Evaluation of flow formulas for submerged vegetation

D.C.M. Augustijn and A.A. Galema
Water Engineering & Management, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

F. Huthoff
Water Engineering & Management, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
HKV Consultants, P.O. Box 2120, 8203 AC Lelystad, The Netherlands

ABSTRACT: Much research has been dedicated to the interaction between flow and vegetation, however, this knowledge is only to a limited extend incorporated in models that are being used for river management practices. This may be partly due to the unknown reliability of the developed flow formulas. This contribution evaluates five different flow formulas for submerged vegetation: Klopstra et al. (1997); Stone and Shen (2002); Baptist et al. (2007); Huthoff et al. (2007); and Yang and Choi (2010). Each of these models is based on measurable vegetation characteristics to account for flow resistance by the vegetation. The evaluation of the flow formulas is based on the agreement with experimental data from literature, on their behaviour with respect to submergence ratio and on predicted water levels for different vegetation types. All models showed reasonable correlation to experimental data for rigid and flexible vegetation, however, average relative deviations were quite significant in the range of 24 to 43%. Some models showed unexpected behaviour in the velocity ratio between vegetation and surface layer and deduced roughness parameters as function of submergence ratio. Predicted water levels for a given velocity varied up to several meters for some vegetation types. This shows that a particular choice for a model may have huge consequences when being used to predict water levels during flood conditions. The flow formulas proposed by Klopstra et al. (1997) and Yang and Choi (2010) show the best fit to experimental data and also show consistent physical behaviour.

Keywords: vegetation resistance, flow formulas, prediction, model comparison

1 INTRODUCTION

Currently many rivers in Europe are being rehabilitated to improve the ecological status. This provides more room for natural processes and less predictable developments in vegetation and morphological processes. In densely populated areas safety against flooding needs to be guaranteed. Uncontrolled natural developments may jeopardize safety requiring active management. Therefore, to predict hydraulic responses to vegetation developments in river floodplains computational models are commonly employed that include vegetation obstruction as part of the roughness parameterization. Many of such models have been developed in recent years, but only few are actually used in practice. The objective of this study is to evaluate some of these models and determine their reliability to ease the choice in applying recently developed flow models in current day river management practice.

2 FLOW FORMULAS

In this study five different flow formulas for submerged vegetation will be evaluated. Figure 1 shows a typical flow profile for submerged vegetation, including some characteristic parameters. All five models are briefly described below.

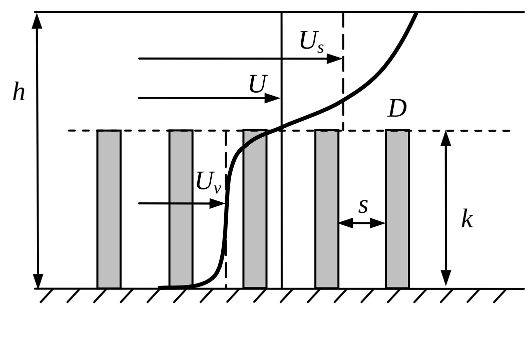

Figure 1. Typical flow profile for submerged vegetation.

2.1 *Klopstra et al. (1997)*

The formula by Klopstra et al. (1997) is based on the momentum equation for the vegetation layer and a logarithmic velocity profile in the surface layer. The analytical solution is a rather lengthy expression for which is referred to the original paper. The only unknown parameter in the model is the scaling parameter α. Various authors have derived empirical relations for α. Here we will use the relation of Van Velzen et al. (2003) which is also used for Dutch river management practice:

$$\alpha = 0.0227k^{0.7} \quad (1)$$

where k is the height of the vegetation.

2.2 *Stone and Shen (2002)*

Stone and Shen (2002) derived a flow formula based on the momentum balance and accounting for solidity. The depth averaged velocity is given by:

$$U = \sqrt{\frac{2g}{C_D mDk^2}}\left(h - mDk\right)\sqrt{i} \quad (2)$$

where g is the acceleration of gravity, C_D the drag coefficient, m the vegetation density, D the diameter of the plants, h the water depth and i the slope.

2.3 *Baptist et al. (2007)*

The flow formula of Baptist et al. (2007) is derived by genetic programming from a large number of simulations of a numerical turbulence model and reads:

$$U = \left(\sqrt{\frac{2g}{C_D mDk}} + \frac{\sqrt{g}}{\kappa}\ln\left(\frac{h}{k}\right)\right)\sqrt{hi} \quad (3)$$

where κ is the Von Karman constant taken as 0.4.

2.4 *Huthoff et al. (2007)*

Huthoff et al. (2007) derived an analytical expression for bulk flow through and over vegetation using scaling assumptions. The resulting expression for the depth-averaged velocity is:

$$U = \sqrt{\frac{2gi}{C_D mD}}\left(\sqrt{\frac{k}{h}} + \frac{h-k}{h}\left(\frac{h-k}{s}\right)^{\frac{2}{3}\left(1-\left(\frac{h}{k}\right)^{-5}\right)}\right) \quad (4)$$

where s is the spacing between the vegetation.

2.5 *Yang and Choi (2010)*

The flow formula of Yang and Choi (2010) is based on a uniform velocity in the vegetation layer added to the integration of a logarithmic velocity profile in the surface layer:

$$U = \left(\sqrt{\frac{2g}{C_D mDk}} + \frac{2\sqrt{g(h-k)/h}}{\kappa}\left(\ln\left(\frac{h}{k}\right) - \frac{h-k}{h}\right)\right)\sqrt{hi} \quad (4)$$

All parameters are as defined before.

3 EVALUATION

The five formulas are evaluated in four different ways: (1) by comparison with experimental data for rigid and flexible vegetation; (2) by comparing the velocity in the vegetation layer and surface layer at different submergence ratios; (3) by comparing the behaviour of predicted roughness parameters; and (4) by comparing predicted water depths for a given velocity.

3.1 *Comparison to experimental data*

In many studies experimental data is collected in flumes for flow through and over vegetation. Galema (2010) made a compilation of these data. Difficulty with experimental data is that not all data are measured in the same way and not all information is given. Some data which gave clear outliers were left out. In Table 1 the performance of the different flow formulas compared to experimental data is given. On average the difference between measured and computed velocities ranges from 24 to 43%, which is considerable. For predicted water depths the deviations are usually smaller (Augustijn et al., 2008). The flow formulas perform slightly better for rigid vegetation than for flexible vegetation, except for Baptist et al. (2007). The formula of Stone and Shen (2002) performs the least. Figure 2 shows the best fit for the flexible data.

Table 1. Averages of relative deviations between measured and computed velocities in percentages for different flow formulas

	rigid (N=214)	flexible (N=119)
Stone and Shen	30.5	43.2
Klopstra et al.	23.9	24.5
Baptist et al.	35.5	34.8
Huthoff et al.	21.9	34.3
Yang and Choi	24.8	27.3

3.2 *Velocity ratio*

The velocity in the resistance layer is expected to be lower than the velocity in the surface layer and the difference will increase with growing water depth. So, the ratio between the average velocity in the surface layer and resistance layer U_s/U_v should be approaching 1 when h is slightly higher

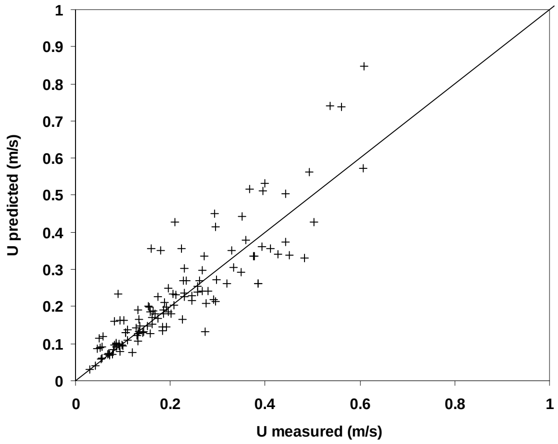

Figure 2. Best fit for data on flexible vegetation by model of Klopstra et al. (1997)

than k and increase with h. This ratio is independent of the slope and therefore only depends on plant characteristics and water depth. The flow formula of Baptist et al. (2007) does not provide a distinction between flow velocities in the resistance layer and surface layer. The flow formula of Stone and Shen (2002) gives a unique relationship for U_s/U_v only depending on the submergence ratio h/k and starts at a value of 1.5 which does not coincide with the expected behaviour. The descriptions for U_s and U_v by Huthoff et al. (2007) show for low submergence ratios values for U_s/U_v smaller than unity, especiallly for sparse vegetation. This means that the formula of Huthoff et al. (2007) is physically incorrect. The formulas by Klopstra et al. (1997) and Yang and Choi (2010) show expected behaviour, where the method by Klopstra et al. gives larger values for U_s/U_v for different vegetation types as defined by Van Velzen et al. (2003). Figure 3 shows U_s/U_v as function of submergence ratio h/k for natural grassland ($m = 4500$ m^{-2}; $D = 0.003$ m; $k = 0.15$ m; $C_D = 1$).

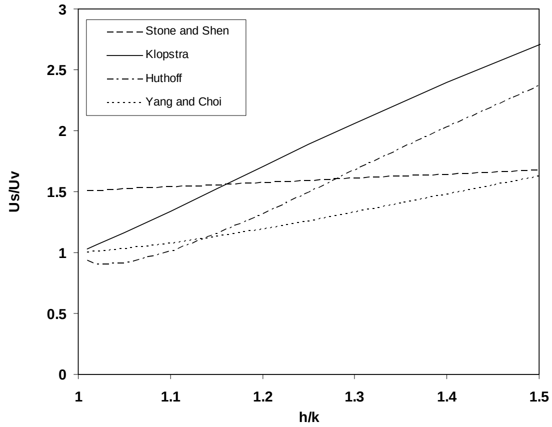

Figure 3. Ratio between velocity in surface layer and vegetation layer U_s/U_v versus submergence ration h/k for natural grass land for different flow formulas

3.3 *Roughness parameters*

From the flow formulas roughness parameters can be derived such as Manning, Darcy-Weisbach or a Nikuradse roughness length. It is generally agreed that for submerged vegetation these parameters decrease in value with increasing submergence ratio. For Manning this behaviour is shown by all five flow formulas. The Nikuradse roughness length decreases with increasing submergence ratios for three out of the five flow formulas (see Figure 6). For the formula of Stone and Shen (2002) the Nikuradse roughness length increases with relative water depth. The flow formula of Baptist et al. (2007) reduces to a constant Nikuradse roughness length which can be expressed as a function of plant characteristics (Augustijn et al., 2008). For submergence ratios larger than 5 the flow formulas approach constant values for n, for a constant k_N submergence ratios need even be larger.

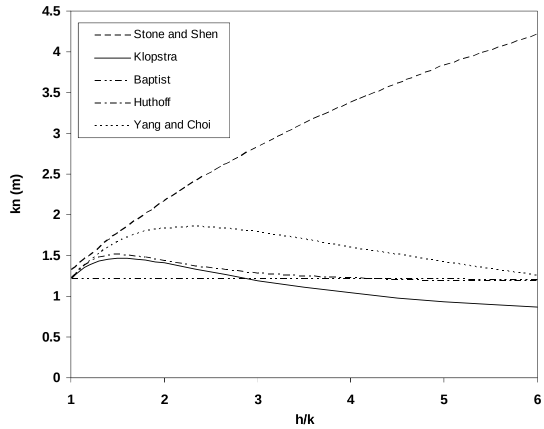

Figure 4. Nikuradse roughness length (k_N) as function of submergence ratio (h/k) for different flow formulas

3.4 *Predicted water depths*

Figure 5 shows the predicted water depths for several vegetation types as defined by Van Velzen et al. (2003) at a velocity of 1 m/s. The predicted water levels by the different flow formulas are quite different. The formula by Stone and Shen (2002) predicts the highest water level for almost all vegetation types. For orchards, with low vegetation density, the predictions of all formulas are relatively close. The reliability of this prediction however is questionable because in sparse vegetation the bottom roughness, which is ignored in all formulas, becomes more important. For management purposes the predicted differences are relatively large, varying up to several meters for reed.

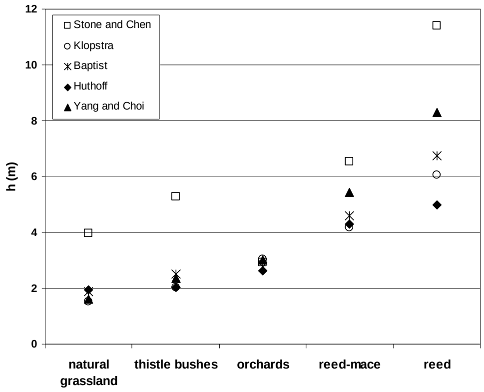

Figure 5. Differences in predicted water level *h* by the flow models for different vegetation types for a flow velocity of 1 m/s

4 DISCUSSION AND CONCLUSIONS

Based on the evaluation it can be concluded that the flow formula of Stone and Shen (2002) performs the least when compared to experimental data. This formula also shows physical incorrect behaviour as the ratio between the velocity in the surface layer and vegetation layer is the same for all vegetation types and approaches 1.5 for low submergence ratios ($h/k \rightarrow 1$). Moreover, the Nikuradse roughness length derived from the flow formula of Stone and Shen (2002) increases with increasing submergence ratio which is unexpected.

The flow formula of Huthoff et al. (2007) has the smallest relative deviation for experimental data on rigid vegetation (Table 1), but for low submergence ratios the model predicts larger velocities in the vegetation layer than in the surface layer which is not in accordance with the general theory.

The formula of Baptist et al. (2007) has the largest average of the relative deviations between measured and computed velocities for rigid vegetation, but for other indicators of the goodness of fit (e.g. linear correlation coefficient or root of the mean squared difference) the formula performs better. The formula of Baptist is equivalent with the White-Colebrook equation with constant Nikuradse roughness length for a given vegetation type, independent of water depth.

The two best performing and physically most correctly behaving flow formulas are those of Klopstra et al. (1997) and Yang and Choi (2010). Both are based on similar principles, i.e. a uniform flow velocity in the vegetation layer based on a force balance and a logarithmic velocity profile in the surface layer. Of these two formulas, the expression by Yang and Choi (2010) is the most simple one.

If the flow formulas by Klopstra et al. (1997) and Yang and Choi (2010) are considered most reliable, they still only predict experimental flow velocities within a band width of approximately 50%. This means they still do not give accurate predictions. For different plant configurations they also predict differences in water levels of up to 2 m at a depth averaged flow velocity of 1 m/s (Figure 5). The existence of this uncertainty should be realized when applying one of these formulas in models used for management applications.

Given the vast amount of research already performed in this area it is questionable whether yet another flow formula would perform any better. Research initiatives should be taken to monitor the resistance in the field where non-ideal conditions may introduce aspects which are unaccounted for in flow formulas evaluated here.

References

Augustijn, D.C.M., Huthoff, F., Van Velzen, E.H. 2008. Comparison of vegetation roughness descriptions. In: Altinakar, M.S., Kokpinar, M.A., Aydin, I., Cokgor, S. Kirkgoz, S. (eds.) River Flow 2008, pp. 343-350.

Baptist, M.J., Babovic, V., Rodríguez Uthurburu, J., Keijzer, M., Uittenboogaard, R.E., Mynett, A., Verwey, A. 2007. On inducing equations for vegetation resistance. Journal of Hydraulic Research 45, 435-450.

Galema, A.A. 2010. Vegetation resistance; Evaluation of vegetation resistance descriptors for flood management. MSc-report, University of Twente, Enschede, The Netherlands.

Huthoff, F., Augustijn, D.C.M., Hulscher, S.J.M.H. 2007. Analytical solution of the depth-averaged flow velocity in case of submerged rigid cylindrical vegetation. Water Resources Research 43, W06413, DOI:10.1029/2006WR005625.

Klopstra, D., Barneveld, H.J., Van Noortwijk, J.M., Van Velzen, E.H. 1997. Analytical model for hydraulic roughness of submerged vegetation. Proceedings of the 27th IAHR Congress theme A Managing Water: Coping with Scarcity and Abundance, San Francisco, 775-780.

Stone, M., Shen, H.T. 2002. Hydraulic resistance of flow in channels with cylindrical roughness. Journal of Hydraulic Engineering 128(5), 500-506.

Van Velzen, E.H., Jesse, P. Cornelissen, P., and Coops, H. 2003. Stromingsweerstand vegetatie in uiterwaarden; Handboek. Part 1 and 2. RIZA Reports 2003.028 and 2003.029, Arnhem, The Netherlands.

Yang, W., Chou, S.-U. 2010. A two-layer approach for depth-limited open-channel flows with submerged vegetation. Journal of Hydraulic Research 48(4), 466-475; DOI:10.1080/00221686.2010.491649.