FLOW CHARACTERISTICS IN OPEN CHANNEL WITH SUBMERGED FLEXIBLE VEGETATION

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ABSTRACT

Influence of submerged flexible vegetation on various flow characteristics such as the flow velocity, turbulence intensity and turbulent kinetic energy was experimentally analyzed in an open channel system. Artificial plants were used to mimic the natural vegetation. Flow characteristics was measured at six different locations along the centerline of vegetation area. It was found that the maximum value of turbulence intensities and turbulent kinetic energy was located at two location; one at the intersection of sheath and canopy layer and another at the intersection of canopy and free water layer. The stablized profile of vertical stream-wise velocity looks like a 'S' shape with the minimum value located at the canopy area where the frontal width was maximum and the maximum value located at the free water layer.

Keywords: *Flexible vegetation, Flow characteristics, Turbulence intensity, Vertical stream-wise velocity profile, Turbulent kinetic energy.*

1. INTRODUCTION

Vegetation plays an important role in an open channel or river flow and its presence alters various flow characteristics such as the Reynolds shear stress, flow velocity, turbulence intensity, turbulence kinetic energy and Manning's roughness coefficient as compared with non-vegetated condition. Such variations influence the hydrodynamics of the flow field. The presence of in-channel vegetation is sometimes regarded as a problem because it can reduce flow capacity of the channel. The existence of vegetation within river systems is advantageous to their environmental functions, also by suppressing erosion and stabilization of the soil through the plant root system and enhancing water purification. Thus, a better understanding of hydraulic characteristics in vegetated flow is important in the management of rivers, channels and their ecosystems.

Chen et al. (2011) evaluated the effects of three configurations (aligned, staggered and columnar) of submerged flexible vegetation on flow structure. Distribution of stream-wise velocity separated into three layers each were associated with different logarithmic equation. Li et al. (2014) studied the effect of submerged flexible vegetation on flow structure (e.g. flow velocity, Reynolds shear stress, turbulence intensity and manning's coefficient). The study provided understanding of flow patterns, variation in velocity profile and turbulence structure because of flexible vegetation with varying density. With increasing vegetation density, the velocity and corresponding flow rate increased in the upper non-vegetated layer and decreased within the middle canopy layer and the lower sheath layer. Experiments demonstrated that vegetation affects the flow structure and increase the sedimentation (Leonard and croft, 2006). Noarayanan et al. (2011) investigated that Manning's *'n'* also effected by vegetation density, diameter, flexibility and height. Some common parameter of the plant which can cause impact on various flow characteristics are plant structure, distribution of sheath, branches and leaves (Hui and Hu, 2010). Impact of vegetation on flow parameters is also dependent on flexibility of the plants (Wilson et al., 2003).

Many researchers separated the vertical stream-wise profile into two or three layer: the upper non-vegetated layer, middle canopy layer and the lower sheath section layer (Klopstra et al., 1997; Righetti and Armanini, 2002; Neary, 2003; Cheng, 2007; Huai et al., 2009; Pietri et al., 2009; Chen et al., 2011; Li et al. 2014). Klopstra et al. (1997) simply divided the layers into vegetation layer and surface layer. Jarvela (2005) carried out an experimental study with natural submerged flexible wheat plants and found that flow structure above submerged flexible plants follow the logarithmic law. Flow resistance of the natural grasses, sedges and willows was studied in a laboratory flume. The objective was to investigate how type, density, placement of vegetation, flow depth and velocity influence friction losses (Jarvela, 2002). The streamwise velocity profile distributed within the submerged vegetation is principally affected by vegetation drag, resulting in complex flow conditions (Huai et al., 2009; Wilson, 2007; Zhang and Nepf, 2009). Kubrak et al. (2010) developed one-dimensional steady-state model and used to study vertical profiles of longitudinal velocities in open channel flow through, and above submerged vegetation. The model of water velocity profiles takes into account the surface roughness of the channel bottom and the drag exerted by submerged flexible stems. The experiments showed that, in such cases, the flow conditions depend on the bed roughness, flow depth, as well as the density, length, diameter and modulus of elasticity of the stems.

Huai et al. (2013) Proposed two-layer model for predicting the vertical distribution of stream-wise velocity in open channel flow with submerged flexible vegetation, using the predicted deflection height of the flexible vegetation. The flow is vertically separated into a bottom vegetation layer and an upper free water layer and corresponding momentum equations for each layer are formulated. In the bottom vegetation layer, the resistance caused by the deflected plants is calculated accounting for plant bending rather than adopting the existing resistance formula for rigid vegetation. For the upper free water layer, a new type of polynomial velocity distribution was suggested instead of the traditional logarithmic velocity distribution to obtain a zero velocity-gradient at the water surface. Pu et al. (2019) presented the analytical model for stream-wise velocity distribution for open channel flow with submerged flexible vegetation. They separated whole flow field into two layers (vegetated and non-vegetated layer). They also investigated the impact of drag coefficient C_d and friction coefficient C_f on the flow with flexible vegetation using an analytical model. The flexibility of vegetation is difficult to measure (Fathi-Moghadam and Kouwen, 1997).

The main objective of this study is to investigate the impact of submerged flexible vegetation at different stream-wise location within a rectangular channel flume on the various flow characteristics (vertical stream-wise velocity distribution, turbulence intensity and turbulent kinetic energy).

2. MATERIALS AND METHODS

2.1 Experimental flume and material

Experiments were conducted in a rectangular open channel tilting flume of 10 m long, 0.6 m wide and 0.6 m height located in Hydraulic Engineering Laboratory of Civil Engineering Department at the National Institute of Technology, Rourkela, India. The channel had a test section of 3 m long and 0.6 m wide with a slope of 5.012×10^{-4} with overall length of 4 m from channel entrance. The channel also had 1m long glass side wall at the test section so that interaction between vegetation and water could be observed clearly. The experimental setup consists of an overhead tank, sump, volumetric tank and a pump to fed water flow through the system and to maintain re-circulation in the system. The discharge in the channel was provided by the centrifugal pump. Supply of water in the channel is regulated by the turning valve provided in the inlet section at the upstream end and depth of water in channel is adjusted by a tailgate provided at the outlet section in downstream end. The discharge measurement is made volumetrically with the help of a volumetric tank provided just after the downstream end of the channel and also with the help of flow meter. Flow straighteners and baffle wall are used at the inlet section of channel to reduce the pump turbulence (Fig. 1).

The water level were kept constant at 0.27 m with constant discharge of Q = 0.0245 m^3/s. Based on a discharge and a water level, the corresponding mean stream-wise velocity of fully developed turbulent flow were recorded as U_{m} = 15.124 cm/s. Based on a discharge and flow depth Froude number and Reynolds number were obtained as 0.1 and 24148, respectively. An ADV was placed over the test section in the flume at the measuring point to measure the 3-dimensional instantaneous velocity and turbulence characteristics within and above the vegetation zone. ADV used in this experiment is having three probes to measure lateral, longitudinal and vertical velocity with fluctuations. ADV is working on the principal of Doppler effect to measure the 3-D instantaneous velocity of very small suspended particle at sampling volume. The velocity components in the cartesian coordinate system x, y, and z are represented by u, v, and w respectively. ADV was used to collect the data on various point at the frequency of 50hz in a sampling volume of 0.09 cm^3 which was 5cm away from the sensing element with a 60 s sampling time. Thus, a total of 3000 data measurements were collected at each location. ADV can measure the velocity up to 0.5cm above the bed.

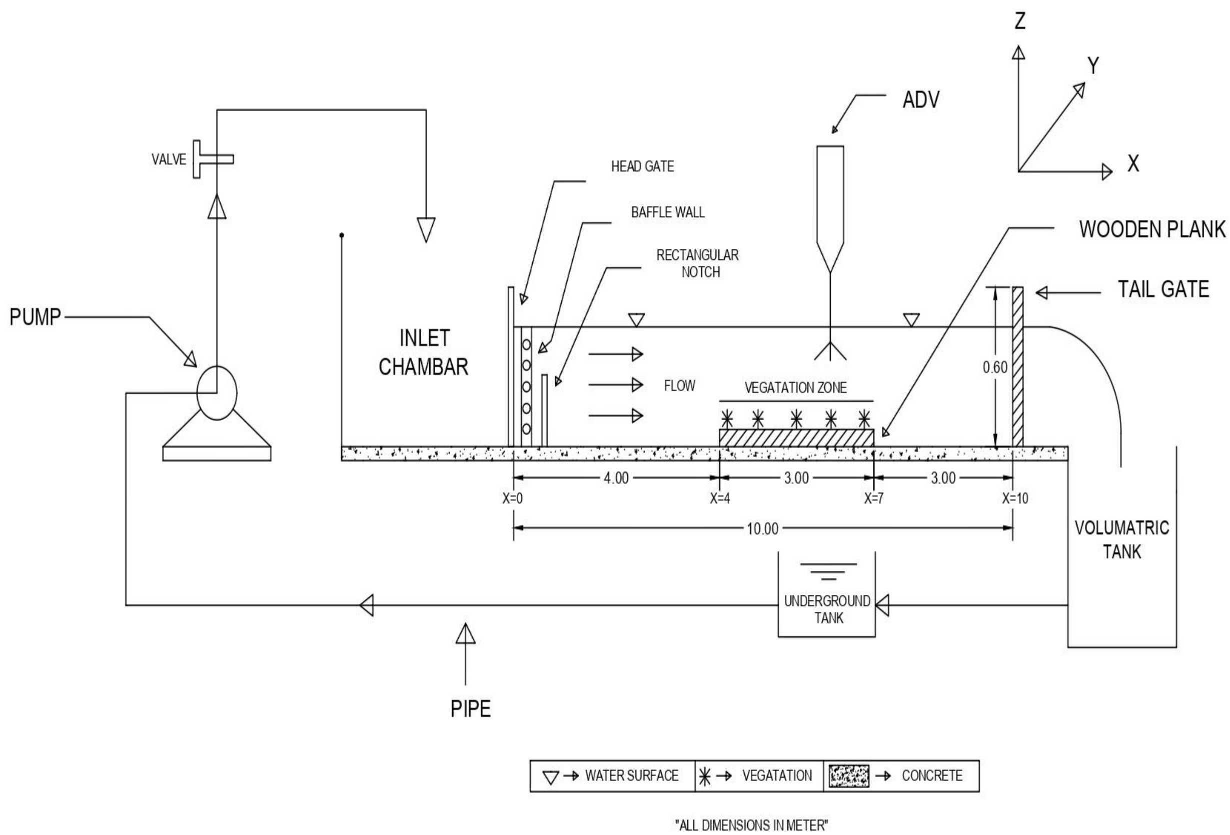


Fig. 1. A schematic diagram of experimental set-up, NITR

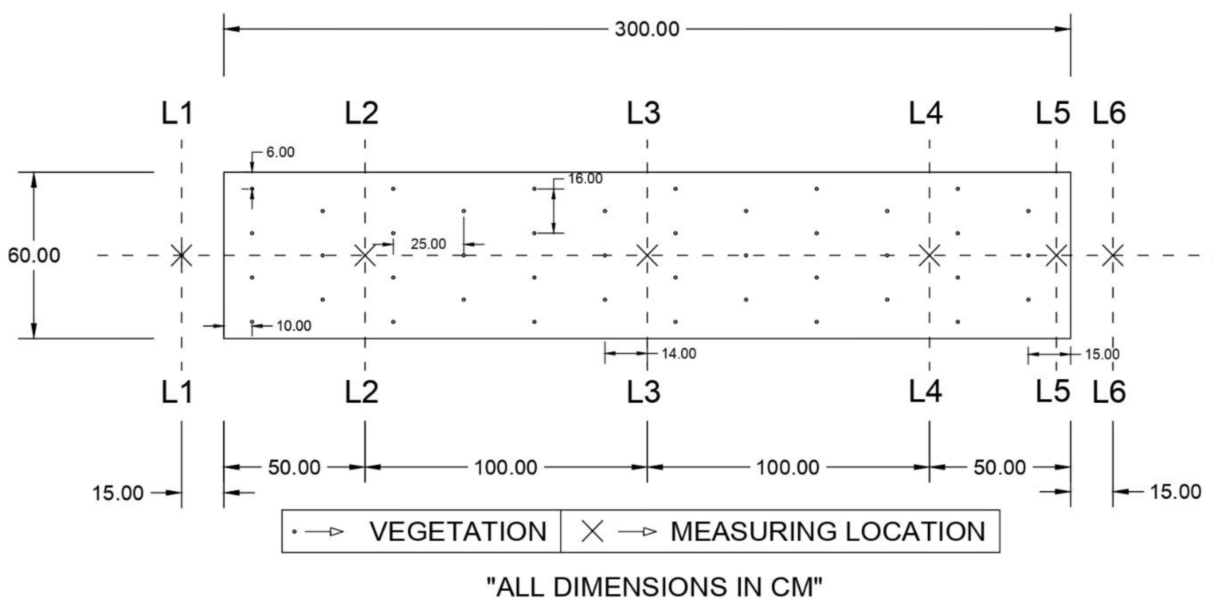
2.2 Vegetation specifications and configurations

Artificial plants with appreciable flexural rigidity of sedge shape is used to represent the natural vegetation (Grass / sedge shape) (Fig. 3a). The flexibility of pant is difficult to measure. However, in this study artificial plants were considered in such a way that they had sufficient flexibility so that they were not bend more or less during the flow. Each artificial plant has 5 plastic stem which are connected at plant root, forming a plant clump. Each stem has 14 leaves which are equally distributed around the stems. These artificial plants are suitable to represent the sedge because they do not have high bending.

The mean height of the plant is 21 cm. Diameter of each sheath section was varied from 0.6 cm to 1.7 cm and the diameter of leaf section was varied from 1.7 cm to 13 cm (Fig. 3b). Each sheath section was 4 cm long. The projected front width of the plant increased with the height of the plant, with maximum value at the canopy area (z = 15 – 20 cm) and minimum value at the sheath section (z = 0-4 cm) (Fig. 3b). All plants were fixed to a wooden plank (3 m × 0.6 m × 0.012 m) with pre-drilled holes (Fig. 2b), placed 4 m from the upstream inlet. The density of plants in a staggered arrangement was 24 stems/m^2 (Fig. 2c).

(a)

(b)

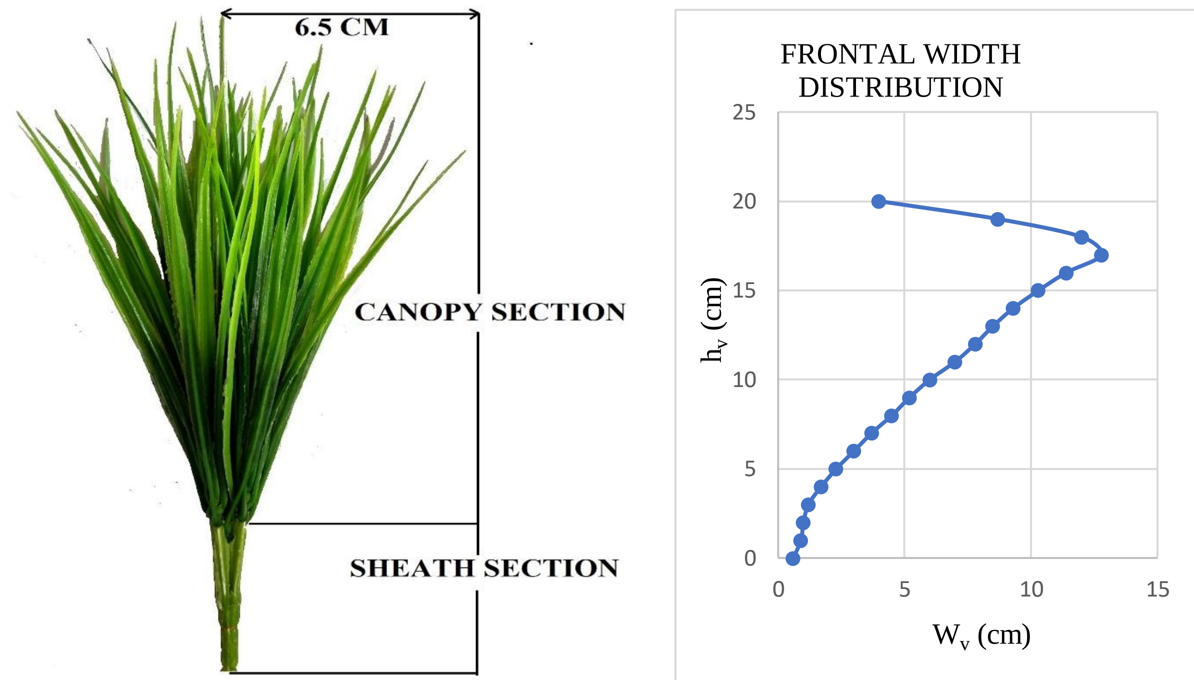


(c)

Fig. 2. (a) Image of experimental flume at NITR laboratory. (b) Pictorial view of flume with flexible vegetation in staggered arrangement. (c) Schematic top view presentation of test section with six measuring location and vegetation arrangement.

2.3 Positions of measurements

Flow characteristics were investigated at six locations, numbered location L1 to L6 (Fig. 2c). Location 1 and 6, located outside of the vegetation area at the upstream and downstream side respectively, were intended to study effect on flow characteristics before and after vegetation. Location 2 and 4 located at the upstream and downstream edge of the vegetation area respectively. Location 3 located at the center of the vegetation area and location 5 located at the downstream vegetation edge in the centerline just after the plant. At each location flow characteristics (velocity, turbulence intensity and turbulence kinetic energy) were measured over 20 – 30 points starting from 0.5 cm above the bed to 0.5 cm near the water surface. The measurement was done at 0.5 cm to 2 cm increments. The ADV was placed in the center line of the channel and measurements were taken along the center line locations mentioned above (Fig. 2c).



(a) (b)

Fig. 3. (a) Image of the experimental artificial flexible vegetation of sedge shape made by plastic material. (b) Frontal width distribution of submerged flexible vegetation changes at different vegetation heights, 'W_v' represents frontal width of a plant and 'h_v' represents vegetation height.

3. RESULTS AND DISCUSSIONS

The raw data collected from the ADV needed to be filtered first to examine the characteristics of flow. Raw data of instantaneous three-dimensional velocity collected through ADV were filtered with post-treatment software WinADV (Wahl, 2000). Data of ADV after filtering was reduced but still the data was sufficient for evaluation. The vertical stream-wise velocity profile, turbulence intensity and turbulence kinetic energy measured at each location are analyzed and presented. Fig. (4 - 6). Each flow characteristics shows distinct variations due to presence of vegetation. The analysis of these flow characteristics is discussed next.

3.1 Velocity profiles

The vertical distribution of stream-wise velocity can be divided into three layers: the upper free water (non-vegetated) layer (1.0 - 1.4 h_v), the middle layer with canopy (0.2 – 1.0 h_v) and lower layer with sheath section (0 – 0.2 h_v), where h_v is the height of vegetation. The shape of the velocity profile in each layer was dependent on the location of the profile in a channel with respect to vegetation area. The stream-wise velocities (u) are normalized by the local depth-averaged velocity (U_m).

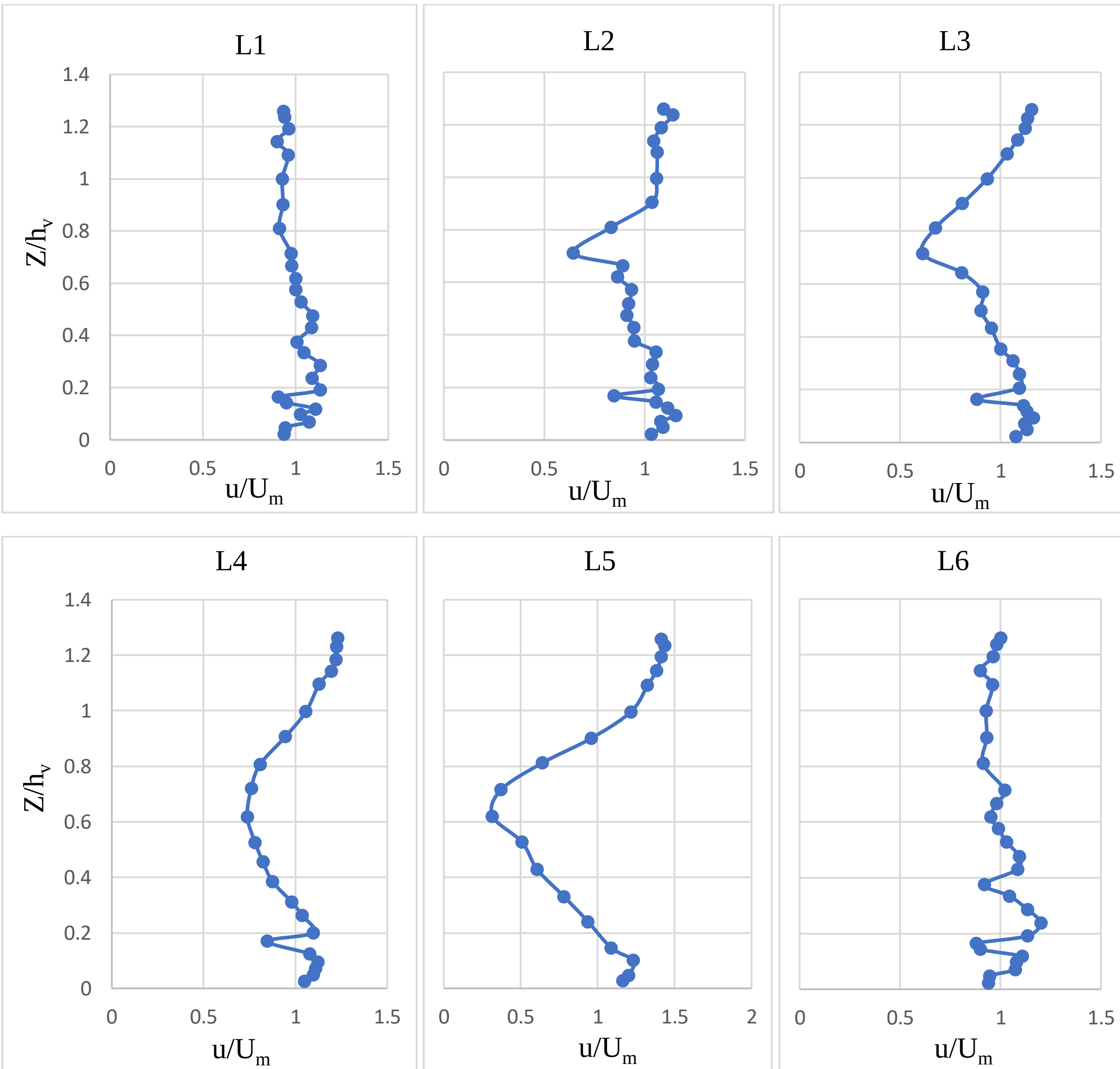


Fig.4. vertical distribution of stream-wise velocity at different locations from L1 to L7. Here z represents the vertical distance from bottom, h_v represents vegetation height, u represents the measured stream-wise velocity and U_m represents the local depth-averaged velocity.

As can be seen in Fig. 4, the vertical stream-wise velocity profile in upper free water layer is disordered at locations L1, L2 and L6. It is logarithmic at locations L3, L4 and L5. In middle canopy layer, the magnitude of stream-wise velocity fluctuated from L1 to L3 but was stable at L4 and L5. The stablized profile look like a 'S' shape with the minimum value located at the canopy area where the frontal width was maximum (0.6 – 0.8 h_v). and the maximum value located at the free water layer (1.0 – 1.2 h_v). In lower sheath layer also velocity profile fluctuated between L1 to L2 and become stable at L3, L4 and L5 with minimum value at the intersection of sheath and canopy (Fig. 4).

3.2 Turbulence intensity

The turbulent intensity represented by the root mean squared value of fluctuating velocity component (u', v', w') of instantaneous velocity. $u_{rms}, v_{rms}, w_{rms}$ are the turbulence intensity in x, y and z direction respectively.

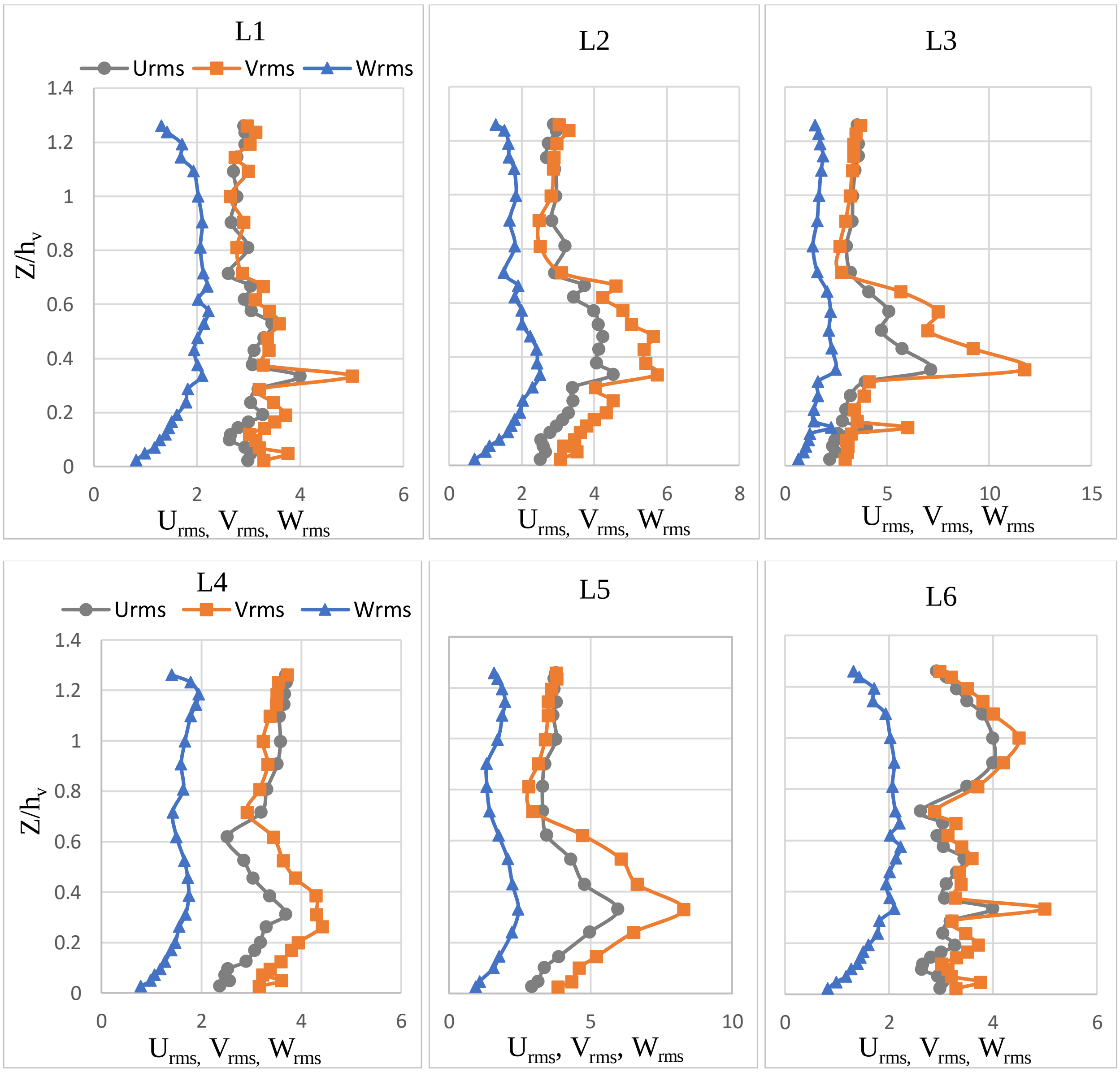


Fig. 5. Vertical distribution profiles of turbulence intensity ($u_{rms}, v_{rms}, w_{rms}$) at locations L1, L2, L3, L4, L5 and L6.

The vertical profiles of turbulence intensity was fluctuating from L1 to L3 and stablized at L4 and L5. The maximum value of turbulence intensities located at two locations, one at the intersection of sheath and canopy layer or starting of canopy layer (0.2 h_v to 0.4 h_v) and another at the intersection of canopy and free water layer (1.0 h_v to 1.2 h_v). The minimum value of turbulence intensity was located between 0.6 h_v to 0.8 h_v, where the canopy projected area was reported maximum (Fig. 5).

3.3 Turbulent kinetic energy (TKE)

TKE is one of the parameters of turbulence flow and is computed as per equation

$$TKE = \frac{(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})}{2} \quad (1)$$

TKE is normalized with square of shear velocity corresponding to approach flow as per equation

$$TKE^* = \frac{TKE}{u_*^2} \quad (2)$$

Where TKE^* is normalized velocity

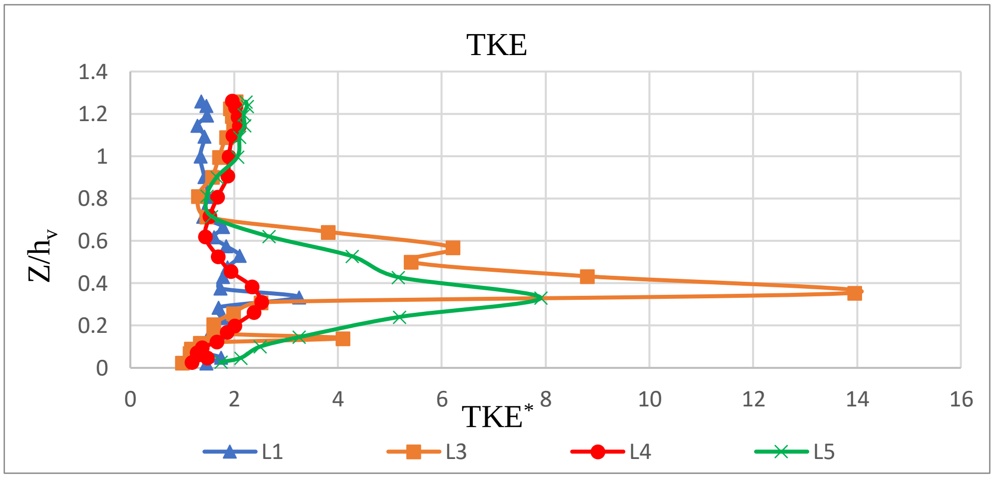


Fig. 6. Vertical distribution profiles of turbulent kinetic energy (TKE) at locations L1, L3, L4 and L5. Here 'z' represents the vertical distance from bottom and 'h_v' represents vegetation height.

As we can see the vertical distribution profiles of turbulent kinetic energy was fluctuating at L1, L3 and L5. At L4 The vertical distribution profiles of turbulent kinetic energy was stablized with maximum value at two locations, one is intersection of sheath and canopy layer (0.2 h_v – 0.4 h_v) and another one is intersection of canopy and free water layer (1.0 h_v – 1.2 h_v) (Fig. 6).

4. CONCLUSION

This study inquired the effect of submerged flexible vegetation on various flow characteristics (vertical stream-wise velocity, turbulence intensity and turbulent kinetic energy). To mimic the natural vegetation in an open channel system artificial plants of sedge shape and made up of plastic were used. In this experiment Acoustic Doppler Velocimeter (ADV) was used to collect data of three-dimensional velocity in x, y and z direction. The data was collected at six different locations and processed by post treatment software WinADV. The vertical distribution profile of various flow characteristics such as stream-wise velocity, turbulence intensity and turbulent kinetic energy was analyzed. The stablized profile of vertical stream-wise velocity look like a 'S' shape with the minimum value located at the canopy area where the frontal width was maximum and the maximum value located at the free water layer. The maximum value of turbulence intensities and turbulent kinetic energy was located at two locations; one at the intersection of sheath and canopy layer and another at the intersection of canopy and free water layer.

REFERENCES

Chen, S. C., Kuo, Y. M., & Li, Y. H. (2011). Flow characteristics within different configurations of submerged flexible vegetation. *Journal of Hydrology*, *398*(1-2), 124-134.

Cheng, N. S. (2007). Power-law index for velocity profiles in open channel flows. *Advances in water Resources*, *30*(8), 1775-1784.

Fathi-Maghadam, M., & Kouwen, N. (1997). Nonrigid, nonsubmerged, vegetative roughness on floodplains. *Journal of Hydraulic Engineering*, *123*(1), 51-57.

Huai, W. X., Zeng, Y. H., Xu, Z. G., & Yang, Z. H. (2009). Three-layer model for vertical velocity distribution in open channel flow with submerged rigid vegetation. *Advances in Water Resources*, *32*(4), 487-492.

Huai, W. X., Zhang, J., Katul, G. G., Cheng, Y. G., Tang, X., & Wang, W. J. (2019). The structure of turbulent flow through submerged flexible vegetation. *Journal of Hydrodynamics*, *31*(2), 274-292.

Huai, W., Wang, W., & Zeng, Y. (2013). Two-layer model for open channel flow with submerged flexible vegetation. *Journal of Hydraulic Research*, *51*(6), 708-718.

Hui, E. Q., Hu, X. E., Jiang, C. B., & ZHU, Z. D. (2010). A study of drag coefficient related with vegetation based on the flume experiment. *Journal of Hydrodynamics, Ser. B*, *22*(3), 329-337.

Järvelä, J. (2002). Flow resistance of flexible and stiff vegetation: a flume study with natural plants. *Journal of hydrology*, *269*(1-2), 44-54.

Järvelä, J. (2005). Effect of submerged flexible vegetation on flow structure and resistance. *Journal of Hydrology*, *307*(1-4), 233-241.

Klopstra, D., Barneveld, H. J., Van Noortwijk, J. M., & Van Velzen, E. H. (1997). Analytical model for hydraulic roughness of submerged vegetation. In *Proceedings of the congress-international association for hydraulic research* (pp. 775-780). LOCAL ORGANIZING COMMITTEE OF THE XXV CONGRESS.

KUBRAK, E., Kubrak, J., & ROWIŃSKI, P. M. (2010). Vertical velocity distributions through and above submerged, flexible vegetation. *Hydrological sciences journal*, *53*(4), 905-920.

Leonard, L. A., & Croft, A. L. (2006). The effect of standing biomass on flow velocity and turbulence in Spartina alterniflora canopies. *Estuarine, Coastal and Shelf Science*, *69*(3-4), 325-336.

Li, Y., Wang, Y., Anim, D. O., Tang, C., Du, W., Ni, L., ... & Acharya, K. (2014). Flow characteristics in different densities of submerged flexible vegetation from an open-channel flume study of artificial plants. *Geomorphology*, *204*, 314-324.

Neary, V. S. (2003). Numerical solution of fully developed flow with vegetative resistance. *Journal of engineering mechanics*, *129*(5), 558-563.

Noarayanan, L., Murali, K., & Sundar, V. (2012). Manning's 'n'co-efficient for flexible emergent vegetation in tandem configuration. *Journal of hydro-environment research*, *6*(1), 51-62.

Pietri, L., Petroff, A., Amielh, M., & Anselmet, F. (2009). Turbulent flows interacting with varying density canopies. *Mechanics & Industry*, *10*(3-4), 181-185.

Pu, J. H., Hussain, A., Guo, Y. K., Vardakastanis, N., Hanmaiahgari, P. R., & Lam, D. (2019). Submerged flexible vegetation impact on open channel flow velocity distribution: An analytical modelling study on drag and friction. *Water Science and Engineering*.

Righetti, M., & Armanini, A. (2002). Flow resistance in open channel flows with sparsely distributed bushes. *Journal of Hydrology*, *269*(1-2), 55-64.

Wahl, T. L. (2000). Analyzing ADV data using WinADV. In *Building partnerships* (pp. 1-10).

Wilson, C. A. M. E. (2007). Flow resistance models for flexible submerged vegetation. *Journal of Hydrology*, *342*(3-4), 213-222.

Wilson, C. A. M. E., Stoesser, T., Bates, P. D., & Pinzen, A. B. (2003). Open channel flow through different forms of submerged flexible vegetation. *Journal of Hydraulic Engineering*, *129*(11), 847-853.

Zhang, X., & Nepf, H. M. (2009). Thermally driven exchange flow between open water and an aquatic canopy. *Journal of Fluid Mechanics*, *632*, 227-243.