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Improved floodplain vegetation roughness for 1D hydraulic models

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ABSTRACT: 1D hydraulic models are largely used to simulate the propagation of flood waves and for flood mapping along river systems. The most common approach to account for the hydraulic effects of vegetated floodplains consists of imposing higher roughness coefficients. However, the flow resistance of vegetation is governed by plant submergence, which is water-depth dependent and varies with the discharge, and thus with time. An improved method properly incorporating floodplain vegetation roughness in 1D models is presented here. The Manning coefficient is derived from a simplification of Baptist's formula assuming horizontal floodplains, i.e., with the same water depth everywhere. Considering the dependency of vegetation roughness on local water depth (in case of variable flow conditions), a predictor-corrector approach of the derived formula is proposed to be applied at every computational time-step. If different types of vegetation are present, the roughness coefficient, one for each floodplain, is derived as a weighted average. The method is tested on a recently restored stream located in the Netherlands, the Lunterse Beek, using the HEC-RAS code. The results support the implementation of the proposed method, but validation is needed for river floodplains with non-uniform vegetation cover.

1 INTRODUCTION

The presence of aquatic vegetation affects water flow and the sediment dynamics in rivers at different spatial scales (e.g. Nepf, 2012; Aberle and Järvelä, 2015). Vegetation on floodplains rises high flow levels and affects the river morphology, because it locally increases the flow resistance and reduces the flow velocity above and between the plants. As a consequence, the flow concentrates in un-vegetated areas (e.g. Villada Arroyave and Crosato, 2010) which results in channel incision and sediment deposition on vegetated areas (Tsujimoto, 1999; Vargas-Luna et al., 2015). Recent research has demonstrated that the growth of floodplain vegetation decreases river braiding (Crosato and Samir Saleh, 2011), whereas vegetation growth on point bars triggers river meandering. Pushing the flow towards the opposite side of the river, vegetation enhances opposite-bank erosion and bend growth (Perucca et al., 2007; Parker et al., 2011; Vargas-Luna, 2016; Vargas-Luna et al., 2019). By increasing the flow resistance, riparian vegetation results in a clear increase of water levels during high-flow events when also river floodplains contribute in conveying water (e.g. Corenblit et al., 2007; Villada Arroyave and Crosato, 2010). It is therefore important to thoroughly take into account vegetation effects when modelling flood levels, in particular for flood wave propagation studies and flood risk mapping. This is especially relevant for river restoration projects involving floodplain re-naturalization and vegetation management (e.g. Solari et. al., 2015).

The assessment of flood wave propagation along river systems is often carried out using one-dimensional (1D) models. This type of studies requires fast simulations operating on large spatial scales, often covering the entire river basin. Models constructed on the free codes of HEC-RAS (www.hec.usace.army.mil/), ISIS (help.floodmodeller.com/isis/ISIS.htm) or 1D commercial software are widely used for this purpose. 1D hydrodynamic modelling of vegetated river channels requires a good reproduction of flow resistance. This is represented in different ways by means of a roughness coefficient, such as Manning, Chézy, etc., which is normally expressed as a function of vegetation density and plant characteristics (e.g. Yen, 2002).

The current approach of implementing the flow resistance in 1D models consists in imposing a single value to the roughness coefficient which is then kept constant. In the HEC-RAS environment this is done for each area of the river: main channel, left floodplain, right floodplain. The imposed value is not water-depth dependent although, as pointed out by Nikora et al. (2008), Nepf (2012) and Vargas-Luna et al., (2015) among others, vegetation roughness is dominated by the degree of plant submersion. This parameter is normally represented by the "plant submersion ratio", corresponding to the local value of the water depth, h, divided by the wet plant height, h_v. If the water depth is smaller than the total plant height, vegetation emerges, and the wet plant height equals the water depth. If the water depth is larger than the total plant height, vegetation is submerged. In this case, h_v, refers then to the entire plant height. The roughness exerted by vegetation is much larger at submersion ratios close to 1 and decreases towards a specific value if the submergence ratio increases. Consequently, in case of variable discharge, imposing a temporally constant value of vegetation roughness results in overestimation or underestimation of flow resistance, leading to incorrect water level assessments and distorted flood wave in propagation studies.

In river floodplains, vegetation cover is not homogeneous and 1D hydraulic models that use a single roughness coefficient for each river component have to consider the contribution of the various vegetation types into an "overall roughness coefficient". Horton (1933) and Einstein (1934) suggest deriving a composite Manning coefficient by weighted averaging, i.e. by assigning a weight to each value of the roughness coefficient; the weight being proportional to the percentage of cross-sectional perimeter that pertains to the considered roughness. Similarly, Larsen et al. (2017) upscaled vegetated roughness coefficients over large vegetated areas by spatial averaging. With a different approach, Kim et al. (2012) upscaled roughness coefficients from high-resolution numerical simulations.

This paper presents the development of a simple method to derive the roughness coefficient of river floodplains covered by vegetation, represented in terms of Manning coefficient, for applications in 1D hydraulic models. The base algorithm is derived from Baptist's flow resistance formula for vegetated beds (Baptist, 2005), which provides the local Chézy coefficient for uniform vegetation. However, Baptist's approach is not easily applicable to 1D models, basically because of the assumption of uniform vegetation and because of its complexity. The water levels computed with the model are compared to the water levels computed with a well-calibrated 2D Delft3D model adopting Baptist's method on the Lunterse Beek, a small restored stream located in the Netherlands. (see Crosato and Samir Saleh, 2011, and Vargas-Luna et al., 2018). The results of the validation procedure show that the developed method improves the performance of 1D modelling when vegetated floodplains contribute to convey the river discharge.

2 BABTIST FORMULA

Treating aquatic plants as rigid cylinders, Baptist (2005) developed a formula to compute Chézy's coefficient for vegetated beds meant for applications in 2D models and valid for uniform dense vegetation. Like most existing methods, Baptist (2015) describes vegetation as a dense set of rigid cylinders, characterized by uniform diameter, height and (high) density, the latter defined as the number of stems per unit area. This approach, however, is not suitable for describing the effects of sparse vegetation, such as trees (Vargas-Luna et. al., 2015). Moreover, Boothroyd et al. (2016) recently demonstrated the importance of including the complex morphology of plants to model river flows. The performance of Baptist's formula was assessed by Vargas-Luna et al., (2015), who demonstrated that it is nevertheless able to describe the roughness exerted by different types of vegetation at several hydrodynamic conditions rather well.

Baptist's formula for the hydraulic resistance of flows with submerged vegetation reads:

$$C_r = \sqrt{\frac{1}{1/C_b^2 + C_D a h_v/2g}} + \frac{\sqrt{g}}{\kappa}\ln\left(\frac{h}{h_v}\right) \tag{1}$$

where C_r is the vegetated-bed roughness expressed as Chézy's coefficient ($m^{1/2}s^{-1}$), C_b is the Chézy coefficient of bare soil among the plants ($m^{1/2}s^{-1}$), C_D is the mean drag coefficient of vegetation (-), g is the acceleration due to gravity (ms^{-2}), h_v is the plant height (m), h is the local water depth (m), κ is the Von Kármán coefficient = 0.41 (-), and a is the projected plant area in the direction of water flow (m^{-1}), defined as $a = mD$, where m is the number of stems per bed surface area (m^{-2}) and D is the reference cylinder diameter (m). For herbaceous and marsh-type vegetation the projected plant area, a typically ranges between 0.1 and 1.0 m^{-1}; whilst for natural grass this parameter varies between 10 and 15 m^{-1}. Considering that the approach treats plants as rigid cylinders, Vargas-Luna et al. (2016) recommend using $C_D = 1$ for all vegetation types, including in the value of D (reference diameter) the effects of leaves and other irregularities. Equation 1 is valid only for submerged plants. For emergent vegetation, the part of the plants that contributes to increasing the flow resistance has height that is equal to the water depth ($h_v = h$ in Equation 1). In this case, Equation 1 simplifies to:

$$C_r = \sqrt{\frac{1}{1/C_b^2 + C_D ah/2g}} \tag{2}$$

If plants emerge, the water flows only between plants and not above plants. In this case, the flow resistance, strongly affected by plant drag, is expected to increase if the water depth increases. This behaviour is reproduced by Equation 2, for which the Chézy coefficient decreases if the water depth increases. For wide channels with uniform flow, the Manning roughness coefficient can be derived from Chézy's roughness coefficient as:

$$n = h^{1/6}/C_r \tag{3}$$

3 PROPOSED METHOD

3.1 *Vegetation roughness assessment*

The new algorithm to assess the Manning coefficient of vegetated beds is derived from Baptist's formula (Baptist, 2005). Analysing the form of Equations 1 and 2, it is possible to note that the soil roughness appears in the term $1/C_b^2$, which generally has a small value. This term becomes negligible for dense vegetation if compared to $C_D a h_v/2g$, showing that the characteristics of the soil between the plants hardly affect the roughness of densely vegetated beds. By neglecting this term and imposing C_D=1, Equation 1, valid for submerged vegetation, transforms in:

$$C_r = \sqrt{\frac{2g}{ah_v}} + \frac{\sqrt{g}}{\kappa}\ln\left(\frac{h}{h_v}\right) \tag{4}$$

The first term of Equation 4 is a constant that depends only on vegetation characteristics. This term coincides with the value of the Chézy coefficient of a vegetated bed if the plant submersion ratio is equal to 1 ($h = h_v$). The second term depends on submersion ratio. In case of submerged vegetation, the first term remains constant and for this it is named here "C_{Veg}". Equation 4 is then rewritten as:

$$C_r = C_{Veg} + \frac{\sqrt{g}}{\kappa}\ln\left(\frac{h}{h_v}\right) \tag{5}$$

Note that Eq. 5 is only valid if $h/h_v \geq 1$. In case of emerging vegetation, i.e. for $h/h_v < 1$, the entire water depth is filled by plants. In this case, neglecting the term $1/C_b^2$ and imposing C_D=1, Equation 2 simplifies to:

$$C_r = \sqrt{2g/ah} \tag{6}$$

Van Velzen et al. (2003), Baptist (2005) and Vargas-Luna et al., (2018) provide the characteristics of various types of vegetation. Imposing C_D=1, the values of D, m, a, h_v and C_{Veg} for typical floodplain vegetation are provided in Table 1 together with the corresponding Manning coefficient values suggested for HEC-RAS applications (Brunner, 2016), named n_{Min}, n_{Mean} and n_{Max}.

Table 1. Typical floodplain vegetation characteristics, C_{Veg} and Manning's reference values.

Vegetation Type	D	m	a	h_v	ah_v	C_{Veg}	n_{Min}	n_{Mean}	n_{Max}
	m	m^{-2}	m^{-1}	m	-	$m^{1/2}s^{-1}$	$m^{-1/3}s$	$m^{-1/3}s$	$m^{-1/3}s$
Garden grass	0.0045	3000	13.5	0.05	0.68	5.39	0.025	0.030	0.035
Natural grass	0.0054	4000	21.60	0.10	2.16	3.01	0.030	0.035	0.050
Softwood shrub	0.0510	3.8	0.19	6.0	1.16	4.11	0.070	0.100	0.160
Close shrub	0.0150	10.2	0.15	5.0	0.77	5.06	0.045	0.070	0.110
Reed	0.00828	80	0.6624	2.5	1.66	3.44	0.030	0.050	0.070
Herbaceous vegetation	0.0075	400	3.0	0.5	1.50	3.62	0.040	0.050	0.060
Pioneer vegetation	0.0054	50	0.27	0.15	0.04	22.01	0.010	0.020	0.030

After having derived the value of C_r, using either Equations 5 or 6, Equation 3 can be applied to derive the corresponding Manning roughness coefficient, but only if vegetation cover is homogeneous. This approach is thus suitable for implementation in 2D models, assigning to every grid cell the corresponding characteristics of vegetation (assumed uniform in each cell). Note that computing the value of vegetated bed roughness requires the knowledge of the local water depth, but this can only be computed if the roughness in known. Therefore, the application of the method requires a predictor-corrector method to compute the local water depth and vegetated bed roughness and this should be applied every time the hydraulic conditions change in a relevant way.

3.2 *Spatially variable vegetation*

Another issue to solve when representing floodplain vegetation in 1D models is the spatial variability of plants. To take this into account, we suggest using a composite Manning coefficient for each cross-section in a way that is similar to the one adopted in HEC-RAS. Horton (1933) and Einstein (1934) suggest subdividing each river cross-section perimeter in N parts, each one having uniform vegetation cover and deriving the composite Manning coefficient as follows:

$$n_c = \left[\sum_{i=1}^{N} \left(P_i n_i^{3/2} \right) \Big/ P \right]^{2/3} \tag{7}$$

where, n_c is the composite or equivalent Manning roughness coefficient ($m^{-1/3}s$), P is the wet perimeter of the entire river area (m), P_i is the wet perimeter of sub-area i (m), n_i is the Manning coefficient of the same sub-area i ($m^{-1/3}s$), and N is the number of sub-areas in which the cross-section is divided.

As spatially-variable vegetation cover is normally given in terms of surface area, we suggest referring to the floodplain surface instead of the wet perimeter, assumption that does not affect the physical meaning of the original formulation. Considering that each type of vegetation covers a certain percentage of the entire floodplain area and that all vegetation types together cover 100%, Equation 7 can be re-written as follows:

$$n_{cv} = \left[\sum_{i=1}^{N} V_i \left(\frac{\overline{h}^{1/6}}{C_{ri}} \right)^{3/2} \right]^{2/3} \tag{8}$$

where n_{cv} is the composite Manning coefficient of the vegetated floodplain ($m^{-1/3}s$) and $\overline{h}$ is the spatially-averaged water depth on the same floodplain (varying with time) (m). For each vegetation type, indicated by subscript i: V_i is the coverage percentage and C_{ri} is the specific Chézy coefficient, computed either with Equation 5 or 6, depending on the ratio $\overline{h} / h_{vi}$, where h_{vi} is the specific plant height (m). Note that using $\overline{h}$ corresponds to assuming quasi-horizontal floodplains in crossflow direction, since the approach neglects the topographic variations that cause water depth differences on floodplains. This assumption may thus result in errors in the local roughness assessment.

3.3 *Predictor-corrector approach*

Considering that the flow resistance of a vegetated bed depends on local water depth and vice versa, in case of variable discharge the computations of roughness coefficient and water depth should be conducted with a predictor-corrector approach. The iteration process should be repeated at each time step or every time there is a non-negligible change in hydraulic conditions. It proceeds as follows:

a) Imposes an initial roughness value (first time step), for instance the one obtained from the HEC-RAS manual table (n_0), or the roughness value derived at the previous time step (subsequent time steps).
b) Runs the model with the above roughness value to have a first assessment of spatially-averaged floodplain water depth h.
c) For each type of vegetation, indicated by subscript i, computes the submersion ratio h/h_{iv} and then C_{ri} with Equation 5 or 6.
d) For uniform vegetation cover: computes the Manning coefficient using Equation 3. For non-uniform vegetation cover: computes the composite Manning coefficient, taking into account the cover percentage and the submersion ratio of each vegetation type, using Equation 8.
e) Runs the model again using the computed Manning coefficient and repeats until the difference between the last computed average floodplain water depth and the previous one is smaller than a chosen value (for instance 5%).

The predictor-corrector procedure is not necessarily applied at every time step. In particular, when the discharge is slowly varying with small water depth variations. This should be established by the user, based on required level of accuracy.

4 APPLICATION

The proposed method is here applied to the Lunterse Beek, a small stream located in the Netherlands using HEC-RAS. Figure 1 shows the pre- and post- restoration planform of this lowland stream. The results are then compared to those obtained using the current approach.

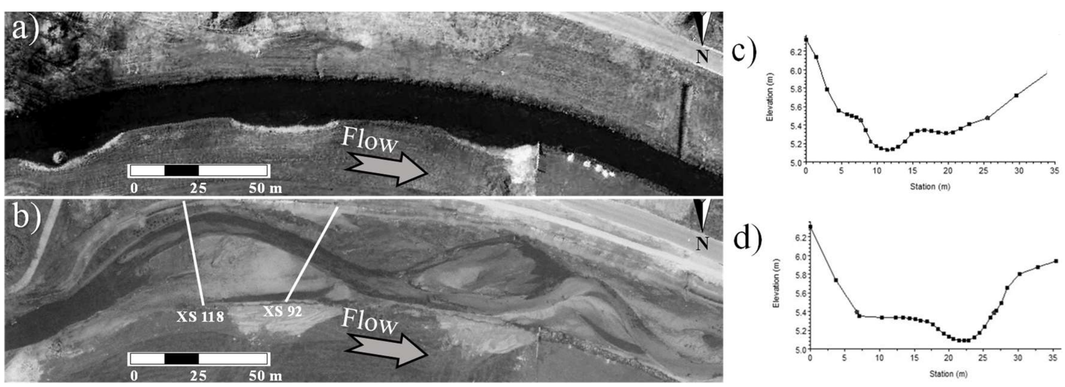

Figure 1. Restored reach of the Lunterse Beek seen from a drone in a) September 2011; b) January 2012. Testing cross-sections indicated in b) with a white line are shown in: c) XS 92 and d) XS 118 (levels are given in m above NAP).

The Lunterse Beek is a small rain-fed stream located in the central part of the Netherlands with a catchment area of 63.6 km^2 and a mean flow discharge of 0.36 m^3s^{-1}. The maximum measured historical flow is about 7 m^3s^{-1} (return period of about 100 years). A reach of this low-land stream, located near Renswoude, has undergone a restoration process since 2011, which basically consisted in bank and floodplain lowering and channel re-meandering. During the restoration works, vegetation was removed from the old floodplains and was later allowed to colonize the lowered floodplain areas. The records of temporal variation of vegetation cover after restoration, the availability of hydrological information and the detailed bed and water level measurements carried out in the framework of previous studies (e.g. Eekhout et al., 2014; Vargas-Luna et al., 2018) allow analysing different conditions.

The reference period for this study is the second half of 2015, four years after restoration, when the river main channel had a width of 5-6 m, a bankfull depth of 0.5-0.6 m and a longitudinal slope of 0.05%. Note that these characteristics were found to slightly vary throughout the year in response to seasonal variations of discharge and vegetation (Vargas-Luna et al., 2018). In 2015, the floodplains of the Lunterse Beek were covered by two types of vegetation: natural grass, covering 6% of the floodplain surface, and herbaceous vegetation, covering 94%.

We developed a HEC-RAS model covering a 250 m long part of the restored reach for which field measurements of floodplain vegetation cover and discharge time series are available. In the model, the study reach is subdivided in thirty cross sections, all presenting floodplains and main channel. The upstream boundary conditions consisted in a daily discharge time series covering the period August-December 2015 and the downstream boundary conditions were given by the corresponding water levels at the end of the model domain. Water level series at different locations in the study area were derived from a 2D model built in Delft3D (https://oss.deltares.nl/web/delft3d) computing the roughness of vegetation with Baptist's approach. This 2D model was calibrated and validated on measured data, as described in Vargas-Luna et al. (2018).

HEC-RAS model calibration was carried out optimising the model performance for the period August 2015 to December 2015, period characterized by floodplain inundation. The calibration parameter was the Manning coefficient describing the main channel bed roughness, which was finally set to a value of 0.035 $m^{-1/3}s$, whereas the values of vegetation roughness were not calibrated. The suggested values of n_{Mean} (Table 1) according the current HEC-RAS approach, based on Chow (1959) are: 0.05 $m^{-1/3}s$ for herbaceous vegetation and 0.035 $m^{-1/3}s$ for natural grass. To apply the proposed method to the Lunterse Beek, an initial composite floodplain roughness coefficient equal to n = 0.05 $m^{-1/3}s$ was assigned to all cross sections. This value was derived as composite roughness coefficient for 94% herbaceous vegetation and 6% grass. Starting from this value, the roughness was then derived using the predictor-corrector approach described in Section 3.3. Figure 2 shows the time series of the computed water levels and computed vegetation roughness, expressed as Manning coefficients, for cross-section 118 (location in Figure 1b). The horizontal lines indicate the relative levels of floodplain bed and plant tops. The computed roughness of each vegetation type is shown to change with time due to its dependency on floodplain water depth. This is particularly relevant for the dominant herbaceous vegetation.

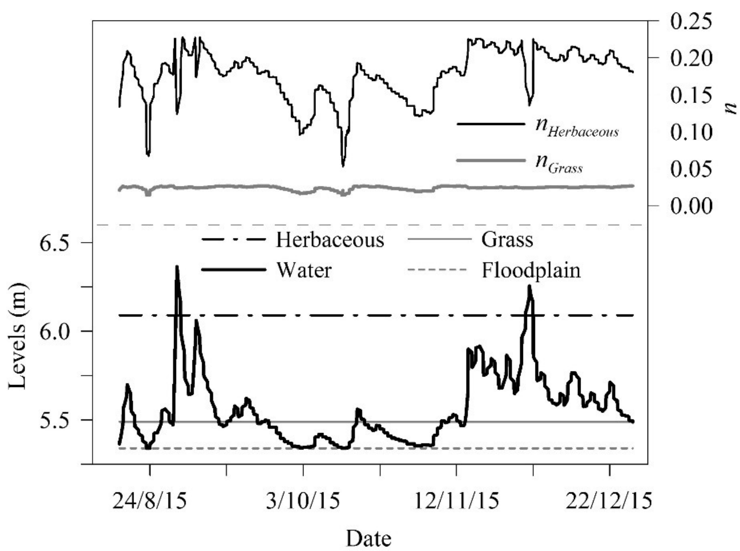

Figure 2. Roughness variation for herbaceous and grass vegetation as a function of time at cross-section 118 of the Lunterse Beek. Water levels correspond to the "Reference water levels", obtained from the calibrated 2D model setup in Delft3D (levels are given in m above NAP).

Figure 3 shows the results obtained using the calibrated model with the current HEC-RAS approach (grey line) and with the proposed approach (red line) at the end of the first iteration. Both cross-sections, 92 and 118, present the same tendency. The water levels computed with the proposed approach present a noticeable improvement, resulting in higher values of correlation coefficient, *r*, for moderate flow conditions: 0.977 against 0.938 for cross-section 92 and 0.964 against 0.922 for cross-section 118. No improvement is detected for high discharge conditions: 0.985 vs. 0.986 for cross-section 92 and 0.977 vs. 0.980 for cross-section 118. A clear quantitative improvement can be also observed by comparing the root mean square errors. As expected, the improvement is more noticeable for the moderate discharge conditions (average reduction of *RMSE* of about 75%), while an average reduction of RMSE of about 40% is obtained for the high discharge conditions. Although there are still some differences with the reference water levels, it is possible to see the potential of the proposed method.

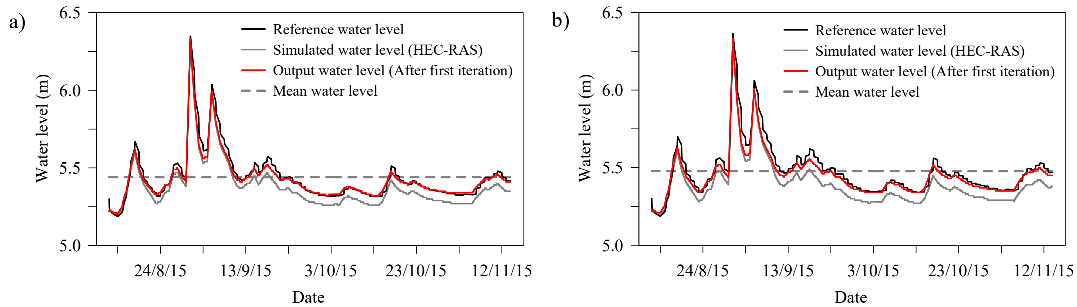

Figure 3. Water level profile comparison after one iteration of the proposed method at a) Cross-section 92, and b) Cross-section 118. "Reference water level" (black line) refers to the values computed for the same cross-sections with the Delft3D model (levels are given in m above NAP).

5 CONCLUSIONS

Currently, 1D models consider the hydraulic effects of river floodplain vegetation by simply increasing the local bed roughness, without considering the dependency of the roughness exerted by vegetation on water depth. This affects model outputs, reducing accuracy in flood level assessments. In this study, we show that the dependency of vegetation roughness on local water depth is indeed important for the assessment of flood water levels, particularly for high flows resulting in plant submersion ratios below 5. For this reason, a constant roughness coefficient should not be assigned to vegetated floodplains, in particular for simulating flood wave propagation and flood mapping.

A new approach taking into account the effects of plant submersion is therefore proposed for implementation in 1D models. It is based on the application of an algorithm derived from the one developed by Baptist (2005), which was meant for applications in 2D models. 1D models do not allow for spatially-varying characteristics in cross-flow direction, as 2D models do. For this, 1D models apply a single value of flow resistance to each component of the river. In HEC-RAS, for instance, three river components are considered: main channel, right floodplain and left floodplain. To take into account the presence of various types of vegetation on the river floodplains, a composite Manning roughness coefficient is therefore derived as a function of cover percentage, under the assumption of relatively flat floodplains. The new approach requires a predictor-corrector procedure, because bed roughness and water depth affect each other. The iterative procedure is particularly important for strongly varying discharge.

A final point of attention regards the need for iterations. 1D models are especially applied for their short computational times and the application of the proposed method could increase them to an undesirable level. In the two applications carried out in the framework of this study one iteration was enough. Moreover, the iteration was not necessary at every time step. In general, it is not necessary when the flow is slowly varying, resulting in small temporal differences in water depth. In this case, the value of roughness coefficient computed at the previous time step might still result in acceptable predictions. Optimization of computational time should therefore include a check to be applied at every time step, based on users' requirements, to establish whether the iteration is needed or not.

Notwithstanding the shortcomings listed above, the first positive results are encouraging, since they show the potentiality of the method in improving water level predictions of 1D models during floods.

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