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Folke, Frederik; Attieh, Mohamad; Kopmann, Rebekka

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In search of friction laws for vegetated flow within 2D large-scale applications

Frederik Folke [a]

Mohamad Attieh [a]

Rebekka Kopmann [a]

[a] Department of Hydraulic Engineering, Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, Germany

Abstract

As restoration and conservation of the ecosystem in federal inland waterways in Germany are of growing importance, vegetation in open-channels plays an increasingly important role. New approaches to estimate the vegetation effects on the flow within large-scale applications are needed, e.g. for flood protection planning and for more nature-friendly designs of inland waterways. In an ongoing research at the BAW, five promising approaches to estimate the flow resistance due to vegetation are examined with numerical simulations of experimental data using Telemac-2D software first and are then analytically investigated. The essence of the governing physics of vegetated open-channel flows is given first with a focus on the most challenging issue of this subject, i.e. vegetation flexibility, which can significantly alter the flow resistance due to vegetation. In the numerical simulations, the approaches of Järvelä (2004), Whittaker et al. (2015) and Baptist et al. (2007) performed best and showed good agreement with the measured values from low to high vegetation friction. The analytical investigation was performed using three vegetation types. Results showed similar behaviors of the friction coefficients estimated by the approaches in the case of non-submerged vegetation, but widely dissimilar behaviors in the case of submerged vegetation. Also, results showed high sensitivity of the Järvelä (2004) and Whittaker et al. (2015) approaches to the empirical flexibility parameters used. In terms of largescale applications the leaf-area index seems to be a suitable parameter to determine the vegetation density.

Keywords: Hydrodynamics; Rivers; Numerical hydraulic modeling; Flow resistance; Vegetated flow

1 Introduction

The German federal waterways are strongly influenced by river regulation measures, such as groynes and longitudinal structures, and by a well monitored sediment management system. Besides the regulated partly free-flowing and partly dam-controlled rivers, e.g. Rhine, Danube, Elbe and Oder, artificial channels are part of the waterway system.

In order to achieve the objectives of the European Water Framework Directive, bank and floodplain vegetation is becoming increasingly important in the context of maintenance and restoration of the German federal waterways. At present, vegetation is in the focus of several ongoing projects, e.g. using vegetation components such as bank protection measures (technical-biological bank protection) or within the federal governmental program "Germany's Blue Belt". Therefore, the Federal Waterway Engineering and Research Institute (BAW) will be increasingly required to assess vegetation-induced effects of measures with regard to their compatibility to the ease and safety of shipping and their influence on water levels at higher discharges.

Already today, large parts of floodplains and embankments of the German federal waterways are covered by bushes, shrubs, and trees, which significantly influence flow patterns during flood discharges. This influence ranges from small-scale eddy structures in the wake of leaves to changes in the discharge distribution over the entire flow cross-section and overall increasing water levels. Additionally, the vertical velocity profile changes and depth-averaged velocities are lowered. Due to these hydrodynamic impacts, sediment transport processes occurring in the main channel and on floodplains are also affected.

The analysis and evaluation of structural measures for near-natural redesign and connection of river floodplains as well as the maintenance and management of the foreland in the planning state necessitate the accurate calculation of corresponding hydraulic conditions for the current and planning states. Especially for large-scale applications, an easy and fast method to measure the required vegetation parameters as input for numerical models is essential. Furthermore, temporal variations such as seasonal changes or plant growth need to be considered. At BAW river stretches of up to 100 km and real-times of several years or even decades are modeled using two-dimensional depth-averaged methods.

In this paper, the approaches accounting for vegetation-induced effects on the flow field are evaluated against the background of the German federal inland waterways and the dominating vegetation, such as hardwood and softwood alluvial forests or willows. In terms of German federal inland waterways, the influence of aquatic vegetation, e.g. algae, is small compared to other dominating roughness factors and can therefore be neglected.

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The flow resistance due to vegetation is defined by the total vegetation-induced drag f_D, which is the sum of the pressure induced form drag f_P and the viscous drag f_V resulting from skin friction due to local velocity gradients at the surface of the vegetation elements,

$$f_D = f_P + f_V. \tag{1}$$

The contribution of each of the two drag terms to the total drag force depends on the shape of the vegetation element and its orientation relative to the flow (Whittaker et al., 2015). Due to the high complexity of vegetation geometry, it is unfeasible to determine the two drag components analytically. Instead, the total drag in streamwise direction is determined experimentally and represented by the classical quadratic drag law

$$f_D = \frac{1}{2} C_D m_p \cdot D \cdot U_m^2 \,, \tag{2}$$

with the dimensionless bulk drag coefficient C_D, the vegetation density m_p, the plant diameter D, and the bulk velocity in streamwise direction U_m. The momentum balance for vegetated open-channel flow in streamwise direction x under steady-flow conditions can be expressed as

$$g \left(sin\theta + \frac{\partial h}{\partial x} \right) + \frac{1}{p} \frac{\partial \tau_{xz}}{\partial z} - f_D = 0 \,, \tag{3}$$

with the gravity g, the slope angle θ, the water depth h, the fluid density ρ, the total shear stress τ_{xz}, and the total drag f_D. The drag force is the resisting force to the flow, while the stress gradient and the potential force terms are the driving forces. For vegetated flow the contribution of the two driving-force terms to the total driving force depends on the relative submergence ratio (Nepf and Vivoni, 2000).

In the last decade many new approaches to introduce vegetation in numerical flow modelling were developed. In this paper, selected friction approaches for vegetated flows are investigated using the open-source software Telemac-2D. The focus is on flexible vegetation and on the suitability of the methods with regard to large-scale applications. The friction approaches are tested in one-dimensional flume experiments with non-submerged and just-submerged vegetation. Using the definition of the dimensionless Darcy friction factor, the different approaches are investigated, both for non-submerged and for submerged conditions.

2 Vegetated flow

2.1 Vegetated open-channel flow resistance

According to the ratio of water depth h to plant height h_p, so-called relative submergence, flow in vegetated open-channels can be segregated into three different categories: deeply submerged ($h/h_p \geq 10$), submerged ($1 < h/h_p < 10$), and non-submerged vegetation ($h/h_p \leq 1$). For deeply submerged vegetation, a logarithmic velocity profile exists above the vegetation layer. Hence, it is a well-accepted method to use a bed shear stress model (e.g. based on the equivalent sand roughness) to account for flow resistance. Deeply submerged vegetation is therefore not covered in this study. However, the velocity profile is strongly affected by submerged and non-submerged vegetation and must therefore be described by alternative friction approaches.

In contrast to an undisturbed (free) flow, the turbulence length scale of flow through vegetation is controlled by the geometrical length scales of the plants, e.g. the plant diameter or the plant spacing, and not by the water depth. Hence, the flow through non-submerged vegetation, where the whole water column is affected, is potential driven (cf. Eq. [3]). In the case of submerged vegetation, the flow is segregated into a potential driven vegetation layer and a both stress and potential driven surface layer above (e.g. Nepf, 2012). In this vegetation layer, flow conditions are similar to the case of non-submerged vegetation. To describe the velocity profile in the stress driven surface layer, there is no definite opinion in the literature. Some researchers (Baptist et al., 2007; Klopstra et al., 1997) adopt a fully-developed logarithmic profile in the free surface layer. In contrast, other researchers (Ghisalberti and Nepf, 2002; Katul et al., 2002) favor the theory of the existence of a mixing layer above the vegetation layer. They describe the vertical velocity profile using the hyperbolic-tangent function with an inflection point near the top of the vegetation. Supporting this idea is the fact that the flow within the vegetation layer is slowed down by vegetation drag, while in the overlying water columns it is accelerated, resulting in a shear layer with maximized shear stress and turbulence production at the top of the vegetation layer (Folkard, 2011). Furthermore, e.g. Nepf (2012) assumes the existence of Kelvin-Helmholtz vortices triggered by the instabilities at the interface between the vegetation layer and the free surface layer.

Since most of the research so far focused on non-submerged vegetation and due to lack of sufficient experimental data for the non-submerged case, especially for flexible vegetation, the above mentioned debate remains an open research question. Possibly, one could introduce a distinguish criteria based on the plant density, where for sparse vegetation the mixing layer hypothesis is most representative, while for dense vegetation adopting a logarithmic layer could be reasonable.

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2.2 Vegetation characteristics

Many vegetation characteristics are species-specific, and depend on several factors such as plant age, seasonality, succession, and local habitat conditions which add to the complexity of vegetation modeling in open-channels (Aberle and Järvelä, 2015). According to Nikora (2010), the plant characteristics can be divided into three main groups: morphological, biomechanical, and plant-flow interaction characteristics.

Morphological characteristics describe shape, form and structure of a single plant and plant communities. They include linear characteristics (e.g. plant height h_p, plant diameter D, spacing between plants Δ), areal characteristics (e.g. frontal plant projected area perpendicular to the flow), volume characteristics (e.g. plant volume), and density characteristics (e.g. solid volume fraction) (Nikora, 2010). Aberle and Järvelä (2015) provide a summary for the major morphological parameters. It must be noted that a clear definition of a parameter and the possibility for a good and extensive data acquisition is required for large-scale applications. For example, both the definition and the large-scale determination of a representative plant diameter for branched plants are not simple. The leaf area index LAI is an adequate parameter to be used in this context. It is a dimensionless parameter that is defined as the ratio between the one-sided area of foliage per unit bed surface area. The LAI can be measured over large areas (e.g. by satellite remote sensing) as described by Jalonen et al. (2013) and seasonal-changes can be captured. For foliated vegetation the major part of the total drag is due to leafs (Västilä and Järvelä, 2014).

For flexible vegetation the plant biomechanics plays a major role as it is controls the interaction between the flow field and vegetation. The flow resistance can significantly be reduced by plant bending and plant reconfiguration (Miler et al., 2010; Schoneboom, 2010). In this context, the reduction of the projected area and the streamlining effect both depend on flow velocity. Consequently, the drag force does not grow with the square of the velocity as in the case of rigid obstacles, but more slowly. This deviation from the quadratic drag force formula was widely studied and described by Vogel (1984). He introduced the Vogel exponent χ to account for the deviation of the drag force for flexible bodies from the quadratic drag law:

$$F_D \propto {U_m}^{2+\chi} \tag{4}$$

Although the Vogel exponent lacks any theoretical basis and is entirely empirical, it is widely used by researchers to describe the plant reconfiguration behavior (Järvelä, 2004; de Langre et al., 2012; Gosselin and de Langre, 2011; Chapman et al., 2015). Whittaker et al. (2015) developed a more physically based vegetation model, also based on the concept of Vogel, but additionally using the flexural rigidity to describe the behavior of flexible vegetation. Aberle and Järvelä (2015) remarked the difficulty in deriving reliable and meaningful values for the needed area moment of inertia, due to complex cross-sectional shapes of natural plants. In this study, blockage effects are neglected due to the large porosities of natural bushes, shrubs, and trees.

2.3 Vegetation friction approaches

Most of the existent vegetation friction approaches are not ideal regarding their means of validation, completeness of parameters or inter-comparability. In most cases, the approaches were only tested and validated in laboratory (flume) experiments. The available data for validation at a natural scale is scarce and often lacks necessary information. Furthermore, the parameters used in different vegetation formulas are not unified. Especially in the context of large-scale applications, large numbers of input parameters should be avoided due to the great costs of data acquisition. Nevertheless, a vegetation model must be capable of describing the physical mechanisms properly. To the authors' knowledge no model exists at present, which considers all relevant vegetation characteristics, such as flexibility, from deeply-submerged up to non-submerged flow conditions.

In this paper five promising vegetation models were selected from the literatures which were developed for different vegetation types and relative submergence (cf. table 1). Järvelä (2004) proposed an approach for flexible just-submerged and submerged vegetation using the vegetation parameter LAI and the above mentioned empirical concept of Vogel (1984). Whittaker et al. (2015) use a Cauchy number Ca defined as a function of the flexural rigidity EI for their more physical vegetation model. Furthermore, they introduced the frontal projected area A_{p0} and the corresponding drag coefficient C_{D0} of undeformed plants. Järvelä (2004) and Whittaker et al. (2015) are proposing species specific values ($C_{D\chi}$, C_{D0}), and are using species specific coefficients to account for the flexibility (χ and a corresponding reference velocity U_{χ}, and the Vogel coefficient ψ used by Whittaker et al., 2015), analogue to the concept of Vogel (1984). The other three models (Baptist et al., 2007; Huthoff et al., 2007; Luhar and Nepf, 2013) consider the vegetation as rigid and use a two-layer approach – a vegetation layer and a free layer above – for submerged vegetation, and use the bulk drag coefficient C_D to determine the resistance. Luhar and Nepf (2013) additionally introduced a friction coefficient at the top of the vegetation layer C_v, and a frontal area per volume of vegetated region a which can be estimated for natural vegetation using LAI and the undeflected plant height h_{p0} based on the recommendation of Finnigan (2000):

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$$a = \frac{D}{\Delta^2} = \frac{1}{2} \cdot \frac{LAI}{h_{p0}} \ . \tag{5}$$

For further details of the vegetation models see the related literature.

Table 1: Overview of the investigated vegetation models.

Vegetation Model	Basis	Vegetation Type	Relative Submergence	Input Parameters (Selection)
Järvelä (2004)	Theory experiments	Flexible, foliated	Non-submerged (Just submerged)	$C_{D\chi}$, χ, U_{χ}, LAI, (h_p)
Whittaker et al. (2015)	Theory (physics)	Flexible	Non-submerged (Just submerged)	C_{D0}, ψ, Ca, A_{p0}, Δ, (h_p)
Baptist et al. (2007)	Genetic programming, experiments	Rigid (cylinder)	Non-submerged submerged	C_D, D, h_p, Δ
Huthoff et al. (2007)	Analytical derivation, scaling assumptions	Rigid (cylinder)	Non-submerged submerged	C_D, D, h_p, Δ
Luhar and Nepf (2013)	Flume experiments	Rigid	Non-submerged submerged	C_D, C_v, h_p, a

3 Numerical and analytical investigation

The aim of the ongoing study is to identify a suitable approach which considers the hydrodynamic effects of vegetation in the flow field. Laboratory experiments were simulated with a two-dimensional hydrodynamic model and the results were compared to the measurements. Due to the lack of data, especially for submerged vegetation, the five approaches were studied also analytically, both for non-submerged and for submerged vegetation.

3.1 Numerical investigation based on experimental data

The experiments of Schoneboom et al. (2010) in a 32 m long and 0.6 m wide tilting flume were selected for the numerical investigation. All plant characteristics and flow parameters are known for these experiments so the experiments are adequate as validation case. The numerical simulations could be done nearly without calibration and the different approaches can be validated.

For the numerical simulations, the open source code Telemac-2D (www.opentelemac.org; Hervouet, 2007) was used. At BAW, Telemac-2D is widely applied in project work investigating free surface flow in German federal waterways. In the program suite Telemac, several schemes (finite element, finite volume), roughness laws and turbulence models can be chosen. For this application a semi-implicit finite element scheme, the Nikuradse roughness law and the horizontal mixing length turbulence model were selected. In the current Telemac-2D version (v8p0), only the approach of Lindner (1982) and Pasche and Rouvé (1985), evaluated for rigid non-submerged cylinders, is available to consider the vegetation influence on the flow in a more physical way than just increasing the bottom friction.

The bottom friction is considered via the dimensionless friction coefficient C_f. For the Nikuradse approach it can be calculated using the equivalent roughness coefficient k_s, the water depth h, and the von-Kármán constant κ:

$$C_f = 2 \cdot \left[\frac{\kappa}{\ln(11{,}036 \cdot \frac{h}{k_s}}\right]^2 . \qquad (6)$$

A common technique to consider the vegetation is to derive a friction factor based on a one-dimensional approach. One possibility is to use the formula of Darcy-Weisbach with the dimensionless friction factor λ,

$$C_f = \frac{\lambda}{4}. \qquad (7)$$

According to the linear superposition principle, the total friction λ is the sum of the bed roughness coefficient λ' and the vegetation form resistance per unit surface λ''. If vegetation is apparent, the vegetation friction coefficient is usually much higher and therefore decisive for the total friction.

3.1.1 Experimental setup and numerical model

Figure 1 shows a sketch of the numerical model which is similar to the laboratory experiment of Schoneboom et al. (2010). An 18.5 m long vegetated part is set after a 4 m inflow part with bottom friction

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only. It was assumed that the configuration would lead to nearly normal flow condition in the vegetated part. In the experiments, artificial plants with an undeflected height of 0.23 m were used. The vegetation characteristics are similar to that of natural poplar. The bottom of the whole flume was covered by a rubber mat with 3 mm high pyramidal shaped roughness elements. The simulation mesh consists of triangles with around 27,600 elements and an average node distance of approximately 3 cm.

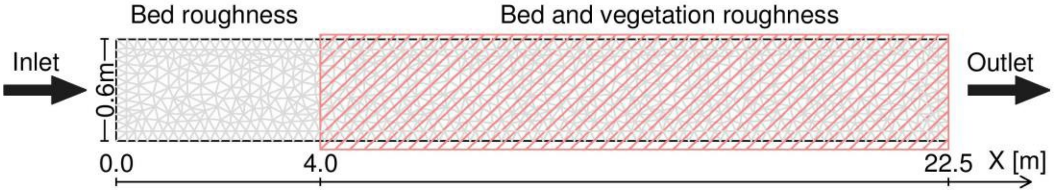

Figure 1: Sketch of the numerical model

As the original experiments were done with a tilting flume, different slopes were investigated. The experiments were conducted using two different arrangements (inline and staggered) and three different plant spacing Δ to vary the plant density under normal flow conditions within the vegetation part. For each slope, a corresponding volume flux was adjusted to achieve a water depth similar to the deflected plant height resulting in just-submerged or rather non-submerged conditions. Slopes from 0.1 % to 1.6 % with corresponding discharges from 0.017 m^3/s to 0.093 m^3/s resulting to water depths between 0.192 m and 0.259 m were investigated. Six different vegetation configurations resulting in 32 different measurements were simulated for the current comparison (cf. table 2).

Table 2: Geometrical setup of the 32 experiments

Arrangement	**Spacing, Δ [m]**	**Slope, I_0 [%]**
Inline (L)	0.30	0.10; 0.30; 0.45; 0.60; 0.70
	0.20	0.14; 0.30; 0.45; 0.70; 0.90; 1.13; 1.45
	0.15	0.43; 0.75; 1.15; 1.60
Staggered (S)	0.30	0.10; 0.30; 0.40; 0.55; 0.75; 0.90
	0.20	0.19; 0.30; 0.40; 080; 1.17; 1.50
	0.15	0.22; 0.57; 0.95; 1.24

To determine the bed roughness of the used structured rubber mat, experimental data for a configuration without vegetation were used. This resulted in an equivalent sand roughness k_s of 2.75 mm to model the 3 mm high pyramidal shaped elements.

In table 3, the vegetation parameters used for the numerical investigation are shown (cf. Schoneboom et al., 2010; Whittaker et al., 2015). For the species-averaged rigid drag coefficient C_{D0} and the Vogel exponent ψ used by Whittaker et al. (2015), no values for the investigated artificial poplar were found in the literature. Instead, the drag coefficient at the lowest measured velocity and the Vogel exponent according to the model of Järvelä (2004) were used. In computing friction according to the approaches of Baptist et al. (2007), Huthoff et al. (2007), and Luhar and Nepf (2013), a drag coefficient C_D of 1.0 was assumed. The friction coefficient at the interface between the vegetation and the overlying flow C_v was set to 0.06 to be consistent with the range of values reported by Luhar and Nepf (2013).

Table 3: Vegetation parameters for numerical investigation

Arr.	Δ [m]	h_{p0} [m]	A_{p0} [m]	LAI [-]	E [N/m^2]	$C_{D\chi}$ [-]	χ [-]	U_χ **[m/s]**	C_D **[-]**	C_v **[-]**
L	0.30	0.23	0.0148	0.437	6.97x10^9	0.34	-0.73	0.13	1.0	0.06
	0.20			0.984						
	0.15			1.748						
S	0.30			0.437		0.50	-0.74	0.11		
	0.20			0.984						
	0.15			1.748						

As described above, the experimental setup was chosen to achieve just-submerged or rather non-submerged conditions considering the deflected plant height. To account for this the measured deflected plant height was used within the numerical investigation, except for some cases where it was not available the minimum of the water depth and the undeflected plant height was applied instead.

Baptist et al. (2007) and Huthoff et al. (2007) simplify the vegetation as rigid cylinders. To model the geometrical shape of the artificial poplar, the estimator for natural vegetation (cf. eq. 7) proposed by Luhar and Nepf (2013) was used instead. Thus, within the numerical study the vegetation density was based always on the *LAI* except for the approach of Whittaker et al. (2015). The sensitivity of alternative methods for the determination of vegetation density (e.g plant diameter) was not investigated yet.

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3.1.2 Results of the numerical model

At the outlet ($x = 22.5\ m$) the water depth was set to the measured mean value as the experimental setup was chosen to achieve normal flow conditions within the vegetation section, as described by Schoneboom et al. (2010). For validation the different calculated Darcy friction factors λ were compared to the measured ones.

In Figure 2, the simulated friction factors (top) and water depths (bottom) are presented along the flume length for the staggered configuration with a plant spacing of 0.20 m and a slope of 0.30 % exemplarily. It is apparent that the friction factors are approximately constant throughout the vegetation section, whereby the vegetation model of Baptist et al. (2007) shows a slight decreasing friction factor in streamwise direction. The measured water levels show almost constant values in streamwise direction within the vegetated part, verifying the assumption of uniform flow conditions.

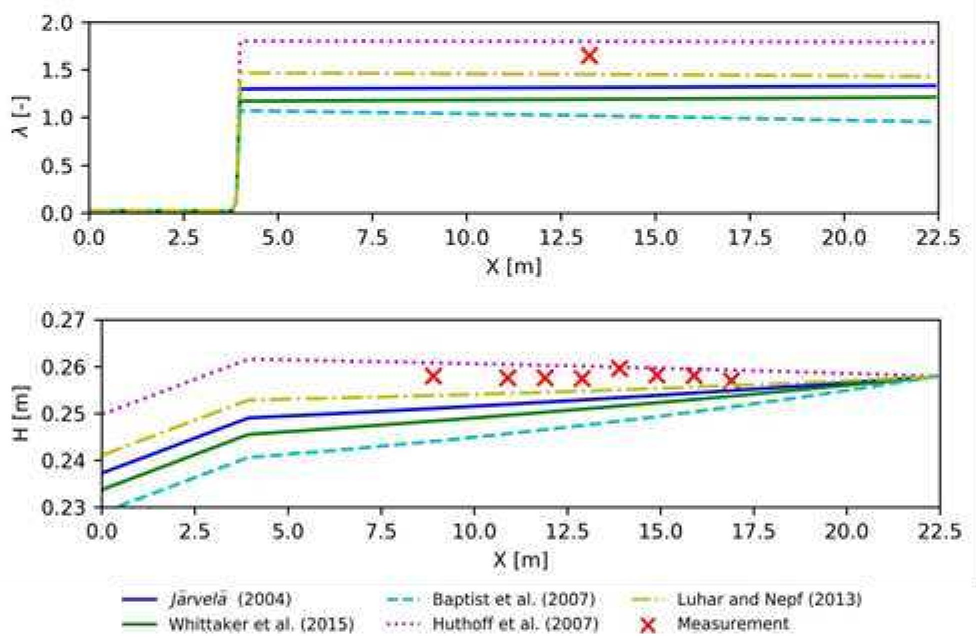

Figure 2: Evaluation of Darcy friction factor (top) and water depth (bottom) in streamwise direction (Telemac-2D, vegetation models), and streamwise averaged values of the measurement within the vegetated section of the flume (setup: staggered, $\Delta = 0.20\ m$, $I_0 = 0.30$ %)

In Figure 3, the results of all 32 experiments for all five vegetation approaches are presented. The friction values calculated with the equation of Järvelä (2004) show a close fit to the measured values over the whole range of investigated vegetation densities. It seems that Järvelä (2004) slightly underestimates the measured values. This is similar to the findings of Dombroski (2014) within their applied study of a vegetation influenced part of the San Joaquin River. The vegetation models of Whittaker et al. (2015) and of Baptist et al. (2007) also approximates the measured values well, but both show higher deviations for some cases.

The approach of Luhar and Nepf (2013) approximates the measured values only for small friction coefficients. For higher values an increasing underprediction can be observed. The friction values predicted by the vegetation model of Huthoff et al. (2007) show a different behavior. The model shows higher friction values than the measured ones and furthermore, the values show no continuous increase. This is due to the high sensitivity to the plant spacing, resulting in a step like trend.

In summary, the formula of Järvelä (2004) is most suitable for this validation case of flexible and just- submerged vegetation but also the models of Whittaker et al. (2015) and Baptist et al. (2007)

show reasonable results. The introduction of the leaf-area index into the vegetation model of Baptist et al. (2007) appears promising, especially for species with no well-defined plant diameter.

Considering large-scale applications, especially the approach of Järvelä (2004) and the adapted model of Baptist et al. (2007) are promising due to the used input parameters of the models. For further investigation, it is recommended to take different cases into account, such as non-submerged and submerged vegetation with water levels several times the plant height. Additionally, the behavior of different plants needs to be considered.

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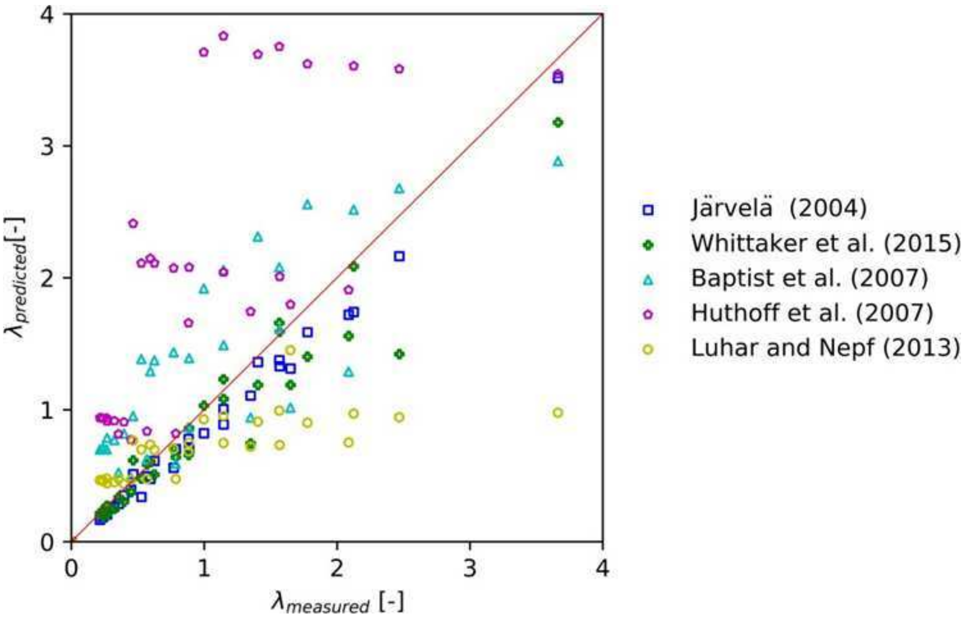

Figure 3: Comparison of simulated and measured Darcy friction factors for five different vegetation approaches and all 32 experiments.

3.2 Analytical investigation

To be independent of experimental data, an analytic investigation was performed for the chosen approaches where the behavior of the Darcy friction factor in reference to the relative submergence ratio h_p/h is studied. In Table 4, the Darcy friction factors of the investigated vegetation models are summarized, both for submerged and non-submerged conditions. As mentioned in section 2.3, all approaches are based on a drag coefficient and on a measure for the vegetation density. As mentioned above, originally only Järvelä (2004) and Luhar and Nepf (2013) use *LAI* to estimate the density, whereas the others use the spacing and a plant diameter.

Table 4: Darcy friction factors of the investigated vegetation models

Vegetation Model	Submerged	Non-Submerged
Järvelä (2004)	$\lambda' + 4\, C_{D_\chi} \left(\frac{U_m}{U_\chi}\right)^{\chi} LAI$	$\lambda' + 4\, C_{D_\chi} \left(\frac{U_m}{U_\chi}\right)^{\chi} LAI \cdot \frac{h}{h_p}$
Whittaker et al. (2015)	$\lambda' + 4\, C_{D_0} Ca^{\Psi/2} \cdot \frac{A_{p0}}{\Delta^2}$	$\lambda' + 4\, C_{D_0} Ca^{\Psi/2} \cdot \frac{A_{p0}}{\Delta^2} \frac{h}{h_p}$
Baptist et al. (2007)	$\frac{4}{\left(\frac{1}{\sqrt{\frac{\lambda'}{4} + C_D \frac{Dh_p}{\Delta^2}}} + \frac{1}{\sqrt{2_K}} \ln \frac{h}{h_p}\right)^2}$	$\lambda' + 4\, C_D \cdot \frac{Dh}{\Delta^2}$
Huthoff et al. (2007)	$\lambda' + \frac{4 C_D \frac{Dh}{\Delta 2}}{\left[\sqrt{\frac{h_p}{h} + \frac{h-h_p}{h}\left(\frac{h-h_p}{\Delta}\right)^{\frac{2}{3}\left(1-\left(\frac{h}{h_p}\right)^{-5}\right)^{-2}}}\right]}$	$\lambda' + 4\, C_D \cdot \frac{Dh}{\Delta^2}$
Luhar and Nepf (2013)	$\lambda' + \frac{4}{\left[\left(\frac{1}{C_v}\right)^{1/2}\left(1-\frac{h_p}{h}\right)^{3/2} + \left(\frac{1}{C_D a h_p}\right)^{1/2}\left(\frac{h_p}{h}\right)\right]^2}$	$\lambda' + 4\, C_D\, ah$

3.2.1 Assumptions and input parameters

For the analytical investigation three different types of vegetation were examined: artificial poplar (analogue to the numerical investigation), natural black poplar, and rigid aluminum cylinders. The plant height was set constant to 0.23 m. For the two flexible plants a spacing of 0.20 m was chosen since almost all studied approaches gave a reasonable estimation of the friction coefficient for set-ups with sparse vegetation. For the rigid cylinders, a spacing of 0.1 m was used instead to obtain a friction coefficient in the same order of magnitude.

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The flow velocity was set constant to 0.13 m/s for artificial poplar and rigid cylinders, and to 0.10 m/s for natural poplar, the bed slope to 0.1 %, and the water depth varies from 0.01 m up to four times the plant height. The plant height and the bottom roughness were chosen according to the numerical investigation.

The vegetation parameters were taken from the literature (Schoneboom et al., 2010; Västilä and Järvelä, 2014; Whittaker et al., 2015; Chapman et al., 2015) and are summarized in Table 5. Since no C_{D0} and ψ values were found in the literature for the artificial poplars, the values of $C_{D\chi}$ and χ were used instead in the Whittaker et al. (2015) approach. The drag coefficient C_D used by Baptist et al.

(2007), Huthoff et al. (2007), and Luhar and Nepf (2013) was assumed at 1.0 for all vegetation types. In computing friction according to the Luhar and Nepf (2013) approach, the friction coefficient at the interface between the vegetation and the overlying flow C_v was set to 0.06 (cf. chapter 3.1.1).

Table 5: Vegetation parameters for analytical investigation

	D [m]	A_{p0} [m²]	LAI [-]	E [N/m²]	C_{D_χ} [-]	χ [-]	U_χ [m/s]	C_{D0} [-]	Ψ [-]
Artificial poplar	0.0030	0.0148	0.437	6.97×10^9	0.50	-0.74	0.11	1.33	-
Natural poplar	0.0036	0.0370	2.975	5.94×10^9	0.33	-1.03	0.10	1.08	-1.11
Rigid cylinders	0.0066	0.0015	-	7.00×10^{10}	-	-	-	-	-

3.2.2 Results of the analytical investigation

In Figure 4 the determined Darcy friction factors are illustrated for all three vegetation types. As described above, artificial poplar (left) and natural poplar (middle) are expected to have similar plant characteristics. According to this, all approaches show very similar behavior of the friction factor as function of relative submergence. The higher vegetation density of natural poplar leads to higher values of the friction factors compared to the artificial poplar (cf. Table 5). In all cases the proportion of the bed friction is small compared to the friction due to vegetation, and in most instances even negligible. As expected, all approaches based on rigid vegetation predict the same friction factors for non-submerged conditions. For the case of rigid cylinders (right) no differences between the approaches can be observed for the non-submerged flow condition. In this case the Vogel coefficient is set to zero and for all approaches the same drag coefficient is used. Furthermore, the used definition of vegetation density for this case results in congruent formulations of the five vegetation approaches. The approaches of Järvelä (2004) and Whittaker et al. (2015) are only valid for non-submerged flow conditions, since both do not consider the effect of the surface layer. For all three vegetation types the friction factor is constant for h/h_p larger than 1. The approaches considering the influence of flexibility of Järvelä (2004) and Whittaker et al. (2015) predict smaller friction factors in the cases of artificial poplar and natural poplar. The approaches of Järvelä (2004) and Whittaker et al. (2015) show a linear behavior of the friction factor due to the chosen constant velocity yielding to a constant ratio of U_m/U_χ, independent of the relative submergence. In case of flexible vegetation both models show for low velocities a high sensitivity to the bulk velocity, and an asymptotic behavior for high velocity values (not shown here).

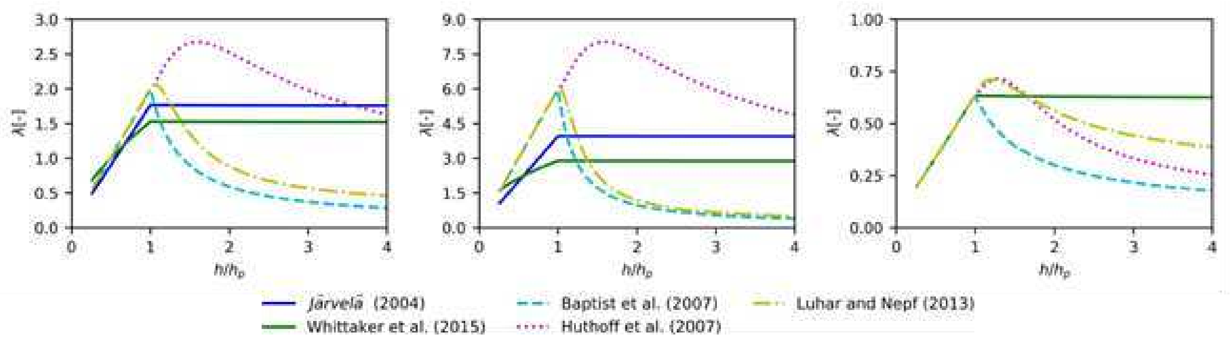

Figure 4: Darcy friction factor as a function of the relative submergence for five different vegetation approaches (left: artificial poplar; middle: natural black poplar; right: rigid cylinders)

After switching to submerged flow conditions the three two-layer approaches show varying behaviors. The model of Baptist et al. (2007) predicts continuous decreasing friction factors with increasing submergence. Whereas the approaches of Huthoff et al. (2007) and Luhar and Nepf (2013) show a further increase of the friction factor for small submergence ratios reaching a maximum friction factor and then continuously decreasing values for higher submergence. Based on experimental data, Huthoff et al. (2015) proposed that the maximum of vegetation friction occurs for a relative submergence of $h/h_p \approx 2.5$. This is not in accordance to other authors. The non-linear behavior at the transition from non-submerged to submerged flow conditions of the approach of Luhar and Nepf (2013) is claimed to be a physical behavior in a later paper (Shields et al. 2017). It is conspicuous, that at very high submergence the model of Luhar and Nepf (2013)

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approaches a constant non-zero value $\left(\lim_{h/h_p \to \infty} \lambda'' = 4 \cdot C_v\right)$. This effect is not physical, where it is expected to continue decreasing since the effect of the vegetation on the flow decreases with higher submergence. Furthermore, the model of Luhar and Nepf (2013) is very sensitive to the input parameters. Baptist et al. (2007) and Huthoff et al. (2007) show more physical behaviors where they both tend towards zero with higher submergence.

The results show that a multi-layer approach is necessary to provide reasonable friction factors for submerged vegetation. Furthermore, the different behavior of the two-layer models in case of submerged conditions, especially at the transition between non-submerged and submerged vegetation, indicates the need for further experimental investigation and a current lack of data. All models do not consider potential failing of structures.

4 Conclusion

Against the background of vegetation-induced hydrodynamic forces on German federal inland waterways, five vegetation friction approaches were selected and evaluated. For a specific validation case, the approaches were investigated numerically and within an analytical study the general behavior of the results for non-submerged and submerged conditions were tested. Despite the limited range of considered vegetation and flow configurations, first conclusions can be drawn.

In the case of just-submerged flexible vegetation, the approaches of Järvelä (2004), Whittaker et al. (2015) and Baptist et al. (2007) show good agreement to the measurements from low to high vegetation friction. Similar to the findings of Dombroski (2014), the approach of Järvelä (2004) systematically underpredicts the actual vegetation friction; however, it produces the best fit. Furthermore, the introduction of the leaf-area index into the vegetation model of Baptist et al. (2007) appears promising, especially for species with no well-defined plant diameter. For general validation further investigations are needed.

The analytical investigation focused on the general behavior of the vegetation approaches, assessing three types of plants and plant simplifications (natural poplar, artificial poplar, and rigid aluminum cylinders). As expected, all approaches predict increasing friction factors with increasing ratios of water depth to plant height for non-submerged vegetation, reaching their maximum at the transition between non-submerged and submerged conditions. The approaches considering the influence of flexibility, Järvelä (2004) and Whittaker et al. (2015), predict smaller friction factors in the cases of artificial poplar and natural poplar. For submerged vegetation, only the two-layer approaches predict a reasonable friction-factor behavior: decreasing values with increasing submergence ratios. For high submergence ratios, the approach of Luhar and Nepf (2013) does not result in continued decrease of the friction factor which cannot be explained physically. Which behavior at the transition from non-submerged to submerged flow conditions is a valid approximation of the prevailing conditions in German federal inland waterways is still unclear.

Regarding large-scale applications, *LAI* is a promising parameter to account for vegetation density since it can be measured over large areas and even seasonal-changes can be captured. Beside the drag coefficient, it is also the dominant parameter defining the vegetation-induced drag force. In addition, the concept of the Vogel exponent proved to be adequate to account for vegetation flexibility. Considering the required input parameters and the results of this study, the approaches of Järvelä (2004) and Baptist (2007) are the most promising for large-scale applications. However, for submerged vegetation, an improvement of the approach of Järvelä (2004) is necessary and a two-layer concept like the one of Baptist (2007) may be chosen instead. The influence of flexibility has to be investigated in future studies.

Generally, further investigations are highly recommended including numerical simulations, laboratory experiments and field studies. A lack of adequate two-dimensional experiments as well as experiments with submerged flexible vegetation was discovered. Furthermore, assessing typical variation ranges of natural vegetation in German federal inland waterways would help to focus future investigations. In any case, an evaluation of natural conditions in the form of a pilot reach is absolutely necessary, but not easy to implement at German federal inland waterways, since it requires a thorough planning.

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References

Aberle, J. and Järvelä, J. (2015). Hydrodynamics of Vegetated Channels. Rivers – Physical, Fluvial and Environmental Processes, GeoPlanet: Earth and Planetary Sciences, Springer, Switzerland, 519-541.

Baptist, M.J., Babovic, V., Rodríguez Uthurburu, J., Keijzer, M., Uittenbogaard, R.E., Mynett, A. and Verwey,

A. (2007). On Inducing Equations for Vegetation Resistance. J. of Hydr. Res., 45(4), 435-450.

Chapman, J.A., Wilson, B.B. and Gulliver, J.S. (2015). Drag force parameters of rigid and flexible vegetal elements. Water Resour. Res., 51.5, 3292-3302.

de Langre, E., Gutierrez, A. and Cossé, J. (2012). On the scaling of drag reduction by reconfiguration in plants. Comptes Rendus Mécanique, 340.1, 35-40.

Dombroski, D. (2014). A deterministic spatially-distributed ecohydraulic model for improved riverine system management. Technical Report No. SRH-2014-26. Bureau of Reclamation, Denver, CO.

Finnigan, J. J. (2000). Turbulence in plant canopies. Ann. Rev. Fluid Mech., 32(1), 519-571.

Folkard, A.M. (2011) Vegetated flows in their environmental context: a review. Eng Comput Mech. 164(EM1), 3-24

Ghisalberti, M. and Nepf, H.M. (2002). Mixing layers and coherent structures in vegetated aquatic flows. J Geophys Res 107(C2):3.1–3.11.

Gosselin, F., de Langre, E. (2011). Drag reduction by reconfiguration of a poroelastic system. J. Fluid Struct. 27(7), 1111–1123.

Hervouet, J.M. (2007). Hydrodynamics of Free Surface-Flows: Modelling with the Finite Element Method. Edt. Wiley & Sons.

Huthoff, F., Augustijn, D.C.M. and Hulscher, S.J.M.H. (2007). Analytical solution of the depth-averaged flow velocity in case of submerged rigid cylindrical vegetation. Water Resour. Res., 43, W064131.

Jalonen, J., Järvelä, J. and Aberle, J. (2013). Leaf area index as vegetation density measure for hydraulic analyses. J Hydraul. Eng. 139(5), 461-469.

Järvelä, J. (2004). Determination of Flow Resistance Caused by Non-submerged Woody Vegetation. Int. J. River Basin Manage. 2(1), 1-10.

Katul, G., Wiberg, P., Albertson, J. and Hornberger, G. (2002). A Mixing Layer Theory for Flow Resistance in Shallow Streams. Water Resour. Res. 38(11), 32-1-32-8.

Klopstra, D., Barneveld, H.J., Van Noortwijk, J.M. and Van Velzen, E.H. (1997). Analytical Model for Hydraulic Roughness of Submerged Vegetation. 27th Int. IAHR Conference, San Fransico, CA, 775-780.

Lindner, K. (1982). Der Strömungswiderstand von Pflanzenbeständen. Mitteilungen 75. Leichtweiss-Institut für Wasserbau, Technische Universität Braunschweig. (in German)

Luhar, M. and Nepf, H.M. (2013). From the blade scale to the reach scale: a characterization of aquatic vegetative drag. Adv. Water Resour., 51, 305-316.

Miler, O., Albayrak, I., Nikora, V. and O'Hare, M. (2011). Biomechanical properties of aquatic plants and their effects on plant–flow interactions in streams and rivers. Aquatic Sciences. 74. 31-44.

Nepf, H. (2012). Flow and Transport in Regions with Aquatic Vegetation. Ann. Rev. Fluid Mech., 44.1, 132- 142.

Nepf, H.M. and Vivoni, E.R. (2000). Flow structure in depth-limited, vegetated flow. J. Geophys. Res., 105(C12), 28457-28557.

Nikora, V. (2010). Hydrodynamics of Aquatic Ecosystems: An interface between ecology, biomechanics and environmental fluid mechanics". River Res. and Applications, 26, 367–384.

Pasche, E. and Rouvé, G. (1985). Overbank flow with vegetatively roughened flood plains. J. Hydr. Engrg., 111(9), 1262-1278.

Schoneboom, T., Aberle, J. and Dittrich, A. (2010). Hydraulic resistance of vegetated flows: Contribution of bed shear stress and vegetative drag to total hydraulic resistance. River Flow 2010, Braunschweig, 8-10 September, 269-276.

Shields, F.D., Coulton, K.G. and Nepf, H. (2017). Representation of Vegetation in Two-Dimensional Hydrodynamic Models. J. of Hydraul. Eng., 143(8): 0251700.

Västilä, K., Järvelä, J. and Aberle, J. (2013). Characteristic reference areas for estimating flow resistance of natural foliated vegetation. J. of Hydrologie, 492, 49-60.

Västilä, K. and Järvelä, J. (2014). Modeling the flow resistance of woody vegetation using physically based properties of the foliage and stem. Water Resour. Res., 50(1), 229-245.

Vogel, S. (1984). Drag and Flexibility in Sessile Organisms1. American Zoologist, 24.1, 37-44.

Whittaker, P., Wilson, C. and Aberle, J. (2015). An improved Cauchy number approach for predicting the drag and reconfiguration of flexible vegetation. Adv. Water Resour., 83, 28-35.

Autoren

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

Mohamad Attieh
Department of Hydraulic Engineering
Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, Germany

Rebekka Kopmann
Department of Hydraulic Engineering
Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, Germany