*Larhyss Journal, ISSN 1112-3680, n°15, Septembre 2013, pp. 55-63*


# CONTRIBUTION TO THE STUDY OF THE FLOW RESISTANCE IN A FLUME WITH ARTIFICIAL EMERGENT VEGETATION

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## ABSTRACT

Vegetation growing in the water along rivers has been the subject of several studies since it was recognized that it could have a significant impact on the water flow. It may increases resistance to flow and causes higher water levels. Also, it has affects on the turbulent structure such as the mean velocity profiles. For flow of water through emergent vegetation, previous investigations show different results. Hence, better knowledge on its impact on flow conditions is needed. The purpose of this paper is to investigate, how density and placement of emergent vegetation influence flow resistance, water depth and velocity profile. Experiments using artificial vegetation selected to simulate emergent vegetation were carried out in a laboratory flume instead of natural channel, and Manning's n is used to denote the resistance coefficient. The results show large variations in the Manning resistance coefficient with depth of flow and vegetative density. Vegetation causes resistance to flow; it reduces flow velocities and increases water depth. For the vegetation densities considered, the presence of foliage significantly reduces the mean velocities. Also mean velocity profile is set by the vertical structure of the vegetative drag.

**Keywords:** emergent vegetation, density, Manning resistance coefficient, Drag.

## INTRODUCTION

Vegetation is known to increase bank stability, reduce erosion and turbidity, provide habitat for aquatic and terrestrial wildlife, attenuate floods, present aesthetic properties, and filter pollutants (David, 2008). It has traditionally been viewed as an obstruction to channel flow by increasing flow resistance and the risk of flooding. In recent years, vegetation has become a major component of erosion control and stream restoration.

Flow resistance in open-channel is a very complicated concept and there are no exact methods to determine it. One of the most remarkable factors for determination of flow resistance is shape variety, roughness variety and vegetation (Järvelä, 2002). The existence of vegetation within the watercourse tends to increase the hydraulic resistance by causing a loss of energy through turbulence and by exerting additional drag forces on the moving fluid. The drag coefficient $C_D$ is one of the most important coefficients, which influences the mean velocity and the turbulence characteristics (Nepf, 2000). Tanino and Nepf (2008) and Cheng (2011) have derived empirical relationships of $C_D$ for flow through emerged rigid vegetation. Both studies confirm that $C_D$ is related to canopy properties (plants density, diameter, etc.) as well as flow conditions. The $C_D$ relation proposed by Cheng (2011) has been modified by Hu et al. (2012).

The relationship between flow velocity and flow depth in rivers is commonly established through a resistance relationship, such as Manning's equation. To improve resistance relationships, researchers have been simulating vegetation with artificial roughness, both flexible and rigid elements, in laboratory flume experiments (e.g. Wu et al., 1999; Nepf, 2000; Stone and Shen, 2002; James et al., 2004). Most of these research efforts focus on determining drag coefficients and empirical formulas for resistance under various vegetation configurations. Aberle and Järvelä, (2013) summarize in their paper current practices for the estimation of flow resistance caused by floodplain vegetation in emergent flow conditions.

Better knowledge on the impact of emergent vegetation on flow conditions is needed. The purpose of this paper is to investigate, how type, density and placement of vegetation influence flow resistance and velocity profile.

## THEORITICAL CONSIDERATIONS

Manning equation is the most commonly used in open channel flow, it can be expressed as:

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

In which n is the Manning roughness coefficient ($s/m^{1/3}$); R is the hydraulic radius (m); U is the cross sectional average velocity (m/s) and S is the channel slope (m/m).
On the basis of the study conducted by Wu et al. (1999), the total resistance of the testing flume is a result of the sidewall and bottom resistance. Since the bed resistance is dominated by the vegetative roughness rather than the surface friction of the bottom, the bottom resistance (n) may be used to represent the vegetative roughness coefficient. The procedure to calculate the vegetative roughness coefficient is represented by Wu et al. (1999) as follows:

## DRAG COEFFICIENT FOR EMERGENT VEGETATION

To estimate the drag induced by the vegetal elements, force balance for uniform flow is applied in the flow wise direction of a vegetated reach L. Basically, this equilibrium can be expressed as:

$$F_G = F_D + F_S \tag{2}$$

In which the gravitational force $F_G$:

$$F_G = \rho . g\, (A . L) . S \tag{3}$$

Where ρ is the mass density of water ($Kg/m^3$), g is the gravity constant ($m^2/s$), A is the cross sectional flow area ($m^2$), S is the bed slope (m/m), $F_D$ is the drag force exerted on the vegetation and $F_S$ is the surface friction of the sidewalls and bottom. For uniform flow in vegetated channel, $F_S$ is negligible compared to $F_D$.
The drag force $F_D$ is given by:

$$F_D = C_D (\lambda .A.L) \frac{\rho .U^2}{2} \tag{4}$$

Where $C_D$ is the drag coefficient, λ is the vegetal area coefficient representing the vegetation density per unit channel length ($m^{-1}$) and (λ.A.L) is the total frontal area of vegetation in the channel reach L.
Equating $F_G$ and $F_D$ gives:

$$C_D = \frac{2.g.S}{U^2 \lambda} \tag{5}$$

Equation (5) can be used to evaluate the vegetal drag coefficient $C_D$, Which accounts for the features of vegetation, as indicated above.

## RELATIONSHIP BETWEEN DRAG COEFFICIENT AND ROUGHNESS COEFFICIENT

For the flume used in this study, the roughness of the walls is negligible compared to the roughness of the bottom. Hence, the flume is assumed to be very wide. Thus, the water depth h is used instead of the hydraulic radius R. Using Equation (5), we can convert the vegetal drag coefficient $C_D$ to the roughness coefficient n, i.e.

$$n = h^{0.5}\left[\frac{C_D\,.\lambda}{2\,.g}\right]^{0.5} \tag{6}$$

The blockage provided by the vegetation is characterized by its frontal area per volume, called the vegetation density λ ($m^{-1}$). The frontal area $A_f$ ($m^2$) of ten randomly selected plants was estimated at centimeter intervals in the vertical, $\Delta z$ = 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 (Nepf, 2000):

$$\lambda = n_P \frac{A_f}{\Delta z} \tag{7}$$

## EXPERIMENTS IN FLUME

The tests were conducted in a 26 m long, 0.7 m height and 0.5 m wide rectangular, glass-walled flume. The slope of the flume was 0.07692 %, and at the downstream there was a submerged weir to measure discharge, and uniform flow was ensured by the adjustment of a tail- gate at the downstream end. Flow depths were measured with two depth gauges (Figure 1). The uniform flow depth was measured at the equilibrium condition. The bed of the flume (study area see Figure 1) was roughened by a 12 m long layer of PVC. For the vegetated bed, a longitudinal section of artificial vegetation selected to simulate emergent vegetation was installed over the study area. The model vegetation was about 60 cm height. Each plant consisted of six blades of 1.9 cm width made from plastic, bundled to a basal stem of an average diameter 1.15 cm and average height 9.12 cm. The plants were arranged in a staggered pattern, with longitudinal and transverse spacing of 15 cm, 30 cm and 45 cm, by sticking the upper end of the plant into drilled holes. Four densities (280, 120, 60 and 40plants) were used. Acoustic Doppler Velocimeter was used for local velocity measurements in the case of 280 and 60 plants. The velocity was measured at several points in the vertical. Three minutes records were collected and the sample-reporting rate 25Hz was used. For the filtering and analysis of ADV data, WinADV-program was used.

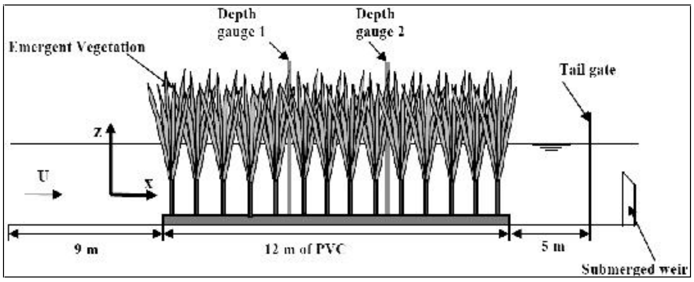


**Figure 1:** Experimental set-up in the flume with vegetation

## RESULTS AND DISCUSSIONS

### Water depth-discharge relationship

The relationship between water depth and discharge for flow through different vegetation densities is represented in Figure 2.
As it was expected, the relationship between flow depth and discharge depends strongly on the vegetation density (Figure 2): for the same discharge, a higher density leads to a higher water depth. For very low water depths, the curves are very close to each other. In the channel without vegetation, water depth increases with discharge and the measured water depths and discharges agree with the computed values using an n = 0.011.

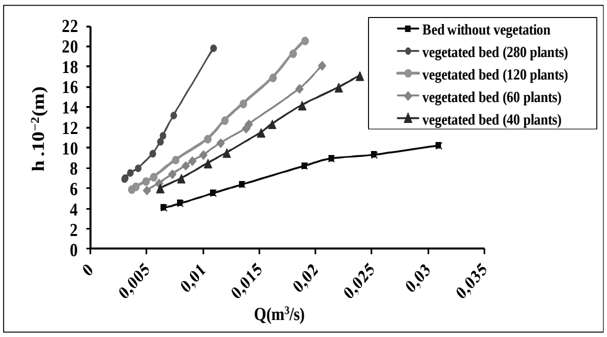


**Figure 2:** Water depth-discharge relationship for flow through different vegetation densities

## MANNING'S n FOR EMERGENT VEGETATION

Profiles of the vegetation density λ and the drag coefficient $C_D$ in the case of 280 plants are shown in Figure 3. The presence of foliage has a significant influence on the interaction between vegetation and flow. From Figure 3, it is clear that the increase in vegetation density λ is attributed to increased leaf density with height for the measured water depths.

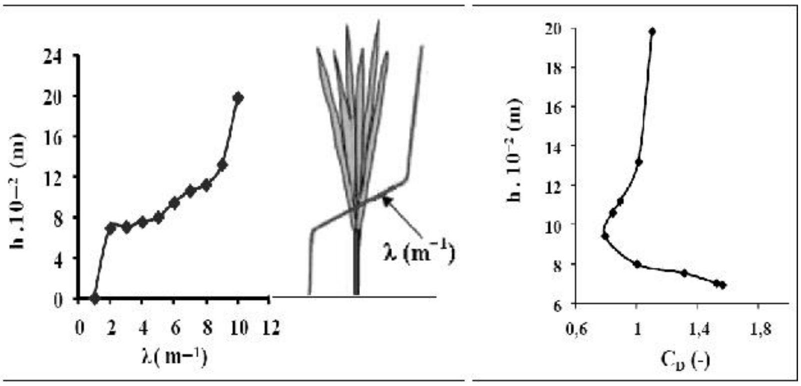


**Figure 3:** Profiles of vegetation density λ (left) and drag coefficient $C_D$ (right): (the case of 280 plants)

Over the lower half of the plant (Figure 3, right), the drag coefficient $C_D$ increases towards the bed, reflecting the increasing importance of viscous effects. Above the bed, the emergent plant produces a constant value of $C_D \approx 1$(Nepf, 2000). Vegetation density is however one of the most important parameters for drag control: An increase in the vegetation density leads to an increase of the flow resistance and to reduction of the drag coefficient.

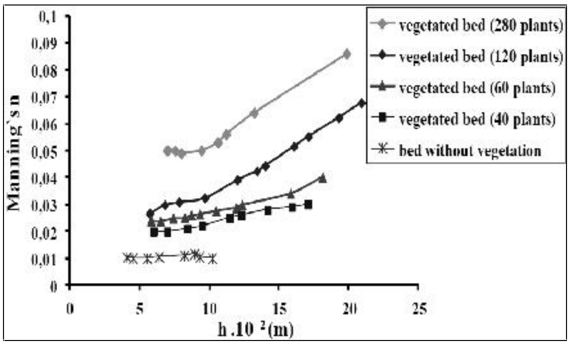


**Figure 4**: Manning's n-Water depth relationship for flow through emergent vegetation

Manning's n is calculated using Equation (6) and is plotted against flow depth in Figure 4. For channel without vegetation, Manning's n is approximately constant (about 0.011), which is equal to n expected and used in the calculations. For vegetated channel, the presence of vegetation increases the hydraulic resistance. Manning's *n* is clearly related to the vegetation density: an increase of the vegetation density leads to reduce cross sectional area and increases flow resistance. Vegetation produces high resistance to flow and, as a result increases water levels. The curves of the four densities show that creating additional boundaries to the clear channel area, by separating them with grasses significantly increases resistance.

## VELOCITY PROFILE FOR EMERGENT VEGETATION

Profiles of the mean velocity u, corresponding to the stream wise direction, in the case of 280 and 60 plants with a discharge Q = 0.0128 $m^3$/s are represented in Figure 5. u is plotted against z/h, where z is the vertical distance from the channel bed.

The mean velocity profile is set by the vertical structure of the vegetation density (Figure 3), thus the mean velocity is linked to details of vegetation morphology. From velocity profiles (Figure 5), two zones could be distinguished: the stem part (lower part) where velocity increases and the leaf part where the velocity decreases slowly (Nepf, 2000). So, the presence of foliage significantly reduces the mean velocities; leaves increase the resistance area of plants, which reduces the flow velocity (Naden et al., 2006). The mean velocities in the case of 280 plants are lower than within 60 plants. The emergent vegetation causes energy loss through the creation of turbulence around the vegetation stems and leaves and creates drag force on the moving water. Hence, 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.

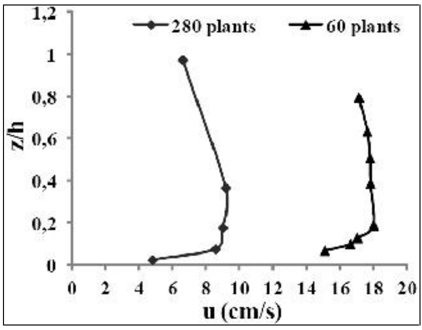


**Figure 5:** Profile of mean velocity for 280 and 60 plants (Q = 0.0128 $m^3$/s)

In the vegetation pattern investigated, when the flow reaches an area of dense vegetation, most flow is deflected and concentrated in the clear channels between the vegetation where the flow is faster. Much of the flow resistance in these channels originates from the momentum transfer between the slow flow within the grasses and the relatively fast flow in the clear channels (Yang et al., 2007). 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.

## CONCLUSION

The experiments described in this work investigate the influence of emergent vegetation density and distribution pattern on flow. The measurements show that the water depth-discharge relationship depends strongly on the density of vegetation. The latter produces a high resistance to flow and therefore increases water levels. Manning's n coefficient depends on vegetation density. This parameter is however very important for drag control.

Vegetation markedly reduces the flow capacity of the channel and retards the flow. The mean velocity profile is set by the vertical structure of the vegetation density: the presence of foliage significantly reduces the mean velocity. Vegetation grouped into staggered pattern is very effective in retarding flow.

Hopefully other tests will be carried out in natural channels to confirm the results. To compare the influence of different types of emergent vegetation on the flow, tests should be made.

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