An Experimental Study of Turbulent Flow Over a Weir-Like Structure With and Without Vegetation

Shahid Ali[1], Usman Ghani[2], Abid Latif[3], Naeem Ejaz[2], Ghufran Ahmed Pasha[4]

[1]Senior Engineer, Atomic Energy Commission, Islamabad, Pakistan
[2.] Assistant Professor, Civil Engineering Department, UET Taxila, Pakistan
[3]Assistant Professor, Department of Civil Engineering, UCET, BZU Multan, Pakistan
[4.] Lecturer, Civil Engineering Department, UET Taxila, Pakistan
usman.ghani@uettaxila.edu.pk

Abstract: The experiments in an open-channel flume with modeled vegetated weir-like structures have been used to understand how the flow is affected by them. Laser Doppler velocimeter measurements of the water flow velocities over trapezoidal vegetated and non-vegetated weir-like structures (dike, groyne) have been made. The measurements extended to a distance of 20 weir heights downstream of the weir crest, it also included the flow separation zone behind the weir crest. The Reynolds's number was of the order of 10^4 in the flume, and imperfect flow conditions with Froude number<0.4 above the weir crest were considered. Two discharge values were considered in the experimental work. A comparison between the flow characteristics of vegetated and non vegetated weir-like structure was made. The variables investigated included longitudinal and vertical velocity components. Reynolds shearing stresses have also been investigated. The measured mean and turbulent velocities provided more detailed insight about the flow behind vegetated weirs. Strong vortices and turbulent intensities in region especially downstream of vegetated weir crest showed that the flow in the region near bed (on downstream slope of weir the recirculation zone is the main contributor) and at the top of the modeled vegetation is very unstable and leads to the formation of the coherent structures and it is the area of significant mass and momentum exchange. The results indicated that regaining of the logarithmic velocity profile behind the vegetated weir-like structures are delayed due to the presence of vegetation.

[Shahid Hussain Ali, Usman Ghani, Abid Latif, Naeem Ijaz, Ghufran Ahmed Pasha. **An Experimental Study of Turbulent Flow Over a Weir-Like Structure With and Without Vegetation.** *Life Sci J* 2013;10(9s):315-323**]** (ISSN:1097-8135). http://www.lifesciencesite.com. 44

Keywords: Vegetation; weir; floodplains; Reynolds stresses; longitudinal velocity.

1. Introduction

An understanding of flow resistance and conveyance capacity is the most basic knowledge required by hydraulic engineers for determining stage and discharge characteristics of river channels. A reliable estimate of flow resistance and conveyance capacity in rivers is desirable during floods. Natural floodplains typically grow grasses, bushes, trees etc. Also there are lots of other features such as summer dikes, approach roads, ditches etc. which are also covered with bushes, trees and grass.

The above mentioned features are the weir-like structures in the floodplains and groyne fields and these could be called vegetated weir-like structures. These weir-like structures contribute a lot to increased flood levels and when these weir-like structures are vegetated, these can enhance the flooding even more due to increase in the flow resistance. Computer models often don't include such features and due to limitation in computer memory and computing speed these small scale features could not be resolved and should therefore be improved with respect to representation of flow resistance.

Traditionally the river managers used the calibrated roughness coefficient for the flood and water level predictions but these are not based on physics. Most of the time the bed resistance caused by these features has been lumped into a single coefficient. Although these approaches are used extensively in the field but these are risky and unreliable in flood level predictions. So it is utmost important to understand physical behavior of these type of vertically resistant elements in the flow path and then to incorporate the effect of these element in floods and water level predicting computer models on physics based techniques. The resistance to the flow and flow behavior around the vegetation and the weir like structure and spur dikes has been studied extensively but the combined submerged vegetated dike and groynes has not yet been studied in details.

The effects of submerged and non-submerged rigid and flexible vegetation on the flow have been studied by many researchers such as; Kouwen et al. (1969) conducted a laboratory study using polyethylene plastic strips to simulate vegetation and developed an empirical formula for an average velocity. Kouwen and Unny(1973) , Kouwen and

Fathi-Moghadam (2000) studied the resistance due to the flexible vegetation. Li and shen (1973), Petryk and Bosmajian (1975) and Pasche and Rouvé (1985) developed the law for flow resistance for the stiff vegetation, and Freeman et al. (2000), Järvelä (2002 and 2004) studied various combinations of the vegetation. Many studies focused on velocity profiles and turbulent characteristics of vegetated channels e.g. Shimizu and Tsujimoto (1994) , Naot et al. (1996) etc. Recent works attempted to quantify flow resistance by calculating the drag created by a cylindrical array and related it as a function of plant density or Reynolds number e.g. Nepf (1999). Other researchers sought to understand the physical processes by analyzing the velocity and turbulence within an array of cylinders e.g. Nepf and Vivoni (2000), Liu et al.(2008). Many of them developed numerical models of flow through a uniform array of vegetation to predict the mean flow and turbulence structure e.g. Neary (2003). All these studies focused on a single layer of vegetation that is either submerged by the flow or remained emergent.

Lightbody and Nepf (2006) performed one of the few studies that addressed an arrangement different than a single layer of dowels using a denser canopy above a sparser one to study how longitudinal dispersion is affected by the morphology of the canopy.

Measurements of the turbulent velocity characteristics were performed by Long et al. (1990). They used a laser Doppler anemometer (LDA) to measure submerged hydraulic jumps over a wide range of Froude numbers and submergence factors.

The objective of the present study is to describe the detailed characteristics of the complex turbulent flow behind the vegetated weir-like structures and to understand the phenomena's which are contributing the energy dissipation caused by these sort of hindrances to the flow during high water situations. For this purpose, an experimental study was conducted and it was accomplished by taking the velocity profile measurements at several cross sections up and down stream of a vegetated weir. Two discharge values were considered. The main focus was to examine how the longitudinal and vertical velocity profiles are varying. Comparison between Reynolds stresses for the two cases has also been made.

2. Experiments

An Experimental study was conducted in the laboratory of Environmental Fluid Mechanics of Delft University of Technology, Netherlands. In order to perform the experiments which are representative for the processes on a prototype scale, requirements regarding Froude number and Reynolds number have to be fulfilled. To this end the prototype conditions were schematized and down scaled approximately 1:50, doing so a Froude number scaling was achieved. The low Reynolds number was not considered a problem as long as the flow was fully turbulent. The Reynolds number was of the order of 10^4.

The laboratory experiments were conducted in a 14 m long, glass-walled flume. The flume was rectangular 0.4 m wide and 0.4 m deep and was kept horizontal (the bed slope was zero). The glass wall provides optical access for flow visualization as well as laser Doppler anemometry (LDA). To control the downstream water level a vertical gate was placed at the downstream end of the flume. Water was pumped to the constant head tank which was situated at the upstream end of the flume. Discharge to the flume was regulated by means of a valve, and measured using a calibrated Rehbock weir in the return section. Flume bed and weir were made rough by gluing 5 mm to 8 mm diameter gravel to represent the actual field conditions as in the floodplain (Figure 1).

For this study, a trapezoidal embankment dike was selected. It had a height of 6 m, crest width of 3 m and side slopes of 1V:4H both on the upstream and downstream sides (Figure 2).

The model was made of smooth wood on a scale of 1:50. So the model weir has a height of 12 cm and a crest width of 6 cm. The model was constructed from three parts: the upstream face, downstream face and the rectangular crest. The side slopes of the model weir were the same as with the prototype. The surface was made hydraulically rough by gluing gravels to it.

The vegetation on the weir crest was modeled by using circular cylinders. The blockage area on the top of weir due to the modeled vegetation was 25 % (inside the vegetated region). The height of all plants was equivalent to weir crest height (12 cm) (Figure 2).

On the top of flume rail-mounted point gauges were installed to measure the water level at section 0 (which is 2 m upstream of the weir), section 1 (at the crest of the weir) and section 3 (4 m downstream of the weir) at the centre line of the flume (Figure 1). These gauges can move in the vertical as well as in the horizontal directions so that the water surface and channel bed level can be measured at the above mentioned locations. To measure the water level at different locations first the elevation of the surface of flow was measured and then the elevation of the bottom was observed at that point. The later was subtracted from the first to get the value of the flow depth. In order to simplify the reading of the last significant number behind the decimal, a direct vernier attached to the scale was used and this scale enabled an accuracy of 0.1 mm.

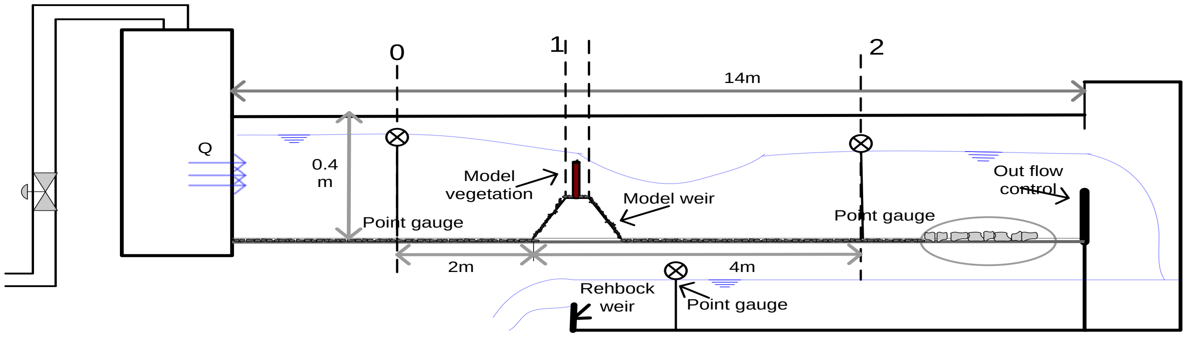

Figure 1. Experimental rectangular flume

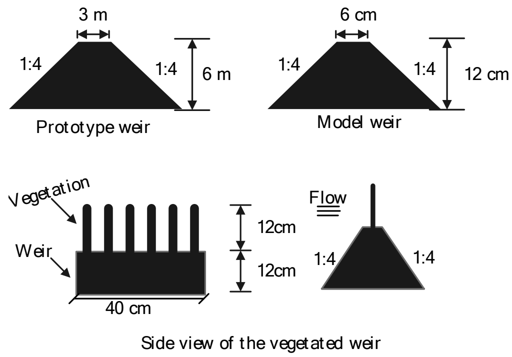

Figure 2. Prototype weir and Model weir (scaled 1:50)

In the flume, ISO standard Rehbock weir (Figure 1) was used to measure the discharge. The discharge was also measured by the electromagnetic flow meter. An LDV was used to measure the velocity profiles at different locations around the vegetated weir.

Two-dimensional velocity measurements (u, w) and turbulent intensities were taken via LDV (Ruck, 1987). It measures the instantaneous velocity at a single point in the water. Two laser beams (for two velocity directions) and a reference beam entered the water mass and were scattered by small particles in the water. Seeding with particles was not necessary because the water contained sufficient micro particles (small enough to move entirely with the flow) to receive a steady signal. Due to the Doppler shift, the frequency of the scattered laser light changed, defining the velocity of the water in each direction. Instantaneous velocity data was captured at a sampling rate of 100 Hz for a duration of 3 min. From this data the mean velocities, and Reynolds stresses were calculated. The instantaneous velocities were measured in the middle of the flume at several cross sections upstream and downstream of the flume. Two discharge values (25 and 40 l/sec) were used. At one cross section, approximately 12 velocity points were measured with increasing distance between them form bottom to top starting from 5 mm above the channel bottom as shown in Figure 3.

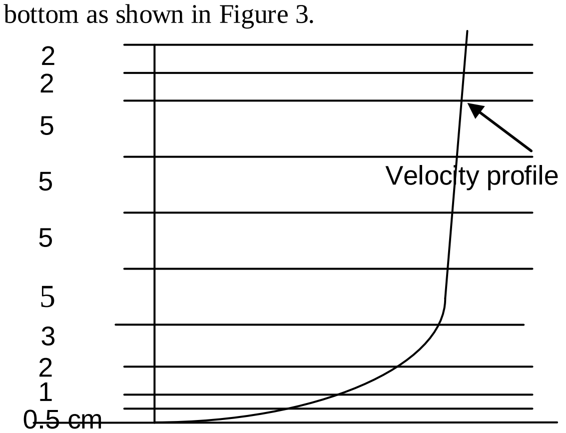

Figure 3.Vertical positions for velocity measurements at a cross-section

Ten horizontal velocity profiles (at ten cross-sections along the channel) were measured. Two velocity profiles were taken on the up-stream, one at 1 m upstream of the weir and one on the upstream slope (section 0 and 1 respectively). One profile was measured on the crest of the weir just behind the vegetation. Two to three velocity profiles were taken on the down stream slope of the weir and rest were taken on the down stream side of the weir. Figure 4 shows location of these sections. Different parameters used in the experimental set-up have been summarized in Table 1.

Table 1. Various parameters used in the experimentation

Vegetation type	Discharge (m^3/sec)	Froude number on the weir crest behind the vegetation	Water depths(m)		
			Upstream of weir	On the weir crest	Downstream of weir
Weir without vegetation	0.025	0.25	0.32	0.185	0.313
	0.04	0.40	0.32	0.18	0.317
Weir with vegetation	0.025	0.25	0.35	0.20	0.345
	0.04	0.40	0.35	0.189	0.339

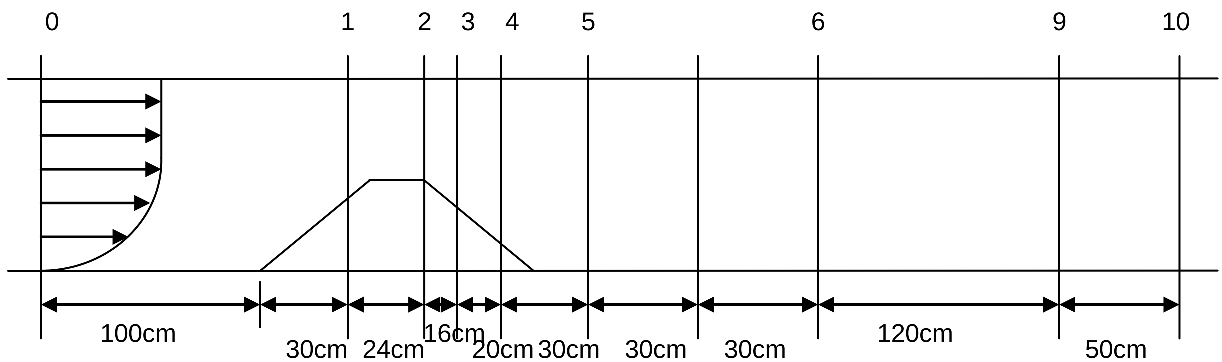

Figure 4: Cross-sectional locations for measuring velocity profiles.

3. Experimental results and discussions

This section presents results and discussion of the experimental work and has been divided in three parts i.e. longitudinal, vertical velocity characteristic along with Reynolds shear stresses. Note that the longitudinal and vertical velocities have been normalized by u_o (mean longitudinal velocity) whereas Reynolds stresses have been normalized by u_o^2 and the vertical depth has been normalized by weir depth Δ.

3.1. Longitudinal velocity measurements:

Figure 5 (a-b) depicts the longitudinal velocity profiles for non-vegetated and vegetated weir at five different locations one on upstream slope of the weir, one on the crest of the weir and two profiles on the leeward slope of the weir and one on the down stream side of the weir. The general trend of these profiles on downstream side clearly indicates the recirculation zone in both cases (weir without vegetation and weir with vegetation). In both cases the velocity is highest on the crest of the weir and the velocity decreases behind the weir crest as there is an expansion zone in this region. Additional drag exerted by the plants reduces the mean flow within the vegetated region relative to non-vegetated ones.

There is a spike in longitudinal velocity profile near the bed (Figure 5a) and it is most pronounced immediately downstream of the vegetation (locations 3 and 4). It decreases as the flow progresses downstream. The velocity spike is most probably caused by the horse-shoe vortex that forms at the base. The horse-shoe vortex draws the faster moving fluid from the surroundings into the base of the cylinders (dowels) causing a spike in the velocity profile near the bed and this spike disappears as we move away from the vegetation. The velocity increased near the top of the vegetation and that is associated with an inflection point in the velocity profile. This inflection point is associated with the Kelvin-Helmholtz instabilities caused by two co-flowing streams of different velocities, mentioned by Ghisalbarti and Nepf (2002) analogous to a mixing layer. The two fluids moving at different velocities cause the flow to fold in a clockwise motion, creating rolling vortices that become larger in downstream direction, forcing the inflection point deeper into the array as shown in Figure 5(a). It is the same phenomenon like near bed.

Velocity profiles at locations 3 and 4 show the recirculation zone on the leeward slope of the weir. In the region lower than crest the velocity profiles are same in both cases (vegetated and non-vegetated weir). In the region where the longitudinal velocity becomes positive, in case of the vegetated weir the velocity is low in lower layer due to the resistive force of the vegetation and the velocity is large in the upper layer.

The above mentioned observations are more pronounced in case of the higher discharge as shown in the Figure 5 (b).

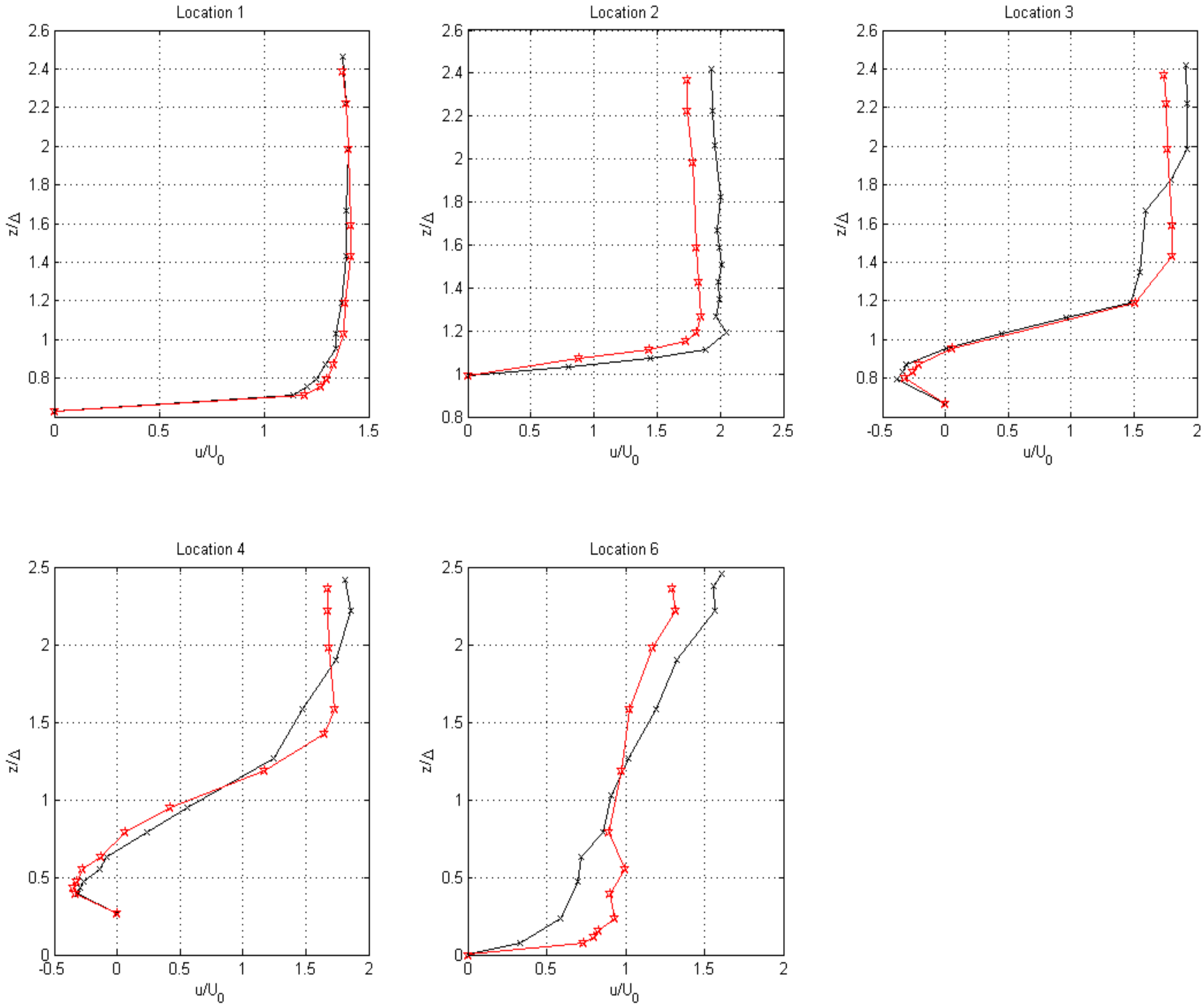

Figure 5 (a): Comparison of longitudinal velocity profiles at different locations for the vegetated and non-vegetated weir (*(red) non-vegetated weir and x (black) vegetated weir Q=25 l/sec).

3.2. Vertical velocity

The results for vertical velocity have been shown in Figure 6(a-b). It shows that the vertical velocity is higher near the bed (location 1) and decreases gradually and becomes almost zero near the surface. The vertical velocity at location 1 is due to the upward movement of the flow on the upstream slope of the weir. The results suggest that in general a strong upward velocity spike is present near the bed immediately behind the vegetation and dissipated as the flow moves downstream. The spike in velocity profile near the bed behind the vegetation is caused by the same reason as mentioned in previous section. On the downstream slopes of vegetated and non-vegetated weirs the near bed higher vertical velocity is present; it is due to the recirculation of the flow on the leeward side of the weir. In case of the weir without vegetation there is no spike in velocity profile on the crest as there is no vegetation like contraction and region of fast and slow moving fluids behind the vegetation does not exist.

The vertical velocity profile behind the vegetation shows another spike near the top of the vegetation. Flow near the top of the array of cylinders moves upward. When the flow passes the vegetation, the mixing of the fast and slow moving flow creates the instabilities and these instabilities generates the strong negative vortices and results in the upward movement of flow.

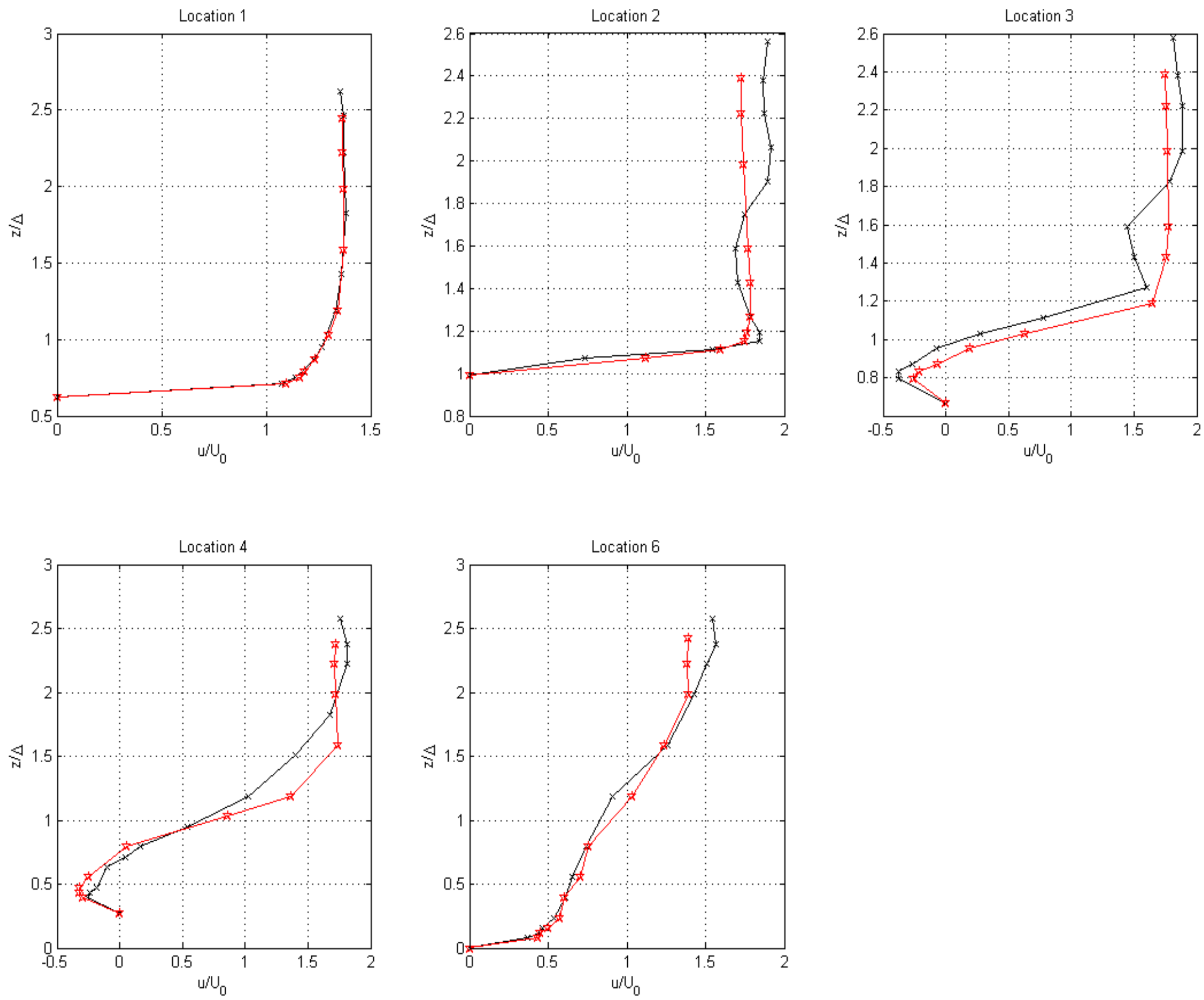

Figure 5(b): Comparison of longitudinal velocity profiles at different locations for the vegetated and non-vegetated weir (*(red) non-vegetated weir and x (black) vegetated weir Q=40 l/sec).

3.3. Reynolds shear stresses

The Reynolds shear stresses $-\overline{u'w'}$ are relevant for the proper understanding of the flow characteristics. These stresses represent the fluctuating part of the velocities caused by the turbulence and unsteady behavior of flow. The turbulent shear stresses are closely related to the velocity gradients in the different flow regions and these show highest values at the shear layer where the momentum exchange due to the turbulent eddies is also high. Figure 7(a-b) shows these stress profiles for the two discharge values. In Figure 7(a), at the upstream measurement location (1) the Reynolds shear stresses were relatively very small. At the downstream side of the weir crest and the vegetation, the Reynolds shear stresses are much higher. The presence of vegetation also gives boost to them due to high shear and vortex shedding.

The Reynolds shear stress near the bed just behind the vegetation stems (at the weir crest) increases as the velocity is also showing spikes near the bed and then these stresses start to decrease and reach to minimum value just at the top of the vegetation stems and return again to zero in upper flow layer. In case of the non-vegetated weir the Reynolds shear stresses have a spike near the bed and then return to zero. At the location 3 and 4, the near bed spike in the Reynolds shear stress profile pronounce very much caused by recirculation zone in sudden expansion region of the weir and then have same trend as in the stress profile at location 2 just behind the vegetation at weir crest. Further downstream the stress profiles diffused over the complete height as shown at location 6. The difference of the Reynolds's shear stress distribution can be seen for both vegetated and non-vegetated weir cases. In case of 40 l/sec discharge, the Reynolds shear stresses are higher as shown in Figure 7(b). These are due to high velocity values.

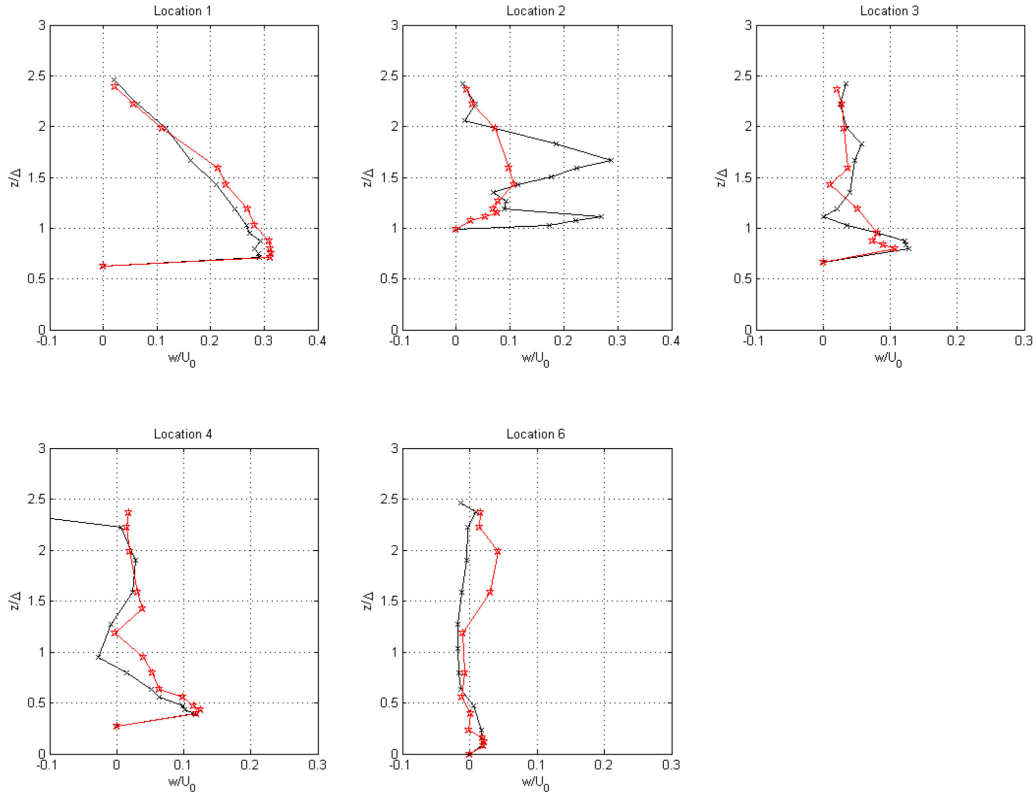

Figure 6(a)

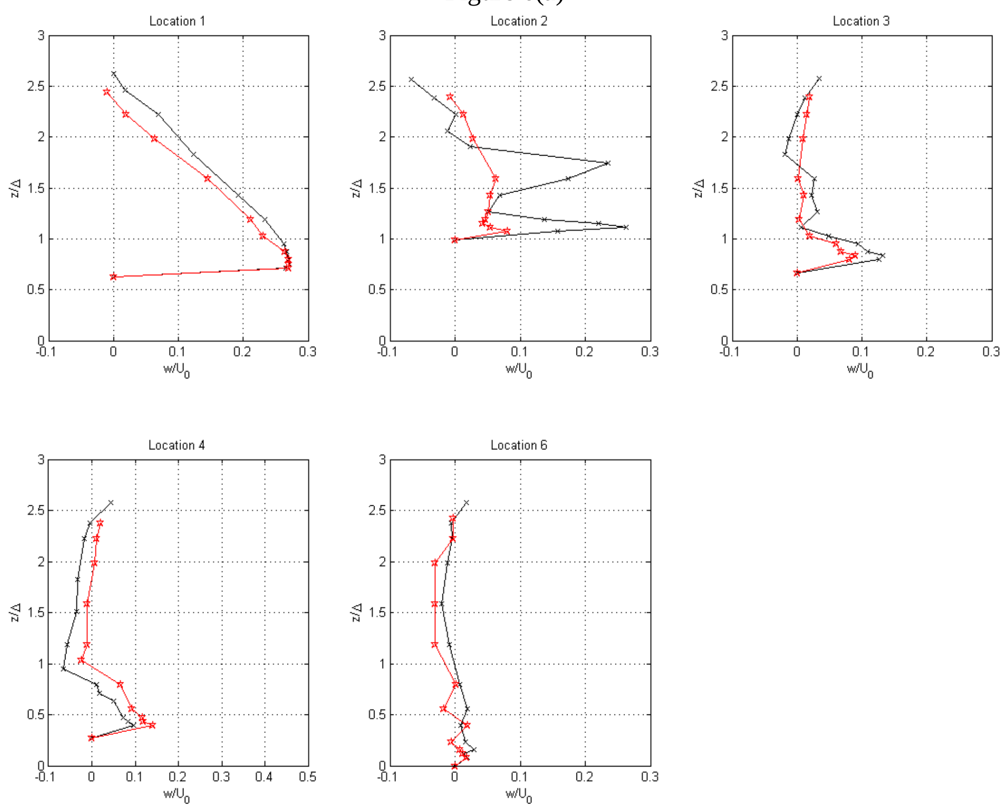

Figure 6 (b): Comparison of vertical velocity profiles at different locations for the vegetated and non-vegetated weir (*(red) non-vegetated weir and x (black) vegetated weir) (a) Q=25 l/sec, (b) Q=40 l/sec.

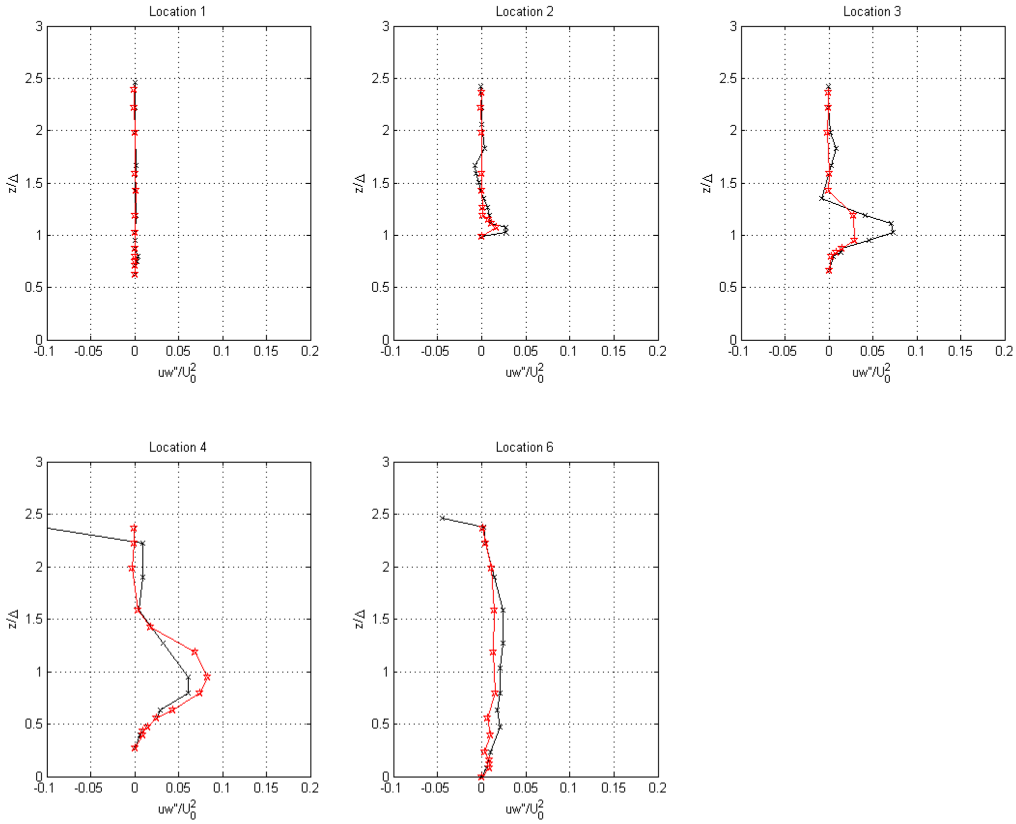

Figure 7(a): Comparison of Reynolds stresses at different locations for the vegetated and non-vegetated weir (*(red) non-vegetated weir and x (black) vegetated weir Q=25 l/sec).

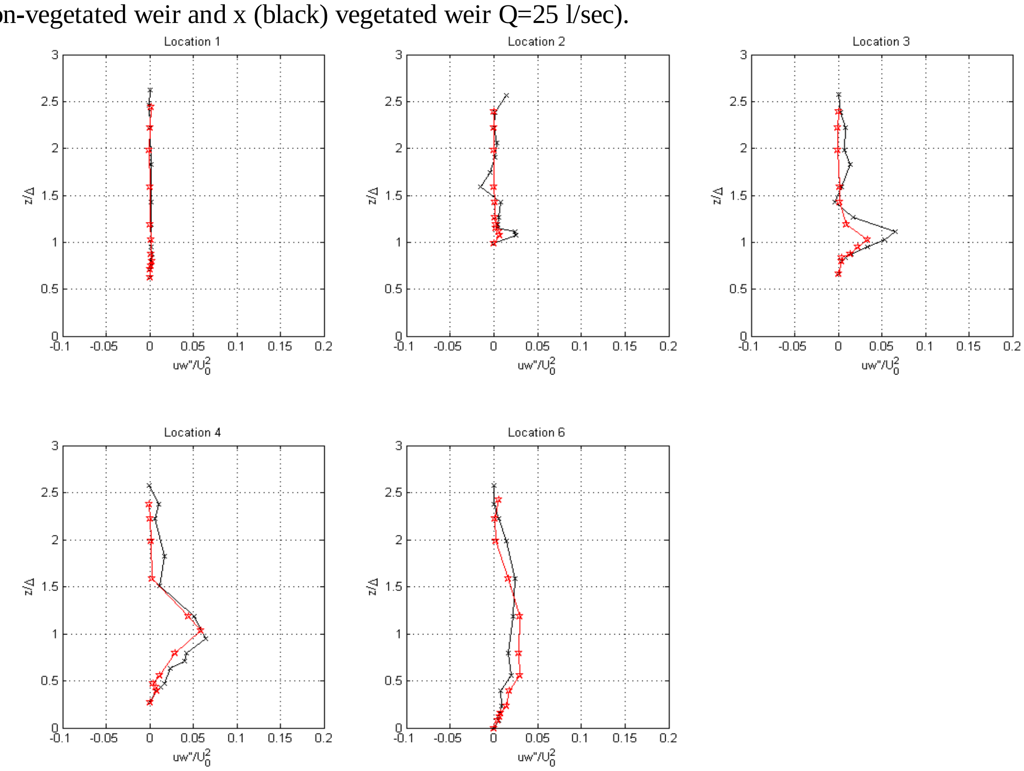

Figure 7(b). Comparison of Reynolds stresses at different locations for the vegetated and non-vegetated weir (*(red) non-vegetated weir and x (black) vegetated weir Q=40 l/sec).

4. Conclusions

The experimental investigations of flow over the vegetated weir-like structures provide the valuable information about the longitudinal and vertical flow velocities and Reynolds stresses.

The longitudinal velocity profiles behind the vegetation show the near bed spikes followed by the inflection points below the top of the vegetation and the velocity is more in the upper flow layer above the vegetation. These inflection points are related to the coherent structures formed by the mixing layer created by the two different flow layers. At location (2) the vertical velocity is higher near the bed then decreases and again becomes maximum below the top of the vegetation dowels and from there it again start decreasing. Vertical velocities away from the vegetated crest are maximum near the bed due to the recirculation of flow in weir expansion region.

At location 2, the Reynolds shear stress near bed is positive and maximum; below the top of vegetation dowels it becomes negative. The Reynolds stresses are also higher in the recirculation zone and the vegetated region of the flow.

Acknowledgments:

The first author would like to acknowledge the Higher Education Commission of Pakistan, and Ministry of Transport, Public works and water management, Netherland for their support to conduct this research work.

Corresponding Author:
Dr. Usman Ghani
Assistant Professor
Civil Engineering Department
University of Engineering & Technology
Taxila, Pakistan
E-mail: usman.ghani@uettaxila.edu.pk

References

1,Kouwen N, Unny T, Hill H.M. Flow retardness in vegetated channels. Journal of Irrigation and Drainage Division 1969; 95 (IR2): 329-42.
2,Kouwen N, Unny T.E. Flexible roughness in open channels. Journal of the Hydraulic division 1973; 99(10): 713-28.
3,Kouwen N, Fathi-Moghadam M. Friction factors for coniferous trees along rivers. Journal of Hydraulic Engineering 2000; 126 (10): 732-40.
4,Li RM, Shen HW. Effect of tall vegetations on flow and sediment. 1973; 99(HY5): 793- 814.
5,Petryk S, Bosmajian G. Analysis of flow through vegetation. Journal of Hydraulic Division 1975; 101(HY7): 871-84.
6,Pasche E, Rouve G. Overbank flow with vegetatively roughened flood plains. Journal of Hydraulic Engineering 1985; 111 (9): 1262-78.
7,Freeman GE, Rahmeyer WH, Copland RR. Determination of resistance due to shrubs and woody vegetation. Technical Report, TR-00-25.US. Army Engineering Research and development Centre, Vicksburg, 2000.
8,Järvelä J. Flow resistance of flexible and stiff vegetation: a flume study with natural plants. Journal of Hydrology 2002; 269: 44-54.
9,Järvelä J. Determination of flow resistance caused by non-submerged woody vegetation. Journal of river Basin Management 2004; 2 (1): 61-70.
10,Shimizu Y, Tsujimoto T. Numerical analysis of turbulent open-channel flow over a vegetated layer using K- ξ turbulence model. Journal of Hydro-science and Hydraulic Engineering 1994; 11(2): 57-67.
11,Naot D, Nezu I, Nakagawa H. Unstable patterns in partly vegetated channels. Journal of Hydraulic Engineering 1996; 122(11): 671-73.
12,Nepf HM. Drag, turbulence and diffusion in flow through emergent vegetation. Water Resources Research 1999; 35(2): 479-89.
13,Nepf HM, Vivoni ER. Flow structure in depth-limited vegetated flow. Journal of geophysical research 2000; 105(C12): 547-57.
14,Liu D, Diplas P, Fairbanks JD, Hodges CC. An experimental study of flow through rigid vegetation. Journal of geophysical research 2008; 113: 532-46.
15,Neary VS. Numerical solution of fully developed flow with vegetative resistance. Journal of Engineering Mechanics 2003; 129(5): 558-63
16,Lightbody AF, Nepf HM. Prediction of velocity profiles and longitudinal dispersion in emergent salt marsh vegetation. Limnology and Oceanography 2006; 51(1): 218-28.
17,Long DF, Steffler P, Rajaratnam N. LDA study of flow structure in submerged hydraulic jump. Journal of Hydraulic Research 1990; 28(4): 437-60.
18,Ruck B. Laser Doppler Anemometry-a non-intrusive optical measuring technique for fluid velocity. Particle &particle systems characterization 1987; 4(1-4): 26-37.
19,Ghissalberti M, Nepf HM. Mixing layers and coherent structures in vegetated aquatic flow. Journal of Geophysical Research 2002; 107(C2): 1-11.

8/12/2013