Advanced representation of near-natural vegetation in hydrodynamic modelling

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***Abstract* – The correct representation of the hydraulic resistance of flexible floodplain vegetation in two-dimensional hydrodynamic models is still a challenging task. In previous studies [1, 2], different vegetation resistance approaches have been implemented in TELEMAC-2D, and their performance has been tested. However, the vegetation resistance approaches implemented so far work well for emerged flexible vegetation, and both emerged and submerged rigid vegetation. The existing two-layer approaches have been shown to work well for submerged conditions but do not account for plant flexibility.**

Box et al. [3, 4] conducted laboratory experiments to investigate the flow resistance of flexible vegetation at relative submergence levels of 1 to 3.4. To model submerged flexible vegetation, Box et al. [4] extended the existing one-layer approaches of Järvelä [5] by assuming a logarithmic velocity profile in the free surface layer above the vegetation. A similar approach was presented in parallel by Folke et al. [6].

In this study, we describe the implementation of the developed two-layer approach by [4] in TELEMAC-2D. Subsequently, the laboratory tests according to Box et al. [3] are simulated in TELEMAC-2D using the existing two-layer approach of Baptist et al. [7] and the newly implemented two-layer approach. To model the mixture of understory grass and flexible woody vegetation, the resulting individual vegetation resistances were superimposed. The results demonstrate the applicability of this method in the present case. In addition, several parameters influencing the approaches are varied. The Darcy-Weisbach friction values of the simulations are compared with the experimentally obtained ones. The results show good agreement between the measured and simulated friction factors. Using these insights, users are encouraged to apply vegetation approaches for modelling the hydraulic resistance in vegetated areas.

Keywords: flow resistance, submerged vegetated flow, numerical hydraulic modelling.

I. CHALLENGES OF MODELLING SUBMERGED FLEXIBLE VEGETATION AND MIXTURES OF VEGETATION

In numerical modelling, the representation of the hydraulic resistance of floodplain vegetation remains a challenging task. With its diverse and complex forms, vegetation plays a crucial role in altering flow patterns, affecting water levels, and influencing sediment transport in riverine environments [3, 4]. Over the years, several approaches have been developed to simulate the interaction between hydrodynamics and vegetation. These approaches share the common feature of considering the underlying fundamental physical mechanisms – even though the assumptions may differ significantly. Especially the influence of flexibility is often not adequately considered.

Early studies focused on emerged rigid vegetation. Typically, in these studies, vegetation was simplified as rigid cylinders. Despite the known shortcomings of such approaches in capturing crucial vegetation properties, valuable insights into the effects of vegetation on flow patterns and turbulence were provided. To account for the impact of submergence, subsequent multi-layer approaches were developed, e.g. [7]. However, these approaches generally rely on the simplified assumption of rigid cylinders, limiting their transferability to natural vegetation. Parallel to these developments, Järvelä [5] has presented an approach for flexible foliated vegetation. While this approach considers the flexibility of plants, allowing for a more realistic representation of natural vegetation, it is limited to emerged vegetation. Accurately representing submerged flexible vegetation in hydrodynamic modelling is crucial for comprehensively representing flow dynamics on floodplains. Therefore, approaches for submerged flexible vegetation have recently been developed by extending the formulation of [5] to submerged conditions, as presented by [4,6].

Within this study the two-layer approach of [4] was implemented into TELEMAC-2D. The performance of the new approach is tested using data from the laboratory experiments of [3], and compared with the results of the already available two-layer approach of [7]. The mixture of the understory grass and the flexible woody vegetation used in the laboratory experiments are each represented by a vegetation approach. The resulting vegetation roughness is determined using the superposition principle. In addition, the influence of the sensitivity of various input parameters is investigated. The aim of this contribution is to draw attention to the new vegetation approaches and their potential within 2D hydrodynamic modelling. Users are encouraged to take advantage of the use of vegetation approaches in TELEMAC-2D and critically question the use of conventional roughness laws to model vegetation induced resistance.

II. ROUGHNESS MODELLING OF VEGETATION

A. Principle of superposition

The total resistance can be determined according to the principle of superposition of the individual resistances. For flow influenced by vegetation, the total Darcy-Weisbach friction coefficient λ is the sum of the bottom friction λ' and the vegetation form roughness per unit surface λ''

$$\lambda = \lambda' + \lambda''. \quad (1)$$

Based on this principle, different vegetation modelling approaches are implemented in TELEMAC-2D [2]. The vegetation approaches can be coupled with all available laws of bottom friction. In this study, the Nikuradse roughness law is used to model the bottom friction. The vegetative drag is modelled using the vegetation approaches of Baptist et al. [7] (referred to as BAPT) and the new extended hybrid approach of [4,6] (referred to as HYBR). Both vegetation approaches are briefly described below.

B. Two-layer approach for rigid vegetation (BAPT)

The BAPT two-layer approach assumes constant velocity within the vegetation layer and a logarithmic velocity profile within the free surface layer. The resistance of vegetation λ'' is calculated as:

$$\lambda'' = \begin{cases} 4 \cdot \left(\frac{1}{\sqrt{C_D \cdot mD \cdot h_p}} + \frac{1}{\kappa\sqrt{2}} ln\left(\frac{h}{h_p}\right)\right)^{-2} & for\ h_p \leq h \\ 4 \cdot C_D \cdot mD \cdot h & for\ h_p > h \end{cases}, \quad (2)$$

with the drag coefficient C_D [-], the hydrodynamic density mD [m^{-1}], the plant height h_p [m], the flow depth h [m], and the von Kármán constant $\kappa = 0.41$ [-]. The hydrodynamic density is defined as the sum of the projected plant area per unit volume.

The BAPT two-layer approach was initially developed for rigid vegetation only, simplifying vegetation as rigid cylinders. To account for flexible leafy vegetation, [2] suggests to estimate the hydrodynamic density based on the leaf area index (LAI), which is defined as the one-sided green leaf area per unit ground area, and the vegetation height h_p. Both in [4] and [8], a direct proportionality of the hydrodynamic density to the ratio of the leaf area index to the plant height is assumed:

$$mD = k \cdot LAI/h_p, \quad (3)$$

with the constant of proportionality k. In [8], a value of 0.5 for k is proposed, while [4] suggests a value of 1 since they assume the LAI to be evenly distributed over the plants canopy. It should be noted that the parameters cannot be directly converted to the respective other format. These two formulas only provide rough estimates of the relationship between the vegetation density parameters.

C. Two-layer approach for flexible vegetation (HYBR)

To account for flexible emerged and submerged vegetation, [4] and [6] have developed a two-layer approach in parallel. This new approach represents an advancement of the one-layer approach of [5], which was developed to model the hydraulic resistance of emerged flexible woody vegetation.

As described above, the BAPT vegetation approach has the advantage of being suitable to calculate the hydraulic resistance of emerged as well as submerged vegetation due to the two-layer concept that describes the velocity profile in and above the vegetation. However, the approach was only developed for rigid vegetation. Järvelä's [5] approach quantifies the flexible foliated plant characteristics but is only suitable for emerged and just-submerged flow conditions due to the one-layer approach. [4] and [6] have combined the benefits of both approaches, resulting in a two-layer approach for flexible woody vegetation. In this way, the flexible plant properties and the velocity profile within the free surface layer, and thus different relative submergences depths, can be considered.

In addition to merging the equations, [4] introduced the scaling factor α for the von Kármán constant to account for the dependence on the velocity profile, the roughness of the plant canopy, and the relative submergence. They proposed a value of $\alpha = 1.5$, while [7] assumed a value of 1.0 for α in the original equation. Finally, the following formulas were obtained

$$\lambda'' = \begin{cases} 4 \cdot \left(\frac{1}{\sqrt{C_{D,\chi} \cdot LAI \cdot \left(\frac{u}{u_\chi}\right)^{\chi}}} + \frac{1}{\alpha\kappa\sqrt{2}} ln\left(\frac{h}{h_p}\right)\right)^{-2} & \text{for } h_p \leq h \\ 4 \cdot C_{D,\chi} \cdot LAI \cdot \left(\frac{u}{u_\chi}\right)^{\chi} \cdot \frac{h}{h_p} & \text{for } h_p > h \end{cases}, \quad (4)$$

with the species-specific drag coefficient $C_{D,\chi}$ [-], the species-specific Vogel exponent χ [-], the species-specific reference velocity u_χ [m/s], and the flow velocity u [m/s]. The species-specific reference velocity u_χ is the lowest flow velocity in the experimental determination of the species-specific vegetation parameters.

During the implementation of the approaches of [4] and [5] into TELEMAC-2D, the equations were slightly modified. In both approaches, the ratio u/u_χ is limited so that it cannot become smaller than 1. Otherwise, a too high vegetative Darcy-Weisbach friction factor would occur for flow velocities much smaller than the reference velocity. The treatment of lower velocities needs further research.

III. METHODOLOGY

A. Laboratory datasets

This study uses the dataset of the flume experiments of [3] to investigate the performance of the newly implemented hybrid vegetation friction approach in TELEMAC-2D. The original experiments were conducted to determine the hydraulic resistance of a mixture of vegetation using understory grass and flexible woody foliated plants at different relative submergences. The dataset of the laboratory experiments of [3] were conducted using the Aalto Environmental Hydraulics Flow Channel. In a 16 m long and 0.6 m wide working section, fully developed flow conditions were produced. Since the flume bottom is horizontal for the experimental runs, non-uniform flow conditions were achieved. The nature-like flexible woody plants used to model the vegetation elements had an undeflected height of 0.22 m, and the understory grass was 0.03 m tall. Three different densities of flexible woody foliated plants (LAI of 1.4, 3.8, and 5.2) combined with understory grass at different relative submergences H/h_p (1, 1.5, and 2) were used. Water levels were measured at two positions, X_{up} and X_{down}, within the vegetated section using high-accuracy pressure sensors. The location of these pressure sensors is shown in Figure 1 (P_{up} and P_{down}). The longitudinal distance dx between the two sensors is 3.45 m in the case of sparse vegetation ($LAI = 1.4$), while the sensors are located at a distance of 1.25 m at higher vegetation densities ($LAI = 3.8 \div 5.2$). In addition, eight more pressure sensors were installed (P1-P8), which have been used to check the water level slope but have not recorded any data for post-processing. Using the measurements at the locations X_{up} and X_{down}, the bulk friction factors are obtained using the water surface slope and the Darcy-Weisbach equation. More information can be found in [3].

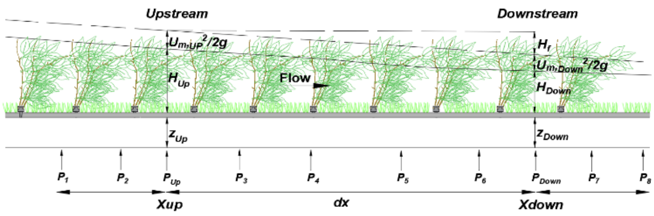


Figure 1. Longitudinal representation of measurement setup [3]

B. *Numerical Hydrodynamic Model*

A simplified two-dimensional numerical model of the laboratory flume described above was set up (TELEMAC-2D v8p3r1). Installations, such as weirs of rectifiers, are not represented in the numerical model. The numerical model has a length of 32.5 m to ensure fully developed flow conditions and a width of 0.60 m. At the model outlet, the average flow depth determined from the experiments is uniformly applied across the cross-section, while the corresponding discharge is imposed at the inlet. Much like the experimental setup, the numerical model features a horizontal bed. The side walls are assumed to be smooth.

The computational grid has an average edge length of 0.05 m and comprises 9613 nodes and 17920 unstructured triangular elements. The time step Δt was chosen between 0.1 s and 0.5 s based on the mean velocity in the experiments to ensure acceptable Courant numbers for all scenarios. A semi-implicit finite element scheme and the mixing-length turbulence model were chosen for this application.

The total friction of the numerical model was obtained by superposing the bottom roughness obtained through Nikuradse's law and the friction due to understory grass obtained using the vegetation approach of BAPT. The woody vegetation elements are modelled using the above presented vegetation approaches. It is assumed that the vegetation is uniformly distributed throughout the entire channel.

IV. RESULTS AND DISCUSSION

A. *Modelling understory grass*

Since [3] investigated mixed vegetation in laboratory experiments comprising understory grass and flexible woody plants, the hydraulic resistance of the understory grass is also modelled using a vegetation approach in this study. For this purpose, the vegetation approach BAPT is used in combination with the Nikuradse roughness law. The vegetation approach calculates the hydraulic roughness of the grass cover, while a small value of 0.001 m was chosen for the equivalent sand roughness k_s to map the bottom friction of the flume. The values of the BAPT friction approach used to model the understory grass are $mD = 74\,m^{-1}$ and $h_p = 0.03\,m$, accordingly to the experiments of [3].

Figure 2 shows the results of the simulation of the understory grass using the BAPT approach. Since [3] determined the Darcy-Weisbach friction factors λ using formula (5), λ_{bulk} of the simulation results is also determined here using this formula.

$$\lambda_{bulk} = \frac{8gH}{u_m^2} \cdot \frac{H_f}{dx}, \quad (5)$$

with the mean water depth H of the water depth H_{up} at X_{up} and the water depth H_{down} at X_{down}, the mean velocity u_m calculated using the continuity equation, and the friction loss H_f calculated using Bernoulli's equation.

Figure 2 shows the comparison of the Darcy-Weisbach friction factors λ obtained from the measurements (exp) and the simulations (sim). Here, a good agreement between the measured and simulated values is achieved using the vegetation parameters above and without any further adaption. Consequently, using the BAPT approach can be assumed to be suitable for modelling the hydraulic resistance of the understory grass.

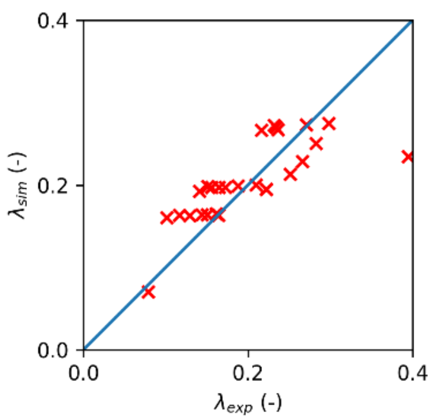


Figure 2. Comparison of measured (exp) and simulated (sim) Darcy-Weisbach friction factors for the calibration of the understory grass

B. *Emerged and submerged flexible woody vegetation*

The laboratory experiments, including the flexible woody vegetation and the understory grass, are simulated using the BAPT and HYBR approaches and subsequently compared. The parameters used for the vegetation approaches according to [3] are listed in Table 1. [3] conducted drag force measurements at velocities ranging from 0.2 to 0.8 m/s to determine these plant-specific parameters. The drag forces were measured using a force sensor, with one specimen on the flume bottom covered with a grass mat. In addition to the functionality of the newly implemented vegetation approach HYBR, the influence of the parameters α, mD, and the used plant height $h_{p,0}$ (undeflected plant height) or $h_{p,defl}$ (deflected plant height) on the simulation results are investigated. In order to compare the BAPT approach with the HYBR approach, the Darcy-Weisbach friction factors are calculated for each simulation. For this purpose, equation (5) is applied.

Table I Vegetation parameters used for the simulations [3]

Parameter	Box et al. (2021)
$C_{D,\chi}$ [-]	0.51
χ [-]	-0.95
u_χ [m/s]	0.20
C_D [-]	1.0
α [-]	1.0 / 1.5
$h_{p,0}$ [m]	0.22
$h_{p,defl}$ [m]	0.13 – 0.22

In TELEMAC-2D, the HYBR approach is implemented using a limit for the ratio u_m/u_χ of 1, which means that for $u_m < u_\chi$ the ratio is limited to 1. Otherwise, the friction coefficient would approach infinity for very low flow velocities. For the data of [3], u_m is lower than u_χ in 28 of 116 experimental runs. This leaves the question of how to deal with flow velocities smaller than u_χ. Consequently, they behave more or less rigid up to this flow velocity. Therefore, only the experimental runs with $u_m > 0.2\ m/s$ were selected for the simulations.

The simulated and experimentally obtained Darcy-Weisbach friction factors of the dataset of [3] are shown and compared in Figure 3. The simulations have been conducted using the undeflected plant height $h_{p,0}$, since in nature often only this parameter is available and the deflected plant height is difficult to determine in the field. For the simulations where the HYBR approach has been used, α was varied by using once the proposed value of 1.5 [4] and once the value of 1.0 [7]. For applying the BAPT approach, the influence of the method used to estimate the hydrodynamic density was investigated (see formula (3)). $k = 0.5$ describes the method of [8], while $k = 1$ defines the approach of [4]. The blue line defines the values of the optimal agreement of the measured and simulated Darcy-Weisbach friction factors. The red crosses show the actual correspondences for each experimental run.

When using the HYBR approach, the simulated and measured Darcy-Weisbach friction factors λ fit slightly better for $\alpha = 1.5$ (see Figure 3a) than for $\alpha = 1.0$ (see Figure 3b). For $\alpha = 1.0$, the friction factors are slightly underestimated by the HYBR approach. However, the differences in the results are minor compared to the change in the value of α. Therefore, the influence of the used value for α can be assumed to be small as both configurations give good agreement of the results. When the BAPT approach is used, the simulated Darcy-Weisbach friction factors are significantly overestimated when the hydrodynamic density is determined with $k = 1.0$ (see Figure 3d). In comparison, the simulated and measured values show a better agreement when using the approach according to [8] with the factor $k = 0.5$ (see Figure 3c). If the results of the two approaches, HYBR and BAPT, are compared, a larger scatter of the results is visible when using the BAPT approach. The best fit of simulated and measured friction factors is achieved using the HYBR approach with $\alpha = 1.5$ (see Figure 3a).

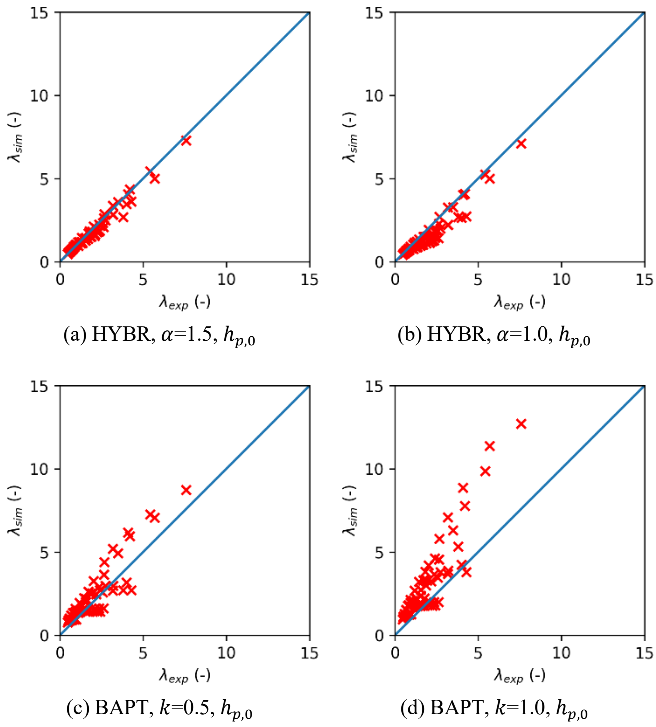
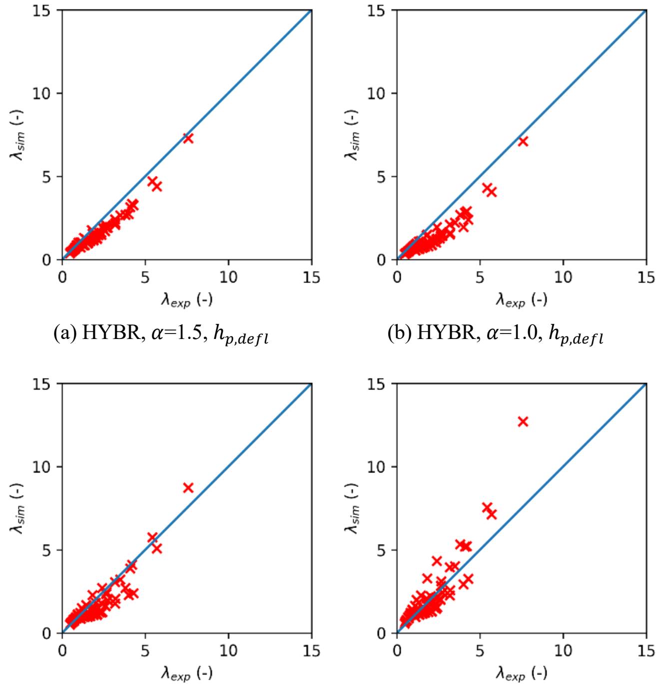


Figure 3. Comparison of measured (exp) and simulated (sim) friction values for different combinations of vegetation approaches and parameters, using the undeflected plant height $h_{p,0}$ evaluated for the data of [3]

In order to investigate the influence of the used plant height, further simulations were carried out using the deflected plant height $h_{p,defl}$. Here, α was again varied for the HYBR approach and k for the BAPT approach. The results are shown in Figure 4. When using the HYBR approach, the Darcy-Weisbach friction factors λ are underestimated for both $\alpha = 1.5$ and $\alpha = 1.0$ when applying $h_{p,defl}$ (see Figure 4a and b). Here, the results show also a better agreement of measured and simulated λ for $\alpha = 1.5$ than $\alpha = 1.0$. This trend confirms the results of the simulations with $h_{p,0}$. In general, however, the HYBR approach performs better when using $h_{p,0}$. When using the BAPT approach with $h_{p,defl}$, the same trends are visible when using $h_{p,0}$. The results also show a significantly larger scatter at $k = 1$ than at $k = 0.5$. In general, using $h_{p,defl}$ in the BAPT approach provides a better agreement of the results. However, it must be noted that $h_{p,defl}$ must be calculated using an additional model, since is difficult to determine in the field. Furthermore, it varies for different hydraulic conditions, so it needs to be implemented dynamically for each setting.



(a) HYBR, α=1.5, $h_{p,defl}$ (b) HYBR, α=1.0, $h_{p,defl}$

(c) BAPT, k=0.5, $h_{p,defl}$ (d) BAPT, k=1.0, $h_{p,defl}$

Figure 4. Comparison of measured (exp) and simulated (sim) friction values for different combinations of vegetation approaches and parameters, using the deflected plant height $h_{p,defl}$ evaluated for the data of [3]

Figure 5 shows the deviations of the simulated and measured Darcy-Weisbach friction factors λ for each combination of vegetation approach and used parameters. Here, the observations described above are clearly presented and the conclusions supported. The HYBR approach with $\alpha = 1.5$ and $h_{p,0}$ shows the best agreement between the measured and simulated roughness values. The largest scatter, on the other hand, can be seen with the BAPT approach with $k = 1$ and $h_{p,0}$. For the use of the BAPT approach, the deflected plant height $h_{p,defl}$ seems to give better results, whereas, for the use of the HYBR approach, a slightly better fit for the undeflected plant height $h_{p,0}$ can be seen. However, it must also be considered how easily the input values can be determined since $h_{p,0}$ can be obtained from field measurements or remote sensing while $h_{p,defl}$ needs to be determined in a more complex way. Hence, the error that is made when simulating with input values from e.g. literature or field measurements may be small compared to the accuracy of the simulation results.

V. Conclusion

In this study, a new two-layer approach for calculating the hydraulic resistance of flexible woody plants in TELEMAC-2D was implemented. The functionality of the approach was tested using the laboratory experiments of [3] and compared with the existing BAPT two-layer approach. Since the experiments investigated the hydraulic resistance of mixed vegetation consisting of understory grass and flexible woody plants, the understory grass was also modelled using the BAPT vegetation approach. In the simulations, the influence of the input parameters, the von Kármán scaling factor α, the method for the estimation of mD, and the used plant height, were investigated. The simulation results show a good agreement of the measured and simulated values for both the existing BAPT and the newly implemented HYBR approach. The best fit was achieved using the HYBR approach with $\alpha = 1.5$ and $h_{p,0}$.

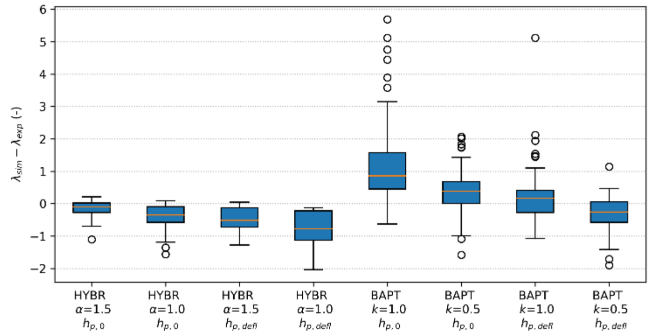


Figure 5. Deviations of the simulated (sim) and measured (exp) friction factors for each combination of vegetation approach and used parameters

Applying both vegetation approaches, BAPT and HYBR, generally works well. The simulations provide satisfactory results with a good agreement of the measured and simulated friction factors. The von Kármán scaling factor α shows minimal effect on the quality of the results with relatively large variation. The same applies to the use of undeflected or deflected plant height. Furthermore, it has to be investigated how to deal with flow velocities smaller than the species-specific reference velocity u_χ, since the HYBR has been implemented with a limit, so that in the case of $u_m < u_\chi$ the ratio is limited to 1. The influence of this limit on the quality of the results has to be further investigated.

The study shows that a new two-layer approach has been successfully implemented in TELEMAC-2D. The simulations using this and an existing approach show that applying the vegetation approaches provides satisfactory results with relatively few input parameters. Regarding the quality of the results, this makes the vegetation approaches superior to conventional roughness approaches, especially in vegetated floodplains. Although the vegetation approaches require more input parameters than conventional roughness approaches, these parameters can easily be taken from the literature or collected by remote sensing or field measurements. Although some questions remain unsolved, e.g. predicting the deflection height of plants under different flow conditions and accurately describing the vertical velocity profile in the free surface layer, the vegetation approaches implemented in TELEMAC-2D offer a promising and easy-to-use alternative to conventional roughness approaches.

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