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Flow resistance in open channel flows with sparsely distributed bushes

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Abstract

The paper faces the problem of the resistance due to vegetation in a river characterized by fully submerged vegetation formed by concentrated colonies of bushes. The flow presents strong spatial variations between plants that make unreliable the traditional approach based on time averaging of turbulent fluctuations. A more useful model, based on time and spatial averaging is proposed. In the paper the necessary closure hypotheses are also discussed. The vertical distribution of mean velocity and turbulence stress have been measured with laser Doppler anemometry techniques, by means of spatial and time-averaging rules. Based on the double-averaged velocity and Reynolds stress profiles, an analytical two-layer model is proposed, in order to describe uniform flow conditions in the whole flow depth. Theoretical results are compared with the results of a series of experimental tests carried out in a laboratory flume.

Keywords: Vegetated channels, Turbulence model; Laser Doppler anemometry

1. Introduction

The vegetation along the bed and banks of rivers plays an important role on the hydrodynamic behavior, on the ecological equilibrium and on the characteristics of the river. Hydraulic aspects of the vegetation, hereafter investigated, concern some general features of the flow, and in particular turbulence, mixing and resistance to the flow.

As far as flow resistance is concerned, the vegetation can be roughly classified into two different categories:

- plants having height h_v markedly lower than the flow depth h, like in grassed channels. In this case, the equivalent resistance due to vegetation can be described as a wall shear stress and the related roughness coefficient can be expressed as a function of vegetation height and of some biomechanical vegetation characteristics (Kouwen et al., 1969; Kouwen, 1988);
- plants, the height of which is of same order of magnitude of the flow depth or higher, like bushes or trees. In this case, the equivalent resistance can be evaluated as the combined effect of the hydrodynamic drag of the single plants. (Petryk and Bosmanjian, 1975).

Following this approach (Petryk and Bosmanjian, 1975), in case of partially submerged plants, the pressure unbalance due to vegetation p_P (drag force per bed surface) can be expressed as:

$$p_P = nD_{pi} = nC_D A_{pi} \rho \frac{U^2}{2} \tag{1}$$

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where n is the number of plants per bed surface, D_{pi} is the force exerted by the flow on the single ith plant; A_{pi} is the area of the ith plant projected in streamwise direction, ρ is the water density and C_D is the drag coefficient of a single plant, U is the mean flow velocity. In this case the momentum balance in streamwise direction, applied to a control volume of length L, allows one to estimate the global flow resistance coefficient, here expressed in terms of Strickler coefficient:

$$K_{eq} = \frac{1}{\sqrt{R_h^{4/3}\left(\frac{C_D \sum A_{pi}}{2gA_cL} + \frac{1}{K_b^2 R_h^{4/3}}\right)}} \qquad (2)$$

where R_h is the hydraulic radius, A_c, the cross-section area of the flow, K_b, the Strickler coefficient due to bed roughness, g, the gravity acceleration, and K_{eq} is the equivalent Strickler coefficient. The summation index $\sum$ is extended to the N number of plants that are present in the reach having length L.

Eq. (2) has been validated in different situations (Ming and Shen, 1973; Petryk and Bosmanjian, 1975).

In Eq. (2), however, the drag coefficient C_D is probably the most uncertain parameter: its value depends on many factors and on the reference velocity U used in its definition. Differently from the case of an isolated cylinder, here U is not an undisturbed velocity but is the mean velocity, the value of which is determined by the plant itself. Other important parameters, influencing the value of the drag coefficient, are the relative position of the plants and their density.

The influence of the Reynolds number $Re_p = Ud_p/\nu$, where d_p is the diameter of the cylinders used to simulate the plants and ν the cinematic viscosity, on the drag coefficient has also been widely analyzed (Nepf, 1999). One of the most important conclusions is that the presence of upstream plants affects the wakes dynamics of downstream plants, because of the *sheltering effect* that diminishes the drag of the downstream elements. The strength of the sheltering depends on the plants mutual position: staggered or randomly distributed plants configurations experience higher drag rather than the aligned ones (Ming and Shen, 1973). Vegetation density is however one of the most important parameters for drag control: an increase of the vegetation density leads to an increase of the flow resistance and to a reduction of the drag coefficient (Ming and Shen, 1973; Petryk and Bosmanjian, 1975; Armanini and Righetti, 1998; Nepf, 1999).

The ratio between the vegetation drag and the bed shear resistance has not been directly measured yet. The numerical simulations of Lopez and Garcia (1998) show that, increasing the plants density, the intensity of the uncovered bed shear stress is reduced. This corroborates the usual approximation where, if the density of the plants is sufficiently high, the global resistance of a water course is determined only by the plants resistance (Temple, 1987).

Also the flexibility of the plants exerts a significant influence on the hydraulic resistance, increasing the complexity of the problem. The bending of the plants under the effects of the flow let the plants assume a more streamlined configuration, this can lead to a significant reduction of the drag coefficient (Tsujimoto et al., 1995; Kouwen and Fathi-Moghadam, 2000; Oplatka, 1998).

The above described method cannot be applied when the vegetation is fully submerged by the flow. In this case, a two-layer flow takes place: the lower one characterized by the flow through the vegetation and the upper one by the flow above the vegetation. In general, the portion of the flow passing through the vegetation is not negligible, if compared with that flowing above, even if the mean velocity in the vegetated region is much lower than that in the surface-flow layer. The turbulent structure through and above the vegetation has not been fully understood yet; the extensive studies of unconfined canopy flow in meteorology and agricultural engineering can be helpful to understand it (Finnigan, 2000), even though differences exist in the turbulence structure of the upper layer between canopies and confined free surface flows (Nepf and Vivoni, 1999).

Several types of two-layer turbulence models exist, trying to describe the vertical flow velocity profile and the hydraulic roughness of submerged vegetation (Tsujimoto and Kitamura, 1990; Tsujimoto et al., 1992; El-Hakim and Salama, 1992; Klopstra et al., 1997; Armanini and Righetti, 1998; Meijer and Van Velzen, 1999). Most of them are based on simple turbulence closure schemes. However, these schemes have often been validated based just on local

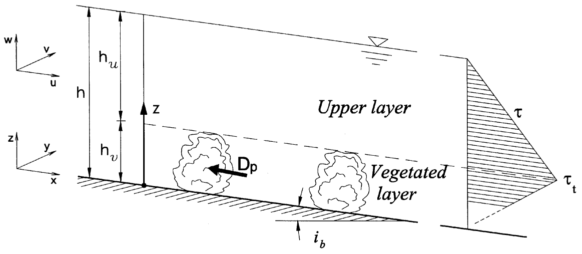

Fig. 1. Sketch of coordinate axes and two-layer structure.

measurements of mean velocities and turbulence mean characteristics. This implies that these local measurements have been implicitly considered as representative of the entire flow field.

Fully submerged vegetation acts on the flow field as a low relative submergence roughness, characterized by spatial variability of the length scales of the same order of magnitude of the upper layer depth. In this case, a proper approach derives from a double averaging procedure on the classical Navier–Stokes equations, where the classical time-averaged Reynolds equations should be supplemented by spatial area averaging procedure in the plane parallel to the average bed. A similar procedure has been firstly applied to canopies problems (Wilson and Shaw, 1977; see Finnigan, 2000 for references) and also to rough bed, open-channel flows with small relative submergence (Nikora et al., 2001).

The present paper proposes an analytical two-layer model, able to describe the characteristics of open channel flows with sparsely distributed bushes on the bed. The present method is based on a generalized mixing length closure that takes into account the spatial heterogeneities of the flow field, due to presence of plants. The model was validated on the basis of laboratory experiments; data were treated following the above-mentioned double-averaging technique.

2. Mathematical framework

The concepts of spatial and temporal averaging, used to build up the mathematical frame to set the analytical model, are hereafter briefly summarized. Fully submerged vegetation is considered as a 2D, steady flow in the x–z plane (see Fig. 1). Applying the double averaging technique (in time and in the space) to the Navier–Stokes equation, and neglecting viscous terms, two sets of differential equations are obtained:

- *upper layer*:

$$gi_{\mathrm{b}} - \frac{\partial\langle\overline{u'w'}\rangle}{\partial z} - \frac{\partial\langle\tilde{u}\tilde{w}\rangle}{\partial z} = 0 \tag{3}$$

$$g - \frac{1}{\rho}\frac{\partial\langle\bar{p}\rangle}{\partial z} + \frac{\partial\langle\overline{w'2}\rangle}{\partial z} + \frac{\partial\langle\tilde{w}^2\rangle}{\partial z} = 0 \tag{4}$$

- *vegetated layer*:

$$gi_{\mathrm{b}} - \left\langle\frac{\partial\tilde{p}}{\partial x}\right\rangle - \frac{1}{A}\frac{\partial A\langle\overline{u'w'}\rangle}{\partial z} - \frac{1}{A}\frac{\partial A\langle\tilde{u}\tilde{w}\rangle}{\partial z} = 0 \tag{5}$$

$$g + \frac{1}{\rho}\frac{\partial\langle\bar{p}\rangle}{\partial z} + \frac{1}{\rho}\left\langle\frac{\partial\tilde{p}}{\partial z}\right\rangle + \frac{1}{A}\frac{\partial A\langle\overline{w'2}\rangle}{\partial z} + \frac{1}{A} \times \frac{\partial A\langle\tilde{w}^2\rangle}{\partial z} = 0 \tag{6}$$

where the brackets ($\langle X\rangle$) and the linear overbar ($\bar{X}$) refer respectively to the spatial averaging along (x, y) plane and to time-averaging, i_{b} the bed slope, A is the ratio between the area occupied by fluid and the total area of the averaging region in the xy plane at level z: it's values ranges between 0 and 1 in the vegetated region. Wavy overbars denote the difference between time-averaged and double-averaged values ($\tilde{X} = \bar{X} - \langle\bar{X}\rangle$) and represent the dispersive stresses due to spatial averaging of the Navier Stokes equations.

Eqs. (3) and (5) represent the momentum balances in the longitudinal direction, while Eqs. (4) and (6) the balances in the vertical one. The integration of Eqs. (3) and (5) from the free surface flow to the generic level z, leads to the following relationships for the total stress distribution:

- *upper layer*:

$$\frac{\langle\tau\rangle}{\rho} = gi_{\mathrm{b}}[h - z] = -\langle\overline{u'w'}\rangle - \langle\tilde{u}\tilde{w}\rangle \tag{7}$$

- *vegetated layer*:

$$\frac{\langle\tau\rangle}{\rho} = gi_b\left\{h - h_v + \int_z^{h_v} A(z)\mathrm{d}z\right\}$$
$$= -A\langle\overline{u'w'}\rangle - A\langle\tilde{u}\tilde{w}\rangle + \int_z^{h_v}\left[\frac{A(z)}{\rho}\left\langle\frac{\partial\tilde{p}}{\partial x}\right\rangle\right]\mathrm{d}z \tag{8}$$

According to Nikora et al. (2001) the last term in Eq. (7), which is usually negligible in uniform flow condition, becomes important in the region near to the bed surface in case of rough wall with low submergence. In the present situation, bushes act as roughness elements, so we would expect a certain influence of this term near to vegetation crests.

In Eq. (8) the gravity forces are balanced by the two turbulence terms (first and second terms right hand side of Eq. (8)) incremented by an additional tem (third term on the right hand) which is due to the normal stresses acting on the plants, the same terms responsible of the drag resistance.

3. The simplified analytical turbulence model

Starting from Eqs. (7) and (8) a generalized two-layer mixing length model has been established: the generalized mixing length, $\langle l\rangle$, can be considered as a horizontally averaged length scale, characterizing the turbulent momentum exchange between adjacent horizontal fluid layers; $\langle l\rangle$ is in general a function of the distance z from the bed surface.

The hypothesis on the vertical distributions of shear stresses $\langle\tau\rangle$ and on the vertical distribution of the mixing length $\langle l\rangle$ in the two layers are the crucial point of this model. These hypotheses are assumed as follows (Fig. 1):

- *in the upper layer*: a linear profile for shear stresses is assumed, as a consequence of the momentum balance in uniform flow conditions:

$$\langle\tau\rangle = \tau_t[1 - (z - h_v)/h_u] \cong -\rho\langle\overline{u'w'}\rangle(z) \tag{9}$$

where τ_t is the shear stress at layers interface, i.e. from Eq. (7): $\tau_t = \rho g h_u i_b$; and for the mixing length the following profile:

$$\langle l\rangle = [l_0 + k(z - h_v)]\sqrt{\langle\tau\rangle/\tau_t}$$
$$= [l_0 + k(z - h_v)]\sqrt{1 - (z - h_v)/h_u} \tag{10}$$

where l_0 is the value of the mixing length at the interface level and $\kappa = 0.41$ is the von Kàrmàn constant;

- *in the vegetated layer*: the simpler possible distribution, a linear profile for shear stress is also assumed:

$$\langle\tau\rangle = \tau_t(z/h_v) \tag{11}$$

and a constant value for the mixing length is assumed:

$$\langle l\rangle = \text{constant} = l_0 \tag{12}$$

Applying the boundary conditions to these equations, the following mean velocity profiles are obtained:

- *upper layer*:

$$\frac{\langle\bar{u}\rangle}{u_{*t}} = \frac{1}{k}\ln\left[1 + \frac{\kappa(z - h_v)}{l_0}\right] + \frac{2}{3}\frac{h_v}{l_0} \tag{13}$$

- *vegetated layer*:

$$\frac{\langle\bar{u}\rangle}{u_{*t}} = \frac{2}{3}\frac{h_v}{l_0}\left(\frac{z}{h_v}\right)^{3/2} \tag{14}$$

where $u_{*t} = \sqrt{\tau_t/\rho}$ is the shear velocity at the top of the vegetated layer. The integration of Eqs. (13) and (14) through the flow depth allows one to obtain the ratio (α) between the averaged velocity in the vegetated layer, U_v, and the averaged flow velocity, U:

$$\alpha = \frac{U_v}{U} = \frac{4}{15}\left[\frac{2}{3} - \frac{l_0}{\kappa h_v} + \frac{h_v}{h}\left(\frac{l_0}{\kappa h_v} - \frac{2}{5}\right)\right.$$
$$+ \frac{l_0}{\kappa h_v}\left(1 + \frac{h_v}{h}\left(\frac{l_0}{\kappa h_v} - 1\right)\right)$$
$$\left.\times\ln\left(1 + \frac{\kappa h}{l_0} - \frac{\kappa h_v}{l_0}\right)\right]^{-1} < 1 \tag{15}$$

Some consideration about the assumptions on the mixing length formulation and the shear stress distribution in the vegetated layer are worth of note.

In particular the problem of closure of the proposed turbulent model now concerns the evaluation of l_0, the mixing length in the vegetated layer.

The mixing length represents an integral scale of the turbulent diffusion–dispersion process, deriving from the *temporal* and *spatial* integration of Navier–Stokes equations; it has to be validated on the basis of the experimental data, as it is usually done for this kind of semi-empirical algebraic turbulence models. In particular, as far as concerns the vegetated layer, l_0 can be reasonably related to the two integral length-scales that are the responsible of the turbulence production:

- the characteristics dimension of the plants, that is the plants height h_v, and
- the characteristic distance between plants, that can be represented by means of the dimensionless parameter vegetation density $V_d = h_v^2/(a_x a_y)$, where a_x, a_y are the longitudinal and transversal distances between adjacent plants respectively.

Therefore the following formulation is proposed for l_0 :

$$\frac{l_0}{h_v} = C_1(1 - e^{-C_2}) \tag{16}$$

Concerning the values assumed by the parameter C_1, it is expected that they should increase with the vegetation density V_d, taking reason to the expected reduction of the ratio $\alpha = U_v/U$ with vegetation density (cf. Eq. (15)).

This formulation for the mixing length l_0 presents some analogies to the exponential mixing-length formulae proposed for rough boundary-layer flows (Cecebi and Chang, 1978; see also Hinze, 1975; Nezu and Nakagawa, 1993), except for the dependence of l_0 also on the vegetation density through C_1.

The relationship between the parameters C_1 and C_2 and the vegetation density have to be experimentally evaluated.

The assumptions on the shear stress profile in the vegetated layer affects the velocity profile distribution all along the flow depth. The shear stress distribution proposed in Eq. (11) is very simple and it is consistent with the hypothesis of constant value for the mixing length l in the vegetated layer (Eq. 12). From Eq. (11) it follows that the bed shear stress vanishes; this hypothesis is already used by other authors (Tsujimoto and Kitamura, 1990; El-Hakim and Salama, 1992) and restricts the application of the model to sufficiently dense vegetation, for which the bed shear stress is negligible compared to plants hydrodynamic resistance.

The proposed two-layer model allows one to extend the evaluation of hydrodynamic resistance to situations in which the plants are completely submerged, as proposed in Eqs. (1) and (2). In this case, the vegetation drag can be evaluated as a function of the averaged vegetated layer velocity U_v instead of the overall averaged velocity U. The result of the modification of the Eqs. (1) and (2) is the following:

$$p_P = nC_D A_{p_i} \rho \frac{U_v^2}{2} = \alpha n C_D A_{p_i} \rho \frac{U^2}{2} \tag{17}$$

and

$$K_{eq} = \frac{1}{\sqrt{R_h^{4/3}\left(\alpha^2 \frac{C_D \sum A_{pi}}{2gA_c L} + \frac{1}{K_b^2 R_h^{4/3}}\right)}} \tag{18}$$

Moreover, neglecting the bed shear stress, Eq. (18) can be further simplified:

$$K_{eq} = \frac{1}{r_h^{2/3}\alpha}\sqrt{\frac{2gA_c L}{C_D \sum A_{pi}}} \tag{19}$$

A series of laboratory experiments were carried out, in order to test the assumptions about turbulent shear stress and mixing length hypothesis on which the proposed model is based.

4. Experimental set-up

The experiments were carried out in a rectangular 0.31 m wide and 12 m long tilting flume. All the experiments were performed in uniform flow conditions, in the test area of the flume.

The bottom of the flume was covered by a plastic flat plate, over which sparsely distributed bushes were reproduced. The bushes were simulated by means of plastic wools with nearly spherical shape with 4 cm diameter. The simulated vegetation was set in two

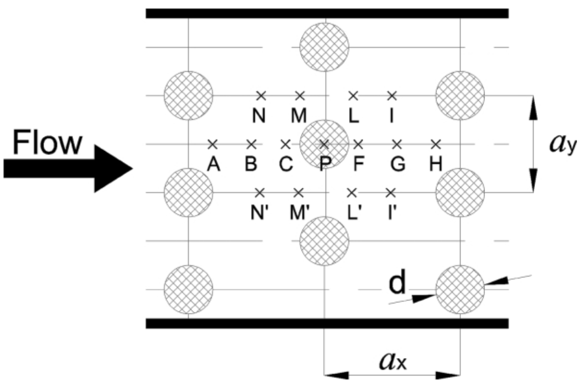

Fig. 2. Top view of the bed, with position of measurements profiles.

different staggered configurations (*sparse* and *dense*), where the relative distances, a_x, a_y were varied (Fig. 2). For each configuration, various runs were performed, where the bed slope varied from 1% to 2% and, as a consequence, also the relative submergence of the bushes, h/h_v. Mean velocities and turbulence characteristics were measured by means of a two-component laser Doppler anemometer for the eight runs summarized in Table 1. A pattern of 11 vertical measurements was performed for each run (Fig. 2). From 10 to 30 point measurements were made at each vertical.

5. Results

In Fig. 3(a) and (b) the data relevant to shear stress and longitudinal velocity profiles respectively for the run 1 ($h/h_v = 3.8$, sparse configuration) are reported. From the figures, the strong variability of the mean flow and turbulence characteristics with the position are evident. This circumstance reinforces the utility of the double averaging procedure.

The shear velocity at the top of vegetated layer used for the dimensionless data has been calculated by linear interpolation of the double-averaged shear stress profile, $-\langle\overline{u'w'}\rangle(z)$, measured in the upper layer by LDA; these values differ for less then 8% to the corresponding values obtained by momentum balance: $u_{*_t} = \sqrt{\tau_t/\rho} = \sqrt{gh_u i_b}$.

The comparison between the double averaged shear stress profiles in Fig. 4 with the corresponding dispersive stresses for sparse configuration in Fig. 5, shows that the latter are almost negligible with respect to the former in the outer part of the upper layer, as assumed in Eq. (9). The dispersive stresses have their maximum values near to the simulated vegetation crests: these stresses become more important at lower submergences; however, they never exceed 25% of the corresponding double-averaged shear stress. Moreover, the double averaged shear stress profiles in the vegetated layer seem to be linear, as assumed in Eq. (11).

In Figs. 6 and 7 the double-averaged velocity profiles are plotted semilogaritmically for sparse and dense configurations respectively. From the figures, it is clear that the velocity profile follows the logarithmic law for the most part of the upper layer. The most evident deviations from this distribution occur near the top of the simulated vegetation, where the actual velocity is higher than the log distribution and deviations increase, diminishing the relative submergence.

In Fig.8 the values of the relative interface mixing length l_0/h_v are reported. The points represent the mixing length values calculated on the basis of

Table 1
Hydraulic conditions for experiments where LDA measurements where performed

Run	Q (m^3/s × 10^3)	H (m)	h/h_v	i_F %	*Re*	*Fr*	Vegetation configuration, $a_x \times a_y$, vegetation density: $V_d = h_v^2/(a_x a_y)$
1	47.8	0.153	3.8	2	77,600	0.82	Sparse configuration, 15 cm × 10 cm, $V_d = 0.107$
2	18.5	0.125	3.1	1	33,000	0.43	
3	16	0.096	2.4	2	38,500	0.67	
4	3.9	0.066	1.65	1	8830	0.24	
5	19.6	12.5	3.1	1	63,250	0.46	Dense configuration, 10 cm × 10 cm, $V_d = 0.16$
6	11.2	10.2	2.5	1	36,130	0.35	
7	5.7	8.04	2	1	18,400	0.26	
8	2.3	0.062	1.5	1	7420	0.15	

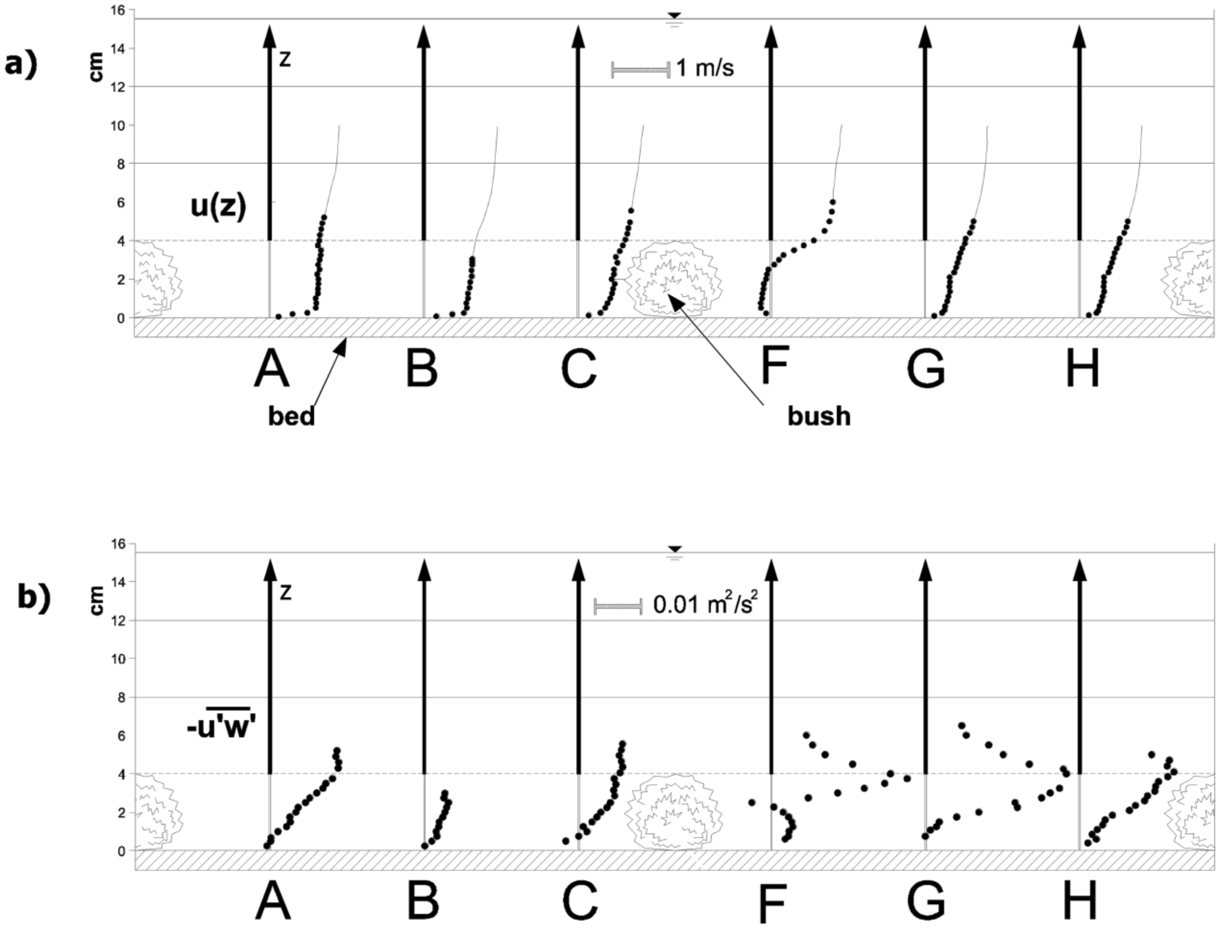

Fig. 3. Longitudinal velocity (a) and turbulent shear stress (b) profiles measured in points A, B, C, F, G, H for run 1.

Eq. (13), in which the experimental data of the velocity profiles are best fitted for each run. The value of the relative mixing length decreases with the relative submergence and increases with the simulated vegetation density. In the same figure, the lines represent the best fit of the calculated mixing length values, according to Eq. (16). The parameter C_1 increases with the vegetation density (0.135 and 0.16 for sparse and dense configuration, respectively), while C_2 outcomes to be independent from the simulated vegetation density and equal to 0.4.

The discharge can be calculated by integrating Eqs. (13) and (14) by means of Eq. (16). The calculated values are compared to the directly measured values in Fig. 9.

This comparison is particularly significant, because it was made on the basis of the measurements of more than forty runs, totally independent from the eight runs reported in Table 1: bed slopes, discharges and consequently flow depths were different from the values of Table 1. Fig. 9 shows a good agreement between the discharge predictions of the proposed mixing length model and the experiments, especially for the higher relative submergence values and the higher simulated vegetation density, and so confirm the validity of the procedure.

6. Conclusions

Open channel flows with fully submerged vegetation were analyzed. The double-averaged (in time

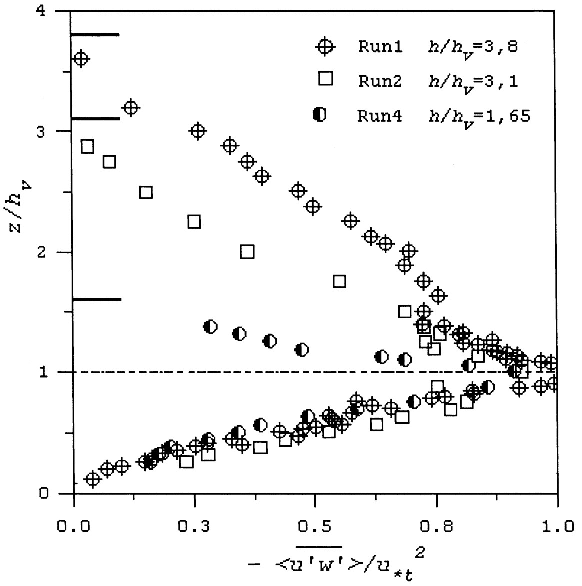

Fig. 4. Double averaged shear stress profiles for runs (sparse configuration).

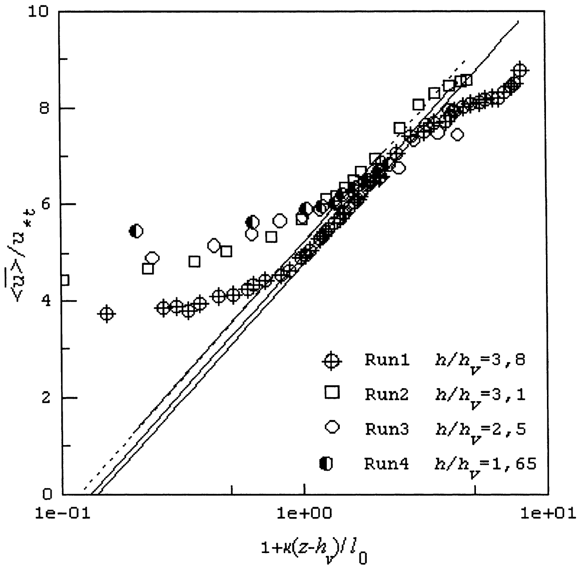

Fig. 6. Double averaged velocity profile for sparse configuration.

and in space) momentum equations were used as a mathematical scheme. In order to solve the closure problem of the double-averaged equations, a generalized two-layer, mixing length model is proposed and validated with velocity and turbulence flume measurements. The assumptions for its formulation were confirmed by the experiments. In particular, the turbulent shear stress profiles in the vegetated layer seem to be quasi-linear. Starting from these hypotheses, a new formula for the evaluation of vegetation resistance and uniform flow conditions (Eqs. 15, 16 and 17) was proposed, which is confirmed by experimental data.

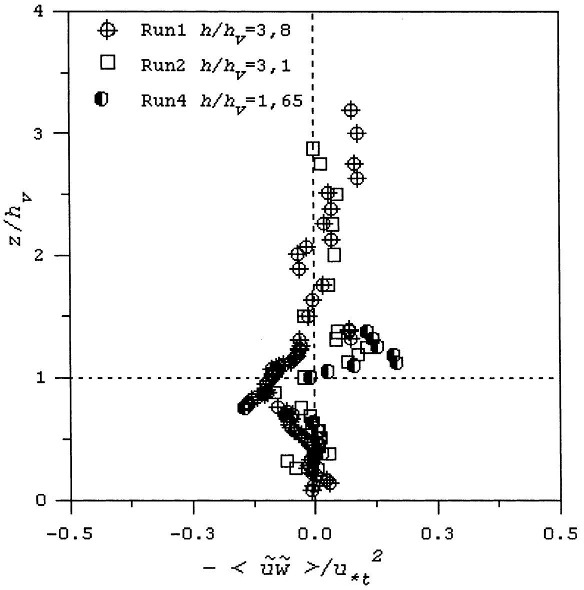

Fig. 5. Dispersive stress profiles for sparse configuration.

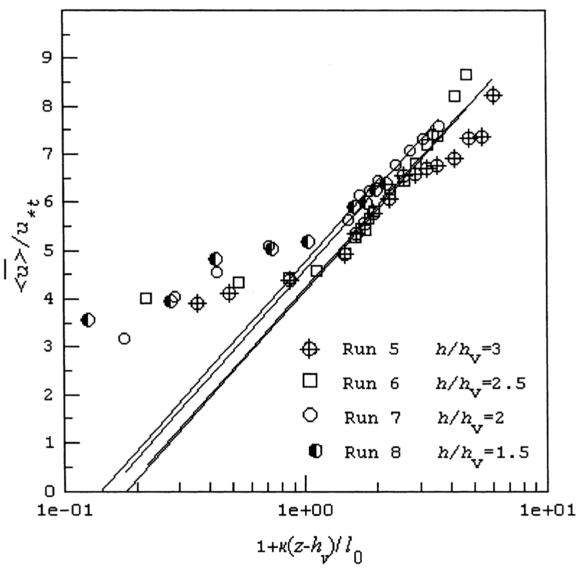

Fig. 7. Double averaged velocity profile for dense configuration.

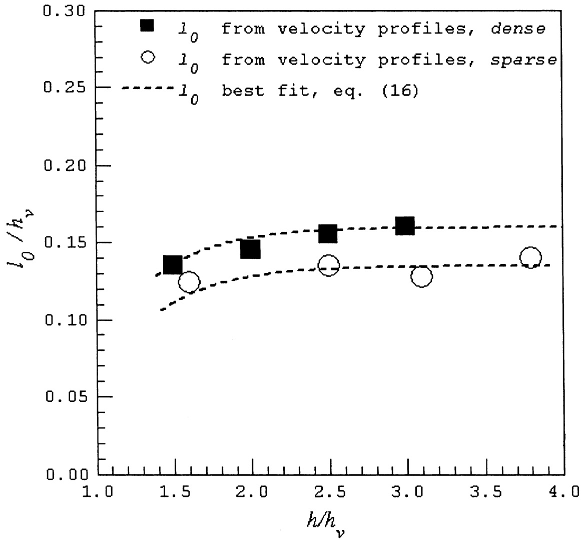

Fig. 8. Mixing length l_0 estimation by velocity profiles (dots) and by interpolation with Eq. (16).

Some pending points still remain:

- the general formulation could be affected by the mechanical characteristics of the bush simulation material, which is not elastic and little permeable;
- the analysis has been validated on the basis of only two simulated vegetation densities. The extension of the experiments to different vegetation densities and to plants with different characteristics is to be hoped for. This circumstance could allow to have a better insight on the scaling of l_0 values with vegetation density; for example, lower vegetation densities might also require a modification of the model, in order to allow a non-negligible shear stress on the bed.

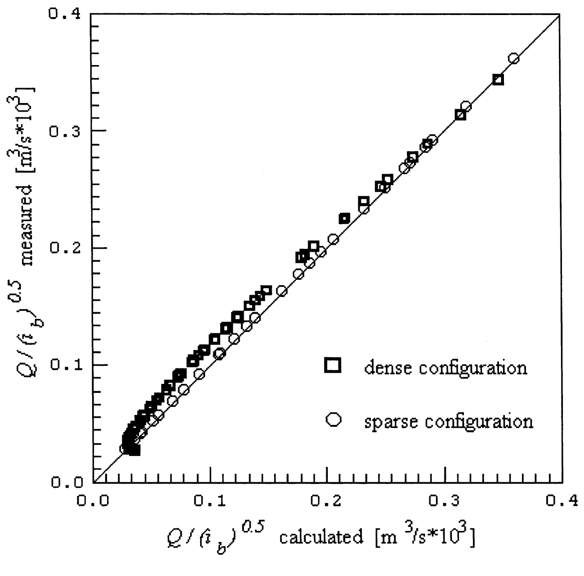

Fig. 9. Comparison between calculated and measured discharge.

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Appendix A

Notation

The following symbols are used in this paper

A ratio between the area occupied by fluid and the total area of the averaging region in the (x, y) plane at level z;
A_c cross-section area of the flow;
A_{pi} area of the ith plant projected in streamwise direction;
a_x distance between adjacent plants in longitudinal direction;
a_y distance between adjacent plants in transversal direction;
C_1 parameter;
C_2 parameter;
C_D drag coefficient of a single plant;
d_p plant diameter;
D_{pi} force exerted by the flow on the single ith plant;
G gravity acceleration;
$\bar{G}$ temporal averaging of variable G;
$\langle G \rangle$ spatial averaging of variable G along (x, y) plane at level z;

$\tilde{G}$	dispersive contribution of variable G, $\tilde{G} = \bar{G} - \langle \bar{G} \rangle$;
H	flow depth;
h_u	upper layer height;
h_v	plants height;
i_b	bed slope;
κ	von Kàrmàn constant $= 0.41$;
K_b	Strickler coefficient due to bed roughness;
K_{eq}	equivalent Strickler coefficient;
l	mixing length;
$\langle l \rangle$	generalized mixing length;
l_0	value of the mixing length at the interface level and in vegetated layer;
L	length of the considered reach;
n	number of plants per bed surface;
N	number of plants that are present in the reach having length L;
p	pressure;
p_P	pressure unbalance due to vegetation;
Re_p	plants Reynolds number, $Re_p = U_d/\nu$;
R_h	hydraulic radius;
u, v, w	instantaneous components of fluid velocity vector in x, y, z coordinate directions;
$u', v,' w'$	instantaneous fluctuations of the three velocity components;
u_{*t}	shear velocity at the top of the vegetated layer, $u_{*t} = \sqrt{\tau_t/\rho}$;
U	mean flow velocity;
U_v	averaged velocity in the vegetated layer;
V_d	vegetation density, $V_d = h_v^2/(a_x a_y)$;
x, y, z	orthogonal coordinate system, attached to the bed, with x longitudinal direction, y transversal direction, z vertical direction;
$\sum$	summation index;
α	ratio between averaged velocity in the vegetated layer and mean flow velocity, $\alpha = U_v/U$;
ρ	water density;
τ_t	shear stress at layers interface;
τ	shear stress;

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