Mean Velocity Predictions in Vegetated Flows

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ABSTRACT

Vegetation plays an important role in influencing the hydrodynamic behavior, ecological equilibrium and environmental characteristics of water bodies. Several previous models have been developed, to predict hydraulic conditions in vegetated rivers, but only few are actually used in practice. In this paper six analytic models derived for submerged vegetation are compared and evaluate: Klopstra et al. (1997); Stone and Shen (2002); Van velzen (2003); Baptist et al. (2007); Huthoff et al. (2007) and Yang and Choi (2010). The evaluation of the flow formulas is based on the comparison with experimental data from literature using the criteria of deviation. Most descriptors show a good performance for predicting the mean velocity for rigid vegetation. However, the flow formulas proposed by Klopstra et al. (1997) and Huthoff et al. (2007) show the best fit to experimental data. Only for experiments with low density, these models indicate an underestimation. Velocity predicted for flexible vegetation by the six models is less accurate than the prediction in the case of rigid vegetation.

Keywords: Mean velocity; Vegetation; Analytic models; Measured data; Performance; Underestimation.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>solid angle</td>
</tr>
<tr>
<td>a</td>
<td>density of elements in the canopy</td>
</tr>
<tr>
<td>aν</td>
<td>integration constant</td>
</tr>
<tr>
<td>CD</td>
<td>drag coefficient</td>
</tr>
<tr>
<td>CP</td>
<td>turbulent intensity, height-averaged over vegetation height</td>
</tr>
<tr>
<td>C3</td>
<td>constant in Klopstra et al. (1997) model</td>
</tr>
<tr>
<td>Cu</td>
<td>constant in Yang and Choi (2010) model</td>
</tr>
<tr>
<td>D</td>
<td>diameter of plant stems</td>
</tr>
<tr>
<td>d</td>
<td>zero-plane displacement</td>
</tr>
<tr>
<td>E</td>
<td>the mean error</td>
</tr>
<tr>
<td>Fd</td>
<td>drag force</td>
</tr>
<tr>
<td>g</td>
<td>acceleration due to gravity</td>
</tr>
<tr>
<td>h</td>
<td>water depth</td>
</tr>
<tr>
<td>hp</td>
<td>vegetation height</td>
</tr>
<tr>
<td>hν</td>
<td>distance between the vegetation top and the surface layer virtual bed</td>
</tr>
<tr>
<td>i</td>
<td>energy gradient</td>
</tr>
<tr>
<td>Kr</td>
<td>roughness height</td>
</tr>
<tr>
<td>L</td>
<td>length scale</td>
</tr>
<tr>
<td>l</td>
<td>mixing length</td>
</tr>
<tr>
<td>l*</td>
<td>submergence ratio</td>
</tr>
<tr>
<td>m</td>
<td>density of vegetation</td>
</tr>
</tbody>
</table>

MAE mean absolute error  
RMSE mean square error  
R² coefficient of determination  
s separation between individual resistance elements  
u(z) vertical velocity  
u* shear velocity  
u0 characteristic constant flow velocity in non-submerged vegetation  
U1 mean velocity flow inside the vegetation  
U2 mean velocity flow above the vegetation  
U average velocity over the total depth  
UC the maximum velocity in the vegetation layer  
z0 length scale for bed roughness of the surface layer  
z the vertical coordinate  
α closure parameter  
κ Von Karman’s constant (0.41)  
τ(z) the shear stress  
τb the bed shear stress  
ρ the density of water  
σ the standard deviation of the mean error

1. INTRODUCTION

The presence of vegetation affects stream process may change the river hydraulic conditions, the morphology, as well as the local fine sediment deposition; it may have significant influence on the
overall discharge capacity of a river and may increase flood risks (Wu and He, 2009; Liu and Shen, 2008; Gharbi et al., 2014). The vegetation occurs under different forms within rivers and flood plains; it can be flexible or rigid and submerged or emergent in flows. The drag on vegetation increased overall flow resistance and reduced the shear stress. Therefore, it’s important to have suitable prediction of increased resistance caused by vegetation to control floods and the ecosystem of the stream and to understand the processes that contribute to velocity distributions (Yang and Choi, 2010; Katul et al., 2011; Huthoff et al., 2007; Nepf, 2012).

The mean velocity may be useful in the estimation of shear velocities and the bed shear stresses. These parameters are key factors in estimating the bed load transport and the related scour, deposition, entrainment and bed changes in rivers. Velocity distribution is related directly to the bed shear stress for non-vegetated flow; while, for vegetated flow, it’s related to the vegetation drag because the vegetation roughness is much larger than the river bed roughness (Samani and Mazaheri, 2009; Wu and He, 2009). Due to the importance of vegetation resistance in rivers, many studies have been devoted to this topic over the last decades. As a result, different experiments in laboratory flumes have been carried out (Shimizu and Tsujimoto, 1994; Lopez et Garcia, 2001; Tsujimoto et al, 1993; Jarvela, 2005) and several vegetation-resistance methodologies have been proposed to model the effects of vegetation on open-channel flow (Augustijn et al., 2011, Morri et al., 2015). Such relations exist that relate the average flow velocity to the hydraulic roughness (Chézy, 1769; Darcy-weisbach, 1845; Manning, 1889; Strickler, 1923; Keulegan, 1938). These equations are widely used in hydraulic engineering and surface hydrology, especially in the context of flood routing (Katul et al., 2011). They were originally derived to describe the roughness of bottom and side walls, and they were not derived to describe the complex interactions of vegetation with flow (Huthoff et al., 2007). Traditional descriptors were used for predicting the losses of the flume and didn’t include shape drag. That’s why constant roughness parameter is not useful for describing vegetation resistance; except for a very large submergence ratio, vegetation could be calculated with a constant roughness coefficient (Augustijn et al., 2008). In addition, many experimental studies of vegetation related resistance to flow have shown that detailed plant characteristics may have important influences on flow resistance. Therefore, newly approaches have been derived based on vegetation characteristics (vegetation height \(h_p\), density of vegetation \(m\), diameter of plant stems \(D\), drag coefficient \(C_D\)), instead of using a constant roughness coefficient using analytical models. These approaches, account for the turbulence caused by surface properties, geometrical boundaries, obstructions and other factors causing losses (Huthoff et al., 2007). Most of these relationships adopted a two-layer model (Klopstra et al., 1997; Stone and Shen, 2002; Van velzen, 2003; Baptist et al., 2007; Huthoff et al., 2007; Yang et Choi, 2010). In this approach, the flow domain was divided into two layers, a “vegetation layer” through the vegetation and “the surface layer” above it (Fig.1). The flow in each of the two layers was described separately. The logarithmic flow velocity profile is adopted for solving the velocity above the vegetation, and the momentum equation within the vegetated layer. The continuity of the velocity and the shear stress between the two layers is ensured by boundary conditions at the interface. The average velocity \((U)\) over the total depth is given by combination between the mean velocity flow inside \((U_i)\) and above the vegetation \((U_d)\) (Klopstra et al., 1997; Huai et al., 2009; Jarvela, 2005).

![Fig. 1. Velocity profile within and above vegetation (Augustijn et al., 2011).](image)

However, the wide variety of vegetation types and hydrodynamic conditions considered in these works make it difficult to compare results and draw general conclusions useful in the in practice (Augustijn et al., 2011). In this context, this study aims to understand and determine the range of validity and applicability of some analytical models (Van Velzen et al., 2003, kloprsa et al., 1997, Stone and Shen, 2002, and Huthoff et al., 2007, Yang and Choi, 2010) and select the most adequate for predicting the mean flow velocity through submerged vegetation. These models are validated using measurement data in flume with flexible and rigid vegetation.

2. Analytical Models Description

2.1 Klopstra et al. (1997) Model

Kolpstra et al. (1997) proposed an analytical expression for the velocity distribution. This method based on the momentum equation for the vegetation layer assuming uniform steady flow and using the Boussinesq concept, to describe the shear stress.

\[
\frac{\partial \tau}{\partial z} = F_D(z) - \rho g
\]  

(1)

where \(\tau(z)\) is the shear stress, \(\rho\) is the density of water, \(z\) is the vertical coordinate, \(g\) is the
acceleration gravity, \( i \) is the energy gradient and \( F_D \) is the drag force determined by the following expression:

\[
F_D(z) = \frac{1}{2} \rho m D C_a u(z)
\]  
\[ (2) \]

With \( m \) is the density of vegetation (\( m^{-2} \)), \( D \) is the diameter of plant stems (\( m \)), \( C_D \) is the drag coefficient and \( u(z) \) is the vertical velocity (\( m/s \)).

Using the Boussinesq concept, the shear stress, can be described by the following expression:

\[
\tau(z) = \rho u(z) \frac{\partial u(z)}{\partial z}
\]  
\[ (3) \]

\( \alpha \) is the turbulent length scale derived from experimental data. Klopstra et al. (2007) proposed the following expression to determine this parameter:

\[
\alpha = 0.079 h_p \ln \left( \frac{h}{h_p} \right) - 0.0009
\]  
\[ (4) \]

\( h \) is the water depth (\( m \)) and \( h_p \) is the vegetation height (\( m \)).

Then, the momentum equation (1) becomes:

\[
u(z) \frac{\partial^2 u(z)}{\partial z^2} + \left( \frac{\partial u(z)}{\partial z} \right)^2 = \frac{m D C_a u(z)^2}{2 \alpha} \cdot \frac{\partial u(z)}{\partial z} - \frac{g i}{\alpha}
\]  
\[ (5) \]

The analytic solution of this momentum equation gives the velocity distribution in the vegetated layer. The bottom shear stress is neglected behind the vegetation shear stress.

In the surface layer, the velocity follows a logarithmic profile that was derived using Prandtl’s mixing length theory. The connection between the boundary conditions at the interface ensures the continuity of the velocity and the shear stress between the two layers, allows the determination of the logarithmic law parameters and the mean velocity in the surface layer:

\[
u(z) = \frac{u_0}{k} \ln \left( \frac{z - (h_p - h)}{z_0} \right)
\]  
\[ (6) \]

\( k \) is Von Karman’s constant (0.41), \( h \) is the distance between the vegetation top and the surface layer virtual bed (\( z_0 < h < h_p \)), \( z_0 \) is the length scale for bed roughness of the surface layer (\( m \)) and \( u_0 \) is the virtual bed shear stress.

The average velocity over the total depth \( (U) \) is given by combination between the mean velocity flow inside \( (U_1) \) and above the vegetation \( (U_2) \):

\[
U = \frac{h_k}{h} U_1 + \frac{h - h_k}{h} U_2
\]  
\[ (7) \]

Klopstra et al. (1997) determined the total average velocity through submerged vegetation and it is given by the following expression:

\[
U = \frac{U_1}{1 - D \sqrt{m}}
\]  
\[ (16) \]

Substituting equations (12) and (15) in equation (11) and neglecting the bed shear stress gives the expression of the mean velocity in the vegetation layer:
\[ U_i = U_0 \sqrt{l - D^2} \left( \frac{h_0 - 1}{4} \pi D^2 \right) \]  
\hfill (17)

The total average velocity (\( U \)) over the total depth:

\[ U = U_i \frac{h}{h_0} \]  
\hfill (18)

Then, it’s given by the following expression:

\[ U = \alpha_0 \sqrt{l - D^2} \left( \frac{h_0 - 1}{4} \pi D^2 \right) \frac{h}{h_0} \]  
\hfill (19)

### 2.3 Van Velzen (2003) Model

In the vegetation layer, Van velzen (2003) assumed uniform velocity which is unaffected by the surface layer flow (Gualtieri and Mihailovic, 2012). The forces acting on the flow are the shear stress and drag forces on the plants. The sum of these forces in the streamwise direction is equal to zero because the bed shear stress is neglected and the following equation is derived:

\[ \rho gh h U p + 1 = 0 \]  
\hfill (20)

\( F_D \) is the drag force, which can be expressed as:

\[ F_D = \frac{1}{2} \rho \alpha_0 m D U_i \]  
\hfill (21)

Substitution of equation (21) in equation (20) and solving it for \( U_1 \) gives the velocity inside the vegetation:

\[ U_i = U_0 \sqrt{l} \]  
\hfill (22)

The flow in the surface layer is described by a logarithmic term:

\[ U = U_1 + 18 \sqrt{h - h_0} \log \left( \frac{12(h - h_0)}{k_z} \right) \]  
\hfill (23)

Then the total average velocity through submerged vegetation is given by the following expression:

\[ U = U_1 + 18 \sqrt{h - h_0} \log \left( \frac{12(h - h_0)}{k_z} \right) \]  
\hfill (24)

\( K_z \) is the roughness height and it’s given by the empirical function:

\[ K_z = 1.6 h_i^{0.7} \]  
\hfill (25)

### 2.4 Baptist et al. (2007) Model

Baptist et al. (2007) model is based on an analytical solution of the momentum balance of flow through and over vegetation, using the Boussinesq’s eddy viscosity approach and the mixing-length theory.

The expression of the velocity in the vegetation layer is given by:

\[ U_i = \frac{1}{h_i} \left[ \frac{2(u(h_i) - (u_{0v} + u_{0v}^*) \left( \frac{(h - h_i)}{h_i} \right)}{u_{0v} + u_{0v}^*} \left( \frac{(h - h_i)}{h_i} \right)} \right] \]  
\hfill (26)

\( L \) is the length scale (m), \( a_i \) is the integration constant.

\[ L = \frac{C_p l}{C_0 m D} \]  
\hfill (27)

\[ a_i = \frac{2 \pi (h - h_0)}{C_i \exp \left( \frac{h_0}{l} \right)} \]  
\hfill (28)

The coefficient \( C_p \) is the turbulent intensity, height – averaged over the vegetation height and \( l \) is the mixing length.

For the surface layer, Prandtl’s mixing length concept is adopted, and the mean velocity is given by the following expression:

\[ U_z = \sqrt{\frac{C_p l}{C_0 m D}} \left( \frac{(h - h_i)}{h_0} \right) \log \left( \frac{h - d}{z_0} \right) + \left( \frac{h - d}{z_0} \right) \]  
\hfill (29)

Where \( d \) is the zero-plane displacement (m), which is located at distance from the bed inside the vegetation.

The total average velocity is given by the following expression:

\[ U = \sqrt{\frac{2 \pi (h - h_0)}{C_i \exp \left( \frac{h_0}{l} \right)}} \left( \frac{(h - h_i)}{h_0} \right) \log \left( \frac{h - d}{z_0} \right) + \left( \frac{h - d}{z_0} \right) \]  
\hfill (30)

### 2.5 Huthoff et al. (2007) Model

Huthoff (2007) derived an analytical expression for the velocity flow through and over vegetation by describing the flow by its bulk behavior to avoid the necessity of integration over depth and the associated complications of depth-dependent turbulence intensities.

In the vegetation layer, the mean velocity is given by the following expression:

\[ U_i = \sqrt{\frac{U_i}{h_i}} \]  
\hfill (31)

In the upper layer, using assumption scaling the velocity is given by the following equation:

\[ U_z = \sqrt{\frac{(h - h_i)^{2 + (1/k_z)}}{s}} \]  
\hfill (32)

With, \( s \) is the separation between individual
resistance elements:

\[ s = \frac{1}{\sqrt{m}} - D \]  

(33)

The expression for the average velocity of the entire flow depth becomes:

\[ U = U_s \sqrt{\frac{h_p}{h}} \left( \frac{h}{h} + \frac{h - h_s}{h} \right) \left( \frac{2}{2} \right)^{1/2} \]  

(34)

2.6 Yang et Choi (2010) Model

Yang and Choi (2010) used the two layer approach to determine the velocity profile. The velocity is assumed to be uniform in the vegetation and it has been determined by applying a momentum balance. In the upper layer, the velocity profile follows a logarithmic distribution.

The equation of the velocity in the vegetation layer \((U_1)\) is given by:

\[ U_1 = U_s \sqrt{\frac{h}{h_v}} \]  

(35)

In the upper layer, the expression of the velocity \((U_2)\) is given by:

\[ U_2 = U_1 + \frac{C_u u_0}{\kappa} \left( \frac{h}{h_v} \right) \ln \left( \frac{h}{h_v} \right) - 1 \]  

(35)

With \(u_0\) is the shear velocity.

The average velocity over the total depth \((U)\) is given by combination between the mean velocity flow inside \((U_1)\) and above the vegetation \((U_2)\):

\[ U = \frac{C_u u_0}{\kappa} \left( \ln \left( \frac{h}{h_v} \right) - \left( \frac{h - h_s}{h} \right) \right) + U_s \]  

(36)

\(\kappa\) is Von Karman’s constant \((0.41)\) and \(C_u\) is a constant where:

\( C_u=1 \) for \( a \leq 5 \) \( m^1 \)  

(37)

\( C_u=2 \) for \( a > 5 \) \( m^1 \)  

(38)

\( a\) is the density of elements in the canopy \((m^1)\) which is described by the frontal area per canopy volume.

3. ANALYTICAL MODELS EVALUATION

The use of experimental data flume available in the literature (Table 1, 2), concerning the free surface flow in presence of vegetation (rigid and flexible), allows the verification of the validity and the ability of these models in predicting the mean velocity.

For flexible vegetation, the average deflected height is taken in some experiments (Kouwen et al., 1969; Murota et al., 1984; Tsujimoto et al., 1993; Tsujimoto et al., 1991; Ikeda et kanazawa, 1996; Jarvela, 2003; Carollo et al., 2005). However, others authors used the erected height of vegetation (Ree and Crow, 1977; Meijer, 1998 (a); Yang and Choi, 2009).

The bed roughness was assumed negligible in the experiments.

The drag coefficient used is these experiments, is defined by different ways:

Some authors used an equation depending on the Reynolds number (Rowinski et al., 2002; Poggi et al. 2004)

Other calculated the drag value based on Petryk and Bosmajian (1975) equation (Meijeri, 1998 (a,b); Tsujimoto et al.,1993) and the bed shear stress (Stone and Shen, 2002).

The equation of Petryk and Bosmajian (1975) is given by the following expression:

\[ U = \sqrt{\frac{2g}{C_o mD_0}} \]  

(39)

Lopez and Garcia (1997, 2001), Yang and Choi (2009), used a constant value based on experiments done by Dunn et al., 1997.

Murphy et al. (2007) assumed a drag coefficient varied with depth and used the average value. Others, use a constant value and they didn’t mention how they derived a value for the drag coefficient (Tsujimoto and Kitamura, 1990; Einstein and Banks, 1950; Kouwen et al. (1969); Murota et al.,1984; Murota et al.,1984 and Tsujimoto et al.,1991).

When no drag coefficient was given by authors (Ree and Crow, 1977; Ikeda and kanazawa, 1996; Jarvela, 2003; Carollo et al., 2005) a value of 1 was assumed.

The Drag coefficient of flexible vegetation is not constant due to the bending of vegetation. It decreases when the vegetation is deflected. For rigid emergent vegetation, a constant value is expected. However, for submerged vegetation, the average drag coefficient is used.

The verification of the performance of these six descriptors for predicting the mean velocities is determined due to a comparison between the measured and simulated velocities using the criteria of deviation (the mean error \(E\), the Mean Absolute Error (MAE), the Root-Mean Square Error (RMSE), the Coefficient of determination \((R^2)\) and the standard deviation of the mean error \((\sigma)\).

\[ E = \frac{1}{N} \sum_{i=1}^{N} (\text{measured}_{value} - \text{calculated}_{value}) \]  

(40)

\[ \text{MAE} = \frac{1}{N} \sum_{i=1}^{N} \left| \text{measured}_{value} - \text{calculated}_{value} \right| \]  

(41)

\[ \text{RMSE} = \frac{1}{N} \sqrt{\sum_{i=1}^{N} (\text{measured}_{value} - \text{calculated}_{value})^2} \]  

(42)

\[ \sigma = \frac{1}{N} \sqrt{\sum_{i=1}^{N} (\text{measured}_{value} - \text{calculated}_{value} - E)^2} \]  

(43)
Table 1 Experiments data used for verification the performance of the models in the prediction the mean velocity in the case of rigid vegetation

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Nombre of experiments</th>
<th>Vegetation characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lopez and Garcia (1997)</td>
<td>6</td>
<td>h_v(m) 0.07-0.14, D(m) 0.0064, m (m^2) 42-388, C_D 1.13</td>
</tr>
<tr>
<td>Lopez and Garcia (2001)</td>
<td>12</td>
<td>h_v(m) 0.12, D(m) 0.0064, m (m^2) 42-384, C_D 1.13</td>
</tr>
<tr>
<td>Tsujimoto and Kitamura (1990)</td>
<td>8</td>
<td>h_v(m) 0.045, D(m) 0.0015, m (m^2) 2500, C_D 1.46</td>
</tr>
<tr>
<td>Meijeri (1998 b)</td>
<td>36</td>
<td>h_v(m) 0.9-1.5, D(m) 0.008, m (m^2) 64-256, C_D 0.96-1</td>
</tr>
<tr>
<td>Einstein and Banks (1950)</td>
<td>20</td>
<td>h_v(m) 0.038, D(m) 0.0064, m (m^2) 3-108, C_D 1.4</td>
</tr>
<tr>
<td>Stone and Shen (2002)</td>
<td>92</td>
<td>h_v(m) 0.124, D(m) 0.0127, m (m^2) 481, C_D 1.11</td>
</tr>
<tr>
<td>Poggi et al. (2004)</td>
<td>5</td>
<td>h_v(m) 0.12, D(m) 0.004, m (m^2) 67-1072, C_D 1.5</td>
</tr>
<tr>
<td>Murphy et al. (2007)</td>
<td>24</td>
<td>h_v(m) 0.07-0.139, D(m) 0.006, m (m^2) 250-800, C_D 0.61-1</td>
</tr>
</tbody>
</table>

Table 2 Experiments data used for verification of the models in the prediction of the mean velocity in the case of flexible vegetation

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Nombre of experiments</th>
<th>Vegetation characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kouwen et al. (1969)</td>
<td>27</td>
<td>h_v(m) 0.05-0.1, D(m) 0.005, m (m^2) 5000, C_D 3</td>
</tr>
<tr>
<td>Ree and Crow (1977)</td>
<td>30</td>
<td>h_v(m) 0.2-0.3, D(m) 0.005, m (m^2) 1076-1464, C_D 1</td>
</tr>
<tr>
<td>Murota et al. (1984)</td>
<td>8</td>
<td>h_v(m) 0.048-0.06, D(m) 0.00024, m (m^2) 4000, C_D 2.75</td>
</tr>
<tr>
<td>Tsujimoto et al. (1993)</td>
<td>12</td>
<td>h_v(m) 0.06, D(m) 0.00062, m (m^2) 10000, C_D 2</td>
</tr>
<tr>
<td>Tsujimoto et al. (1991)</td>
<td>8</td>
<td>h_v(m) 0.02-0.04, D(m) 0.0015, m (m^2) 2500, C_D 3.14</td>
</tr>
<tr>
<td>Ikeda and kanazawa (1996)</td>
<td>7</td>
<td>h_v(m) 0.04, D(m) 0.00024, m (m^2) 20000, C_D 1</td>
</tr>
<tr>
<td>Meijer (1998 a)</td>
<td>7</td>
<td>h_v(m) 1.55-1,65, D(m) 0.0057, m (m^2) 254, C_D 1.81</td>
</tr>
<tr>
<td>Rowinski et al. (2002)</td>
<td>8</td>
<td>h_v(m) 0.165, D(m) 0.000825, m (m^2) 2500-10000, C_D 1.22-1.35</td>
</tr>
<tr>
<td>Jarvela (2003)</td>
<td>12</td>
<td>h_v(m) 0.15-0.29, D(m) 0.0028, m (m^2) 512-12000, C_D 1</td>
</tr>
<tr>
<td>Carollo et al. (2005)</td>
<td>80</td>
<td>h_v(m) 0.04-0.08, D(m) 0.0045, m (m^2) 28000-44000, C_D 1</td>
</tr>
<tr>
<td>Yang and Choi (2009)</td>
<td>5</td>
<td>h_v(m) 0.035, D(m) 0.0002, m (m^2) 1400, C_D 1.13</td>
</tr>
</tbody>
</table>

3.1 Analytical Models Compared with Data of Rigid Vegetation

The comparison between the measured and simulated mean velocities by different analytical models using data of rigid vegetation is summarized in the table 3.

A High value of R^2 and a low value of MAE, RMSE and σ indicate the good performance of the model. Most descriptors show a good performance in this case. However, Baptist et al. (2007) model performs less well, with a low value of R^2 (26 %) and High value of (MAE, RMSE and σ). The model of Huthoff et al. (2007) and Klopstra et al. (1997) show the best agreement with a high coefficient of determination (80%).

The difference between the models depends on the transition of the velocity in the vegetation layer and the surface layer.

Baptist et al. (2006), Van Velzen et al. (2003), Stone and Shen (2002) and Yang and Choi (2010) assume a constant velocity over the depth in the vegetation layer neglecting the influence of the higher velocities in the vegetation layer.

Van Velzen et al. (2003) defined the velocity in the surface layer, by an empirical roughness height used in the Keulegan equation. Baptist et al. (2006) used simulated data to find an equation for the surface layer, by genetic programming. Stone and Shen (2002) model differs from the method of Baptist et al. (2006) and Van Velzen (2003) by the using of the solidity and they define the relation between the velocity in the vegetation layer, and the mean velocity over the entire depth.

In fact, the velocity profile at the top of the vegetation is needed to define the velocity profile in the surface layer because between these two layers the turbulence is the highest, due to the difference in velocity. That’s why the theoretical background
of the descriptions of Klopstra et al. (1997) and Huthoff (2007) is most realistic, because they describe the mean velocity taking the interaction between the vegetation layer and surface layer into account. Klopstra et al. (1997) used the turbulent length-scales to define the energy exchange between the two layers. Huthoff (2007) used scaling considerations of the bulk flow field to avoid complications associated with smaller scale flow processes. Therefore, the theoretical soundness of these descriptions is better than the other descriptions.

Table 3 Mean velocities calculated by analytic models compared to the mean velocities measured with data of rigid vegetation

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>σ (m/s)</th>
<th>MAE (m/s)</th>
<th>RMSE (m/s)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klopstra et al. (1997)</td>
<td>0.148</td>
<td>0.073</td>
<td>0.148</td>
<td>0.793</td>
</tr>
<tr>
<td>Huthoff and al (2007)</td>
<td>0.127</td>
<td>0.068</td>
<td>0.132</td>
<td>0.816</td>
</tr>
<tr>
<td>Van Velzen (2003)</td>
<td>0.223</td>
<td>0.128</td>
<td>0.252</td>
<td>0.774</td>
</tr>
<tr>
<td>Yang and Choi (2010)</td>
<td>0.234</td>
<td>0.092</td>
<td>0.235</td>
<td>0.714</td>
</tr>
<tr>
<td>Stone and Shen (2002)</td>
<td>0.376</td>
<td>0.138</td>
<td>0.380</td>
<td>0.691</td>
</tr>
<tr>
<td>Baptist and al (2007)</td>
<td>3.039</td>
<td>0.529</td>
<td>3.079</td>
<td>0.260</td>
</tr>
</tbody>
</table>

Mean velocity calculated by Klopstra et al. (1997) and Huthoff et al. (2007) show a reasonable agreement with data of rigid vegetation.

The differences between the performances of the two remaining descriptors are small. However, these models, indicate an under estimation of Einstein and Banks (1950) data. This experiment used very sparse vegetation (2.7-108 m²), however, for sparse vegetation, bed roughness becomes higher and has an effect on the flow. In this case, this parameter shouldn’t be neglected. That could explain the deviation between the measured and calculated velocities spatially for higher velocities.

In general, river models are used to set a safety standard, so, it’s very important that a method can predict higher velocities as accurate as possible. Therefore, graphs are presented with the mean error between the predicted and measured velocities for each model to investigate under which circumstances the model shows the largest/smallest errors (Fig. 4).

For smaller velocities, more data sets were available. However, the difference in performance of the different descriptors is small. For higher velocities, the prediction of the mean velocities by the different models indicates an under-estimation or over-estimation and the error is often greater than 0.1 m/s in this case, spatially for the velocities measured by Meijeri (1998 b); Einstein and Banks and Poggi et al. (2004). These experiments are done with sparse vegetation; however, the descriptors are validated for dense vegetation neglecting the bed shear stress effect, which can be the main raison of this deviation between the measured and calculated velocities.

The model of Huthoff et al. (2007) shows the smallest error in the prediction of the average velocities.

In general, the comparison between the measured and simulated mean velocities using the criteria of deviation and the graphs of the mean error shows the performance of Huthoff et al. (2007) model in the prediction of the mean velocity for submerged, rigid and dense vegetation. Following Figure 4, the validity of this model in the prediction of the mean velocity could reach to 0.8 m/s. That’s very import for flood management to set a safety standard.

3.2 Analytical Models Compared with Data of Flexible Vegetation

All of these analytical models are set for rigid vegetation and it’s questioned about their performance in calculating the behavior of flexible vegetation.

The comparison between the measured and simulated mean velocities by the different analytic models using data of flexible vegetation is summarized in the table 4.
Fig. 4. Mean error (E) between the measured mean velocities and the predicted ones by the different analytic models in the case of rigid vegetation.

Table 4 Mean velocities calculated by analytic models compared to ones measured with data of flexible vegetation

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>σ (m/s)</th>
<th>MAE (m/s)</th>
<th>RMSE (m/s)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klopstra et al. (1997)</td>
<td>0.258</td>
<td>0.184</td>
<td>0.302</td>
<td>0.208</td>
</tr>
<tr>
<td>Huthoff et al. (2007)</td>
<td>0.226</td>
<td>0.170</td>
<td>0.254</td>
<td>0.383</td>
</tr>
<tr>
<td>Van Velzen (2003)</td>
<td>0.598</td>
<td>0.305</td>
<td>0.601</td>
<td>0.131</td>
</tr>
<tr>
<td>Yang and Choi (2010)</td>
<td>0.245</td>
<td>0.211</td>
<td>0.312</td>
<td>0.261</td>
</tr>
<tr>
<td>Stone and Shen (2002)</td>
<td>0.277</td>
<td>0.267</td>
<td>0.373</td>
<td>0.06</td>
</tr>
<tr>
<td>Baptist et al. (2007)</td>
<td>0.252</td>
<td>0.297</td>
<td>0.385</td>
<td>0.224</td>
</tr>
</tbody>
</table>

The determination of deviation’s criterion between the measured mean velocity and the predicted velocity by the six models shows a small value of a coefficient of determination (< 50%). However, the prediction by stone and Shen (2002) and Baptist et al. (2007) performs again the least in comparison to the other descriptors.

In general, the prediction of flexible vegetation by the different models is less accurate than prediction of rigid vegetation. Figure 5 show the mean error between the measured and calculated velocities. In the case of flexible vegetation, the mean error is often greater than 1 when u > 1m/s.

Predicting the vegetation resistance in this case is very complex since the flexiblity of the vegetation is not even taken into account by some models. In Addition, All these descriptors, used vegetation in simplified form with fixed and identical plant height and diameter. However, for flexible vegetation, the deflected plant height decreases, due to the increasing of the velocity, therefore the drag coefficient should also decrease at higher velocities. Using a constant coefficient isn’t suitable in this...
Fig. 5. Mean error (E) between the measured mean velocities and the predicted ones by the different analytic models in the case of flexible vegetation.

These could explain the deviation between the measured and calculated velocities in this case.

4. CONCLUSION

Several descriptions for rigid vegetation under emergent and submerged conditions were found in literature. The aim of this study was to identify and evaluate the capacity of six analytic models, for predicting the mean velocity by compiling a wide data set of flow experiments.

A data set for submerged rigid and flexible vegetation used in this article to evaluate and determine the range of applicability of these descriptors for predicting the mean velocity.

In the case of rigid vegetation, Most of descriptors show a good performance, with $R^2$ above (60%). Only Baptist et al. (2007) model performs less well ($R^2=26\%$). However, Huthoff et al. (2007) and Klostra et al. (1997) model show the best agreement ($R^2=80\%$).

For smaller velocities, the difference in the performance between these descriptors is small but, for higher velocities, the error between the measured velocity and predicted velocity is often greater than $0.1\mathrm{m/s}$.

These models were validated for dense vegetation and they neglect the bed shear stress. However, for sparse vegetation, bed roughness becomes higher and has an effect on the. That could explain the deviation between the measured and calculated velocities spatially for higher velocities.

The prediction of flexible vegetation by the six models is less accurate than the prediction in the case of rigid vegetation. For flexible vegetation, the deflected plant height decreases, due to the increasing of the velocity, therefore the drag coefficient should also decrease at higher velocities. Using a constant coefficient isn’t suitable in this case. Moreover, all descriptions use simplified representation of the reality. These reasons may explain the deviation between the measured and calculated velocities.
In perspective, we will include the model of Huthoff et al. (2007) in a computer code (Telemac 2D) to predict the mean velocity in flow through vegetation and we will apply the new model in a real cases (rivers).

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