3D numerical modelling of open-channel flow with submerged vegetation

Modélisation numérique 3D d'un écoulement en canal avec végétation submergée

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ABSTRACT

Velocity distributions in channels partially covered with vegetation have been computed using a three dimensional model. The Navier-Stokes equations were solved, using the SIMPLE method and the k-ε turbulence model. The vegetation was modeled as vertical cylinders. A formula for the drag force on the vegetation was included as a sink term in the Navier-Stokes equations. The advantage with this method compared with using large roughness is that effects of the vegetation over the whole water depth can be taken into account, instead of only affecting the velocity near the bed. The numerical model was tested against three laboratory experiments from straight flumes with uniform flow, where vegetation partially covered the cross-section. The velocity and vegetation density varied in both vertical and horizontal directions in the different cases. The experiments also included varying cross-sectional shapes. All tests gave fairly good correspondence between computed and measured velocity profiles.

RÉSUMÉ

Les distributions de vitesse dans les canaux partiellement couverts de végétation ont été calculées en utilisant un modèle tridimensionnel. Les équations de Navier-Stokes sont résolues en utilisant la méthode SIMPLE et le modèle de turbulence k-ε. La végétation est représentée par des cylindres verticaux. Une formule modélisant la force de frottement sur la végétation a été introduite comme un terme puits dans les équations de Navier-Stokes. L'avantage de cette méthode par rapport à l'utilisation d'une forte rugosité est que l'effet de la végétation peut être pris en compte sur la totalité de la profondeur d'eau au lieu d'affecter seulement la vitesse près du fond. Le modèle numérique a été testé sur trois expériences de laboratoire portant sur un écoulement uniforme dans des canaux rectilignes dont la section transversale était partiellement couverte de végétation. Dans les différents cas, la vitesse et la densité de végétation étaient variables tant dans la direction horizontale que verticale. Les expériences comportaient également des sections de formes variables. Tous les tests ont donné une assez bonne correspondance entre les profils de vitesse calculés et mesurés.

Introduction

Many rivers are more or less vegetated and it is essential for the practical engineer to determine velocity distributions and thus discharge capacity for floodplain management, river training works or water resources activities that account for such processes. In earlier times vegetation in channels was often considered undesirable since it hampered flood conveyance and reduced the discharge capacity of a floodplain tremendously. More recently however, fundamental understanding of the hydraulic effects of submerged aquatic vegetation has become of major interest for ecological river restoration purposes as well as for the creation of flood retention space.

In the past, vegetation in open-channels was treated as additional flow resistance to be added to the bed roughness, since submerged and non-submerged vegetation along riverbanks and/or on floodplains is often found to be responsible for the largest amount of energy losses. Cowan (1956) and Chow (1959) first introduced this approach, producing recommended values for the Mannings coefficient to account for the additional form resistance due to grass, bushes or trees. A similar method was later followed by Petryk and Bosmaijan (1975), who developed a method to account for varying flow depths and vegetative characteristics. Due to varying depth and flow resistance along the width of a compound channel, the determination of discharge capacity can be complicated. Overbank areas have to be subdivided into different regions having different roughness than the main channel. More recently Masterman and Thorne (1982) introduced the conveyance method. They applied the continuity equation after having subdivided the channel width into different sub-regions, accounting for the depth/resistance variation. Assuming a constant energy grade line in each section and constant water level along the channel width, the total discharge can be computed iteratively as the sum of the discharges of each section. However, many variations of this method exist to additionally account for the production of turbulence energy within the contact region between main channel and floodplains (e.g. Pasche, 1985). Since these aforementioned methods are considered to be one-dimensional Nakagawa et al. (1992), Shimizu et al. (1994) and Lopez et al. (1997) followed a multi-dimensional two-equation turbulence closure approach. This was first introduced by Wilson and Shaw (1977), who modeled atmospheric flows over plant canopies. A modified k-ε model was used, introducing drag related sink terms into the momentum as well as into the turbulent transport equations. Laboratory experiments, conducted at the Hydraulic Laboratory, Kanazawa University, Japan (Tsujimoto et al., 1991) were used to validate the model. Shimizu et al. calibrated their model by the modification of two of the five universal turbulence constants of

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the two-equation closure to reproduce observed mean velocities and Reynolds stresses. Lopez et al. conducted similar experiments and modified the same weighting factors of the k-ε model but reported calibrated values which differed by about 500% from those of Shimizu et al. In this paper a similar approach is introduced, applying the drag-related sink terms previously introduced to the momentum equations. This methodology has been tested against existing flume data and yielded satisfying results compared to the observations. The method appears to be transferable without numerical calibration of the turbulence parameters into natural waterway engineering. The cases used in the present study only used cylindrical vegetation stems where the drag coefficient was known. For practical applications, the drag coefficient for the complex shaped vegetation with leaves will probably have to be determined for each vegetation species. Also, certain assumptions have to be made in order to determine the effective momentum absorbing area of vegetational elements i.e. the projected area of the plant hindering the flow and the effect on the hydrodynamic behaviour. This is beyond the scope of the present study.

The numerical model

Numerical calculations were conducted using the SSIIM model, which has proven to be capable of simulating small scale physical models as well as natural streams (Olsen, 1994, 1995, Stoesser, 1997). The program calculates hydrodynamics for a general three-dimensional geometry solving the Reynolds averaged Navier-Stokes equations with the continuity equation, written as:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_i} = \frac{1}{\rho}\frac{\partial}{\partial x_i}\left(-P\delta_{ij} - \rho\,\overline{u_i u_j}\right) - F_i \tag{2}$$

U is the velocity averaged over the time t, x is the spatial geometrical scale, is the water density, P is the pressure, is the Kronecker delta and u is the velocity fluctuation in time during the time step δt, when U is subtracted. The left term on the left side of the equation is the transient term. The next term is the convective term. The first term on the right hand side is the pressure term. The second term on the right side of the equation is the Reynolds stress term, which needs to be modeled by a turbulence model. F represents external forces e.g. coriolis force, gravity forces, drag forces etc. The SIMPLE or SIMPLEC methods serve as a method for pressure corrections in SSIIM. A two-equation k-ε turbulence model is used for calculating the turbulent Reynolds stress term (Rodi, 1980). To model the additional flow resistance of submerged vegetation the drag force on a rigid obstacle has been introduced as a sink term into the Navier-Stokes equations. Drag on a vegetative element, with unity height, can thus be calculated as:

$$F_{D,i} = \rho \frac{U_i^{\,2}}{2} C_D \lambda \tag{3}$$

where the vegetative coefficient λ is defined as:

$$\lambda = \frac{\textit{projected area of plant}}{\textit{total volume}} = \frac{D}{s^2} \;\; or \;\; \lambda = \frac{D}{s \cdot l} \tag{4}$$

The experimental drag coefficient C_D, which corresponds to the shape and diameter of the vegetational elements can be approximated as 1.0 for Reynolds numbers above 10^3 for a round shape of the projected area of the stems of bushes and trees. D is the diameter of a plant, s and l are the lengths of the control volume (Figure 1). To avoid any calibration of simulations for different flow situations the k–ε model was not modified and only the Navier-Stokes equations were supplied with a sink term. It was assumed that the sink terms dominated the turbulent diffusive terms, so the values of k and ε within the vegetation layers did not affect the velocity.

The Navier-Stokes equations were transformed through the discretization to the following formula for the velocity in cell P (e.g. Melaaen, 1992):

$$a_P U_P = \sum_{m=1}^{6} a_m U_m + \hat{S}_U \,, \qquad m = E,W,N,S,T,B \tag{5}$$

where the a_m's are weighing coefficients for the six cells surrounding cell P. $\hat{S}_U$ is the source term, including for example pressure gradients. The control volume method is used for discretization. This method makes use of the Gauss theorem, where the volume integral of the conservative form of the equations is transformed into a surface integral of the 6 surfaces m (East, West, North, South, Top, Bottom) of a control volume. A detailed derivation of this approach is given by Olsen (1999) and will not repeated herein. The contribution from the drag force on the vegetation/cylinders was therefore added to the source term:

$$\hat{S}_U = \hat{S}_{U,0} - F\Delta z \,, \tag{6}$$

where F was taken from Eq. 3, and Δz is the height of the cell. The subscript 0 denotes the original source term before the modification. Alternatively, manipulations of Eq. 3 and Eq. 5 can give the following modification of a_p:

$$a_p = a_{p,0} + \rho \frac{U_i}{2} C_D \lambda \Delta z \tag{7}$$

The latter option was more stable in some cases, as also shown theoretically by Patankar (1980).

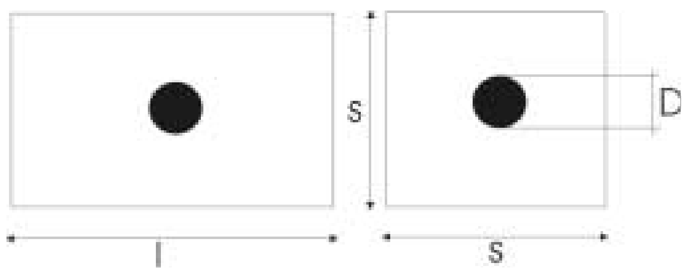

Fig. 1. Definition of plant density λ

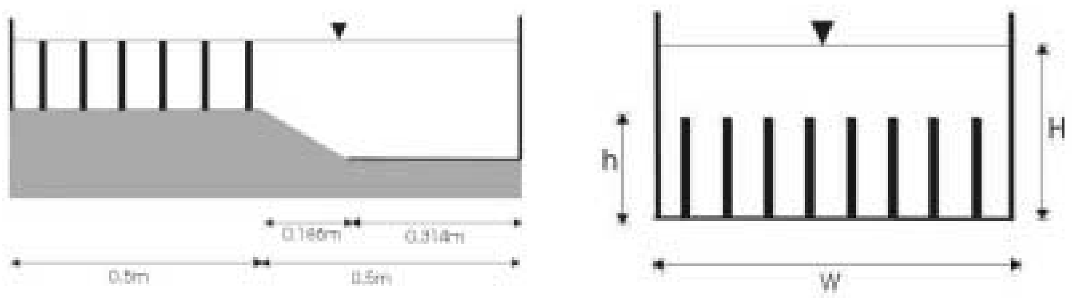

Fig. 2. Cross-sections of geometry with vegetation arrangements

The laboratory experiments

As mentioned previously, several laboratory experiments dealing with flow through vegetation have been conducted in the past. Velocities within and outside of vegetation layers have been measured. These results were used in this study to test the numerical model.

The laboratory experiments can be divided into two groups. Whilst Tsujimoto et al and Lopez et al. conducted experiments in a rectangular flume having measured vertical velocity profiles in the streamwise direction, Pasche measured lateral velocity distributions in a compound channel. Lopez and Tsujimoto et al. used a rectangular tilting flume, vegetated along the entire width using rigid cylinders. Different vegetation densities, λ, different vegetative element diameters and different vegetative heights, h, were used. Vertical velocity profiles were measured to show the influence of submerged vegetation at different vegetation-height/water depth ratios. Besides experiments dealing with the vertical velocity distributions, experiments by Pasche examined the influence of a vegetated floodplain on the horizontal velocity profile with emerging vegetation elements. Measurements were conducted for the case of vegetated and non-vegetated floodplains. The geometry and vegetation arrangements of the laboratory experiments are shown in Figure 2 below, a detailed overview can be found in Table 1. Tsujimoto et al. and Lopez conducted velocity measurements inside and above a vegetation layer in a tilting flume. Whereas Tsujimoto et al. obtained their experimental data with a hot-film anemometer or a propeller, respectively for velocity and turbulence measurements Lopez et al sampled data with an acoustic doppler velocimeter.

As Figures 3a indicates, the vertical velocity profile of flow above a vegetation layer differs from a logarithmic distribution. The experiments of both Lopez et al. and Tsujimoto et al. demonstrated that the velocity distribution is linear within the vegetation layer changing to logarithmic outside. Pasche however, collected experimental data with a laser doppler anemometer. Experiments on a vegetated floodplain showed a tremendous lateral reduction of flow velocity due to the presence of vegetation (Figure 3b).

The numerical model tests

The need for a global parameter set, which is independent of model calibration, to describe flow through vegetation has been mentioned in the previous section. In the following section comparison will be made with three sets of well-documented lab experiments introduced above. In addition, a sensitivity analysis will be conducted to show the applicability of the method for large scale as well as for small-scale simulations. Table 1 gives an overview on the number of grid cells for the numerical simulations conducted herein.

Tsujimoto et al.

Numerical simulations for the flume experiments of Tsujimoto et al. were carried out first to simulate submerged vegetation. First

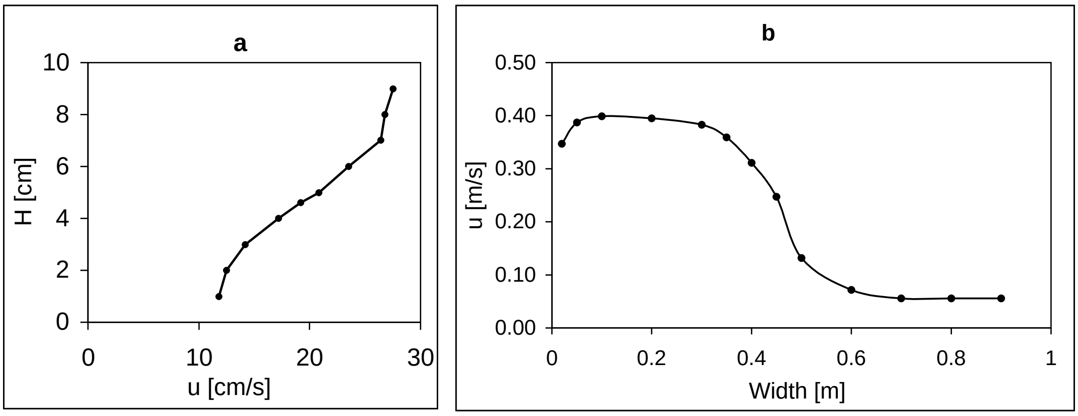

Fig. 3. Experimental Results of a. Tsujimoto et al., b. Pasche

Table 1. Experimental and numerical boundary conditions for the simulations

	Tsusjimoto		Lopez		Pasche		
Experiment	R32	A31	Exp1	Exp9	p224	p222	p225
Geometry							
Type	rectangular flume		rectangular flume		compound channel		
Length L [m]	n/a		19.50		25.50		
Width W [m]	n/a		0.91		1.00		
Depth H [m]	0.0747	0.0936	0.335	0.214	0.20 (mc[#]) 0.076 (fp[##])	0.21 (mc) 0.076 (fp)	0.20 (mc) 0.076 (fp)
Slope I [$*10^{-3}$]	2.13	2.60	3.60		1.00	0.5	0.50
Vegetation							
Type	fully vegetated, submerged		fully vegetated, submerged		vegetated floodplain, emerging		
Vegetation Height h [m]	0.041	0.046	0.12		0.076	0.076	0.076
Plant Diameter D [$m*10^{-3}$]	1	1.5	6.4		12	12	12
Plant density λ [1/m]	10	3.75	1.09	2.46	1.34	2.69	10.76
Measuring Technique	hot-film anemometry micro propeller		acoustic doppler velocimetry		laser doppler anemometry		
Simulations							
No. of Cells	60,000	15,000	12,000	3,000	23,660	38,304	63,000
Sensitivity Simulations							
No. of Cells	4,576	-	3,000	-	-	17,745	23,835
No. of Cells	-	-	-	-	-	-	11,970

[#] mc: main channel
[##] fp: floodplain

of all the drag force coefficient C_D was evaluated. For a smooth cylinder, the drag coefficient may be shown to be a function of the Reynolds number. For all experiments, the drag coefficient was determined to be equal to 1.0 for the given Reynolds numbers. Calculated velocity distributions were compared to observed data. As can be seen in Figure 4, good agreement between measured and calculated results could be achieved for Tsujimotos experiments. It has to be noted that the velocity profile of Figure 4 is averaged over the cross section. Since the simulation of the Tsujimoto *et al.* data was relatively successful, the experiments of Lopez et al. were replicated next to test the methods ability to reproduce a vertical vegetative velocity profile in the presence of a submerged vegetation layer.

Lopez et al.

Figure 5 shows the width averaged vertical velocity distribution of the flow over a vegetation layer. As Figure 5a indicates, an even better agreement to the observed data of Lopez was achieved. As before the typical vertical velocity profile of flow over and through a vegetated layer could be reproduced. The drag force accounts for the vertical variation of flow resistance due to vegetation and reduces the flow velocity accordingly.

Finally tests were undertaken to test this approach's ability to reproduce a lateral velocity distribution for a floodplain with fully emerging vegetational elements.

Pasche

Figure 6 shows the comparison of simulated results against observed data for different flow situations and vegetational densities (see Table 1). It can be seen that the match for all three setups is reasonably good. The reduction of flow velocities through the vegetational elements can be simulated fairly well. The flow pattern however becomes similar to a non-vegetated compound channel flow, differing in the magnitude of reduction of flow velocities between main channel and floodplain. The obvious mismatch in the transient region, where additional shear forces be-

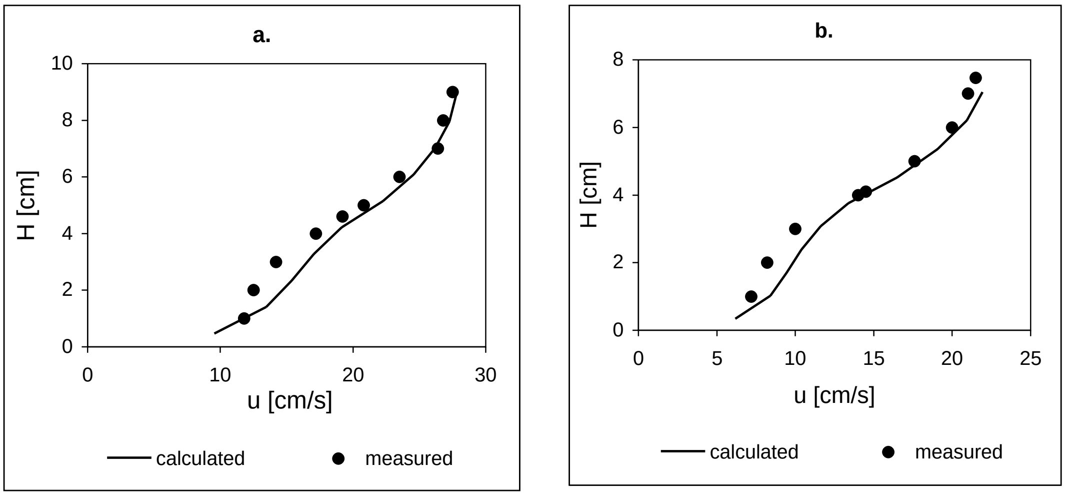

Fig. 4. Calculated and measured width averaged velocity profiles of Tsujimotos experiments. a. plant density $\lambda = 10.0$, b. plant density $\lambda = 3.75$

tween main-channel and floodplain cause extra energy diffusion may potentially be explained by the lack of a higher turbulence closure rather than a need to calibrate the used two-equation turbulence closure scheme.

Sensitivity tests

Since the definition of plant density employs a dimension, i.e. [1/m], numerical modeling of flow through or over vegetation strongly depends on the correct use of spatial grid distribution. As shown above, high-resolution meshes are necessary in order to describe the drag force on every element by use of its correct vegetative density to guarantee accurate prediction of velocity distributions. Whilst this is feasible for laboratory conditions, i.e. for fairly small domains and with a uniform plant density, many long river reaches with a natural distribution of vegetational elements may require a compromise between accuracy of a simulation and computational efficiency. Thus, further simulations were carried out in order to test the drag force approach's capability at coarser grid resolutions without loosing its accuracy in prediction of flow distribution. Figure 7 shows sensitivity simulations of the experiments of Tsujimoto et al. and Lopez et al., where the number of grid cells has been reduced. Figure 7a indicates that only a slight difference in the prediction of the vertical velocity profile for the Tsujimoto experiment can be seen, although the number of cells has been reduced by 92%. No visible difference can be seen for the reduction of grid cells by 75% for the experiments of Lopez et al. Three sets of simulations with a reduced numbers of grid cells were conducted for Pasches experiments (see Figures 8a-c). Figure 8a. shows the comparison of simulated results and observed data for the experiment with a plant density of $\lambda = 2.68$ and a grid cell reduction of 54%. It can be seen that with a halv-

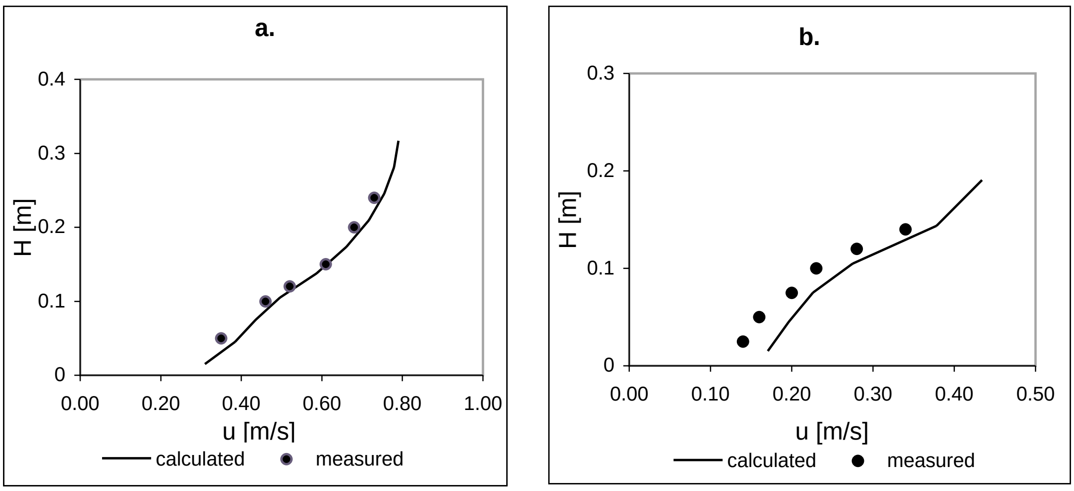

Fig. 5. Calculated and measured width averaged velocity profiles of Lopez' experiments. a. plant density $\lambda = 1.09$. b. plant density $\lambda = 2.46$

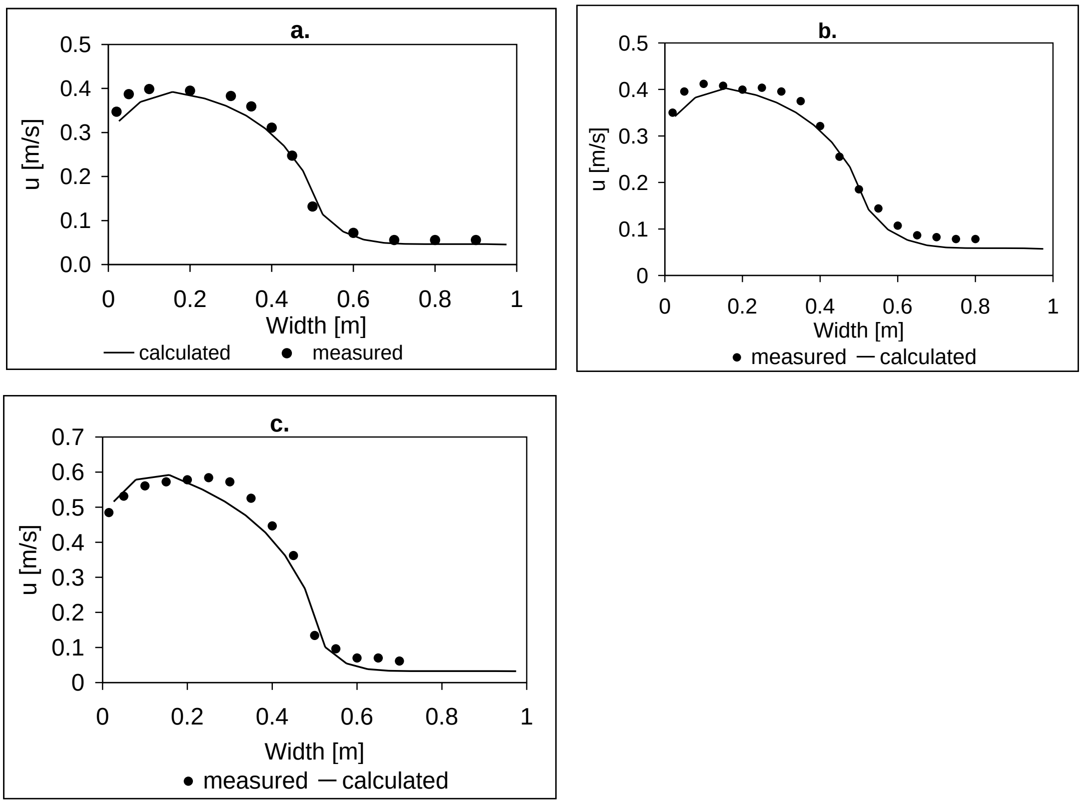

Fig. 6. Calculated and measured depth averaged velocity profiles of Pasches experiments a. plant density $\lambda = 2.69$ b. plant density $\lambda = 1.34$ c. plant density $\lambda = 10.76$

ing of discrete points in the streamwise direction nearly the same accuracy in prediction of the flow could be achieved. A further reduction of the number of cells i.e. a reduction by 81%, for the high vegetative density experiment also showed nearly no loss of accuracy in predicting the velocity distribution (see Figure 8b).

Conclusion

Prediction of flow through and above aquatic vegetation is currently a major concern for hydraulic engineers. Numerical models can be used as cost-effective tools to understand the multi-dimensional processes of flow interaction in vegetated floodplains or river banks with the main channel. Therefore, multi-dimensional reliable numerical methods have to be developed and validated. Clearly these should require the minimum of calibration and thus be applicable to many different flow situations. In this paper we introduced a method fulfilling these practical demands. Simulations of different well-documented laboratory experiments yielded encouraging results. The drag force approach simply requires a plant density to be determined. This method however, yielded fairly accurate results for the given rigid vegetation for each different flow situation where vegetative elements changed

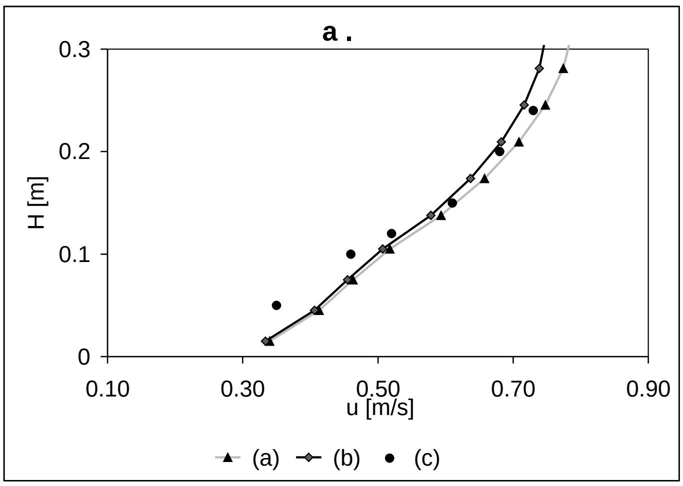

Fig. 7a. Sensitivity simulations of Tsujimotos experiment for original grid (a), coarse grid (b), and measurements (c)

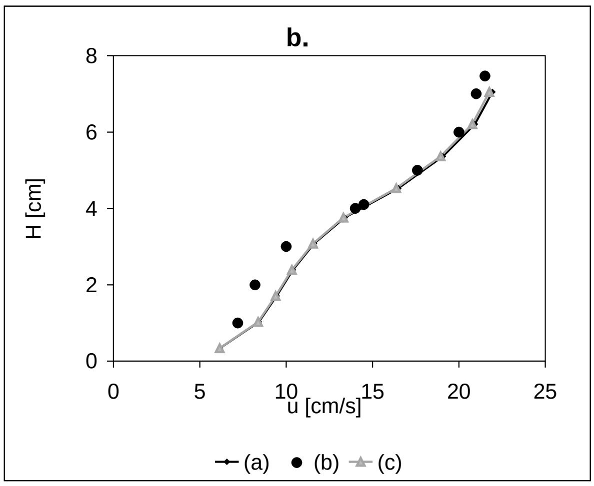

Fig. 7b. Sensitivity simulations of Lopez' experiment for original grid (a), measurements (b), and coarse grid (c)

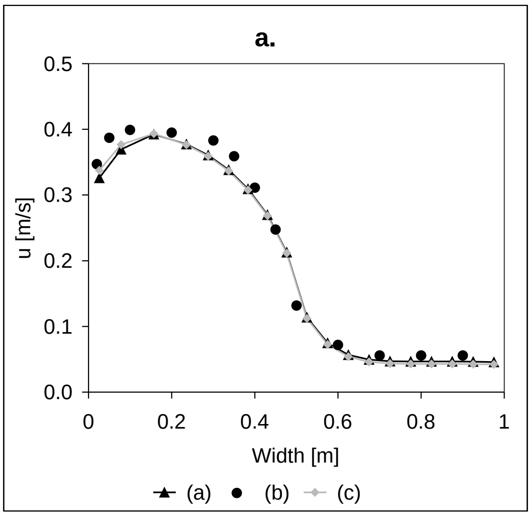

Fig. 8a. Sensitivity simulations of Pasches experiment with a plant density of $\lambda = 2.69$ for original grid (a), measurements (b), and coarse grid (c)

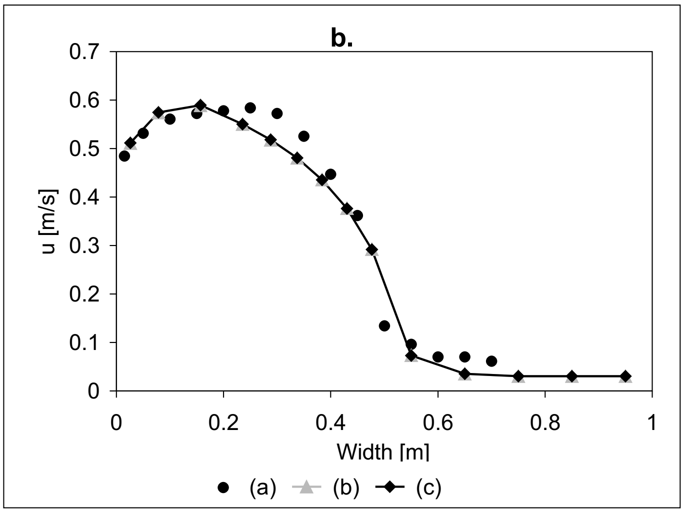

Fig. 8b. Sensitivity simulations of Pasches experiment with a plant density of $\lambda = 10.76$ for measurements (a), original grid (b) and coarse grid (c)

the flow behavior. Introduction of the drag force, simply determined by the proper use of the drag coefficient and the vegetative plant diameter offers the possibility to apply this method to large scale river reaches. Sensitivity tests herein showed that this approach also presents the possibility to reduce computational effort without loss of accuracy in predicting flows through or over submerged vegetation. However, these numerical model investigations were only conducted for rigid vegetation following the experimental conditions. Thus a number of laboratory experiments have been conducted recently or are currently underway to show the effects of plant bending due to the flow. Hence, the velocity field and flow characteristics are expected to change in certain situations due to the flexibility of the vegetation. For example Vischer et al. (1998) conducted studies to examine this influence and found that a young willow in a flow is forced to a non-negligible grade of deformation. Hence, its drag force did not increase with the square of the velocity as for a rigid obstacle but increased only linearly. Kouwen et al. (1980) pointed out the importance of flexibility of aquatic plants and proposed the determination of a flexural rigidity as parameter to account for the effect of stiffness and for the ability of a plant to resist bending due to the stream flow (Fahti-Maghadam and Kouwen, 1997). Thus, effects of vegetative flow resistance on turbulence and its mathematical representation needs further consideration. The need for a more sophisticated turbulence closure scheme also seems to be a challenging task for future research on this topic. Moreover, the transfer to natural open-channel flow needs further numerical modifications as well as its validation. This however relies on proper determination of drag coefficients of grass, bushes crops etc. and field data collection which is highly also recommended.

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Notations

U	average velocity in time
t	time
x	spatial geometrical scale
ρ	water density
P	pressure
δ	Kronecker delta
u	velocity fluctuation
C_D	drag coefficient
λ	vegetative coefficient
D	diameter of a plant
s, l	lengths of the control volume
k	turbulent kinetic energy
ε	turbulent diffusion
$\hat{S}_U$	source term
a_P	weighing coefficient cell P
a_k	weighing coefficients for the six cells surrounding cell P
Δz	height of the cell