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An improved Cauchy number approach for predicting the drag and reconfiguration of flexible vegetation

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ABSTRACT

An improved model to describe the drag and reconfiguration of flexible riparian vegetation is proposed. The key improvement over previous models is the use of a refined 'vegetative' Cauchy number to explicitly determine the magnitude and rate of the vegetation's reconfiguration. After being derived from dimensional consideration, the model is applied to two experimental data sets. The first contains high-resolution drag force and physical property measurements for twenty-one foliated and defoliated full-scale trees, including specimens of *Alnus glutinosa*, *Populus nigra* and *Salix alba*. The second data set is independent and of a different scale, consisting of drag force and physical property measurements for natural and artificial branches of willow and poplar, under partially and fully submerged flow conditions. Good agreement between the measured and predicted drag forces is observed for both data sets, especially when compared to a more typical 'rigid' approximation, where the effects of reconfiguration are neglected.

1. Introduction

It is generally accepted that global climate change is set to increase the frequency of extreme weather events, such as heat waves, storms, droughts, and more intense flooding [1–3]. With respect to flooding, and fluvial flooding in particular, there is growing recognition that 'hard' engineering defences are unsustainable and that a more holistic, whole-catchment approach is required in order to effectively manage flood risk [4–6]. Within this framework and where suitable, riparian vegetation and woodland can play an important role in mitigating fluvial flood risk by providing additional roughness and blockage to flood flows, reducing run-off via increased infiltration rates [7], and encouraging large woody debris dams to form [8].

Numerical models are widely employed to estimate the hydraulic impact of riparian vegetation and woodland [9–11]. Within such models, the total hydraulic resistance of vegetation in terms of the Darcy–Weisbach friction factor f can be decomposed into a bed friction factor f' and a form factor f'', according to the linear superposition principle $f = f' + f''$ [12,13].

Investigations into the parameterization of the form factor have typically focused on rigid and cylindrical roughness elements [14–16]. In such cases, the form factor is related to the average drag force exerted on the elements per unit bed area, i.e. the spatially-averaged drag force $\langle F \rangle$, via the following relationship:

$$f'' = \frac{8\langle F \rangle}{s_x s_y \rho U^2} \tag{1}$$

where s_x and s_y are the longitudinal and lateral spacing of the roughness elements; ρ is the density of the fluid; and U is the reference velocity, typically taken as the mean velocity. The drag force acting on a single element can be obtained using the following classical drag force equation:

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

where C_d is the dimensionless drag coefficient and A_p is the frontal projected area of the body. The combined term $C_d A_p$ is also known as the 'characteristic' drag coefficient [29,40,41].

For rigid roughness elements at a given level of submergence, the projected area is constant with velocity by definition and the variation in drag coefficient with Reynolds number Re for cylinders and other standard objects is well documented [17]. For flexible vegetation, however, the drag force becomes much harder to predict as both the projected area and drag coefficient are a function of the flow velocity [18–21]. This is due to the tendency of flexible vegetation to reconfigure and streamline in response to aero- or hydro-dynamic loading [22], thus reducing the magnitude of the drag force they experience [23,24]. Indeed, many atmospheric and hydraulic studies involving flexible vegetation have observed a deviation away from the

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quadratic force–velocity proportionality described by Eq. (2) [25–32] for constant values of C_d and A_p. The extent of this deviation has often been expressed in terms of a Vogel exponent ψ [22,33–35]. In general terms and not considering the dependency of C_d on *Re*, the Vogel exponent modifies the power to which the velocity is raised in the classical drag formula, so that

$$F \propto U^{2+\psi} \tag{3}$$

where $\psi = 0$ is valid for a rigid roughness element and $\psi = -1$ indicates a linear force–velocity relationship, as suggested for flexible vegetation at certain velocity ranges [26,36–39].

It can be seen from Eqs. (2) and (3) that the value of the Vogel exponent is directly related to the rate at which the projected area and drag coefficient decrease with increasing flow velocity, i.e. the rate of reconfiguration. As a result, the correct parameterization of the dependence of A_p and C_d on the flow velocity remains one of the most important problems to solve for the accurate modelling of flexible vegetation. Although some progress has been made by using the 'characteristic' drag coefficient C_dA_p [29,40,41], this approach does not address the underlying issue that the variation of A_p and C_d depends not only on flow properties, but also on the vegetation's morphology [20,42–44], biomechanical properties [25,45–48], and level of foliation [29,41,49,50].

A number of recent studies have sought to characterize A_p and C_d in terms of the leaf area index (LAI) and a number of species-specific parameters [20,21,51,73]. The idea was first proposed by Järvelä [27], who determined the form factor f'' for just submerged vegetation as follows:

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

where $C_{d\chi}$ is a species-specific drag coefficient; χ is also unique to a particular species and accounts for the reconfiguration of flexible vegetation; and $U\chi$ is a scaling value included to ensure dimensional homogeneity, equal to the lowest velocity used in determining χ from experimental data. It can be found from rearranging Eqs. (1) and (4) that the χ value is equivalent to the Vogel exponent, i.e. $F \propto U^{2+\chi}$ [52].

Eq. (4) can also be extended via linear superposition to describe the friction factors of the stem and foliage independently so that the flow resistance can be determined for vegetation with varying levels of foliation [51,73]. However, such an advanced consideration doubles the amount of parameters that are required, since separate values of $C_{d\chi}$, U_χ, and χ are needed for the stem and foliage, and available data sets for the parameterization of these variables are still rare. On the other hand, based on the analysis of recent towing measurements with four tree species, Jalonen and Järvelä [73] concluded that the interspecies variation of χ and $C_{d\chi}$ is small when the stem and leaf area are considered separately. However, a drawback of approaches according to Eq. (4) is that the empirical scaling factor U_χ represents the lowest velocity used in experimental investigations for the parameterization of Eq. (4), i.e. it must be considered as an empirical parameter. In addition, Eq. (4) is asymptotic in nature, so that even small deviations in U_χ can potentially introduce large errors in the predicted friction factor at velocities close to U_χ.

To address these issues, Whittaker et al. [48] presented a drag force model that accounts for the reconfiguration of flexible vegetation through a vegetative Cauchy number

$$F = \frac{1}{2}\rho K\left(\frac{\rho U^2 VH}{EI}\right)^{\psi/2} U^2 \tag{5}$$

where K corresponds to a combined C_dA_p value at low velocities where the trees may be considered to behave like a rigid body; *V*, *H*, and *EI* are the vegetation's volume, height in undisturbed conditions and flexural rigidity, respectively; and the terms within the parentheses represent the vegetative Cauchy number *Ca*.

This approach allows the drag force to scale with varying plant size and foliation level through the combined projected area and drag coefficient terms within the parameter *K*, while the effects of flexible reconfiguration are explicitly incorporated through the term including the vegetative Cauchy number. However, while the model predicted the observed drag force with reasonable accuracy for full-scale submerged trees in both foliated and defoliated states, it relies on empirical relationships for the coefficient *K*. This coefficient was obtained in [48], together with the Vogel exponent ψ, by a power-law regression analysis of the force–velocity data according to Eq. (5). Thus the *K* coefficient was obtained solely from the analysis of the force–velocity data without further considerations of the projected area in undisturbed conditions where the trees may be assumed to behave like a rigid body. Such data is in general not available a priori for general modelling scenarios and hence it is desirable to parameterise the *K* coefficient through a species-specific drag coefficient (similar to [51,73]) and a reference area which can be directly measured, such as the frontal projected area in undisturbed conditions.

A further issue is related to the use of the plant volume *V* in the parameterization of the Cauchy number in Eq. (5). Whilst such an approach is appealing, it must be acknowledged that corresponding data will be difficult to obtain for most practical applications compared to investigations under controlled conditions. In fact, volume measurements of trees and other vegetation typically requires destructive methods (e.g. displacement tests) which are not practical in field studies. In this context, Jalonen and Järvelä [73] concluded, based on independent tests of Eq. (4), to express the Cauchy number with the characteristic area and the squared plant height instead of the product of plant volume and height, in order to reduce the number of characteristic dimensions.

Therefore, this paper seeks to further improve Eq. (5) by replacing the initial lumped C_dA_p coefficient with its constituent parts at flow conditions where the plant may be assumed to behave like a rigid body, namely C_{d0} and A_{p0}, so that the dependence on empirical relationships is reduced. This is made possible by a re-analysis of the tree data used in the study of Whittaker et al. [48] which enabled the estimation of the frontal projected area. Taking the recent results of Jalonen and Järvelä [73] into account, the Cauchy number is also redefined based on physical reasoning in order to better reflect the forces acting on the vegetation. The revised model will then be applied to high-resolution force–velocity measurements from full-scale trees, before being validated against an independent branch-scale data set.

2. Data and methodology

The drag force and physical property data sets analysed in this paper are sourced from two previous experimental studies. The larger of the two data sets was collected at the Canal de Experiencias Hidrodinamicas de El Pardo, Madrid, within the framework of the EU Hydralab III scheme and is reported in [38,48,53,54]. The second data set was obtained from experiments undertaken at the Leichtweiß-Institut für Wasserbau (LWI), Technische Universität Braunschweig. The corresponding data sets are described below.

2.1. Hydralab experiments

In the Hydralab experiments, full-scale riparian trees were sampled from a local floodplain site and towed under fully-submerged conditions in a ship towing tank. The trees were attached upside down to a high-resolution dynamometer, which measured the forces and moments in the three Cartesian axes at a rate of 10 Hz and with an accuracy of 0.0098 N. The dynamometer itself was mounted on the underside of a towing carriage, the speed of which could be adjusted with a tolerance of 0.001 m/s (see [53,54] for full details of the experimental setup). In total, 21 full-scale trees were tested, including five *Alnus glutinosa* (common alder; A1–A5), four *Populus*