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ABSTRACT

Different models for the determination of vegetation induced flow resistance are tested for just submerged and submerged flow conditions using a combined experimental and numerical framework. A new approach is introduced considering both plant flexibility, and in case of submerged vegetation, the free layer above the vegetation elements. This new vegetation model shows the best agreement to the measured values and appears to be promising.

## 1. Introduction

Vegetation on river banks and floodplains induces additional hydraulic resistance and many investigations have focused on the development of models to determine the vegetation-induced hydraulic resistance. However, for the case of flexible submerged vegetation, experimental data are still lacking for the validation of novel approaches and to the authors' knowledge no suitable vegetation model is available. The aim of this study is therefore to extend the experimental database and to enhance existing vegetation models for this specific case, with special focus on large-scale applications.

## 2. Methods

### 2.1. Experimental setup

The experiments for the determination of the hydraulic resistance of just-submerged and submerged vegetation were carried out in a 32 m long, 0.6 m wide and 0.4 m high tilting flume. The flume had a rough bottom and foliated artificial flexible plants were used. In a total of 42 experiments, the plant arrangement, number of leaves, and water depths were varied. The plant density was set to 11, 25 and 44 plants per square meter and the leaf-area index (*LAI*) ranged between 0.27 and 1.09. The slope of the flume and the discharge were adjusted resulting in depth-averaged velocities of approximately $u_m = 0.1$ m s$^{-1}$, $u_m = 0.4$ m s$^{-1}$ and $u_m = 0.7$ m s$^{-1}$ and a relative submergence (ratio of water depth to deflected plant height) between 1 and 4. All experiments were carried out with quasi-uniform flow conditions.

### 2.2. Numerical model

The numerical simulations were carried out with the open source code Telemac-2D (opentelemac.org) using a semi-implicit finite element scheme, the Nikuradse roughness law and the horizontal mixing length turbulence model. Vegetation induced resistance was modelled using the one-layer approaches of Lindner (1982) and Järvelä (2004), and the two-layer approaches of Baptist et al. (2007), Huthoff et al. (2007) and Luhar and Nepf (2013). The boundary conditions were set analogue to the experiments.

### 2.3. Introduction of an enhanced vegetation model

Natural vegetation has a highly complex shape and its characteristics (e.g., flexibility) varies not only between individual plants but also between the different plant parts; a proper characterization is therefore not trivial. Järvelä (2004) proposed a friction law for flexible just-submerged and non-submerged vegetation using the leaf area-index to describe the vegetation density and the Vogel-exponent to account for flexibility. However, the approach is, strictly speaking, only valid for non-submerged and just-submerged conditions. Baptist et al. (2007) introduced a simple approach for non-submerged and submerged rigid arranged cylinder assuming a logarithmic velocity profile in the free layer above the vegetation. Based on both models a new approach is proposed to account for both submerged and non-submerged flexible vegetation, as shown in Eq. (1) and Eq. (2), respectively.

$$\lambda = 4 \cdot \left( \left( \frac{\lambda'}{4} + C_{D\chi} \left( \frac{U_m}{U_\chi} \right)^{\chi} LAI \right)^{-0.5} + \frac{1}{\sqrt{2}\kappa} \ln \frac{h}{h_p} \right)^{-2} \quad , \text{for } h > h_p \tag{1}$$

$$\lambda = \lambda' + 4 C_{D\chi} \left( \frac{U_m}{U_\chi} \right)^{\chi} LAI \cdot \frac{h}{h_p} \quad , \text{for } h \leq h_p \tag{2}$$

with the total Darcy friction factor $\lambda$, the grain roughness Darcy friction factor $\lambda'$, the flow depth $h$, the undeflected plant height $h_p$, the depth-averaged mean flow velocity $U_m$, the vegetation specific parameters $C_{D\chi}$, $\chi$ and $U_\chi$ and the von Kármán constant $\kappa$.

## 3. Results

Fig. 1 presents the comparison of measured and predicted total friction factors for all 42 experiments using the investigated vegetation approaches. Both one-layer approaches overestimate the measured values due to the assumption that the whole water column is occupied by vegetation. On the other hand, the values predicted by the Järvelä (2004) approach agree reasonably well with the measured ones and deviations are much smaller than for the approach of Lindner (1982). The two-layer vegetation models of Baptist et al. (2007) and Luhar and Nepf (2013) also approximate the measured values well, despite somewhat inconsistently over- and underestimating them. Similar to the one-layer approaches, the approach of Huthoff et al. (2007) tends to predict too high friction values. The best fit between measured and calculated values is produced by the newly introduced two-layer approach.

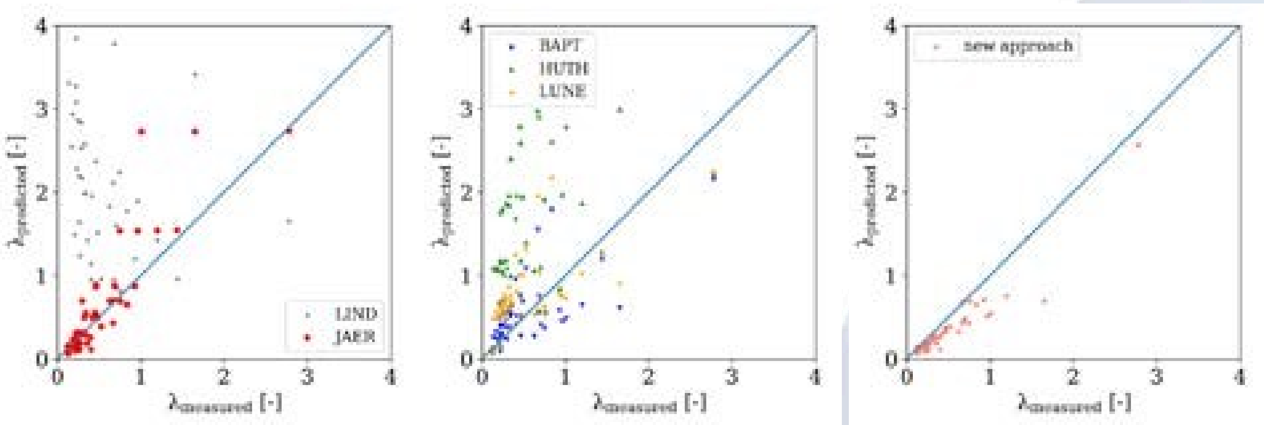


**Fig. 1.** Comparison of simulated and measured Darcy friction factors of two one-layer approaches (left), three rigid two-layer approaches (middle), and the new two-layer approach (right); solid lines represent best fit between simulation and measurement

## 4. Discussion and conclusions

Appropriate modelling of vegetation requires suitable models to capture the physical mechanisms. Due to the complexity of both plant morphology and flow patterns induced by vegetation, simplifications are needed with regard to large scale applications. In this regard, a new vegetation approach for flexible submerged and non-submerged vegetation was introduced. This new introduced approach exhibits closest agreement with the measured values and appears to be promising, even though it is based on several simplifications. Furthermore, the used vegetation parameters for this new two-layer approach were determined based on the one-layer approach of Järvelä (2004) for just-submerged flow conditions. Possible changes of vegetation parameters have to be verified.

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