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Investigation on Flow Resistance of Large-Scale Channels With Unmanaged Spontaneous Vegetation

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ABSTRACT

The formulation of methods that are both simplified and sufficiently accurate for estimating flow resistance in vegetated channels constitutes a critical challenge in the context of flood hazard mitigation and management of riparian species that directly influence channel conveyance capacity, channel morphological evolution and sediment deposition. In this study, measurements collected by the US Army Corps of Engineers in a large-scale channel with unmanaged spontaneous vegetation were used to verify the suitability of a theoretical flow resistance equation in open-channel conditions and floodplains. This equation, deduced by applying dimensional analysis and the incomplete self-similarity condition for the velocity profile of open-channel flow, was initially reported. The available meausurements, referring to different vegetation density values, were used for relating the Γ function of the power velocity profile to the slope energy, the flow Froude number and vegetation density. This investigation showed that the Darcy–Weisbach friction factor f can be accurately estimated using the proposed theoretical flow resistance equation, with errors in the f estimate that are less than or equal to 15% for 92.2% of the investigated cases and less than or equal to 10% for 75.5% of the cases. The findings of this study also demonstrated that the characteristics of the investigated vegetation, such as vegetation density, appreciably affect the estimate of flow resistance.

1 | Introduction

The existence of vegetation within a channel implies a reduction of flow conveyance capacity, affects the morphological development of the channel and sediment deposition, and significantly influences the interplay between river hydraulics and aquatic ecosystems (Sandercock and Hooke 2010). The presence of vegetation alters flow velocities at multiple scales—from the level of individual stems and branches to entire plant communities (Nepf 2012). By generating zones of low-flow, plants can decrease sediment transport, which in turn helps stabilise both hillslopes and river channels. Vegetation also absorbs excess nutrients from the water and enhances oxygen production, contributing to improved water quality (Luhar and Nepf 2013). Overall, riparian vegetation plays a key role in maintaining landscape stability and in lowering the amount of pollutants carried by runoff into streams and rivers (Olley et al. 2015).

Modelling open-channel flows in vegetated channels is also relevant to establishing propensity to flooding and river management actions finalised to scientifically-based interventions of flood mitigation (Green 2005; Vargas-Luna et al. 2015). During a flood, riparian vegetation with dense foliage and branched structure provokes higher water depths and lower mean flow velocities and conveyance capacities (Yagci and Kabdasli 2008; Vargas-Luna et al. 2015).

Even if many researchers studied flow resistance due to vegetation in open channels, the applicability of these results is limited by the different hydrodynamic behaviour of

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different vegetation species (García Díaz 2005; Nicosia and Ferro 2023). In this scenario, the current use of too simple tables for evaluating the roughness indices, even if coupled with photographic guides (Barnes 1967), combined with the high spatio-temporal variability of vegetation distribution, supports the idea that more accurate methods to estimate flow resistance in vegetated rivers need to be developed (Green 2005). Another limit of the available flow resistance investigations in channels with vegetation is due to the common use of small-scale installations for these experimental investigations (Green 2005).

Research on flow resistance in vegetated channels (Kouwen et al. 1969; Kowobary et al. 1972; Kouwen and Unny 1973; Kouwen and Li 1980; Kouwen 1988; Errico et al. 2018, 2019; Ferro 2019) has historically focused on grass-like species, which are flexible and typically submerged since their height h_s is lower than the water depth h (Gourlay 1970). The configuration of such vegetation (erect, waving or prone) results from the interaction between its biomechanical properties (bending stiffness and moment of inertia) and the hydrodynamic flow action (Ferro 2019).

For grass-like vegetation, Kouwen and collaborators (Kouwen and Unny 1973; Kouwen and Li 1980; Kouwen et al. 1981; Kouwen 1988, 1992) developed a wide line of research finalised to obtain an estimate method of the Darcy–Weisbach friction factor and pointed out that the friction factor increases with stem density. Later experiments by Carollo et al. (2005) using different species (*Lolium perenne*, *Festuca rubra* and *Poa pratensis*) and stem densities M (280, 310, 337 and 440 stems dm^{-2}) coupled with literature data (Kouwen et al. 1969; Wilson and Horritt 2002; Raffaelli et al. 2002) led to the conclusion that, for $M < 50$ stems dm^{-2}, the friction factor rises with stem density, while above this limit (i.e., highest M values), it results independent on the stem density (Ferro 1999) due to the occurrence of the quasi-smooth skimming flow regime (Morris 1959).

Most of the available experimental work has been conducted in small-scale flumes with very young plants or limited portions of vegetation (Righetti and Armanini 2002; Wilson et al. 2003; Armanini et al. 2005; Rhee et al. 2008; Yagci et al. 2010; Västilä et al. 2013), while full-scale field studies (Freeman et al. 2000; Västilä et al. 2013; Errico et al. 2018, 2019; Chiaradia et al. 2019) are less developed. Even if small-scale flume experiments allowed for controlled conditions and accurate measurements, scaling issues due to the interaction between flow and vegetation should be considered when applying laboratory results to natural conditions (Florineth et al. 2003; Chiaradia et al. 2019).

Flow resistance of other vegetation species (*Zoysia matrella* [Korean zoysia], *Pennisetum alopecuroides* (L.) Spreng. [Korean native vegetation] and *Phragmites communis* Trin. [Korean reed]) in two wide (1–3 m) laboratory flumes was studied by Rhee et al. (2008). For each investigated species, 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, were determined. These authors performed experiments for *green* (active growth) or *dormant* (inactive, wilted, or dead) vegetation. The authors concluded that the flow resistance of *dormant* vegetation, only affected by stems, is generally lower than that of *green* one, which is also influenced by leaves.

Large-scale field studies finalised to establish the effects of the *Phragmites australis* distribution in drainage channels were developed by Errico et al. (2018, 2019), who studied the role of different management practices (full-vegetation in natural conditions, bank removal or cutting the vegetation in the central part of the channel and extensive cutting of vegetation) on flow velocity distribution, flow turbulence and flow resistance. The main conclusions of these investigations were that (i) the streamlined behavior of this species reduces drag effects and flow resistance, and (ii) cutting the plants exclusively in the middle of the channel can improve conveyance as much as complete removal. A large-scale channel was also used in the investigation by Chiaradia et al. (2019), who investigated flow resistance for different shrub species (*Alnus glutinosa* L., *Salix alba* L. and *Salix caprea* L.). These measurements allowed for concluding that the Manning's coefficient values due to vegetation were dependent on vegetation species, density and foliage condition.

The application of the uniform motion equation by Chezy (Govers et al. 2007; Powell 2014) remains the most used method for the estimation of flow resistance in open-channels. For representing flow resistance, Manning's n or Darcy-Weisbach's f are frequently used for channels with vegetation (Yen 1992):

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

where 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.

In open-channel flow hydraulics, the relationship between velocity distribution and flow resistance continues to be a challenge, as the theoretical deduction of the flow-resistance equation can be obtained by the integration of the flow-velocity profile (Ferro 1997).

Some literature studies (Ferro 2017, 2019) demonstrated that integrating a power-velocity profile, deduced by dimensional analysis and the self-similarity theory, allows for obtaining a theoretical expression of the Darcy–Weisbach friction factor and recent studies (Nicosia et al. 2024, 2025) tested its reliability for vegetated channels. By using the field measurements obtained by Chiaradia et al. (2019) in a full-scale vegetated channel, Nicosia et al. (2021) assessed the applicability of the theoretical flow resistance equation. This analysis showed that the relationship for the estimate of the velocity profile parameter Γ, with a scaling factor that depends on the studied vegetation species, leads to the most accurate f estimation (errors generally lower than 20%).

Furthermore, Nicosia et al. (2023) also tested the applicability of the theoretical flow resistance law using the field measurements by Errico et al. (2018, 2019). The analysis of the relationship between the velocity profile parameter Γ, the flow Froude number and the slope energy was carried out and showed that the theoretical approach allows for obtaining reliable estimates of the Darcy–Weisbach friction factor (errors always less than or equal to ±10%).

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Nicosia and Ferro (2023) also verified this approach using large-scale channel (2.44 m wide and 152.4 m long) data by Freeman et al. (2000) corresponding to 10 different shrubs and woody species. Errors in the f estimate were generally lower than ±10%.

Even though the abovementioned previous studies (Nicosia et al. 2021, 2023; Nicosia and Ferro 2023) assessed the reliability of Ferro's (2019) theoretical approach for large-scale field channels, these validations were primarily limited to specific vegetation species (i.e., without considering spatial variability and heterogeneity of vegetation). Moreover, previous applications have generally focused on datasets where vegetation was either deliberately planted or managed, leaving unexplored the case of spontaneously colonised channels where density, morphology and biomechanical properties evolve without human control. For this reason, further testing of the theoretical law by Ferro (2019) for a vegetation arrangement characterised by species heterogeneity with natural development and unmanaged conditions should be performed.

In this paper, the theoretical approach by Ferro (2019) was assessed by field measurements by Flippin-Dudley et al. (1998) carried out in a long, large-scale channel colonised by volunteer and heterogeneous vegetation (trees, shrubs and grasses). The general aim of this study is to test this theoretical approach to estimate the Darcy–Weisbach friction factor for large-scale channels with unmanaged spontaneous and heterogeneous vegetation and demonstrate that its characteristics can be usefully considered in the estimate of flow resistance.

2 | Materials and Methods

2.1 | Theoretical Flow Resistance Law

Using the Buckingham's theorem of the dimensional analysis (Barenblatt 1979, 1987, 1993) and the incomplete self-similarity (ISS) in $u_* y/\nu_k$ (Barenblatt and Monin 1979; Barenblatt and Prostokishin 1993), Ferro (2017) proposed the following velocity profile (Nicosia et al. 2024):

$$\frac{v}{u_*} = \Gamma\left(\frac{u_* h}{\nu_k}, \frac{h}{H_v}, M, s, F\right)\left(\frac{u_* y}{\nu_k}\right)^{\delta} \tag{2}$$

where $\Gamma\left(\frac{u_* h}{\nu_k}, \frac{h}{H_v}, M, s, F\right)$ is a function that has to be determined by velocity measurements, v is the local velocity, y is the distance from the bottom, ν_k is the water kinematic viscosity, h is the water depth, H_v is the vegetation height in the absence of flow, M is the stem density, s is the energy slope, $F = V/\sqrt{g h}$ is the flow Froude number and δ is a coefficient that can be obtained by the equation proposed by Castaing et al. (1990):

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

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

Given that the ratio between $u_* h/\nu_k$ and h/H_v is equal to the shear Reynolds number Re_*, and since F and Re_* are related (Ferro 2018), Equation (3) can be rewritten as follows:

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

Integrating the velocity distribution (Equation 4) permits for deducing the equation of the Darcy–Weisbach friction factor f that follows (Barenblatt 1993):

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

Setting into Equation (4) $y = \alpha h$, being αh the distance from the bottom where the local velocity equals the cross-section average velocity V, the estimate Γ_v of the Γ function (Ferro 2017) can be obtained as follows:

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

The coefficient α, which is less than 1, considers the following effects: (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). The coefficient α has to be calculated by the following relationship (Ferro 2017):

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

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

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

where a, b, c and e are coefficients to be determined by experimental measurements.

For an experimental dataset characterised by a constant value of the stem density M, Equation (8) reduces to

$$\Gamma_v = A\,\frac{F^b}{s^c} \tag{9}$$

where A, b and c are coefficients that can be determined by measurements.

2.2 | Experimental Data by Flippin-Dudley et al. (1998)

The field tests by Flippin-Dudley et al. (1998) were performed at the ARS Outdoor Hydraulic Laboratory near Stillwater, Oklahoma, US. The channel was 117 m long, and the cross-section was V-shaped (Gwinn and Ree 1980), with top widths varying from 12 to 18 m. Since 1950, the channel had not been maintained and volunteer vegetation (trees, shrubs and grasses) (*Cornus drummondii*, *Ulmus rubra*, *Celtis tenuifolia*, *Juniperus virginiana*, *Gleditsia triacanthos*, *Carya illinoensis*, *Rhus glabra*, *Rhus copallina*, *Salix* spp., *Vaccinium pallidum*, *Toxicodendron rydbergii*, *Cocculus carolinus*,

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TABLE 1 | Ranges of the main characteristic hydraulic data (water depth h, hydraulic radius R, mean flow velocity V, flow Reynolds number Re, flow Froude number F and Darcy–Weisbach friction factor f) referring to the survey of November 1995.

Experimental series	Flow discharge ($m^3 s^{-1}$)	h (m)	R (m)	V ($m s^{-1}$)	Re	F	f
1	0.1	0.16–0.24	0.08–0.12	0.23–0.28	35 151–46 135	0.15–0.22	3–6.23
2	0.33	0.25–0.35	0.15–0.18	0.27–0.41	74 146–90 623	0.15–0.26	2.33–6.86
3	0.64	0.32–0.47	0.18–0.23	0.45–0.54	135 582–166 338	0.21–0.3	1.14–3.65
4	0.85	0.37–0.49	0.2–0.26	0.49–0.57	165 475–188 386	0.22–0.3	1.52–3.31
5	1.34	0.43–0.55	0.23–0.27	0.57–0.72	237 032–276 812	0.25–0.35	1.25–2.23
6	1.78	0.49–0.55	0.24–0.28	0.67–0.8	273 360–318 240	0.3–0.36	1.47–1.75
7	2.28	0.5–0.64	0.28–0.32	0.75–0.87	341 308–376 615	0.3–0.39	0.76–1.86
8	3.07	0.56–0.66	0.3–0.32	0.88–1.01	443 778–476 732	0.35–0.43	0.78–1.35
9	3.97	0.61–0.69	0.33–0.34	0.96–1.11	502 154–578 262	0.37–0.45	0.61–1.31

TABLE 2 | Ranges of the main characteristic hydraulic data (water depth h, hydraulic radius R, mean flow velocity V, flow Reynolds number Re, flow Froude number F and Darcy–Weisbach friction factor f) referring to the survey of June 1996.

Experimental series	Flow discharge ($m^3 s^{-1}$)	h (m)	R (m)	V ($m s^{-1}$)	Re	F	f
1	0.11	0.16–0.23	0.08–0.09	0.26–0.42	36 720–75 794	0.2–0.28	1.4–4.7
2	0.34	0.26–0.32	0.13–0.14	0.42–0.66	85 680–139 818	0.26–0.41	0.8–2.6
3	0.66	0.34–0.37	0.16–0.19	0.55–0.82	146 723–225 185	0.3–0.44	1.07–2.27
4	0.93	0.38–0.41	0.18–0.22	0.59–0.9	184 855–276 655	0.29–0.47	0.74–2.12
5	1.39	0.4–0.44	0.19–0.25	0.76–1.05	256 412–329 538	0.37–0.53	0.6–1.44
6	1.86	0.43–0.47	0.22–0.27	0.87–1.18	320 829–398 114	0.41–0.57	0.51–1.32
7	2.28	0.44–0.52	0.22–0.28	0.94–1.25	350 331–456 960	0.43–0.6	0.46–1.34
8	2.97	0.53–0.62	0.25–0.3	1–1.18	424 163–518 474	0.42–0.5	0.64–1.11
9	3.42	0.56–0.59	0.27–0.32	0.98–1.21	445 975–531 655	0.41–0.52	0.72–1.33

Verbena scabra, *Artemisia eudoviciana*, *Danthonia spicata*, *Carex* spp., *Solidago canadersis*, *Leersia virginica*) had been permitted to grow. Measurements of vegetation density were carried out using systematic sampling methods with line transects for horizontal point frame data (used for grasses, forbs, shrubs and woody vines) and belt transects for tree data. In particular, for both measurement types, Flippin-Dudley et al. (1998) calculated the ratio between the area of vegetation below water surface projected onto a plane perpendicular to direction of flow and the flow cross-sectional area referred to a characteristic length (pin length for horizontal point frame measurements and transect length for tree measurements). The mean vegetation density of the entire test channel was 0.123 elements m^{-1} for November 1995 and 0.627 elements m^{-1} for June 1996. More details on the measurement procedure are reported in the original report by Flippin-Dudley et al. (1998).

Six cross-sections were established, and flow depth and velocity measurements were performed in November 1995 and June 1996. For both surveys (November 1995 and June 1996), nine experimental series characterised by different flow discharge values were

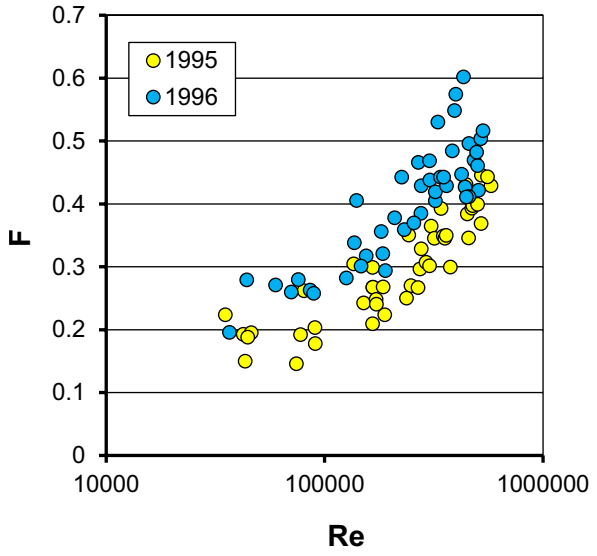

FIGURE 1 | Relationship between the Froude and Reynolds numbers for the investigated conditions.

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performed. These measurements were carried out according to the procedures described in the *National Handbook of Recommended Methods for Water-Data Acquisition*, U.S. Geological Survey (1977).

The main characteristic hydraulic data (mean flow velocity V, water depth h, hydraulic radius R, flow Froude number F, flow Reynolds number Re and Darcy–Weisbach friction factor f) referring to November 1995 and June 1996 are listed in Tables 1 and 2, respectively.

The studied flows were turbulent ($35\,151 \leq Re \leq 578\,262$) and had Froude number values varying from 0.146 to 0.602 (subcritical flows) (Figure 1). Moreover, the investigated flows are characterised by R/h values in the range 0.39–0.6, highlighting that narrow hydraulic cross-sections are considered.

3 | Results and Discussion

At first, the measurements carried out in the two field surveys (1995 and 1996) were represented by the plot Γ_v–f, in which Γ_v are the measured values obtained applying Equation (6). Figure 2 demonstrates that a strong relationship exists between the measured values of the Darcy–Weisbach friction factor and the corresponding Γ_v values, which depend on the measured values of slope, mean flow velocity and water depth. Figure 2a points out that, in the plot Γ_v—f, the measurements of the 2 years (November 1995 and June 1996), corresponding to different vegetation composition, growth phases and vegetation density, are overlaid. In other words, the overlay of the measured pairs (Γ_v, f) is independent of both the specific vegetation condition and density. Figure 2a also shows that the Darcy–Weisbach friction factor values detected in November 1995 are generally higher than those measured in June 1996, and this result can be explained considering that Flippin-Dudley et al. (1998) highlighted that *<<Grass was present in the channel during the November tests>>*. Therefore, the November measurements are characterised by an additional flow resistance contribution due to the presence of grass vegetation.

Figure 2b shows that a power equation can be empirically fitted to the pairs (Γ_v, f) of both surveys, confirming that the measurements agree with a relationship like Equation (5), which, for a given δ value, reduces f to a power function of Γ_v.

Using the 45 experimental runs corresponding to the measurements performed in November 1995 and characterised by a single value of M equal to 0.123 elements m^{-1}, the following equation for estimating Γ_v was obtained

$$\Gamma_v = 0.4014 \frac{F^{1.0322}}{s^{0.5423}} \quad (10)$$

Equation (10) is characterised by a coefficient of determination equal to 0.987. Figure 3a shows the comparison between the measured Γ_v values, obtained by Equation (6) and the measured values of s, V and h, and those calculated by Equation (10). Applying the theoretical expression of the Darcy–Weisbach friction factor (Equation 5) coupled with Equation (10), the f values were calculated for the measurements carried out in November 1995. Figure 3b shows that the f values calculated by Equation (5) and (10) have a good agreement (root mean square error [RMSE] equal to 0.20) with the measured ones, and the errors in their estimate E are less than or equal to 15% for 97.8% of the examined cases and less than or equal to 10% for 86.7% of the cases. Figure 4 shows the comparison between the empirical cumulative frequency distribution of the errors E and a normal law having mean and standard deviation equal to those (0.2 and 6.43, respectively) of the empirical sample. This figure demonstrates that the errors E are normally distributed. The normality of the errors was also assessed by the Shapiro–Wilk test (Shapiro and Wilk 1965), which yielded a p value (0.817) higher than the significance level of 0.05 (i.e., the null hypothesis of normality cannot be rejected). This result establishes, for a database characterised by a constant stem density, the completeness of the flow resistance model constituted by Equations (5) and (10), that is, no further variable has to be considered for explaining the variance of the measured f values. These results also agree with the previous solutions obtained by Nicosia et al. (2021) using

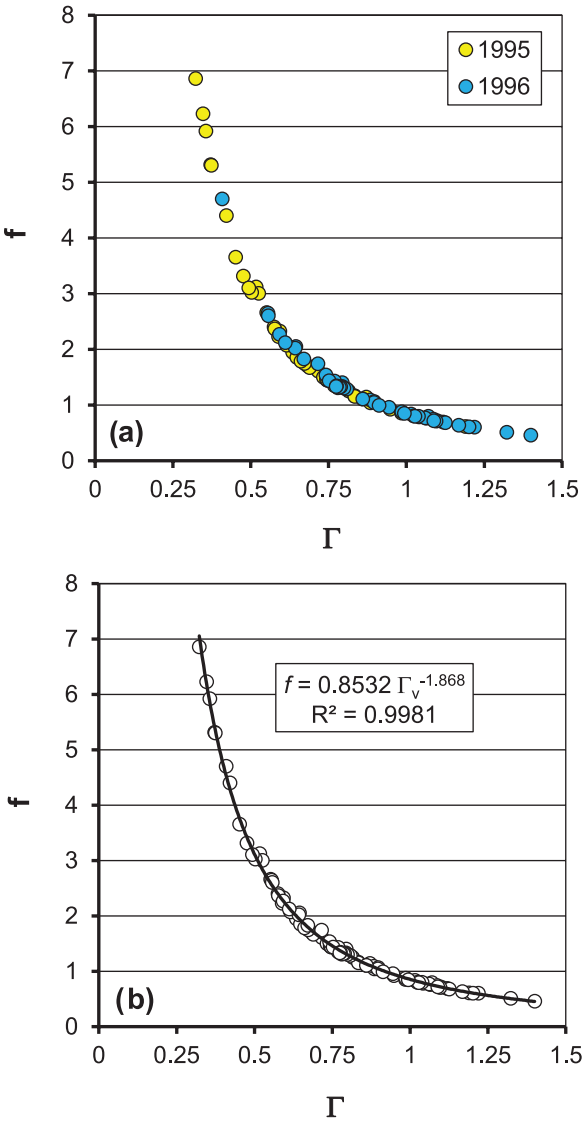

FIGURE 2 | Experimental relationship between the measured friction factors and the corresponding Γ_v values calculated by Equation (6) for (a) the two surveys and (b) all data.

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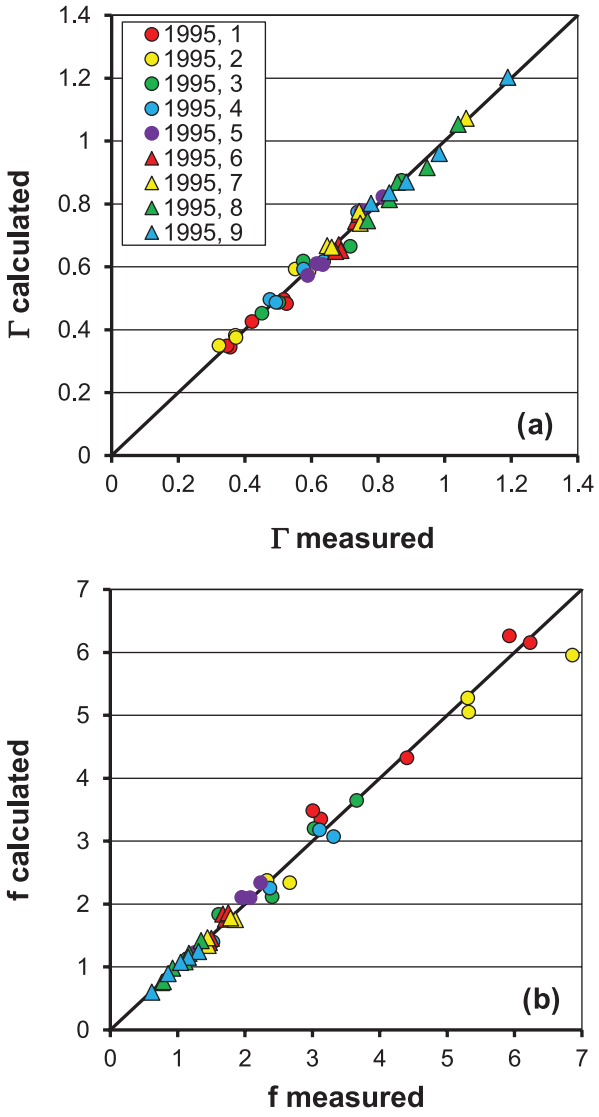

FIGURE 3 | Comparison, for the dataset November 1995 (nine experimental series), between the (a) Γ_v values calculated by Equation (6) and those calculated by Equation (10) and between the (b) measured f and those calculated by Equations (5) and (10).

full-scale Darcy–Weisbach friction factors measured in channels vegetated by riparian species.

Using the 45 experimental runs corresponding to the measurements performed in June 1996 and characterised by a single value of M equal to 0.627 elements m^{-1}, the following equation for estimating Γ_v was obtained

$$\Gamma_v = 0.4471 \frac{F^{0.9882}}{s^{0.5046}} \quad (11)$$

This equation is characterised by a coefficient of determination equal to 0.951. Figure 5a shows the comparison between the measured Γ_v values, obtained by Equation (6), and those calculated by Equation (11). Applying Equation (5) coupled with Equation (11), the Darcy–Weisbach friction factors f were calculated for the measurements carried out in June 1996. Figure 5b shows that the f values calculated by Equations (5) and (11) have good agreement (RMSE equal to 0.15) with the measured ones, and the errors in their estimate E are less than or equal to 15% for 88.9% of the examined cases and less than or equal to 10% for 64.4% of the cases.

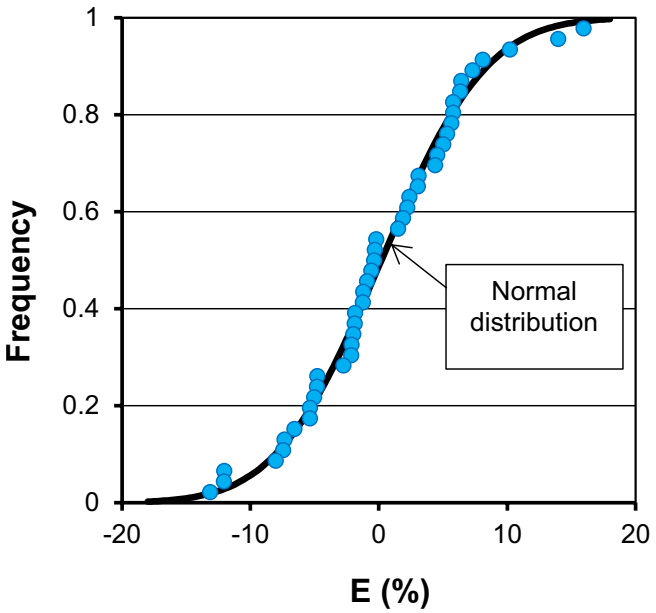

FIGURE 4 | Comparison, for the dataset November 1995, between the empirical cumulative frequency distribution of the errors E and a normal law.

Equations (10) and (11) have the same mathematical shape detected in previous studies performed for flumes covered with flexible grass-like vegetation (Ferro 2019), emergent rigid vegetation (Nicosia et al. 2024), and large-scale channels covered with common reed (Nicosia et al. 2023) and riparian species (Nicosia et al. 2021; Nicosia and Ferro 2023). Previous studies for grass-like vegetation demonstrated that the scale factor A of Equation (9) was related to stem density, as a threshold value of M identifying the quasi-smooth (skimming) flow regime can be identified. Instead, for full-scale studies in vegetated channels, the effect of the vegetation biomechanical properties was dependent on the vegetation type or related to the bending stiffness (Nicosia et al. 2021).

Since, according to Equation (8), Γ_v depends on stem density, channel slope and flow Froude number (Ferro 2018), this equation was calibrated using the entire database (90 experimental runs) characterised by two values of stem density, and the following power equation was obtained:

$$\Gamma_v = 0.428 \frac{F^{1.0135} M^{0.0210}}{s^{0.5289}} \quad (12)$$

where M has to be considered as the ratio $M/1$, being 1 stem m^{-1} a reference concentration (Ferro 2019), and which is characterised by a coefficient of determination equal to 0.978. Equation (12) has the same mathematical shape obtained by Ferro (2019) using flume measurements (Kouwen et al. 1969; Wilson and Horritt 2002; Raffaelli et al. 2002; Carollo et al. 2005) of the Darcy–Weisbach friction factor collected in grass-like vegetated channels. For the complete database (November 1995 and June 1996), Figure 6a shows the comparison between the measured Γ_v values, obtained by Equation (6), and those calculated by Equation (12), while Figure 6b shows that the f values calculated

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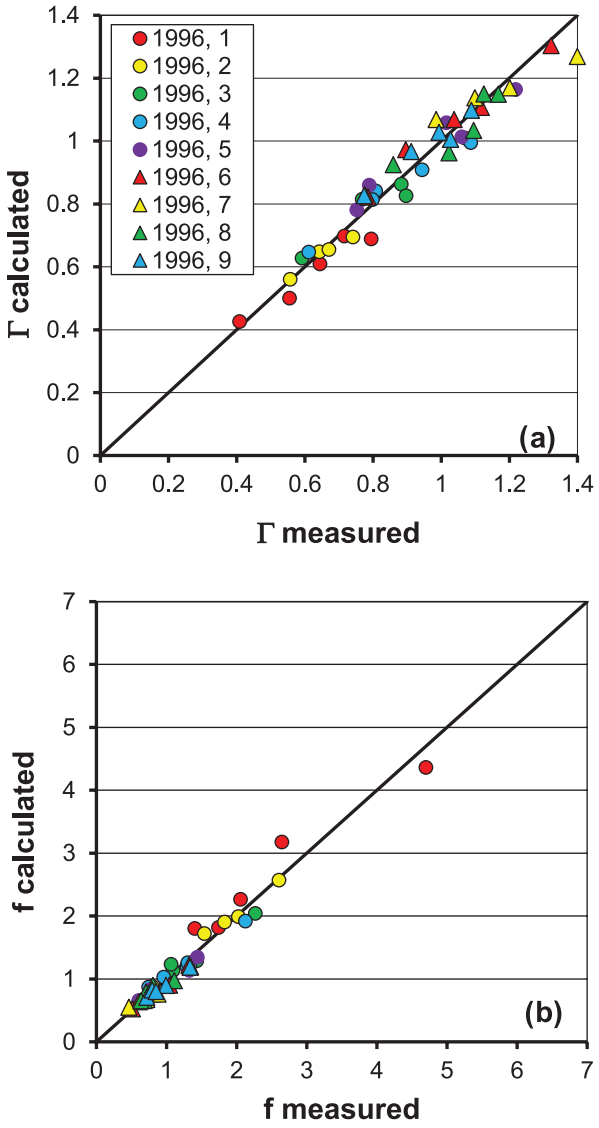

FIGURE 5 | Comparison, for the dataset June 1996 (nine experimental series), between the (a) Γ_v values calculated by Equation (6) and those calculated by Equation (11) and between the (b) measured f and those calculated by Equations (5) and (11).

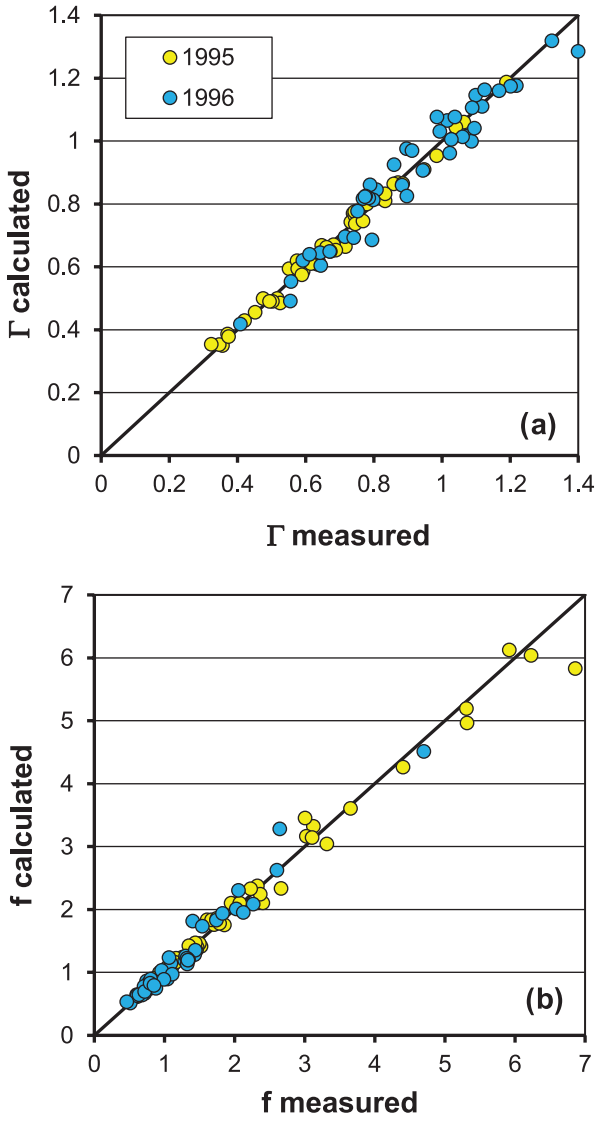

FIGURE 6 | Comparison, for the complete dataset (November 1995 and June 1996), between the (a) Γ_v values calculated by Equation (6) and those calculated by Equation (12) and between the (b) measured f and those calculated by Equations (5) and (12).

by Equations (5) and (12) have a good agreement, characterised by a RMSE equal to 0.19, with the measured ones. The errors in the estimate E of the friction factor values are less than or equal to 15% for 92.2% of the examined cases and less than or equal to 10% for 75.6% of the cases. Figure 7 shows the comparison between the empirical cumulative frequency distribution of the errors E and a normal law having mean and standard deviation equal to those (0.36 and 8.74, respectively) of the empirical sample. This figure demonstrates that the errors E are normally distributed. Also in this case, the Shapiro–Wilk test, with a p value (0.0558) higher than the significance level of 0.05, confirmed the normality of the errors. These results confirmed the completeness of the flow resistance model constituted by Equations (5) and (12) for a database characterised by varying stem density values.

Finally, for detecting the influence of the stem density, which is characterised by an exponent value of 0.021, on the estimate of the Darcy–Weisbach friction factor, Equation (12) was applied by setting this exponent equal to 0. Figure 8 shows the comparison between the measured f values and those calculated under this last hypothesis. This analysis demonstrates that neglecting the effect of M produces a relevant scattering of the data points and a significant worsening of the Darcy–Weisbach friction factor estimates in comparison with the results shown in Figure 6b. The scale factor of Equation (12), equal to $0.428\,M^{0.021}$, allows for taking into account the differences in stem density to be considered for joining the two experimental series having a different vegetation composition and spatial heterogeneity.

In conclusion, the flow resistance law proposed by Ferro (2019) yields satisfying results in terms of the estimate of the Darcy–Weisbach friction factor also for the vegetation species investigated in this study.

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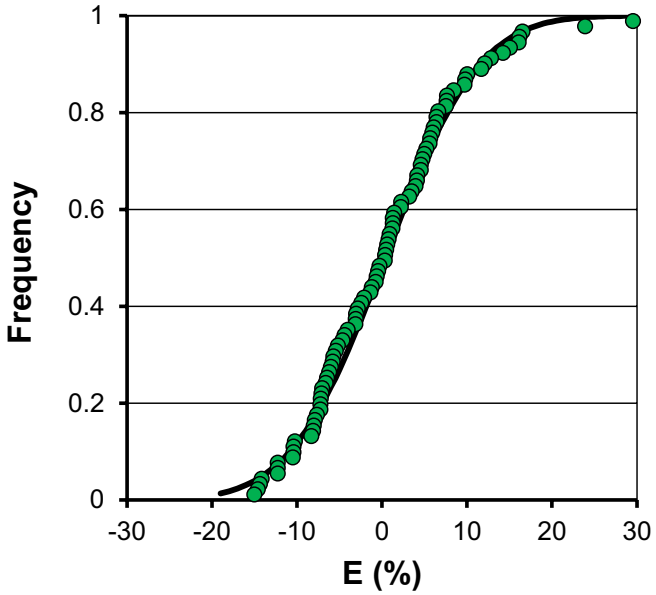

FIGURE 7 | Comparison, for the complete dataset, between the empirical cumulative frequency distribution of the errors E and a normal law.

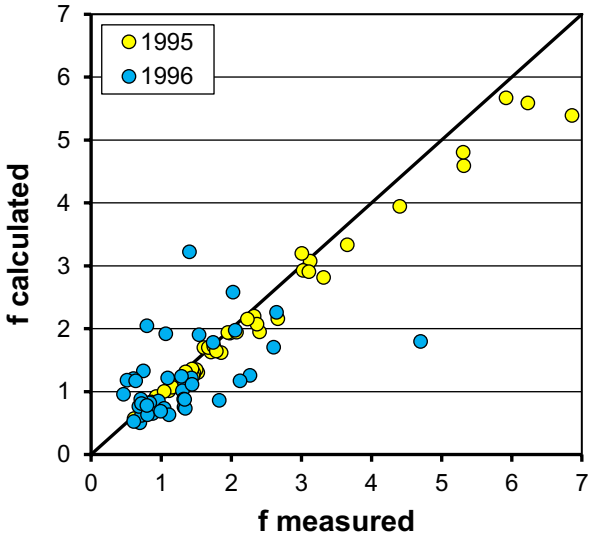

FIGURE 8 | Comparison between the measured f values and those calculated by introducing Equation (12) with $e = 0$ into Equation (5).

4 | Conclusions

Previous studies on flow velocity profile in vegetated channels suggested that a power velocity distribution, derived by applying dimensional analysis and self-similarity theory, can be integrated to deduce a flow resistance law in which the Γ parameter and δ exponent of the velocity profile are present. Field measurements carried out in two different periods (November 1995 and June 1996) by Flippin-Dudley et al. (1998) in a large-scale vegetated channel and referring to two vegetation density values were used to assess the applicability of the theoretical flow resistance equation proposed by Ferro (2019), which was widely tested for grass-like, shrubs and woody vegetation. The theoretical law was calibrated by establishing the relationship between the Γ parameter, the flow Froude number, the energy slope and the stem density of the available data sets.

For the complete data set (90 measurements corresponding to two stem density values), the performed analysis showed that the proposed approach allows for obtaining estimates of the Darcy–Weisbach friction factor that are characterised by errors less than or equal to 15% for 92.2% of the examined cases. In other words, the analysis confirmed that the model proposed by Ferro (2017) gives an accurate f estimate and is complete (i.e., no further variable has to be considered for explaining the variance of the measured f values) also for these vegetation species.

Recently, Nicosia et al. (2025) demonstrated that, for known hydraulic conditions (slope, Froude number), the Γ values corresponding to laboratory conditions (flumes), Γ_L, must be upscaled by a scale factor to obtain Γ values, Γ_F, estimated by field data (streams, rivers). In other words, the flow resistance similitude between flow resistance in a flume and in a vegetated river is governed by the Γ function. Furthermore, according to Pasquino et al. (2025), the leaf area index (LAI) is a robust predictor of canopy biomass and is able to contemporaneously synthesise the effects of vegetation density and canopy cover. LAI is an *<<independent and nearly unbiased metric for quantitatively characterizing plant density>>* and it can be used for assessing flow resistance for just-submerged plants typical of vegetated floodplains and riparian zones.

In conclusion, to compare laboratory flumes and large-scale vegetated channels, other measurements are required to investigate different hydraulic conditions and stem density values and applying LAI for characterizing vegetation arrangements with the same stem density and a different canopy structure.

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Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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