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Comparison of different vegetation models using TELEMAC-2D

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***Abstract*— Riparian vegetation on German federal waterways is of growing importance. The occurrence of vegetation significantly increases the hydraulic resistance. In most cases classical friction formulations in depth-averaged models fail to model the effect of vegetation. For skin friction and form roughness the hydraulic resistance decreases with increasing water depth. In contrast, the hydraulic resistance increases with depth for non-submerged vegetation. It is highly important to capture the vegetation effects on the flow field adequately by special friction formulations. The only vegetation formulation in the current TELEMAC-2D version (v8p0r2) is from Lindner [1] and Pasche and Rouvé [2], evaluated for rigid non-submerged cylinders.**

In a previous study [3] the approaches of Järvelä [4] and Baptist et al. [5] were recommended to model the hydraulic resistance of bushes, shrubs and trees. Within the current study these approaches are investigated using a 1D-flume model and an existent model of the river Rhine and compared to the current approach in TELEMAC-2D.

The predicted friction values of both new approaches are in good agreement with data from a flume experiment. The current approach in TELEMAC-2D shows only reasonable results using a constant drag coefficient but still has significant deviations from the experimental data. For a certain discharge, the measured water levels in the main channel of the 11 km long Rhine model can be captured equally well independently from vegetation approach used. The need for a two-layer vegetation approach is highlighted. The results show that the current vegetation formulation in TELEMAC-2D should be improved and additional vegetation models are needed.

I. Introduction

Riparian vegetation on German federal waterways is of growing importance. To satisfy the requirements of the EU Water Framework Directive the connection and restoration of branches covered by riparian vegetation and technical-biological bank protection measures are focus of several ongoing projects. The occurrence of vegetation significantly increases the hydraulic resistance. In most cases classical friction formulations in depth-averaged models, such as the Chézy, fail to model the effect of vegetation. Furthermore, the vertical velocity profile changes and the logarithmic velocity distribution over the whole water column is not valid anymore, so that also the law of Nikuradse cannot be applied. For grain roughness and form roughness the hydraulic resistance decreases with increasing water depth – but in the case of non-submerged vegetation the hydraulic resistance increases with water depth. In regard to river engineering it is highly important to capture the vegetation effects on the flow field adequately by special friction formulations. The only vegetation formulation in the current TELEMAC-2D version (v8p0r2) is from Lindner [1] and Pasche and Rouvé [2] (hereafter referred to as Lindner approach), evaluated for rigid non-submerged cylinders.

In recent decades many new approaches to model the effect of vegetation have been developed. Their scope ranges from very flexible sea grass through bushes to rigid tree stumps. In a previous study [3] the authors investigated the suitability of five different vegetation models with regard to large scale applications at German federal waterways. The approaches of [4] and [5] (hereafter referred to as Järvelä approach and Baptist approach) were both recommended to model the hydraulic resistance of bushes, shrubs and trees. Additionally, the study highlighted the suitability of the leaf area index to account for vegetation density term in large-scale applications, which is not discussed further herein.

An overview of the vegetation models is given and their implementation into TELEMAC-2D is presented. The implementation is done in such a way that it can easily be extended to additional vegetation models including a flexible number of input parameters. Within this study, the existing Lindner approach and the two recommended approaches are investigated using a 1D-flume model and an existing model of the river Rhine. Recommendations for further TELEMAC-2D versions are provided in the discussion.

II. Modelling vegetation using Telemac-2D

To consider the additional resistance caused by vegetation the principle of linear superposition is used. Thus, the total friction λ is the sum of the bed roughness coefficient λ' and the vegetation form resistance per unit surface λ'':

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

In TELEMAC-2D different friction laws for the bed roughness are available (keyword: LAW OF BOTTOM FRICTION). For the combination with vegetation the law of

Nikuradse is recommended, as it is independent of the water level. When vegetation exists, the vegetation friction coefficient is usually much higher and therefore decisive for the total friction. To model vegetation friction different approaches are used within this study and are described below. Further information can be found in [3].

A. Vegetation models

Based on the vegetation density [6] analytically derived a formula to describe the resistance induced by vegetation. Simplifying the vegetation as rigid cylinders the friction of non-submerged vegetation (flow depth h, smaller than plant height h_p) can be expressed as

$$\lambda'' = 4C_D \cdot \frac{Dh}{\Delta^2}, \quad (2)$$

with the drag coefficient C_D, the diameter D, and the spacing between the plant Δ. Equation (2) is the basis for most of the existing vegetation models.

1) *Lindner approach:* [1] adopted the Petryk and Bosmajian formula and enhanced the approach by quantifying the drag coefficient C_D at the reach scale. He assumed that the drag coefficient is dependent on the drag coefficient of a single cylinder, the resistance due to narrowing effects of the adjacent cylinders, and the resistance due to gravity wave [2]. The vegetation model of the Lindner approach is already available in TELEMAC-2D (v8p0r2). The drag coefficient is determined iteratively based on the flow velocity, the flow depth and the vegetation parameters diameter and spacing between the vegetation elements (not shown here).

2) *Järvelä approach:* [4] developed an approach for flexible non-submerged ($h < h_p$) and just submerged ($h \approx h_p$) vegetation.

$$\lambda'' = \begin{cases} 4C_{D\chi}\left(\frac{U_m}{U_\chi}\right)^\chi LAI \cdot \frac{h}{h_p} & \text{for } h < h_p \\ 4C_{D\chi}\left(\frac{U_m}{U_\chi}\right)^\chi LAI & \text{for } h \approx h_p \end{cases} \quad (4)$$

Proposing the foliage as the main contributor to vegetation resistance, the vegetation parameter leaf-area index (LAI) is used to account for the vegetation density. In case of non-submerged vegetation a linear distribution of the LAI is assumed in vertical direction. To account for the streamlining effect due to the flexibility of the plants, the exponent χ, based on the empirical concept of [7], and the corresponding reference velocity U_χ are used. The Järvelä approach is only valid for flow velocities larger than the used reference velocity. It is assumed that plant deformation occurs only for velocities larger than the reference velocity. Therefore, a limit for the velocity ratio to values greater than or equal one is introduced.

3) *Baptist approach:* Both models above mentioned are only valid in case of non-submerged flow conditions. [5] introduced a two-layer approach to model both non-submerged and submerged vegetation. Using the simplification of rigid cylinders, the vegetation friction coefficient is defined as

$$\lambda'' = \begin{cases} 4C_D \cdot \frac{Dh}{\Delta^2} & \text{for } h \le h_p \\ 4 \cdot \left(\frac{1}{\sqrt{C_D \cdot \frac{Dh_p}{\Delta^2}}} + \frac{1}{\sqrt{2}\kappa}\ln\frac{h}{h_p}\right)^{-2} & \text{for } h > h_p \end{cases} \quad (5)$$

with the von Kármán constant κ.

For species with no well-defined plant diameter, the rigid cylinder approaches are not appropriate. In this case, [3] recommended using the relation between the vegetation density parameters of rigid cylinders (diameter and spacing) to the LAI by [8].

$$\frac{D}{\Delta^2} = \frac{1}{2} \cdot \frac{LAI}{h_p}. \quad (6)$$

This relation was used in the current study to compare the individual models.

B. Implementation

In the TELEMAC-2D release (v8p0r2) the effect of vegetation can be modelled by the Lindner approach using the keyword NON-SUBMERGED VEGETATION FRICTION. In the new implementation this is changed to VEGETATION FRICTION since some of the new models are valid for both non-submerged and submerged vegetation. To use the vegetation friction models, the logical keyword FRICTION DATA has to be activated, in order to define individual bottom friction laws and vegetation models by area. Furthermore, two additional files are needed: the zones file (a list of nodes and corresponding friction IDs) and the friction data file (a table which defines the friction laws and its parameters for each friction ID). In Tab. 1 all needed keywords for vegetation friction are summarised. In the friction data file the setting of the bottom friction and the vegetation friction have to be defined as described below.

TABLE 1: KEYWORDS FOR VEGETATION FRICTION (TELEMAC-2D)

FRICTION DATA	=	YES
VEGETATION FRICTION (old keyword: NON-SUBMERGED VEGETATION FRICTION)	=	YES
ZONES FILE (not needed if FRIC-ID is defined in geometry file)	=	'list.bfr'
FRICTION DATA FILE	=	'friction.tbl

Taking into account more than one vegetation approach the friction table had to be enhanced. For each friction ID a specific vegetation friction law can be specified in the new implementation. In the adjacent columns the corresponding vegetation parameters have to be set (cf. Tab. 2). The maximum number of vegetation parameters is set to 15. As described above, the vegetation friction is added to the bottom friction by linear superposition. Just like in the current version of TELEMAC-2D, the user can choose between eight different bottom friction laws (cf. Telemac2D User Manual). In this study only the bottom friction law of Nikuradse (keyword NIKU) is used.

TABLE 2: FRICTION DATA FILE EXAMPLE (NEW: GREY COLUMNS, COMMENT LINES START WITH *)

Friction ID	Bottom friction law	Parameter for bottom friction	Vegetation friction law	Parameter 1 for vegetation friction	Parameter 2 for vegetation friction	Parameter x for vegetation friction
*				D	Δ	
1	NIKU	0.1	LIND	0.05	2.0	
*				C_D	mD	hp
2	NIKU	0.05	BAPT	1.0	0.0025	2.0

[9] implemented seven new vegetation approaches into TELEMAC-2D. All available approaches in the new implementation and the corresponding keywords and number of needed vegetation parameters are listed in Tab. 3. To make a simple addition and an easy modification possible, each vegetation approach is implemented in its own subroutine. From the new approaches only [4] and [5] are used in this paper. For further information see [3] and [9].

TABLE 3: KEYWORDS FOR VEGETATION FRICTION (TELEMAC-2D)

Vegetation approach	Keyword	Number of parameters
no vegetation	NULL	-
Linder [1] and Pasche and Rouvé [2]	LIND	2
Järvelä [4]	JAER	5
Whittaker at al. [10]	WHIT	6
Baptist et al. [5]	BAPT	3
Huthoff [11]	HUTH	4
Van Velzen et al. [12]	VANV	3
Luhar and Nepf [13]	LUNE	4
Västilä and Järvelä [14]	VAST	8

To simplify, an additional modification was done to remove the zones file. The friction IDs can now be read from the variable "FRIC-ID" in the geometry file. With this procedure the program code is optimized and the friction handling is less prone to errors.

III. NUMERICAL INVESTIGATION

In this study the recommended vegetation approaches [3] of Baptist and Järvelä were compared to the vegetation approach of Lindner, which is currently the only one available in TELEMAC-2D (v8p0r2). A numerical model of a vegetation flume experiment [15] was setup and the numerical results were compared to the measurements. This enabled the calculation of the vegetation friction coefficients to be validated. In addition, the differences between the different vegetation approaches were highlighted by simulating an 11 km long stretch of the River Rhine.

A. 1D flume model

A 1D-flume model was used to investigate the prediction accuracy of the individual vegetation approaches with TELEMAC-2D. The laboratory experiments [15] were performed using a 32 m long flume with a rough bed (k_s≈3 mm) and smooth sidewalls. Artificial plants with an undeflected height of 0.23 m were used to model the vegetation elements. The vegetation characteristics were similar to that of natural poplar. The setups of the experiments were chosen to achieve just-submerged flow conditions. Two different vegetation configurations (inline: L and staggered: S) and three different plant spacings (0.15 m, 0.20 m and 0.30 m), resulting in 6 data sets of measurements, were simulated. Detailed information can be found in [3] and [9]. In the current study the approaches of Lindner with and without the iterative calculation of the drag coefficient are compared to the Järvelä and Baptist approaches. To derive the vegetation parameters for the rigid approaches, the relation given in (6) was used. The vegetation parameters are summarized in Tab. 4. The vegetation parameters were chosen analogue to [3].

TABLE 4: USED PARAMETERS FOR THE VEGETATION LAWS

Arr.	Δ	h_p	LAI	$C_{D\chi}$	U_χ	χ
	[m]	[m]	[-]	[-]	[m/s]	[-]
Inline (L)	0.30 0.20 0.15	0.23	0.437 0.984 1.748	0.34	0.13	-0.73
Staggered (S)	0.30 0.20 0.15	0.23	0.437 0.984 1.748	0.50	0.11	-0.74

Initially, the friction coefficients calculated by the TELEMAC-2D approach were validated by measurements. In Fig. 1 the predicted friction coefficients of the Lindner approach compared to the measured ones are shown. Using default settings the implemented Lindner approach estimates friction values which are too high (cf. Fig. 1, left). Use of a constant value of C_D of 1.0 produces much improved results (cf. Fig. 1, right). It seems that the iterative method for the estimation of C_D fails in this example. In both cases the predicted friction coefficient shows a high sensitivity to the spacing which cannot be observed in the measurements from [15].

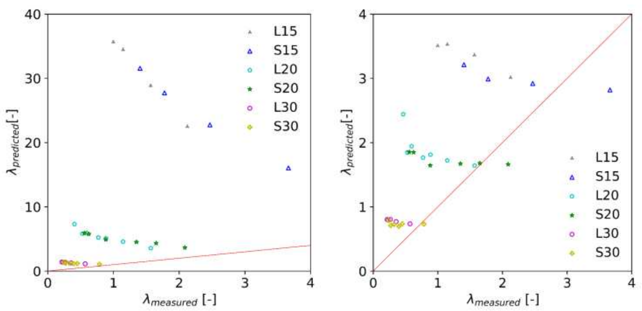

Figure 1: Comparision of predicted and measured friction coefficients of the vegetation approach in the official Telemac-2D release (left: iterative estimation of C_D; right: C_D=1.0) with two different vegetation configurations (inline: L and staggered: S) and three different plant spacing (0.15 m, 0.20 m and 0.30 m)

The predicted friction values by the Järvelä and the Baptist approaches are in good agreement with the measurements for all configurations (cf. Fig. 2). For the Baptist approach a C_D of 1.0 was set. It should be noted that the vegetation parameter for the Järvelä approach (cf. Tab. 4) were directly derived from the present experimental data.

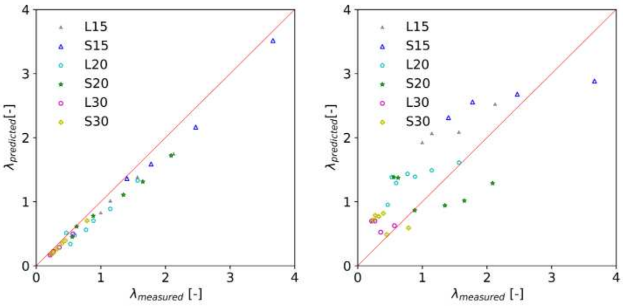

Figure 2: Comparision of predicted and measured friction coefficients of Järvelä (left) and Baptist (right) with two different vegetation configurations (inline: L and staggered: S) and three different plant spacing (0.15 m, 0.20 m and 0.30 m)

For further investigations both new implemented vegetation approaches are promising. The Järvelä approach considers the effect of flexibility but is only valid for non-submerged conditions. In case of submerged vegetation a two-layer approach should be chosen like the Baptist approach.

B. Rhine model

In the study of [16] an 11 km long section of the lower Rhine River (Rhine-km 738.5 – 749.5) near Düsseldorf (Germany) was used for a comparison between the different vegetation models. Fig. 3 gives an overview of the model boundaries and its topography. The main flow direction is from south to north. The flow field is affected by strong bends and, at higher discharges, by vegetation on the floodplains.

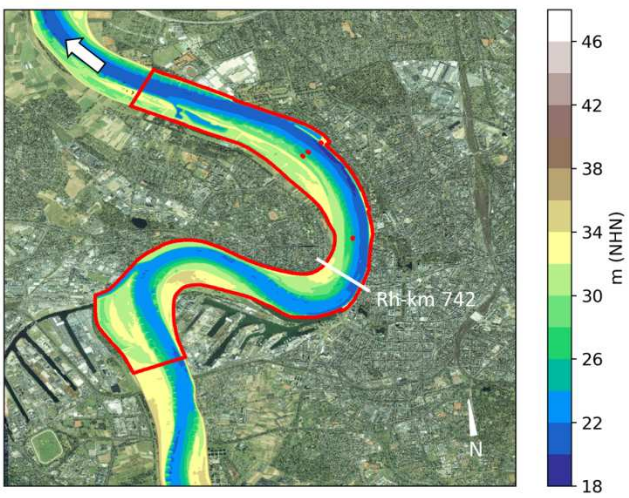

Figure 3: Lower Rhine river topography and numerical model boundaries (red polygon) nearby Düsseldorf. ([16], Copyright © 2019 Esri and its licensors)

To keep the model simple, four friction zones for groynes (k_s=0.30 m), floodplains (k_s=0.10 m), banks (k_s=0.08 m) and river bed (k_s=0.07 m) are distinguished (Fig. 4). To model the influence of the vegetation on the floodplains the same approaches was used as in the 1D-flume model. In this study a constant high water discharge of 7870 m^3/s (> HQ_5) was chosen. In this study the floodplains are assumed to be fully covered by vegetation, regardless of the real situation.

As a reference, the model was calibrated against measured water levels in the main channel using the Lindner approach. A plant diameter of 10 cm was chosen. The distance between the plants was calibrated to 2 m resulting in water level deviations less than ±5 cm between numerical predictions and the measured values. Fig. 5 shows that at the chosen discharge large parts of the floodplains are inundated with water depths up to 5 m. Water depths lower than 10 cm only occur on the floodplain on the first inner bend and on the northern left-sided floodplain (marked grey).

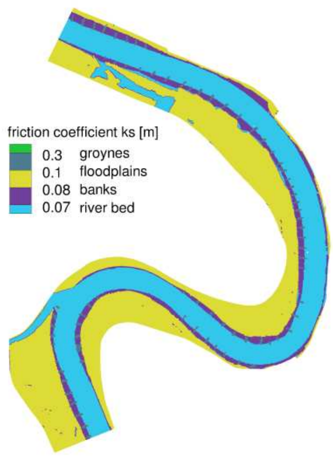

Figure 4: Friction zones

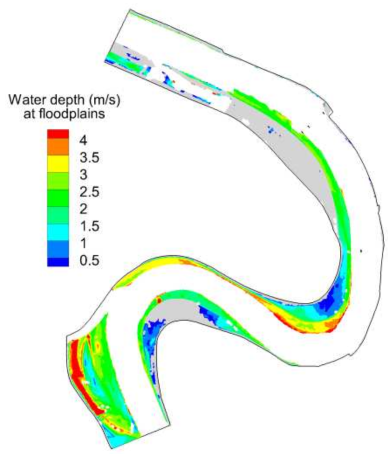

Figure 5: Water depths on the floodplains at a discharge of 7870 m³/s (grey areas: water depths lower than 0.1 m) simulated with Lindner.

The scalar velocities at a discharge of 7870 m³/s are shown in Fig. 6. On most parts of the floodplains the velocities are small, except for the floodplain located at the second inner bend (Rhine-km 742 – 744). In this part velocities up to 2 m/s occur.

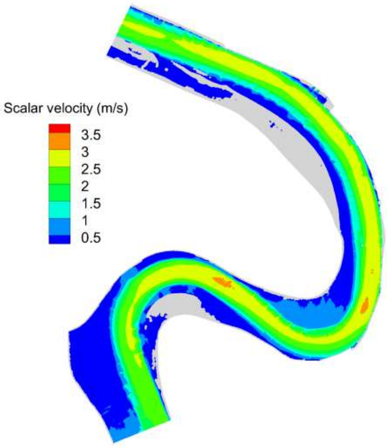

Figure 6: Scalar velocity at a discharge of 7870 m³/s (grey areas: water depths lower than 0.1 m) simulated with Lindner.

To investigate the influence and the behaviour of the other vegetation approaches, the same vegetation density was used. The plant height was set to 4.0 m resulting in non-submerged flow conditions on most parts of the floodplains. The LAI was derived by the relation in (6). For Baptist c_D was set to 1.0 and for Järvelä $c_{D\chi}$ was set to 0.5 as recommended in the literature. Furthermore, the approach of Lindner was modified using a constant value for C_D, also set to 1.0. The vegetation was assumed as rigid (χ=0). The vegetation parameters are summarized in Tab. 5.

TABLE 5: USED PARAMETERS FOR THE VEGETATION LAWS

Vegetation approach	C_D ($C_{D\chi}$)	D	Δ	h_p	LAI	U_χ	χ
	[-]	[m]	[m]	[m]	[-]	[m/s]	[-]
Lindner	-	0.1	2	-	-	-	-
Linder, C_D=const.	1.0	0.1	2	-	-	-	-
Baptist	1.0	0.1	2	4	-	-	-
Baptist	1.0	0.1	2	2	-	-	-
Järvelä (rigid)	(0.5)	-	-	4	0.2	-	0
Järvelä (flexible)	(0.5)	-	-	4	0.2	0.1	-0.9

In Fig. 7 the differences between the predicted water levels H and the measured values are presented. All approaches show very similar results. Only close to the inlet very small deviations occur. In case of non-submerged rigid vegetation the approaches of Baptist and Järvelä behave the same as the Lindner approach with a constant C_D value. Due to the chosen plant height, resulting in mainly non-submerged conditions and the assumption of rigid plants only these small deviations between the approaches are observed in this case study.

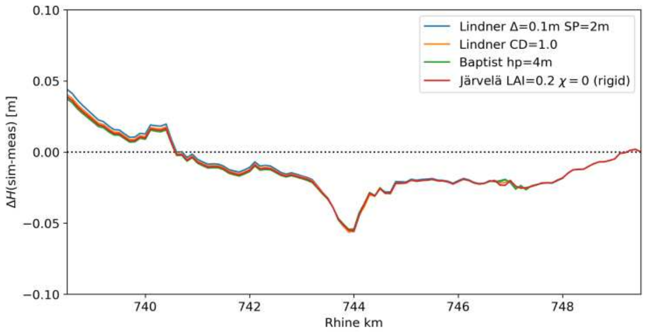

Figure 7: Differences between simulated and measured water levels in the main channel for the different vegetation laws with mostly non-submerged conditions and without flexibility

The C_D-estimator of Lindner depends on the specified vegetation parameters (diameter D and spacing Δ) and on the occurring flow conditions defined by the water depth and the scalar velocity. In Fig. 8 the predicted C_D values by Linder in the study are presented. The values show a high sensitivity to the flow depth with an asymptotic behaviour and no clear trend depending on the scalar velocity. For water depth higher than 1 m a drag coefficient of about one is predicted. Therefore, only small deviations between the original Lindner approach and the one with a constant drag coefficient occur.

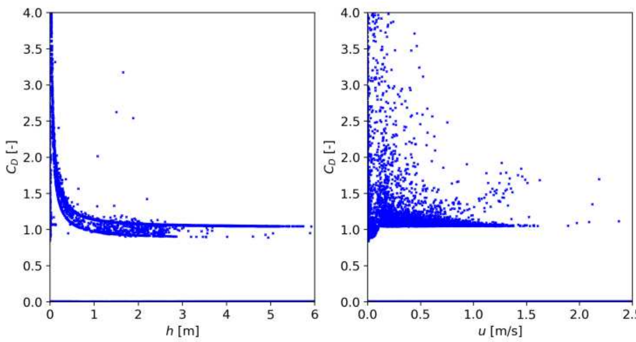

Figure 8: Drag coefficitent predicted by Lindner approach depending on the water depth (left) and on the scalar velocity (right)

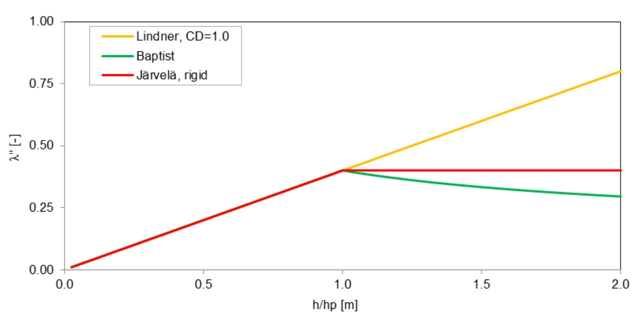

Figure 9: Vegetation friction coeffficient as a function of relative submergence

In Fig. 9 the vegetation friction coefficients of the three approaches with a constant drag coefficient are shown for this case as a function of relative submergence. If the water level is lower than the plant height, no difference between the three approaches can be found. In case of shallow submergence, the assumption of a constant value of Järvelä might be acceptable. For deeper submerged vegetation, only the two-layer approach predicts reasonable results.

To investigate the influence of the vegetation height, the plant height was reduced to h_p=2 m. Only the approach of Baptist is used in this case since it is the only two-layer approach. Fig. 10 shows the friction coefficients for both plant heights. For flow depths larger than 2 m large differences occur, since the vegetation is submerged in one case and non-submerged in the other one. At a flow depth of 6 m the vegetation friction is still more than twice as high for the case of the h_p=4 m.

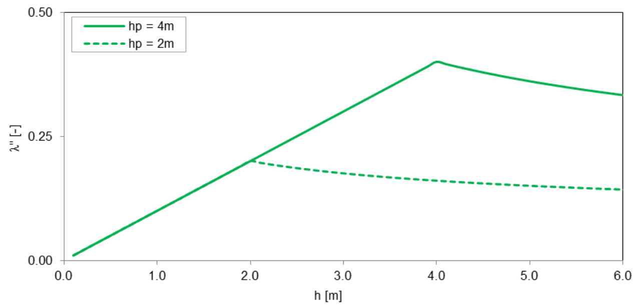

Figure 10: Vegetation friction coeffficient of Baptist for h_p=4 m (solid line) and h_p=2 m (dashed line) depeneding on the water depth

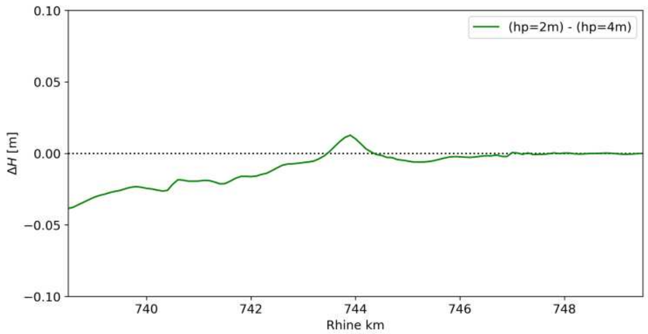

Figure 11: Differences between simulated water levels of mostly submerged (h_p=2 m) and mostly non-submerged (h_p=4 m) vegetation in the main channel for the Baptist approach.

The influence on the water level of the reduced vegetation friction due to the smaller plant height in the Baptist approach can be seen in Fig. 11. As described above, the vegetation friction is reduced for water levels higher than 2 m. As expected, water levels are decreased. Only at Rhine-km 744 an increase of the water level in the main channel can be observed. The reason for this is explained below.

The influence of flexibility is investigated using the approach of Järvelä. For this, a Vogel coefficient of χ=-0.9 and a reference velocity of U_χ=0.1 m/s was used. In Fig. 12 the friction coefficient as a function of scalar velocity is shown. In case of flexible vegetation, the friction coefficient is decreasing with increasing velocities. At a scalar velocity of u=0.5 m/s the friction is reduced by 77%, and at u=1.0 m/s by 87% compared to rigid vegetation. For velocities lower than the reference velocity the friction coefficient is set to a constant.

The plant bending and the so-called streamlining effect of flexible plants reduce the induced drag force. According to the reduced plant height, this results also in lower water levels as shown in Fig. 13. Like in the previous case, the low water levels at Rhine-km 744 are diminishing when flexible vegetation is considered.

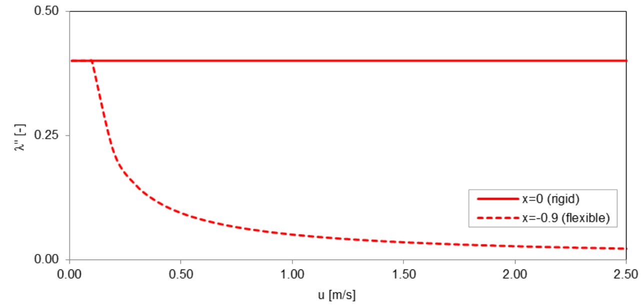

Figure 12: Vegetation friction coefficient of Järvelä for rigid (χ=0, solid line) and flexible (χ=-0.9, dashed line) plants depending on the scalar velocity

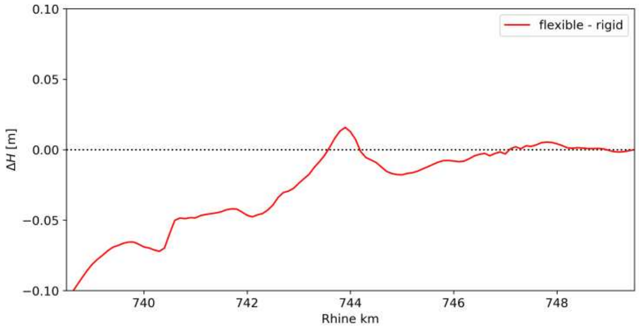

Figure 13: Differences between simulated water levels in the main channel for the Järvelä approach with and without considering flexibility.

Considering submerged conditions with Baptist approach or flexible plants with Järvelä approach lead to reduced vegetation friction. In Figs. 14 and 15 the resulting increase of the scalar velocity at the floodplains and a small decrease in the main channel at the second bend are visible. Due to the chosen parameters the influence of flexibility is larger than the influence of the submergence. Therefore the scale in the figures differs. But the qualitative behaviour in both cases is the same. Noticeable is the redistribution of the discharge at the second bend (Rhine-km 744). As mentioned above, reduced friction at the floodplains is leading to higher velocities at the floodplains resulting in a redistribution of the specific discharge. The higher velocities also accelerate the flow field over the banks and groynes adjacent to the floodplains. Furthermore, higher crossflows occur in the sharp bend. Both phenomena are leading to higher flow resistance resulting in locally higher water levels (see Figs. 11 and 13).

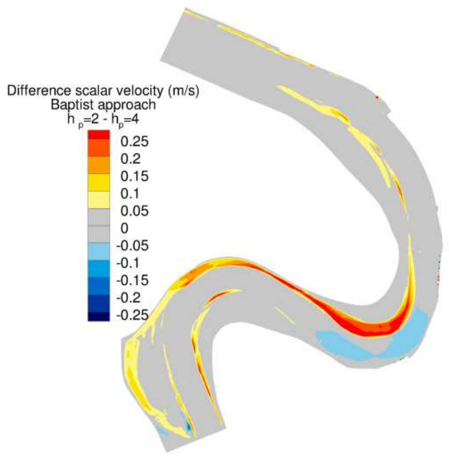

Figure 14: Scalar velocities differences between mostly submerged (h_p=2 m and mostly non-submerged (h_p=4 m) conditions considered by Baptist approach.

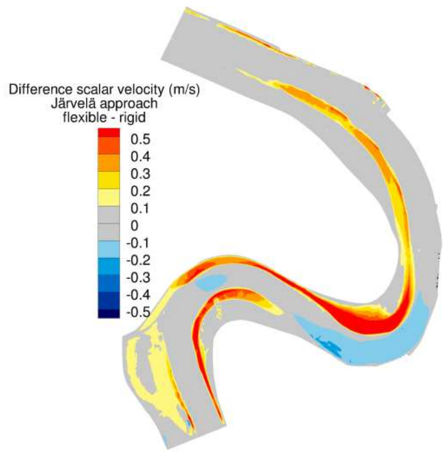

Figure 15: Scalar velocities differences between flexible and rigid condition considered by Järvelä approach.

In Tab. 6 the computing times at 40 processors of the BAW cluster (CPU Intel(R) Xeon(R) Gold 6138, 2x20 cores per node) for the different vegetation approaches are summarised. The iteration of the C_D value in the Lindner formulation takes a lot of computing time. In typical BAW models including sediment transport 20% of the overall computing time is dedicated to the C_D iteration. The results are very similar using a constant C_D value (see Fig. 7). Therefore a constant C_D value is more reasonable as default option in TELEMAC-2D.

TABLE 6: COMPUTING TIMES FOR DIFFERENT VEGETATION FORMULAS

Vegetation approach	computing time	
	[min:s]	[%]
no vegetation	1:11	-
Lindner	4:44	400
Linder, C_D=const.	1:18	110
Baptist	1:25	120
Järvelä	1:20	113

IV. RESULTS AND DISCUSSIONS

Currently only one vegetation approach is available in the official TELEMAC-2D release (v8p0r2). This vegetation approach was developed for rigid non-submerged vegetation and simplifies the vegetation as single, equally spaced cylinders. One peculiarity of the approach is the determination of the drag coefficient. Firstly, vegetation like trees or bushes is simplified into cylinders. The drag coefficient is afterwards computed using a complex iterative method considering different effects of the interaction of a group of cylinders. From the authors' point of view, this iterative method to determine the drag coefficient should only be applied if the shape of the vegetation is cylindrical and both diameter and spacing are well known. Moreover, this determination is only valid for regularly arranged non-submerged smooth cylinders.

[9] implemented seven new vegetation approaches into TELEMAC-2D. Within this study two of the new approaches were investigated and compared to the current approach. In accordance to the new approaches, a constant drag coefficient was used for the implemented approach additionally.

Based on comparison between the results of a 1D-flume model and experimental data with flexible just-submerged vegetation, this study shows the limitations of the current approach (Lindner) in TELEMAC-2D and the advantages of alternative methods. Both the predicted friction coefficients of the Järvelä approach, developed for flexible non-submerged vegetation, and of the Baptist approach, agree well with the measured data from [15].

The application "Rhine model" shows the influence of relative submergence and flexibility. Although it is possible to fit the water levels within the fairway to measured values with all approaches, local effects cannot be reproduced. Furthermore, extrapolation to other water levels is difficult with the current approach, as the vegetation friction coefficient increases linearly with increasing water levels, which is not physical in case of submerged vegetation. Moreover, the strong influence of canopy flexibility is shown. It should be noted that not all natural vegetation show such high flexibility as used in this study. Therefore, the relevance of considering the flexibility has to be estimated in each individual case.

The advantages of the iterative predictor of the drag coefficient of the current approach could not be observed in the present study. For the 1D-flume model the method does not reveal reasonable results. In the case of the application example, the differences from the method of using a constant drag coefficient are negligible. Regarding the computational costs, the iterative method needs nearly four times longer than the other ones. Using a constant C_D value the results are very similar. Therefore, a constant C_D value should be the default option in TELEMAC-2D for the Lindner approach.

The present study has shown the need for new vegetation approaches in river modelling. In particular, a two-layer approach should be available in the standard version since in real case applications both non-submerged and submerged vegetation occur. This also should be set as default option for vegetated flow.

The new vegetation models require additional input data, as the plant height or flexibility parameters. This requirement places new demands on the field data collection on floodplains. The quality of the input parameters directly determines the effectiveness of the applied vegetation model.

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