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Sediment patterns near a model patch of reedy emergent vegetation

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ABSTRACT

This laboratory study describes the sediment patterns formed in a sand bed around circular patches of rigid vertical cylinders, representing a patch of reedy emergent vegetation. The patch diameter was much smaller than the channel width. Two patch densities (solid volume fraction 3% and 10%) and two patch diameters (22 and 10 cm) were considered. For flows above the threshold of sediment motion, patterns of sediment erosion and deposition were observed around and within the patch. Scouring within the patch was positively correlated with turbulent kinetic energy in the patch. For sparse patches, sediment scoured from within the patch was mostly deposited within one patch diameter downstream of the patch. For dense patches, which experience greater flow diversion, sediment scoured from the patch was carried farther downstream before deposition along the patch centerline. Differences between the sparse and dense patch patterns of deposition are explained in the context of flow diversion and wake structure, which are related to a nondimensional flow blockage parameter. While sediment was redistributed near the patch, observations suggest that net deposition was not recorded at the reach scale.

1. Introduction

Vegetation can increase flow resistance and reduce flow conveyance so that many consider it a nuisance in culverts and stream channels (Kouwen and Unny, 1975). However, vegetation improves water quality by removing nutrients from and releasing oxygen to the water column (Chambers and Prepas, 1994; Wilcock et al., 1999; Schulz et al., 2003). It also promotes habitat diversity by creating a diversity of flow regimes (Crowder and Diplas, 2000; Kemp et al., 2000; Crowder and Diplas, 2002). The bed stabilization effects of vegetation have been widely recognized (Wynn and Mostaghimi, 2006; Afzalimehr and Dey, 2009; Wang et al., 2009; Li and Millar, 2010; Pollen-Bankhead and Simon, 2010). As an example, vegetation has been shown to stabilize both single thread (Tal and Paola, 2007) and meandering (Braudrick et al., 2009) channel morphologies. Sediment loading from bank erosion is also diminished by vegetation (Lawler, 2008). The reduction of velocity within vegetated regions can encourage deposition of fine particles and sediment retention (Abt et al., 1994; Lopez and Garcia, 1998; Cotton et al., 2006; Gurnell et al., 2006) and promote the growth of ridges and islands (Edwards et al., 1999; Tooth and Nanson, 1999; Gurnell et al., 2001, 2008). Similarly, aeolian literature reports that vegetation accelerates the nucleation of dunes (Luna et al., 2011). While most studies have focused on enhanced deposition within vegetated regions, vegetation also promotes erosion under some conditions. Specifically, close to vegetated regions of finite width, the diversion of flow away from the vegetation leads to the acceleration of flow along the vegetation edge, which causes localized erosion (Fonseca et al., 1983; Bouma et al., 2007; Bennett et al., 2008; Rominger et al., 2010).

Recognizing the benefits of vegetation to river health, ecologically minded management and replanting of denuded regions are now encouraged (Mars et al., 1999; Pollen and Simon, 2005). However, successful river restoration requires an understanding of how vegetation impacts flow and sediment transport. For example, Larsen and Harvey (2011) explained the stability of different landscape patterns in the Everglades by coupling vegetation dynamics to both sediment transport and flow. While many studies have described long, uniform reaches of vegetation, only a few have considered finite patches of vegetation. Bennett et al. (2002, 2008) described how the introduction of finite patches along the wall of a channel changes the flow and erosion pattern. The channel response was found to depend on both the shape and density of the rigid model stems. In particular, alternating patches of semicircular shape were recommended to promote the restoration of meandering geometries.

In this study we consider the erosion pattern associated with a circular patch of emergent vegetation located at mid-channel, making connections to flow structure previously described by Zong and Nepf (2012). Zong and Nepf considered circular arrays of diameter D constructed from circular cylinders, each of diameter d, at a density of n cylinders/m^2. This produced a frontal area per unit volume of $a = nd$, and a solid volume fraction of $\phi = n\pi d^2/4$ within the patch. Upstream of the patch, the velocity is uniform with magnitude U_o (Fig. 1). As flow approaches the patch, the velocity begins to decelerate about $1D$ upstream, as flow is diverted around this region of high

Abbreviations: SAFL, Saint Anthony Falls Laboratory; TKE, turbulent kinetic energy.

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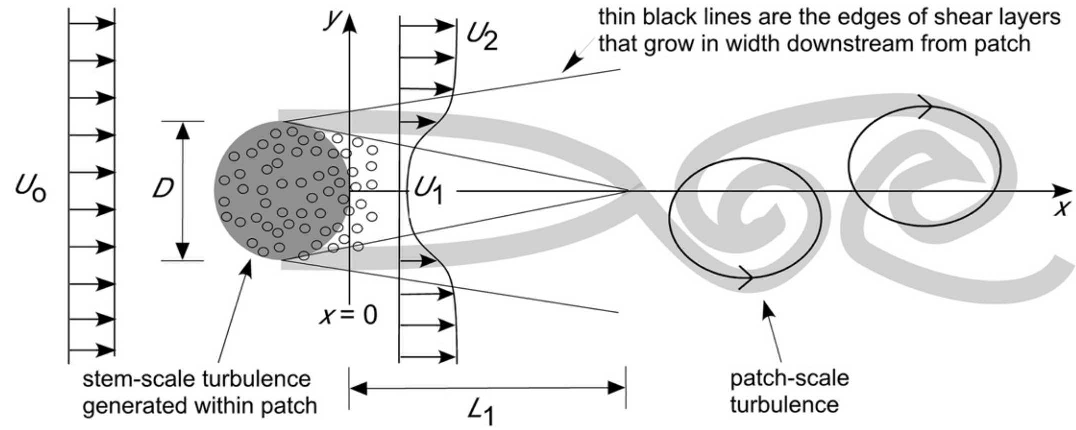

Fig. 1. Schematic diagram of wake behind a porous circular patch (grey shaded circle) showing upstream velocity (U_o), steady wake velocity (U_1), velocity outside the wake (U_2), and the length of the steady wake region (L_1). Stem-scale turbulence shown by small black circles within and just behind the patch. Light grey lines represent tracer released at the two sides of the patch. The tracer reveals the eventual onset on the von Kármán vortex street.

drag. Diversion and flow deceleration continue through the patch. While the mean velocity within the patch is diminished relative to the free stream, the turbulence levels may be enhanced, as turbulent eddies form in the wake of each individual cylinder.

Because the patch is porous, some flow penetrates through the patch, creating an area of slow streamwise velocity directly behind the patch, which we call the steady wake region. The presence of flow in the steady wake delays the onset of the von Kármán vortex street and thus alters the wake structure relative to that observed behind a solid obstruction (Nicolle and Eames, 2011; Zong and Nepf, 2012). The flow in the steady wake (U_1) separates two regions of faster velocity (U_2), creating a shear layer on either side of the steady wake. These layers grow linearly with distance from the patch, eventually meeting at the wake centerline (Fig. 1). At this point, the interaction between the shear layers results in the von Kármán vortex street. The length L_1 between the end of the patch and the onset of the von Kármán vortex street defines the length of the steady wake region (Ball et al., 1996). The length of the steady wake region (L_1) may be predicted from the growth of the linear shear layers and the patch geometry (Zong and Nepf, 2011),

$$L_1 = 2.5D\frac{(1+U_1/U_2)}{(1-U_1/U_2)} \approx 2.5D\frac{(1+U_1/U_o)}{(1-U_1/U_o)} \quad (1)$$

The right most expression assumes $U_2 = U_o$, which is reasonable if D is much less than the channel width, which is valid in our experiments.

The formation of the von Kármán vortex street provides a lateral flux of momentum that erodes the velocity deficit in the wake. After the additional distance L_2, the velocity profile again approaches the upstream value, U_o. The region L_2 is called the wake recovery region. Based on data given in Zong and Nepf (2012), we propose the following empirical relation:

$$\frac{L_2}{D} = 13\frac{U_1}{U_o} + 4 \quad (2)$$

The total length of the wake is $L_1 + L_2$.

For a solid cylinder, the von Kármán vortex street begins immediately behind the obstruction, so that $L_1 = 0$, and $L_2/D \approx 3$ ($Re_D =$ 23000; Zong and Nepf, 2012). Behind a porous obstruction, L_1 and L_2 increase with increasing steady wake velocity, U_1 (Eqs. (1) and (2)). Because U_1 increases with increasing patch porosity (i.e. decreasing ϕ), L_1 and L_2 increase with decreasing ϕ. Because these length scales describe important features of the flow field, i.e., the onset of the von Kármán vortex street (L_1) and the end of the wake velocity deficit ($L_1 + L_2$), we hypothesize that they can be connected to the pattern of erosion and deposition observed near a patch. This hypothesis will be tested in the current study.

Bedload transport is characterized by the bed shear stress,

$$T = \rho u_*^2 \quad (3)$$

with ρ the fluid velocity and u_* the bed shear velocity. When the bed shear stress exceeds a critical value (τ_c), sediment motion is initiated; for conditions of $\tau > \tau_c$, sediment motion increases monotonically with increasing τ (e.g., Julien, 1998). Bed shear stress is known to increase with velocity, but it may also be elevated by turbulent motions (Diplas et al., 2008). From the flow description given above, we expect increased bed shear stress, and therefore increased sediment movement, along the sides of the patch and within the von Kármán vortex street. Because small-scale turbulence may also be generated within the patch, scour is also possible within the patch. Alternatively, we expect bedload accumulation in regions of reduced bed shear stress, specifically in the steady wake region of length L_1, where both velocity and turbulence are diminished.

While we anticipate that a finite patch of vegetation will change bedload transport locally (described above), at the reach scale we expect that the introduction of an isolated patch of vegetation will have little impact. This is because a finite patch alters the flow field over a limited distance (L), beginning about D upstream of the patch and extending downstream a distance $L_1 + L_2$ (i.e., $L = 2D + L_1 + L_2$). Beyond this distance, the flow—and therefore the bedload transport—should be unaffected by the patch. This idea will be tested experimentally by considering the change in net deposition integrated over the length scale L. Note, this length scale should be slightly extended to reflect the saltation distance (L_s). Once a particle of diameter d_s is set in motion, it travels (on average) over a length scale $L_s = 150d_s$ (Habersack, 2001). For typical sand grain sizes, this length scale is on the order of 10 cm.

The scour and deposition associated with a circular patch of vegetation will be compared to that observed for a solid cylinder. Dargahi (1990) investigated scour and deposition around an emergent circular cylinder of diameter $D = 0.15$ m, in a flow of 20-cm depth and 26 cm/s, which are comparable to the flow conditions used here. We use D to denote diameter to allow comparisons to patches of diameter D. Dargahi observed scour beginning 25 s after the initiation of the experiment. The scour hole was roughly circular, extending 1.5D upstream from the leading edge and 2D downstream from the trailing edge of the cylinder. The sediment scoured from around the cylinder was deposited in a mound that extended to nearly 6D downstream from the back of the cylinder. The lateral motion associated with the von Kármán vortex street carried sediment toward the