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INTEGRAL LENGTH SCALES IN VEGETATED OPEN CHANNEL FLOWS

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ABSTRACT

The problem of turbulent flow-canopies interaction has been extensively studied in literature. Interaction between flow and aquatic riparian vegetation is an extremely complex problem.
Although many studies have attempted to explore it, flow through vegetation phenomenon has not yet been fully described quantitatively. At the beginning, effects of vegetation on turbulent air flow have been studied through wind tunnel and fields measurements. Afterwards researcher's attention has been aimed at turbulent characteristics of a water flows developing in experimental flumes with vegetated bottom. Generally, turbulence characteristics whose changes were described were mean velocity, standards deviation, skewness, kurtosis. In their studies some researchers deepened the effect of vegetation on more specific characteristics of the turbulent flow as the integral length scales. The aim of the paper is to experimentally study the effects of vegetation density on the longitudinal integral length scales of a uniform turbulent flow above and inside sparse canopies. Water flume experiments were conducted in a channel 8m long and with a square section $0.40 \times 0.40 m^2$. The model of canopies consisted of sparse rigid cylinders of the same heights but set in three different aligned allocations (squares or rectangles), with three different densities. Two different measurement locations were considered, in any case in a reach of the channel where the uniform flow was attained. In order to measure instantaneous velocities an LDA system was used. Experiments were carried out by varying the flow rate and the slope of the channel. Starting from instantaneous velocity data collected, distributions of longitudinal integral length scales were determined and analyzed. Finally more correct methodologies in order to evaluate integral length scales and to normalize them were proposed.

INTRODUCTION

The problem of turbulent flow-canopies interaction has been extensively studied in literature. In fact, nowadays, vegetation is regarded as a means for providing stabilization for banks and channels, habitat and food for animals, and pleasing landscapes for recreational use. Therefore the preservation of vegetation is of great relevance for the ecology of water systems and it is important to deepen the problem of turbulent flow-canopies physical interaction, that is extremely complex .

Effects of vegetation on water flow are the following ones: decrease of the water velocity and raising of the water levels i.e. reduction of flow discharge capacity; deposition of suspended sediment; increasing or reducing of local erosion; interference with the use of the water for conveyance, navigation, swimming and fishing.

Such effects depend mainly on height, density, distribution, stiffness and type of vegetation. These characteristics may change with the season, e.g. the flow resistance may increase in the growing season and diminish in the dormant season.

Many of the earlier studies on the hydraulic effects of vegetation were concentrated on determining flow resistance rather than obtaining a better understanding of the physical processes.

At the beginning, effects of vegetation on turbulent air flow were studied through wind tunnel and fields measurements. Afterwards researcher's attention was aimed at turbulent characteristics of a water flows developing in experimental flumes with vegetated bottom. Generally, turbulence characteristics whose changes were considered were mean velocity, standards deviation, skewness, kurtosis. In their studies some researchers deepened also the effect of vegetation on more specific characteristics of the turbulent flow as the integral length scales [1] [2] [3] [4] [5] [6] [7]. In particular, integral length scales are estimated from the single-point integral time scales by applying Taylor "frozen turbulence" hypothesis. The integration is carried out to the time of the first zero-crossing of the autocorrelation function. Integral length scales are made non dimensional by vegetation height h. This methodology has been applied by many researchers in their wind tunnel, experimental flume and fields measurements as [1] [2].

Brunet et al. [1] carried out experiments in a wind tunnel on a model of vegetation made with cylindrical stalks modelling cereal stalks, spaced on a uniform square grid. Vertical distributions of turbulence statistical quantities of velocity field were measured through some triple hot-wire probes, suitably set in the flow field.

Green et al. [2] carried out his experiments in a forest of Sikta spruce, near Edinburgh. Measurements were developed by some three components anemometer spaced uniformly at different heights from about 0.25h to 1.25h, being h the mean tree height.

Measurements of the turbulence statistical quantities within and above diverse set of canopies, including models in wind tunnel and vegetation in the field are reported by [3]. Moreover, in [3] single-point length scales were compared with two-point length scales [4] and turned out that the single-point scales were smaller than the two-point scales by factors of 2 or more especially within the canopy. He scaled integral length scales using the vegetation height. He observed that probably the single-point approach was fraught with difficulty within canopies because of high turbulence intensities.

Afterwards, Novak et al. [5] carried out experiments in a wind tunnel on model forest made from artificial Christmas tree branches. Instantaneous velocity distributions in the flow field were measured through a triple hot-wire probe and the results were compared with field experiments described in [2]. He measured single-point length scales and scaled them either using the vegetation or using the tree spacing, showing that it plays a significant role.

Velasco et al. [6] developed experiments in an experimental flume with a gravel bed. In the central zone of the channel was set a simulated vegetated zone, with plastic plants directly fixed on the gravel bed. In the study of turbulent structures, a 2D and a 3D acoustic Doppler velocimeter were used. He measured single-point length scales but noticed some incoherence in the experimental autocorrelation function, due, in his opinion, to an insufficient measurement frequency (25 Hz). He scaled the integral length scales using an average transversal distance between plants in the bed.

Nezu et al. [7] developed experiments in an experimental flume. The elements of vegetation model were composed of rigid strip plates. Instantaneous velocity distributions in the flow field were measured through laser Doppler anemometer (LDA) and PIV measurements. The integral length scales were estimated from the two-points space-time autocorrelation function, and he affirmed that no existing data of integral length scales obtained with this method for aquatic canopy flows were available at that time. He scaled integral length scales using the vegetation height

Recently, another problem concerning the estimation of integral length scales has arisen in [8].

Integral length scale is important in characterising the structure of the turbulence. It is a measure of the longest correlation distance between the flow velocity at two points of the flow field. Integral length scale of the velocity is generally defined by:

$$L = \int_0^\infty R_{ii}(r,t)dr \qquad (1)$$

where the i subscript denotes the considered direction, the double-*i* subscript in R_{ii} indicates the autocorrelation function (i.e. correlation of a velocity component in the i direction with itself) defined by:

$$R_{ii}(r) = \frac{\langle u_i(x_i,t)u_i(x_i+r,t)\rangle}{\langle u_i^2\rangle} \qquad (2)$$

and r is the distance between two points in the flow. The autocorrelation function is longitudinal if the distance r is considered parallel to i direction, ~~u_i,~~, and transverse if the distance r is considered perpendicular to i direction ~~u_i,~~ ~~where~~ and finally u_i is the instantaneous velocity in the *i*-direction.

The determination of the integral length scale from equation (1) is not straight-forward. The shape of the autocorrelation function is such that it generally decreases rapidly to its first zero-crossing, after which it may become negative and proceeds to oscillate about zero. While equation (1) involves the determination of the integral over an infinite domain, the domain of the autocorrelation function from experimental or numerical data is finite, and consequently there is some uncertainty on how best to define the integration domain.

The integration domain for the determination of the integral length as a representative length scale of the turbulence can be specified in a number of ways. [8] investigated the following four methods:

- Integrate over the entire available domain;
- If the autocorrelation function has a negative region, integrate only up to the value where the autocorrelation function is a minimum,
- Integrate only up to the first zero-crossing;
- Integrate only up to the value where the autocorrelation function falls to 1/e.

In this paper, to deepen the effect on longitudinal integral length scales of vegetation density, an experimental study was conducted in an open channel with model vegetation of fully submerged rigid cylinder rods set in regular aligned arrays with different densities.

In particular, two problems are dealt with: evaluating integral length scale from autocorrelation function, using different time lags (1/e and $1/e^2$), and scaling integral length scale using different scales (i.e. h, height of the cylinder and a, average transversal distance between the cylinders that, in case of uniform canopies, can be expressed as $a=1/(NV)^{1/2}$).

NOMENCLATURE

h	[m]	Vegetation height
d	[m]	Vegetation diameter
VD	[-]	Vegetation density
NV	[m^{-2}]	Number of canopies/ m^2
L	[m]	Integral length scale of the velocity
R_{ii}	[-]	Autocorrelation function in the i direction
x_i	[m]	Position where autocorrelation function is calculated
τ	[m]	Space lag in autocorrelation function calculation
u_i	[m/s]	Velocity component of which autocorrelation function is calculated
t	[s]	Time instant of
e	[-]	Neper's number
s	[-]	Slope of the experimental channel
Q	[m^3/s]	Fow rate
h_u	[m]	Uniform flow depth
Re	[-]	Reynolds Number
τ	[s]	Time lag of a time-autocorrelation point
y	[m]	Distance of a measurement point from the channel bottom

EXPERIMENTAL PLANT AND MEASUREMENT CONDITIONS

Water flume experiments were conducted in a channel with variable slope 8m long and with a cross section 0.40 × 0.40m^2 (Figure 1).Vegetation covered the whole bottom of the channel and consisted of sparse rigid cylinder rods of the same height and diameter (h=1.5cm, d=0.4cm) but set in three different shapes lways aligned with flow allocation patterns (rectangles or squares), with three different densities, 0.024, 0.048, 0.096, respectively called MD, SD, DD in the following diagrams. The vegetation density was defined as the total roughness frontal area per unit ground area. The vegetation was always fully submerged. Each type of vegetation was tested with different bottom slopes and flow rates, in order to obtain three groups of three tests each one characterised by almost the same flow depth and by the three considered densities. Therefore, nine different hydraulic conditions were tested. A summary of the experimental flow conditions is listed in the Table 1. In the test section there was in any situation uniform flow.

Figure 1 Experimental flume

Test	VD and NV	Bottom slope s	Flow type	Flow rate Q (l/s)	Uniform flow depth h_u (cm)	Reynolds number Re
1	0.024 (MD) 400/m^2	0.03 (s3)	Supercr.	33	6.35	330000
2	0.048 (SD) 800/m^2	0.02 (s2)	Supercr.	22	6.44	220000
3	0.096 (DD) 1600/m^2	0.03 (s3)	Supercr.	22	6.29	220000
4	0.024 (MD) 400/m^2	0.01 (s1)	Supercr.	45	7.82	450000
5	0.048 (SD) 800/m^2	0.01 (s1)	Subcr.	22	7.80	220000
6	0.096 (DD) 1600/m^2	0.03 (s3)	Supercr.	33	7.71	330000
7	0.024 (MD) 400/m^2	0.01 (s1)	Supercr.	33	8.53	330000
8	0.048 (SD) 800/m^2	0.03 (s3)	Supercr.	45	8.55	450000
9	0.096 (DD) 1600/m^2	0.01 (s1)	Subcr.	22	8.49	220000

Table 1

The measurement locations can be a very important factor when studying the flow structure of a vegetated flow [9]. Therefore to compare their effects in the same test section, two different measurement locations were chosen: the first one (A) at the centre of a rectangle or a square of cylinders, and the second one (B) in the middle between two cylinders aligned in the flow direction. In each location, about thirty points were considered along the two verticals, where instantaneous velocity data were measured by an LDA system with frequency shifter and frequency tracker.

Starting from the collected velocity data, distributions of longitudinal integral length scales (L), were evaluated through a Virtual Instrument of the software called LabView. In particular, the integral timescales were assumed corresponding to the time lags where the time-autocorrelation function R(τ) drops, respectively, to 1/e and 1/e^2. Starting from integral timescales, longitudinal integral length scales were evaluated by applying Taylor "frozen turbulence" hypothesis which is applicable if the turbulence intensity of the flow is small.

Finally, the integral length scales distributions were normalized in two different ways: •) by the height of the cylinders, h ••) by the average distance between cylinders, a. The vertical distances y of the measurement points from the bottom of the channel were always scaled by the height of the cylinders, h.

PROCESSING AND RESULTS

In Figure 2, 3, 4, 5, some characteristic dimensional distribution of longitudinal integral length scales are shown. In each figure in ordinates the distances y from the bottom (in cm), and in abscissae the integral length scale L (in m) are reported.

Test 7 was carried out with the lowest density and the highest flow depth, while Test 3 was carried out with the highest density and the lowest flow depth. In each Test, two different measurements location were chosen (A and B).

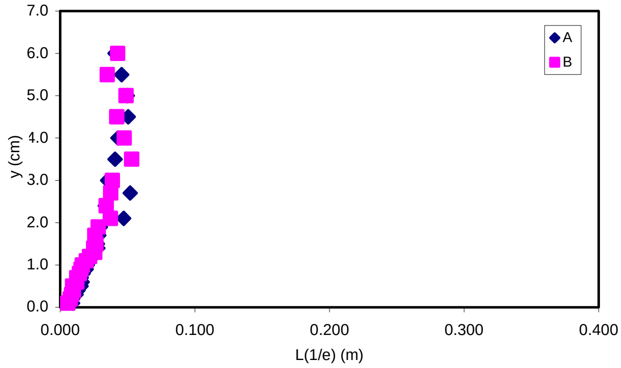

Figure 2 Test 7 L(1/e)

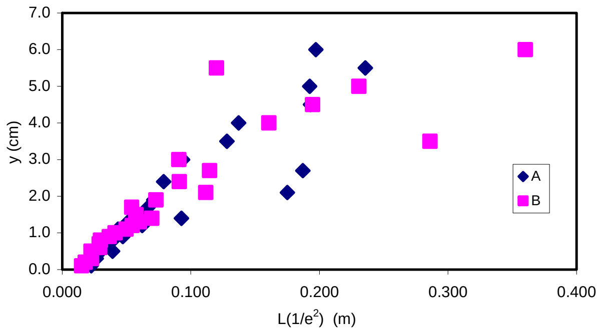

Figure 3 Test 7 l(1/e^2)

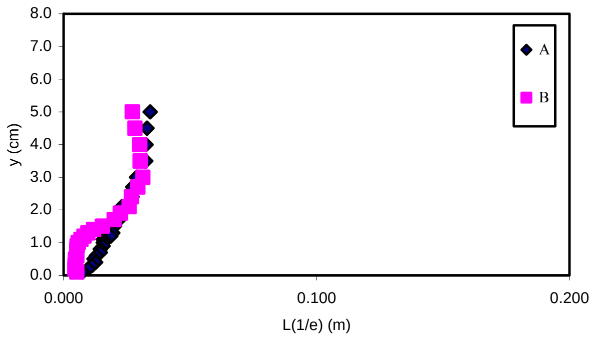

Figure 4 Test 3 L(1/e)

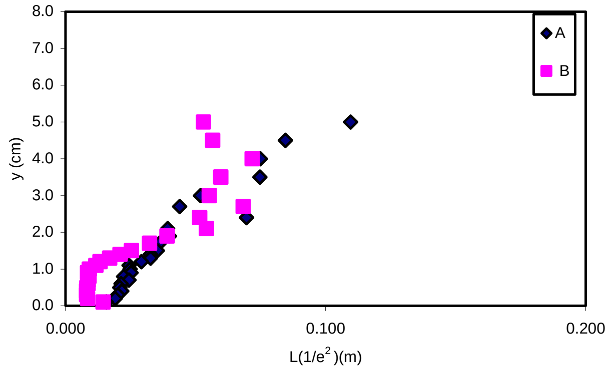

Figure 5 Test 3 L(1/e^2)

Comparing Figure 2 and Figure 3, longitudinal integral length scales significantly grow, increasing the time lag from 1/e to 1/e^2, while the measurement location does not affect their distribution. Comparing Figure 4 and in Figure 5, longitudinal integral length scales yet grow increasing the time lag from 1/e to 1/e^2, but the two distributions are significantly affected by the measurement location.

THE PROBLEM OF THE TIME LAG IN EVALUATING INTEGRAL LENGTH SCALES

Generally in literature, integral length scales are evaluated integrating the autocorrelation function till the first “zero crossing” of this function. During the experiments a true “zero crossing” was not found. Alternatively [8] suggests to integrate till the autocorrelation function drops to 1/e. From the experimental measurements result that this method determines an underestimation of the integral length scale. It is interesting to stress that O’Neill, investigating the effects of the spatial domain on the integral length scale determination, suggests that, in order to obtain accurate integral length scales, the time lag must be at least equal to six times larger than the integral length scale, whereas [10] suggested that a reasonable lower limit is at least eight times larger than the integral length scale.

In order to deepen the impact of different values of the integration domain (1/e and 1/e^2) on the longitudinal integral length scales, the following comparison were developed.

In Figure 6 to Figure 8, the distributions of ratios of longitudinal integral length scales evaluated for time lag 1/e^2 and longitudinal integral length scales evaluated for time lag 1/e are reported.

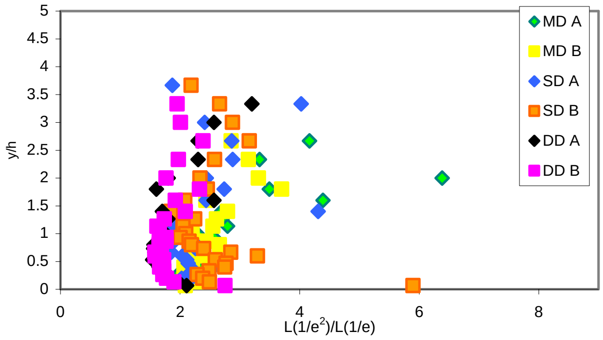

Figure 6 Tests 1, 2, 3

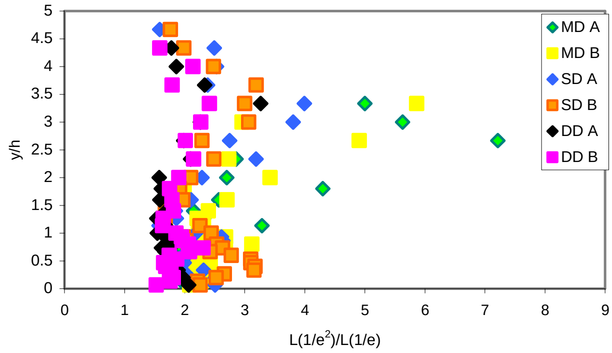

Figure 7. Tests 4, 5, 6

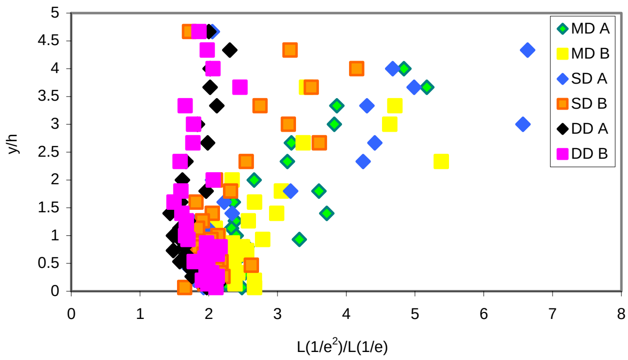

Figure 8. Tests 7, 8, 9

It can be observed that longitudinal integral length scales values increased about twice (within the canopy) or more, with increasing the integration domain from 1/e to 1/e^2. The first result is that it is not sufficient to assume as integration domain 1/e because it triggers and underestimates the longitudinal integral length scales values. Moreover, this result seems to be qualitatively independent of vegetation density, flow depth and measurement location.

THE PROBLEM OF NORMALIZATION OF INTEGRAL LENGTH SCALES

Another problem is the choice of a scale for the integral length scales. In literature, the scale commonly used is the vegetation height.

Novak et al. [5] observes that, the vegetation height is considered the scale that dominates the real dimensions of the big vortices [3]; nevertheless he judged, on the ground of his experimental data, that also the canopies spacing plays a relevant role in scaling the vortices. In fact, observing his diagrams, it can be noted that, using the canopies spacing as scale, the experimental points fit better than using canopy height. This result supports the use of canopies spacing as scale.

Following this idea, in this paper, integral length scales have been scaled either with vegetation height (Figures 9, 10, 11 in case of time lag 1/e and Figures 15, 16, 17 in case of time lag 1/e^2), or with vegetation spacing (Figures 12, 13, 14 in case of time lag 1/e and Figures 18, 19, 20 in case of time lag 1/e^2).

Comparing the correspondent integral length scales scaled with vegetation height h or vegetation spacing a, it can be observed that:

a) In case of time lag 1/e, the distributions scaled with vegetation spacing fit better than the correspondent ones scaled with vegetation height h.

b) In case of time lag 1/e^2, the distributions scaled with vegetation spacing fit more clearly better than the correspondent ones scaled with vegetation height h probably due to the more correct evaluation of the integral length scales calculated with time leg 1/ e^2.

All that further supports the hypothesis that it would be suitable to scale the integral length also with vegetation spacing and that it is better to evaluate the integral length using as time lag 1/e^2 than 1/e.

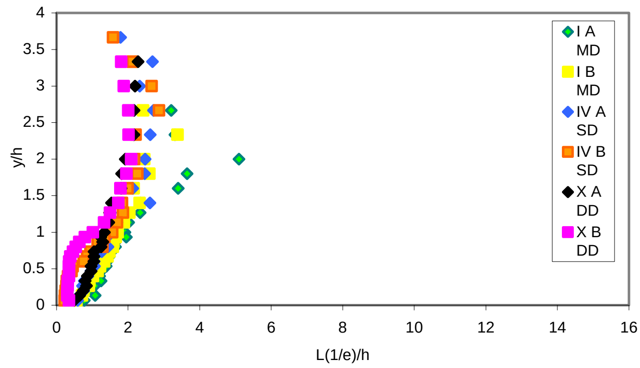

Figure 9. Tests 1, 2, 3

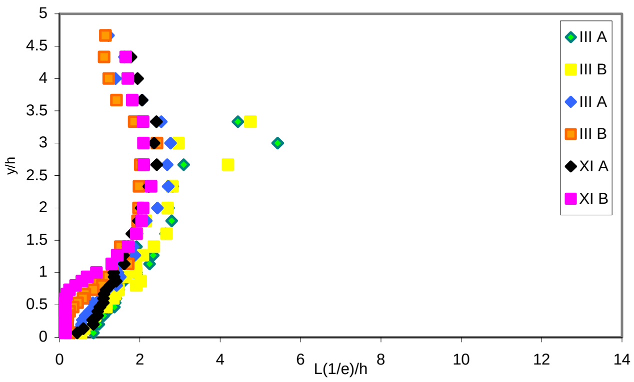

Figure 10. Tests 4, 5, 6

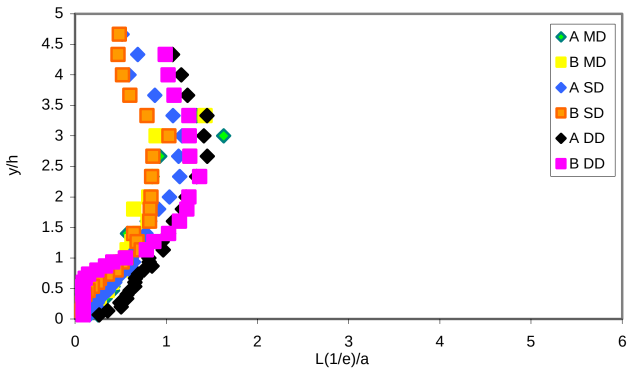

Figure 13. Tests 4, 5, 6

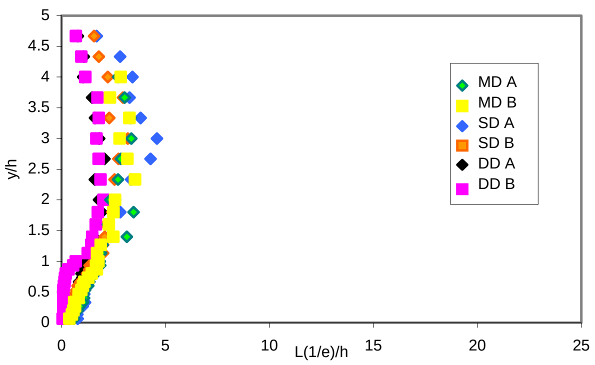

Figure 11. Tests 7, 8, 9

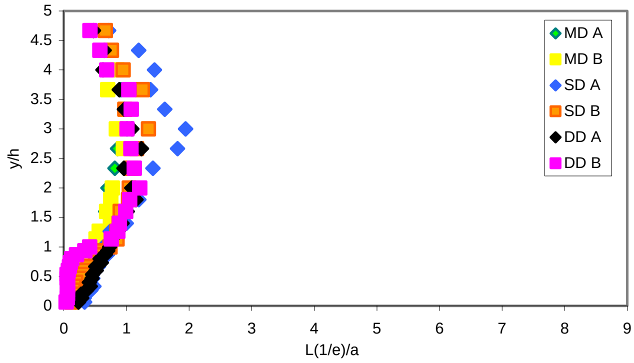

Figure 14. Tests 7, 8, 9

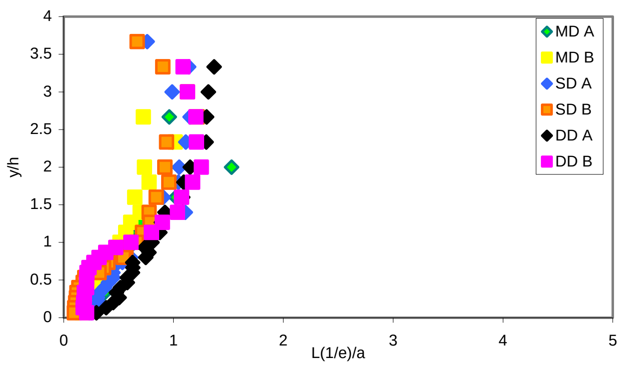

Figure 12. Test 1, 2, 3

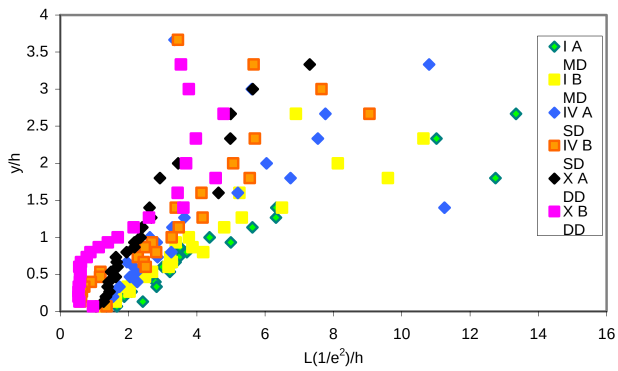

Figure 15. Tests 1, 2, 3

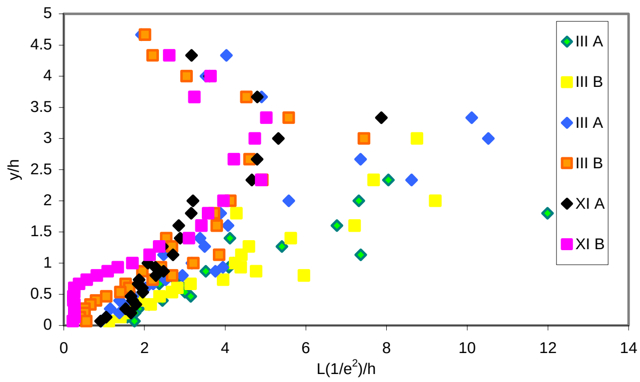

Figure 16. Tests 4, 5, 6

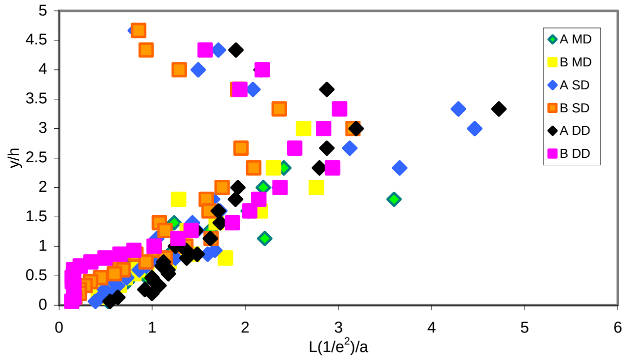

Figure 19. Tests 4, 5, 6

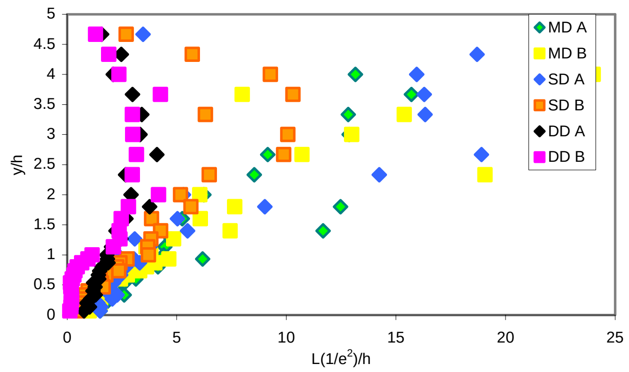

Figure 17. Tests 7, 8, 9

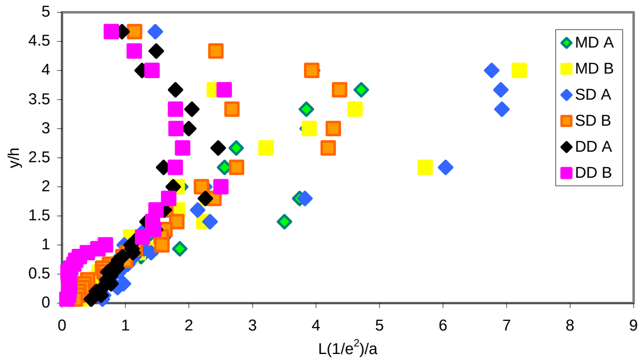

Figure 20. Tests 7, 8, 9

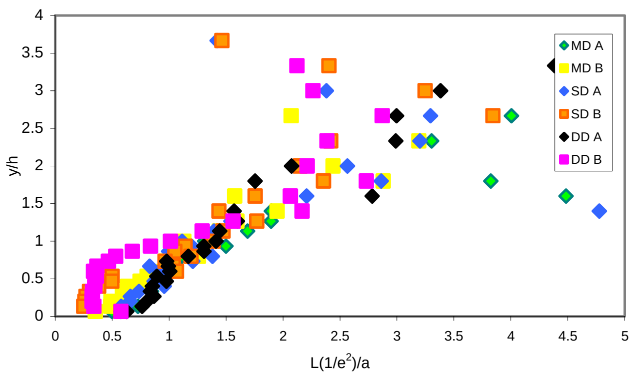

Figure 18. Tests 1, 2, 3

CONCLUSION

The problem of turbulent flow-canopies interaction has been extensively studied in literature. Interaction between flow and aquatic riparian vegetation is an extremely complex problem.

Although many studies have attempted to explore it, flow through vegetation phenomenon has not yet been fully described quantitatively. Generally, turbulence characteristics whose changes were described were mean velocity, standards deviation, skewness, kurtosis. In their studies some researchers deepened the effect of vegetation on more specific characteristics of the turbulent flow as the integral length scales.

In the paper the effects of vegetation density on the longitudinal integral length scales of a uniform turbulent flow above and inside sparse canopies is experimentally studied.

In particular, two problems have been deepened: the extension of the integration domain in the evaluation of the integral length scales and the possibility of scaling them with a quantity alternative to canopy height.

The results confirm that it is better to evaluate the integral length using as time lag $1/e^2$ than $1/e$ and that it would be suitable to scale the integral length also with vegetation spacing.

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