Flow Characteristics on Floodplain Vegetation in Compound Straight Channels

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Keywords: flow characteristics, compound straight channel, bed morphology, floodplain

Abstract. In this decade, flood have been occur more widely rather than before. And it tends to cause damage to building, crops, infrastructures and the most important, loss of life. Finding the way to minimise the flooding phenomenon are very important. The experimental research on flow behaviour in vegetated compound straight channel has been carried out in the Hydraulics Laboratory, Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM). The objectives of this study are to determine the stage-discharge, roughness coefficient, streamwise velocity distribution and secondary flow in compound straight channels with different arrangement of vegetation elements on the floodplain. The effects of two-line emergent vegetation riparian zone of the floodplain were identified by using the an asymemetric compound straight channels with fixed bed straight compound channel. 5mm diameter and 15cm high steel rods with 2d spacing were used to stimulate the floodplain vegetation. The results on stage-discharge relationship showed that the staggered vegetation gives the highest (0.53) compared to tandem vegetation (0.51) and non-vegetated (0.49). For the Manning's n, staggered vegetation (0.026) also gave the highest results compared to tandem vegetation (0.025) and non-vegetated (0.022). The depth averaged velocity over the vegetation floodplain increases in the main channel. Also, the depth averaged velocity decreases in the main channel and floodplain with an increase in the vegetation density. The maximum value of the streamwise velocity was found to decreases with vegetation density. And it was found that a major vortex forms in the main channel for smooth floodplain, free surface and bottom vortexes were observed for the tests with the vegetated floodplain.

Introduction

Nowdays, floods has become a common natural disaster and became a frequent event occurring in Malaysia also many parts of the world. The adverse effects are loss of life, human suffering and widespread damages to buildings, crops and infrastructure. This phenomenon could be caused by natural disaster or human activities. Some of the possible reasons in occurring flooding are caused from heavy rainfall, breach the levee and also very high tidal waves. The Wikipedia said that, there are 189 basins in Malaysia and Malaysia is prone to flooding due to an average rainfall of over 2000 to 4000 mm per year. [11]

Previous Studies

Rivers are a part of hydrological cycle that have a unique behavior and characteristics. The research on the hydraulic characteristics of a river are needed in order to overcome the flood because it behavior will create the flood disaster and cause the human suffering and damages the infrastructures. There are many researches regarding the flood hydraulic behaviour has been conducted with different parameter such as velocity distribution, stage-discharge, Manning's, n and so on.

Stage-Discharge

Conditions in natural rivers are rarely stable especially after the flood flows. In a vegetated compound channel, depth of flow on the floodplain relative to that on the main channel is the major factor which affects the discharge capacity. When the water level arises and inundated floodplain, the water on the floodplain will be slower than in the main channel. Hence, interference will occur between the flow in main channel and from floodplain. The lower discharge capacity due to extra roughness from the floodplain will retard the overall discharge. [1]. In compound channel with vegetation, there is many factors which can affect the discharged capacity which are relative depth of the floodplain, roughness, number of floodplain, aspect ratio of the main channel, and so on.

Manning's roughness coefficient

The exponent of the hydraulic radius in the Manning formula is varies in a range depend on the channel shape and roughness. The Manning's is a coefficient which represents the roughness or friction applied to the flow by the channel.

The average Manning's n for vegetated case is higher compared with non-vegetated case. The staggered arrangement of vegetation has higher resistance compared with non-vegetated and tandem vegetation due to effects of arrangement vegetation contributes the higher value of Manning's value [2].

Momentum Transfer

Momentum transfer is defined as the transition mechanism between main channel and floodplain. Water flowing to the main channel from floodplain or vice versa can affect the sediment transport for the channel and the intensity of this interaction is highly dependent on the relative depth. The interaction is most efficient for relative depths comprised between 0.1 and 0.3 [1].

The relative depth, DR, is defined by Knight as the ratio of the depth of flow on the floodplain to that in the main channel which plays such an important role in the momentum exchange to confirm the outward flow at re-entrant corners. The discharge and flow velocity of floodplain will increase if the flow depth increases. Momentum transfer between the main channel and the floodplain generally decreases the discharge in the main channel, increases the discharge on the floodplain, and decreases the channel's total discharge capacity. This has been called the "kinematic effect." [3].

Streamwise Velocity Distribution

Velocity distribution is one of the important flow characteristic in vegetation condition compared with non-vegetated conditions in river. The "velocity dip" phenomenon is where the maximum velocity cell drops below the free surface of main channel [4]. For vegetated flow, it is mainly decided by the vegetation drag since the vegetation roughness is much larger than river bed roughness [5]. Meanwhile, the bulging that appear in the contour in the shear layer between the main channel and floodplain are caused by the different water depth apply on the compounds channels flow [2]. As the water depth increase, the bulging phenomenon will become more obvious [6]. This is due to secondary currents and the transferring of high momentum fluid from the main channel to the floodplain. [7].

For non-vegetated case, the maximum velocity usually produces in the middle of the main channel and decreases towards the channel walls and bed. While at the vegetated case, the maximum velocity still occur at the middle of the main channel due to presence of vegetation that push up the flow to the centre of main channel. The increase of the water depth leads to a reduction of the interaction between the flows due to the decrease of the velocity gradient between the subsections [8].

Secondary Flow

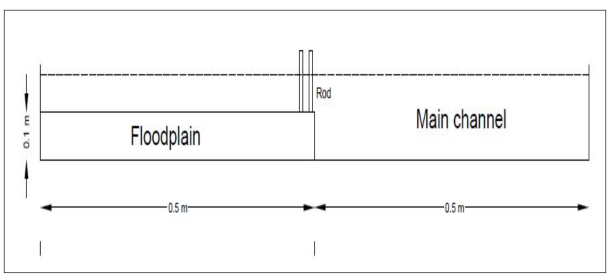
The lateral distribution of the secondary flows closely related with the bed erosion and the sediment accumulation. The secondary flows affect the primary mean flow, and it is discovered that the vegetation affect the rotational directions of secondary flows greatly. It was controlled by the flow interaction in the cross-over section [7]. The momentum exchange which enhanced the intensities of the secondary flows was increased rapidly at the vegetation edge. [9]. A high secondary flow gives high energy loss and thus produces high channel resistance. A major vortex forms in the main channel (called as the free surface vortex) whereas a weaker vortex can be observed at the interface [10].

The interaction between the main channel and the floodplain will increase the flow resistance. Therefore, the pattern of velocity distribution of secondary flow might be difference in both condition either in the presence of vegetation and non-vegetation.

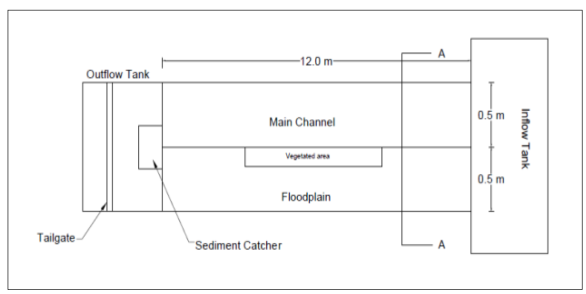
Research Methodology

This research is necessary in order to know the behaviour of river especially during flooding. The aims of the study are to enhance the knowledge on the river hydraulics during flooding. Thus, with this research, all the regarding information about stage-discharge, flow resistance, velocity distributions and secondary flow can be obtained.

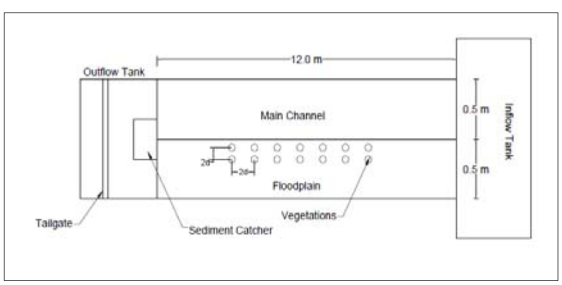
The straight compound channel is a rectangular cross-section with main channel dimension of 0.5 m wide, 0.1 m deep with 0.5 m wide floodplain. A temporary wall was placed on one of the floodplain to transform it as an asymmetric compound straight channel. A uniform graded sand (d_{50} = 0.8 mm) was used as erodible bed material and base layer with 0.2 m deep for the main channel. The sand layer was later frozen using cement powder to form fixed bed main channel. The longitudinal slope of the channel was fixed to 0,001. Steel rods of 5mm diameter and 15 cm high are used to stimulate the emergent floodplain vegetation. A spacing of 2d is adopted in the study. The tandem and staggered arrangements of rods were placed on the floodplain at a distance between 4 m to 8 m from the channel inlet. The experiment is conducted under study uniform flow condition which is the slope of the water and the slope of the main channel bed remains same. Figure 1(a), (b), (c) and (d) showed the physical model use in the research.



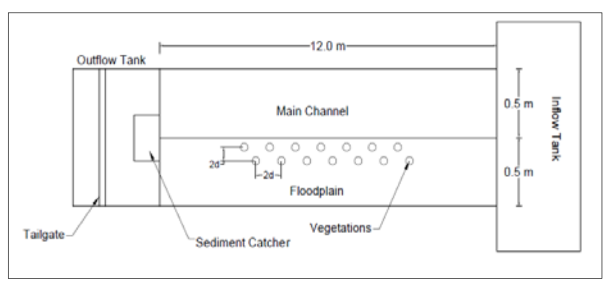
(a) Plan view of main channel



(b) Cross section A-A of compound main channel



(c) Tandem arrangement



(d) Staggered arrangement

Figure 1: Physical Model

Preparation of Experiment Work

The preparation of experiment is necessary to ensure the experiment can be conducted as planning. The establishment of uniform flow must be achieved. Vegetation on the floodplain must be done to accomplish this experiment based on objectives earlier.

Uniform Flow

This study was carried out under uniform flow condition. The uniform flow has been achieved when slope of water surfaces (Sw) is equal to slope of channel bed (So) at all time. Uniformity of water slope was determined by measured the surface of flow water and channel bed in the main channel. The bed slope is fixed to 1/1000. It is because the tank is designed for that value for previous case study. The uniform flow has been achieved when the relative discrepancy between So and Sw are less than 5%.

Vegetation

Vegetation is arranged along the floodplain area. The rods were used to replace the vegetation during the experiment. Furthermore, 2d spacing with diameter 5mm of rods was used in this study. The presence of vegetation generally increases the flow resistance, changes the velocity distribution, and affects the discharge capacity and sediment transport rate. [3]. The comparison between the existing of vegetated in tandem and staggered arrangement and non-vegetated will be discussed in this study.

Experimental Equipment

The experiments involve several important equipment in order to gain the satisfactory results.

Velocity Measurement

Velocity was measured by determining the point velocities. The measurement sections were selected at the distance of 4.5m, 6.0m, and 7.5m for non-vegetated case, while for vegetation case, 3.0m, 4.5m, 6.0m, 7.5m, 9.0m were selected. The data for velocity is collected at each section consists of different stage of flow for the main channel width and floodplain. The readings of point velocity are taking 2 cm for both horizontal and vertical. Moreover, Acoustic Doppler Velocity Meter is used to record the velocity through decided section. The raw velocity data will be collected by using 'Vectrino Plus' software. The data can only be read only when the distance between bed form to the transmit transducer of the ADV greater than 5cm to 10cm. otherwise, the data cannot be read or false data can be obtained. Meanwhile, the data that was done pressing will be plotted by using 'Tecplot 360 software' to gain the contour of velocity. Figure 2 is Acoustic Doppler Velocity Meter that was used in this study.

Figure 2: Acoustic Doppler Velocity (ADV)

Point Gauge

A digital point gauge was used to measure flow depth and bed profile. The accuracy level of point is up to +- 0.1mm several times of measurement has been taken to obtain appropriate mean reading flow depth. The readings of the flow depth need to be taken for every change of flow rates to ensure the flow in uniform condition.

Experimental Procedure

The data from the experiment was been recorded after all experiment is act up successfully. In order to get the final result, some relative formula needs to be considered.

Relative Depth and roughness coefficient

Relative depth is measured form point gauge after the water totally stabilized and uniform flow is formed. Meanwhile, the Manning's n is a coefficient which represents the roughness or friction applied to the flow by the channel. The equation of the relative depth and Manning's, n are shown in Equation (1) and (2). The equivalent relative depth will be obtained by using (equation (1) below:

$$DR = \frac{H-h}{H} \tag{1}$$

where H is mean water depth in main channel (m), and h is height of main channel from bed level (m).

The equivalent Manning's n will be obtained by using Equation (2) below:

$$n = \frac{AR^{\frac{2}{3}}So^{\frac{1}{2}}}{Q} \tag{2}$$

where, R is hydraulic radius (m), So is slope gradient (m/m), Q is discharge (m^3/s), n is Manning's, n roughness coefficient ($sm^{-1/3}$), and A = cross sectional area of flow (m^2).

Classification of Flow

(a) Froude Number

Froude number is defined as a dimensionless number which indicates the relative effects of gravity and inertia forces on the state of the flow. The Froude number has three type conditions of flow which are critical, subcritical and supercritical flow. If the Froude number is less than 1, the flow is supercritical. The flow will become supercritical if Froude number is greater than 1. Otherwise, the flow is critical when Froude number reach 1. So,[8] said the greater the Froude number has higher resistance. The Froude number, Fr is calculated by using Equation (3) in order to classify the type of flow:

$$Fr = \frac{V}{\sqrt{gD}} \tag{3}$$

where V is mean velocity of flow (m/s), g is gravitational acceleration (m/s^2), and D is hydraulics depth (m).

(b) Reynolds Number

In open channel, three states of flow are possible need to consider which are laminar, turbulent or transitional. The effects of viscosity relative to inertial forces of the flow determine the state of flow. Therefore, the relative effects of velocity to inertia can be represented by the Reynolds number which is dimensionless number derived through dimensional analysis of the flow. The flow condition which is classified based on the Reynolds number is stated as : laminar flow (Re < 2000), transition (2000 <Re< 4000), and lastly turbulent flow (Re <4000). The value of Re was calculated using the Equation (4) to determine the state of flow in the channel.

$$Re = \frac{4RUm}{V} \tag{4}$$

where R is hydraulic radius (A/P) (m), A is cross sectional area (m^2), P is wetted perimeter (m), Um is mean velocity (m/s), and V is kinematic viscosity (m^2/s).

Discussion of Results

This study was carried out under uniform flow condition. The uniform flow has been achieved when slope of water surfaces (Sw) is equal to slope of channel bed (So) at all time.

Stage-Discharge Relationship

Non-vegetated floodplain give that the value of water depth is lower than the tandem and staggered arrangement of vegetation which is. It is occur it is occur because of the resistance exist on the floodplain. Besides that, the value of discharge,Q for the vegetation give the higher value than the non-vegetation floodplain. It shows that the floodplain with vegetation can carries less discharge rather than smooth floodplain. Meanwhile, staggered arrangement give the highest value of water depth, hence, it can resist more resistance for the flood rather than tandem arrangement. Table 1 shows the summary of non-vegetated, tandem and staggered arrangement of fixed bed compound straight channels and Figure 3 shows the graph of relationship between discharge and stage discharge.

Table 1: Summary of Non-vegetated, tandem and staggered arrangement of fixed bed compound straight channels.

Discharge, Q	Relative Depth, DR		
	Non-Vegetated Channel	Tandem Vegetation	Staggered Vegetation
0.025	0.17	0.18	0.19
0.030	0.28	0.30	0.32
0.036	0.37	0.39	0.43
0.043	0.45	0.47	0.49
0.048	0.49	0.51	0.53

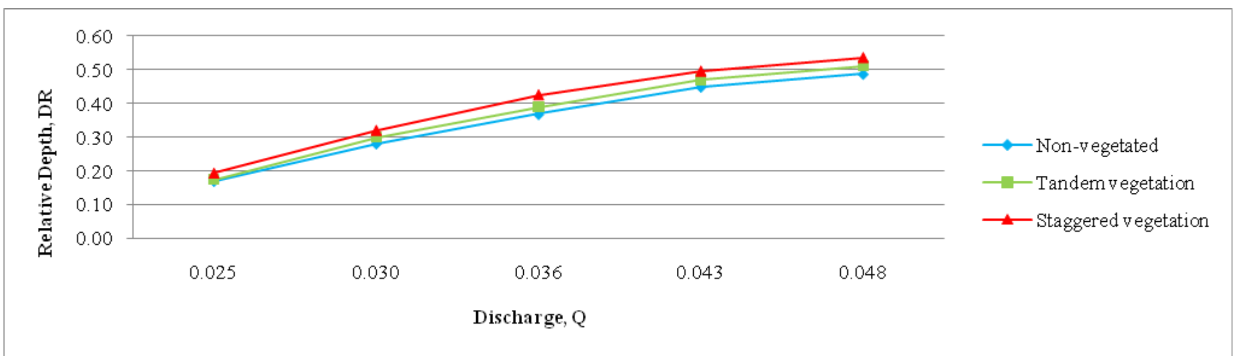


Figure 3: Discharge-Relative Depth, DR for compound straight channels.

Manning's Roughness Coefficient

The value of manning's n are increase along the channel in downstream direction. As stated by [4], Manning's, n will increase due to differential roughness between main channel and floodplain boundaries. From the Table 2, the presence of the vegetation affect the value of manning's n but slightly difference for tandem and staggered arrangement of vegetation.

Vegetation is one of the main factor that changing the Manning's n as stated by [2]. It is clearly shown in the Table 2 that the presence of the vegetation gives the higher value compared to non-vegetated floodplain which indicate the roughness coefficient for staggered vegetation is higher than tandem vegetation due to the vegetation arrangement which creates additional resistance flow. It is already prove by [4], which the Manning's n increased when higher density vegetation present on the floodplain. Table 2 shows the Summary of Manning's computation on floodplain for non-vegetated, tandem and staggered arrangement and Figure 4 shows the relationship of Manning's n and discharge.

Table 2: Summary of Manning's computation on floodplain for non-vegetated, tandem and staggered arrangement.

Discharge, Q (m^3/s)	Manning's n		
	Non-Vegetated Channel	Tandem Vegetation	Staggered Vegetation
0.025	0.012	0.013	0.014
0.030	0.017	0.017	0.018
0.036	0.020	0.021	0.022
0.043	0.022	0.023	0.024
0.048	0.022	0.025	0.026

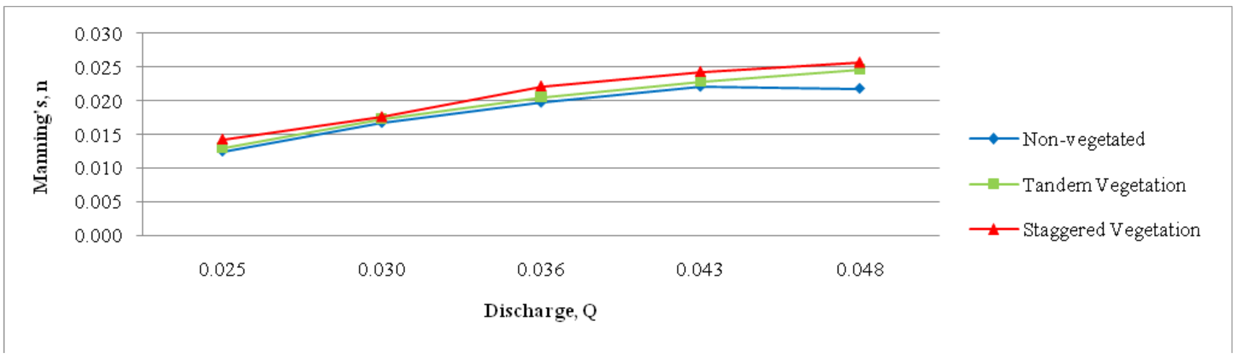


Figure 4: Relationship of Manning's and discharge

Streamwise Velocity Distribution

Velocity distribution profile is obtained from streamwise velocity components which have been plotted using Tecplot 360 software. Plots are made based on the velocity values to describe the flow patterns in the main channel. The cross-sectional distribution of streamwise velocity in the compound straight channel is focus at two relative depths of 0.3 and 0.5.

Normalised velocity for non-vegetated floodplain

Figure 5 and 6 shows that the tendency of transferring water into the floodplain is slow due to low relative depth. It shows that the momentum transfer is obviously taking place at higher relative depth thus decreasing the velocity along the centre of the main channel. It is proved by [4] which the velocity-dip phenomenon near the water surface in the main channel becomes less remarkable when relative depth of the imaginary compound channel higher.

Besides, the bulging phenomenon more pronounced at the non-vegetated cases. This is because, well-dispersed of momentum transfer is takes place when no rods on the floodplain region. It is because the rods on the floodplain are restricted the main channel flow from entering the floodplain.

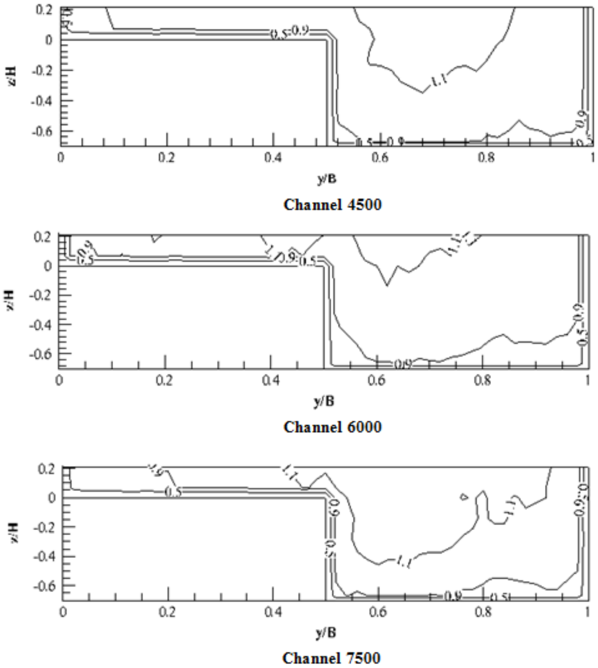


Figure 5: Velocity distribution of cross section non-vegetated floodplain with relative depth 0.3.

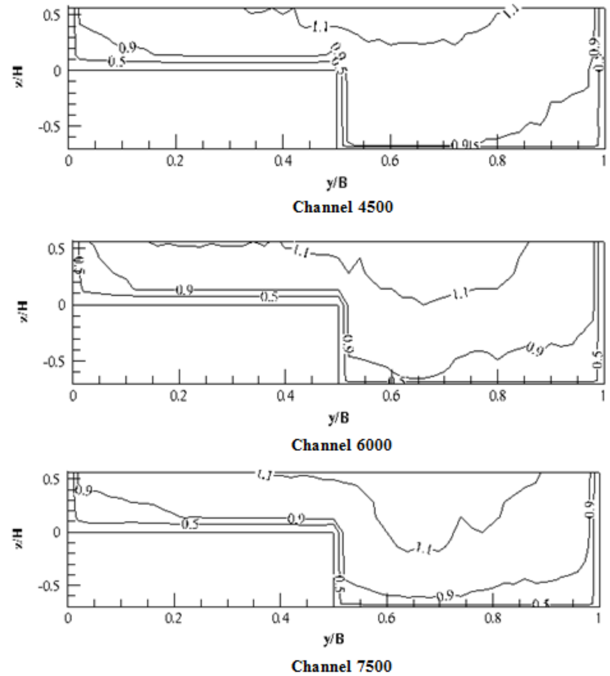
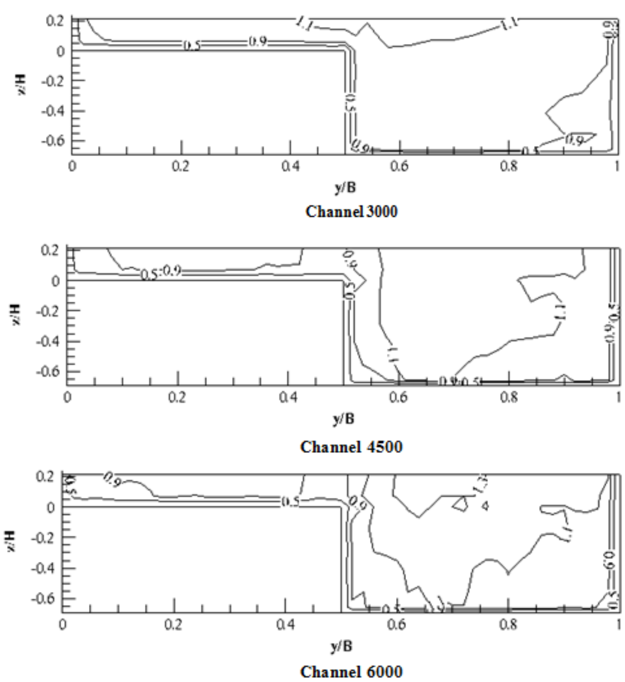
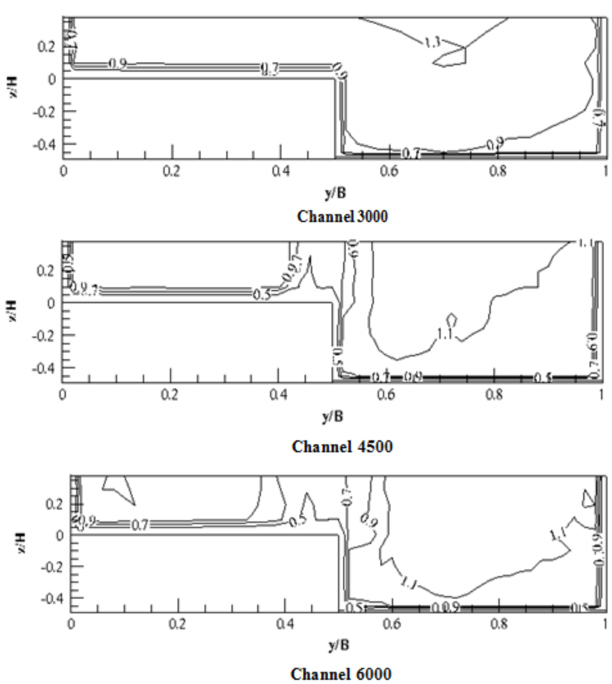


Figure 6: Velocity distribution of cross section of non-vegetated floodplain with relative depth 0.5.

Normalised Velocity Distribution For Tandem Floodplain Vegetation

After floodplain is vegetated, the velocity of the main channel increased while the velocity on the floodplain becomes decreased. This is because, the rod existing on the floodplain prevent the water distribute to the floodplain area hence it indirectly increase the velocity in the channel. The formation of free shear is observed on the vegetated zone due to resistance produces by the rods arrangement at the edge of the floodplain. It is clearly observed on the Figures 7 and 8 where the velocity at the intersection region becomes slower in the presence of rods. In other words, higher flow resistance is observed at the floodplain area make it slowly in velocity distribution.





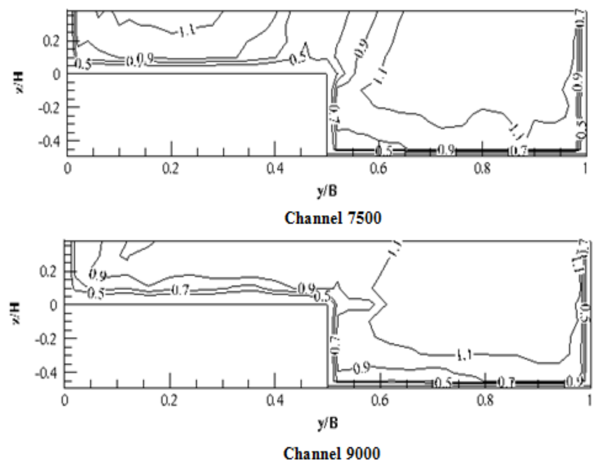


Figure 7: Velocity distribution of cross section vegetated floodplain with relative depth 0.3.

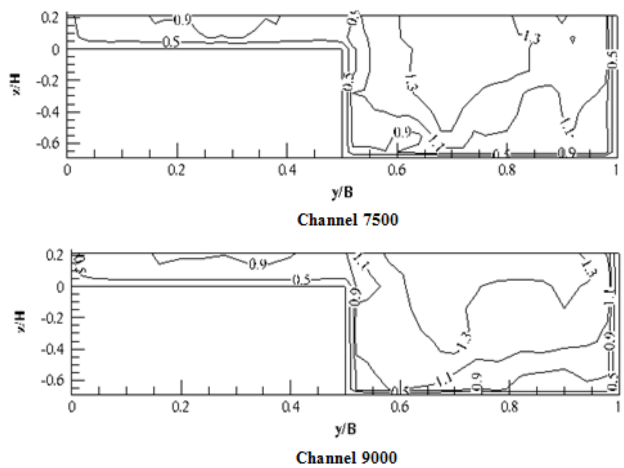
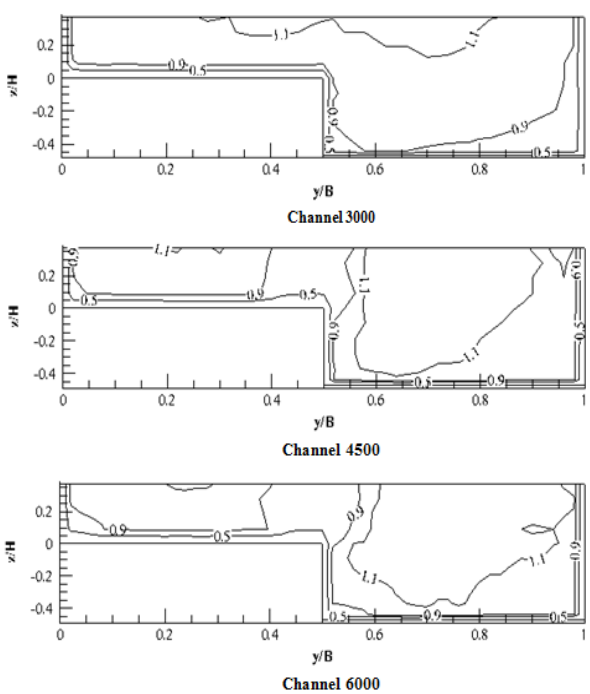
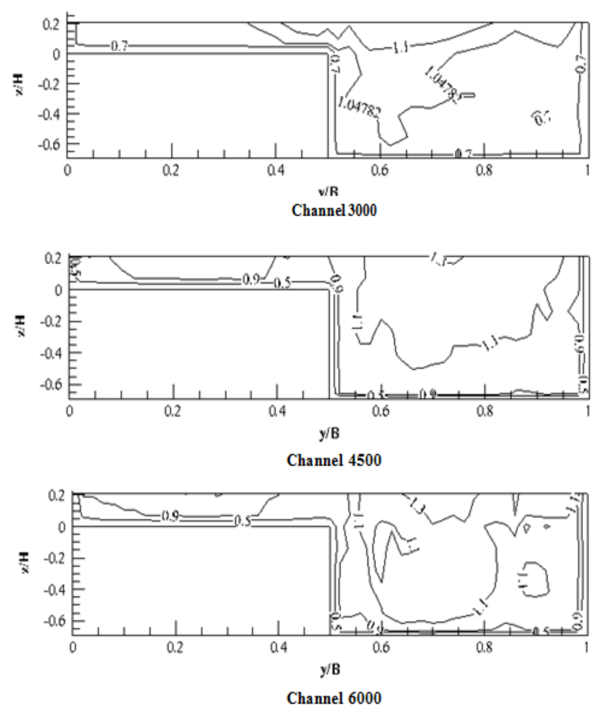


Figure 8: Velocity distribution of tandem cross section of tandem vegetated flood-plain with relative depth 0.5.

Normalised Velocity Distribution for Staggered Floodplain Vegetation

Figure 9 and 10 show the velocity distribution cross section along the channel in staggered arrangement vegetation on the floodplain area with relative depth 0.3 and 0.5 respectively. The velocity distribution pattern is slightly similar to the tandem vegetated case for the same relative depth. It means that both tandem and staggered vegetation do not have much difference in terms of denser rods but it can be seen at the relative depth 0.5, the maximum velocity zone moves slightly further towards the main channel wall in the main channel. Although there is not much effect between these two types of arrangement vegetation, the alignment of staggered vegetation still seems a little bit denser than tandem vegetation.





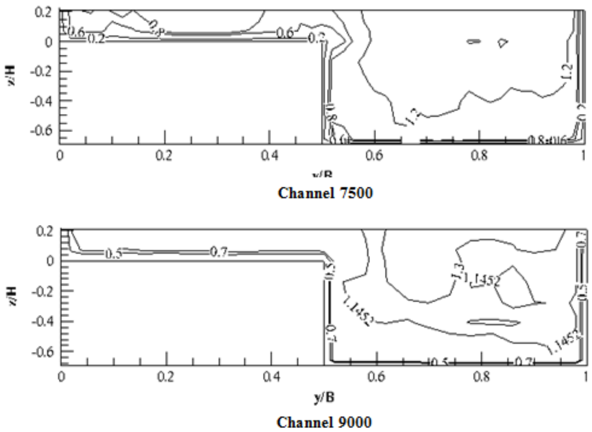


Figure 9: Velocity distribution of cross section staggered vegetated floodplain with relative depth 0.3

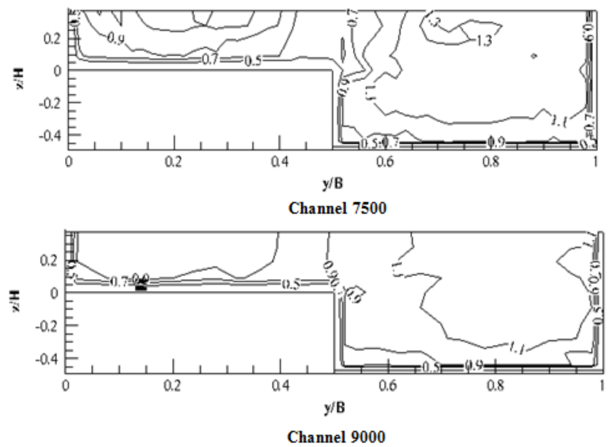


Figure 10: Velocity distribution of cross section of staggered vegetated floodplain with relative depth 0.5.

Secondary Flow Velocity Distribution

Secondary flow is the movement of water particles in longitudinal direction of the channel. A high secondary flow gives high energy loss and thus produces high channel resistance.

Normalised secondary flow for non-vegetated floodplain

Free surface vortex usually developed on the non-vegetated floodplain. Interaction between the fast main channel and slow floodplain flow near the interface turns the momentum transfer from the main channel to the floodplain as illustrates in the Figure 11 and 12. It rotates in the anticlockwise direction. This is because there is no resistance occurs at the floodplain region due to no rods attached on the floodplain and the intensities of the secondary flows increase with the increase of the flow depth [9].

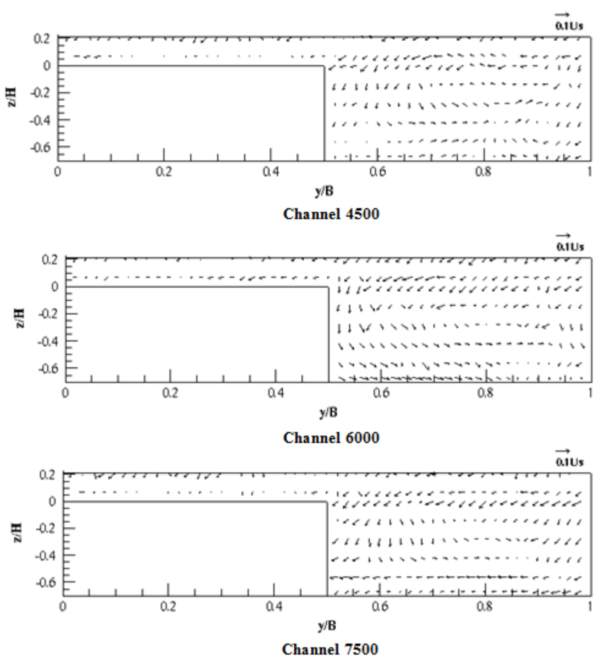


Figure 11: Secondary flow of cross section non-vegetated floodplain with relative depth 0.3.

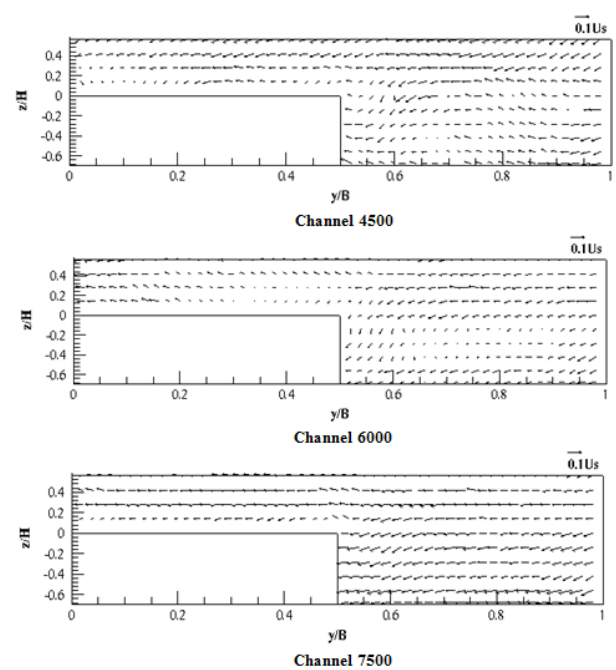


Figure 12: Secondary flow of cross section non-vegetated floodplain with relative depth 0.5.

Normalised secondary flow for tandem vegetation floodplain

Major vortex is formed in the main channel as free surface vortex whereas weaker vortex can be seen at the interface due to existing of the rods that resist the flow of water which can be formed in the presence of vegetation. It is because the vegetation has weekend the strength of the secondary currents over the floodplain. The results are illustrated in the Figure 13 and 14.

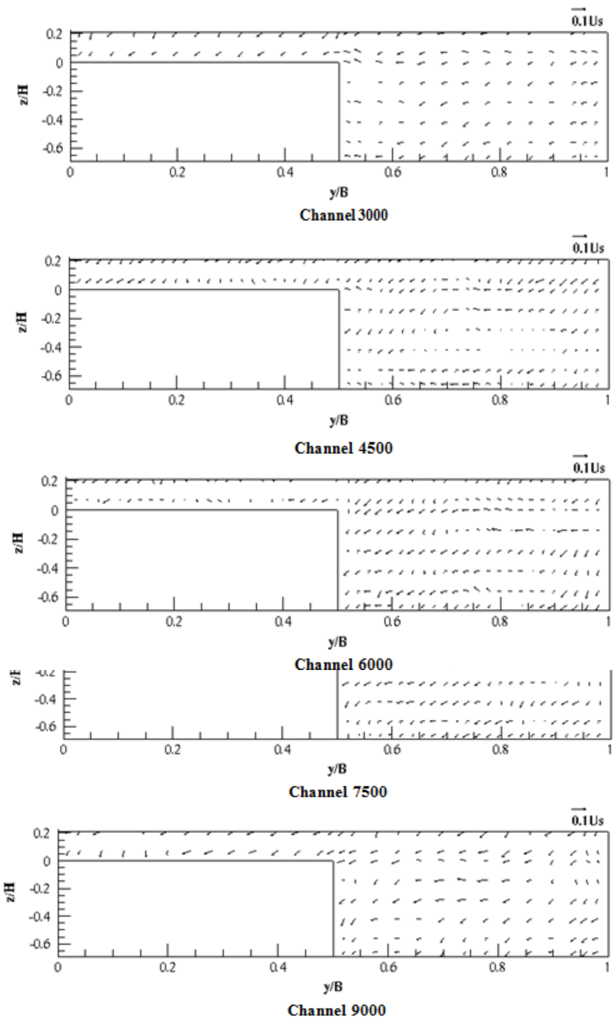


Figure 13: Secondary flow of cross section tandem vegetated floodplain with relative depth 0.3.

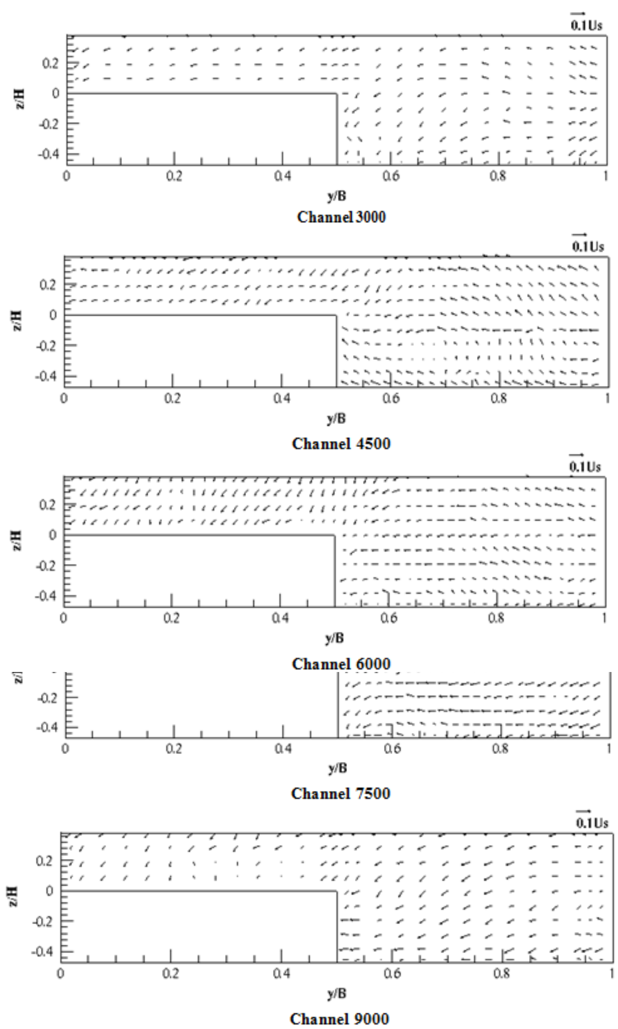


Figure 14: Secondary flow of cross section tandem vegetated floodplain withrelative depth 0.5.

Normalised secondary flow for staggered vegetation floodplain

Staggered and tandem did not have much difference in secondary flow pattern. But staggered slightly produce smaller vortex than tandem vegetation. It means that, staggered vegetation produces more resistance rather than tandem vegetation which indicates velocity reduction at the interphase and weakens the strength. The results are illustrates in the Figure 15 and 16.

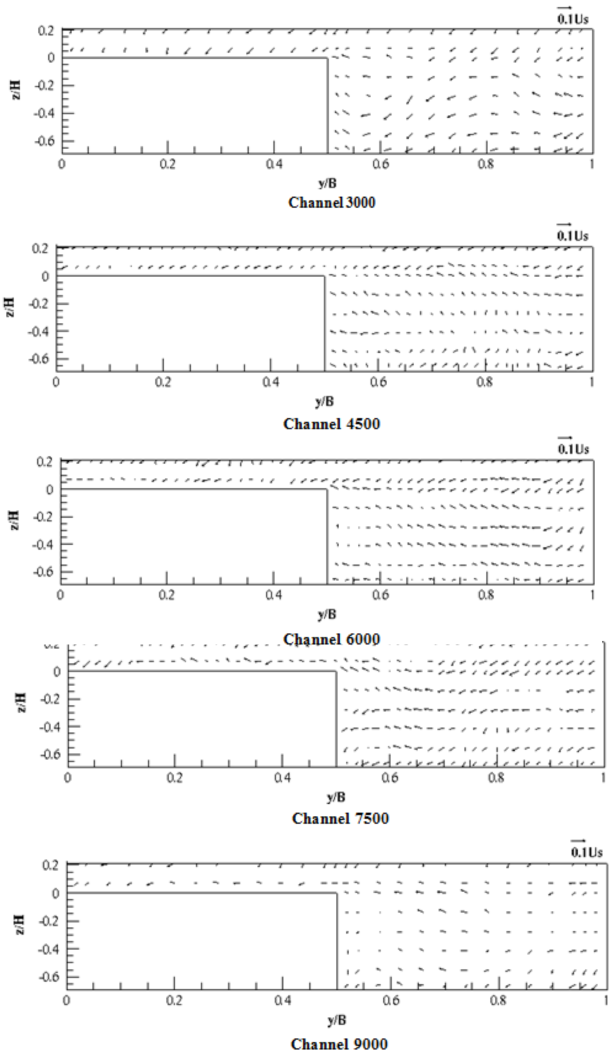


Figure 15: Secondary flow of cross section staggered vegetated floodplain with relative depth 0.3.

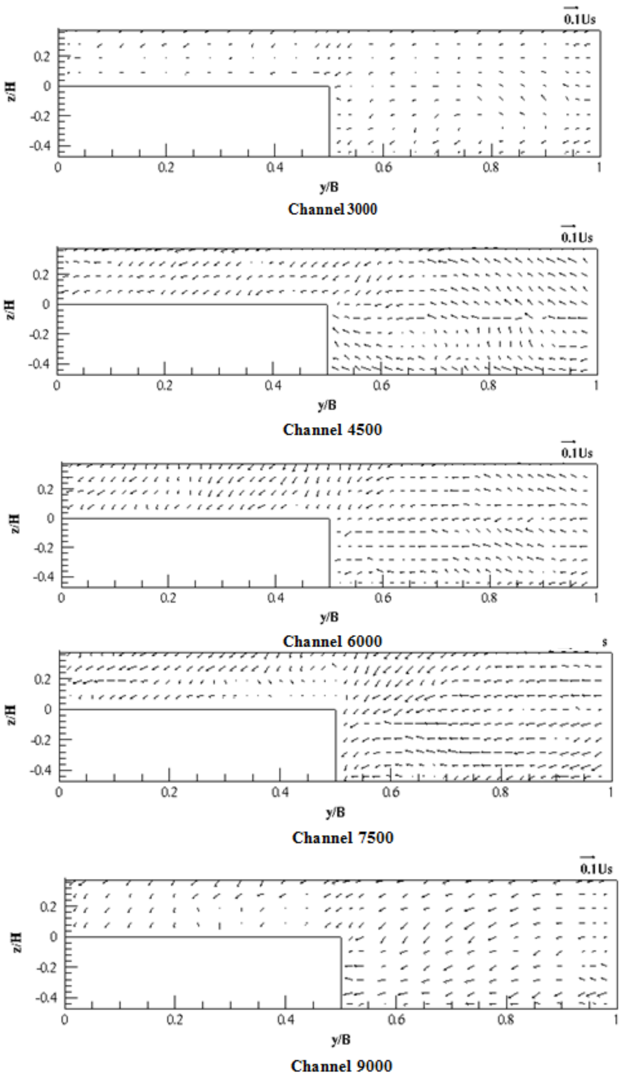


Figure 16: Secondary flow of cross section staggered vegetated floodplain with relative depth 0.5.

Conclusion

As we can conclude here based on the analysis are:

For stage-discharge, it is cleared that for water flow with resistance, it will increase as the relative water depth and discharge are corresponding to each other. Vegetation floodplain give the higher value of water depth compared to smooth channel due to the interruption on the floodplain that will reduce the capacity of water to be carried. Velocity of flow will reduce due to obstacle. Thus, the conveyance of the channel will be decrease.

Manning's roughness coefficient increase as the higher resistance on the floodplain due to the existence of vegetation. It is shown that the staggered arrangement of vegetation has higher resistance compared with non-vegetation and tandem arrangement vegetation.

The velocity distribution are obtained. It shown that the velocity distribution for the non-vegetated floodplain has higher tendency of transferring water into floodplain. At the higher relative depth, momentum transfer are decreasingly the velocity and the bulging phenomenon are more obvious than vegetation. The increase of the water depth leads to a reduction of the interaction between these flows due to the decrease of the velocity gradient between the subsections.

The secondary flow distributions are obtained. Non-vegetation produces major surface vortex while the tandem and staggered arrangement produce smaller vortex. But, staggered had slightly produce small vortex rather than tandem because it produces more resistance.

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