Experimental Investigation on Flow Configuration in Flexible and Rigid Vegetated Streams

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Research Article

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Experimental Investigation on Flow Configuration in Flexible and Rigid Vegetated Streams

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Abstract

Riparian vegetation can be a suitable option for the flood control and sustainable river management as it is beneficial for the energy dissipation of flows. The present experimental investigation is aimed at understanding the flow field and energy dissipation of flows in the presence of rigid and flexible vegetation. Physical laboratory-based models are tested in a rectangular flume to observe the flow field in upstream and downstream of both rigid and flexible vegetated streams. Rigid vegetation is simulated by wooden dowels of equal height and almost uniform diameter in this study whereas for flexible vegetation paddy plants are used. These vegetations are installed in a wooden box and fixed in middle of the channel. A constant discharge is maintained throughout the experiment. Acoustic Doppler Velocimeter is utilized to inspect the three-dimensional velocities and flow configuration in upstream and downstream of
the both rigid and flexible vegetations. The velocity profile isthen compared for both flexible and rigid vegetation. The velocity retardation near and within vegetation for the flexible vegetative model is found to be nearly 90%, whereas for the rigid model, it is around 24%. Additionally, energy dissipation at all the sections of both the vegetation typeis found to get a more comprehensive understanding of the flow field. Overall, this study observed that there is reduction in the stream velocity due to vegetation, which further decreases scouring in the channel, thereby reducing erosion and sediment discontinuity.

**Keywords:** Riparian, Sustainable, Rigid vegetation, Flexible vegetation, Velocity-profile.

1. Introduction

Riparian vegetation such as submerged, emergent and floating are found to be major source of ecological restoration by maintaining the sediment continuity in the channel by reducing the scouring. Generally, riparian vegetation shows a complex hydrodynamic phenomenon because of different morphology of plant species and flexibility. In the river course, it is found that vegetation consists of deciduous woody trees and shrubs, distributed with branches and leaves throughout the height (Schnitzler, 2007). The presence of emergent vegetation in the rivers alters the flow configuration, water level and the conveyance capacity of the channel (Nepf, 2012; Rowiński et al., 2018). In the past, several researches have been done for observing the flow resistance and water conveying capacity in order to determine the stage and discharge characteristics of artificial and natural streams. Several empirical equations have been suggested for estimating the river-bed roughness and flow resistance in the channels. Numerous literatures show that the well established flow resistance formulas such as Darcy-Weisbach, Chezy and Manning equations have been widely used to observe the river flows. Sustainable river
management could be done by the restoration of the aquatic and riparian vegetation. Both experimental and numerical studies were attempted to understand the hydrodynamics of the bed morphology in vegetated streams. Flow resistance developed by vegetated streams can be predicted considering the cylindrical roughness rods (Li and Shen, 1973). The flow characteristics of aquatic vegetation have been studied by various investigators in the past and it was seen that turbulence is significantly associated with the vegetation (Nepf and Vivoni, 2000; Finnigan et al., 2009; Nepf, 2012). Wilson et al. (2003) conducted experimental tests on two different kind of submerged vegetation and noticed that the extra thinnest zone affected the momentum transfer between the vegetative and upper zone of the aquatic vegetation. Chen et al. (2011) studied turbulent characteristics on the different patterns of submerged flexible vegetation arranged longitudinally and transverse with various spacing of plants. Interestingly, it was found that fully developed flow is divided into three zones such as top non-vegetated zone, middle vegetated zone and the sheath zone (separated zone). The flow profile along the stream direction of the submerged vegetation was greatly influenced due to the drag of the aquatic vegetation which resulted into the complicated velocity profile (Huai et al., 2009; Wilson, 2007; Zhang and Nepf, 2009, Cheng, 2007; Huai et al., 2009; Klopstra et al., 1997; Neary, 2003; Pietri et al., 2009; Righetti and Armanini, 2002). However, the velocity profile was different for flexible vegetation when compared with the rigid type aquatic vegetation (Ghisalberti and Nepf, 2006). The existence of vegetation plays a significant role in the shear layer dynamics by considering the drag force acting in the lateral vegetated area and the total settled velocity difference. Also, it was seen that large scale vortices are liable for the exchange process between the main channel and the vegetation portion (Ghisalberti and Nepf, 2002; White and Nepf, 2007), providing a
significant role in river system by regulating the movement of sediments, nutrients and pollutant (Jirka, 2001; Montakhab et al., 2012; Box et al., 2019).

However, uncontrollable growth of the vegetation throughout the channel length may also reduce the performance of the channel. For instance, emergent vegetation provides large hindrance to the channel flow and if not controlled, affects the conveyance capacity of the channel (Montakhab et al., 2015). Therefore, controlled vegetation growth has the full potential to be an important, efficient and sustainable way of river restoration and erosion prevention works. A brief insight into the advantages and disadvantages is shown below in Fig.1 for a better understanding of the effects of vegetation in a channel.

**Figure1**: Effect of vegetation in a channel.

Although many studies have investigated flow characteristics in vegetated open-channel flows, the flow and turbulence profiles within natural vegetative models have not been explored
extensively. Moreover, there is also a lack of comparative study to understand the effects of vegetation type (i.e., flexible and rigid) on the flow field. The main objective of this study is to investigate the effects on the flow structure within emergent flexible and rigid vegetation. Therefore, the flow velocity profile across different water depths and sections were found out and compared so as to gain an insight into this complex vegetation-flow interaction. The results of this study would help the readers to get a comprehensive idea about the flow in a vegetated channel and the results may be further extended to understand the process of sedimentation and ecological restoration of polluted rivers.

2. Experimentation

A number of laboratory tests were performed in the Fluids and Water Resources Laboratory of the Civil Engineering Department, National Institute of Technology, Warangal considering a 10.0 m long tilted flume with a width (B) of 0.4m and height of 0.75m having glass-walled in its major portion for proper three-dimensional view of the flow. A schematic plan for the experimental flume is shown in Fig. 2. The upstream part of the flume was facilitated by baffle wall to minimize the flow disturbances and cross-currents. A storage tank was available for continuous supply of clear water. An inlet pipe of diameter 0.1 m was mounted with a valve for discharge regulation. An ultrasonic flowmeter with accuracy ±1% and point gauge (least count = 0.0001 m) were used to observe the discharge and head, respectively. The flowmeter was connected to the inlet pipe and the point gauge was placed on the top of the channel for measuring the head at different sections. Acoustic-Doppler velocimeter (ADV) of Nortek-AS made with 10 megahertz (MHz) was used to study the three dimensional. The ADV applied in the study had an accuracy of ± 0.5 % of observed value ±1 mm/s as shown in Fig. 2(b). The velocity was measured at different local points as given in. 1(b). The values of the minimum
measured depth of water (at 0.5 m upstream of the vegetation) and flow velocity (at 0.1235 m upstream of the vegetation) were 0.260 m and 0.192 m/s, respectively. Therefore, the maximum uncertainty may be 

\[ 1+ \left( \frac{0.0001}{0.260} \right) \times 100 + \left( \frac{0.0001}{0.192} \right) \times 100 \% = 1.09 \% \text{ (say 1.1\%)} \]

which is very nominal.

A wooden box consisting of two kinds of vegetation was provided in the mid section of the flume in order to measure the velocity at different sections of the vegetation field. The dimensions of the boxes were 0.5m × 0.38m × 0.1m and were constructed with the waterproof ply board. Flexible and rigid vegetation chosen for the present studywere represented by using natural rice plants grown in the laboratory and wooden dowels respectively. Several wooden dowels were arranged in the columnar pattern for the investigation of flow field and the same pattern was also adopted for the flexible rice plants as shown in Fig.3. Discharge was maintained at \( 20 \times 10^{-3} \text{ m}^3/\text{s} \). For comparison purpose two similar boxes (for flexible vegetation only) were placed in order to measure the velocity across the vegetation for emergent case. The flow depth (H) was maintained at 0.26m during the experiment.

![Figure 2: (a) Experimental Setup (b) ADV setup for the experimental runs](image)
3. Methodology

A physical laboratory based models were tested in a rectangular flume to observe the flow field in the upstream and downstream of both rigid and flexible vegetated streams. The rigid vegetation of equal height and almost uniform diameter were considered in this study whereas for the flexible vegetation paddy plants were used. A constant discharge of $20.0 \times 10^{-3}$ m$^3$/s was maintained throughout the experiments. Three dimensional velocities were measured considering one discharge for both flexible and rigid vegetative model in the study. The flow field in the upstream and the downstream of the vegetative model were observed by the help of ADV at local points as shown by the grids in Fig.4. Data collected from each grid point was stored for a time span of 5 minutes having frequency equals to 50 Hertz which gives better results with least amount of noise interventions. For each local grid point, the vertical grid points along the flow
depth were varied from downwards to upwards i.e. 1 cm near to the bed and 2 cm from centre to the free surface of the flow. After the collection of experimental data, the recorded raw data were filtered on the basis of minimum SNR (Signal to Noise Ratio) = 15 and minimum COR (Coefficient of Restitution) = 70 (Voulgaris and Trowbridge 1998). These filtered data were finally processed to calculate the mean velocities along XY plane for constructing vector fields near vegetative models using MATLAB software. The velocity profile for both the vegetation was compared at the different sections. The same procedure was adopted to compare the effect of increased vegetative density (flexible vegetation only) on the flow field. Finally, the flow field with and without the vegetation were found in order to understand the hydrodynamics and bed morphology of vegetative streams.

![Figure 4: (a) Flexible grid patterns (b) Rigid grid patterns](image-url)
The time-averaged streamwise velocity (u), transverse velocity (v) and vertical velocity (w) for all the sections were determined by the following equations:

\[
\begin{align*}
u &= \frac{1}{n} \sum_{i=1}^{n} u_i \\
v &= \frac{1}{n} \sum_{i=1}^{n} v_i \\
w &= \frac{1}{n} \sum_{i=1}^{n} w_i
\end{align*}
\] (1) (2) (3)

The energy dissipation for the respective vegetation type was found by using the concept of Specific Energy (E) as shown below:

\[
E = Y + \frac{u^2}{2g}
\] (4)

Where Y is the water depth at the respective section and U is the mean flow velocity at the respective section.

4. Results and Discussions

4.1. Time-averaged velocity

The variation of time-averaged velocities gives an idea about the effects of vegetation on the flow. Flow measurements were taken along different vertical points (Z) as well as along the transverse direction, i.e., along the y direction. The collected data were then used to plot graphs, which were non-dimensionalized with Z/B along the Y-axis and u/u₀ along the X-axis. Here, u₀ denotes the mean flow velocity of fully developed flow. It was observed that there was a considerable decrease in the near-bed streamwise time-averaged velocity (u) as flow approaches
vegetation. At section 2, there was a decrease of about 24% in $u$ for rigid vegetation whereas the presence of flexible vegetation reduces $u$ by about 90%. Further reduction in $u$ was observed as flow moves through vegetation, i.e. section 3 for flexible vegetation. However, the reduction of velocity near the bed resulted in an increased velocity near the water surface for section 2 (rigid and flexible) and section 3 (flexible) as shown in Fig. 5 (a) to (f) and Table 1.

As the flow moves downstream, there is an increase in the near-bed velocity (sections 4 and 5 for flexible vegetation and sections 3 and 4 for rigid vegetation), but the magnitude is much lesser than upstream sections 1 and 2. Thus, it can be seen that the flow gets deviated from the vegetated zone to the unvegetated zone, thereby increasing the stream-wise near-bed velocity $u$. This will ultimately result in more bed shear stress and bed material transport in the unvegetated region as compared to the vegetated region. This is similar to what was observed by Devi et al. (2017) and Devi and Kumar (2016) in their work.
The three-dimensional velocity profiles for both flexible and rigid vegetation were then plotted using MATLAB for a better understanding of the flow field in the presence of vegetation as shown in Fig. 6. It is seen that for flexible vegetation, as the flow moves towards the vegetation, the vertical velocity component (w) starts acting downwards with comparatively less magnitude than the upstream section 1. This is also observed within the vegetative region, i.e., section 3. Whereas at section 4, ‘w’ starts acting upwards along with an increase in magnitude. The same is observed in the case of rigid vegetative model. This observation supports the fact that vegetation helps in stabilizing the channel bed and hence reducing erosion.

However, the magnitude of ‘w’ at section 4 (flexible vegetation) was found to be less than that of section 3 (rigid vegetation). This may be due to the greater wake being produced by the rigid wooden dowels as compared to the flexible rice plants. Hence, flexible vegetation could prove to be more beneficial in stabilizing channel bed and countering the menace of erosion.
**Figure 6:** Three-dimensional velocity profiles in MATLAB for (a) and (b) Flexible vegetation (c) and (d) Rigid vegetation

Further calculations were carried out to compare the stream-wise velocity \( u \) in the presence of both flexible and rigid vegetation. It was observed that flexible vegetation retards the velocity profile more efficiently and hence would prove to be more efficient in stabilizing the channel bed and reduce erosion. This comparison is depicted in the graphs shown in Fig. 7. Moreover, the quantification of the velocity data (without vegetation vs Section 1 of each vegetation type) is provided in Table 1 for a comprehensive understanding of the effect of vegetation type on the flow.
Figure 7: Stream-wise velocity distributions at different measurement locations for comparative study.

A clear look at the graphs in Fig. 7 reveals that there exist certain points where the velocity profile of flexible vegetation intersects the velocity profile of rigid vegetation. This may be attributed to the flexibility of the vegetation, which induces swaying motion in them.

Table 1: Percentage reduction in stream-wise velocity (u).

<table>
<thead>
<tr>
<th>Distance from channel bed (Z) (cm)</th>
<th>Percentage (%) reduction in stream-wise velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible vegetation</td>
<td>Rigid vegetation</td>
</tr>
<tr>
<td>5</td>
<td>90.16</td>
</tr>
<tr>
<td>6</td>
<td>51.494</td>
</tr>
<tr>
<td>8</td>
<td>51.065</td>
</tr>
<tr>
<td>14</td>
<td>-3.948</td>
</tr>
</tbody>
</table>
In Table 1, the negative sign implies that the flow velocities near the surface for both the vegetative models are higher than the flow velocity near the surface observed in the flume without vegetation. This may be due to the energy transfer by the vegetation from the channel bed towards the surface, thereby making the bed more stable.

4.2 Energy Dissipation

The mean flow velocity ($u_o$) for the fully developed flow without vegetation was found to be 9.92197cm/s and this value was further used to calculate the energy dissipation using equation 4 for each vegetation type.

4.2.1 Rigid vegetation

The mean-flow velocities ($U$) and the corresponding water depths ($Y$) at different sections for rigid vegetation are listed in Table 2

<table>
<thead>
<tr>
<th>Measurement sections</th>
<th>Mean-flow velocity ($U$) (cm/s)</th>
<th>Water depth ($Y$) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1</td>
<td>11.0467</td>
<td>26</td>
</tr>
<tr>
<td>Section 2</td>
<td>9.1957</td>
<td>26</td>
</tr>
<tr>
<td>Section 3</td>
<td>7.619</td>
<td>28</td>
</tr>
</tbody>
</table>
Using equation 4, it was found that there is a small gain of 0.012 cm of energy at section 1 with respect to the fully developed unvegetated flow. Similarly, there is a loss of 0.019 cm of energy as flow moved from section 1 to section 2. Further comparisons have been tabulated in Table 3 below.

**Table 3:** Specific Energy difference at different measurement sections

<table>
<thead>
<tr>
<th>Flow movement</th>
<th>Energy difference (cm)</th>
<th>Loss/Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 2 to Section 3</td>
<td>1.986</td>
<td>Gain</td>
</tr>
<tr>
<td>Section 3 to Section 4</td>
<td>1.01</td>
<td>Loss</td>
</tr>
</tbody>
</table>

**4.2.2 Flexible vegetation**

The mean-flow velocities (U) and the corresponding water depths (Y) at different sections for flexible vegetation are listed in Table 4.

**Table 4:** Mean-flow velocity at different sections for flexible vegetation

<table>
<thead>
<tr>
<th>Measurement sections</th>
<th>Mean-flow velocity(U) (cm/s)</th>
<th>Water depth (Y) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1</td>
<td>9.998</td>
<td>26</td>
</tr>
<tr>
<td>Section 2</td>
<td>7.997</td>
<td>26</td>
</tr>
<tr>
<td>Section 3</td>
<td>4.0703</td>
<td>25</td>
</tr>
<tr>
<td>Section 4</td>
<td>6.2678</td>
<td>27</td>
</tr>
</tbody>
</table>
Using equation 4, it was found that there is a negligible gain of 0.00077 cm of energy at section 1 with respect to the fully developed unvegetated flow. Similarly, there is a loss of 0.0184 cm of energy as flow moved from section 1 to section 2. Further comparisons have been tabulated in Table 5 below.

**Table 5: Specific Energy difference at different measurement sections**

<table>
<thead>
<tr>
<th>Flow movement</th>
<th>Energy difference (cm)</th>
<th>Loss/Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 2 to Section 3</td>
<td>1.024</td>
<td>Loss</td>
</tr>
<tr>
<td>Section 3 to Section 4</td>
<td>2.011</td>
<td>Gain</td>
</tr>
<tr>
<td>Section 4 to Section 5</td>
<td>0.00033</td>
<td>Loss</td>
</tr>
</tbody>
</table>

On the other hand, there is a loss of energy of 0.00297 cm at section 1 as compared to the unvegetated flow as the vegetation density is increased. Further loss of energy of 0.02 cm is observed as flow moves from section 1 to 2.

Thus, it is seen that increasing the vegetation density results in further retardation of velocity profile and subsequently, the energy dissipation is also increased.

**Conclusions**

Flow structures of emergent flexible and rigid vegetation with aligned columnar arrangements are analyzed in a flume using an Acoustic Doppler Velocimeter (ADV). The flow discharge and depth are kept constant for all the runs. Experimental analysis has shown that the velocity
reduces as the flow moves through vegetative models. The near-bed stream-wise velocities \((u)\) at upstream sections for each vegetation type decreases as flow moves towards vegetation. However, the decrease is more prominent in the case of flexible vegetation (around 90% as compared to 24% in rigid vegetation), signifying its importance in stabilizing the channel bed and reducing erosion. This decrease in the near-bed stream-wise velocity is accompanied by an increase in \(u\) near the water surface, signifying the transfer of energy from the channel bed towards the water surface. On the other hand, the velocity keeps on increasing as flow starts moving downstream so as to achieve the velocity distribution of the fully-developed unvegetated flow. Thus, it can be observed that vegetation diverts the flow from vegetated region towards the unvegetated region, thereby increasing the risk of bed instability and erosion in the downstream unvegetated regions.

These variations in flow field significantly affect the process of sedimentation and hence the bed stability in rivers and streams with the presence of vegetation. The present study aims at providing the readers an idea about these flow variations in vegetated streams. The work can further be extended to understand the turbulence characteristics in such streams which will help engineers and researchers in carrying out various river restoration works including the ecological restoration of rivers.

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**Conflicts of Interest:** The authors have no conflict of interest.

**Authors Contributions:** The first author has analysed the experimental data and prepared the manuscript, the second author has conducted the experimental tests and plotted the graphs and third author has checked the manuscript.

**Ethical Approval:** Authors declare that they have followed the ethical standards in conducting the present research.

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