Influence of riparian vegetation on flow resistance in mobile bed straight compound channels

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Abstract. Riparian vegetation is an important feature in rivers and essential in hydraulic engineering including flood management and river restoration. Deforestation activities have been pointed out as a contributing factor to the severity of flood damages. This shows that the importance of riparian vegetation in river restoration schemes in order to lessen the issues of flood risk and flood protection. The riparian vegetation creates additional resistance to flood flow which resulted in velocity reduction, increasing of flow depth and transportation of sediment in rivers. The hydraulics of flood flows in vegetated floodplain of mobile bed straight channel was experimented in the Hydraulics Laboratory, Faculty of Civil Engineering, Universiti Teknologi Malaysia. Two-lined steel rods with tandem and staggered arrays to simulate as rigid emergent vegetation were placed along the riparian zone of an asymmetrical channel. The flow resistance including Manning’s $n$, Darcy’s $f$ and drag force, $F_D$ were studied. The findings showed that the riparian vegetation had increased the Manning’s $n$ by 20%. Meanwhile, staggered arrangement of vegetation was found to generate the highest Darcy’s $f$ of about 16% as compared to tandem arrangement. The presence of riparian vegetation also found to induce 20% more drag force compared to the main channel roughness effect. The dramatically changes of bed morphology also led to the increase of the flow resistance in the channel.

1. Introduction
Deforestation activities on floodplain areas for agricultural, commercial or housing purposes have raised the issues of flood risk and flood protection [1]. Vegetation along river banks were pointed out to play important roles for river banks stabilisation, erosion prevention, habitat creation and riparian buffer zones development for flood protection [2]. Generally, vegetation may be regarded as kind of surface roughness which increases the flow resistance, alters velocity distribution, affects the conveyance of rivers, raises water levels and also influences a transportation rate of sediment in rivers [3]. Therefore, it is important to further understand the floodplain vegetation influence on the river hydraulics.

Several researchers have shown that vegetation properties have enormous influence on flow resistance [4, 5, 6 and 7]. Bouma et al. [8] stated that the factors affecting flow resistance including surface roughness, vegetation, channel size, shape and irregularity. Vegetation markedly reduces the flow capacity of the channel and retards the flow. In particular, drag acting on the vegetation elements

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reduces the mean flow velocity and the momentum exchange between main channel and floodplain [9]. As stem density continually increases, it significantly alters the flow patterns with decreases the flow velocity and affects the turbulence properties [10, 11 and 12]. It was due to the contribution of drag forces induced by the emergent vegetation.

Vegetation characteristics such as height, density, distribution, stiffness, and type of vegetation have remarkable impact on the flow velocity as well as flow resistance. The reduced velocity will then reduce the forces necessary to cause scour and erosion processes that influenced the changes in channel morphology [13 and 14]. Simons and Richardson suggested that the flow resistance at low flows was due to the grain roughness, while at higher flows was due to bed form roughness from dune formation [15]. Knight and Brown [16] reported that the bed will deform under the action of flow, changing its roughness, and then affecting the flow itself.

Experimental investigations on the influence of riparian vegetation on flow resistance in straight compound mobile bed channels had been undertaken. The experiment in the physical model was conducted in the Hydraulic Laboratory in Universiti Teknologi Malaysia. The study was limited to an asymmetric straight mobile bed channel which involved shallow and deep flood inundation conditions.

2. Methodology
The experiments were carried out in the Hydraulics Laboratory, Faculty of Civil Engineering, Universiti Teknologi Malaysia where the experimental flume was 12 m long, with 0.5 m wide and 0.1 m deep rectangular main channel and a 0.5 m wide floodplain. The flume bed was set at a gradient of 0.1%. Figures 1 and 2 illustrate the layout of experimental set-up and the cross-sectional configuration of the flume.

![Figure 1](image1.png)

**Figure 1.** Plan view of the flume.

![Figure 2](image2.png)

**Figure 2.** Cross-sectional view of the flume.

Uniform graded sand with mean diameter, $d_{50}$ of 0.8 mm was filled in the main channel to form as bed material. A similar uniform sediment size was also used by many researches including Knight and...
Brown [16], Atabay et al. [17], Tang and Knight [18] and Bousmar et al. [19]. It is hard to find a river bed with a uniform size of sediment particles. The main reason for using uniform graded sand in this research was to minimise the “sheltering” and “hiding” effects. Ismail [20] did mention that as bed forms propagate to the downstream, sediment moves from the ridge of the bed forms to the trough. In the trough, the sediment is sheltered and overlaid by the advancing grains from the upstream bed forms.

Two-line artificial rigid emergent riparian vegetation was placed on the floodplain as resistance elements. Steel rods with 5 mm diameter were used as artificial resistance elements in this study. The steel rods were arranged in two-line either with tandem and staggered arrays as illustrated in Figure 3. The rod spacing $L$ of $2d$ was studied where $d$ represented the diameter of steel rod. The resistance elements were placed at the edge along the floodplain at a distance between 4 m to 8 m from the channel inlet.

![Figure 3. Arrangement of steel rods in (a) tandem and (b) staggered]

A re-circulating flume system was used in the study and the discharge was measured using a Portaflow PF 330 flow meter. A flow depth in the channel was controlled by an adjustable a tailgate located at downstream of flume. Meanwhile, flow depth and bed morphology levels were measured using a point gauge or digital water surface profiler attached on a mobile carrier. The digital profiler was operated with an accuracy of ± 0.1 mm and the 3-dimensional velocities were measured using a Nortek Vectrino+ Acoustic Doppler Velocimeter (ADV) with a sampling rate of 100 Hz. The maximum recording time for point velocity was 2 minutes. For most turbulent statistics, sufficient record length for measurement was 60 s to 90 s [21].

The measurement sections were located at normalised longitudinal distance $x/L$ of 0.38, 0.50 and 0.63 for non-vegetated floodplain, while at normalised longitudinal distance $x/L$ of 0.25, 0.38, 0.50, 0.63 and 0.75 along the compound straight channel for vegetated floodplain. For both of shallow and deep relative flow depths, the calculated Reynolds number ($Re$) exceeded 2000 and the Froude number ($Fr$) was less than 1. Therefore, the regimes of flows were classified as sub-critical with turbulent condition. The relative depth ($DR$) is defined as $(H - H_{mc})/H$ where $H$ represents the total flow depth in the main channel and $H_{mc}$ is the depth of main channel.

3. Discussion of results

The experimental results on flow resistance include Manning’s $n$, Darcy’s $f$ and drag force, $F_D$ through rigid riparian vegetation in compound straight channels are discussed in this section. The classification of experimental cases in this study is shown in Table 1.

| Case | Condition                  |
|------|----------------------------|
| A    | Non-vegetated              |
| B    | Vegetated in Tandem Arrangement |
| C    | Vegetated in Staggered Arrangement |
3.1. Manning’s n
The flow resistance is often expressed in terms of a resistance coefficient such as Manning’s $n$ or Darcy’s $f$. The Manning’s $n$ remains the most commonly used in flow resistance formula in hydraulic engineering. The standard equation for calculating Manning’s $n$ is as given in equation (1):

$$n = \frac{R^{2/3}S_0^{1/2}}{U}$$  \hspace{1cm} (1)

where $R$ is hydraulic radius, $S_0$ is channel bed slope and $U$ is mean stream-wise velocity. The flow resistance in a compound channel is represented by the Manning’s $n$ value for each interval of normalised longitudinal distance ($x/L$). $x$ is longitudinal distance and $L$ is total length of the channel. $n_{fp}$ and $n_{mc}$ are the Manning’s $n$ for floodplain and main channel, respectively.

Figures 4 and 5 illustrate the variation of Manning’s $n_{fp}$ and $n_{mc}$ along the channel for relative depths of 0.30 and 0.50. It can be seen that the Manning’s $n$ increased along the channel length in downstream direction due to the effect of surface roughness. The minimum Manning’s $n$ occurred in Case A and the maximum Manning’s $n$ resulted in the Case C with staggered arrangement of riparian vegetation. The $n_{mc}$ values are higher of about 20% than the $n_{fp}$ for both relative depths in all cases. As suggested by Einstein and Barbarossa [22], Engelund [23] and Simons and Richardson [15], flow resistance in low flow was due to the grain roughness; meanwhile, bed form roughness due to dune formation was important for increased of flow resistance at higher flow in mobile bed channels. Zhang et al. [24] and Ali et al. [25] reported that the roughness of mobile bed noticeably was higher than non-mobile bed channel due to variance of formation bed morphology.

As the floodplain was roughened with steel rods or vegetation, the Manning’s $n$ increased. The average increment of $n_{fp}$ for Cases B and C were 20% and 30% as compared to Case A for the relative depths of 0.30 and 0.50. This indicates that staggered array of vegetation is pronounced to have larger value $n$ due to higher flow resistance by vegetation with that arrangement. Ibrahim et al. [26] and Jumain et al. [27] also found that the roughness coefficient for staggered vegetation arrangement was higher than tandem arrangement. However, the percentages difference between vegetation arrangements were not too high since the study was only concentrated on two-lined emergent riparian vegetation placed at the middle of channel length.

![Figure 4](image_url)

**Figure 4.** Manning’s $n$ profiles of (a) floodplain and (b) main channel regions for shallow relative flow depth of 0.30
3.2. Darcy’s $f$

The flow resistance in open channel can also be expressed in term of the Darcy’s friction factor, $f$, calculated using the measured stream-wise velocity data $U$ as given in the equation (2):

$$f = \frac{8gRS_o}{U^2}$$

where $g$ is gravitational acceleration, $R$ is hydraulic radius, $S_o$ is channel bed slope and $U$ is mean streamwise velocity. The sectional mean velocities $U_x$ for floodplain, vegetated zone and main channel were used to determine the zonal $f$ values in the study.

Table 2 presents the computed $f$ values in each section for all cases at relative depths of 0.30 and 0.50. As relative depth increased, the $f$ values also increased. The highest increment of the $f$ values occurred in floodplain areas. As the relative depth changed from 0.30 to 0.50, the mean increment of the $f$ values for Cases B and C in floodplain zones were about 18% and 20%, while in main channel zone increased by 6% and 8% as compared to Case A. The influence of main channel bedform roughness can be seen for Cases B and C at shallow relative flow depth of 0.30, where the $f$ values were larger than values in vegetated and floodplain zones. Similar finding was reported by Bousmar et al. [19].

The influence of vegetation on the flow resistance was obvious since the $f$ values in the vegetated zone were larger than in main channel and floodplain. The $f$ values in the vegetated zone also increased as the relative depth changed from 0.30 to 0.50. This shows that resistance induced by the vegetation to the flow increases when the flow depth rises. It can be clearly seen that the highest $f$ values occur in Case C which are particularly in the vegetation zone of about 16% compared to Case B. Hence, staggered arrays of riparian vegetation generate the highest flow resistance and reduce the floodplain flow velocity.

Table 2. Zonal Darcy’s $f$ for cases studied in compound straight channels.

| Case | $f$ for $DR = 0.30$ | $f$ for $DR = 0.50$ |
|------|---------------------|---------------------|
|      | Floodplain | Vegetation | Main Channel | Floodplain | Vegetation | Main Channel |
| A    | 0.039  | - | 0.067 | 0.054  | - | 0.077 |
| B    | 0.051  | 0.107 | 0.109 | 0.071  | 0.122 | 0.116 |
| C    | 0.064  | 0.118 | 0.119 | 0.076  | 0.136 | 0.128 |
3.3. Drag force, \( F_D \)

The presence of vegetation in main channel or floodplain produces drag force which increases flow resistance. The estimation of vegetation influence on total flow resistance must consider the drag force exerted by the vegetation on the flow. The classical approach to measure total drag force exerted by vegetation or an object is as given in equation (3):

\[
F_D = \frac{1}{2} \rho C_D A_p U_d^2
\]  

where \( \rho \) is the water density, \( C_D \) is the drag coefficient, \( A_p \) is the projected area of stem in a streamwise direction, and \( U_d \) is the depth-averaged approach velocity.

The drag force can also be estimated by a force balance approach. The force balance approach considers the forces in equilibrium exerted on a control volume for quasi-uniform flow conditions. Nezu and Sanjou [28], Wu [29], Terrier [30] and Ibrahim [31] are among researchers who applied the force balance approach to evaluate the drag of the vegetation with cylindrical stems. The force balance approach is expressed in equation (4), where the drag force \( F_D \) is expressed as per unit channel length as follow:

\[
F_D = \rho g H S_o - \int_P \tau_b(y) dy
\]  

where \( \rho \) is the water density, \( g \) is the gravitational acceleration, \( H \) is the water depth, \( S_o \) is channel bed slope, \( \tau_b(y) \) is the boundary shear stress in \( y \) direction and \( P \) is the channel wetted perimeter.

The calculation carried out considered (i) forces across the whole channel section, \( F_D(\text{whole}) \) and (ii) forces on the floodplain section, \( F_D(\text{fp}) \) in non-vegetated and riparian vegetated compound straight channels are summarised in Table 3. It can be seen that the values of \( F_D(\text{fp}) \) and \( F_D(\text{whole}) \) were almost equal for each interval of normalised longitudinal distance (\( x/L \)) along the straight channels. It can be seen for each case at both relative flow depths. This is due to the similarity of boundary shear stress distributions along the channel length in downstream direction.

| Table 3. Calculated drag force \( F_D \) using force balance approach along the channel length for shallow and deep flood inundations. |
|---|---|---|---|---|---|---|
| \( DR \) | \( x/L \) | Case A | Case B | Case C |
| | \( F_D(\text{fp}) \) | \( F_D(\text{whole}) \) | \( F_D(\text{fp}) \) | \( F_D(\text{whole}) \) | \( F_D(\text{fp}) \) | \( F_D(\text{whole}) \) |
| 0.30 | 0.25 | - | - | 0.371 | 0.444 | 0.380 | 0.464 |
| | 0.38 | 0.234 | 0.418 | 0.288 | 0.448 | 0.314 | 0.467 |
| | 0.50 | 0.238 | 0.418 | 0.295 | 0.448 | 0.320 | 0.468 |
| | 0.63 | 0.249 | 0.418 | 0.299 | 0.448 | 0.334 | 0.468 |
| | 0.75 | - | - | 0.381 | 0.446 | 0.403 | 0.465 |
| 0.50 | 0.25 | - | - | 0.926 | 1.051 | 1.003 | 1.120 |
| | 0.38 | 0.770 | 0.991 | 0.858 | 1.056 | 0.932 | 1.124 |
| | 0.50 | 0.781 | 0.992 | 0.875 | 1.056 | 0.944 | 1.124 |
| | 0.63 | 0.789 | 0.992 | 0.884 | 1.056 | 0.953 | 1.124 |
| | 0.75 | - | - | 0.963 | 1.053 | 1.032 | 1.121 |

As observed in Case A, the floodplain surface and main channel bed morphology also give such contribution to the drag force. In order to quantify the effect of vegetation in the compound channel, the analysis on percentage difference between non-vegetated and vegetated floodplain had been carried out. The percentage difference of drag force \( \Delta F_D \) due to the emergent riparian vegetation is computed using equation (5):
in which $F_{D_{	ext{veg}}}$ is the drag force in vegetated case and $F_{D_{	ext{NV}}}$ is the drag force in non-vegetated case.

The calculated percentage differences of $\Delta F_D$ for Cases B and C compared to Case A are as illustrated in Figures 6 and 7. The largest $\Delta F_D$ was observed in floodplain area at location $x/L = 0.50$ for Case C which was about 35%. The $\Delta F_D$ for Cases B and C in the main channel section were obtained with average difference range from 5% to 6% and 4% to 9% for relative depths of 0.30 and 0.50, respectively. Larger $\Delta F_D$ values were obtained in floodplain section. For example, $\Delta F_D$ of more than 20% for a relative depth of 0.30 in Figure 6(a) clearly indicates that the floodplain vegetation section induced more drag force compared to the main channel roughness effect in Figure 6(b). It was also found that the effect of riparian vegetation on $F_D$ was reduced as the flood flow depth increased (Figure 7).

![Figure 6](image6.png)

**Figure 6.** Variation of percentage difference $\Delta F_D$ in (a) floodplain and (b) main channel sections of compound straight channel flows at relative depth of 0.30

![Figure 7](image7.png)

**Figure 7.** Variation of percentage difference $\Delta F_D$ in (a) floodplain and (b) main channel sections of compound straight channel flows at relative depth of 0.50

4. **Conclusion**

The influence of riparian vegetation on flow resistance in mobile bed straight channels for shallow and deep overbank flows had been investigated through flume simulations. The findings of the experimental study were: (i) riparian vegetation increased the flow resistance which resulted larger
Manning’s $n$ in deeper flood flow, (ii) the $f$ values in the vegetated compound straight channels also increased as the relative depth changed from 0.30 to 0.50. Staggered arrays of riparian vegetation was found to generate the highest $f$ values of about 16% compared to tandem arrays case, (iii) a significant variation of bed morphology patterns contributed to the drag force values, (iv) the presence of riparian vegetation increased the drag force as compared to the effect of main channel bed morphology.

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