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Flow resistance of flexible vegetation in real-scale drainage channels

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Abstract

The definition of simple and accurate methods to estimate flow resistance in vegetated channels is still a challenging issue in soil bioengineering practices and programming riparian vegetation management to control channel conveyance capacity, sediment deposition, and flooding propensity. In this paper, measurements collected by Errico et al. (2018, 2019) in drainage channels colonized by common reed (*Phragmites australis*) were used to study the effect of flexible vegetation and its management in flow resistance estimate. At first, a theoretical flow resistance equation, obtained applying dimensional analysis and incomplete self-similarity condition for the velocity distribution of an open channel flow, was briefly summarized. Then, this flow resistance equation was calibrated and tested by open-field hydraulic experiments carried out by Errico et al. (2018, 2019) at the real scale of existing vegetated drainage channels. In particular, the Γ function of the power velocity profile was empirically related to the slope energy and the flow Froude number by using the available measurements. Taking into account the hydrological regime of the flow in the investigated channels, the original data set was divided into two sub-data sets (calibrating and testing data set) exploring the same range of measured discharges. The calibration and testing of the flow resistance equation were carried out without distinguishing measurements corresponding to different vegetation conditions (full-vegetated, half-vegetated, non-vegetated, central vegetation cut, extensive vegetation cut). The analysis demonstrated that the theoretical flow resistance equation allows an accurate estimate of the Darcy-Weisbach friction factor which is characterized by errors that are always less than 10% and less than or equal to 5% for 90.9% of the investigated cases. The finding of this study also allowed to evaluate the effects of different vegetation management scenarios on flow resistance.

KEYWORDS

biomechanical characteristics, dimensional analysis, flexible, flow resistance, open channel, self-similarity, vegetation, velocity profile

1 | INTRODUCTION

Many scientific and management issues are related to the presence of vegetation inside a channel as it reduces flow conveyance capability, affects morphological channel evolution and sediment deposition, and plays a significant role in the interaction between aquatic ecosystems and river hydraulics (Sandercock & Hooke, 2010). Modelling open channel flows in vegetated streams is useful to establish the river's propensity to flooding and to establish river management aimed to flood mitigation (Green, 2005). During a flood, the presence of vegetation characterized by compact foliage and branch structure determines an increase in water depth and a reduction in mean flow velocity and conveyance capacity (Yagci and Yagci & Kabdasli, 2008). The uncontrolled vegetation growth determines an increase in flow resistance, a progressive reduction in the channel conveyance, and a rising in flood hazard (Vargas-Luna et al., 2015).

Riparian vegetation has an important role in bank stabilization and can reduce pollutant loads entering the waterways (Olley et al., 2015). Riparian vegetation on riverbanks and floodplains has a key role in providing habitats and food resources for animal life, supporting channel stability, and enhancing the aesthetic value of a river (Coreblint et al., 2009).

The use of vegetation as a soil bioengineering stabilization practice (e.g., live staking, live fascine installation, vegetated geogrids, vegetated crib walls) (Ferro, 2019b; Florineth, 2007) is considered a good river restoration practice to preserve natural ecosystems and reduce the channel erosive phenomena. However, a simple and accurate method for estimating vegetation flow resistance is still a challenging issue in soil bioengineering practices and management of riparian vegetation in river channels (Lama et al., 2020).

The main limits of the flow resistance investigations in open channels are due to the high variability of vegetation types which affects the hydraulic behaviour (García Díaz, 2005) and the small-scale installations which are generally used in the experimental studies (Green, 2005).

Previous researches were mainly for grass-like vegetation (Carollo et al., 2005, 2008; Errico et al., 2018, 2019; Ferro, 2019a; Kouwen, 1988; Kouwen et al., 1969; Kouwen & Li, 1980; Kouwen & Unny, 1973; Kowobary et al., 1972). Grass-like vegetation is flexible, and is generally completely submerged as its height h_s is less than the flow depth h (Gourlay, 1970). Moreover, the hydraulic behaviour of a single vegetation type is dependent on whether the plant elements are emergent, for $h < h_s$, or completely submerged ($h > h_s$). The interaction between the hydrodynamic flow action and the bending stiffness of the vegetation element determines its configuration (erect, waving, prone) (Ferro, 2019a).

A wide experimental investigation was developed by Kouwen and co-workers (Kouwen, 1988; Kouwen et al., 1981; Kouwen & Li, 1980; Kouwen & Unny, 1973) to estimate the Darcy-Weisbach friction factor of grasslike vegetated channels. The theoretical analysis, related to the biomechanical properties of the vegetation, and the experimental data used for calibrating Kouwen's method (Kouwen & Li, 1980; Kouwen & Unny, 1973) demonstrated that the friction factor increases with stem density. This last result can be justified considering that the stem density M values used for Kouwen's experiments (7.5–50 stems dm^{-2}) are moderate and less than the limit value M^*, corresponding to the quasi-smooth skimming flow regime, for which the friction factor becomes invariant with the stem density (Ferro, 1999).

Experiments with three grass vegetation species (*Lolium perenne*, *Festuca rubra*, and *Poa pratensis*) and different values of stem density M (280, 310, 337, and 440 stems dm^{-2}) were carried out by Carollo et al. (2002, 2005, 2007, 2008). These experiments (Carollo et al., 2005) demonstrated that Kouwen's method systematically overestimates the flow resistance, and this bias effect increases with stem concentration. The experiments by Carollo et al. (2005), carried out for $280 \le M \le 440$ stems dm^{-2}, joined with those of Kouwen et al. (1969) ($M = 50$ stems dm^{-2}), Wilson and Horritt (2002) ($M = 25$ stems dm^{-2}) and Raffaelli et al. (2002) ($10.2 \le M \le 20.4$ stems dm^{-2}) allowed to conclude that, for M values less than 50 stems dm^{-2}, the friction factor increases with the stem concentration, while high values of M are characterized by the invariance of the friction factor with the stem density (Ferro, 1999) as the quasi-smooth (skimming) flow regime (Morris, 1959) occurs.

Investigations on rigid and non-submerged vegetation were generally carried out using artificial elements hydraulically similar to natural plants and laboratory flumes (Righetti & Armanini, 2002; Wilson et al., 2003; Yagci et al., 2010). Small-scale flumes were generally used for carrying out experiments with very young real plants or tiny portions of green vegetation (Armanini et al., 2005; Rhee et al., 2008; Västilä et al., 2013). The experiments were rarely carried out using fully developed vegetation in field channel conditions (Chiaradia et al., 2019; Errico et al., 2018, 2019; Freeman et al., 2000; Västilä et al., 2013).

Phragmites australis, also named common reed, is a plant species widespread around the world, and it is recognized as invasive in Canada and USA, while it is endemic in Europe and Asia (Errico et al., 2018). Notwithstanding this species was largely investigated for its diffusion in aquatic environments, the experimental data related to real scale channels are very limited. Even if small-scale experiments in flumes are useful to study the relationship between vegetation and flow under controlled conditions, scaling problems linked to flow hydraulics and vegetation properties may occur, and the results, obtained by accurate laboratory measurements, should be cautiously applied to natural conditions (Chiaradia et al., 2019; Florineth et al., 2003).

Using two large laboratory flumes (1 m and 3 m wide), Rhee et al. (2008) investigated 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 species, these authors obtained 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 experiments used two different states: (i) "*green*" state, in which the plants were fully green and in an active growth state, and (ii) "*dormant*" state, in which the tested plants were inactive and were becoming wilted or dead. The measurements demonstrated that flow resistance of *dormant* plants is generally smaller than that of *green* vegetation, and resistance coefficients associated with a condition in which the flow is affected by both the leaf and stem part of vegetation are higher than those representing a flow only affected by the stem part.

Errico et al. (2018, 2019) 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.

Notwithstanding numerous experimental and theoretical studies on flow resistance in vegetated channels have been developed, and new methods to estimate the friction factor have been proposed, the application of classical hydraulic equations, such as Manning's and Chezy's (Ferro, 1999; Govers et al., 2007; Powell, 2014), continues to be the most common applied method to estimate open channel flow resistance. For expressing the resistance coefficient, the Manning's n or Darcy-Weisbach's f are applied for vegetated channels (Yen, 1992):

$$\sqrt{\frac{8}{f}}=\frac{V}{u_*}=\frac{R^{1/6}}{\sqrt{g}\,n} \tag{1}$$

in which V is the cross-section average velocity, $u_* = \sqrt{gRs}$ is the shear velocity, g is the acceleration due to gravity, and s is the channel slope. Manning's coefficient has been used to develop analysis based on field and flume measurements in vegetated channels, while f has been frequently applied for developing theoretical analysis (Carollo et al., 2005; Ferro, 2019a).

The relationship between the velocity distribution and flow resistance is a challenging topic of open channel flow hydraulics (Ferro & Pecoraro, 2000) as the integration of the flow-velocity distribution in the cross-section is required to deduce a theoretical flow-resistance law (Ferro, 1997; Ferro & Porto, 2018a).

In previous papers, the integration of a power-velocity distribution, deduced by dimensional analysis and the self-similarity theory, allowed to obtain a theoretical expression of the Darcy-Weisbach friction factor (Ferro, 2017, 2018). The applicability of this theoretical flow resistance equation was verified for gravel-bed rivers (Carollo & Ferro, 2021; Ferro, 2018; Ferro & Porto, 2018a, 2018b), for rill flows (Di Stefano et al., 2019a, 2019b, 2022; Nicosia et al., 2019; Palmeri et al., 2018), overland flows (Nicosia, Di Stefano, Pampalone, Palmeri, & Ferro, 2020; Nicosia, Di Stefano, Pampalone, Palmeri, Ferro, & Nearing, 2020; Nicosia, Di Stefano, Pampalone, Palmeri, Ferro, Polyakov, & Nearing, 2020), and vegetated channels (Ferro, 2019a; Nicosia et al., 2021). Ferro (2019a) deduced the flow velocity profile above the grass-like flexible vegetation and obtained, by its integration, the theoretical flow resistance law. This last law was calibrated and tested by Ferro (2019a) using available small-scale laboratory measurements carried out by Kouwen et al. (1969), Wilson and Horrit (2002), Raffaelli et al. (2002), and Carollo et al. (2005).

Since, to the best of our knowledge, no studies regarding the effect of the vegetation management scenario on flow resistance are available, in this paper, for the first time, the applicability of the theoretical approach by Ferro (2019a) was tested by field measurements (flow depth h, channel slope s, mean flow velocity V, flow Reynolds number Re, flow Froude number F and Darcy-Weisbach friction factor f) carried out by Errico et al. (2018, 2019) in drainage channels colonized by *Phragmites australis*. The general aim of this study is to test a theoretical law to estimate the Darcy-Weisbach friction factor for real-scale vegetated channels colonized by common reed (*Phragmites australis*). The particular aims of this study are: (i) to test the applicability of the theoretical approach by Ferro (2019a) using full-scale measurements to estimate the flow resistance for vegetated and non-vegetated conditions and (ii) to evaluate the effects of different vegetation management scenarios on flow resistance.

2 | MATERIALS AND METHODS

2.1 | Theoretical flow resistance equation

In previous papers, Di Stefano et al. (2017, 2018), using the Π-Theorem of the dimensional analysis (Barenblatt, 1979, 1987, 1993; Ferro, 1997) and the Incomplete Self-Similarity (ISS) in $u_* y/\nu_k$ (Barenblatt & Monin, 1979; Barenblatt & Prostokishin, 1993; Ferro & Pecoraro, 2000), proposed the following expression of the velocity distribution (Ferro & Porto, 2018a):

$$\frac{v}{u_*}=\left[\frac{1}{\delta}\,\phi\left(\frac{u_* h}{\nu_k},\frac{h}{d},s,F\right)\right]\left(\frac{u_* y}{\nu_k}\right)^{\delta} \tag{2}$$

in which v is the local velocity, y is the distance from the bottom, ν_k is the water kinematic viscosity, s is the energy slope, ϕ is a functional symbol, d is the bed particle diameter, $F = V/\sqrt{gh}$ is the flow Froude number, and δ is a coefficient to be calculated by the following theoretical equation (Barenblatt, 1991; Castaing et al., 1990):

$$\delta=\frac{1.5}{\ln Re} \tag{3}$$

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

As the ratio between $u_* h/\nu_k$ and h/d is equal to the shear Reynolds number Re_* and F is related to the depth sediment ratio h/d and Re^* (Ferro, 2018), Equation (3) assumes the following form:

$$\frac{v}{u_*}=\Gamma(s,F)\left(\frac{u_* y}{\nu_k}\right)^{\delta} \tag{4}$$

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

The integration of the velocity profile (Equation 4) allows to deduce the following expression of the Darcy-Weisbach friction factor *f* (Barenblatt, 1993;Ferro, 2017 ; Ferro & Porto, 2018a):

$$f=8\left[\frac{2^{1-\delta}\,\Gamma\, Re^{\delta}}{(\delta+1)(\delta+2)}\right]^{-2/(1+\delta)} \tag{5}$$

The following estimate Γ_v of Γ function (Ferro, 2017; Ferro & Porto, 2018a) was obtained by setting into Equation (4) $y = \alpha h$, being αh the distance from the bottom at which the local velocity is equal to the cross-section average velocity *V*:

$$\Gamma_v=\frac{V}{u_*\left(\frac{u_*\,\alpha h}{\nu_k}\right)^{\delta}} \tag{6}$$

The coefficient α, which is less than 1, considers that (i) the average velocity *V* is located below the water surface, and (ii) a 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). Ferro (2017) proposed the following relationship to calculate the coefficient α:

$$\alpha=\left[\frac{2^{1-\delta}}{(\delta+1)(\delta+2)}\right]^{1/\delta} \tag{7}$$

Considering that Equation (4) states that Γ theoretically depends only on the channel slope and flow Froude number (Ferro, 2018), Γ_v can be estimated by the following power equation:

$$\Gamma_v=a\,\frac{F^b}{s^c} \tag{8}$$

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

2.2 | Experimental data

Errico et al. (2018) carried out some experiments on the final reach of a drainage channel, named Bresciani channel, which is located right outside of the Migliarino-Rossore-Massaciuccoli Regional Park, Tuscany, Italy. The experimental channel is 300 m long. The reach is characterized by an uniform slope and cross-section having a trapezoidal shape, with a scarp equal to 1, a bankfull width of 5.3 m, and a depth of 1 m. The channel is colonized by vegetation composed of common reed (*Phragmites australis*). Hydraulic tests were carried out for three vegetation scenarios: (i) vegetation reaching the maximum development flowering stage (full-vegetated, FV), (ii) vegetation from one bank and the entire channel bottom (half-vegetated, HV), and (iii) complete removing of the vegetation cover (non-vegetated, NV).

The first scenario is characterized by a central part of the cross-section in which leafed emergent reeds become submerged when high-flow conditions occur, while in the banks the vegetation protrudes from the water surface. The second scenario is characterized by emergent reed covering 30% of the channel wetted perimeter. In the third scenario, the vegetation is cut at the base along the whole wetted perimeter. Four full-scale experiments were carried out for each investigated condition (FV, HV, NV). Four flow rate values (0.3, 0.6, 0.9, and 1.2 $m^3\ s^{-1}$) in the experimental stretch were obtained by regulating the water pumped into the channel by four PET pipes connected to just as many pumps. Three operators monitored the water levels, recording the level every 3 min using staff gages. In correspondence of the central section, the flow velocity was measured by a current meter (USGS, Type AA). Further details on the experimental tests are reported in the paper by Errico et al. (2018).

Errico et al. (2019) carried out a field investigation in the channel, named Piaggetta, which is located near Massacciuccoli lake, northern Tuscany, Italy. The experimental channel is 200 m long. The reach is characterized by average width of 5 m and an average bankfull depth of 0.8 m. The channel surface is completely covered by dense canopies of *Phragmites australis*. Hydraulic tests were carried out for three vegetation scenarios: (i) undisturbed vegetation (UV) in natural conditions, (ii) a vegetation management strategy which is practiced by cutting the central part of the channel for a width of 2.7 m (central cut, CC), and (iii) a cut of the vegetation along the whole wetted perimeter (extensive cut, EC). Six full-scale experiments were carried out: one experimental run for the UV condition, two runs for the CC condition, and three runs for the extensive cut (EC). These authors controlled the flow discharges by regulating four pumps, the flow velocity values were measured by ADV, while the flow depths were measured by a staff gauge. Further details on the experimental tests are reported in the paper by Errico et al. (2019).

For both the databases, the available measurements of geometric channel characteristics, flow depths, and flow velocities were used to deduce some hydraulic characteristics as the Darcy-Weisbach friction factor, the Froude number, and the Reynolds number.

3 | RESULTS

The measurements carried out in different management scenarios by Errico et al. (2018, 2019) were firstly represented by the *n*-*VR* plot and the *f*-*VR* plot (Figure 1). Considering that the bending behaviour of the vegetal elements was observed during the experimental runs by Errico et al. (2018), a reduction of drag resistance is expected due to the flow impact on stems and foliage. According to previous studies, bending of flexible vegetation elements affects flow resistance,

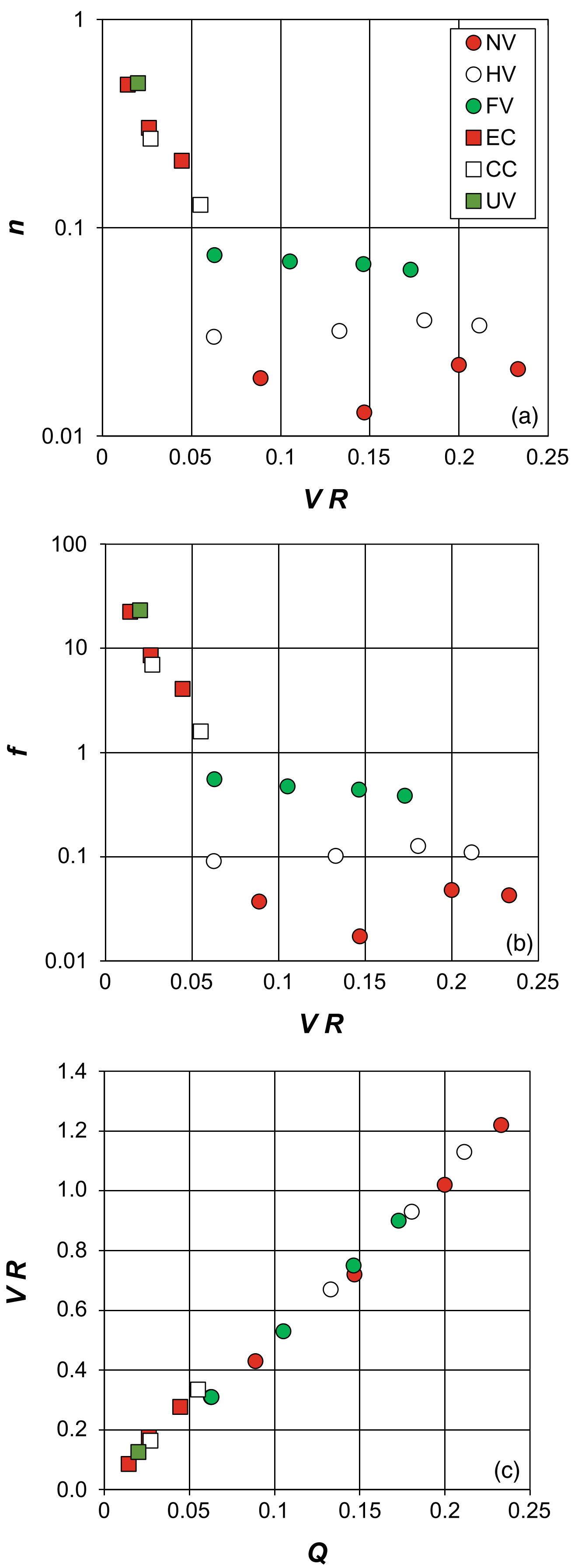

FIGURE 1 Relationships between *n*-*VR* (a), *f*-*VR* (b), and *VR*-*Q* (c) for the examined data.

represented in Figure 1 by Manning's coefficient (Figure 1a) and Darcy-Weisbach friction factor (Figure 1b), which becomes constant for *VR* values greater than 0.05 (Kouwen, 1988, 1992; Kouwen et al., 1969; Kouwen & Li, 1980; Kouwen & Unny, 1973). This last result is also confirmed by the experiments of Rhee et al. (2008), who observed that at about *VR* >0.05, the reeds are significantly deflected by the water flow. Considering that the product *VR* is strongly related to the flow discharge *Q* (Figure 1c), Figure 1a and b demonstrate that in the CC and EC scenarios, the roughness coefficient decrease for increasing discharge for *VR* <0.05. This trend suggests that the measurements by Errico et al. (2019) corresponding to cut vegetation (CC and EC) and *VR* <0.05 represent conditions in which the remnant material behaviours as a submerged layer of rigid vegetation whose resistance decreases for increasing *Q* values.

For applying the theoretical flow resistance (Equation 5), the complete data set of full-scale experiments by Errico et al. (2018, 2019) was divided into two sub-data sets used for calibration and testing aims, respectively. The two sub-data sets were constructed using experimental runs having comparable vegetation and hydraulic conditions (Table 1). In other words, the experimental runs of the complete data set falling into the two sub-data sets were chosen assuring the representativeness of the vegetation management scenarios and that the ranges of the experimental variables (*Q*, *h*, *v*, *s*) were comparable. In particular, the investigated flow conditions correspond to similar values of flow discharge *Q* and mean flow velocity *V*. All the investigated flows are turbulent and always subcritical.

Using the measurements corresponding to the 11 experimental runs of the calibration data set, the following equation for estimating Γ_v is obtained:

$$\Gamma_v = 0.3217\,\frac{F^{1.1248}}{s^{0.5731}} \tag{9}$$

where *s* is set equal to the energy slope, and which is characterized by a coefficient of determination equal to 0.9998. In Figure 2a, the comparison between the measured Γ_v values, obtained by Equations (6) and (7), and those calculated by Equation (9) is plotted, distinguishing the pairs corresponding to different vegetation management scenarios.

Equation (5), associated with Equations (3) and (9), allows calculating the Darcy-Weisbach friction factor values considering different hydraulic conditions (*F*, *s*) and the effect of the common reed biomechanical characteristics in different management scenarios. In Figure 2b, the comparison between the measured Darcy-Weisbach friction factor values and those calculated by Equations (5), (3), and (9) is plotted. This figure demonstrates a good agreement between the measured *f* values and those calculated by the proposed theoretical flow resistance equation joined with Equations (3) and (9). The calculated friction factor values resulted characterized by estimate errors which are always less than or equal to ±10%, and 90.9% of the errors are less than or equal to ±5%.

Equation (9) was also tested by the independent measurements of the seven experimental runs of the testing data-set (Table 1). For the independent testing data-set, Figure 3 confirms that the proposed theoretical flow resistance equation (Equation 5), coupled with

TABLE 1 Characteristic data of the experimental runs used for calibrating and testing the flow resistance equation

Sub- data set	Runs by Enrico et al. (2018;2019)	Q (m^3 s^{-1})	V (m s^{-1})	Re	F
Calibrating	FV, FV, UV1 HV, HV, HV, CC1 NV, NV, NV, EC1	0.09–1.22	0.03–0.43	14 319–258 895	0.01–0.16
Testing	FV, FV HV, CC2 NV, EC2, EC3	0.18–1.02	0.05–0.40	25 421–219 443	0.02–0.15

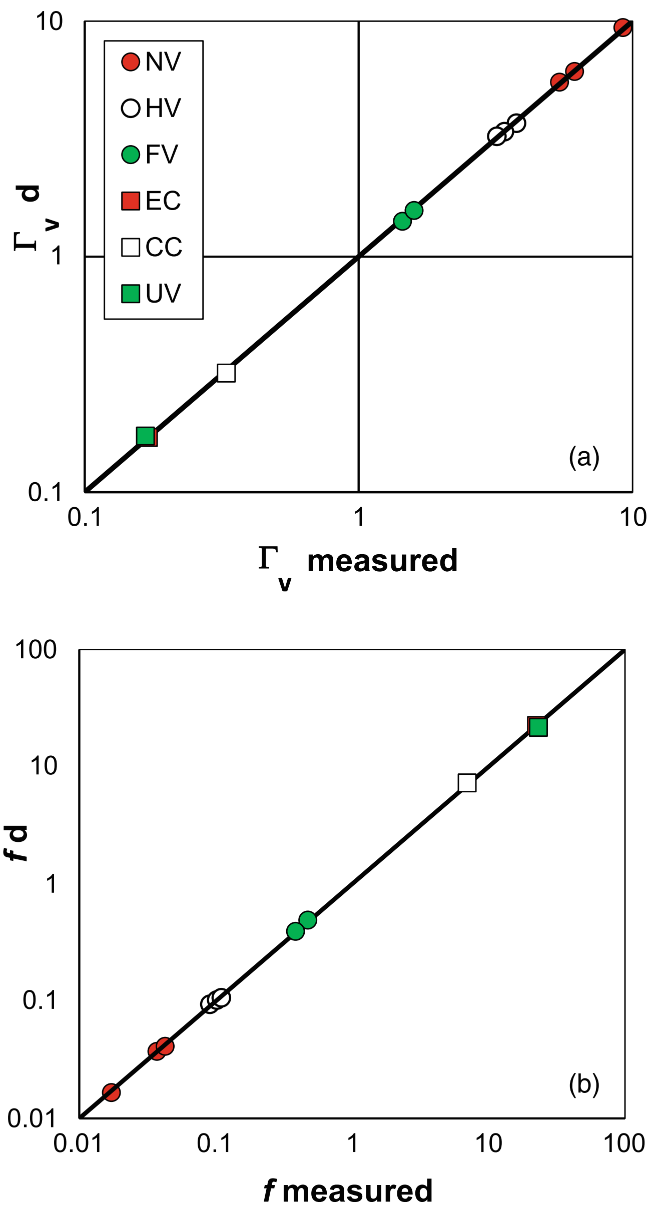

FIGURE 2 Comparison between the measured Γ_v values, obtained by Equation (6) and (7), and those calculated by Equation (9) (a) and between the measured Darcy-Weisbach friction factor values and those calculated by Equations (5), (3), and (9) (b) for the calibrating data set.

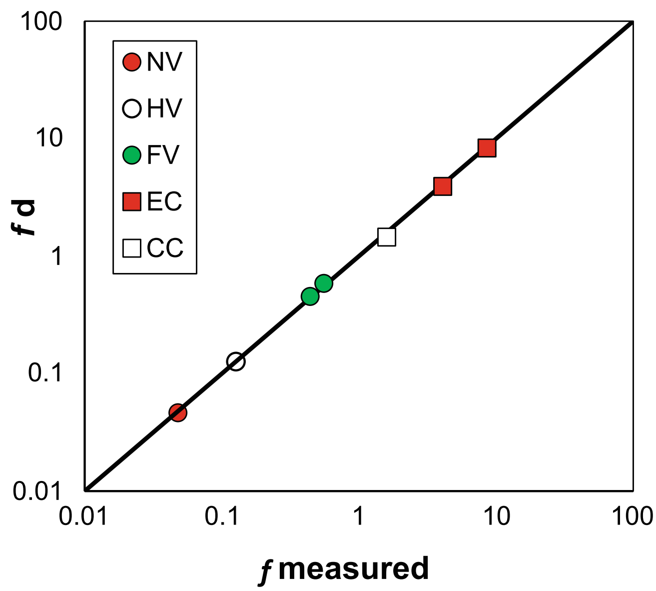

FIGURE 3 Comparison between the measured Darcy-Weisbach friction factor values and those calculated by Equation (5), coupled with Equations (3) and (9) for the testing data set.

Equations (3) and (9), is characterized by a good agreement between the measured f values and the calculated ones.

Finally, Equation (5) was calibrated using all the available measurements listed in Table 1:

$$\Gamma_v = 0.3246 \frac{F^{1.1284}}{s^{0.5728}} \tag{10}$$

which is characterized by a coefficient of determination equal to 0.9997. In Figure 4a, the comparison between the measured Γ_v values, obtained by Equations (6) and (7), and those calculated by Equation (10) is plotted, distinguishing the pairs corresponding to different vegetation management scenarios. The comparison between the measured Darcy-Weisbach friction factor values and those calculated by Equations (5), (3), and (10), plotted in Figure 4b, confirms that a good agreement between the measured f values and those calculated by the proposed theoretical flow resistance equation occurs.

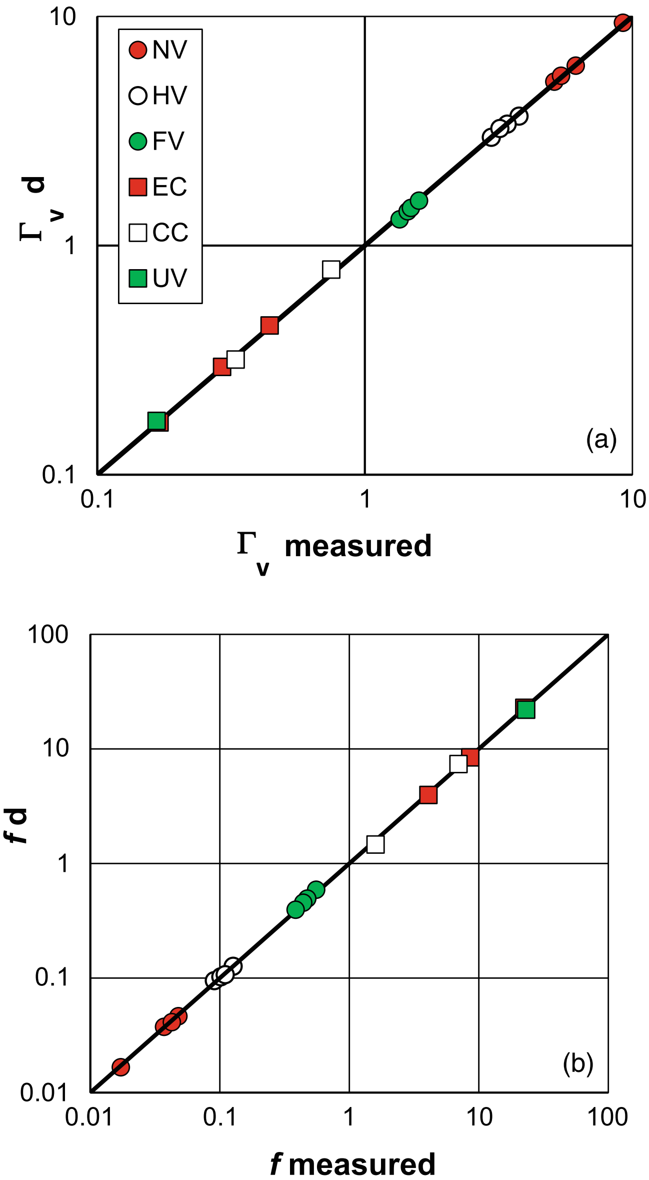

FIGURE 4 Comparison between the measured Γ_v values, obtained by Equation (6) and (7), and those calculated by Equation (10) (a) and between the measured Darcy-Weisbach friction factor values and those calculated by Equations (5), (3), and (10) (b).

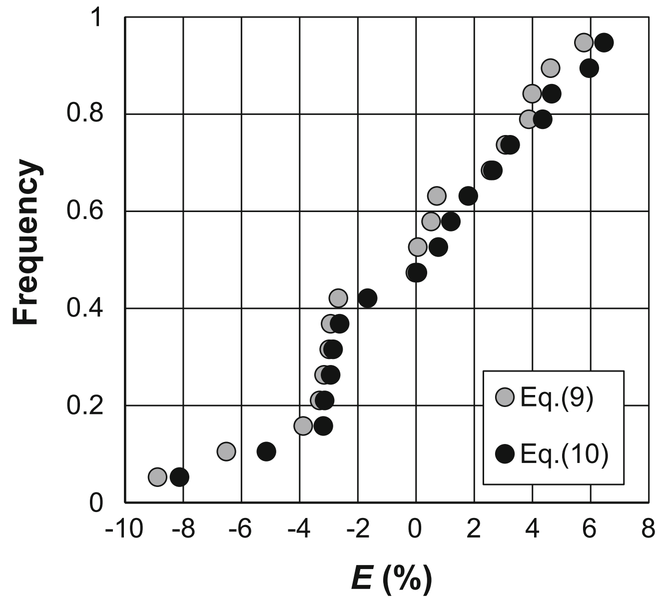

FIGURE 5 Empirical frequency distribution of the errors, *E* (%), of Darcy-Weisbach friction factors estimated by (5), (3), and (9) or (10).

4 | DISCUSSION

Figure 2b demonstrates that the theoretical approach is able to estimate the friction factor values of different vegetation management scenarios, which vary from the lowest values for the non-vegetated condition to the highest ones of the undisturbed vegetation (UV). The agreement between the measured and calculated *f* values was also studied by the frequency distribution of the estimate errors *E*, expressed as a percentage, of the Darcy-Weisbach friction factor calculated by Equation (5), (3), and (9) or (10) (Figure 5). This figure clearly demonstrates that the proposed theoretical approach coupled with Equation (9) or Equation (10) allows estimating the Darcy-Weisbach friction factor values with errors in the estimate always less than or equal to ±10%.

Figure 3 shows that the condition of the full vegetated (FV) scenario is characterized by *f* values higher than those of the half vegetated (HV) one, as the presence of spontaneous vegetation raised the bed roughness in comparison with the cleared scenario due to the partial cut.

Figure 4b highlights that the proposed approach is also able to consider the effects of different vegetation management scenarios on flow resistance. In particular, an increasing trend of the friction factor is obtained from the NV scenario to the HV and FV conditions. An effect of the cutting management is shown in the estimate of the *f* coefficient, which decreases from the undisturbed vegetation condition (UV) to the central cut (CC) and extensive cut (EC) scenarios.

The results highlighted in Figures 3 and 4b agree with those obtained in the investigation by Errico et al. (2018, 2019). In particular, the relationship between flow resistance and vegetation characteristics is affected by vegetation cutting management, which controls stem density (FV > HV) and the vegetation's capability to assume a streamlined arrangement. The trend plotted in Figure 1b demonstrated that flow resistance decreases for increasing discharge values, proving the drag effect of flow is able to reconfigure plants.

The results obtained in this paper highlight that, as expected, cutting management influences flow behaviour. Since the calibrated equation resulted reliable in the estimate of the friction factor, it could be used for studying the channel hydraulics and, consequently, choosing the best cutting management for a drainage channel vegetated by *Phragmites australis*.

The main limitation of this work is the low number of available measurements and the specific investigated conditions. In other words, the obtained results are strictly related to the examined vegetation type (*Phragmites australis*) and the applied cutting management. To better understand the effects of vegetation cutting management on flow behaviour, new experiments should be carried out analysing the relationships between the friction factor and the vegetation characteristics (i.e., density, bending stiffness, etc.) for different cutting management scenarios. Another interesting challenge might be to test the behaviour of different vegetation species for the same experimental conditions in order to select the optimal species for limiting the economic impact (cutting management implies some costs) and hydraulic risk (an extreme increase of the flow resistance leads to the increase of the water levels).

5 | CONCLUSIONS

Field measurements carried out by Errico et al. (2018, 2019) in a real-scale channel colonized by common reed were used to assess the applicability of a theoretical flow resistance law proposed by Ferro (2019a) and frequently calibrated for grass-like vegetation. The theoretical flow resistance equation was calibrated by analysing the relationship between the velocity profile parameter Γ, the flow Froude number, and the slope energy of the available data sets.

The developed analysis demonstrated that the proposed theoretical approach allows obtaining reliable estimates of the Darcy-Weisbach friction factor, which are characterized by errors always less than or equal to ±10%. The analysis also showed that the approach is able to consider the effect of the cutting management in the estimate of the f coefficient as it decreases from the undisturbed vegetation condition (UV) to the central cut (CC) and extensive cut (EC) scenarios.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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REFERENCES

Armanini, A., Righetti, M., & Grisenti, P. (2005). Direct measurement of vegetation resistance in prototype scale. *Journal of Hydraulic Research*, *43*, 481–487.

Barenblatt, G. I. (1979). *Similarity, self-similarity and intermediate asymptotics*. Consultants Bureau.

Barenblatt, G. I. (1987). *Dimensional analysis*. Gordon & Breach, Science Publishers Inc.

Barenblatt, G. I. (1991). On the scaling laws (incomplete self-similarity with respect to Reynolds numbers) for the developed turbulent flows in tubes. *C. R. Acad. Sci., Ser. II*, *313*, 307–312.

Barenblatt, G. I. (1993). Scaling laws for fully developed turbulent shear flows, part 1, basic hypothesis and analysis. *Journal of Fluid Mechanics*, *248*, 513–520.

Barenblatt, G. I., & Monin, A. S. (1979). Similarity laws for turbulent stratified flows. *Archive for Rational Mechanics and Analysis*, *70*, 307–317.

Barenblatt, G. I., & Prostokishin, V. M. (1993). Scaling laws for fully developed turbulent shear flows, part 2. Processing of experimental data. *Journal of Fluid Mechanics*, *248*, 521–529.

Castaing, B., Gagne, Y., & Hopfinger, E. J. (1990). Velocity probability density functions of high Reynolds number turbulence. *Physica D*, *46*, 177–200.

Chiaradia, E. A., Gandolfi, C., & Bischetti, G. B. (2019). Flow resistance of partially flexible vegetation: A full-scale study with natural plants. *Journal of Agricultural Engineering*, *50*, 55–65.

Carollo, F. G., & Ferro, V. (2021). Experimental study of boulder concentration effect on flow resistance in gravel bed channels. *Catena*, *205*, 105458.

Carollo, F. G., Ferro, V., & Termini, D. (2002). Flow velocity measurements in vegetated channels. *Journal of Hydraulic Engineering*, *128*(7), 664–673. https://doi.org/10.1061/(ASCE)0733-9429(2002)128:7(1

Carollo, F. G., Ferro, V., & Termini, D. (2005). Flow resistance law in channels with flexible submerged vegetation. *Journal of Hydraulic Engineering*, *131*(7), 554–564. https://doi.org/10.1061/(ASCE)0733-9429(2005)131:7(554)

Carollo, F. G., Ferro, V., & Termini, D. (2007). Analysing longitudinal turbulence intensity in vegetated channels. *Journal of Agricultural Engineering*, *38*, 25–35.

Carollo, F. G., Ferro, V., & Termini, D. (2008). Determinazione del profilo di velocità e di intensità della turbolenza in canali vegetati, Proc. of 31° Convegno Nazionale di Idraulica e Costruzioni Idrauliche, 9-12 September, Perugia (Italy), 2008 (in Italian).

Coreblint, D., Steiger, J., Gurnell, A. M., Tabacchi, E., & Roques, L. (2009). Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. *Earth Surface Processess and Landforms*, *34*, 1790–1810.

Di Stefano, C., Ferro, V., Palmeri, V., & Pampalone, V. (2017). Flow resistance equation for rills. *Hydrological Processes*, *31*, 2793–2801. https://doi.org/10.1002/hyp.11221

Di Stefano, C., Ferro, V., Palmeri, V., & Pampalone, V. (2018). Testing slope effect on flow resistance equation for mobile bed rills. *Hydrological Processes*, *32*, 664–671. https://doi.org/10.1002/hyp.11448

Di Stefano, C., Nicosia, A., Palmeri, V., Pampalone, V., & Ferro, V. (2019a). Comparing flow resistance law for fixed and mobile bed rills. *Hydrological Processes*, *33*, 3330–3348. https://doi.org/10.1002/hyp.13561

Di Stefano, C., Nicosia, A., Palmeri, V., Pampalone, V., & Ferro, V. (2019b). Rill flow resistance law under equilibrium bed-load transport conditions. *Hydrological Processes*, *33*, 1317–1323. https://doi.org/10.1002/hyp.13402

Di Stefano, C., Nicosia, A., Palmeri, V., Pampalone, V., & Ferro, V. (2022). Rill flow velocity and resistance law: A review. *Earth Science Reviews*, *231*, 104092. https://doi.org/10.1016/j.earscirev.2022.104092

Errico, A., Pasquino, V., Maxwald, M., Chirico, G. B., Solari, L., & Preti, F. (2018). The effect of flexible vegetation on flow in drainage channels: Estimation of roughness coefficients at the real scale. *Ecological Engineering*, *120*, 411–421.

Errico, A., Lama, G. F. C., Francalanci, S., Chirico, G. B., Solari, L., & Preti, F. (2019). Flow dynamics and turbulence patterns in a drainage channel

colonized by common reed (Phragmites australis) under different scenarios of vegetation management. *Ecological Engineering*, *123*, 39–52.
Ferro, V. (1997). Applying hypothesis of self-similarity for flow-resistance law of small-diameter plastic pipes. *Journal of Irrigation and Drainage Engineering, ASCE*, *123*, 175–179.
Ferro, V. (1999). Friction factor for gravel-bed channel with high boulder concentration. *Journal of Hydraulic Engineering*, *125*, 771–778.
Ferro, V. (2017). New flow resistance law for steep mountain streams based on velocity profile. *Journal of Irrigation and Drainage Engineering, ASCE*, *143*(04017024), 1–6. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001208
Ferro, V. (2018). Assessing flow resistance in gravel bed channels by dimensional analysis and self-similarity. *Catena*, *169*, 119–127. https://doi.org/10.1016/j.catena.2018.05.034
Ferro, V. (2019a). Assessing flow resistance law in vegetated channels by dimensional analysis and self-similarity. *Flow Measurement and Instrumentation*, *69*, 101610. https://doi.org/10.1016/j.flowmeasinst.2019.101610
Ferro, V. (2019b). *Opere di sistemazione idraulico-forestale*. Mc-Graw Hill education (Italy).
Ferro, V., & Pecoraro, R. (2000). Incomplete self-similarity and flow velocity in gravel bed channels. *Water Resources Research*, *36*, 2761–2770.
Ferro, V., & Porto, P. (2018a). Applying hypothesis of self-similarity for flow resistance law in Calabrian gravel bed rivers (Fiumare). *Journal of Hydraulic Engineering, ASCE*, *144*, 1–11. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001385
Ferro, V., & Porto, P. (2018b). Assessing theoretical flow velocity profile and resistance in gravel bed rivers by field measurements. *Journal of Agricultural Engineering*, *49*, 220–227.
Florineth, F. (2007). *Piante al posto del cemento*. Il Verde Editoriale.
Florineth, F., Meixner, H., Rauch, H. P., & Vollsinger, S. (2003). Prove di Forza. *Ingegneria Naturalistica*, *2*, 73–78 (in Italian).
Freeman, G. E., Rahmeyer, W. H., & Copeland, R. R. (2000). Determination of resistance due to shrubs and woody vegetation. US Army Corps of Engineers. *Engineer Research and Development Centre Report*, *No. ERDC/CHL TR-00-25*.
García Díaz, R. (2005). Analysis of manning coefficient for small-depth flows on vegetated beds. *Hydrological Processes*, *19*(16), 3221–3233. https://doi.org/10.1002/hyp.5820
Gourlay, M. R. (1970). Discussion of "flow resistance in vegetated channels", in: N. Kouwen, T.E. Unny, H.M. Hill (eds.). *Journal of Irrigation and Drainage Engineering. ASCE*, *96*(3), 351–357.
Govers, G., Gimenez, R., & Oost, K. V. (2007). Rill erosion: Exploring the relationship between experiments, modeling and field observations. *Earth Science Reviews*, *8*, 87–102.
Green, J. C. (2005). Modelling flow resistance in vegetated streams: Review and development of new theory. *Hydrological Processes*, *19*, 1245–1259.
Kouwen, N. (1988). Field estimation of the biomechanical properties of grass. *Journal of Hydraulic Research*, *26*(5), 559–568.
Kouwen, N. (1992). Modern approach to design of grassed channels. *Journal of Irrigation and Drainage Engineering*, *118*(5), 733–743.
Kouwen, N., & Li, R. M. (1980). Biomechanics of vegetated channel linings. *Journal of Hydraulics Division, ASCE*, *106*(6), 1085–1103.
Kouwen, N., Li, R. M., & Simons, D. B. (1981). Flow resistance in vegetated waterways. *Transactions of ASAE*, *24*(3), 684–698.
Kouwen, N., Unny, T. E., & Hill, H. M. (1969). Flow retardance in vegetated channels. *Journal of Irrigation and Drainage Div. ASCE*, *95*(2), 329–342.
Kouwen, N., & Unny, T. E. (1973). Flexible roughness in open channels. *Journal of Hydraulics Division, ASCE*, *99*(5), 713–728.
Kowobary, T. S., Rice, C. E., & Garton, J. E. (1972). Effect of roughness elements on hydraulic resistance for overland flow. *Transactions of ASAE*, *15*(5), 979–984.
Lama, G. F. C., Errico, A., Francalanci, S., Solari, L., Preti, F., & Chirico, G. B. (2020). Evaluation of flow resistance models based on field experiments in a partly vegetated Reclamation Channel. *Geosciences*, *10*, 47. https://doi.org/10.3390/geosciences10020047
Morris, H. M. (1959). Design methods for flow in rough conduits. *Journal of Hydraulic Engineering ASCE*, *85*(7), 43–62.
Nicosia, A., Di Stefano, C., Pampalone, V., Palmeri, V., Ferro, V., & Nearing, M. A. (2019). Testing a new rill flow resistance approach using the water erosion prediction project experimental database. *Hydrological Processes*, *33*(4), 616–626. https://doi.org/10.1002/hyp.13348
Nicosia, A., Di Stefano, C., Pampalone, V., Palmeri, V., & Ferro, V. (2020). Flow resistance of overland flow on a smooth bed under simulated rainfall. *Catena*, *187*, 104351. https://doi.org/10.1016/j.catena.2019.104351
Nicosia, A., Di Stefano, C., Pampalone, V., Palmeri, V., Ferro, V., & Nearing, M. A. (2020). Testing a theoretical resistance law for overland flow on a stony hillslope. *Hydrological Processes*, *34*, 2048–2056. https://doi.org/10.1002/hyp.13709
Nicosia, A., Di Stefano, C., Pampalone, V., Palmeri, V., Ferro, V., Polyakov, V. O., & Nearing, M. A. (2020). Testing a theoretical resistance law for overland flow under simulated rainfall with different types of vegetation. *Catena*, *189*, 104482. https://doi.org/10.1016/j.catena.2020.104482
Nicosia, A., Bischetti, G. B., Chiaradia, E., Gandolfi, C., & Ferro, V. (2021). A full-scale study of Darcy-Weisbach friction factor for .channels vegetated by riparian species. *Hydrological Processes*, *35*, e14009.
Olley, J., Burton, J., Hermoso, V., Smolders, K., McMahon, J., Thomson, B., & Watkinson, A. (2015). Remnant riparian vegetation, sediment and nutrient loads, and river rehabilitation in subtropical Australia. *Hydrological Processes*, *29*, 2290–2300.
Palmeri, V., Pampalone, V., Di Stefano, C., Nicosia, A., & Ferro, V. (2018). Experiments for testing soil texture effects on flow resistance in mobile bed rills. *Catena*, *171*, 176–184.
Powell, D. M. (2014). Flow resistance in gravel-bed rivers: Progress in research. *Earth Science Reviews*, *136*, 301–338.
Raffaelli, S., Domenichini, F., & Solari, L. (2002). Resistenza al moto in un alveo vegetato: indagine sperimentale di laboratorio, Italy, in: Potenza Bios (Ed.), Proc. of XXVIII Convegno di Idraulica e Costruzioni Idrauliche, 5, 223-230 (in Italian).
Rhee, D. S., Woo, H., Kwon, B. A., & Ahn, H. K. (2008). Hydraulic resistance of some selected vegetation in open channel flows. *River Research and Applications*, *24*, 673–687. https://doi.org/10.1002/rra.1143
Righetti, M., & Armanini, A. (2002). Flow resistance in open channel flows with sparsely distributed bushes. *Journal of Hydrology*, *269*(1–2), 55–64. https://doi.org/10.1016/S0022-1694(02)00194-4
Sandercock, P. J., & Hooke, J. M. (2010). Assessment of vegetation effects on hydraulics and of feedbacks on plant survival and zonation in ephemeral channels. *Hydrological Processes*, *24*, 695–713.
Vargas-Luna, A., Crosato, A., & Uijttewaal, W. S. J. (2015). Effects of vegetation on flow and sediment transport: Comparative analyses and validation of predicting models. *Earth Surface Processes and Landforms*, *40*, 157–176. https://doi.org/10.1002/esp.3633
Västilä, K., Järvelä, J., & Aberle, J. (2013). Characteristic reference areas for estimating flow resistance of natural foliated vegetation. *Journal of Hydrology*, *492*, 49–60. https://doi.org/10.1016/j.jhydrol.2013.04.015
Wilson, C. A. M. E., & Horritt, M. S. (2002). Measuring the flow resistance of submerged grass. *Hydrological Processes*, *16*, 2589–2598.
Wilson, C. A. M. E., Stoesser, T., Bates, P. D., & Batemann Pinzen, A. (2003). Open Channel flow through different forms of submerged flexible vegetation. *Journal of Hydraulic Engineering.*, *129*(11), 847–853. https://doi.org/10.1061/(ASCE)0733-9429(2003)129:11(847)
Yagci, O., & Kabdasli, M. S. (2008). The impact of single natural vegetation elements on flow characteristics. *Hydrological Processes*, *22*, 4310–4321.

Yagci, O., Tschiesche, U., & Kabdasli, M. S. (2010). The role of different forms of natural riparian vegetation on turbulence and kinetic energy characteristics. *Advances in Water Resources*, *33*(5), 601–614. https://doi.org/10.1016/j.advwatres.2010.03.008

Yen, B. C. (1992). Hydraulic resistance in open channels. In B. C. Yen (Ed.), *Channel flow resistance: Centennial of Manning's formula* (pp. 1–135). Water Resources Publications.

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