Effect Of Vegetation Density On The Hydrodynamic Of Submerged Vegetated Flow

[1] Busari Afis Olumide[*], [1,2] Gbadebo Anthonia Olukemi, [1] Jimoh Ibrahim Olayinka,

[*1]Civil & Environmental Engineering Department

Federal University of Technology, Minna Nigeria

[2]Hydraulic Engineering & River Basin Development

UNESCO-IHE Institute for Water Education, Westvest 7, 2611 AX, Delft, The Netherlands.

Abstract

Vegetation density affects the hydrodynamic of flow field, increasing the hydraulic roughness scale; accelerate the conversion of mean kinetic energy into turbulent kinetic energy at the scale of the plant stems and branches. This study presents the laboratory experiment on the effect of increase in vegetation density using PIV techniques. The vegetation densities was varied while the channel bed-slope and submergence depth were kept constant. The results showed a remarkable reduction in flow rate, resulting in high turbulent shear stresses at the top of vegetation layer. It is evident that vegetation density is a significant vegetation parameter on the induction of hydraulic roughness.

Keywords: *Hydraulic roughness, submerged vegetation, vegetation density*

1. Introduction

Freshwater and saltwater wetlands are important medium between aquatic and terrestrial systems, mediating exchanges of sediment (Phillips, 1989), metals (Orson et al., 1992), nutrients (Nixon, 1980) and other contaminants (Dixon and Florian, 1993). Aquatic plants control these exchanges both directly through uptake and biological transformation and indirectly by changing the hydrodynamic conditions. They are, therefore, fundamental components of a natural water environment, and the current environmental river management prefers to preserve natural wetland and floodplain vegetation, although a lot of aquatic plants have been removed to prevent water disaster in actual rivers. Currently, aquatic plants environments have reached a different status.

Vegetation is no longer regarded merely as an obstruction to the movement of water, but rather as a means of providing stabilization for banks and channels (Lopez and Garcia, 2001), habitat and food for animals and pleasing

landscapes for recreational use (M.Zhang et al., 2012). Therefore, the preservation is of great relevance to ecology of natural and artificial systems. Hence, the hydro-mechanic interaction between the flow and vegetation elements needs to be studied.

Uniform flow in an open channel or river is characterized by depthwise logarithmic shear velocity and turbulence. The presence of vegetation interrupts the shear and increases the turbulence in the vegetation region. A large scale of coherent vortex is generated near the canopy edge, which dominate the momentum and scalar transport through and over the canopy. Therefore, estimation of the flow resistance of vegetation flows is of great importance to river engineers.

The presence of vegetation along the open channel called for vegetation term. It has been established by various research that the presence of vegetation in a channel induced flow resistance in the channel. Based on the research conducted by (Carollo et al, 2005 and Baptist et al, 2007), the flow resistance depends on shear Reynolds number, the relative submergence and degree of vegetation inflection (a function of flexibility and stem density). The experimental

Busari et al, (2013a) evaluates the best probability distribution model for the prediction of rainfall- runoff for Tagwai basin, and suggested appropriate model for the estimation of annual runoff from the basin. The overflow

contribution of Okamoto and Nezu, (2010) on relationship between the vegetation motion and flow resistance property in a vegetated open channel flow showed influence of flexibility of vegetation on the turbulence structure and inflection point. Nikora et al, (2008) studied the impact of vegetation on hydraulic resistance and suggested simple quantitative relation to predict these effects based on vegetation parameter. The research has provided relative improvement in the understanding of vegetation resistance.

The vegetated open-channel flows have received much attention in the past decades. However, in such vegetated open-channel flows, both the vegetation parameters and turbulence characteristics may affect the hydrodynamic behaviour of flows. Therefore, in the present study, the effect of vegetation density and associated turbulence characteristics were studied in laboratory flume using PIV technique. The focus of this study is specifically, to understand the impact of vegetation density on the hydrodynamic of flow fields as it is becoming a significant issue in vegetated waterways. The practical significance has been observed along the river channel at the downstream of Tagwai dam leading channel widening and flooding.

from Tagwai (weir) is the chief source erosion to the downstream channel along which Chanchaga bridge is located. This has been the subject of local scour on the bridge piers.

Recently, Busari et al, (2013b) examined the local scour on the bridge pier using onsite-empirical models approach and suggested the suitability of the models future measurement. However, during low flow vegetation growth are un-avoidable, it retards flow and allows sediment deposition. This results in increase in water level and subsequent flooding. This study is based on experimental study and no specific model scale is taken into consideration. Hence aspect ratio is not required and the results can be generalized for vegetated channel flows.
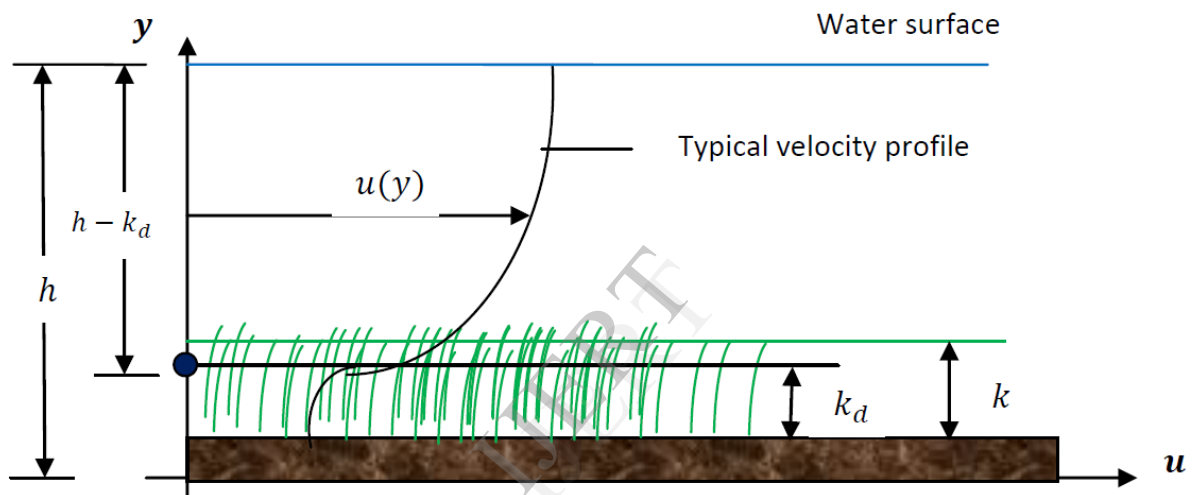

Figure 1: Definition sketch for the used variables

2. Background: Velocity profile and resistance

It has been shown that when vegetation is sufficiently submerged, the vertical distribution of velocity above the vegetation layer obeys a logarithmic profile. A common approach to the determination of flow resistance is based on relating a roughness factor f to mean cross-sectional velocity U_m and shear velocity u_* as

$$\frac{U_m}{u_*} = \sqrt{\frac{8}{f}} \qquad (1)$$

The velocity profile is given by Prandtl's log law modified by Nikuradse as:

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\frac{y}{y_o} + A \qquad (2)$$

Where κ is von Karman constant; y_o, is equivalent sand roughness; y, vertical coordinate; and A is constant of integration. The integration

of equation (2) yields the mean velocity, U_m. Stephan, (2002) modified the log law and derived an equation for the velocity profile above vegetation canopy

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\frac{y - k_d}{k_d} + 8.5 \qquad (3)$$

Where $\kappa = 0.4$ and k_d = mean deflected height of vegetation (see Figure **1**). In this study, the relative submergence h/k is kept constant throughout the experiments while the vegetation density remains variable. Based on the sensitivity analysis on the shear velocity determination, the shear velocity in this study is defined as:

$$u_* = \sqrt{g(h - k_d)S_o} \qquad (4)$$

Equation (4) has been tested among other different definitions of shear stresses as it offers better practical applicability than the original formulation $u_* = \sqrt{-(u^\iota v^\iota)_{max}}$ which required complicated turbulence measurements (Jarvela, 2005). More significantly, equation (4) is adopted in this study because it is straightforward to apply within a numerical modeling framework, which is part of our future focus relating hydraulic roughness parameter for Tagwai basin.

Wilson, et al. (2003), Tam and Li, (2005), Okamoto and Nezu, (2010) have defined

vegetation density a as the total frontal area A per vegetation volume V as shown in equation (5).

$$a = \frac{A}{V} = \frac{n*hw}{hS} = n\frac{w}{S} \qquad (5)$$

$$\lambda = ah \qquad (6)$$

Where n is the number of vegetation elements allocated in the area $S = 60cm \times 60cm$ on the channel and the frontal area of one vegetation element is $hw = 100mm \times 6mm$ in this study. For this study $\lambda = ah$ is used as the vegetation density because it is a dimensionless factor and therefore, can be compared with terrestrial canopy flow (for example, Raupach et, al. 1996).

3. Experimental set up

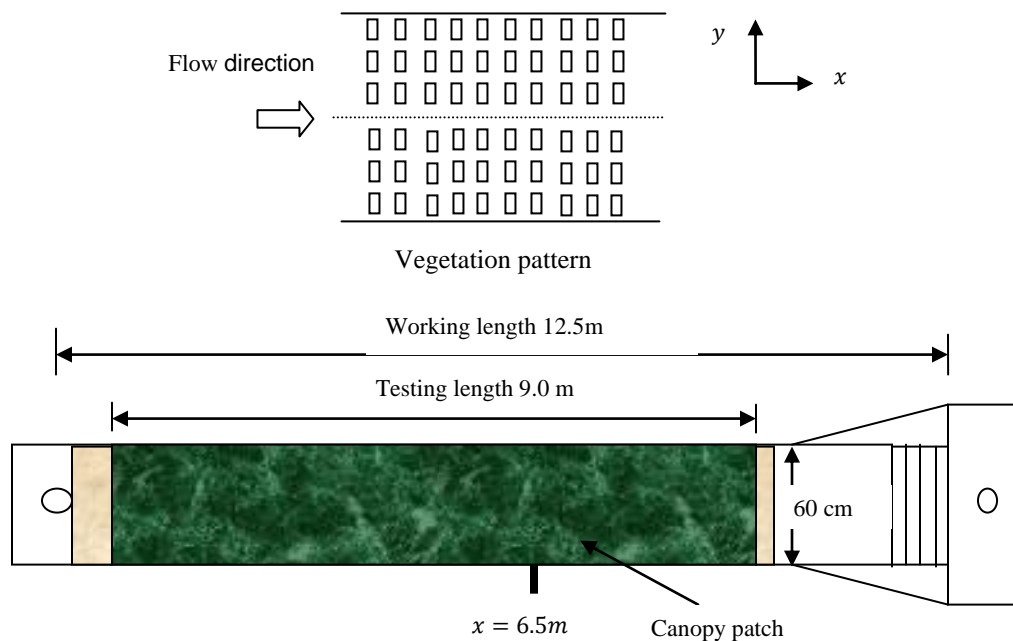### 3.1 *Hydraulic conditions and vegetation model*

The experiments were conducted in a 12.5 m long and 60 cm wide tilting flume. The sides were made of optical glass for Particle Image Velocimetry (PIV) measurements. The set up consists of varying vegetation density $\lambda = ah$ on turbulence structure for constant submergence depth, i.e., $h/k = 3.0$. Table 1 shows the hydraulic conditions in which U_m is the mean bulk velocity, $F_r \equiv U_m/\sqrt{gh}$ and $R_e = U_m h/\nu$ are Froude number and Reynolds number respectively.

Table1: Hydraulic conditions

λ	U_m (m/s)	h(m)	u∗ (m/s)	S$_o$ (-)	K_d (m)	F$_r$	Re
0.170	0.458	0.225	0.075	0.0036	0.072	0.305	103050
0.420	0.327	0.225	0.073	0.0036	0.078	0.218	73575
0.830	0.257	0.225	0.071	0.0036	0.084	0.171	57825
1.250	0.226	0.225	0.070	0.0036	0.086	0.151	50850
1.670	0.207	0.225	0.069	0.0036	0.09	0.138	46575
2.080	0.194	0.225	0.069	0.0036	0.09	0.129	43650

The elements of vegetation model were composed of strip plates with flexural rigidity of 4.75Nm². The size of one vegetation element was $k = 100mm$ height, $d = 6mm$ width and $t = 1mm$ thickness. The elements were attached vertically on the channel bed using the miniature lego blocks as shown in Figure **2**. A transition zone of 1 m length was set from the channel entrance. Then, the vegetation zone was set through 9 m length in the stream-wise direction and the full channel width of $B = 60\ cm$ in span-wise direction. L_v and B_v are the streamwise and spanwise spacing between the neighbouring vegetation elements, respectively. They decrease with increase in λ. The measurement was set 6.5 m downstream of the leading edge of the vegetation, i.e., $x = 0$. The preliminary runs found that the flow at the measurement zone $x = 6.5\ m$ was fully developed and uniform two-dimensional one.

Flow direction

y

x

Vegetation pattern

Working length 12.5m

Testing length 9.0 m

60 cm

$x = 6.5m$

Canopy patch

Figure 2: Schematic experimental set up

3.2   *Procedures of PIV measurements*

A laser light sheet (LLS) was projected into the water vertically from the free surface. The 2mm thick LLS was generated by 2W Argon-ion laser using a cylindrical lens and fiber-optical cable. The illumination position of LLS was located at $x = 6.5\ m$. The illuminated flow pictures were taken by a high speed CCD camera ($1 \times 1K$ pixels) with the frame rate and sampling time were set 200Hz and 60s, respectively. The diameter and specific density of tracer particles (Nylon 12) were 0.1 and 1.02, respectively. The instantaneous velocity vectors $(\tilde{u}, \tilde{v})$ in the vertical plane of $(20 \times 20\ cm)$ and the resolution was 0.2
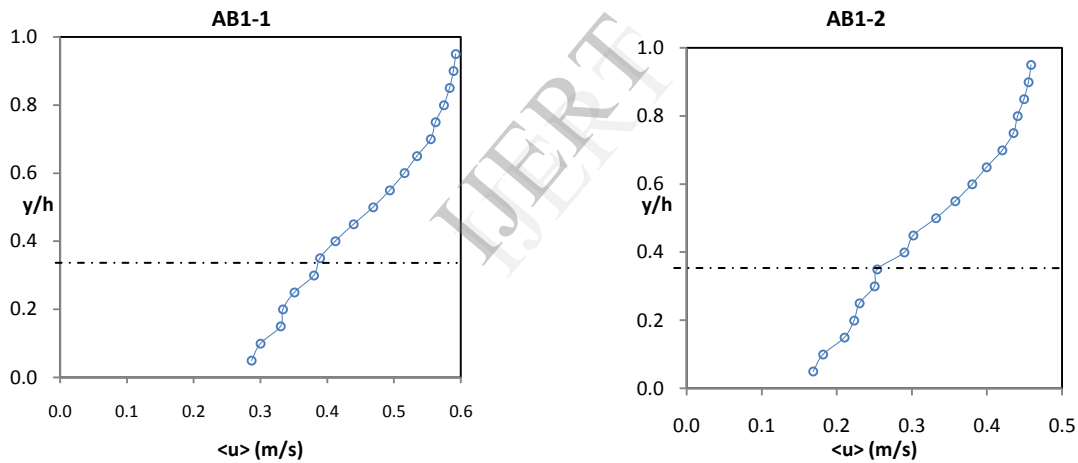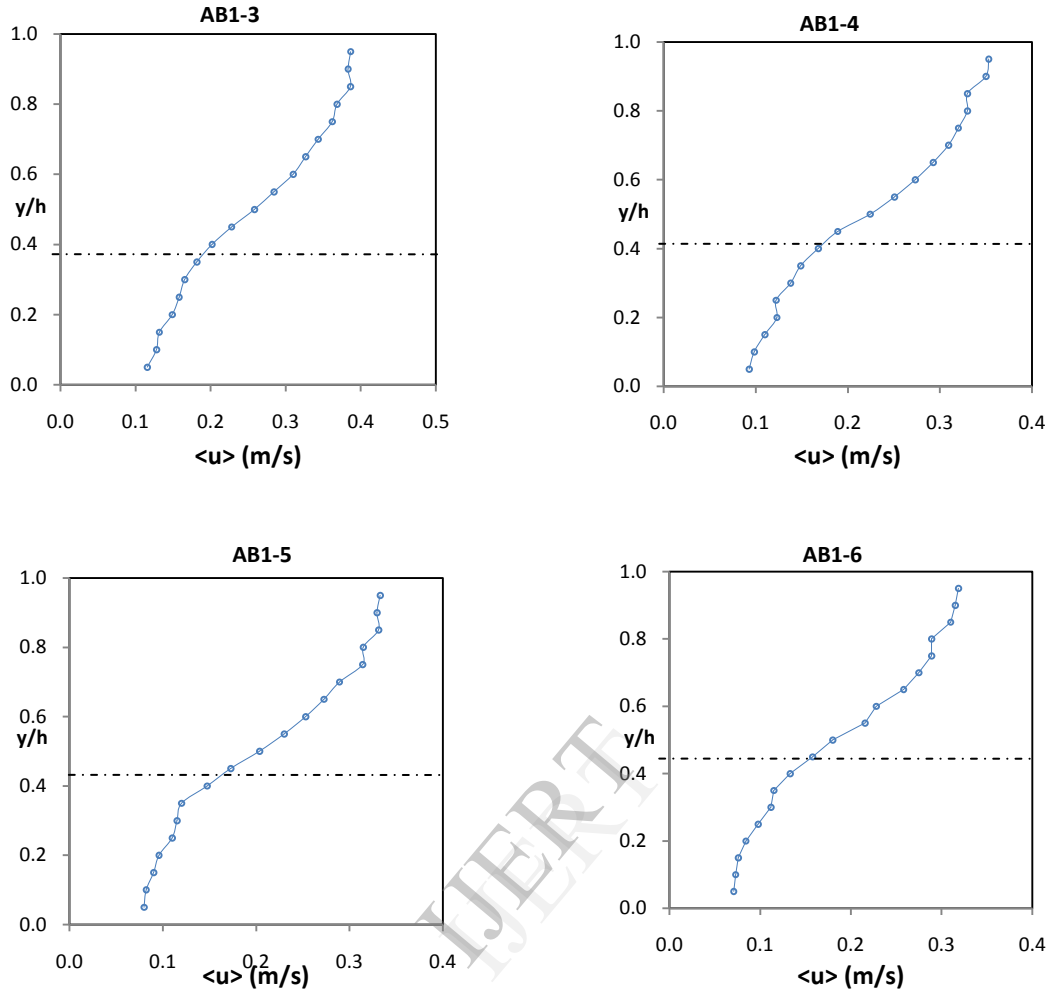
Figure 3: Mean velocity profile and normalized flow depth. The dashed line denotes the mean deflected plant height (see Table 1 for series description).

mm/pixel were measured using available standard PIV software. More detailed information about PIV is available in Nezu et al, (2007), Okamoto and Nezu, (2010).

4. Results and discussion

Figure **3**, showed velocity distribution profile, water depth was normalized by depth *y*, above the channel bed. The flow reduces with increase in vegetation density under constant submergence depth. Overall, the observed velocity profiles above the dotted line were comparable to typical profiles above vegetation. Thus, the flow above the vegetation reasonably followed the logarithmic law. Stronger shear layer near the top of the canopy is produced and a significant inflection point appears near the vegetation top ($y = k$), which is in good agreement with Okamoto and Nezu, (2010).

The deflected height of vegetation (dotted lines, Figure **3**) showed that deflection decreases with increase in vegetation density due to additional increase in drag from the vegetation. Consequently, the hydraulic roughness increases as velocity is reduced. Doubling vegetation density could result in 25% attenuation of discharge as shown in the velocity profile; this could increase the level of uncertainty in the forecast of lead time. From Table 1, the Froude numbers were less than unity, indicating subcritical flow throughout the experiments. However, the Reynolds numbers were found to be within the range of (40,000 – 105,000). This signifies the level of turbulence in the flume as a characterization of flow regime.

Figure **4**, shows the vertical distribution of Reynolds stress $-\overline{uv}$ normalized by the bulk mean velocity U_m for different vegetation density models. The ratio of $-\overline{uv}/U_m^2$ is a measure of momentum exchange efficiency. The strong shear layer near the vegetation edge generate large scale coherent vortex and larger momentum is transported towards within the vegetation. This increase as the vegetation density increases, resulting in higher turbulent shears. The maximum turbulence intensity was found at the interface of the vegetation layer. In figure **5**, the measured velocity was correlated with the predicted velocity using equation (3), the results showed a good agreement. Furthermore, Figure **6**, showed the roughness increase with increase in vegetation density. This implies that vegetation density increase the hydraulic resistance. Consequently, the friction factor increase as k_d becomes larger, thereby, increasing the water level.
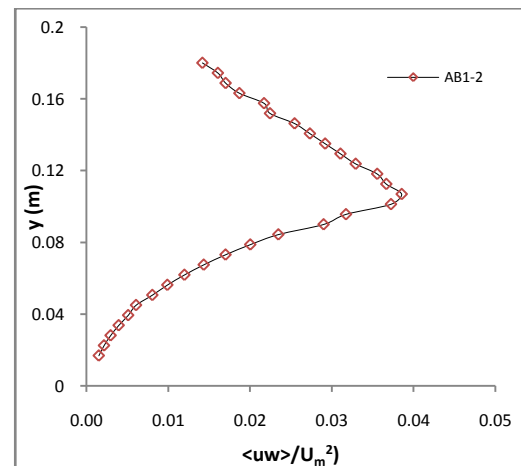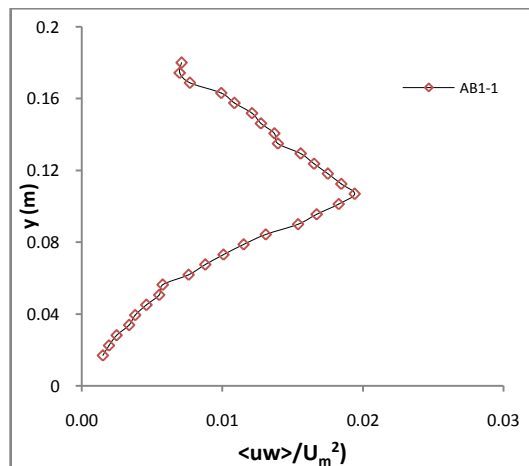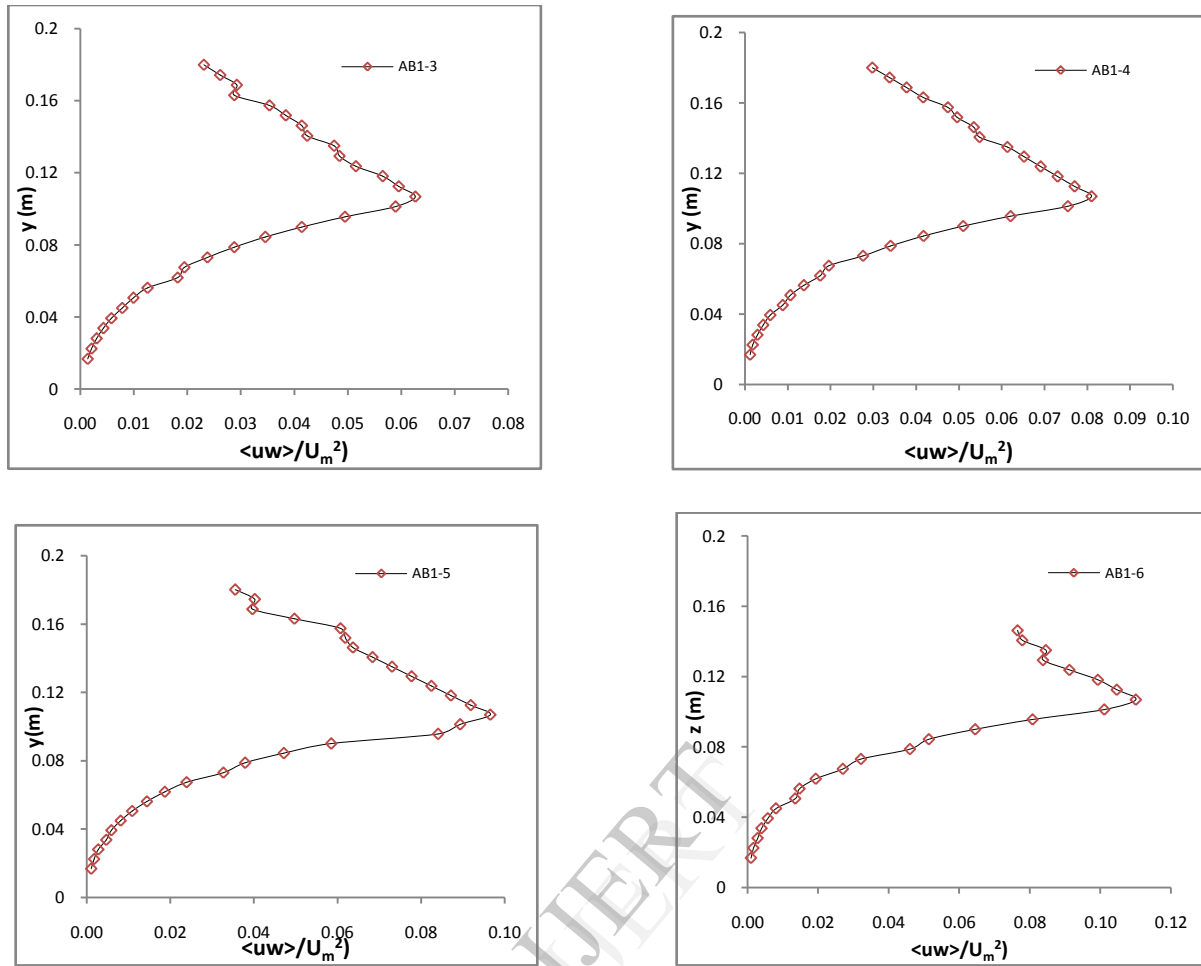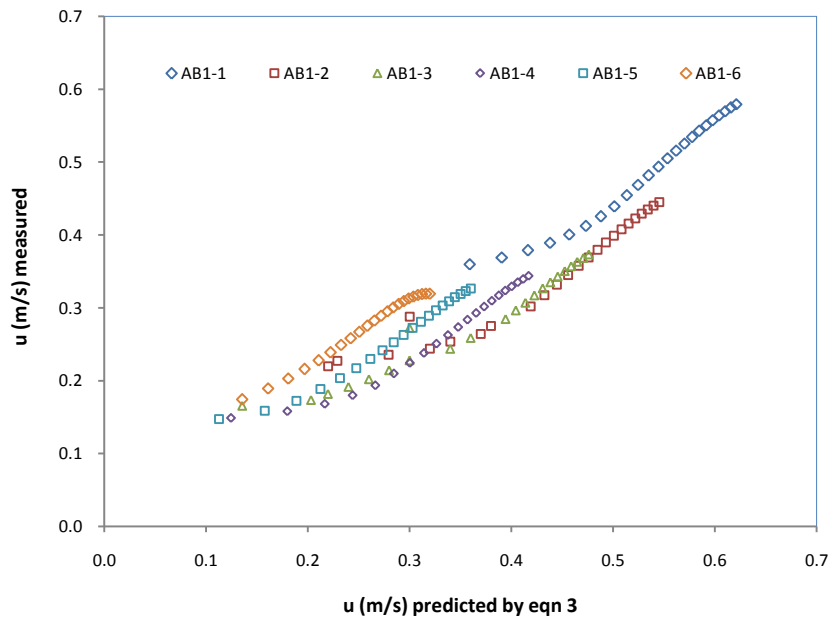
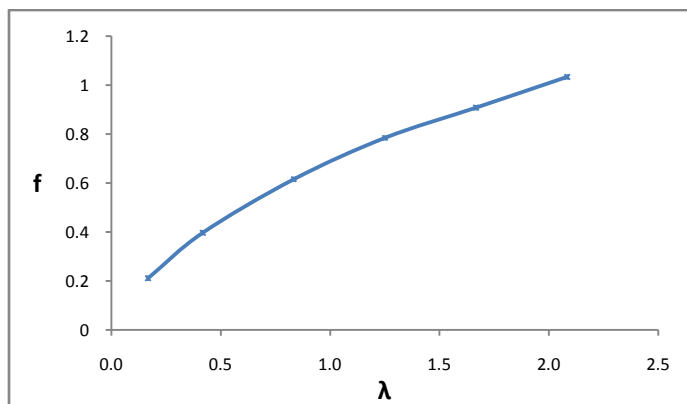**Figure 4:** Vertical distribution of Reynolds stresses

Figure 5: Velocity measured and predicted by equation (3)

The fitted model for the variation of vegetation densities and the corresponding friction factor is

well represented by equation (7).

$$f = 0.669\lambda^{0.6297} \tag{7}$$

Figure 6: Variation of vegetation density with friction factor

5. Conclusion

The flow structure within and above submerged artificial canopy was comparable to previous studies involving submerged vegetation. The velocity profile is more of "S" shape and the peak Reynolds stresses were found corresponding the top of the vegetation. The flow velocity far above the vegetation obeys logarithmic law when compared with equation (3). The simple shear velocity definition of u_* in

equation (4) based on the mean deflected plant height yielded good results. The friction factor and Reynolds stresses were found to be increasing with increase in vegetation density. This is an indicator that vegetation density is a relevant parameter for describing hydraulic roughness in vegetated flow. The impact of vegetation density on the hydraulic roughness was revealed. Special attention is required on the effect of vegetation density in river restoration and flood risk management.

References

Baptist, M.J, Babovic, V, Keijzer, M, Uttenbogaard, R.E, Mynett, A and Verwey, A (2007). On inducing equations for vegetation resistance. Journal of Hydraulic Research, Vol. 45, No. 4, pp 435 -450.

Busari A. O, Saidu, M and Ajibola, S, (2013a). Evaluation of Best Fit Probability Distribution Models for the Prediction of Rainfall and Runoff Volume (Case study Tagwai dam, Minna-Nigeria).International Journal of Engineering and Technology UK, Volume 3 No. 2, pp 94-98.

Busari A. O, Gbadebo A. O, Jimoh I. O, Takeet, O.E and Enifu, J. E, (2013b). Evaluation of performance of empirical models for the prediction of local scour at bridge piers (Case study Chanchaga Bridge, Minna, Nigeria). International Journal of Engineering Research & Technology (IJERT). Vol. 2 Issue 3, pp 1-11.

Carollo, F.G., Ferro, V. and termini, D (2005): Flow resistance law in channels with

flexible submerged vegetation. Journal of Hydraulic Engineering, Vol.131, No.7., pp 554-564.

Dixon, K. and Florian, J., (1993). Modelling mobility and effects of contaminants in Wetlands. Environmental Toxicology Chem., 12, 2281-2292.

Jarvela, J (2005). Effect of submerged flexible vegetation on flow structure and resistance. Journal of hydrology, 307, pp. 233-241.

Lopez, F and Garcia, M.H (2001). Mean flow turbulence structure of open-channel flow through non-emergent vegetation. Journal of Hydraulic Engineering, Vol.127, No.5., pp 392-402.

M. Zhang et al., (2012). Depth-averaged modeling of free surface flows in open channels with emerged and submerged vegetation. Applied Mathematical Modelling. Published by Elsevier Inc.

Nezu, I., Sanjou, M., Okamoto, T. (2007). PIV measurements in vegetated open channelflows, Proc. of 32nd IAHR Congress of Venice, No. 466 (10 pages on CD-ROM).

Nikora, V., Scott, L., Nina, N., Koustuv, D., Glenn, C. and Michael, R., (2008). Hydraulic resistance due to aquatic vegetation in small streams: Field study. Journal of Hydraulic Engineering, Vol.134, No.9., pp 1326-1332.

Nixon, S.,(1980). Between coastal marshes and coastal waters – A review of twenty years of speculation and research on the role of salt marshes in estuarine productivity and water chemistry, in Estuarine and Wetland processes, edited by P. Hamilton and K. MacDonald, pp. 438-525, Plenum, New York.

Okamoto, T., and, Nezu, I., (2010). Flow resistance law in open-channel flows with rigid and flexible vegetation. River Flow 2010-dittrich, Koll, Aberle & Geisenhainer (eds) Bundesanstalt fur Wasserbau ISBN 97-3-939230-00-7.

Orson, R., Simpson, R. and Good, R., (1992). A mechanism for the accumulation and retention of heavy metals in tidal freshwater marshes of the Upper Delaware River estuary, Estuarine Coastal Shelf science, 34, 171 -186.

Phillips, J., (1989). Fluvial sediment storage in Wetlands, Water Resources Bull., 25, 867-872.

Raupach, M.R., Finnigan, J.J., Brunet, Y., (1996). Coherent eddies and turbulence in vegetation canopies: the mixing-layer analogy. Boundary-Layer Meteorology 78, 351-382.

Stephan,U., Gutknecht,D., (2002). Hydraulic resistance of submerged flexible vegetation. Journal of Hydrology. 269 (1/2), 27–43.

Tam, B.Y.F. and **Li, C.W., (2005).** Gradually varied flow through semi-rigid vegetation, In: Lee, Lam (Eds.), Environmental Hydraulics and Sustainable Water Management Taylor & Francis Group, London, pp. 859-864.

Wilson, C.A.M.E., Stoesser, T., Bates, P.D., Batemann Pinzen, A., (2003). Open channel flow through different forms of submerged flexible vegetation. J. Hydraulic Eng. 129 (11), 847–853.