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# Effect of Floodplain Obstructions on the Discharge Conveyance Capacity of Compound Channels

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**Abstract:** Results of an experimental study into steady uniform flows in compound open channels with cylindrical obstructions designed to mimic emergent vegetation is presented. Two configurations – fully-covered floodplain and one-line obstructions - are considered, and the hydraulic properties are compared to those of a smooth, unobstructed compound channel. Particular attention is given to the effect of obstruction (i.e. vegetation) density on the rating curve, drag coefficients and spanwise profiles of streamwise velocity. Flow resistance is estimated using the approach introduced by Petryk and Bosmajian and the results are in agreement with other experimental studies. It was shown that the obstruction configuration significantly influences the flow velocity in the main channel, and in the case of one-line obstructions the floodplain velocity is higher than for an unobstructed channel for a given flow rate. Spanwise velocity profiles exhibit markedly different characters in the one-line and fully-covered configurations.

**CE Database subject headings:** Vegetated floodplain; Drag coefficient; Water depth-discharge relationship; Spanwise velocity distribution.

**Author keywords:** Compound channel; Vegetation; Drag; Rating curve; spanwise velocity profile.

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## Introduction

The middle and lowland stretches of most rivers are characterised by compound cross sections that comprise one or two floodplains and a deeper main channel. Vegetation may be distributed across the floodplains in a variety of ways, including patches of bushes, grassy meadows and regular arrays of trees that line the edges of the main channel and follow its meanders. Such arrays may occur naturally or by design as part of flood protection or habitat creation programs, and may exert significant influence on the hydraulic properties of the compound channel during flood events. One of the most prevalent arrangements is commonly known as “one-line” vegetation which comprises a single line of trees along the side of the main channel, but arrays of trees that extend much further across the floodplain may also occur.

Although a number of studies have focused on turbulence, secondary currents and momentum transfer in non-vegetated compound channels (Tominaga and Nezu 1991, van Prooijen et al. 2005, Yang et al. 2007, Vermaas et al. 2011), the influence of floodplain vegetation on the flow conditions and discharge conveyance in compound channels is less well understood and quantified. The impact of vegetation density, $\phi$, on the water depth-discharge curve has been studied experimentally by a number of authors for different vegetation configurations: (Ismail and Shiono 2006, Sun and Shiono 2009, Terrier 2010) considered one-line vegetation, while (Nehal et al. 2012, Hamidifar and Omid 2013) investigated a wholly-vegetated floodplain. Masterman and Thorne (1992) established a theoretical method to estimate the effects of bank vegetation on the channel flow capacity, and showed that it is possible to relate these effects to the channel width-to-depth ratio; the authors showed that the effect of bank vegetation on channel discharge capacity declines rapidly as the width-to-depth ratio increases. Ben-sheng et al. (2002) carried out experiments on a compound channel with a narrow floodplain and showed that the influence of vegetation on the floodplain flow capacity in such cases is not significant. Ismail and Shiono (2006) performed experiments in compound meandering channels with floodplains that were covered with small rectangular blocks to simulate vegetation. The authors carried out tests with fixed and mobile bed sediments to assess the influence of floodplain vegetation on sediment transport. The results showed that the influence of vegetation density on stage discharge curve was minimal for the fixed bed case, but some variation was observed for the mobile bed case. Yang et al. (2007) performed experiments in a compound channel that was either unvegetated or fully covered with model structures that were intended to represent grass, shrubs and trees. The authors found that for a non-vegetated channel the streamwise velocities always followed a logarithmic distribution, whereas S-shape velocity profiles were observed when vegetation was introduced on the floodplain. Hirschowitz and James (2009) estimated the total channel discharge in the presence of emergent vegetation along the banks of a river as the sum of the discharges of the vegetated and clear channel zones calculated seperately.

A number of researchers have studied the impact of vegetation density on the drag coefficient for flow past arrays of emergent rigid cylinders (Petryk and Bosmajian 1975, Nepf 1999, Tanino and Nepf 2008, Kothyari et al. 2009, Stoesser et al. 2010, Cheng and Nguyen 2011, Tinoco and Cowen 2013). Nepf (1999) proposed a model for drag, turbulence and diffusion within emergent vegetation and showed that the bulk drag coefficient decreases as vegetation density increases for both random and staggered arrays. Tanino and Nepf (2008) conducted experiments involving flow through a random array of emergent, rigid cylinders, investigating the effect of Reynolds number and vegetation density on the resistance properties. It was found that the bulk resistance decreased with increasing Reynolds number and increased with increasing solid volume fraction ($\phi$).

Nehal et al. (2012) performed experiments to investigate the resistance properties of one specific type of aquatic plant, *Acorus Calmus L*, showing that increases in vegetation density are accompanied by significant increases in the water depth; a staggered arrangement of the plants was found to produce the largest decrease in flow rate. Hamimed et al. (2013) also found that the relationship between flow depth and discharge depends strongly on the vegetation density; higher density leads to larger water depth except for very shallow flows, which are largely insensitive to changes in vegetation density. Hin et al. 2008 performed in situ flow measurements in vegetated equatorial streams in Malaysia, arriving at an expression for the apparent friction factor for a natural compound channel in terms of easily measurable hydraulic parameters. The floodplains of the streams were very densely vegetated, and as a result the floodplain flow was very small except when the overbank flow was very large. The researchers observed that the apparent shear was very high at the interface between the main channel and floodplain. Järvelä (2002) and Wunder et al. (2011) studied the hydraulic characteristics of natural willows and sedges to understand how type, density and combination of vegetation affects the bulk resistance in a channel. It was shown that the resistance is highly dependent on the flow depth, velocity, Reynolds number and vegetal characteristics. Shucksmith et al. (2011) investigated experimentally flow resistance properties of two types of live vegetation grown within a laboratory channel and quantified bulk drag coefficients as a function of plant property during growth.

In the case of one-line vegetation, a number of researchers have chosen to focus on the influnece of the spacing ratio $L/D$, where $L$ is the centre-to-centre distance between the trees and $D$ is the trunk diameter. Terrier (2010), for example, carried out experiments for two spacing ratios, $L/D = 8$ and $L/D = 16$. Circular cylinders and brushes were employed to represent vegetation with and without foliage, respectively. The results showed that flow rate increased as $L/D$ increased (i.e. vegetation density decreased), except when foliage was added. Sun and Shiono (2009) investigated the flow characteristics in a straight compound channel, with and without one-line vegetation. Two vegetation densities were applied, $L/D = 3.8$ and 13.3, and it was observed that spanwise distribution of streamwise velocity changed markedly with the introduction of vegetation. The boundary shear stress was also significantly lower with one-line vegetation than without, which lead the authors to conclude that sediment transport and bed scour during flood events will be reduced by the introduction of rigid vegetation along floodplain edges, although there will be an associated increase in water levels. Sun and Shiono (2009) also reported that the discharge was reduced by 20-26% for $L/D = 13.3$ and 21-36% for $L/D = 3.8$ compared to the unvegetated floodplain case. Sanjou et al. (2010) tested a spacing ratio of $L/D = 5$ in a compound channel of width ratio $B_{\mathrm{comp}}/B_{mc} = 2.50$, where $B_{comp}$ is the overall width and $B_{mc}$ is the main channel width. They reported reduced main channel velocities and altered spanwise distribution of velocities with the inclusion of the one-line vegetation compared to the unvegetated base case; with one-line vegetation two inflection points were observed in the spanwise profiles near the main channel-floodplain interface, while there was just one inflection point for the unvegetated compound channel section. These results suggest that significantly less momentum transfer occurs between the main channel and floodplain when one-line vegetation is introduced. Shiono et al. (2012) carried-out experiments in a flume of length 9m and width 0.915m, with one-line vegetation with $L/D$ = 17.8 and bed width ratio $B_{\mathrm{comp}}/B_{mc}$ = 2.0. The velocity distribution was characteristics by bulges in at the shear layer region near the water surface. Azevedo et al. (2012) modelled one-line vegetation using steel rods of diameter $D$ = 1.0cm placed at a distance 1.0m apart, i.e. $L/D$ = 100. Laser Doppler Velocimetry (LDV) was used to measure velocities in a flume of length 11.6m and width 0.79m with $B_{\mathrm{comp}}/B_{mc}$ = 3.85. Secondary currents were observed and two types of vortical structures, “bottom vortex” and “free surface vortex”, that were absent from the unvegetated case, were identified. Inclined up-flows were also observed to have higher magnitudes than in the unvegetated case. Time-averaged velocities at different vertical cross sections were shown to be similar except in the area near to the free surface due to the presence of secondary currents. In the centre of the main channel the velocity profiles were similar with and without one-line vegetation.

The effects of flow interaction between vegetated and non-vegetated regions in compound open channels result in a spanwise distribution of the depth-averaged mean velocity that is of tangential hyperbolic shape (van Prooijen and Uijttewaal 2002, White and Nepf 2007). Physical, mathematical, and analytical models have been studied by a number of authors with a view of achieving accurate representations of the spanwise distribution of streamwise velocities (Shiono and Knight 1991, Pasche and Rouvé 1985, Pope 2000, van Prooijen and Uijttewaal 2002, van Prooijen et al. 2005, Rameshwaran and Shiono 2007, White and Nepf 2007, Liu and Shen 2008 , White and Nepf 2008, Tang and Knight 2008, Chen et al. 2010, Tang et al. 2010, Li et al. 2014, Teymourei et al. 2013, Yang et al. 2013). Experimentally, Pasche and Rouvé (1985) confirmed that depth-averaged velocities are affected by vegetation in compound channel flows and showed that the inclusion of vegetation reduced longitudinal flow velocities. van Prooijen et al. (2005) proposed mechanisms for the momentum exchange in a straight uniform compound channel flow by considering the spanwise profile of streamwise velocity. White and Nepf (2007) showed that the velocity profiles separate the channel into two sections of uniform velocity; vegetated and open channel, and a transitional region between them. The spanwise variation of streamwise velocity in this transitional region is characterised by a hyperbolic tangent curve. Yang et al. (2007) showed that spanwise distribution of velocity in vegetated compound channels followed an S-shaped curve with three distinct flow regions. Hamidifar and Omid (2013) found that inclusion of vegetation on floodplains led to a decrease in the depth-averaged velocity over the floodplain and an increase in the main channel. In their study the depth-averaged velocity in both the main channel and floodplain decreased as vegetation density increased. Valyrakis et al. (2015) showed experimentally how increasing riverbank vegetation density decreases the streamwise velocity on the riverbank while increasing it at the main channel.

In this paper, the effect of vegetation (or “obstruction”) density and distribution on the floodplain on the rating curve, the drag coefficients and the stream-wise velocity distribution in an asymmetric compound channel is investigated experimentally. The paper is organised as follows: the next sections outline the theoretical framework on which the analysis is based; after which the experimental methodology and set-up are introduced. The experimental results are then discussed and finally some conclusions are drawn.

## Theoretical Considerations

Flow resistance in vegetated streams is due to a combination of form drag and skin friction. The vegetation-induced drag force is given as follows:

$$F_D = \frac{1}{2}\rho C_D A_f {U_a}^2 \tag{1}$$

where $F_D$ is the drag force acting on an individual stem, $C_D$ is the drag coefficient, $A_f$ is the frontal area of the stem, $\rho$ is the density of water and $U_a$ is the average velocity approaching the stem, which Cheng and Nguyen (2011) propose can be well approximated by the average pore velocity through the vegetated region, $U_{veg} = (Q/BH)/(1-\phi)$, where $Q$ is the bulk flow rate, $B$ is the channel width, $H$ is the flow depth and $\phi$ is the obstruction volume fraction or obstruction density, defined as the ratio of the volume occupied by the obstructions, $V_{veg}$, to the total volume, $V_{tot}$. Note that in the following analysis the term "obstruction" is used rather than "vegetation" as in some other similar studies, in order to be clear that the rigid rods are not representative of all types of vegetation. Note also that Cheng and Nguyen (2011) suggest $U_{veg} = U_\alpha = U_b$ for low obstruction density, where $U_{veg}$ is the flow through the obstructions and $U_b$ is the bulk flow velocity. Estimation of the drag coefficient induced by obstructions in streams under steady, uniform flow conditions can be established by equating the gravity force, $F_G$, to the drag force exerted by the obstructions , $F_D$, as follows:

$$F_G = F_D \tag{2}$$

Where,

$$F_G = \rho g (Al) S \tag{3}$$

where $\rho$ is the fluid density, $g$ is the gravitational acceleration, $A$ is the channel cross-sectional area, $l$ is the channel reach, and $S$ is the bed slope (refer to the schematic in Fig. 1). Equations (1-3) can be rearranged to give the following expression for the drag coefficient, $C_D$:

$$C_D = \frac{2gS}{{U_a}^2 a} \tag{4}$$

where $a$ is the obstruction density per unit length of the reach ($m^{-1}$), and can be expressed as $a = m\pi D^2/4Bl$ , where $m$ is number of stems per unit area occupied by the stems. $a$ and $\phi$ are related as $\phi = al$. Equation 4 shows that the drag will decrease as $a$ increases.

Tanino and Nepf (2008) formulated the drag coefficient for floodplain flow through an array of rigid circular cylinders as:

$$C_D = \left\{ \frac{\alpha_0}{Re_D} + \alpha_1 \right\} \tag{5}$$

where $\alpha_0$ and $\alpha_1$ are functions of the vegetation volume fraction, $\alpha_1 = 0.46 + 3.8\ \phi$, $\alpha_0 = 5.0 + 313.17\phi$, and $Re_D = U_{veg}D/\nu$ is the cylinder Reynolds number, where $\nu$ is the fluid kinematic viscosity and $U_{veg}$ is defined by Petryk and Bosmajian (1975) as:

$$U_{veg} = \sqrt{\frac{2gAlS}{C_D mDH}} \qquad (6)$$

Kothyari et al. (2009) proposed the following equation for the drag coefficient of emergent cylindrical stems based on a set of fluid force measurements in subcritical and supercritical flows:

$$C_D = 1.8\xi {Re_D}^{-0.06}[1 + 0.45\ln(1 + 100\phi)] * (0.8 + 0.2Fr - 0.15Fr^2) \qquad (7)$$

where, $\xi$ is a parameter representing the effect of the vegetation staggering pattern, with $\boldsymbol{\xi}$ = 0.8 for a regular square staggering pattern and $Fr = \frac{U_{veg}}{\sqrt{gH}}$ is the Froude number. The authors found that the drag coefficient varied only slightly with Reynolds number but was very sensitive to changes in obstruction density. It should be noted that, owing to the shortness of the flume, the flow was not fully developed and the authors speculated that drag coefficients were therefore higher than they would have been for fully developed flow.

Cheng and Nguyen (2011) related the drag coefficient to Reynolds number by a new parameter, the vegetation-related hydraulic radius, $r_v$, which is defined as the ratio of the volume occupied by water to the total frontal area of all cylinders:

$$r_v = \frac{\pi D}{4}\left(\frac{1-\phi}{\phi}\right) \qquad (8)$$

The drag coefficient and vegetation Reynolds number can then be expressed as follows:

$$C_D = 2gr_vS/{U_{veg}}^2 \qquad (9)$$

$$Re_v = U_{veg}r_v/\nu \qquad (10)$$

The authors found that dependence of $C_D$ on $Re_v$ varies with obstruction density and configuration (random or staggered) as also observed by (Tanino and Nepf 2008, Kothyari et al. 2009).

In compound channel flows an apparent shear stress, $\tau_{int}$, arises due to the high velocity gradients that are experienced at the interfaces between neighbouring regions of the cross-section. The shear stress force is considered as:

$$F_\tau = \tau_{int} A_{shear} \tag{11}$$

Where, $A_{shear}$ is the shear area, and $\tau_{int}$ is the apparent shear stress

This apparent shear stress was defined by Huthoff (2007) as follows:

$$\tau_{int} = \frac{1}{2}\psi\rho\left(U^2{}_{mc} - U^2{}_{fp}\right) \tag{12}$$

where, $\tau_{int} =$ shear stress at the interface between the main channel and the floodplain, $\psi =$ a dimensionless interface coefficient, $\psi \approx 0.020$, $U_{mc} =$ velocity of the flow in the main channel, $U_{fp} =$ velocity of flow above the floodplain.

For one-line vegetation, because there are two dips at the interface between the main channel and the floodplain, the interfacial shear stress is expressed as follows:

$$\tau_{int} = \frac{1}{2}\psi\rho[\left(U^2{}_{mc} - U^2{}_{dip}\right) + \left(U^2{}_{fp} - U^2{}_{dip}\right)] \tag{13}$$

where, $U_{dip} =$ velocity of the flow near to the interface.

In addition to the Huthoff (2007) expression, a number of methods for quantifying the apparent shear stress at the interface between the main channel and the floodplain were reviewed in (Thornton et al. 2000). Two of these methods have been used in the present study. The first of these was derived by Rajaratnam and Ahmadi (1981) and is defined as follows:

$$\tau_{int} = 0.15\left(\frac{H_{mc}}{H_{fp}} - 1\right)^2 \left(\gamma H_{fp} S\right) \tag{14}$$

where, $H_{mc} =$ depth of flow in the main channel, $H_{fp} =$ depth of flow on the floodplain, $\gamma =$ specific weight of water and $S =$ friction slope.

The second approach, derived empirically by Thornton et al. (2000), relates the shear stress, percentage blockage due to vegetation, $F_B$ , flow depth, and flow velocities as follows:

$$\tau_{int} = 0.1025\left(\frac{U_{fp}}{U_{mc}}\right)^{-3.4148}\left(\frac{H_{fp}}{H_{mc}}\right)^2 (1 - F_B) \tag{15}$$

With one-line vegetation, drag coefficient is calculated from the following expression:

$$F_D = F_G - F_S + F_\tau \qquad (16)$$

where $F_S$ is the bed shear stress force and can be written as:

$$F_S = \rho g R S B l \qquad (17)$$

where $R$ is the hydraulic radius.

## Experimental methodology and setups

Experiments were carried out in a 10 m × 1.2 m × 0.3 m glass-walled recirculating flume in the Hyder Hydraulics Laboratory at Cardiff University, UK. The bed slope was set to 0.001 for all test cases. A compound channel with one floodplain was installed in the flume by attaching slabs of plastic, 76 cm wide and 2.4 cm thick, alongside one of the side walls. The floodplain was therefore 76 cm wide, and the bankfull depth of the main channel was 2.4 cm (Fig. 2). The floodplain bed slope was equal to that of the main channel, i.e. $S_{mc} = S_{fp} = S = 0.001$. Flow depths were controlled by a tailgate that was located at the downstream end of the flume's working section. Uniform flow was verified by measuring the water level at 1m intervals along the working section, using a digital surface displacement gauge that outputs a voltage that is proportional to the length of its submerged section. The voltage signal was then amplified and logged on a workstation using data acquisition software. The volumetric flow rate was measured using a Nixon probe velocimeter, which itself was carefully calibrated using a previously established calibration curve for the flume. The surface displacement gauge and Nixon velocimeter were also used for all measurements of water level and velocity that are presented in this article. Level and velocity measurements were taken during 120 seconds at a sampling frequency of 1Hz; 120 samples of instantaneous level and velocity were therefore available. The samples were checked by eye and any anomalous values were removed before the temporal mean was calculated.

Wooden rods of three different diameters ($D$ = 5.0 cm, 2.5 cm and 1.25 cm) were used as laboratory models for rigid emergent vegetation elements. Three canonical configurations were tested:

unobstructed channel, fully covered floodplain and one-line vegetation. For the case of the fully covered floodplain the rods were inserted into holes that were drilled into the plastic floodplain in a staggered fashion; the centre-to-centre separation of the holes in streamwise and spanwise directions was 12.5 cm (Fig. 2a). This arrangement produced solid volume fractions of 24.8% (dense vegetation), 6.2% (medium) and 1.5% (sparse) for the three different rod diameters. These volume fractions represent a broad range and are comparable to fractions that have been studied by other researchers, for example Nepf (1999) and Tanino and Nepf (2008). For the case of one-line vegetation the rods were inserted into holes that were drilled along a line parrallel to the sides of the flume: the streamwise centre-to-centre separation of the holes was 12.5 cm and the hole centres were 2.5 cm from the edge of the main channel (Fig. 2b). This arrangement produced normalised vegetation spacings of $L/D$ = 2.5, 5 and 10 for the three different rod diameters.

Five discharges were tested for all vegetation configurations and rod diameters: 4.66 l/s, 5.87 l/s, 7.51 l/s, 8.87 l/s and 11.03 l/s. Table 1 provides a summary of flow conditions for all test cases.

For each discharge the water depth at the centre of the main channel was measured at streamwise intervals of 1 m in the section 3 m $\leq x \leq$ 9 m. Measurements of mean streamwise velocity, $U$, were carried out in sections in which the flow was considered to be fully developed (refer to Fig. 4 for evidence of this). Figure 3 illustrates the velocity measurement locations for the wholl-vegetated and one-line configurations: for the fully covered floodplain, velocities in two sections were measured ($x$ = 4.76 m, and 8.52 m), while for the one-line case four sections were considered ($x$ = 4.76 m, 7.76 m, 8.15 m and 8.52 m). In the main channel velocities were measured at two depths, $0.2H_{mc}$ and at $0.8H_{mc}$, and the average was taken ($U = (U_{0.2Hmc}+U_{0.8Hmc})/2$). The first spanwise measurement location was 6.5 cm from the main channel side-wall, and further measurements were taken at 5 cm spanwise intervals until a distance 7 cm from the edge of the floodplain (Zone I in Fig. 3); over these last 7 cm (Zone II) measurements were taken at 1 cm spanwise intervals to improve the resolution in this complex region. On the floodplain (Zone III) the velocity was measured at the mid-depth, i.e. $U = U_{0.5Hfp}$, with two measurements between neighbouring rods in the same row taken. For the one-line vegetation case the same procedure was followed in the main channel (Zones I and II) as for the fully covered case but on the floodplain (Zone III) the velocities were measured at 5 cm spanwise intervals from the rod centre to the side wall. For the unobstructed channel case the same procedure was adopted for the main channel (Zones I and II) as for the other two cases, while on the floodplain (Zone III) measurements were taken 5 cm spanwise intervals between the edge of the main channel and the side wall.

## Results and Discussions

### Spanwise distribution of streamwise velocity

Figure 4 presents spanwise profiles of mean depth-averaged streamwise velocity for the fully covered floodplain and one-line vegetation cases. Figures 4a, 4b and 4c correspond to the three different flow rates tested with one-line vegetation and Figs. 4d, 4e and 4f correspond to the different flow rates with a fully covered floodplain. Note that the velocity has been normalised on the bulk streamwise velocity for the whole system, $U_{bulk}$. Profiles measured at two (one-line) or four (fully covered) streamwise locations are presented: the close agreement between profiles measured at different streamwise locations indicates that the flow in the measurement section of the flume was fully developed.

Figure 5 presents comparisons of spanwise profiles of mean depth-averaged streamwise velocity for the different configurations (unobstructed, fully covered and one-line) for the three flow rates that were tested. Note that for the fully covered floodplain and one-line cases only data pertaining to the D = 2.5cm cases have been presented. The velocity is normalised $U_{bulk}$. The plots provide clear confirmation that, as would be expected, flow velocity above a fully covered floodplain is noticeably lower than that above an unobstructed floodplain. However the plots also reveal that the inclusion of one-line vegetation produces higher velocities above the floodplain compared to the unobstructed case. Correspondingly, the streamwise velocities in the main channel are highest for the fully covered floodplain case, lowest for the unobstructed case and intermediate for the one-line case. Also noteworthy are the characters of the velocity distributions: for the fully covered and unobstructed floodplains the spanwise profiles follow an S-shaped curve but for one-line vegetation the profiles exhibit a distinct dip at the interface between the main channel and the floodplain.

Spanwise profiles of depth-averaged mean streamwise velocity for the case of an unobstructed floodplain are shown in Fig. 6, illustrating the effect of flow rate on the velocity distribution. The plot reveals that the normalised velocity in the main channel decreases with increasing flow rate, while increasing above the floodplain.

Figures 7a, 7b and 7c present spanwise profiles of depth-averaged mean streamwise velocity for the case of a fully covered floodplain. Each of the three sub-figures corresponds to a different flow rate, and in each sub-figure data pertaining to the three obstruction densities are plotted. In all cases the data exhibit S-shaped spanwise profiles, and the velocity in the main channel increases with increasing obstruction density. The floodplain velocities are shown to be largely independent of obstruction density, with the exception of the highest flow rate case (Fig. 7c), where the floodplain velocity is slightly larger for the lowest obstruction density.

Figure 7d, 7e and 7f present spanwise profiles of depth-averaged mean streamwise velocity for the case of one-line vegetation, for the three different flow rates that have been considered. The velocity gradients either side of the interface between the main channel and the floodplain are very strong, leading to very high shear stresses and strong large scale vortices as shown by (Mulahasan et al. 2015). The profiles also reveal very pronounced local minima close to the line of vegetation, indicating suppression of momentum transfer between the main channel and the floodplain, which is in agreement with the findings of Sun and Shiono (2009) and Shiono et al. (2012), who also observed similarly pronounced minima at the edge of the floodplain.

## Estimation of mean drag coefficients

Figure 8 presents the variation of drag coefficient with Reynolds number, based on $U_{bulk}$, and stem diameter, for the fully covered floodplain case. The experimental drag coefficient values for the present study have been estimated using the simple streamwise momentum balance, and are plotted alongside experimental data from a number of previous experimental studies. Note that the drag coefficient was calculated at all four measurement cross-sections (Fig. 3) and the mean was calculated**.** In addition, empirical relationships proposed by Tanino and Nepf (2008), Kothyari et al (2009) and Cheng and Nguyen (2011) have been applied to the hydraulic conditions investigated in the present study, and the resulting drag coefficient estimates have also been included in the plot. Clearly the collated data shows that the drag coefficient displays a high degree of sensitivity to changes in both Reynolds number and obstruction density. The experimental data from the present study appears to follow the general trend displayed by the other data sets, although there is considerable scatter. It is interesting that the lowest density ratio data sets of Tinco and Cowen (2013) ($\phi$ = 1.0%) is the notable outlier from the general trend; in this case the drag coefficient appears to be largely independent of Reynolds number. Application of the empirical relationships to the hydraulic conditions tested in the present study generally produces very close agreement with the measured drag coefficients.

Figure 9 shows the influence of rod diameter on the drag coefficient-Reynolds number relationship for the case of one-line vegetation. The figure clearly shows that drag coefficient decreases with increasing Reynolds number, and the range of measured drag coefficient increases with decreasing rod diameter. It is noteworthy that for all three rod diameters the gradients of the lines are noticeably steep. The drag coefficient is therefore very sensitive to changes in Reynolds number in the range investigated. As discussed in the “Theoretical Considerations” section of this article, various researchers have proposed different empirical relationships to allow the determination of the interfacial shear stress in compound channels. Equations 12 to 15 have been used to estimate the interfacial shear stress for the flow cases investigated in the present study, and Fig. 10 reveals the effect of the choice of equation on the estimated drag coefficient.  Also included in the plot are data from the experimental study of Tanino and Nepf (2008) and Tanino and Nepf (2008)’s proposed drag coefficient equation for the wholly vegetated case. The plot reveals that the data from the present investigation, which populate the Reynolds number range 1800 < Re < 8400, largely follow the same trend as the experimental data of Tanino and Nepf. The plot also suggests that the choice of empirical equation does not significantly affect the estimation of drag coefficient: there is relatively little scatter between the four data sets.

## Impact of Vegetation on the Water Depth-Discharge Curve

The influence of obstruction density on the water depth-discharge relationship for the fully covered floodplain case is shown in Fig. 11a. The plot clearly illustrates that in general the inclusion of a fully covered floodplain produces a marked increase in water depth compared to the unobstructed case for a given flow rate. The increase is smallest at the lowest flow rate and becomes more noticeable as flow rate increases. As would be expected, increasing the rod diameter, and therefore the obstruction density, results in further increases in water level. The water level increases with flow rate in all cases: interestingly, water depth appears to increase linearly with flow rate when the floodplain is vegetated but this is not the case for the unobstructed channel.

Figure 11b presents the variation of water depth with flow rate for the one-line vegetation case. The inclusion of one-line vegetation produces a much smaller increase in water depth compared to the fully covered floodplain (Fig. 11a). This is due to the fact that the overall obstruction density, and therefore flow blockage, for the one-line case is naturally much smaller than in the full-vegetated case. The plot does indicate, however, that water depth is noticeably more sensitive to changes in L/D for one-line vegetation than to changes in density for a fully covered floodplain. It can clearly be seen that there has been a significant increase in the water depth as the obstruction density is increased in comparison with non-vegetated floodplain (Fig. 11a). The mean increase in the water depth is 15.88%, 15.13% and 13.1% for dense, medium and sparse obstruction densities respectively.

## Conclusions

Laboratory experiments were carried out to quantify the influence of floodplain vegetation on the rating curve, mean drag coefficient and spanwise distribution of streamwise velocity in compound open channels. Two configurations - fully covered floodplain and one-line obstructions - were tested along with a smooth unobstructed compound channel. Vegetation elements were modelled by emergent rigid wooden rods of circular cross-section. For the cases with obstructions (i.e. vegetation) the effect of obstruction density was investigated, and in all cases three flow rates were tested.

The results showed that for a fully covered floodplain the water depth increased by 15.88%, 15.13% and 13.1% for dense, medium and sparse obstruction densities respectively compared to the unobstructed case. One-line obstructions produced a smaller increase in flow depth than the fully covered floodplain.

It was observed that for a fully covered floodplain the drag coefficient increases with increasing obstruction density. For all obstruction densities the drag coefficient was observed to decrease as Reynolds number increased. Applying the empirical equations of Tanino and Nepf (2008), Kothyari, et al. (2009) and Cheng and Nguyen (2011) to estimate the drag coefficients for the hydraulic conditions presently tested produced values in the range of experimental data from the literature, with relatively little scatter. The experimentally-recorded drag coefficients agreed well with Tinco and Cowen's (2013) results for medium obstruction density, but the agreement for low obstruction density is less convincing.

For one-line obstructions, it was observed that drag coefficient increases with decreasing rod diameter. Empirical equations from the literature were used to estimate the interfacial shear stress at the interface between the main channel and the floodplain: accounting for the interfacial shear stress in this way produced more accurate estimations of the overall drag coefficient compared to simply equating drag force to the overall bed shear stress. Using Tanino and Nepf's (2008) empirical equation for the range of hydraulic parameters presently tested produced estimations for drag coefficient in the region of 1.0.

Spanwise profiles of depth-averaged mean streamwise velocity confirmed that introduction of a fully covered floodplain results in a considerable reduction in floodplain velocities compared to the unobstructed case, while one-line obstructions produce an increase in floodplain velocity. Velocity in the main channel is lower for fully covered floodplains and higher for one-line obstructions. The spanwise distributions of streamwise velocity for fully covered and unobstructed floodplains follow S-shaped curves whereas for one-line obstructions a very pronounced dip is observed at the interface between the main channel and the floodplain.

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## Notation

The following symbols were used in this paper:

$A =$ cross sectional area of flow;

$a =$ obstruction (or vegetation) density per unit length of reach;

$A_{bed} =$ area of bed occupied by vegetation;

$A_f =$ projected area;

$A_{shear} =$ shear area;

$A_{veg} =$ area of vegetation;

$C_D =$ drag coefficient;

$C_{D_v} =$ vegetated drag coefficient;

$D =$ cylinder diameter;

$FB =$ percent flow blockage;

$F_D =$ drag force per unit volume;

$F_G =$ gravity force;

$Fr =$ Froude number;

$F_\tau =$ interface shear stress;

$g$ = gravitational acceleration;

$H_{mc}$ = depth of flow in the main channel;

$H$ = flow depth;

$H_{fp}$ = depth of flow on the floodplain;

$L$ = spanwise spacing;

$l$ = channel reach length;

$m$ = number of cylinders per unit area;

$Q$ = discharge;

$R$ = hydraulic radius;

$Re_D$ = cylinder Reynolds number;

$Re_v$ = vegetated Reynolds number;

$r_v$ = vegetated-related hydraulic radius;

$S$ = channel bed slope;

$SVF$ = solid volume fraction;

$U$ = average velocity;

$U_{bulk}$ = bulk velocity for whole flume;

$U_a$ = average velocity approaching the cylinder;

$U_{fp}$ =velocity of flow on the floodplain;

$U_{mc}$ = velocity of the flow in the main channel;

$U_{veg}$ = velocity of flow within the vegetation elements;

$y$ = lateral streamwise width;

$w$ =flume width;

$\alpha_0$ & $\alpha_1$ = functions of solid volume fraction;

$\gamma$ = specific weight of water;

$\xi$ = parameter representing the cylinder staggered pattern;

$\nu$ = kinematic viscosity;

$\rho$ = density of water;

$\tau_{int}$ = apparent shear stresses at the interface;

$\phi$ = obstruction (or vegetation) density ;

$\psi$ = proportionality coefficient.

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TABLE 1 Summary of flow conditions

| Config. | D (cm) | Q (l/s) | $H_{mc}$ (cm) | $H_{fp}$ (cm) | $U_{bulk}$ (cm/s) | $Re_D$ | $Re_R$ | Fr | SVF (%) | L/D |
|---|---|---|---|---|---|---|---|---|---|---|
| **Non-vegetated floodplain** | - | 4.66 | 3.96 | 1.56 | 16.07 | - | 3661 | 0.26 | - | - |
| | - | 5.82 | 4.61 | 2.21 | 15.81 | - | 4523 | 0.24 | - | - |
| | - | 7.51 | 5.26 | 2.86 | 16.84 | - | 5782 | 0.23 | - | - |
| | - | 8.87 | 5.59 | 3.19 | 18.27 | - | 6794 | 0.25 | - | - |
| | - | 11.03 | 6.12 | 3.72 | 20.08 | - | 8376 | 0.26 | - | - |
| **One-line** | 5.00 | 4.66 | 4.39 | 1.99 | 13.64 | 6781 | 3635 | 0.21 | - | 2.5 |
| | 5.00 | 5.82 | 5.12 | 2.72 | 13.55 | 6736 | 4486 | 0.19 | - | 2.5 |
| | 5.00 | 7.51 | 5.83 | 3.43 | 14.60 | 7257 | 5730 | 0.19 | - | 2.5 |
| | 5.00 | 8.87 | 6.49 | 4.09 | 14.94 | 7427 | 6699 | 0.19 | - | 2.5 |
| | 5.00 | 11.03 | 6.98 | 4.58 | 16.90 | 8400 | 8267 | 0.20 | - | 2.5 |
| | 2.50 | 4.66 | 4.22 | 1.82 | 14.51 | 3606 | 3646 | 0.23 | - | 5.0 |
| | 2.50 | 5.82 | 4.71 | 2.31 | 15.31 | 3804 | 4516 | 0.23 | - | 5.0 |
| | 2.50 | 7.51 | 5.39 | 2.99 | 16.27 | 4044 | 5770 | 0.22 | - | 5.0 |
| | 2.50 | 8.87 | 5.95 | 3.55 | 16.78 | 4169 | 6756 | 0.22 | - | 5.0 |
| | 2.50 | 11.03 | 6.54 | 4.14 | 18.39 | 4570 | 8323 | 0.23 | - | 5.0 |
| | 1.25 | 4.66 | 4.22 | 1.82 | 14.51 | 1803 | 3646 | 0.23 | - | 10 |
| | 1.25 | 5.82 | 4.69 | 2.29 | 15.41 | 1914 | 4517 | 0.23 | - | 10 |
| | 1.25 | 7.51 | 5.34 | 2.94 | 16.49 | 2049 | 5774 | 0.23 | - | 10 |
| | 1.25 | 8.87 | 5.78 | 3.38 | 17.45 | 2168 | 6774 | 0.23 | - | 10 |
| | 1.25 | 11.03 | 6.14 | 3.74 | 19.99 | 2484 | 8374 | 0.26 | - | 10 |
| **Fully covered** | 5.00 | 4.66 | 4.46 | 2.06 | 13.32 | 6619 | 3633 | 0.20 | 24.8 | - |
| | 5.00 | 5.82 | 5.14 | 2.74 | 13.48 | 6699 | 4486 | 0.19 | 24.8 | - |
| | 5.00 | 7.51 | 6.18 | 3.78 | 13.50 | 6709 | 5700 | 0.17 | 24.8 | - |
| | 5.00 | 8.87 | 6.99 | 4.59 | 13.57 | 6746 | 6650 | 0.16 | 24.8 | - |
| | 5.00 | 11.03 | 7.95 | 5.55 | 14.34 | 7128 | 8148 | 0.16 | 24.8 | - |
| | 2.50 | 4.66 | 4.37 | 1.97 | 13.74 | 3415 | 3638 | 0.21 | 6.2 | - |
| | 2.50 | 5.82 | 5.01 | 2.61 | 13.98 | 3475 | 4495 | 0.20 | 6.2 | - |
| | 2.50 | 7.51 | 6.20 | 3.8 | 13.44 | 3340 | 5699 | 0.17 | 6.2 | - |
| | 2.50 | 8.87 | 7.00 | 4.6 | 13.55 | 3367 | 6649 | 0.16 | 6.2 | - |
| | 2.50 | 11.03 | 7.95 | 5.55 | 14.34 | 3564 | 8148 | 0.16 | 6.2 | - |
| | 1.25 | 4.66 | 4.35 | 1.94 | 13.87 | 1724 | 3639 | 0.21 | 1.5 | - |
| | 1.25 | 5.82 | 4.89 | 2.49 | 14.48 | 1800 | 4503 | 0.21 | 1.5 | - |
| | 1.25 | 7.51 | 6.05 | 3.65 | 13.89 | 1726 | 5712 | 0.18 | 1.5 | - |
| | 1.25 | 8.87 | 6.69 | 4.29 | 14.36 | 1785 | 6681 | 0.18 | 1.5 | - |
| | 1.25 | 11.03 | 7.78 | 5.38 | 14.73 | 1831 | 8169 | 0.17 | 1.5 | - |

## Figure Captions

**Fig. 1**. Schematic showing an open channel with emergent vegetation represented by circular rods.

**Fig. 2.** Experimental set-ups: a) fully covered floodplain b) one-line vegetation.

**Fig. 3.** Schematics (top-view) of measurement section of flume showing measurement locations; (a) fully covered floodplain, (b) one-line vegetation and unobstructed floodplain. Dashed lines denote water level measurement cross-sections. Zones I, II and III denote zone of different resolution for velocity measurements.

**Fig. 4.** Spanwise profiles of mean depth-averaged streamwise velocity: a) fully covered, Q=4.66l/s; b) fully covered, Q=7.51l/s; c) fully covered, Q=11.03l/s, c) one-line, Q=4.66l/s; d) one-line, Q=7.51l/s; e) one-line, Q=11.03l/s. Medium obstruction density (D=2.5cm) for all cases.

**Fig. 5.** Spanwise profiles of mean depth-averaged streamwise velocity for fully covered floodplain and one-line vegetation in comparison to non-vegetated floodplain: a) Q=4.66 l/s; b) Q=7.51 l/s; and c) Q=11.03 l/s

**Fig. 6.** Spanwise profiles of mean depth-averaged streamwise velocity for unobstructed compound channel

**Fig. 7.** Impact of the obstruction density on the spanwise velocity profiles: a) fully covered, Q=4.66l/s; b) fully covered, Q=7.51l/s; c) fully covered, Q=11.03l/s; d) one-line, Q=4.66l/s; e) one-line, Q=7.51l/s; and f) one-line, Q=11.03l/s.

**Fig. 8.** Drag coefficient-Reynolds number relationship for fully covered floodplain

**Fig. 9.** Impact of rod diameter on the drag coefficient-Reynolds number relationship from water balance equation ($F_D = F_G - F_T - F_S$) for one-line vegetation

**Fig. 10.** Drag coefficient-Reynolds number relationship: effect of choice of theoretical approach to calculate interfacial shear stress

**Fig. 11.** Stage-discharge curves for compound channel flow: a) fully covered and unobstructed floodplains; b) one-line vegetation and unobstructed floodplain.