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Niewerth, Stephan; Aberle, Jochen; Folke, Frederik

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Determination of flow resistance parameters of blackberry for hydraulic modeling considering plant flexibility

Stephan Niewerth [a]

Jochen Aberle [a]

Frederik Folke [b]

[a] Leichtweiß-Institut für Wasserbau, Technische Universität Braunschweig, Braunschweig, Germany
[b] Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, Germany

Abstract

Riparian vegetation essentially influences the flow resistance and therefore reliable plant parameters are necessary for hydraulic modeling. This paper presents results from an experimental study designed to determine species-specific resistance parameters of blackberry plants (Rubus armeniacus Focke) for the use in the flow resistance approaches accounting for plant flexibility of Järvelä (2004) and Västilä & Järvelä (2014). Both approaches are briefly described and presently available species-specific parameters for various species are summarized. Flume experiments to measure the drag force to velocity relationship using foliated and defoliated blackberry twigs collected from nature are described, and the collected data are used to derive the species-specific parameters. The variability of parameter values for individual specimen are shown and briefly discussed. Repeated tests with a specimen carried out with increasing and decreasing velocity steps, respectively, led to the formulation of a hypothesis for a vegetated hysteresis effect. The derived mean values fit into the range of the presently available values for other species so that they can be used to extend the database for both approaches.

Keywords: Flexible vegetation; flow resistance; foliage; Vogel-exponent; species-specific parameters

1 Introduction

The hydrodynamics of vegetated channels is currently in the focus of many scientific disciplines ranging from aquatic ecology to hydraulic engineering and is a rapidly developing research area due to the significance of vegetation for both the natural and built environments. An important aspect for the development of sustainable strategies to manage vegetation in riverine areas in accordance with European water legislation (e.g., Water Framework Directive – Directive 2000/60/ECM and Floods Directive – Directive 2007/60/EC) is the accurate determination of flow resistance due to vegetation. Vegetation has typically been modelled by adjusting Manning's n value or by assuming that natural plants can be represented by rigid cylindrical elements. According to the cylinder analogy, plants are characterized by the spacing of the cylinders, the cylinder diameter, and a drag coefficient C_D which is typically obtained from the Wieselsberger-nomogram to $C_D \approx 1$ for cylinder Reynolds-numbers in the range of approx. 800 - 8000 (e.g. Hoerner, 1965). Consequently, the morphology and flexibility of vegetation as well as the resistance caused by leaves has been largely ignored in practical applications (see Aberle & Järvelä 2013, 2015 for a review of this topic).

New approaches for the determination of flow resistance due to emergent flexible and leafy vegetation, i.e. for vegetation typically found on floodplains, were developed by e.g., Fathi-Maghadam & Kouwen (1997), Freeman et al. (2000, 2002), Järvelä (2004), Whittaker et al. (2013, 2015), Jalonen & Järvelä (2014) and Västilä & Järvelä (2014), and recent studies have highlighted the need to consider the flexibility of floodplain vegetation in computational approaches (e.g., Shields et al., 2017; DWA, 2019). In fact, the comparison of approaches accounting for flexible emergent vegetation with the classical rigid-cylinder analogy in 1-D (e.g., Wang & Zhang, 2019) and 2-D numerical simulations of river reaches (e.g., Dombroski, 2014, Dalledonne et al. 2019) revealed the good performance of the "flexible" approaches compared to the "rigid" approaches. However, the parameterization of these approaches differs from conventional methods, as information on plant characteristics such as the flexural rigidity or species-specific resistance parameters is required. While some species-specific values are available from the aforementioned studies, there is still a lack of values of these parameters for a large number of species. In this context, the Federal Waterways Engineering and Research Institute in Germany plans to apply the approach of Järvelä (2004) in 2D-simulations for the determination of the flow resistance of river reaches characterized by flexible vegetation. One of the reaches is located in a regulated river reach where blackberry is the dominant vegetation type along the banks, and corresponding parameter values to be used in the approach by Järvelä (2004) have not yet been determined and reported in the literature.

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The objective of the present paper is to describe the methodology for the determination of the required species-specific parameter values for the Järvelä (2004) approach and the approach of Västilä & Järvelä (2014, 2018), which can be seen as a further development of the first approach. Both approaches are briefly described in Section 2. The experimental setup and procedure are described in Section 3, and the results of the study are presented in Section 4. Section 5 shortly summarizes and concludes the paper.

2 Methods to assess resistance of flexible leafy vegetation

The approach from Järvelä (2004) to determine the resistance of flexible leafy vegetation in just submerged conditions has been formulated in terms of the Darcy-Weisbach friction factor f'':

$$f'' = 4C_{D\chi}LAI\left(\frac{u}{u_\chi}\right)^\chi \quad (1)$$

where $C_{D\chi}$ = species-specific drag coefficient, LAI = leaf area index (based on the one-sided leaf area), χ = vegetation parameter (Vogel-exponent), u = bulk flow velocity, and u_χ = the lowest flow velocity used in the experiments to determine $C_{D\chi}$ and χ. The parameter u_χ has been introduced in the equation to guarantee dimensional homogeneity of the relationship. Table 1 summarizes the published values for $C_{D\chi}$, χ and u_χ for a number of species (see also DWA, 2019).

Table 1: Parameter values for the use of Eq. (1) for different deciduous and coniferous species

Species	$C_{D\chi}$ [-]	u_χ [m/s]	χ [-]	Data source
Common Osier (*Salix viminalis*)	0.15	0.20	-0.77	Västilä & Järvelä (2014)
Goat Willow (*Salix caprea*)	0.43	0.10	-0.57	Järvelä (2004)
Hybrid Willow (*Salix triandra x viminalis*)	0.53	0.10	-0.90	Järvelä (2006)
Hybrid Crack Willow (*Salix alba × Salix fragilis*)	0.24	0.20	-0.90	Västilä & Järvelä (2014)
Black Poplar (*Populus nigra*)	0.33	0.10	-1.03	Västilä et al. (2013)
Common Alder (*Alnus glutinosa*)	0.21	0.20	-0.89	Västilä & Järvelä (2014)
Silver Birch (*Betula pendula*)	0.26	0.20	-0.86	Västilä & Järvelä (2014)
Eastern White Cedar (*Thuja occidentalis*)	0.56	0.10	-0.55	Fathi-Moghadam (1996)
White Cedar (Picea glauca)	0.57	0.10	-0.39	Fathi-Moghadam (1996)
Eastern White Pine (*Pinus strobus*)	0.69	0.10	-0.50	Fathi-Moghadam (1996)
Austrian Pine (*Pinus nigra*)	0.45	0.10	-0.38	Fathi-Moghadam (1996)

Eq. (1) was derived for plant stands and is hence not directly suitable for the determination of the species-specific coefficients from drag force measurements. However, as discussed in Aberle & Järvelä (2015), the Järvelä (2004) approach can be downscaled from the plant stand scale to the scale of an individual plant to allow for the determination of species-specific coefficients from the force-velocity relationship:

$$F_D = \frac{1}{2}\rho C_{D\chi}A_L\left(\frac{u}{u_\chi}\right)^\chi u^2 \quad (2)$$

with F_D = drag force, ρ = fluid density, and A_L = one-sided leaf area of the plant. Thus, knowing the one-sided leaf area of the tested plant, the parameters $C_{D\chi}$, u_χ, and χ can be determined from experiments with just-submerged conditions in which the drag force F_D is measured as a function of the bulk velocity u.

Västilä et al. (2013) and Jalonen & Järvelä (2014) recommended to modify Eq. (2) by considering additionally the wooden stem area A_S of the plant, i.e. by replacing A_L with the total area of the plant $A_{tot} = A_L + A_S$. In more detailed investigations, Västilä & Järvelä (2014) proposed a model to separately account for the drag force exerted by the foliage (F_F) and the wooden plant parts (F_S):

$$F_D = F_F + F_S = \frac{1}{2}\rho\left(C_{D\chi,F}A_L\left(\frac{u}{u_{\chi,F}}\right)^{\chi F} + C_{D\chi,S}A_S\left(\frac{u}{u_{\chi,S}}\right)^{\chi S}\right)u^2 \quad (3)$$

where the subscripts F and S denote the coefficients related to foliage and stem. Eq. (3) can be parameterized by data from experiments in which the drag forces have been measured for identical flow velocities for both foliated and defoliated specimens. This means that the drag exerted by foliage can be determined from $F_F = F_D - F_S$ allowing for the separate parametrization of the F_F - u and F_S - u relationships. Note that Eq. (3) can be upscaled to plant stands to determine f'' (Västilä & Järvelä, 2014). The advantage of this approach is that it can be more conveniently used to assess the effect of seasonality compared to the Järvelä (2004) approach due to the specific consideration of foliage and wooden plant parts. However, the number of known species-specific coefficients is lower than the number of available coefficients for the approach of Järvelä (2004) (see Table 2).

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Table 2: Parameter values for the use of Eq. (3) for different deciduous species ($u_{\chi,F} = u_{\chi,S} = 0.2$ m s^{-1}). Velocities up to 0.8 m s^{-1} were used in deriving the values (Västilä & Järvelä, 2018)

Species	**$C_{D\chi,F}$ [-]**	**χ_F [-]**	**$C_{D\chi,S}$ [-]**	**χ_S [-]**	**Data source**
Alnus glutinosa (Common Alder)	0.18	−1.11	0.89	−0.27	Västilä and Järvelä (2014)
Betula pendula (Silver Birch)	0.20	−1.06	1.02	−0.32	Västilä and Järvelä (2014)
Betula pubescens (White Birch)	0.10	−1.09	0.82	−0.25	Jalonen and Järvelä (2014)
Populus nigra (Black Poplar)	0.13	−0.97	0.95	−0.27	Västilä and Järvelä (2014)
Salix alba × Salix fragilis (hybrid Crack Willow)	0.19	−1.21	0.96	−0.25	Västilä and Järvelä (2014)
Salix caprea (Goat Willow)	0.09	−1.09	0.84	−0.27	Jalonen and Järvelä (2014)
Salix viminalis (Common Osier)	0.11	−1.21	1.03	−0.20	Västilä and Järvelä (2014)
Species-averaged	0.14	−1.11	0.93	−0.26	

3 Experimental Methodology

3.1 Experimental setup

The experiments for the determination of the species-specific parameter values were carried out in a 32 m long, 0.6 m wide and 0.4 m high tilting flume in the hydraulic laboratory of the Leichtweiß-Institute for Hydraulic Engineering and Water Resources (LWI) at the Technische Universität Braunschweig, Germany. The discharge, delivered by the water circuit of the hydraulic laboratory, was controlled by a valve and measured by a KROHNE Aquaflux 090K inductive flow meter (accuracy of 0.3 % of the measured value) which was installed at the supply pipe to the flume. The water depth in the flume was adjusted by a tail-gate located in a distance of 24.4 m from the flume entrance. Flow depths were determined from point gauge measurements 1 m up and downstream of the tested plants at distances of 15 m and 17 m from the flume entrance, respectively. An additional water-surface level measurement at 10 m distance to the flume entrance allowed for the determination of the water-surface slope to ensure uniform flow conditions during the experiments. The flume bed was covered by a mat with 6 mm high cone shaped roughness elements which has also been used in study of Nardone & Koll (2016).

Drag forces were measured with a drag force sensor (DFS) mounted in the centerline of the flume in a distance of 16 m from the flume inlet in a 1.5 m long box below the flume bottom, so that the DFS did not interact with the flow (Figure 1). Details of the DFS can be found in several studies in which it has already been used (e.g., Schoneboom et al., 2008; Schoneboom & Aberle, 2009; Siniscalchi et al., 2012; Jalonen et al., 2013; Västilä et al., 2013; Asher et al., 2016; Niewerth et al., 2016). The DFS consists of a 140 mm long, 18 mm wide and 2 mm thick stainless-steel beam (X5 Co-NI 18-10 steel) which is connected to a base plate by a rigid joint. A free movable aluminum head plate, flush mounted with the flume bed, is fixed to the top of the steel beam in which vegetation elements can easily be fixed using the screw thread inside the head plate. Drag forces are determined by a total of eight strain gauges which are attached to the steel beam and configured as two Wheatstone full bridges being separated by a distance l. This setup allows for measurements of low drag forces ($F \geq 0.2$ N) with high accuracy (standard error ≈ 2%) and high temporal resolution (1613 Hz). The strain gauges are protected against humidity by a pressurized plastic tube preventing water intrusion. When subjected to flow, the vegetation element attached to the steel beam acts as a cantilever in bending and generates compression strains at positions 1 and 2 which can be converted to drag forces (Schoneboom & Aberle, 2009).

3.2 Blackberry characteristics

Leafy blackberry branches (*Rubus armeniacus* Focke) of approximately 1 m length were sampled in the municipality of Braunschweig along a railroad embankment in February 2019. Rubus armeniacus Focke has biennial stems with evergreen compound leaves consisting of five leaflets. The petioles of the compound leaves were separated by a distance of around 50 mm along the length of the branches. The diameter of the leafy twigs reduced from a diameter of approximately 7 mm at the branch to 3 mm at the end of the twig. For the experiments, the sampled twigs were cut to a length of 0.2 to 0.3 m to fit into the flume, and drag force measurements were carried out using six sub-twigs for which the one-sided leaf area A_L, stem area A_S, maximum (d_{max}) and minimum (d_{min}) stem diameter, the number of compound leaves n, and the twig-height with and without leaves, h_p and h_s, respectively, were determined (Table 3). Both the one-sided leaf area A_L and the stem area A_S were determined after the drag force measurements by placing the leaves and stem on an illuminated box and analyzing the taken digital photographs. Additionally, the modulus of elasticity of the branches was determined through three-point loading tests resulting in an average value of E = 5,200 N/mm (mean variation of ± 50 %) for tested branches with a diameter of d = 3 mm to 11 mm.

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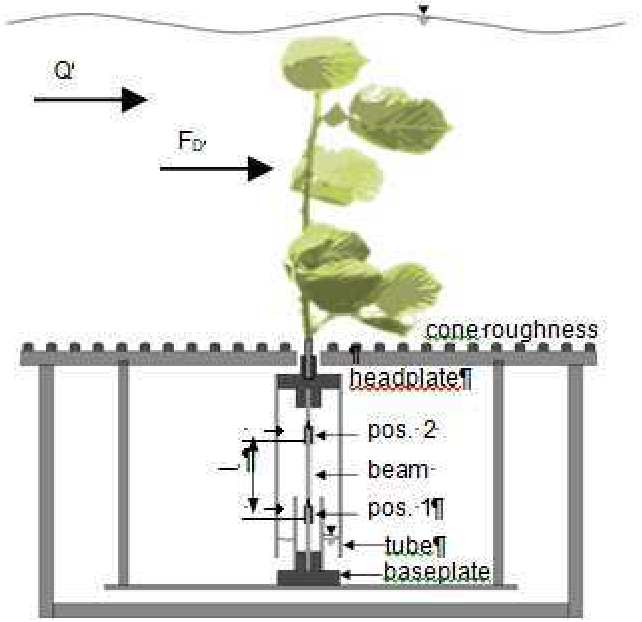

Figure 1: Sketch of the setup of the drag force sensor (DFS) installed in a 1.5 m long box below the flume bottom (Schoneboom, 2011, modified). Not to scale.

Table 3: Characteristics of the tested Rubus armeniacus Focke (blackberry) specimens.

Specimen	A_L [cm²]	A_S [cm²]	A_L/A_S [-]	d_{max} [mm]	d_{min} [mm]	N [-]	h_p [cm]	h_s [cm]
Bb11	337	10	34	5.5	3.5	5	25	19
Bb12	368	19	19	6	4	5	30	25
Bb21	312	10	31	4	3	5*	30	23
Bb22	370	17	22	6	5	5	30	26
Bb23	214	17	13	6	6	4	24	24
Bb32	263	12	22	6	6	3	25	18

3.3 Experimental procedure

Before the measurements, each specimen listed in Table 3 was carefully attached to the DFS and inserted into the flume. Subsequently, both discharge and flume slope were adjusted to obtain uniform flow and just-submerged flow conditions, i.e. the water depth corresponded to the deflected height of the specimen. The bulk velocity (determined by the equation of continuity using the mean value of the water depths measured 1 m up- and downstream of the specimen) was used for the parameterization of the drag force equations [2] and [3]. The bulk velocity was varied between 0.1 m/s and 1.2 m/s with stepwise increments of 0.1 m/s to 0.2 m/s. The velocity range varied slightly between the individual tests due to experimental boundary conditions, i.e. care was taken that the flow conditions were uniform and no significant surface waves occurred. Figure 2 shows exemplarily the specimen Bp21 at different bulk flow velocities and the water levels for just-submerged conditions. Drag forces were measured over a time period of 30 s, which was found to be large enough to obtain a stable mean.

The primary objective of the experiments was the parameterization of the Järvelä (2004) approach. However, in order to extend the parameter values for the approach of Västilä & Järvelä (2014), an additional test series was carried out with the defoliated specimens Bb21, Bb22, and Bb23 (labelled as Bbs21, Bbs22 and Bbs23). Moreover, the test series with the branches Bb11 and Bb32 were repeated to investigate the reproducibility of the experiments (labelled as Bb111, Bb112, Bb321, Bb322, and Bb323), which may be helpful to investigate if a pre-loading of a specimen affects the velocity-force relationship. Flow conditions and measured drag forces are shown in Table 4.

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Table 4: Mean velocity u, drag force F_D, flow depth h and slope S (uniform flow) for all investigated specimen.

Specimen	u [m/s]	F_D [N]	h [m]	S [%]
Bb111	0.10	0.10	0.30	0.004
Bb111	0.20	0.32	0.30	0.015
Bb111	0.30	0.52	0.30	0.048
Bb111	0.40	0.76	0.30	0.080
Bb111	0.50	0.95	0.30	0.120
Bb111	0.60	1.31	0.30	0.165
Bb112	0.20	0.32	0.30	0.014
Bb112	0.30	0.44	0.30	0.048
Bb112	0.40	0.63	0.25	0.073
Bb112	0.50	1.00	0.23	0.121
Bb112	0.70	1.59	0.21	0.255
Bb112	0.90	1.77	0.18	0.481
Bb12	0.10	0.14	0.30	0.004
Bb12	0.20	0.38	0.30	0.015
Bb12	0.30	0.66	0.30	0.048
Bb12	0.40	0.94	0.30	0.080
Bb12	0.50	1.26	0.30	0.120
Bb12	0.60	1.39	0.30	0.165
Bb21	0.10	0.08	0.30	0.004
Bb21	0.20	0.20	0.30	0.015
Bb21	0.40	0.55	0.27	0.069
Bb21	0.60	0.90	0.25	0.136
Bb21	0.80	1.13	0.20	0.347
Bb21	1.00	1.46	0.18	0.593
Bb21	1.20	1.76	0.16	0.830
Bb22	0.10	0.18	0.30	0.004
Bb22	0.20	0.46	0.30	0.015
Bb22	0.40	1.05	0.30	0.080
Bb22	0.60	1.67	0.30	0.143
Bb22	0.80	2.07	0.30	0.238
Bb23	0.10	0.09	0.30	0.005
Bb23	0.20	0.27	0.30	0.016
Bb23	0.40	0.68	0.25	0.073
Bb23	0.60	1.05	0.25	0.163
Bb321	0.10	0.14	0.25	0.004

Specimen	u [m/s]	F_D [N]	h [m]	S [%]
Bb321	0.30	0.53	0.25	0.041
Bb321	0.50	1.02	0.23	0.121
Bb321	0.70	1.30	0.21	0.255
Bb321	0.90	1.90	0.21	0.422
Bb321	1.10	2.14	0.21	0.630
Bb321	1.20	2.18	0.21	0.630
Bb322	0.10	0.10	0.25	0.005
Bb322	0.30	0.35	0.25	0.041
Bb322	0.50	0.66	0.23	0.121
Bb322	0.70	1.06	0.21	0.255
Bb322	0.90	1.56	0.21	0.422
Bb322	1.20	2.18	0.21	0.630
Bb323	0.10	0.10	0.25	0.005
Bb323	0.30	0.43	0.25	0.041
Bb323	0.50	0.83	0.23	0.121
Bb323	0.70	1.17	0.21	0.255
Bb323	0.90	1.73	0.21	0.422
Bb323	1.10	2.26	0.21	0.630
Bbs21	0.10	0.01	0.30	0.004
Bbs21	0.20	0.03	0.30	0.016
Bbs21	0.40	0.11	0.30	0.064
Bbs21	0.60	0.26	0.25	0.163
Bbs21	0.80	0.42	0.25	0.290
Bbs21	1.00	0.63	0.23	0.484
Bbs22	0.10	0.01	0.28	0.004
Bbs22	0.20	0.05	0.28	0.017
Bbs22	0.40	0.22	0.28	0.067
Bbs22	0.60	0.46	0.28	0.150
Bbs22	0.80	0.76	0.28	0.267
Bbs23	0.10	0.01	0.28	0.004
Bbs23	0.20	0.04	0.28	0.017
Bbs23	0.40	0.16	0.28	0.067
Bbs23	0.60	0.48	0.25	0.163
Bbs23	0.80	0.79	0.24	0.299
Bbs23	0.90	1.02	0.25	0.290

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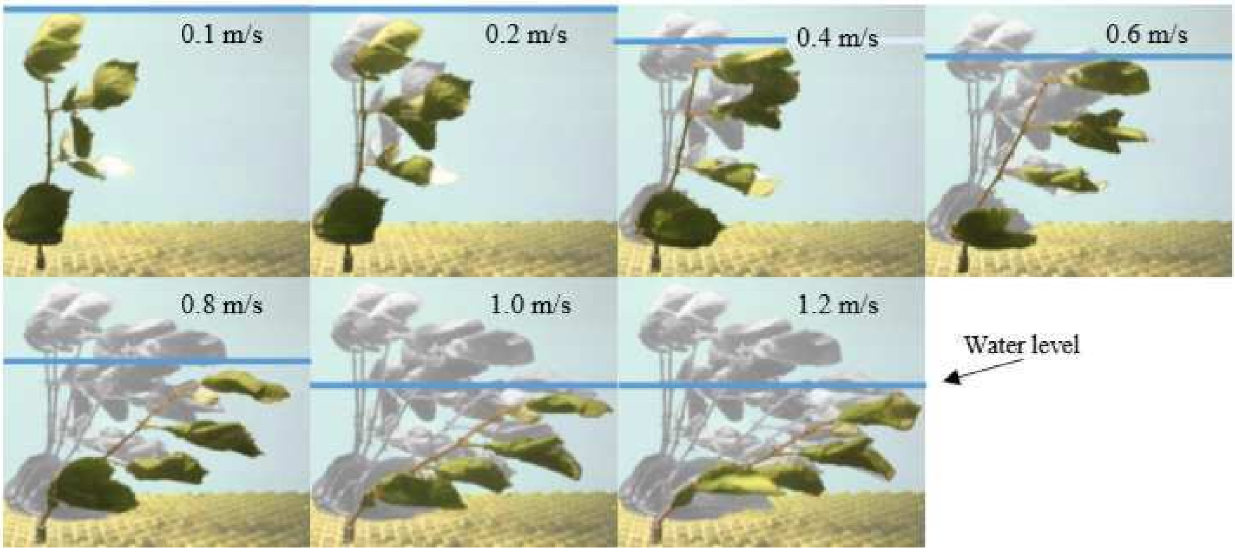
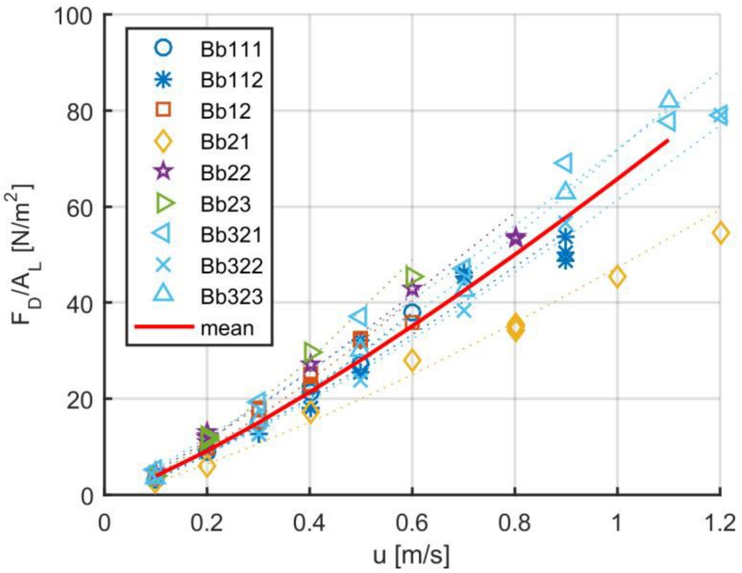


Figure 2: Deformation of specimen Bb21 for flow velocities ranging from 0.1 m/s to 1.2 m/s. Plants in grey indicate the plant positions at lower velocities and the blue line indicates the water level.

4 Results

4.1 Parameterization of the Järvelä (2004) approach

Figure 3 presents the results from measurements with leafy blackberry twigs. The measured drag forces are normalized by the one-sided leaf area A_L and are plotted as a function of the bulk velocity. The lowest bulk velocity used in the measurements was 0.1 m/s so that u_χ = 0.1 m/s. Both χ and $C_{D\chi}$ can be estimated by fitting a power-law to the data (see equation [2]). The corresponding values, all obtained from fits with a regression coefficient R > 0.98, are summarized in the table within Figure 3. It is worth noting that the data points for Bb21 deviate from the other data points, especially for larger flow velocities (Figure 3). The reason for this deviation remains unclear at this stage, although it could be hypothesized that this deviation is an indicator of the natural variability of plant characteristics.



Specimen	u_χ [m/s]	$C_{D\chi}$ [-]	χ [-]
Bb111	0.1	0.63	-0.61
Bb112	0.1	0.73	-0.76
Bb12	0.1	0.76	-0.68
Bb21	0.1	0.53	-0.75
Bb22	0.1	0.98	-0.80
Bb23	0.1	0.83	-0.62
Bb321	0.1	1.08	-0.88
Bb322	0.1	0.68	-0.75
Bb323	0.1	0.73	-0.71

Figure 3: Measured drag forces normalized by the one-sided leaf area as a function of the bulk velocity and the derived parameters for the Järvelä (2004) approach.

The $C_{D\chi}$-values of the leafy branches vary between $0.53 \leq C_{D\chi} \leq 1.08$ and the χ-values vary within the range $-0.61 \leq \chi \leq -0.88$. To determine the averaged values from these measurements a regression analysis was carried out resulting in $C_{D\chi} = 0.78$ and $\chi = -0.77$ for blackberry branches. We note that, compared to existing values, the $C_{D,\chi}$ value is the largest, but the χ value fits well in the range of reported values (see Table 1). Figure 4 presents the normalized Darcy-Weisbach friction factor f''/LAI (calculated by equation [1] and [2]). The

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range is indicated by the curves for Bb21 and Bb321 in Figure 4 representing the minimum and maximum f''/LAI values, respectively.

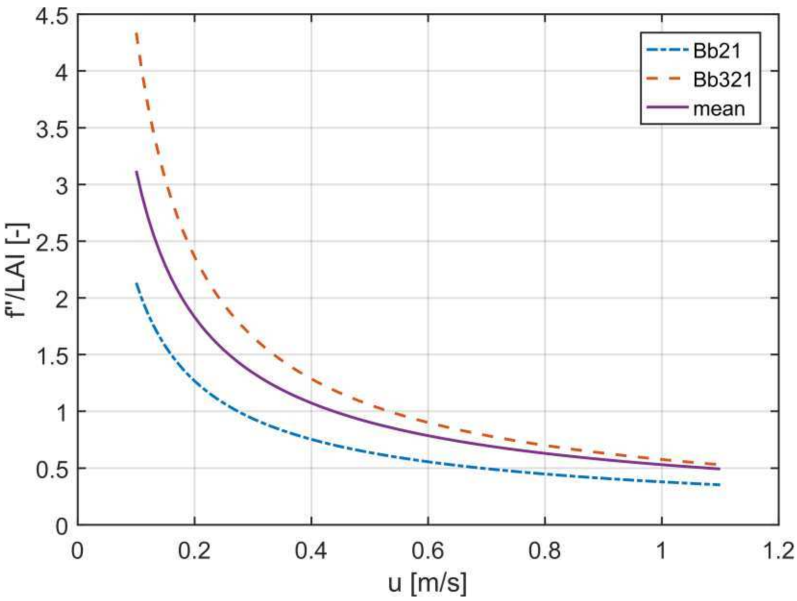

Figure 4: The normalized Darcy-Weisbach friction factor f''/LAI as a function of the bulk velocity. The lines were obtained by using the determined mean parameter values and the parameter values for specimens Bb21 and Bb321 resulting in the minimum and maximum f''/LAI values for all measurements.

4.2 Parameterization of the Västilä & Järvelä (2014) approach

Figure 5a presents the ratio of the drag force, normalized by the sum of the one-sided leaf area and the stem area, $F_D/(A_L + A_S)$ as a function of the bulk flow velocity u in a log-log plot. The figure shows a clear separation of the measurements carried out with foliated and defoliated specimens since the total area of a defoliated specimen is much lower than the area of a foliated one. For the foliated cases, the difference to the results presented in Figure 3 is small since the stem area of the specimen is small compared to their one-sided leaf area (Table 1). The experiments with the specimens Bb21, Bb22, and Bb23 were repeated by using the same specimen in leafless conditions, so that these measurements can be used to derive the parameters for the Västilä & Järvelä (2014) approach (red lines in Figure 5a). For the determination of the parameters u_χ = 0.2 m/s was used to harmonize the results with the already existing data-base (Table 2, Västilä & Järvelä, 2018), and a regression analysis resulted in the following values: $C_{D\chi,F}$ = 0.4, χ_F = -1.00, $C_{D\chi,S}$ = 1. 2, χ_s = 0.16. This set of parameters indicates that the stem of the blackberry branches behaves nearly as a rigid cylinder (χ_s = 0.16 is close to 0 and $C_{D\chi,S}$ = 1.2 is close to the drag coefficient of a rigid cylinder). Note also that the determined parameters follow the same trend as the already reported values (see Table 2). Figure 5b shows the results when the Västilä & Järvelä (2014) approach is used to parameterize each of the aforementioned datasets individually (values not reported) together with the curve representing the mean values.

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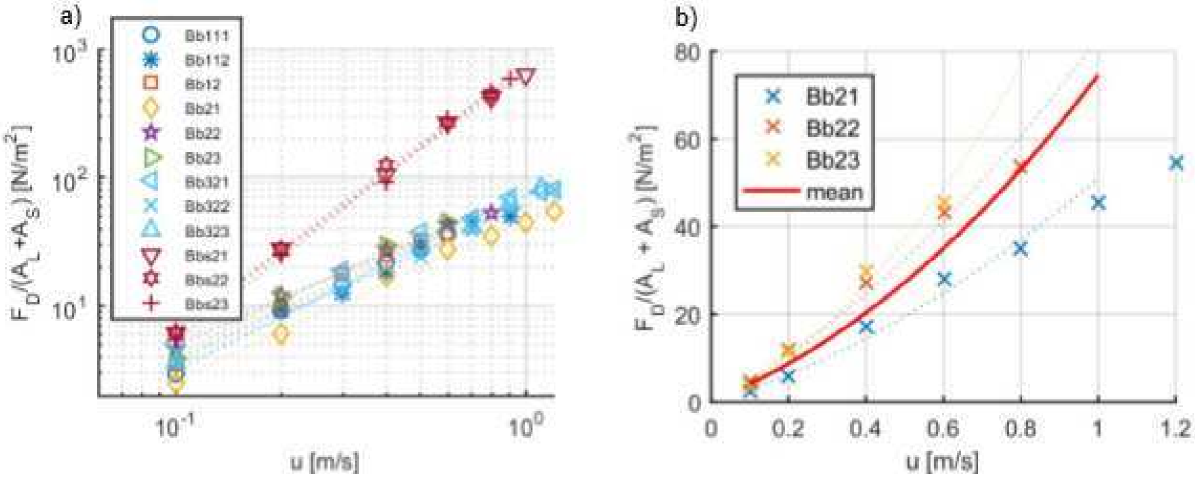

Figure 5: a) Measured drag forces in foliated and defoliated conditions, normalized by the sum of one-sided leaf area and stem area, as a function of bulk velocity; b) measured and modelled drag forces for specimens Bb21, Bb22, and Bb23.

4.3 Further considerations

As indicated in Section 3, some of the drag force measurements were repeated, and the results of these measurements for the branch Bb32 are shown in Figure 6. The first test-series (Bb321) was carried out with increasing velocity steps while the second series (Bb322) was determined by subsequently reducing the bulk velocities again. This is the reason for the identical data point of these two test-series in Figure 6 at the maximum velocity. The third test series (Bb323) was measured again with increasing velocity increments. The three data series are characterized by smaller differences (the drag forces deviate by around 0.2 N at each velocity), which becomes also apparent from the individual values determined for the Järvelä (2004) approach (see Figure 3). For u > 1 m/s, the F_D - u relationship for Bb321 deviates away from the expected behavior, which may be associated with plant instabilities and the reconfiguration of the plant during the first exposure of the specimen to the flow.

It is interesting to note that the largest drag forces are observed for the first loading of the specimen (series Bb321). These experiments were carried out with increasing velocity increments and the specimen reacted to the increasing flow attack by reconfiguration to minimize the drag (e.g., Nikora, 2010). The subsequent decrease of the flow velocities (series Bb322) resulted in the lowest drag forces so that it can be hypothesized that the reconfiguration of the plant during the pre-loading has a certain effect on the drag-force velocity relationship when the flow velocity is reduced instead of increased. This in turn indicates a plant related hysteresis-effect as the specimen has already adjusted its flow-facing structure to withstand the maximum flow conditions. In this context, the drag forces for the third test series (Bb323; carried out with increasing velocity increments directly after Bb322) lie in between the drag forces measured in series Bb321 and Bb322. This means that the plant had the opportunity to readjust its flow-facing structure to the new (and lower) hydraulic forcing and that the subsequent reconfiguration due to the increasing velocity increments was more efficient than during the preloading, but not as efficient compared to the series Bb322 (i.e., decreasing velocity increments). We note that recent results of Boothroyd et al. (2019) highlight the importance of plant orientation to the flow for the resistance behavior. For a flexible plant, plant orientation is affected by reconfiguration so that the results of Boothroyd et al. (2019) can be used to partly support our hypothesis. However, due to the limited data, this hypothesis should be further investigated in future studies.

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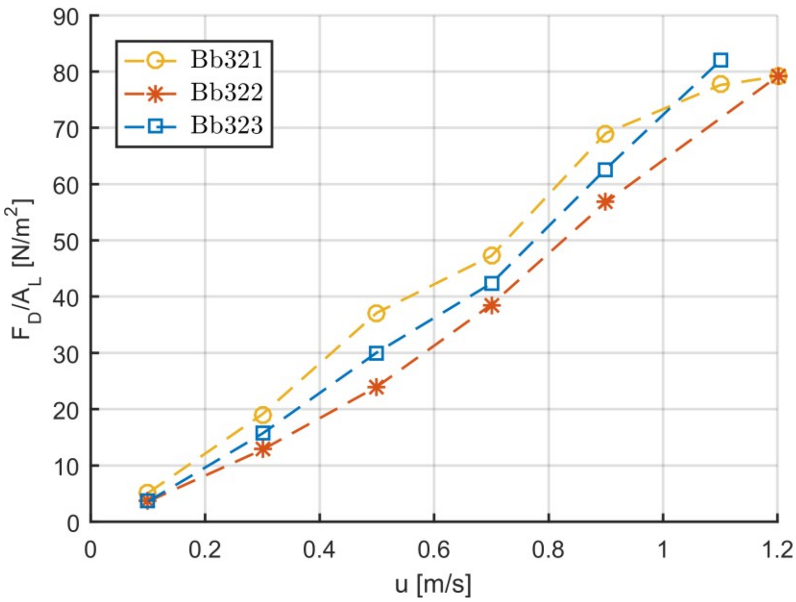

Figure 6: Measured drag forces, normalized by the one-sided leaf area as a function of bulk velocity for the repeated experiments Bb321, Bb322, and Bb323

5 Summary and Conclusions

This paper described the experimental methodology to determine species-specific parameter values of blackberry twigs for the application of the approaches of Järvelä (2004) and Västilä & Järvelä (2014). Using the data from flume experiments carried out with foliated and defoliated blackberry twigs, the variability of the obtained coefficients was highlighted. For practical applications, the values $C_{D\chi}$ = 0.78, u_χ = 0.10 m/s and χ = -0.78 are recommended for the approach of Järvelä (2004), and $C_{D\chi,F}$ = 0.4, $u_{\chi F}$ = 0.20 m/s, χ_F = -1.00, $C_{D\chi,S}$ = 1.2, $u_{\chi S}$ = 0.20 m/s, and χ_S = 0.16 for the approach of Västilä & Järvelä (2014). The measurements were further analyzed by analyzing the data from repeated experiments carried out with the same plant specimen suggesting that the resistance behavior of flexible vegetation may be affected by a hysteresis effect.

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Autoren

Stephan Niewerth
Leichtweiß-Institut für Wasserbau, Technische Universität Braunschweig, Braunschweig, Germany
s.niewerth@tu-braunschweig.de

Jochen Aberle
Leichtweiß-Institut für Wasserbau, Technische Universität Braunschweig, Braunschweig, Germany
jochen.aberle@tu-braunschweig.de

Frederik Folke
Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, Germany
frederik.folke@baw.de