, testing the relationship between the Darcy-Weisbach friction factor f and variables representative of flow and plant characteristics, the main novel element is the introduction of the slope as a parameter of the equation, as compared to that developed by Nicosia et al. [41] for a full-scale vegetated channel, and considering the influence of the rigid vegetation types on flow resistance. Consequently, the main objectives of this paper are to (i) test the applicability of the theoretical approach by Ferro [4] for a large-scale flume with shrub and woody vegetation, and (ii) assess the effect of each vegetation type on flow resistance.

2. Materials and methods

2.1. Theoretical flow resistance equation

Since the Π -Theorem of the dimensional analysis and self-similarity theory [35,42] can be used to obtain a functional relationship representing the flow velocity distribution, the following expression of the velocity profile can be suggested [37]:

$$\frac{y}{u_*} \frac{dv}{dy} = \varphi \left(\frac{u_* y}{\nu_k}, \frac{u_* h}{\nu_k}, \frac{h}{d}, s, F \right) \quad (2)$$

in which v is the local velocity, y is the distance from the bottom, ν_k is the water kinematic viscosity, s is the channel slope equal to the tangent of the slope angle, φ is a functional symbol, d is the roughness height and $F = V/\sqrt{g h}$ is the flow Froude number.

Assuming the Incomplete Self-Similarity in $u_* y/\nu_k$ [36] and integrating Eq. (2), Ferro [36,38] obtained the following power velocity distribution:

$$\frac{v}{u_*} = \left[\frac{1}{\delta} \varphi_1 \left(\frac{u_* h}{\nu_k}, \frac{h}{d}, s, F \right) \right] \left(\frac{u_* y}{\nu_k} \right)^\delta \quad (3)$$

in which φ_1 is a functional symbol and δ is a coefficient to be calculated by the following theoretical equation [43]:

$$\delta = \frac{1.5}{\ln Re} \quad (4)$$

in which $Re = V h/\nu_k$ is the flow Reynolds number.

Taking into account that the ratio between $u_* h/\nu_k$ and h/d is equal to the shear Reynolds number Re^* and that F is related to the depth sediment ratio h/d and Re^* [38], Eq. (3) can be expressed in the following form:

$$\frac{v}{u_*} = \Gamma(s, F) \left(\frac{u_* y}{\nu_k} \right)^\delta \quad (5)$$

in which $\Gamma(s, F)$ is a function of channel slope and flow Froude number to be defined by velocity measurements.

Integrating the velocity distribution (Eq. (5)), the following expression of the Darcy-Weisbach friction factor f is deduced [36,37]:

$$f = 8 \left[\frac{(\delta + 1)(\delta + 2)}{2^{1-\delta} \Gamma R e^\delta} \right]^{2/(1+\delta)} \quad (6)$$

which is independent of R , differently from measured Darcy-Weisbach friction factor having the following expression:

$$f = \frac{8 g R s}{V^2} = 8 \frac{s}{F^2} \left(\frac{R}{h} \right) \quad (7)$$

From Eq. (5) the following estimate Γ_v of Γ function [36,37] can be obtained by setting $y = \alpha h$, being αh the distance from the bottom at which the local velocity is equal to the cross-section average velocity V :

$$\Gamma_v = \frac{V}{u_* \left(\frac{u_* \alpha h}{\nu_k} \right)^\delta} \quad (8)$$

The coefficient α is less than 1 and takes into account that: a) the average velocity V is located below the water surface and, b) the mean velocity profile in the cross-section is considered (i.e., the velocity profile is obtained by averaging for each distance y the velocity values v measured in different verticals, and its integration gives the cross-section average velocity). The coefficient α has to be calculated by the following theoretical relationship deduced by Ferro [36]:

$$\alpha = \left[\frac{2^{1-\delta}}{(\delta + 1)(\delta + 2)} \right]^{1/\delta} \quad (9)$$

In the measured range of flows in riparian-vegetated channels ($154,499 \leq Re \leq 970,483$) α varies in a very narrow range (0.119–0.120).

Considering that, according to Eq. (5), Γ theoretically depends only on channel slope and flow Froude number [38], Γ_v can be estimated by F and s by the following power equation:

$$\Gamma_v = a \frac{F^b}{s^c} \quad (10)$$

in which a , b and c are coefficients to be determined from experimental measurements.

2.2. Large-scale experiments by Freeman et al. [25]

Freeman et al. [25] carried out experiments on a large flume, 2.44 m wide, 1.82 m deep, and 152.4 m long, at the Utah Water Research Laboratory, investigating the effect of vegetation on flow resistance (Fig. 1). The investigated slope varied in the range 0.0002–0.008. In particular, the following ten different broadleaf deciduous species, commonly found in floodplains and riparian zones, were singularly evaluated: Yellow Twig Dogwood (*Cornus stolonifera flaviramea*), Berried Elderberry (*Sambucus racemosa*), Purpleleaf Euonymus (*Euonymus fortunei colorata*), Red Twig Dogwood (*Cornus sericea*), Service Berry (*Amelanchier*), Mulefat (*Baccharis glutinosa*), Valley Elderberry (*Sambucus mexicana*), Salt Cedar (*Tamarix* spp.), Black Willow (*Salix nigra*), and Mountain Willow (*Salix monticola*).

The plants were placed intact, with root structure and original soil, into a 20.3-cm deep experimental bed, in the center of the 22.9-m long experimentation flume section. In the first phase of the study, the bed consisted of a layer of gravel, to promote drainage, covered with compacted clay, which supported plants and avoided that they were washed downstream. In the second phase of the study, the compacted clay was replaced with a gravel bed and a mortar cap, which facilitated the changing of plants and experimental setups. The mortar cap had 158 plant containers in the bed in staggered rows of four and five plants per row. The spacing chosen for the plants was based on that typically found in floodplains, while plant density, M , was calculated as the number of plants per unit area. The plant characteristics (plant height, stem diameter, number of stems, and bending characteristics) are listed in Table 1.

Upstream and downstream of the experimentation section, the flume had a roughened-bed section, determined by the presence of cinder blocks that were adjusted until they produced a fully developed turbulent velocity distribution. At the downstream end of the flume, 91.4 m

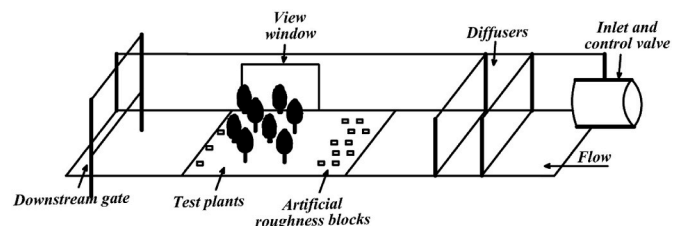


Fig. 1. Sketch of the experimental channel used by Freeman et al. [25].

Table 1
Main characteristics for each analyzed vegetation type.

Plant	Plant height H	Stem diameter	Bending stiffness	N stem	a_v	h/H		$h/H < 1$ (cases in %)
	m	m	10^8 N m^{-2}			mean	condition	
Yellow Twig Dogwood	0.51	0.0095	3.21	1	0.3295	1.84	predominantly submerged	7.7
Berried Elderberry	0.71	0.0095	0.526	1	0.3194	1.27	predominantly submerged	10.0
Purpleleaf Euonymus	0.2	0.0063	4.14	2	0.3228	4.64	submerged	0.0
Red Twig Dogwood	0.97	0.0252	10.2	2	0.3254	1.01	predominantly emerged	60.0
Service Berry	0.71	0.0063	47.6	6	0.3266	1.37	predominantly submerged	16.7
Yellow Twig Dogwood 2	0.71	0.0095	29.9	2	0.3357	1.79	submerged	0.0
Mulefat	0.97	0.0126	5.95	1	0.3398	1.32	submerged	0.0
Valley Elderberry	0.97	0.0268	16.5	1	0.329	1.21	predominantly submerged	25.0
Salt Cedar	1.52	0.0316	13.1	1	0.3325	0.72	emerged	100.0
Black Willow	1.22	0.0189	1.5	1	0.3273	0.87	predominantly emerged	57.1
Mountain Willow	1.52	0.0254	3.41	4	0.3253	0.69	emerged	100.0
Mountain Willow (no leaves)	1.52	0.0254	3.41	4	0.3265	0.69	emerged	100.0

h = water depth.

downstream of the experimental section, flow depth was controlled using a hydraulic gate. Water from the river adjacent to the laboratory entered the flume through a pipe located 50.3 m upstream from the experimentation section.

Water-surface elevations were measured by a stationary transit and a measuring rod along the centerline of the flume, while flow velocities were measured by a Marsh McBirney Model 201 portable water current meter.

Typically, nine runs were made for each series of experiments (three at high depths, with the flume nearly full, and at three different velocities; three at a medium depth; three at a low depth). The plants were usually submerged, even at low depths, because the flow forces were adequate to bend the plants with the flow.

3. Results

The available database for this investigation is characterized by a wide range of the Reynolds number ($154,499 \leq Re \leq 970,483$), denoting a turbulent flow regime, while the experimental Froude number values ($0.04 \leq F \leq 0.47$) suggest that flows are all subcritical. Moreover, in the range of the investigated water depth values, the ratio R/h (Fig. 2) is always less than 1, i.e., the cross-section is not rectangular very-wide. In particular, for all the measured h values, the ratio R/h varies from 0.46 to 0.7 (Fig. 2).

The available 87 data by Freeman et al. [25] were divided into two datasets: 46 data were used for calibrating and 41 for testing. The calibrating dataset allowed to obtain the following equation to estimate the

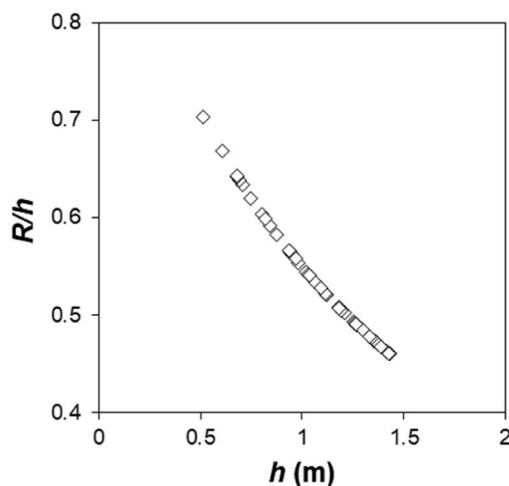


Fig. 2. Relationship between the water depth h and the ratio R/h for the investigated hydraulic conditions.

Γ_v function:

$$\Gamma_v = 0.326 \frac{F^{1.0167}}{s^{0.5633}} \tag{11}$$

which is characterized by a coefficient of determination equal to 0.986. Fig. 3 shows the comparison between the measured Γ_v values, obtained by Eq. (7) with $\alpha = 0.119$, and those calculated by Eq. (11). This figure also demonstrates that Eq. (11) is positively tested by the flow velocity, depth, and slope measurements belonging to the testing dataset.

Introducing Eq. (11) into Eq. (6) and considering that Re^δ is always equal to 4.4817, the following equation to estimate the Darcy-Weisbach friction factor was obtained:

$$f = 8 \left[\frac{(\delta + 1)(\delta + 2)}{2^{1-\delta} 4.4817} \frac{s^{0.5633}}{0.326 F^{1.0167}} \right]^{\frac{2}{1+\delta}} \tag{12}$$

Fig. 4 shows the comparison between the measured values of the Darcy-Weisbach friction factor and those calculated by Eq. (12) for both calibrating and testing datasets. The friction factor values calculated by Eq. (12) are characterized by errors that are always less than or equal to $\pm 20\%$ and less than or equal to $\pm 10\%$ for 86.2% of cases. The agreement between measured f values and those calculated by Eq. (12) is characterized by a MSE equal to 0.000461.

Considering that Re^δ is always equal to 4.4817 and setting δ , being its range narrow (0.11–0.125), equal to its mean value (0.115), Eq. (12) can

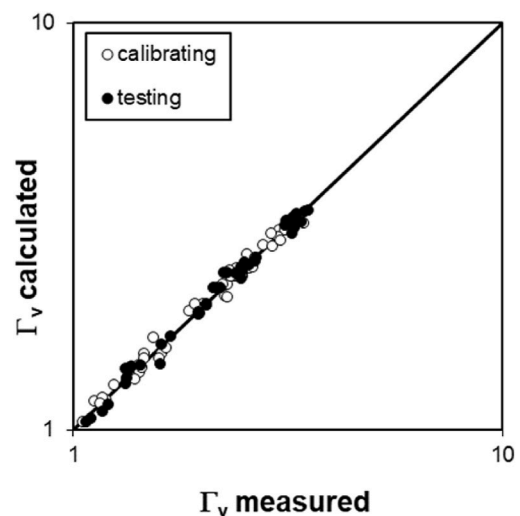


Fig. 3. Comparison between the measured Γ_v values, obtained by Eq. (8) with $\alpha = 0.119$, and those calculated by Eq. (11) for both calibrating and testing datasets.

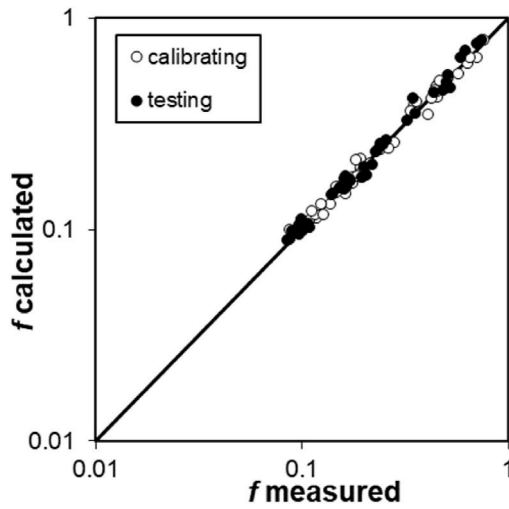


Fig. 4. Comparison between the f measured values and those calculated by Eq. (12) for both calibrating and testing datasets.

be rewritten as:

$$f = 6.29 \frac{s^{1.0102}}{F^{1.8235}} \tag{13}$$

The values of b and c of Eq. (10) were fixed to exclusively attribute the vegetation effect to the a coefficient, renamed a_v , obtaining the following flow resistance equation:

$$f = 8 \left[\frac{(\delta + 1)(\delta + 2)}{2^{1-\delta} 4.4817} \frac{s^{0.5633}}{a_v F^{1.0167}} \right]^{\frac{2}{1+\delta}} \tag{14}$$

For each type of vegetation, the behavior of the pairs $(F^{1.0167}/s^{0.5633}, \Gamma)$ was investigated and a value of the a_v coefficient, equal to the slope coefficient of the best-fit straight line passing through the origin of the axes, was obtained (Table 1). Introducing the specific a_v coefficient of each type of vegetation into Eq. (14), the Darcy-Weisbach friction factor values were recalculated. Fig. 5 shows the comparison between the measured values of the Darcy-Weisbach friction factor and those calculated by introducing the specific a_v coefficient of each type of vegetation into Eq. (14). In this case, the errors in the f estimate are always less than or equal to $\pm 20\%$ and less than or equal to $\pm 10\%$ for 87.4% of cases. The agreement between measured f values and those

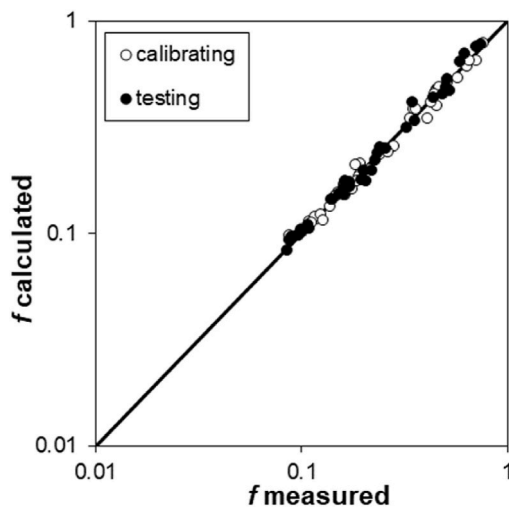


Fig. 5. Comparison between the f measured values and those calculated by introducing the specific a_v coefficient of each type of vegetation into Eq. (14) for both calibrating and testing datasets.

calculated by Eq. (14), introducing the specific a_v coefficient of each type of vegetation, is characterized by a MSE equal to 0.000526 and a coefficient of determination of 0.984.

Since the obtained a_v values varied from 0.3194 to 0.3398, highlighting a low variability depending on the vegetation type, the mean a_v value, equal to 0.3283, was introduced into Eq. (14). Fig. 6 shows the comparison between the measured values of the Darcy-Weisbach friction factor and those calculated by introducing the mean a coefficient (0.3283) into Eq. (14) for both calibrating and testing datasets. In this case, the errors estimating f are always less than or equal to $\pm 20\%$ and less than or equal to $\pm 10\%$ for 85.1% of cases. The agreement between measured f values and those calculated by Eq. (14), with $a_v = 0.3283$, is characterized by a MSE equal to 0.000517 and a coefficient of determination of 0.985.

Considering that Re^δ is always equal to 4.4817 and setting $\delta = 0.115$ and $a_v = 0.3283$, Eq. (14) can be rewritten as:

$$f = 6.21 \frac{s^{1.0102}}{F^{1.8235}} \tag{15}$$

Comparing the performance of Eqs. (12) and (14) in terms of errors estimating f , the slight variations for the error bands of $\pm 20\%$ and $\pm 10\%$ suggest that the effect of the different examined types of vegetation on flow resistance is almost negligible.

Fig. 7 shows the empirical frequency distribution of the errors, E (%), of Darcy-Weisbach friction factors estimated by Eq. (12), Eq. (14) with specific a_v values, and Eq. (14) with $a = 0.3283$.

Finally, the relationship between a_v and bending stiffness values (Table 1) is plotted in Fig. 8.

4. Discussion

Even considering the hypothesis of rectangular very-wide cross-section, i.e., $R/h = 1$, Eq. (7) gives $f = 8s F^{-2}$, which demonstrates that the scale factor (6.29 instead of 8) and the exponents of slope and Froude number are different from those of Eq. (13). Taking into account that Fig. 2 shows that R/h is always different from 1, the comparison between Eq. (7) and Eq. (13) demonstrates that Eq. (6), coupled with Eq. (10), or Eq. (13) are not spurious correlations.

Figs. 4–6 confirm the applicability of the theoretically deduced [4] Eq. (10) to the measurements carried out by Freeman et al. [25] for both calibrating and testing datasets. The good agreement between the measured Darcy-Weisbach friction factor values and those calculated by Eq. (12) (Fig. 4), can be slightly improved using a different a coefficient

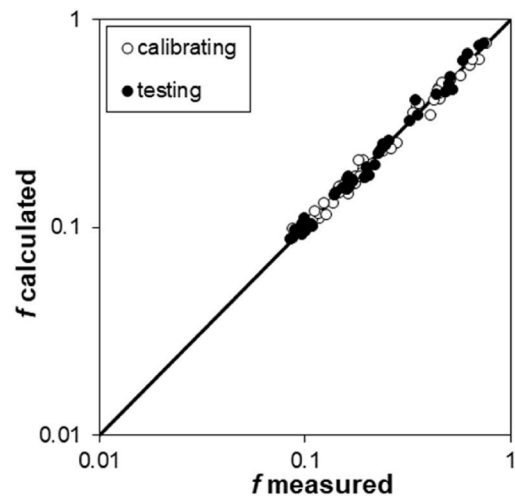


Fig. 6. Comparison between the f measured values and those calculated by introducing the mean a coefficient (0.3283) into Eq. (14) for both calibrating and testing datasets.

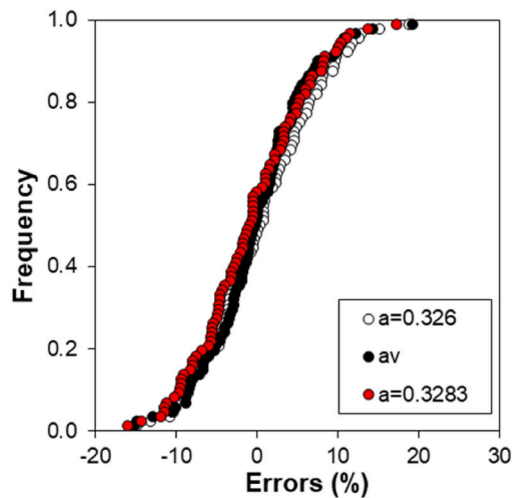


Fig. 7. Empirical frequency distribution of the errors, E (%), of Darcy-Weisbach friction factors estimated by Eq. (12), Eq. (14) with specific a_v values, and Eq. (14) with $a = 0.3283$.

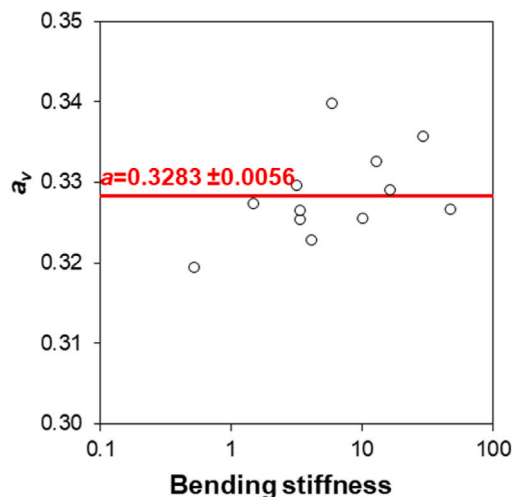


Fig. 8. Relationship between a_v and bending stiffness values.

for each type of vegetation (Eq. (14), Fig. 5). However, for the investigated vegetation species, also a mean value of the scaling coefficient a , equal to 0.3283, into Eq. (14), allows an accurate estimate of the Darcy-Weisbach friction factor (Fig. 6). The comparable performances in f estimate, highlighted in terms of errors by Fig. 7, obtained by the three applied procedures suggest that considering the vegetation type does not significantly affect the flow resistance law. This result is probably due to the circumstance that almost all the examined species are shrubs, except Service Berry, Black Willow, and Mountain Willow, which, however, are not mature plants and, for this reason, are comparable with shrubs.

Fig. 6 shows that, although the range of bending stiffness of the examined species is quite wide (i.e., the plants are characterized by a different degree of flexibility), a_v variability is moderate. This result highlights that no marked differences in flow resistance occur depending on different flexibilities of vegetation. Nicosia et al. [41] proposed an equation capable to consider the behavior of the vegetation elements depending on the bending stiffness. In fact, for low bending stiffness values, vegetation tends to assume a prone position even for low flow velocities, and its behavior from a flow resistance point of view is more streamlined. For increasing bending stiffness, i.e., more rigid vegetation, higher flow velocities are necessary to reach a fixed inflection degree of vegetation, and, consequently, a higher flow resistance should occur.

Instead, in this case, even if the examined vegetation types are characterized by a large range of bending stiffness, stem diameter, plant height, and different conditions of submergence (Table 1), the flow resistance behavior is quite uniform and a single value of a_v allows to represent the effect of vegetation on flow resistance.

5. Summary and conclusions

Literature measurements carried out by Freeman et al. [25] in a vegetated channel were used to test the applicability of a theoretical flow resistance law proposed by Ferro [4] and previously calibrated and tested using available small-scale laboratory measurements carried out with grass-like vegetation. The available measurements were divided into two groups which were separately used to calibrate and test the theoretical approach. At first, the calibrating dataset was used to calibrate the relationship between the scale factor Γ of the velocity profile, the Froude number, and channel slope. Then, the relationship was calibrated varying the scaling coefficient a with the investigated vegetation type. Finally, for the investigated vegetation species, that are characterized by a large range of bending stiffness, also the use of the mean value of the scaling coefficient a , equal to 0.3283, was investigated. The theoretical flow resistance law, coupled with the relationship for estimating the Γ function having a scaling coefficient different for each investigated vegetation type, gave the most accurate estimate of the Darcy-Weisbach friction factor, but also using a unique mean value of a led to satisfying results.

Since few experimental data are available in the literature, many aspects of vegetation effects on channels hydraulics should be yet considered. Further experiments could be carried out to widen the knowledge about different riparian vegetation species and their behavior regarding flow resistance. In the next future, a stimulating challenge might be to investigate the relationship between different degrees of riparian vegetation biodiversity and the consequent flow behavior in channels located in the Mediterranean area, with a specific focus on the species aggregation which characterizes these riparian ecosystems.

Credit author statement

A. Nicosia: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing, V. Ferro: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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