Influence of vegetation density and projected area on streambank hydraulics

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Abstract

Vegetation along the toe of a streambank can slow down water and deflect flow away from banks, altering the forces applied to the bank surface and protecting banks against erosion. Five flume experiments were used to explore how changes in vegetation planform density (number of plants/horizontal area) and projected area (number of leaves/vertical area) influence channel velocity and turbulent kinetic energy (TKE) on a 30° vegetated bank toe at three discharge rates. Increased vegetation density and projected area reduced bank toe streamwise velocities by >34% and increased main channel streamwise velocities by 50-75%. Higher projected area increased turbulence, especially along the bank toe-channel margin interface where turbulence increased five-fold. Results from this study indicate the importance of considering plant density and projected area when studying resistance and turbulence on vegetated banks.

Introduction

Riparian vegetation acts as resistance, slowing flow in vegetated areas and deflecting flow to unvegetated areas. Vegetation also introduces turbulence, roughening flow and introducing localized scour, often along the floodplain-main channel interface (McBride et al. 2007; White and Nepf 2008). Vegetation characteristics that influence resistance and turbulence include plant flexibility, frontal projected area, relative depth of submergence, and density (Li and Shen 1973; Pasche and Rouve 1985; Fathi-Moghadam and Kouwen 1997; Bennett et al. 2002; Järvelä 2002; Wilson et al. 2003, 2006), which may vary by plant type and age.

Variability in plant morphology and biomechanics makes it challenging to accurately represent vegetation in experimental and modeling studies. Accounting for flexibility of woody vegetation is important in accurately estimating vegetative resistance to flow (Fathi-Moghadam and Kouwen 1997), especially when modeling a streambank where much of the woody vegetation is young and small in diameter, and therefore more flexible. Another important plant characteristic to consider is projected area, which has been observed to significantly increase resistance to flow (Järvelä 2002, Wilson et al. 2006). Though both artificial and natural flexible woody vegetation has been used in some studies to determine the value of resistance coefficients (Fathi-Moghadam and Kouwen 1997; Freeman et al. 2000; Järvelä 2002; Wilson et al. 2006), most flume experiments of channel floodplains and banks use woody vegetation in the simplest form, represented as wooden dowels or similar rigid structures (Pasche and Rouve 1985; McBride et al. 2007; White and Nepf 2008) ignoring both flexibility and the influence of projected area.

Several models have been proposed to estimate the effects of vegetation as roughness features on the floodplain (Pashe and Rouve 1985; McBride et al. 2007; White and Nepf 2008), yet few studies have examined the impact of vegetation on the bank (Hopkinson et al. in prep). In this study, a scaled flume experiment was used to estimate the relative magnitude of difference in channel velocity and turbulence on the streambank due to changes in vegetation planform density and projected area. Artificial plants were designed to account for natural flexibility and are modified to estimate both "leaved" and "leafless" conditions.

Methods

Experiments were conducted in a 6.05 × 0.61 × 0.61 m recirculating flume set at a fixed slope of 0.001 m/m (Figure 1). At the inlet, water passed through a rock-filled baffle box and then a baffle box composed of 0.30 m long, 0.02 m diameter tubes (flow straighteners), in order to dampen turbulence and provide uniform flow. To simulate a 30° bank toe, a 4.88 m long, 0.45 m wide inclined insert was installed along one side of the flume immediately downstream of the flow straighteners. Bank and artificial vegetation was scaled by a Froude scaling factor of 4.35 from a prototype streambank representing the toe of a compound bank.

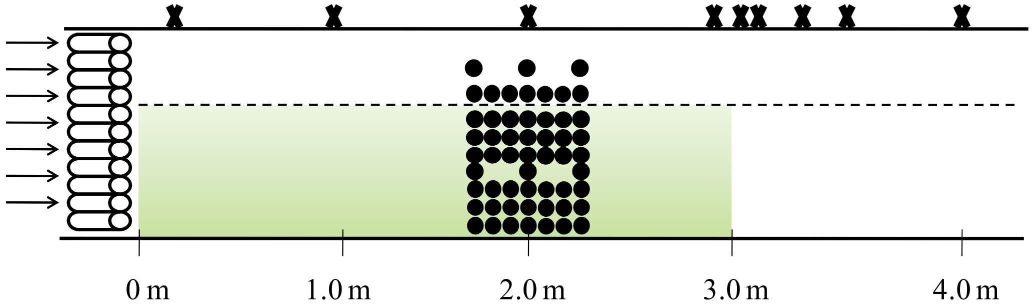

Figure 1. Planform view of flume; arrows indicate direction of flow, shaded region shows location of vegetation array. X's represent 0.6d cross-sections. O's represent locations of boundary measurements. Not drawn to scale.

The vegetation array was 3 m long, beginning immediately downstream of the flow straighteners (Figure 1). Vegetation was in two forms: low projected area (P_{lo}) and high projected area (P_{hi}) (Figure 2). P_{lo} plants were made of 450 mm long, 4.54 mm diameter acrylic rods, scaled down from 2 m tall, 20 mm diameter woody stems. P_{hi} consisted of the same acrylic rods affixed with ten 28-gauge wire "branches" and ten 25 × 35 mm "leaves" made of contact paper (875 mm^2 total) spaced to reflect a pattern of projected area found by Wilson et al. (2006) (see Figure 2). Vegetation was installed in two patterns: low density (D_{lo}) of 202 plants per m^2 and high density (D_{hi}) of 615 plants per m^2, which scale to 8 and 24 plants per m^2, respectively.

To determine flexibility of artificial vegetation, an appropriate range of values of modulus of elasticity (E) for riparian woody plants were obtained from previous studies (Freeman et al. 2000) and scaled for the physical model. The relationship $J = EI$ was used, where J is flexural stiffness (N m^2), I is the second moment of inertia ($I = \pi D^4/64$, in m^4) and E is Young's modulus of elasticity (N m^{-2}):

$$E = \frac{F a^2}{2\delta I}(3L - a)$$

where F is applied force (N), L is length of the beam (m), δ is deflection (m), a is the length at the end of which the force is applied (m), and D is stem diameter (m). I scales by x^4 and E by x, thus J scales by x^5 according to Cauchy similitude (Wilson et al. 2003). E for the acrylic rod was tested using a one-point beam test (Freeman et al. 2000, Wilson et al. 2003) and resulted in $J = 0.04$ N m^2.

Table 1 illustrates the experimental design for four vegetated runs. In addition, one non-vegetated run was undertaken. The three different discharges (0.015, 0.030, and 0.050 m^3s^{-1}) correspond to 0.6, 1.2, and 2.0 m^3s^{-1} in the prototype stream. In order to characterize the depth-averaged velocity without vegetation present, it was assumed that the von Kàrmàn-Prandtl law of the wall was valid and hence velocity was measured at ~0.6 × the flow depth (0.6d) at 7 cross-stream locations within 9 cross-sections (Figure 1). Velocities within vegetation have been demonstrated to be nearly uniform with depth (White and Nepf 2008), hence measures within vegetation also were made at 0.6d. Near-boundary velocity was measured at 7 or 9 cross-stream locations within 7 cross-sections. Velocities were measured over five minutes at 25 Hz with a 10 MHz Nortek acoustic Doppler velocimeter (ADV). Data were filtered and processed using the WinADV software.

Turbulence intensity was quantified using turbulent kinetic energy (TKE):

$$\text{TKE} = 0.5\rho\,(\langle u'^2\rangle + \langle v'^2\rangle + \langle w'^2\rangle)$$

Table 1. Experimental runs.

Run	D	P	Q (m^3s^{-1})
1	lo	lo	0.015
2	lo	lo	0.03
3	lo	lo	0.05
4	lo	hi	0.015
5	lo	hi	0.03
6	lo	hi	0.05
7	hi	lo	0.015
8	hi	lo	0.03
9	hi	lo	0.05
10	hi	hi	0.015
11	hi	hi	0.03
12	hi	hi	0.05

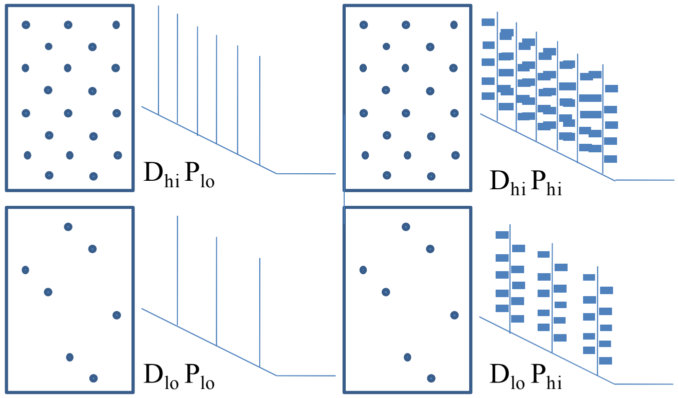

Figure 2. Experimental design.

where ρ is the density of water (assumed constant and equal to 1000 kg m^{-3}), and $<u'^2>$, $<v'^2>$, and $<w'^2>$ are the root mean square differences between instantaneous velocities in the streamwise, lateral, and vertical directions and their corresponding time-averaged velocities (Clifford and French 1993). TKE measurements were grouped into four locations for analysis: top of bank toe, middle of bank toe, bottom of bank toe or bank toe-channel margin, and main channel.

Results

Channel velocity

With the introduction of vegetation, streamwise velocity decreased at the top and middle of the bank toe as both density and projected area increased (Figure 3). Streamwise velocities at the bank toe-channel margin were less sensitive to plant density and only decreased with an increase in projected area. For example, at high discharge, the $D_{lo}P_{lo}$ condition decreased streamwise velocities along the width of the bank toe by 34-50%, while all other combinations of density and projected area decreased streamwise velocities by >50%. On the bank toe-channel margin, low density conditions marginally increased the streamwise velocities, but with high projected area they decreased by >50%. In the main channel, average velocities increased by 50-75% with the introduction of vegetation. This was observed at all cross-sections sampled >2 m down from the beginning of the vegetation, independent of discharge.

Average streamwise velocity in the middle of the bank toe decreased to 30-67% of the non-vegetated value after passing through the vegetation (Figure 4a). Conversely, the addition of vegetation increased average streamwise velocity within

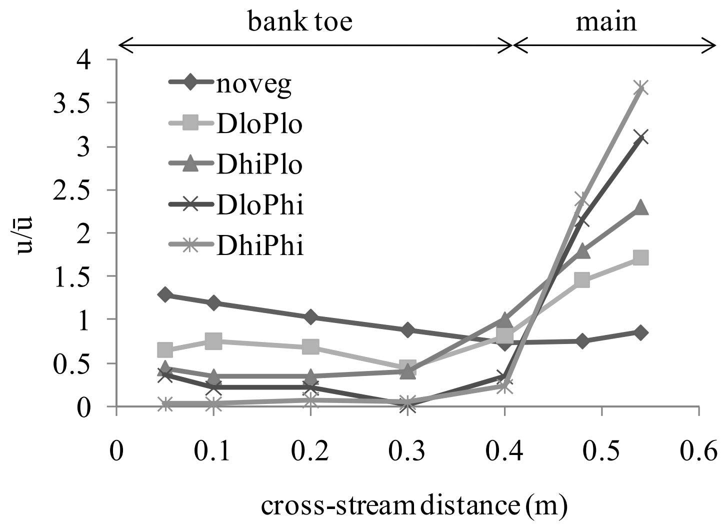

Figure 3. Normalized streamwise velocity at 3 m cross-section under high discharge. Bank toe and main channel are delineated at the top of the figure.

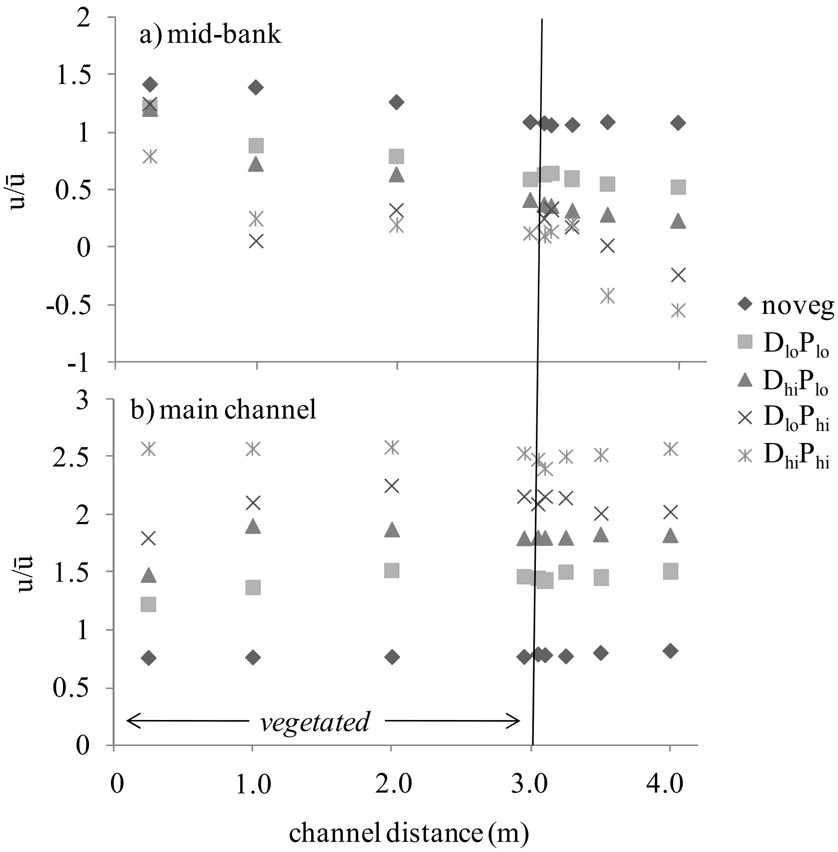

Figure 4. Normalized streamwise velocity over channel length at low discharge.

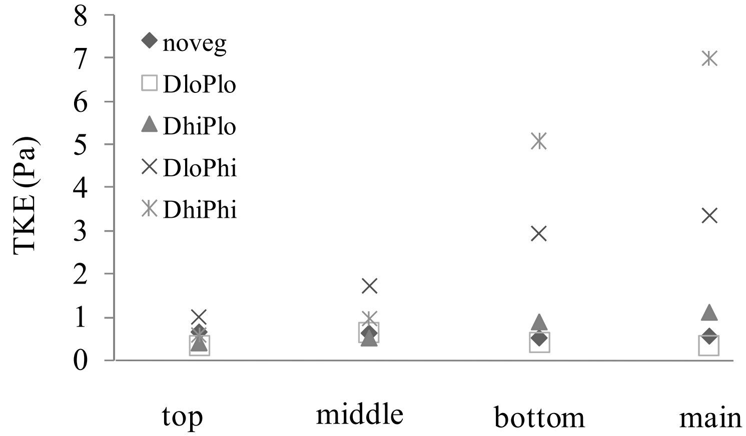

Figure 5. TKE under high flow conditions.

the upstream-most 2 m of the main channel by 22-26%, after which there was little change (Figure 4b). Similar patterns were found for the medium and high discharge rates (results not shown). Preliminary results and interpretations suggest that there is a threshold density and projected area above which the streamwise velocity in the main channel does not increase dramatically along the length of a vegetated bank or bank toe.

Turbulence intensity

Without vegetation, turbulence intensity was greatest at the top of the bank toe and lowest at the margin between the bank toe and the main channel. At the bank toe-channel margin and in the main channel, the introduction of vegetation resulted in more than a five-fold increase in turbulence intensity. At the top and middle of the toe, once vegetation had been introduced, changing plant density had little effect on turbulence intensity when plant projected area was held constant (Figure 5). Conversely, at the bank toe-channel margin, holding plant density constant and increasing projected area resulted in an increase in turbulence intensity. Also along the bank toe-channel margin, an increase in projected area corresponded to an increase in both lateral and vertical boundary velocities, with lateral velocity becoming more negative and vertical more positive (not shown). Overall, increases in discharge had less of an influence than the initial introduction of vegetation or increases in projected area.

Discussion and Conclusions

Other studies of vegetation as resistance to flow describe similar patterns of increases in main channel velocities and decreases in velocity along vegetated floodplains and streambanks (Pasche and Rouve 1985; Bennett et al. 2002; McBride et al. 2007; Hopkinson et al. in prep). Using wooden dowels to represent vegetation, these studies found a similar magnitude of difference between floodplain and main channel velocities as that of the low projected area conditions ($D_{lo}P_{lo}$ and $D_{hi}P_{lo}$) in this study. Inclusion of high projected area ($D_{lo}P_{hi}$ and $D_{hi}P_{hi}$) encouraged an even greater difference between vegetated and non-vegetated surfaces than previously described.

An increase in turbulence suggests higher potential for erosion. McBride et al. (2007) found that, for a forested floodplain, TKE tripled along the bank and increased with discharge. They concluded that higher turbulence may increase erosion and promote channel widening (McBride et al. 2007). White and Nepf (2008) also found that the interface between vegetation and the main channel was especially turbulent and suggest this plays a key role in sediment transport onto the vegetated surface.

Plant density and projected area were expected to have an influence on turbulence intensity. As density increased, competition between reduced velocity and increased turbulence likely led to small changes in TKE (Nepf 1999). Projected area, which differs by vegetation morphology and species, promoted larger increases in TKE. This suggests that previously observed differences in TKE between plant species (Hopkinson et al. in prep) could be due, in part, to a change in projected area.

Turbulence intensity in the main channel is likely elevated due in part to an increase in streamwise velocity due to the small cross-sectional area of the main channel (McBride et al. 2007). Nevertheless, these results suggest that if a channel is not allowed to widen in a location where vegetation is present, there is a high potential for incision if grain size is small. In this study, the bed and bank are smooth surfaces. With the addition of sand and gravel, turbulence may increase and boundary velocity may decrease due to a thicker boundary layer (McBride et al. 2007).

Past research indicates that velocity is expected to decrease with an increase in plant density (Li and Shen 1973; Bennett et al. 2002) and projected area (Järvelä 2002, Wilson et al. 2006), though the effect on specific locations on the bank and bank toe has not previously been explored. Preliminary results from this study indicate the importance of including plant density and projected area when studying resistance and turbulence on vegetated banks. Projected area may be more influential than plant density, due to observed increases in turbulence along the already vulnerable bank toe. Future efforts include exploration of an additional bank angle and a more detailed analysis of the channel hydraulics, including shear stress.

Acknowledgements

Support for this research was provided by an NSF IGERT graduate fellowship (NSF award 0333257) in the Ecosystem Informatics IGERT program at Oregon State

University and the USDA-ARS National Sedimentation Laboratory at Oxford, Mississippi. I greatly appreciate advice and mentorship provided by Desiree Tullos, Andrew Simon, and Robert Thomas. I also am grateful for technical advice provided by Daniel Wren and technical assistance provided by Lee Patterson.

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