HYDRAULIC RESISTANCE OF VEGETATION IN RIVER FLOW APPLICATIONS

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When vegetated regions become part of a river's flow field, the hydraulic resistance of vegetation affects the overall conveyance. Several descriptions exist to describe this type of flow, among which are empirical relations and relations that are physics-based. Empirical relations are often simple in form but have the drawback that their use is limited to the situation where they were determined. On the other hand, theoretical descriptions become increasingly complex (large computational efforts) and pose practical difficulties when gathering necessary input data. In the current work a new scaling expression of the average flow field is put forward that combines advantages of existing flow equations: (i) it is physics-based, (ii) it is dependent on readily measurable quantities and (iii) it requires little computational effort. The performance of the new expression is compared to existing expressions, and limits are given for its practical use.

Vegetation that penetrates a flow field causes drag in the layer occupied by the vegetation. Based on scaling considerations of the forces involved, depth-averaged flow velocities within the vegetation layer and in the free flowing layer above the roughness elements are estimated. The conditions in the two separate flow layers yield a new description of the overall depth-averaged flow velocity (U), which is entirely determined by measurable geometrical boundaries:

$$\frac{U}{u_S} = \sqrt{\frac{k}{h}} + \frac{h-k}{h}\left(\frac{h-k}{s}\right)^{2/3} \tag{1}$$

Where the depth of flow h exceeds the height of the vegetation k. The separation between individual vegetation elements s also determines the characteristic scaling velocity in the vegetation layer u_S:

$$u_S = s\sqrt{\frac{2gi}{C_D D}} \tag{2}$$

With g the gravitational acceleration, i the bed slope, D the stem diameter and C_D the drag coefficient. Note that for large flow depths eq. 1 reduces to Manning's equation (i.e. if $h \gg k$).

Two other methods that rely on the same input parameters for describing vegetative flow resistance are compared to the new description (eq. 1):

- The adapted *Klopstra method* (Klopstra et al. 1997). This method is based on depth-integration of a velocity profile for flow through submerged vegetation. See Huthoff & Augustijn (2006) for details on the adaptation of Klopstra's method.
- The *Baptist method* (Baptist et al. 2006). A simple analytical flow description is deduced from outcomes of a detailed numerical model, based on a genetic algorithm.

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The performance of the three methods is evaluated against 177 flow measurements from laboratory flumes (taken from literature, see Baptist et al. 2006 for references). These experiments were conducted with various vegetation heights and various spacing between individual vegetation elements ($s/C_D D$), and included both flexible and rigid vegetation. The results are shown in Fig. 1.

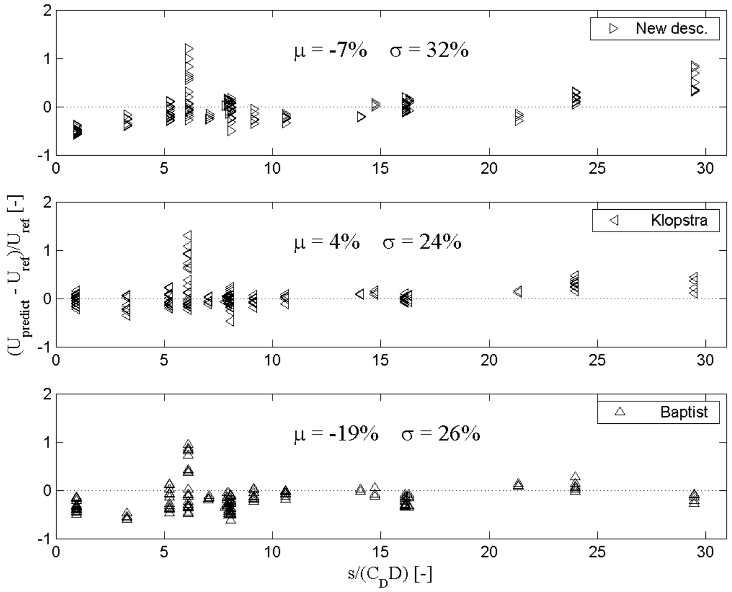

Figure 1 Three vegetation resistance methods and their predicted depth-averaged flow velocities compared to measured values ($U_{predict}$ and U_{ref}). The horizontal axis shows relative spacings between individual vegetation elements ($s/C_D D$); from dense (left) to sparse vegetation coverage (right). Also shown are mean error (μ) and error standard deviations (σ) of predicted flow velocities.

Predicted values of the newly proposed method correspond reasonably well with a wide range of experimental data (Fig. 1), as do predictions of Baptist's and Klopstra's methods. Errors for the three methods range from $\sigma = 24\%$ for Klopstra's method (which describes most flow detail) to 32% in the new method. Overall, Klopstra's method shows the smallest systematic error ($\mu = 4\%$) while the method proposed by Baptist often underestimates flow velocities ($\mu = -19\%$).

The simple mathematical form of the newly proposed method makes it suitable for a quick evaluation of a river's hydraulic response to obstructing vegetation. However, due to increasing errors in case of dense or sparse vegetation coverage, it is advised to restrict its application to flows through intermediate vegetation densities only (i.e. for situations where $5<s/C_D D<25$).

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