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

Saad Mulahasan[1], Thorsten Stoesser[2] and Richard McSherry[3]

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.

1 PhD Student, School of Engineering, Cardiff University, The Parade, Cardiff, CF243AA, UK Email: mulahasansh@cardiff.ac.uk, +44 (0)29 20876586
2 Professor, School of Engineering, Cardiff University, The Parade, Cardiff, CF243AA, UK Email: stoesser@cardiff.ac.uk, +44 (0)29 20876697
3 Research Associate, School of Engineering, Cardiff University, The Parade, Cardiff, CF243AA, UK Email: mcsherryr@cardiff.ac.uk, +44 (0)29 20876814

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, ϕ, 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

52 influence of floodplain vegetation on sediment transport. The results showed that the influence of
53 vegetation density on stage discharge curve was minimal for the fixed bed case, but some variation
54 was observed for the mobile bed case. Yang et al. (2007) performed experiments in a compound
55 channel that was either unvegetated or fully covered with model structures that were intended to
56 represent grass, shrubs and trees. The authors found that for a non-vegetated channel the
57 streamwise velocities always followed a logarithmic distribution, whereas S-shape velocity profiles
58 were observed when vegetation was introduced on the floodplain. Hirschowitz and James (2009)
59 estimated the total channel discharge in the presence of emergent vegetation along the banks of a
60 river as the sum of the discharges of the vegetated and clear channel zones calculated seperately.
61 A number of researchers have studied the impact of vegetation density on the drag coefficient for
62 flow past arrays of emergent rigid cylinders (Petryk and Bosmajian 1975, Nepf 1999, Tanino and
63 Nepf 2008, Kothyari et al. 2009, Stoesser et al. 2010, Cheng and Nguyen 2011, Tinoco and Cowen
64 2013). Nepf (1999) proposed a model for drag, turbulence and diffusion within emergent vegetation
65 and showed that the bulk drag coefficient decreases as vegetation density increases for both
66 random and staggered arrays. Tanino and Nepf (2008) conducted experiments involving flow
67 through a random array of emergent, rigid cylinders, investigating the effect of Reynolds number
68 and vegetation density on the resistance properties. It was found that the bulk resistance decreased
69 with increasing Reynolds number and increased with increasing solid volume fraction (ϕ).
70 Nehal et al. (2012) performed experiments to investigate the resistance properties of one specific
71 type of aquatic plant, *Acorus Calmus L*, showing that increases in vegetation density are
72 accompanied by significant increases in the water depth; a staggered arrangement of the plants was
73 found to produce the largest decrease in flow rate. Hamimed et al. (2013) also found that the
74 relationship between flow depth and discharge depends strongly on the vegetation density; higher
75 density leads to larger water depth except for very shallow flows, which are largely insensitive to
76 changes in vegetation density. Hin et al. 2008 performed in situ flow measurements in vegetated
77 equatorial streams in Malaysia, arriving at an expression for the apparent friction factor for a natural

78 compound channel in terms of easily measurable hydraulic parameters. The floodplains of the
79 streams were very densely vegetated, and as a result the floodplain flow was very small except when
80 the overbank flow was very large. The researchers observed that the apparent shear was very high
81 at the interface between the main channel and floodplain. Järvelä (2002) and Wunder et al. (2011)
82 studied the hydraulic characteristics of natural willows and sedges to understand how type, density
83 and combination of vegetation affects the bulk resistance in a channel. It was shown that the
84 resistance is highly dependent on the flow depth, velocity, Reynolds number and vegetal
85 characteristics. Shucksmith et al. (2011) investigated experimentally flow resistance properties of
86 two types of live vegetation grown within a laboratory channel and quantified bulk drag coefficients
87 as a function of plant property during growth.
88 In the case of one-line vegetation, a number of researchers have chosen to focus on the influnece of
89 the spacing ratio L/D, where L is the centre-to-centre distance between the trees and *D* is the trunk
90 diameter. Terrier (2010), for example, carried out experiments for two spacing ratios, $L/D = 8$ and
91 L/D = 16. Circular cylinders and brushes were employed to represent vegetation with and without
92 foliage, respectively. The results showed that flow rate increased as L/D increased (i.e. vegetation
93 density decreased), except when foliage was added. Sun and Shiono (2009) investigated the flow
94 characteristics in a straight compound channel, with and without one-line vegetation. Two
95 vegetation densities were applied, $L/D = 3.8$ and 13.3, and it was observed that spanwise
96 distribution of streamwise velocity changed markedly with the introduction of vegetation. The
97 boundary shear stress was also significantly lower with one-line vegetation than without, which lead
98 the authors to conclude that sediment transport and bed scour during flood events will be reduced
99 by the introduction of rigid vegetation along floodplain edges, although there will be an associated
100 increase in water levels. Sun and Shiono (2009) also reported that the discharge was reduced by 20-
101 26% for *L*/*D* = 13.3 and 21-36% for *L*/*D* = 3.8 compared to the unvegetated floodplain case. Sanjou et
102 al. (2010) tested a spacing ratio of *L*/*D* = 5 in a compound channel of width ratio B_{comp}/B_{mc} = 2.50,
103 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_{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_{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:

$$F_D = \frac{1}{2}\rho C_D A_f {U_a}^2 \quad (1)$$

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, ρ 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 ϕ 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 ρ 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 ϕ 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 α_0 and α_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 ν is the fluid kinematic viscosity and U_{veg} is defined by Petryk and Bosmajian (1975) as:

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

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:

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

where, ξ 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:

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

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

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

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

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, τ_{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:

$$F_\tau = \tau_{int} A_{shear} \quad (11)$$

Where, A_{shear} is the shear area, and τ_{int} is the apparent shear stress

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

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

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:

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

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:

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

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:

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

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

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

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

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

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:

254 unobstructed channel, fully covered floodplain and one-line vegetation. For the case of the fully
255 covered floodplain the rods were inserted into holes that were drilled into the plastic floodplain in a
256 staggered fashion; the centre-to-centre separation of the holes in streamwise and spanwise
257 directions was 12.5 cm (Fig. 2a). This arrangement produced solid volume fractions of 24.8% (dense
258 vegetation), 6.2% (medium) and 1.5% (sparse) for the three different rod diameters. These volume
259 fractions represent a broad range and are comparable to fractions that have been studied by other
260 researchers, for example Nepf (1999) and Tanino and Nepf (2008). For the case of one-line
261 vegetation the rods were inserted into holes that were drilled along a line parrallel to the sides of
262 the flume: the streamwise centre-to-centre separation of the holes was 12.5 cm and the hole
263 centres were 2.5 cm from the edge of the main channel (Fig. 2b). This arrangement produced
264 normalised vegetation spacings of *L/D* = 2.5, 5 and 10 for the three different rod diameters.
265 Five discharges were tested for all vegetation configurations and rod diameters: 4.66 l/s, 5.87 l/s,
266 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.
267 For each discharge the water depth at the centre of the main channel was measured at streamwise
268 intervals of 1 m in the section 3 m ≤ *x* ≤ 9 m. Measurements of mean streamwise velocity, *U*, were
269 carried out in sections in which the flow was considered to be fully developed (refer to Fig. 4 for
270 evidence of this). Figure 3 illustrates the velocity measurement locations for the wholl-vegetated
271 and one-line configurations: for the fully covered floodplain, velocities in two sections were
272 measured (*x* = 4.76 m, and 8.52 m), while for the one-line case four sections were considered (*x* =
273 4.76 m, 7.76 m, 8.15 m and 8.52 m). In the main channel velocities were measured at two depths,
274 $0.2H_{mc}$ and at $0.8H_{mc}$, and the average was taken (U = ($U_{0.2Hmc}$+$U_{0.8Hmc}$)/2). The first spanwise
275 measurement location was 6.5 cm from the main channel side-wall, and further measurements were
276 taken at 5 cm spanwise intervals until a distance 7 cm from the edge of the floodplain (Zone I in Fig.
277 3); over these last 7 cm (Zone II) measurements were taken at 1 cm spanwise intervals to improve
278 the resolution in this complex region. On the floodplain (Zone III) the velocity was measured at the
279 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

306 case. Also noteworthy are the characters of the velocity distributions: for the fully covered and
307 unobstructed floodplains the spanwise profiles follow an S-shaped curve but for one-line vegetation
308 the profiles exhibit a distinct dip at the interface between the main channel and the floodplain.
309 Spanwise profiles of depth-averaged mean streamwise velocity for the case of an unobstructed
310 floodplain are shown in Fig. 6, illustrating the effect of flow rate on the velocity distribution. The plot
311 reveals that the normalised velocity in the main channel decreases with increasing flow rate, while
312 increasing above the floodplain.
313 Figures 7a, 7b and 7c present spanwise profiles of depth-averaged mean streamwise velocity for the
314 case of a fully covered floodplain. Each of the three sub-figures corresponds to a different flow rate,
315 and in each sub-figure data pertaining to the three obstruction densities are plotted. In all cases the
316 data exhibit S-shaped spanwise profiles, and the velocity in the main channel increases with
317 increasing obstruction density. The floodplain velocities are shown to be largely independent of
318 obstruction density, with the exception of the highest flow rate case (Fig. 7c), where the floodplain
319 velocity is slightly larger for the lowest obstruction density.
320 Figure 7d, 7e and 7f present spanwise profiles of depth-averaged mean streamwise velocity for the
321 case of one-line vegetation, for the three different flow rates that have been considered. The
322 velocity gradients either side of the interface between the main channel and the floodplain are very
323 strong, leading to very high shear stresses and strong large scale vortices as shown by (Mulahasan et
324 al. 2015). The profiles also reveal very pronounced local minima close to the line of vegetation,
325 indicating suppression of momentum transfer between the main channel and the floodplain, which
326 is in agreement with the findings of Sun and Shiono (2009) and Shiono et al. (2012), who also
327 observed similarly pronounced minima at the edge of the floodplain.
328 **Estimation of mean drag coefficients**
329 Figure 8 presents the variation of drag coefficient with Reynolds number, based on U_{bulk}, and stem
330 diameter, for the fully covered floodplain case. The experimental drag coefficient values for the
331 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) (ϕ = 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

358 the same trend as the experimental data of Tanino and Nepf. The plot also suggests that the choice
359 of empirical equation does not significantly affect the estimation of drag coefficient: there is
360 relatively little scatter between the four data sets.

361 **Impact of Vegetation on the Water Depth-Discharge Curve**

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

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

380

381 **Conclusions**

382 Laboratory experiments were carried out to quantify the influence of floodplain vegetation on the
383 rating curve, mean drag coefficient and spanwise distribution of streamwise velocity in compound

384 open channels. Two configurations - fully covered floodplain and one-line obstructions - were tested
385 along with a smooth unobstructed compound channel. Vegetation elements were modelled by
386 emergent rigid wooden rods of circular cross-section. For the cases with obstructions (i.e.
387 vegetation) the effect of obstruction density was investigated, and in all cases three flow rates were
388 tested.
389 The results showed that for a fully covered floodplain the water depth increased by 15.88%, 15.13%
390 and 13.1% for dense, medium and sparse obstruction densities respectively compared to the
391 unobstructed case. One-line obstructions produced a smaller increase in flow depth than the fully
392 covered floodplain.
393 It was observed that for a fully covered floodplain the drag coefficient increases with increasing
394 obstruction density. For all obstruction densities the drag coefficient was observed to decrease as
395 Reynolds number increased. Applying the empirical equations of Tanino and Nepf (2008), Kothyari,
396 et al. (2009) and Cheng and Nguyen (2011) to estimate the drag coefficients for the hydraulic
397 conditions presently tested produced values in the range of experimental data from the literature,
398 with relatively little scatter. The experimentally-recorded drag coefficients agreed well with Tinco
399 and Cowen's (2013) results for medium obstruction density, but the agreement for low obstruction
400 density is less convincing.
401 For one-line obstructions, it was observed that drag coefficient increases with decreasing rod
402 diameter. Empirical equations from the literature were used to estimate the interfacial shear stress
403 at the interface between the main channel and the floodplain: accounting for the interfacial shear
404 stress in this way produced more accurate estimations of the overall drag coefficient compared to
405 simply equating drag force to the overall bed shear stress. Using Tanino and Nepf's (2008) empirical
406 equation for the range of hydraulic parameters presently tested produced estimations for drag
407 coefficient in the region of 1.0.
408 Spanwise profiles of depth-averaged mean streamwise velocity confirmed that introduction of a fully
409 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.

Acknowledgments

This work was supported by the Iraqi government and the UK Engineering and Physical Sciences Research Council (EPSRC; grant number EP/k041088/1).

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;

436 g = gravitational acceleration;

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

438 H = flow depth;

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

440 L = spanwise spacing;

441 l = channel reach length;

442 m = number of cylinders per unit area;

443 Q = discharge;

444 R = hydraulic radius;

445 Re_D = cylinder Reynolds number;

446 Re_v = vegetated Reynolds number;

447 r_v = vegetated-related hydraulic radius;

448 S = channel bed slope;

449 SVF = solid volume fraction;

450 U = average velocity;

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

452 U_a = average velocity approaching the cylinder;

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

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

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

456 y = lateral streamwise width;

457 w =flume width;

458 α_0 & α_1 = functions of solid volume fraction;

459 γ = specific weight of water;

460 ξ = parameter representing the cylinder staggered pattern;

461 ν = kinematic viscosity;

462 $\rho =$ density of water;

463 $\tau_{int} =$ apparent shear stresses at the interface;

464 $\phi =$ obstruction (or vegetation) density ;

465 $\psi =$ proportionality coefficient.

466

467 **References**

468 Azevedo, R., Leal, J. B. and Rojas-Solórzano, L. (2012) 'Influence of vegetation on compound-channel
469 turbulent field' in *River Flow 2012*, CRC Press, 209-216.

470

471 Ben-sheng, H., Guan-wen, L., Jing, Q. and Shu-zhong, L. (2002) 'Hydraulics of compound channel with
472 vegetated floodplain', *Journal of Hydrodynamics,* Ser.B(1), 23-28.

473

474 Chen, G., Huai, W., Han, J. and Zhao, M. (2010) 'Flow structure in partially vegetated rectangular
475 channels', *Journal of Hydrodynamics, Ser. B,* 22(4), 590-597.

476

477 Cheng, N. and Nguyen, H. (2011) 'Hydraulic radius for evaluating resistance induced by simulated
478 emergent vegetation in open-channel flows', *Journal of Hydraulic Engineering,* 137(9), 995-
479 1004.

480

481 Hamidifar, H. and Omid, M. (2013) 'Floodplain vegetation contribution to velocity distribution in
482 compound channels', *Journal of Civil Engineering and Urbanism,* 3(6), 357-361.

483

484 Hamimed, A., Nehal, L., Benslemani, M. and Khalid, A. (2013) 'Contribution to the study of the flow
485 resistance in a flume with artificial emergent vegetation', *Layhyss Journal,* 15, 55-63.

486

487 Hirschowitz, P. M. and James, C. S. (2009) 'Conveyance estimation in channels with emergent bank
488 vegetation', *Water SA,* 35(5), 8.

489

490 Huthoff, F. (2007) *Modeling hydraulic resistance of floodplain vegetation. PhD thesis,* University of
491 Twente.

492

493 Ismail, Z. and Shiono, K. (2006) *"The effect of vegetation along cross-over floodplain edges on stage*
494 *discharge and sediment transport rates in compound meandering channels"Proceedings of*
495 *the 5th WSEAS International Conference on Environment Ecosystems and Development,*
496 *Venice, Italy,* translated by.

497

498 Järvelä, J. (2002) 'Determination of flow resistance of vegetated channel banks and floodplains',
499 *River Flow 2002, International Conference on Fluvial Hydraulics. September 4 - 6, 2002,*
500 *Louvain-la-Neuve, Belgium. Swets & Zeilinger, Lisse. p. 311-318. ISBN 9058095096.,* In:
501 Bousmar, D. & Zech, Y. (eds.) 2002.

Kothyari, U. C., Hayashi, K. and Hashimoto, H. (2009) 'Drag coefficient of unsubmerged rigid vegetation stems in open channel flows', *Journal of Hydraulic Research,* 47(6), 691-699.

Li, Y., Anim, D. O., Wang, Y., Tang, C., Du, W., Yu, Z. and Acharya, K. (2014) 'An open-channel flume study of flow characteristics through a combined layer of submerged and emerged flexible vegetation', *Ecohydrology,* 7(2), 633-647.

Liu, C. and Shen, Y. (2008) 'Flow structure and sediment transport with impacts of aquatic vegetation ', *Journal of Hydrodynamics, Ser. B,* 20(4), 461–468.

Masterman, R. and Thorne, C. (1992) 'Predicting influence of bank vegetation on channel capacity', *Journal of Hydraulic Engineering,* 118(7), 1052-1058.

Mulahasan, S., Stoesser, T. and Alvarez, F. (2015) 'Visualization of shear layers in compound channel flows', *10th Pacific Symposium on Flow Visualization and Image Processing Naples, Italy, 15-18 June,* Paper ID: 25.

Nehal, L., Yan, Z. M., Xia, J. H. and Khaldi, A. (2012) 'Flow through non-submerged vegetation', *Sixteenth International Water Technology Conference, IWTC 16, Istanbul, Turkey*.

Nepf, H. M. (1999) 'Drag, turbulence, and diffusion in flow through emergent vegetation', *Water Resources Research,* 35(2), 479-489.

Pasche, E. and Rouvé, G. (1985) 'Overbank flow with vegetatively roughened floodPlains', *Journal of Hydraulic Engineering,* 111(9), 1262-1278.

Petryk, S. and Bosmajian, G. (1975) 'Analysis of flow through vegetation', *Journal of the Hydraulics Division,* 101(7), 871-884.

Pope, S. B. (2000) 'Free shear flows”. In Turbulent flows, Cambridge University', 139–144.

Rajaratnam, N. and Ahmadi, R. (1981) 'Hydraulics of channels with flood-plains', *Journal of Hydraulic Research,* 19(1), 43-60.

Rameshwaran, P. and Shiono, K. (2007) 'Quasi two-dimensional model for straight overbank flows through emergent vegetation on floodplains', *Journal of Hydraulic Research,* 45(3), 302-315.

Sanjou, M., Nezu, I. and Itai, K. (2010) 'Space-time correlation and momentum exchanges in compound channel flow by simultaneous measurements of two sets of ADVs', *River Flow*, 495-502.

Shiono, K. and Knight, D. W. (1991) 'Turbulent open-channel flows with variable depth across the channel', *J . Fluid Meeh.,* 222, 617-646.

Shiono, K., Takeda, M., Yang, K., Sugihara, Y. and Ishigaki, T. (2012) 'Modeling of vegetated rivers for inbank and overbank flows', *Proceedings of the International Conference on Fluvial Hydraulics: River Flow-September 5-7, San Jose, Costa Rica.*, 263-269.

Stoesser, T., Kim, S. and Diplas, P. (2010) 'Turbulent flow through idealized emergent vegetation ', *Journal of Hydraulic Engineering,* 136(12), 1003-1017.

Sun, X. and Shiono, K. (2009) 'Flow resistance of one-line emergent vegetation along the floodplain edge of a compound open channel', *Advances in Water Resources,* 32(3), 430-438.

Tang, X. and Knight, D. W. (2008) 'Lateral depth-averaged velocity distributions and bed shear in rectangular compound channels', *Journal of Hydraulic Engineering,* 134(9), 1337-1342.

Tang, X., Sterling, M. and Knight, D. W. (2010) 'A General analytical model for lateral velocity distributions in vegetated channels', *River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds) - © 2010 Bundesanstalt für Wasserbau ISBN 978-3-939230-00-7*.

Tanino, Y. and Nepf, H. (2008) 'Laboratory investigation of mean drag in a random array of rigid, emergent cylinders', *Journal of Hydraulic Engineering,* 134(1), 34-41.

Terrier, B. (2010) 'Flow characteristics in straight compound channels with vegetation along the main channel', *Dissertation presented to Department of Civil and Building Engineering Loughborough University*.

Teymourei, E., Barani, G. A., Janfeshan , H. and A., D. A. (2013) 'Determination of SKM mathematical model for estimation of transverse velocity distribution in compound channels', *Journal of Basic and Applied Scientific Research,* 3(2s), PP:682-688.

Thornton, C. I., Abt, S. R., Morris, C. E. and Fischenich, J. C. (2000) 'Calculating shear stress at channel-overbank interfaces in straight channels with vegetated floodplains', *Journal of Hydraulic Engineering,* 126(12), 929-939.

Tinoco, R. O. and Cowen, E. A. (2013) 'The direct and indirect measurement of boundary stress and drag on individual and complex arrays of elements', *Experiments in fluids manuscript,* 54(4), 1-16.

Tominaga, A. and Nezu, I. (1991) 'Turbulent structure in compound open-channel flows', *Journal of Hydraulic Engineering,* 117(1), 21-41.

Valyrakis, M., Liu, D., Mcgann, N., Turker, U. and Yagci, O. (2015) 'Characterrising the effect of increasing river bank vegetation on the flow field across the channel', *E-proceedings of the 36th IAHR World Congress 28 June – 3 July, 2015, The Hague, the Netherland*.

van Prooijen, B. C., Battjes, J. A. and Uijttewaal, W. S. J. (2005) 'Momentum exchange in straight uniform compound channel flow', *Journal of Hydraulic Engineering,* 131(3), 175 - 183.

van Prooijen, B. C. and Uijttewaal, W. S. J. (2002) 'A linear approach for the evolution of coherent structures in shallow mixing layers', *Physics of Fluids,* 14(12), 4105-4114.

Vermaas, D. A., Uijttewaal, W. S. J. and Hoitink, A. J. F. (2011) 'Lateral transfer of streamwise momentum caused by a roughness transition across a shallow channel', *Water Resources Research,* 47(2), 1-12.

White, B. L. and Nepf, H. M. (2007) 'Shear instability and coherent structures in shallow flow adjacent to a porous layer', *Journal of Fluid Mechanics,* 593, 1-32.

White, B. L. and Nepf, H. M. (2008) 'A vortex-based model of velocity and shear stress in a partially vegetated shallow channel', *Water Resources Research,* 44(1).

Yang, K., Cao, S. and Knight, D. (2007) 'Flow patterns in compound channels with vegetated floodplains', *Journal of Hydraulic Engineering,* 133(2), 148-159.

Yang, K., Nie, R., Liu, X. and Cao, S. (2013) 'Modeling depth-averaged velocity and boundary shear stress in rectangular compound channels with secondary flows', *Journal of Hydraulic Engineering,* 139(1), 76-83.

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.