FLOW THROUGH NON-SUBMERGED VEGETATION: A FLUME EXPERIMENT WITH ARTIFICIAL VEGETATION

L. Nehal[1], Z.M. Yan[2], J.H. Xia[2] and A. Khaldi[3]

[1] Assistant prof. University of Mascara. Faculty of Sciences and Technology. Mascara, Algeria, E-mail: laounia2001@yahoo.fr
[2]Professor.Water Conservancy & Hydropower Engineering College. Hohai University Nanjing, 210098. China. E-mails: zmyan@hhu.edu.cn, syjhxia@hhu.edu.cn
[3]Professor. University of Mascara, Biological Systems and Geomatics Laboratory, Mascara. Algeria. E-mail: aekkhaldi@gmail.com

ABSTRACT

Vegetation growing in the water along rivers plays an important role on the hydrodynamic behavior, on the ecological equilibrium and on the characteristics of the river. It has effects on the flow resistance and, as a result, has a large impact on water levels. The influence of non-submerged vegetation on flow is not so clear as yet; it needs to be further studied. The Acorus Calmus L is a kind of typical non-submerged vegetation, it is widely planted in river, but few researches have been done on the effects of these plants on the flow. A laboratory experiment using artificial vegetation selected to simulate Acorus Calmus L, was carried out in a water flume to investigate its influence on flow resistance and velocity distribution. A flow resistance model based on concepts of drag is developed to evaluate the Manning's (n) roughness coefficient for non-submerged vegetation. Experimental tests have shown that the relationship between flow depth and discharge depends significantly on the vegetation density and patterns. Manning resistance coefficient depends strongly on vegetation density and the depth of flow far more than in unvegetated channels; it increases with increasing water depth. Within vegetation, the mean velocity decreases with flow for which the vegetative roughness increases with decreasing velocity.

Keywords: Non-submerged vegetation, vegetation density, Manning's n, drag

1. INTRODUCTION

Vegetation is an important feature of many rivers, providing habitat for other aquatic organisms and enhancing amenity value for people. It is a key element in river functioning, through a three way, mutual feedback relationship with channel morphology and hydraulics, James et al. [1]: Vegetation and channel form determine hydraulic conditions for a given discharge; hydraulic conditions and channel form define habitat for vegetation establishment and growth; vegetation and hydraulics determine channel form by controlling the movement, trapping, and storing of sediment. Environmental management of rivers requires understanding and predictive capability of these processes, and in particular the influence of vegetation on flow resistance, because it may have a significant effect on the conveyance of the channel, Järvelä [2]. There has been increasing interest and research in floodplain management of rivers and natural waterways for a wide range of civil and water resource activities. In areas where flow occurs through vegetation, the characteristics of the flow are largely determined by the type and density of vegetation as well as the depth and velocity of the flow. The flow resistance problem can be classified into two categories: flow over short, submerged vegetation and flow in tall, non-submerged vegetation.

Many references can be found on research into the hydraulic roughness of vegetation, Huthoff et al. [3]. Research has been conducted on experiments with artificial and natural vegetation in flumes, Stephan and Gutknecht [4], Järvelä [2], Righetti & Armanini [5]; on analytical approaches for the vertical velocity profile, Klopstra et al. [6], on biomechanics and streamlining of vegetation, Fahti-Maghadam & Kouwen [7], and on turbulence characterization for submerged rods and vegetation, Nepf and Vivoni [8], López and Garcia [9]. For flow of water through non-submerged vegetation, previous investigations resulted in a series of relationships with only a very limited range of application (i.e., for a very low range of velocity where deflection of vegetation is negligible and for canopies with low vegetation density).

Non-submerged vegetation along rivers and floodplains consumes a great amount of energy and momentum from the flow, and is often found to be in the region with the most roughness. Estimation of the roughness coefficient in this region is a major factor in construction of river stage- discharge curves, especially during flood events. The relationship between flow velocity (and hence discharge) and flow depth (and hence area of inundation) in rivers is commonly established through a resistance relationship, such as Manning's equation. Mostly, practitioner used photographs and tables to estimate Manning's n resistance coefficient values, Chow [10], Barnes [11].

Patryk and Bosmajian [12] developed a quantitative procedure for predicting the Manning's n value of non- submerged vegetations. The analytical results showed that the n value increased as depth if the vegetation density remained relatively constant with flow depth. Turner and Chanmeesri [13] measured the resistance coefficient of wheat vegetation under non- submerged conditions. They found that the resistance coefficient per unit length decreases as the water depth increases. Chiew and Tan [14] published their field observation on the resistance of non- submerged grass to water flow. Their research showed that the flow resistance was independent of water depth. Shen and Chow [15] used horse hair in channel to simulate non- submerged vegetation, the experiment results showed that the flow resistance decreases as the water depth increases in turbulent flow. The different results above are perhaps caused due to the different density and kinds of vegetation in their research. It also means that the effect of non- submerged vegetation on flow resistance is not clear yet. It needs to further study. The Acorus Calmus L (Fig. 1) is a kind of typical non- submerged vegetation. It is widely planted in river or wetland, but few researches have been done on the effects of these plants on the flow. In this paper, the Acorus Calmus L is chosen to model vegetation to study its effects on water flow

.

Fig. 1 Acorus Calmus L

2. THEORETICAL CONSIDERATIONS

Roughness coefficient represents the effect of channel roughness on energy loss in flowing water. A variety of formulas exist for computing the flow resistance for typical open-channel flow cases. The French engineer “Antoine Chézy” (1775) developed probably the first uniform- flow formula, Chézy formula. He related the average velocity U (m/s) of steady uniform flow to the channel slope S (m/m), the hydraulic radius R (m) and a coefficient, which express the boundary roughness. The equation is usually written in the form:

$$U = C\sqrt{RS} \tag{1}$$

Where, *C* [$m^{1/2}/s$] is a factor of flow resistance, called *Chézy's C*. To determine Chézy's factor various formulas have been developed (see Chow [10], pp. 94-98).

Manning formula has become the most widely used of all uniform-flow formulas for open-channel flow computations, Chow [10], owing to its simplicity of form and to the satisfactory results to practical applications. It can be defined in English units as:

$$U = \frac{K_n}{n} R^{2/3} S^{1/2} \tag{2}$$

In which n is the roughness coefficient ($T/L^{1/3}$; $s/m^{1/3}$) specifically known as *Manning's n*; K_n = 1.486 for English units and K_n = 1.0 for SI units; R is the hydraulic radius (L; ft, m); U is the cross sectional average velocity (L/T; ft/s, m/s); S is the water surface slope (L/L; m/m). Application of this equation requires knowledge of an appropriate value for *n*, which depends on channel geometry, substrate, vegetation and flow conditions.

Comparing Equations (1) and (2), it can be seen in meter units that:

$$C = \frac{R^{1/6}}{n} \tag{3}$$

The discharge Q (m^3/s) can be then given by:

$$Q = AU = B\frac{h^{7/6}}{n}\sqrt{RS} \tag{4}$$

Where B: the channel width (m) and A: the cross sectional area of the flow (m^2). In our study R is approximated by the water depth h: R=h.

Drag is generated when a fluid moves through vegetation. The drag creates velocity gradients and eddies that cause momentum losses. These losses are significant for a wide range of flow conditions, and existing techniques for the prediction of resistance do not take these into account, leading to under predictions of resistance. Because vegetative drag can have a profound effect on the velocity and, thus, the water surface elevation, any expression of the flow conditions in a vegetated channel must include it.

In this study, Manning's n is used to denote the resistance coefficient. A relation for non-submerged vegetation can be formulated from the principle of conservation of linear momentum. Following a derivation similar to that for the de Saint Venant Equation, the sum of the external forces in a control volume (CV) is equated to the rate of change of linear momentum:

$$\sum F = ma = m\left(\frac{dU}{dt}\right) \tag{5}$$

Considering only the x-component of the linear momentum, the right side of Equation (5) can be expanded to form Equation (6) as follows:

$$\frac{dM}{dt} = \frac{\partial}{\partial t}\left[\left(\rho U\, A\right)\Delta x\ \right] + \left(\frac{\partial \rho\, U^2\, A}{\partial x}\right)\Delta x - \left(\rho\, q_s\, U_s\right)\Delta x \tag{6}$$

The external forces include gravity (F_g), pressure (F_p), drag (F_d), and friction (F_f), for which the x-component can be described as:

$$F_g = \rho\ g\ A\,\Delta x\ S \tag{7}$$

$$F_p = -\rho\, g\left(\frac{dy}{dx}\right) A\,\Delta x \tag{8}$$

$$F_d = -\frac{\rho}{2} C_d\, A_d\, U^2 A\,\Delta x \tag{9}$$

$$F_f = -\rho\, g\, A\,\Delta x\, S_f \tag{10}$$

Where: F_g = external gravity force on the CV, S = bed slope (L/L); F_p = external pressure force on the CV; F_d = external drag force exerted by the vegetation on the CV; ρ=Fluid density (M/L^3); C_d=an empirical dimensionless drag coefficient; U=approach velocity of the fluid (L/T); A= the cross sectional area of the flow (L^2); A_d= vegetation density (L^{-1}); F_f = external friction force due to shear on the boundary; S_f = friction slope (i.e. the slope of the momentum grade line). Collecting these terms and rearranging, the left-hand side of Equation (5) gives:

$$\sum F = A\rho\, g\,\Delta x\left[S - S_f - \frac{C_d\, A_d\, U^2}{2g} - \frac{dy}{dx}\right] \tag{11}$$

Using Equations (6) and (11), assuming the seepage inflow and the boundary shear are negligible and rearranging yields Equation (12):

$$\frac{A_d\, C_d}{2g} = \frac{S}{U^2} - \frac{1}{g\,U^2}\frac{dU}{dt} - \frac{1}{gU}\frac{dU}{dx} - \frac{1}{U^2}\frac{dy}{dx} \tag{12}$$

Which is the unsteady, gradually varied version of the de Saint Venant Equation for linear momentum replacing the boundary shear term with a drag term. The corresponding steady, gradually varied equation is:

$$\frac{A_d\,C_d}{2g} = \frac{S}{U^2} - \frac{1}{g\,U}\frac{dU}{dx} - \frac{1}{U^2}\frac{dy}{dx} \tag{13}$$

And the steady, uniform equation is:

$$\frac{U^2\,A_d\,C_d}{2g} = S \tag{14}$$

Equating the slope term in Equation (14) to the slope term in Manning's Equation (Equation (2)), a relation for Manning's n is established as:

$$n = K_n\,R^{2/3}\left[\frac{C_d\,A_d}{2\,g}\right]^{1/2} \tag{15}$$

Equation (15) requires an estimate of the drag coefficient C_d and the corresponding vegetation area.

The blockage provided by the vegetation is characterized by its frontal area per volume, called the vegetation density A_d (L^{-1}; m^{-1}). The frontal area, A_f (L^2; m^2) of ten randomly selected plants was estimated at centimeter intervals in the vertical, Δz=1cm, by tracing the plant silhouettes onto grid paper. Averaging over the ten plants and considering n_P is the number of plants/m^2, the vegetation density was then calculated as:

$$A_d = n_P\,\frac{A_f}{\Delta z} \tag{16}$$

3. LABORATORY EXPERIMENTS

The experimental part of the research was made in HOHAI Laboratory of Hydraulics. Tests were conducted in a 26m long, 0.7m height and 0.5m wide rectangular, glass-walled flume. The slope of the flume was fixed at 0.07692%. Discharge was measured with a submerged weir at the end of the flume, and uniform flow was ensured by the adjustment of a tail- gate at the downstream end. Flow depths were measured with two depth gauges at 12m and 16m (Fig. 2); the bed of the flume (study area) was roughened by a 12 m long and 2cm thick layer of PVC.

For the tests without vegetation, a fixed set of 8 discharges was used for the study. The uniform flow depth was measured at the equilibrium condition. For the vegetated bed (Fig. 4), a longitudinal section of artificial vegetation selected to simulate Acorus calamus L, was installed over a length of 12 m (study area see Fig. 2).

The model vegetation was about 50cm - 60cm height. Each plant consisted of six blades of width w=1.7cm – 1.9cm, bundled to a basal stem of an average diameter 1.15cm and average height 9.12cm. The blades were made from plastic. The morphology of a single plant is shown in Fig. 3. The plants were arranged in a staggered pattern, with longitudinal and transverse spacing of 15 cm, 30cm and 45cm, by sticking the upper end of the plant into drilled holes. Four densities (280, 240, 60 and 40plants) were used.

A 3-D Acoustic Doppler Velocimeter “ADV” (Fig. 5) was used to measure the local flow velocities for different vegetation concentrations and discharges. The used ADV was made by SonTek. For the four densities the velocity was measured at several points in the vertical. Three minutes records were collected and the sample-reporting rate 25Hz was used. The data was filtered after measurements. For the filtering and other post-processing and analysis of ADV data, WinADV-program was used.

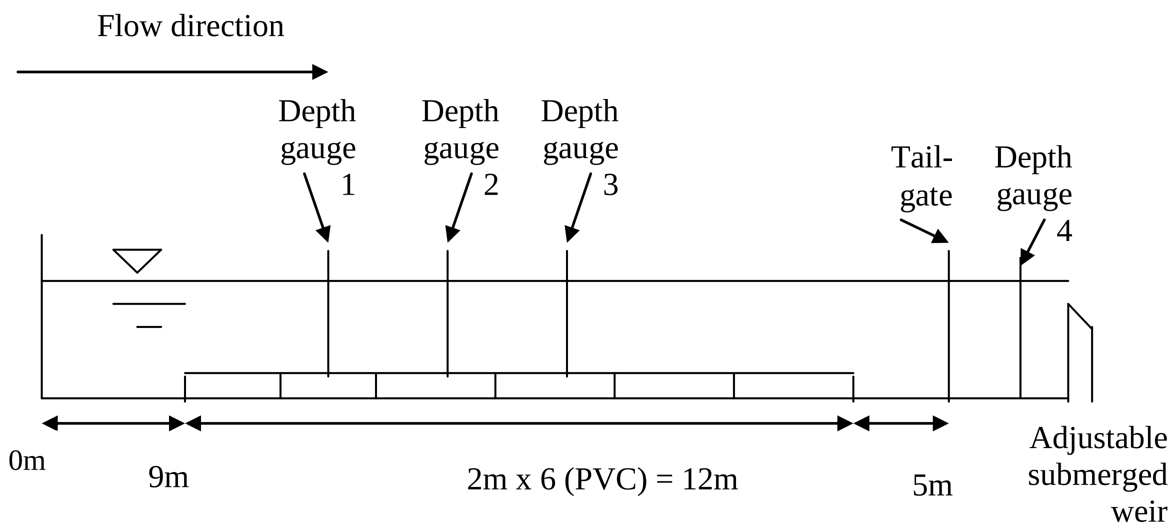

Fig. 2 Experimental set-up in the flume without vegetation. The vegetated-bed test facilities were equal but with vegetation mounted in the PVC layer (long- view; not to scale)

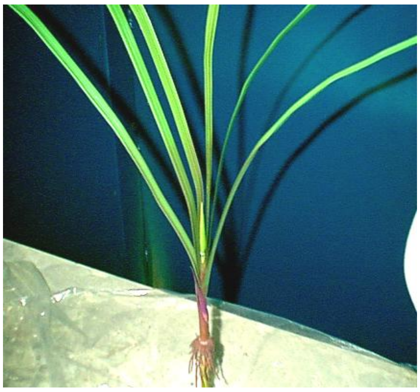

Fig. 3 The morphology of a single plant

Fig. 4 Experimental facilities for vegetated-bed tests.

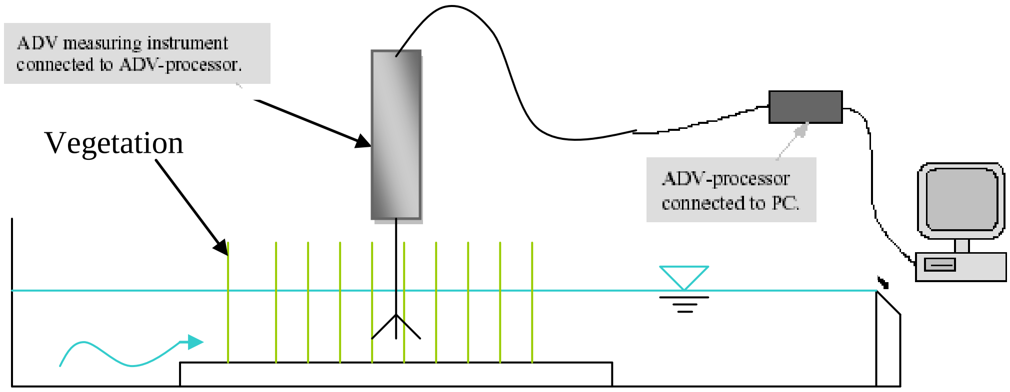

Fig. 5 Experimental facilities for velocity measurement

4. FLOW THROUGH NON-SUBMERGED VEGETATED-BEDS

A series of laboratory experiments have been carried out as it was explained above, to better understand the influence of vegetation density and flow depth on the resistance imposed by vegetation. The roughness of the glass walls is negligible compared to the roughness of bottom. Hence, the flume was assumed to be very wide. Thus for the calculations, the water depth h was used instead of hydraulic radius R. The measured and calculated values (using an n=0,011) of water depths and discharges for the non- vegetated bed are plotted in Fig. 6. Water depth- discharge relationship for flow through different vegetation densities is represented in Fig. 7.

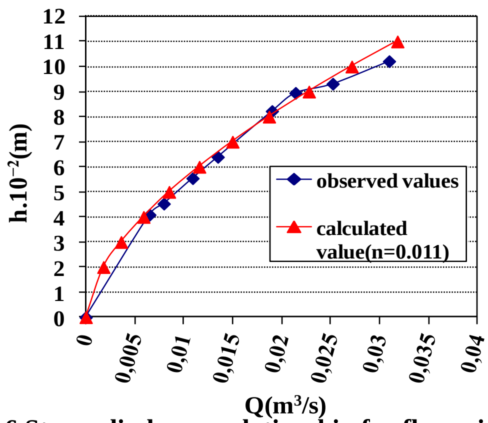

Fig. 6 Stage- discharge relationship for flow without vegetation

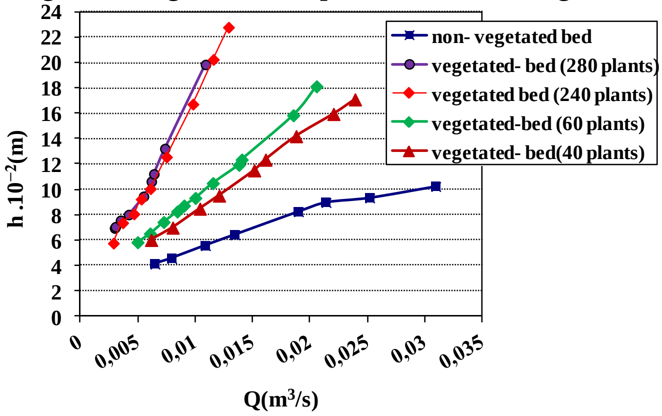

Fig. 7 Water depth- discharge relationship for flow through vegetation.

Fig. 6 shows that the water depth increases with discharge in channels without vegetation, and the measured water depths and discharges agree with the computed values using an n=0.011. The relationship between flow depth and discharge depends significantly on the vegetation density (Fig. 7); as the vegetation density increases, the water depth increases with increasing discharge. The curves for the four patterns show that creating additional boundaries to the clear channel area, by separating them with plants significantly increases resistance. The close correspondence between the curves for 280 and 240 plants is explained by the small difference between the two densities.

The vegetation density is calculated approximately using Equation (16). The profile of A_d for the case of 280 plants is shown in Fig. 8.

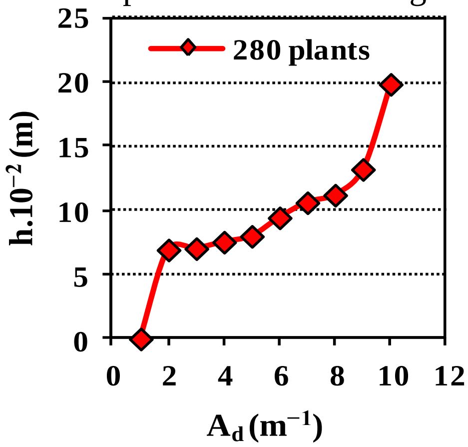

Fig. 8 Profile of vegetation density

From Fig. 8 it is clear that the increase in vegetation density is attributed to increased leaf density, with height for the measured water depths. The drag coefficient is calculated using Equation (14) in SI units and is plotted against water depth in Figure9. Fig. 9 shows that over the lower half of the plant, the drag coefficient C_d increases towards the bed, reflecting the increasing importance of viscous effects. Above the bed, the non-submerged plant produces a constant value of $C_d \approx 1$. An increase in the vegetation density leads to an increase of the flow resistance and to reduction of the drag coefficient.

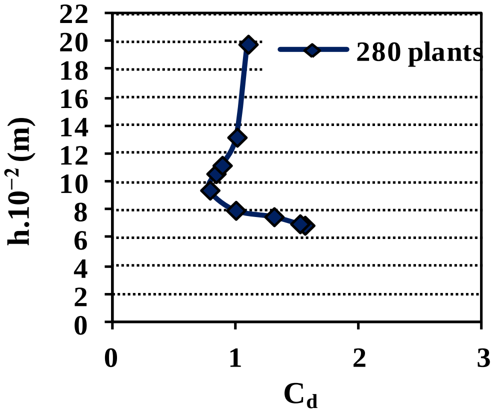

Fig. 9 Profile of drag coefficient for 280 plants.

Manning's n was calculated using Equation (4) for non-vegetated bed and Equation (15) in SI units for channel with vegetation, and was plotted against the flow depth in Fig. 10.

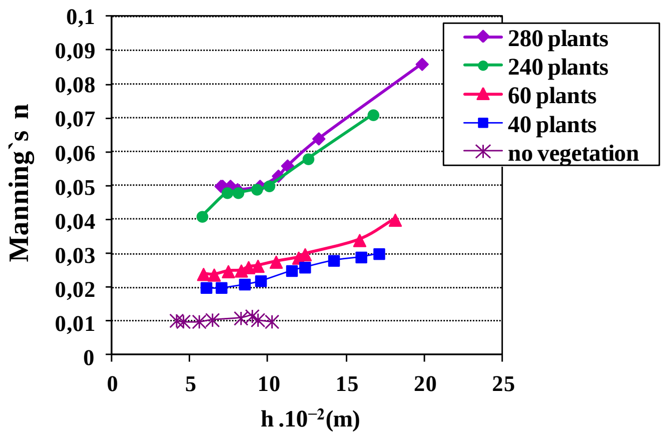

Fig. 10 variation of Manning's n with flow depth for flow through vegetation

Fig. 10 shows for channel without vegetation, Manning's n doesn't change with the increase in water depth; it is approximately constant, varying only between 0.010 and 0.011; which is equal to the value of n expected and used in the calculations.
For the vegetated bed, Manning's n is clearly related to the vegetation density, it also varies with flow condition far more than in unvegetated channels. It is clear that the vegetative roughness increases with water depth. Vegetation density is however one of the most important parameters for drag control: an increase of the vegetation density leads to reduce cross sectional area and increases flow resistance. It is also clear that the distribution pattern of the vegetation has a significant effect on the overall resistance. This shows that not only does the presence of vegetation increase Manning's substantially and that this depends on the pattern, but also Manning's varies with flow depth. The values for the 4th density (40 plants) are consistently lower than for the 1st density (280 plants).

Mean velocities (u, v, w) corresponding to the stream- wise (x), lateral (y), and vertical (z) directions, respectively were measured using three-dimensional acoustic Doppler velocimeter (ADV). The ADV was placed in the center of four plants, the velocity was measured in several points in the vertical and the data was analyzed using WinADV program. Mean velocity profile for vegetated bed for the case of 240 plants with a discharge of 0.0055m^3/s, where u (z) is plotted against z/h, where z is the vertical distance from the channel bed, is illustrated in Fig. 11.

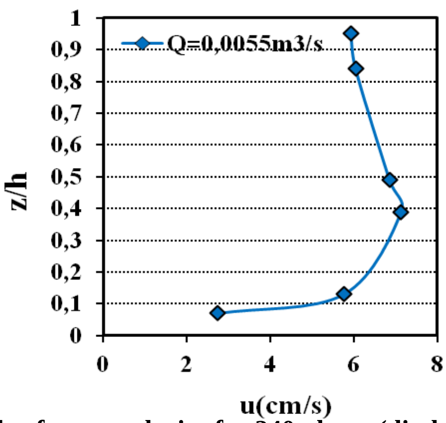

Fig. 11 Profile of mean velocity for 240 plants (discharge Q=0.0055m^3/s)

The observed profile of mean velocity shows the same profile found by Nepf [8]. Vertical variation in velocity reflects the variation in vegetation density Fig. 8. From

velocity profile, two zones could be distinguished: the stem part (lower part) where velocity distribution increases and the leaf part where the velocity decreases slowly. Note that a local velocity maximum appears near the bed in the stem zone, this reflects the decrease in vegetation density in the sheath region of the plant (Fig. 11).
The argument that vegetation significantly reduces velocity is based mostly on the report of increasing Manning's n values in streams with in channel vegetation. So because vegetation contributes to flow resistance, it reduces flow velocities and increases depths. Also the additional drag exerted by plants reduces the mean flow velocity within vegetated region relative to non-vegetated ones. The greater momentum absorbing area provided by the vegetation has significant effect on the mean flow field of the entire channel. For the vegetation density considered the presence of foliage significantly reduces the mean velocities as shown in Fig. 11.

In the vegetation patterns investigated, most flow is concentrated in the clear channels between the vegetation. Much of the flow resistance in these channels originates from the momentum transfer between the slow flow within the vegetation and the relatively fast flow in the clear channels. This momentum transfer decelerates the flow in the clear channels adjacent to the boundaries much more effectively than solid boundaries, causing a highly non-uniform velocity distribution. For the same discharge, vegetation therefore results in lower, but more varied velocities than would otherwise occur. This effect is important not only for resistance assessment, but has implications for sediment movement (and hence morphological change) and the velocity attributes of habitat for aquatic species.

5. CONCLUSIONS

A flow resistance model for non-submerged vegetation conditions is presented. It is quantitatively described by Equation (15). The equation requires an estimate of the drag coefficient C_d and the corresponding vegetation area. A very important variable in the flow resistance model is the vegetation density. The most useful application of the flow resistance model proposed is in predicting the variation of Manning's n with flow depth.

The relationship between flow depth and discharge depends significantly on the vegetation density. Vegetation produces high resistance to flow and, as a result has a large impact on water levels. Manning's n varies significantly with flow depth, and it is related to the vegetation density. Vegetation density is however an important parameter in flow resistance. The flow resistance is also influenced significantly by the distribution pattern of the vegetation. The mean velocity decreases with flow for which the vegetative roughness increases with decreasing velocity. The mean velocity profile is set by the vertical structure of the vegetative drag, thus the mean velocity is linked to details of vegetation morphology. Vegetation grouped into staggered pattern is much effective in reducing flow rate than any other pattern.

In the present research, a limited amount of field data has been used to calibrate and illustrate the use of the flow resistance model. Hopefully, further experiments will be conducted for additional verification of the model and the effects of unsubmerged vegetation on the flow resistance and structure should be investigated more exactly. Only laboratory flume tests were made, tests in natural channels and floodplains should be made to confirm the results. In this study, Only Acorus Calmus L was investigated, in order to compare the influence of different kinds of non-submerged vegetation, tests should be made.

ACKNOWLEDGMENTS

This work is supported by National Natural Science Foundation of China, (No. 30490235).

NOMENCLATURE

The following symbols are used in this paper:
R= the hydraulic radius (R=flow depth for infinitely wide channel), (L; m);
S= the water surface slope (L/L; m/m);
B= the channel width (L; m);
C= Chezy roughness coefficient ($L^{1/2}$/T; $m^{1/2}$/s)
n= the Manning resistance coefficient (T/$L^{1/3}$; s/$m^{1/3}$);
h= water depth (L; m);
Q= the flow discharge (L^3/T; m^3/s);
F_g= external gravity force on the CV;
F_p= external pressure force on the CV;
F_d= external drag force exerted by the vegetation on the CV;
F_f= external friction force due to shear on the boundary;
ρ= Fluid density (M/L^3; kg/m^3);
C_d= an empirical dimensionless drag coefficient;
U= approach velocity of the fluid (L/T; m/s);
A= the cross sectional area of the flow (L^2; m^2);
A_d= vegetation density (L^{-1}; m^{-1});
A_f= the frontal area of the plant (L^2; m^2);
g= gravitational constant (= 9.81m/s^2);
z= the vertical distance from the channel bed (L; m);
u=Mean velocity corresponding to the stream- wise (x) (L/T; m/s).

REFERENCES

[1] James, C. S., Birkhead, A. A., Jordanova, K. A., Kotschky, C. N., & Makoa, M. J., Interaction of reed distribution, hydraulics and river morphology, (Water Research Commission Report No. 856/1/01), Pretoria, South Africa, 2001.

[2] Järvelä, J., Flow resistance of flexible and stiff vegetation: a flume study with natural plants, *Journal of Hydrology,* Vol. 269, pp. 44-54, 2002.

[3] Hutchoff, F., Augustijn, C. M., & Hulstcher, J. M. H. Hydraulic resistance of vegetation in river flow applications, *proceedings of the 7th International Conference on Hydroscience and Engineering (ICHE-2006)*, Sep10-13, Philadelphia, USA, 2006.

[4] Stephan, U., & Gutknecht. D., Hydraulic resistance of submerged flexible vegetation, *Journal of Hydrology*, Vol. 269, pp. 27-43, 2002.

[5] Righetti, M., & Armanini. A., Flow resistance in open channel flows with sparsely distributed bushes, *Journal of Hydrology,* Vol. 269, pp. 55-64, 2002.

[6] Klopstra, D., Barneveld, H.J., Van Noortwijk, J.M. & Van Velzen, E.H. Analytical model for hydraulic roughness of submerged vegetation, *Proceedings of the 27th International IAHR Conference,* San Francisco, 1997.

[7] Fathi-Maghadam, M., & Kouwen, N., Nonrigid, Nonsubmerged, Vegetative Roughness on Floodplains, *Journal of Hydraulic Engineering*, Vol. 123, N° 1, pp. 51-57, 1997.

[8] Nepf, H. M., & Vivoni, E. R., Flow structure in depth-limited vegetated flow, *Journal of Geophysical Research*, Vol. 105, pp. 28547-28557, 2000.

[9] López, F., & García, M. H., Flow and Turbulence Structure of Open-Channel Flow through Non-Emergent Vegetation, *Journal of Hydraulic Engineering*, Vol. 127(5), pp. 392-402, 2001.

[10] Chow, V. T., *Open-Channel Hydraulics*, McGraw-Hill, New York, pp. 74-81, 1959.

[11] Barnes, H. H., Roughness characteristics of natural channels, U.S. Geological Survey Water-Supply Paper 1849, Washington. D. C., 1967.

[12] Petryk, S., & Bosmajian, G., Analysis of flow through vegetation, *Journal of the Hydraulics Division*, Vol. 101, pp. 871-884, 1975.

[13] Turner, A. K., & Chanmeesri, N., Shallow flow of water through non- submerged vegetation, *Agricultural water management*, Vol. 8, pp. 375-385, 1984.

[14] Chiew, Y. M., & Tan, S. K., Frictional resistance of overland flow on tropical turfed slope, *Journal of Hydraulic Engineering*, Vol. 118, N° 1, pp. 92-97, 1992.

[15] Shen, H., & Chow, Y., Variation of roughness coefficients for unsubmerged and submerged vegetation, *Journal of Hydraulic Engineering*, Vol. 125, pp. 934-942, 1999.