Journal of Applied Fluid Mechanics, Vol. 9, No. 3, pp. 1273-1283, 2016.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.18869/acadpub.jafm.68.228.24221

Mean Velocity Predictions in Vegetated Flows

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(Received November 13, 2014; accepted May 13, 2015)

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 model 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 law 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

A_p	solidity
a	density of elements in the canopy
a_v	integration constant
C_D	drag coefficient
C_p	turbulent intensity, height –averaged over vegetation height
C_3	constant integration in the model of Klopstra *et al.*(1997)
C_u	constant in Yang and Choi (2010) model
D	diameter of plant stems
d	zero-plane displacement
E	the mean error
F_D	drag force
g	acceleration due to gravity
h	water depth
h_p	vegetation height
h_s	distance between the vegetation top and the surface layer virtual bed
i	energy gradient
K_n	roughness height
L	length scale
l	mixing length
l*	submergence ratio
m	density of vegetation
MAE	mean absolute error
RMSE	mean square error
R^2	coefficient of determination
s	separation between individual resistance elements
u(z)	vertical velocity
u_*	shear velocity
u_{v0}	characteristic constant flow velocity in non- submerged vegetation
U_1	mean velocity flow inside the vegetation
U_2	mean velocity flow above the vegetation
U	average velocity over the total depth
U_C	the maximum velocity in the vegetation layer
z_0	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
τ_b	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_1) and above the vegetation (U_2) (Klopstra *et al.*, 1997; Huai *et al.*, 2009; Jarvela, 2005).

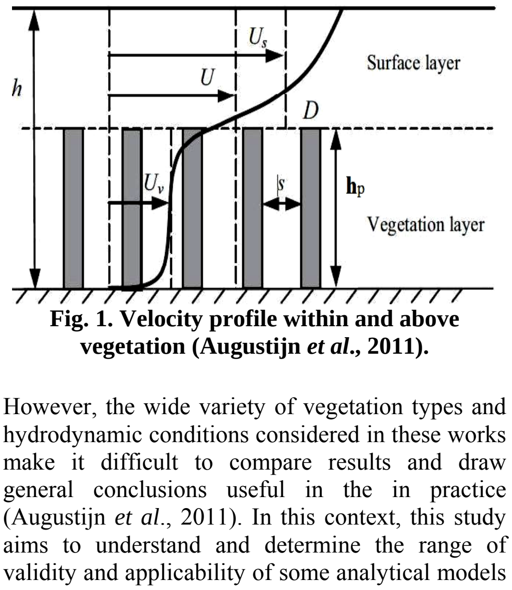

Fig. 1. Velocity profile within and above vegetation (Augustijn *et al.*, 2011).

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, klopstra *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.

$$\frac{\partial \tau}{\partial z} = F_D(z) - \rho g i \tag{1}$$

where τ (z) is the shear stress, ρ 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:

$$F_D(z) = \frac{1}{2}\rho m D C_D u(z) \tag{2}$$

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:

$$\tau(z) = \rho\alpha u(z)\frac{\partial u(z)}{\partial z} \tag{3}$$

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

$$\alpha = 0.079\, h_p \ln(\frac{h}{h_p}) - 0.0009 \tag{4}$$

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

Then, the momentum equation (1) becomes:

$$u(z)\frac{\partial^2 u(z)}{\partial z^2} + (\frac{u(z)}{\partial z})^2 = \frac{mDC_D u(z)^2}{2\alpha} - \frac{gi}{\alpha} \tag{5}$$

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.

$$u(z) = \frac{u_*}{\kappa}\ln(\frac{z-(h_p-h_s)}{z_0}) \tag{6}$$

κ is Von Karman's constant (0.41), h_s is the distance between the vegetation top and the surface layer virtual bed ($z_0<h_s<h$), z_0 is the length scale for bed roughness of the surface layer (m) and u_* 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):

$$U = \frac{h_p}{h}U_1 + \frac{(h-h_p)}{h}U_2 \tag{7}$$

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

$$U = \frac{\sqrt{i}}{h}\left[\begin{array}{l} \frac{2}{\sqrt{2A}}(\sqrt{C_3 e^{h_p\sqrt{2A}} + u_{v0}^2} - \sqrt{C_3 + u_{v0}^2}) \\ + \frac{u_{v0}}{\sqrt{2A}}\ln(\frac{(\sqrt{C_3 e^{h_p\sqrt{2A}} + u_{v0}^2} - u_{v0})}{(\sqrt{C_3 e^{h_p\sqrt{2A)}} + u_{v0}^2} - u_{v0})} * \\ (\frac{(\sqrt{C_3 + u_{v0}^2} + u_{v0})}{(\sqrt{C_3 + u_{v0}^2} + u_{v0})}) + \frac{\sqrt{g(h-(h-(h_p-h_s))}}{\kappa} \\ ((h-(h_p-h_s))\ln(\frac{(h-(h_p-h_s)}{z_0}) - \\ h_s\ln(\frac{h_s}{z_0}) - (h-h_p)) \end{array}\right] \tag{8}$$

where, A is a help variable:

$$A = \frac{mDC_D}{2\alpha} \tag{9}$$

The constants C_3 follow from boundary conditions.

u_{v0} is the characteristic constant flow velocity in non-submerged vegetation:

$$u_{v0} = \sqrt{\frac{2g}{C_D m D}} \tag{10}$$

2.2 Stone and Shen (2002) Model

Stone and Shen (2002), started with the momentum balance in streamwise direction:

$$\tau = \tau_b + F_D \tag{11}$$

With τ_b is the bed shear stress (which is neglected), τ is the total bed shear stress and determined by the following expression:

$$\tau = \rho g h(1 - A_p l^*) \tag{12}$$

A_p is the solidity, which is defined as the fraction of horizontal area taken by the cylinder:

$$A_p = \frac{1}{4}\pi D^2 m \tag{13}$$

l* is the submergence ratio

$$l^* = \frac{h_p}{h} \tag{14}$$

The drag force is determined by the following expression:

$$F_D = \frac{1}{2}C_D \rho m D\, h_p U_c^2 \tag{15}$$

U_C is the maximum velocity in the vegetation layer which is defined as:

$$U_c = \frac{U_1}{(1 - D\sqrt{m})} \tag{16}$$

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:

$$U_l = U_{v0}\sqrt{i}\,(1 - D\sqrt{m})\sqrt{\left(\frac{h}{h_p} - \frac{1}{4}\pi D^2 m\right)} \quad (17)$$

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

$$U = U_l\sqrt{\frac{h}{h_p}} \quad (18)$$

Then, it's given by the following expression:

$$U = u_{v0}\sqrt{i}\left(1 - D\sqrt{m}\right)\sqrt{\left(\frac{h}{h_p} - \frac{1}{4}\pi D^2 m\right)\frac{h}{h_p}} \quad (19)$$

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:

$$\rho g h i - F_D = 0 \quad (20)$$

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

$$F_D = \frac{1}{2}\rho C_D m D U_l^2 \quad (21)$$

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

$$U_l = U_{v0}\sqrt{i} \quad (22)$$

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

$$U = U_l + 18\sqrt{(h - h_p)i}\,\log\left(\frac{12(h - h_p)}{k_n}\right) \quad (23)$$

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

$$U = U_l + 18\sqrt{(h - h_p)i}\,\log\left(\frac{12(h - h_p)}{k_n}\right) \quad (24)$$

K_n is the roughness height and it's given by the empirical function:

$$K_n = 1.6\,h_p^{0.7} \quad (25)$$

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:

$$U_l = \frac{L\sqrt{i}}{h_p}\left[\begin{array}{l} 2(u(h_p) - \sqrt{a_v + u_{v0}^2}) \\ + u_{v0}\ln\left(\frac{(u(h_p) - u_{v0})}{(u(h_p) + u_{v0})} * \frac{(\sqrt{a_v + u_{v0}^2} + u_{v0})}{(\sqrt{a_v + u_{v0}^2} - u_{v0})}\right) \end{array}\right] \quad (26)$$

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

$$L = \sqrt{\frac{C_p l}{C_D m D}} \quad (27)$$

$$a_v = \frac{2Lg(h - h_p)}{C_p l \exp\left(\frac{h_p}{l}\right)} \quad (28)$$

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:

$$U_2 = \frac{\sqrt{g(h - h_p)i}}{\kappa(h - h_p)}\left[\begin{array}{l} (h - d)\ln\left(\frac{h - d}{z_0}\right) + (h_p - d) * \\ \ln\left(\frac{h_p - d}{z_0}\right) - (h - h_p)) \end{array}\right] \quad (29)$$

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:

$$U = \frac{\sqrt{i}}{h}\left[\begin{array}{l} (2(u(h_p) - \sqrt{a_v + u_{v0}^2}) + \\ u_{v0}\ln\left(\frac{(u(h_p) - u_{v0})(\sqrt{a_v + u_{v0}^2} + u_{v0})}{(u(h_p) + u_{v0})(\sqrt{a_v + u_{v0}^2} - u_{v0})}\right) + \\ \frac{\sqrt{g(h - h_p)i}}{\kappa(h - h_p)}\left(\begin{array}{l} (h - d)\ln\left(\frac{h - d}{z_0}\right) + \\ (h_p - d)\ln\left(\frac{(h_p - d)}{z_o}\right) - (h - h_p)) \end{array}\right) \end{array}\right] \quad (30)$$

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:

$$U_l = U_{v0}\sqrt{i}\sqrt{\frac{h}{h_p}} \quad (31)$$

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

$$U_2 = U_{v0}\sqrt{i}\left(\frac{(h - h_p)^{\frac{2}{3}\left(1 - \left(\frac{h}{h_p}\right)^{-5}\right)}}{s}\right) \quad (32)$$

With, s is the separation between individual resistance elements:

$$s = \frac{1}{\sqrt{m}} - D \qquad (33)$$

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

$$U = U_{v0}\sqrt{i}\left(\sqrt{\frac{h_p}{h}} + \frac{(h-h_p)}{h}\left(\frac{h-h_p}{s}\right)^{2/3\left(1-\left(\frac{h}{h_p}\right)^{-5}\right)}\right) \qquad (34)$$

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:

$$U_1 = U_{v0}\sqrt{i}\sqrt{\frac{h}{h_p}} \qquad (35)$$

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

$$U_2 = U_1 + \frac{C_u u_*}{\kappa}\left(\frac{h}{(h-h_p)}\ln\left(\frac{h}{h_p}\right) - 1\right) \qquad (35)$$

With u_* 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):

$$U = \frac{C_u u_*}{\kappa}\left(\ln\left(\frac{h}{h_p}\right) - \left(\frac{h-h_p}{h}\right)\right) + U_1 \qquad (36)$$

κ 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 Bosmaijan (1975) equation (Meijeri, 1998 (a,b); Tsujimoto *et al*.,1993) and the bed shear stress (Stone and Shen, 2002).

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

$$U = \sqrt{\frac{2g}{C_D mD}}\sqrt{i} \qquad (39)$$

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 (σ).

$$E = \frac{1}{N}\left(\sum_{i=1}^{n}(\text{measured}_{\text{value}} - \text{calculated}_{\text{value}})\right) \qquad (40)$$

$$MAE = \frac{1}{N}\left(\sum_{i=1}^{n}\left|\text{measured}_{\text{value}} - \text{calculated}_{\text{value}}\right|\right) \qquad (41)$$

$$RMSE = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{n}(\text{measured}_{\text{value}} - \text{calculated}_{\text{value}})^2\right.} \qquad (42)$$

$$\sigma = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{n}(\text{measured}_{\text{value}} - \text{calculated}_{\text{value}} - E)^2\right.} \qquad (43)$$

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

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

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

Author(s)	Nombre of expriments		vegetation characteristics		
		h_p(m)	D(m)	m (m^{-2})	C_D
Kouwen *et al*.(1969)	27	0.05-0.1	0.005	5000	3
Ree and Crow (1977)	30	0.2-0.3	0.005	1076-1464	1
Murota *et al*.(1984)	8	0.048-0.06	0.00024	4000	2.75
Tsujimoto *et al*.(1993)	12	0.06	0.00062	10000	2
Tsujimoto *et al*.(1991)	8	0.02-0.04	0.0015	2500	3.14
Ikeda and kanazawa (1996)	7	0.04	0.00024	20000	1
Meijer (1998 a)	7	1.55-1.65	0.0057	254	1.81
Rowinski *et al*.(2002)	8	0.165	0.000825	2500-10000	1.22-1.35
Jarvela (2003)	12	0.15-0.29	0.0028	512-12000	1
Carollo *et al*. (2005)	80	0.04-0.08	0.0045	28000-44000	1
Yang and Choi (2009)	5	0.035	0.0002	1400	1.13

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

Author(s)	σ (m/s)	MAE (m/s)	RMSE (m/s)	R^2
Klopstra *et al*.(1997)	0.148	0.073	0.148	0.793
Huthoff and al (2007)	0.127	0.068	0.132	0.816
Van Velzen(2003)	0.223	0.128	0.252	0.774
Yang and Choi (2010)	0.234	0.092	0.235	0.714
Stone and Shen (2002)	0.376	0.138	0.380	0.691
Baptist and al (2007)	3.039	0.529	3.079	0.260

The following figure shows a comparison between the measured mean velocity and calculated by Klopstra *et al*. (1997) and Huthoff *et al*.(2007) in the case of rigid vegetation:

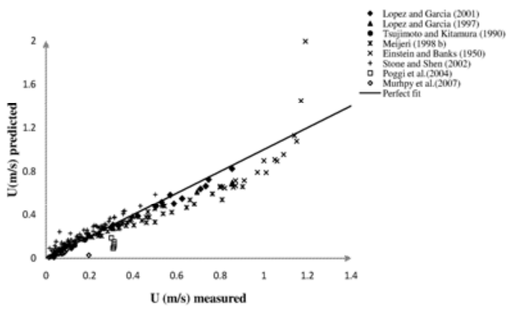

Fig. 2. Measured and calculated mean velocity by Klopstra *et al*.(1997).

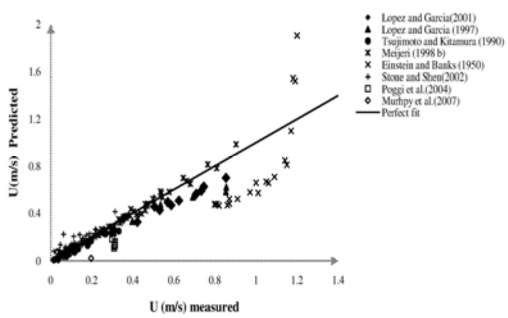

Fig. 3. Measured and calculated mean velocity by Huthoff *et al*. (2007).

Mean velocity calculated by Klopsra *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 m^{-2}), 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 Huthof *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.

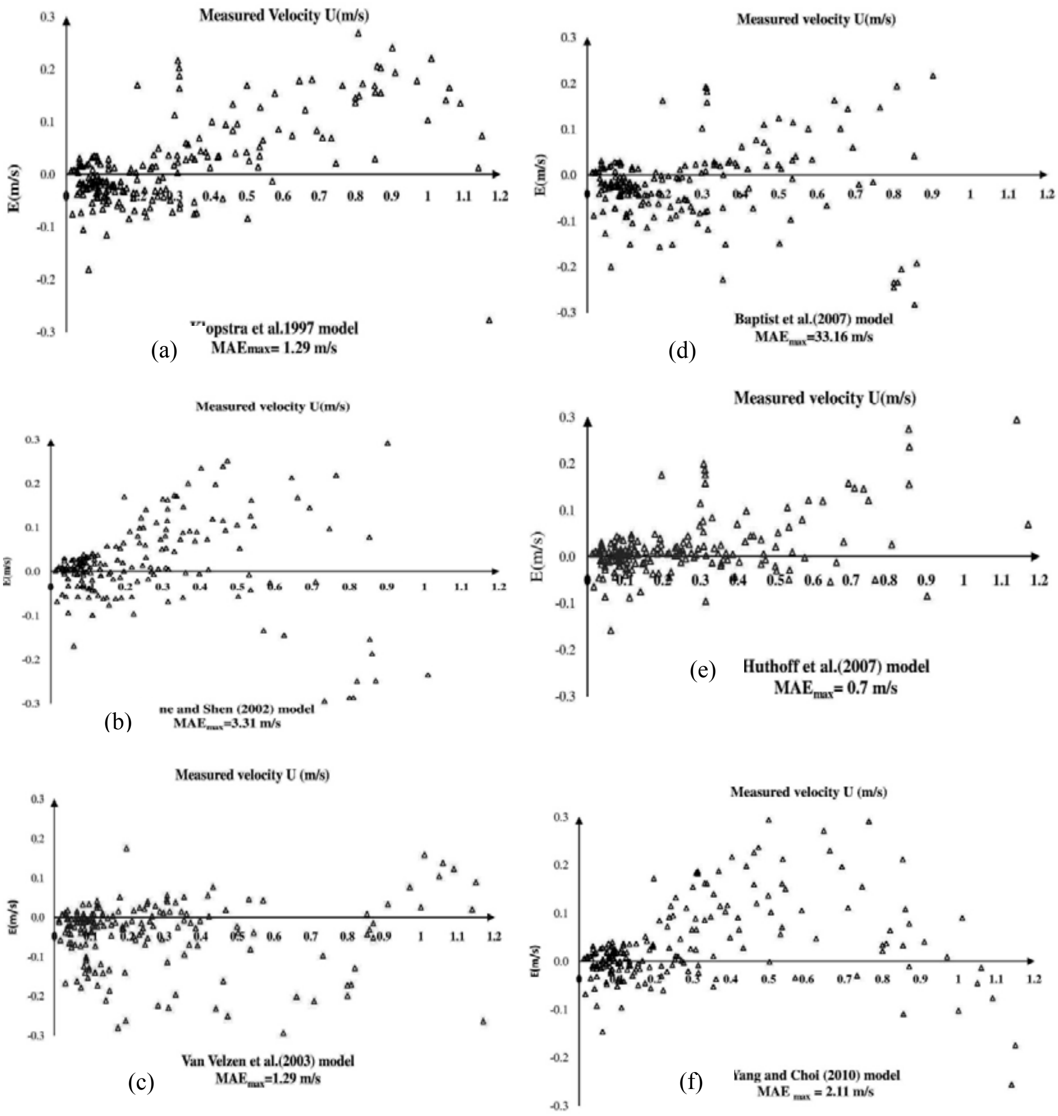

Fig. 4. Mean error (E) between the measured mean velocities and the predicted ones by the different analytic models in the case of rigid vegetation.

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

Author(s)	σ (m/s)	MAE (m/s)	RMSE (m/s)	R^2
Klopstra *et al*. (1997)	0.258	0.184	0.302	0.208
Huthoff *et al*. (2007)	0.226	0.170	0.254	0.383
Van Velzen (2003)	0.598	0.305	0.601	0.131
Yang and Choi (2010)	0.245	0.211	0.312	0.261
Stone and Shen (2002)	0.277	0.267	0.373	0.06
Baptist *et al*. (2007)	0.252	0.297	0.385	0.224

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 flexibility 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

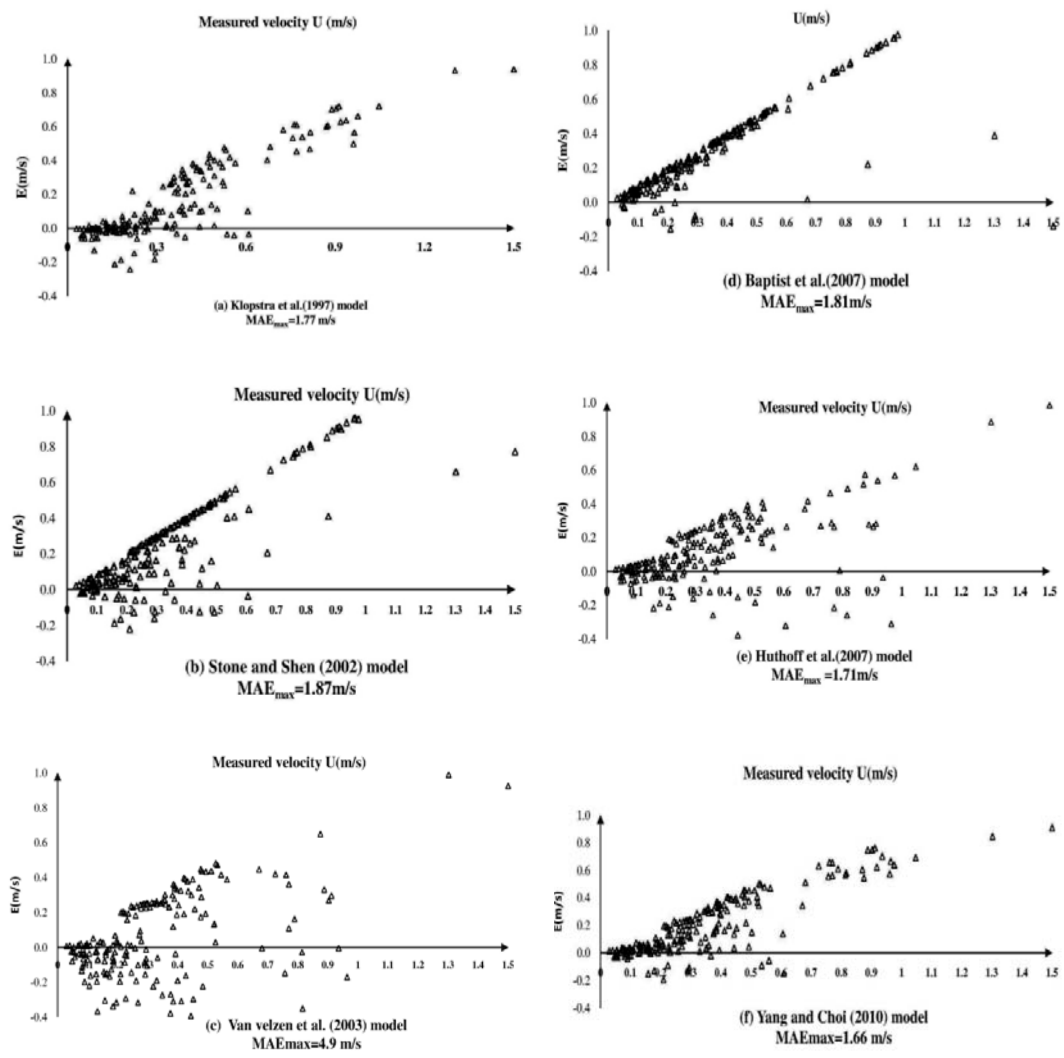

Fig. 5. Mean error (E) between the measured mean velocities and the predicted ones by the different analytic models in the case of flexible vegetation.

case. 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 (R2=26%). However, Huthoff *et al*. (2007) and klopstra *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 0.1m/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 a in a real cases (rivers).

ACKNOWLEDGEMENTS

The authors wish to thank, the group of LTHE specially the RIVER team (Grenoble) for their cooperation and for the helpful comments and suggestions.

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