Spatial distribution of deposition within a patch of vegetation

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Spatial distribution of deposition within a patch of vegetation

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This laboratory study describes the spatial pattern of deposition observed in a patch of vegetation located at the wall of a channel. There are two sources of sediment flux to the patch: the advection of particles across the upstream leading edge and the lateral dispersion of particles from the adjacent open channel. The relative contribution of these two supplies determines the spatial pattern of net deposition in the patch. We define the advection length scale within the patch as the longitudinal distance over which advection contributes a significant sediment source. At distances from the leading edge that are within the advection length scale, net deposition in the patch is laterally uniform, reflecting the laterally uniform mean flow delivering the particles. At distances farther than the advection length scale from the leading edge, the net deposition is highest near the flow-parallel edge and decreases into the patch, which is the signature of dispersive transport from the patch edge. Two processes contribute to the lateral dispersion, both of which are associated with the shear-layer vortices formed at the flow-parallel interface between the patch and the channel. The vortices generate turbulence and enhance the turbulent diffusion of sediment across the interface. In addition, the vortices induce a wave oscillation in the flow field within the patch that appears to enhance the lateral transport inside the patch.


1. Introduction

By producing additional hydrodynamic drag, patches of aquatic vegetation change the mean flow distribution, which in turn will influence the distribution of sediment. The presence of vegetation reduces the local velocity and therefore the local bed stress, so that it creates conditions that favor deposition and buffer against resuspension [Gacia and Duarte, 2001; Cotton et al., 2006; Widdows et al., 2008]. Thus, by changing the velocity field, vegetation can influence channel morphology. For example, Tal and Paola [2007] experimentally showed that single-thread channels could be formed and stabilized by vegetation. Other studies have shown that patches of vegetation are associated with enhanced bed elevation within the patch, attributed to particle retention, and sometimes with diminished bed elevation at the edge of the patch, attributed to flow diversion [Fonseca et al., 1983; Bouma et al., 2007; Rominger et al., 2010]. In addition to altering the bed morphology, the capture of particles within regions of vegetation also enhances the retention of organic matter, nutrients and heavy metals within a channel reach [e.g., Schultz et al., 2003; Brookshire and Dwire, 2003; Windham et al., 2003].

In this study we consider the flow and deposition pattern associated with a finite region of bank vegetation. The model system consists of an open channel partially filled with model emergent vegetation constructed from a staggered array of rigid circular cylinders (Figures 1 and 2).

The cylinder array is described by the following parameters: the cylinder diameter $d$, the number of cylinders per unit bed area $n$, the frontal area per unit volume $a = nd$, and the average solid volume fraction of the array $\Phi = n(\pi d^2 / 4)$.

We denote the stream-wise coordinate as $x$, with $x = 0$ at the leading edge of the vegetated region (Figure 2). The lateral coordinate is $y$, with $y = 0$ at the side boundary. Because the vegetation creates high drag, much of the flow approaching the patch from upstream is diverted away from the patch. As shown in Figure 2, the diversion begins upstream of and extends some distance into the vegetation [Zong and Nepf, 2010]. The end of the flow diverging region is denoted by $x_D$. Beyond this point, the magnitude of flow within the patch ($U_1$) and in the open region ($U_2$) is set by the balance of potential gradient (due to bed and surface slopes) and the hydraulic resistance imposed by the stems and the bed. The difference between $U_1$ and $U_2$ creates a shear layer at the interface between the parallel regions of emergent vegetation and open channel that in turn generates large coherent vortices via the Kelvin-Helmholtz instability, as also seen in free and shallow shear layers [e.g. Ho and Huerre, 1984; Chu et al., 1991]. Similar structures form at the top interface of submerged vegetation [Ghisalberti and Nepf, 2002, 2004]. These energetic vortices dominate mass and momentum exchange between the vegetation and the adjacent open flow. The characteristics of vegetated shear layers are described by White and Nepf [2007, 2008], which include visualizations of the vortex structure. The initial growth and the final scale of the shear-layer vortices and their penetration into the patch $\delta_v$ are shown schematically in Figure 2. Based on scaling and laboratory experiments,
where $C_D$ is the bulk drag coefficient for the vegetation [White and Nepf, 2008]. It is important to note that this penetration scale is not a function of flow speed, except through a weak dependence of $C_D$ on the local velocity. The shear layer vortices extend into the open channel over the length scale $\delta_0$ (Figure 2). White and Nepf [2007] show that $\delta_0 \sim h/C_f$, where $h$ is the flow depth and $C_f$ is the bed friction. There is no direct relation between $\delta_s$ and $\delta_0$.

[5] Because the shear-layer vortices penetrate into the patch, the flow structure inside the patch is not laterally uniform, which can impact the deposition pattern across the patch width. In this paper we consider the case in which the patch width $b$ is greater than the penetration distance $\delta_s$, so that the patch is segregated into two regions (Figure 2).

The outer patch region, which has width $\delta_s$, experiences rapid exchange with the adjacent open water. The inner patch region ($y < b - \delta_s$) has slower exchange. Based on previous studies, the rate of scalar turbulent transport across the outer patch region is 10–100 times faster than across the inner patch region [Ghisalberti and Nepf, 2005; Nepf et al., 2007].

[6] This paper examines the spatial distribution of net deposition within a patch of vegetation, which depends on the flow conditions within the patch, as well as the delivery of particles to the patch. Particles can enter the patch across the leading edge by mean-flow advection, or across the flow-parallel edge through lateral dispersion. The relative contributions of lateral dispersion and mean-flow advection depend on patch length, flow speed, and sediment characteristics. Much of this dependence can be described by the advection length scale. For water depth $h$, particle settling velocity $w_s$, and settling time scale $T_s = h/w_s$, we define the advection length scale $x_a$ as the distance over which particles entering across the leading edge advect before they are lost to deposition.

$$ x_a = U_l T_s = U_l h/w_s, $$

with $x_a$ measured from the end of the flow diverging region ($x_D$), as shown in Figure 2. Similarly, we define a diffusion length scale $x_d$ as the maximum distance particles can be carried from the flow-parallel edge by lateral diffusion. If the open channel provides a constant concentration boundary condition $C_o$, lateral diffusion yields an erfc profile within the vegetation [e.g., see Fischer et al., 1979, section 2.3.2]. For this distribution the concentration boundary layer, defined as the point where the concentration drops to $C = 0.005 C_o$, is described by $\delta = 4\sqrt{D_s t}$, in which $D_s$ is the lateral diffusion coefficient. The maximum distance is constrained by the settling time $T_s$, such that

$$ \delta_{\text{max}} = 4\sqrt{D_s T_s} = 4\sqrt{D_s h/w_s}. $$

[7] If the patch length $l$ is long enough ($l \gg x_D + x_a$) and the width $b$ is wide enough ($b > \delta_s + \delta_{\text{max}}$), there

![Image](a_top_view.png)

**Figure 1.** A schematic of the partially vegetated channel, (a) top view, (b) front view. The longitudinal, transverse, and vertical coordinates and velocity are ($x,u$), ($y,v$), and ($z,w$), respectively.

![Image](b_front_view.png)

**Figure 2.** Conceptual picture of the flow field near a finite patch of vegetation. Flow divergence begins upstream of the patch and extends some distance into the patch. The position $x_D$ indicates the end of the diverging flow and the beginning of the shear-layer development at the flow-parallel edge of the patch. The shear layer penetrates a distance, $\delta_s$, into the patch. The velocity within the patch $U_l$ is laterally uniform. The advection distance $x_a = U_l T_s$ is measured from the end of the diverging flow region.
will be a region within the patch that cannot be reached by particles supplied from the upstream or from the flow-parallel edge. If such a region exists within a patch, then the deposition within the patch will be supply limited.

2. A Model Illustrating the Role of the Advection and Dispersion Length Scales

In this section we use a simple numerical model to illustrate how the advection length scale \( x_a \) and the diffusion length scale \( \delta_{\text{max}} \) influence the deposition pattern within a patch. The flow field used in the model is based on observations made in a previous study, upon which Figure 2 is based [Zong and Nepf, 2010]. As in Figure 2, the coordinate system is \( x = 0 \) at the leading edge and \( y = 0 \) at the channel wall, and the patch extends from \( y = 0 \) to \( y = b \). The flow field is two dimensional with longitudinal and transverse velocities denoted by \( u \) and \( v \), respectively. For simplicity, we only consider the patch domain downstream of the diverging region \( (x > x_D) \), where the flow is laterally uniform within the patch, i.e., \( u = U_l \neq f(x) \) and \( v = 0 \). The loss of suspended sediment associated with deposition is modeled as a first-order process with rate constant \( k = w_i/h \) [e.g., Hosokawa and Horie, 1992]. For \( x > x_D \), we assume there is no resuspension, because Zong and Nepf [2010] note that the bed stress in the patch interior is far below the critical value for resuspension. Finally, we assume that the longitudinal dispersion is negligible compared with advection. The steady, depth-averaged equation for suspended sediment concentration within the patch is then

\[
U_l \frac{\partial C}{\partial x} = \frac{\partial}{\partial y} \left( D_y \frac{\partial C}{\partial y} \right) - kC. \tag{4}
\]

Since the transport across the outer patch region is much faster than that in the inner patch region (as discussed above), we assume that the particle concentration in the outer patch region \( (y > b - \delta_{c}) \) is the same as the free stream, \( C_o \), so that the boundary of our solution domain will be at the edge of the inner patch region \( (y = b - \delta_{c}) \). The boundary conditions are then (1) concentration at the leading edge is equal to the open channel, \( C = C_o \) at \( x = x_D \); (2) concentration in the outer region is equal to the open channel, \( C = C_o \) at \( y \geq b - \delta_{c} \); and (3) no flux through the sidewall, \( \partial C / \partial y = 0 \) at \( y = 0 \).

We assume that the lateral flux across the inner patch region \( (y < b - \delta_{c}) \) is associated with turbulent diffusion, and we estimate \( D_y \), from a model for turbulent diffusivity for the inner patch region \( D_{i,j} \), developed for flow within homogeneous, emergent vegetation with stem diameter \( d \) and velocity \( U_l \) [Nepf, 1999; Lightbody and Nepf, 2006; Tanino and Nepf, 2008]. For solid volume fractions up to 10\%, Nepf et al. [2007] suggests

\[
D_{i,j} = 0.17 U_l d. \tag{5}
\]

Finally, we adopt the following parameter values based on the work of Zong and Nepf [2010], \( d = 0.6 \) cm, \( U_l = 0.5 \) cm/s, \( h = 10 \) cm, \( b = 40 \) cm, \( \delta_{c} = 5 \) cm, and \( w_i = 0.01 \) cm/s. From (5), \( D_y = D_{i,j} = 0.05 \) cm$^2$/s.

The simulated suspended sediment concentration inside the patch is shown in Figure 3a. Particles enter the modeled region at a suspended sediment concentration \( C_o \). As particles travel downstream, some are deposited, so that the water column concentration diminishes with distance from the leading edge, i.e., \( C = f(y) \). The decline is most apparent close to the wall (\( y = 0 \)), because lateral particle flux maintains a high concentration near the flow-parallel edge (\( y = b \)). After the supply from upstream is depleted by deposition, the lateral flux becomes the only supply of new particles to the patch. Considering different longitudinal positions, as shown in Figure 3b, reveals the interplay of particle sources from advection and lateral diffusion. The vertical dashed lines in Figure 3b mark the length scales \( \delta_{c} \) and \( \delta_{\text{max}} \). The region to the left of both dashed lines, i.e., \( (y < b - \delta_{c} - \delta_{\text{max}}) \), is supplied with suspended sediment only by advection from the leading edge. The rest of the patch, \( y > (b - \delta_{c} - \delta_{\text{max}}) \), is supplied with suspended sediment by both advection and lateral diffusion. At distances much less than the advection length scale, e.g., \( (x - x_D)/x_D = 0.1 \) in Figure 3b, the suspended sediment concentration within the patch is similar in magnitude to that at the leading edge \( (C_o) \), because little deposition has occurred by this point; and the concentration is laterally uniform over most of the patch width, reflecting the laterally uniform flow field. Far downstream of the advection length scale, e.g., \( (x - x_D)/x_D = 5 \), nearly all particles that entered across the leading edge have settled out, and the region of the patch supplied only by advection from the leading edge, \( y < (b - \delta_{c} - \delta_{\text{max}}) \), has a very low concentration, specifically \( C < 0.005 \) \( C_o \). This corresponds to the region \( y/b < 0.2 \) in Figure 3b. Particles continue to be supplied by lateral diffusion in the region \( y/b > 0.2 \), and in this region the concentration profile follows the erfc shape expected for diffusion from a constant source, with concentration highest at the patch edge and decreasing toward the wall over the distance \( \delta_{\text{max}} \) [Fischer et al., 1979, section 2.3.2]. If resuspension within the patch is negligible, the spatial pattern of deposition within the patch will mirror the spatial distribution of suspended sediment concentration. In the experiments that follow, observed deposition patterns have a dependency on the parameter \( (x - x_D)/x_D \) that is consistent with the model described here.

3. Experiment Methods

Experiments were conducted in a 16 m long recirculating flume with a test section that is 1.2 m wide and 13 m long (Figures 4a and 4b). The bed of the flume is horizontal. The flume was partially filled with a patch of model emergent vegetation, constructed with a staggered array of circular cylinders of diameter \( d = 6 \) mm. The patch was 0.4 m wide (1/3 of the flume width), 10 m long, and began 2 m from the start of the test section. The cylinders were held in place by perforated PVC baseboards that extended over the entire flume width. Two stem densities were considered, with \( \alpha = 0.04 \) and 0.21 cm$^{-1}$, corresponding to solid volume fractions of \( \Phi = 0.02 \) and 0.10, respectively. These values are representative of densities observed in aquatic vegetation. For example, in mangroves \( \Phi \) can be as high as 0.45 [Mazda et al., 1997], emergent grasses have been observed with \( \Phi = 0.001 \) to 0.02 [Valiela et al., 1978; Leonard and Luther, 1995], and submerged grasses have
been observed with $\Phi = 0.01$ to 0.1 [Gambi et al., 1990; Chandler et al., 1996; Ciraolo et al., 2006].

Three flowrates were tested for each patch density, with upstream channel velocities of $U = 5.0$, 9.0, and 11.6 cm/s. A weir at the downstream end of the test section controlled the water depth. To characterize the flow field, velocity measurements were taken using two Nortek Vectrino ADVs, each with a sampling volume 6 mm across and 3 mm high. The probes were mounted on a platform that could be moved along and across the flume. Since the probes were manually positioned, the positioning accuracy was $\pm 0.5$ cm in the $y$ direction and $\pm 2$ cm in the $x$ direction. A longitudinal transect was made through the centerline of the vegetation patch ($y = 20$ cm), shown in Figure 4b, starting 2 m upstream of the patch ($x = -2$ m) and extending to the end of the patch ($x = 10$ m). In addition, lateral transects were made downstream of the diverging region ($x > x_D$). At each measurement point the probe was positioned midway between adjacent cylinders within the array pattern. At each position the instantaneous longitudinal ($u$) and lateral ($v$) components of velocity were recorded at middepth for 240s at a sampling rate of 25 Hz. Each record was decomposed into its time average ($\bar{u}$, $\bar{v}$) and fluctuating components ($u'(t)$, $v'(t)$). The overbar denotes the time average. The intensity of turbulent fluctuations was estimated as the root-mean-square of the fluctuating velocity, $u_{rms} = \sqrt{\langle u'^2 \rangle}$ and $v_{rms} = \sqrt{\langle v'^2 \rangle}$. The mean velocity had an uncertainty of $\pm 0.1$ cm/s. Measurements made in still water determined that the instrument noise $u_{rms, noise} = 0.3$ cm/s, which set the lower limit at which turbulence intensity can be resolved.

Following the scaling analysis given by Zong and Nepf [2010], we chose a model sediment consisting of glass spheres of diameter $d_p = 12$ $\mu$m and density $\rho = 2.5$ g/cm$^3$ (Potters Industry, Inc., Valley Forge, Pennsylvania), with a settling velocity on the order of $w_s = 0.01$ cm/s. To begin the deposition study, 550 g of the model sediment were vigorously mixed with water in small containers. The mixture was poured across the width of the upstream feeder tank and stirred. From visual inspection, the particles mixed over the width and depth of the flume within a minute, which was much shorter than the 8 h duration of the experiment. The particles circulated with the water through the closed flow system. During each experiment, the concentration in the water was measured every 2 h by filtering a 500 mL water sample taken upstream of the patch. Figure 5 shows the suspended sediment concentration as a function of time for several cases.

The net deposition was measured using rectangular microscope slides (7.5 cm $\times$ 2.5 cm), which were placed on the bed of the flume (Figure 4b). The slides are smooth and have a surface roughness close to that of the PVC boards. The dry slides were weighed before placement. At the end of the experiment, the pump was first shut off and then the flume was slowing drained over a 20 min time span. The drainage was done slowly to prevent scouring.

Figure 3. (a) Simulated suspended particle concentration $C(x,y)$ normalized by the upstream concentration $C_o$, in the vegetation patch at $x > x_D$. (b) Simulated lateral concentration profiles across the patch width ($0 < y < b$).
from the slides. We let the slides sit in the flume for 3 or 4 days, until the surfaces of the slides were dry and the slides could be moved without disturbing the deposited particles. The slides were carefully picked up by hand, placed on trays, and baked overnight in an oven. Finally, the slides were reweighed. The weight of a slide after the experiment minus the weight before was taken as the net mass deposition. From visual inspection, the deposition on the slides was uniform, with no obvious edge effects. We also compared the deposition per area measured by slides of different size. The deposition per area was the same within uncertainty, indicating that the slide size did not influence the measurement. Three replicate experiments were done for each flow condition and patch density. The uncertainty in net deposition was estimated from the standard error among replicates at each position in the flume. The maximum deposition observed inside the patch for each case is recorded in Table 1.

4. Results

4.1. Flow

Each of the velocity statistics $\bar{u}$, $\bar{v}$, $u_{rms}$, $v_{rms}$, and $\sqrt{(-u', v')}$ was normalized by the upstream channel velocity $U$. The normalized profiles collapsed into two groups, corresponding to the two patch densities $\Phi = 0.02$ and $\Phi = 0.1$ (Figures 6 and 7). This shows
that for a given patch density the flow field in and around the patch is self-similar, scaling upon the upstream flowrate. Approaching along the centerline of the patch ($y = 20$ cm), the longitudinal velocity ($\bar{u}$) began to decrease $1$ m upstream of the leading edge for the dense patch ($\Phi = 0.10$, Figure 6a) and $0.5$ m upstream of the leading edge for the sparse patch ($\Phi = 0.02$, Figure 6a). The deceleration in $\bar{u}$ occurred continuously, with no distinct behavior at the leading edge ($x = 0$). The deceleration in longitudinal velocity was necessarily accompanied by an increase in lateral velocity $\bar{v}$, associated with the diversion of flow away from the patch (Figure 6b). Within the patch ($x > 0$), $\bar{u}$ continued to decrease until the diverging flow ($\bar{v}$ in Figure 6b) ended at roughly $x_D = 200$ cm for the dense patch and $x_D = 400$ cm for the sparse patch. Beyond the diverging region ($x > x_D$), the velocity along the centerline of the patch was uniform ($\partial \bar{u}/\partial x = 0$) until the end of the patch ($x = 10$ m) (Figure 6a), and the cross-stream velocity ($\bar{v}$) was 0 (Figure 6b). We define $x < x_D$ as the flow adjustment region and $x > x_D$ as the fully developed region. The patch length is expected to have no influence on the length of the diverging region, provided that the patch is longer than $x_D$. For example, Zong and Nepf [2010] tested an $8$ m patch with the same patch densities and obtained similar values for $x_D$.

[18] Upstream of the patch, the turbulence intensity was similar to that found in open channel flow, specifically $u_{rms}/U \approx 0.1$ [Schlichting, 1960]. The turbulence levels increased sharply at the leading edge of the patch ($x = 0$), even as the mean velocity decreased continuously across this zone. This region of elevated turbulence intensity is associated with the additional production of turbulence in stem wakes, and it is associated with a local region of diminished deposition, as discussed by Zong and Nepf [2010]. The stem-wake production occurs for stem Reynolds number, $Re_d = \bar{u}d/\nu$, greater than approximately 100, although the exact threshold is dependent on the stem density [Nepf, 1999]. As $Re_d$ declined with declining velocity in the patch, this source of turbulence was reduced and eventually shut off. For the dense patches, the measured turbulence intensity dropped below the noise threshold (dashed line in Figure 6c) for $x > x_D$, implying flow conditions. This is consistent with the stem-scale Reynolds numbers ($Re_d = \bar{u}d/\nu$) and the depth-scale Reynolds numbers ($(Re_d = \bar{u}h/\nu)$) reported in Table 1. In contrast, for the sparse patches $u_{rms}/U$ remained above the noise level, indicating that some turbulence was present, consistent with the transitional Reynolds numbers reported in Table 1.

[19] Lateral profiles of velocity were measured in the fully developed region of the patch $x > x_D$ (Figure 7). The solid line at $y = 40$ cm denotes the edge of the patch. The time-mean velocity was laterally uniform over most of the patch width, increasing toward the free stream within the distance $\delta_v$ from the edge. The dashed lines indicate the penetration distance estimated from equation (1) using $C_D = 2, d = 0.6$ cm based on White [2006, 2008], specifically $\delta_v = 1$ and $6$ cm, for the dense and sparse patch, respectively. The estimated penetration distances do reasonably well in describing the points at which the velocity begins to increase near the edge (Figure 7a), as well as the regions of elevated $-\bar{u}\bar{v}$ and $u_{rms}$ within the patch (Figures 7b and 7c). The magnitudes of the peak Reynolds stress observed near the patch edge were consistent with previous studies of vegetated shear layers, specifically White and Nepf [2008], who give the scaling $\sqrt{(-\bar{u}\bar{v})_{max}}/U \approx 0.1$.

[20] The shear layer extends into the open channel ($y > b = 40$ cm) over a distance $\delta_v \sim h/C_f$ [White and Nepf,

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**Table 1. Summary of Experimental Parameters**

<table>
<thead>
<tr>
<th></th>
<th>Dense Patch ($\Phi = 0.10$)</th>
<th>Sparse Patch ($\Phi = 0.02$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Flow</td>
<td>Medium Flow</td>
</tr>
<tr>
<td>$a$ (cm$^{-1}$)</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>$b$ (cm) + 0.5 cm</td>
<td>12.0</td>
<td>13.0</td>
</tr>
<tr>
<td>$U$ (cm/s) + 0.5 cm/s</td>
<td>5.0</td>
<td>9.0</td>
</tr>
<tr>
<td>$U_1$ (cm/s) + 0.1 cm/s</td>
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<td>0.2</td>
</tr>
<tr>
<td>$U_2$ (cm/s) + 0.5 cm/s</td>
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<td>16.2</td>
</tr>
<tr>
<td>$Re_s = \bar{u}d/\nu$</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>$Re_d = \overline{U}\ell/h/\nu$</td>
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<td>260</td>
</tr>
<tr>
<td>$x_D$ (cm) + 10 cm</td>
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<td>200</td>
</tr>
<tr>
<td>$\delta_v$ (cm) from equation (1), $C_D = 2$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$x_s$ (cm) from equation (2)</td>
<td>120</td>
<td>260</td>
</tr>
<tr>
<td>$D_s$ (cm/s$^2$) from equation (5)</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Maximum deposition inside the patch (g/m$^2$)</td>
<td>$30 \pm 3$</td>
<td>$36 \pm 2$</td>
</tr>
</tbody>
</table>
2007, 2008], where \( h \) is the flow depth and \( C_f \) is the bed friction. In this study, the flow depth varied only from 12 to 14 cm and \( C_f = 0.006 \) for all cases, so the width of the shear layer in the open channel was approximately the same for all cases, as seen in Figure 7a. Both mean flow and \( u_{rms} \) were uniform in the open channel beyond the shear layer (\( y > 80 \) cm). For both patch densities, \( u_{rms}/U \approx 0.15 \) (Figure 7c). Since \( U/\bar{u}_{rms} \approx 1.7 \) (Figure 7a), \( u_{rms}/U_2 \approx 0.15/1.7 \approx 0.1 \), which is typical for the open channel flow [Schlichting, 1960].

Figure 6. Velocity measured along the midpatch transect at \( y = 20 \) cm, normalized by the upstream velocity \( U \). Patch extends from \( x = 0 \) to \( x = 1000 \) cm, and \( y = 0 \) to \( y = 40 \) cm. (a) Time averaged stream-wise velocity \( \bar{u} \). (b) Time-averaged lateral velocity \( \bar{v} \). (c) Stream-wise velocity fluctuation \( u_{rms} \). The uncertainty in each velocity measurement is \( \pm 0.1 \) cm/s. The noise level is \( u_{rms}/U \approx 0.05 \).

21] Although \( u_{rms} \) and Reynolds stress were nearly uniform across the inner patch (\( y < h - \delta_v \)), the cross-stream velocity fluctuation (\( v_{rms} \)) was not (Figure 7d). The cross-stream fluctuating velocity was maximum at the edge of the patch and decreased with distance from the edge, both into the channel and into the patch. The elevated \( v_{rms} \) is associated with an edge wave induced by the passage of the shear-layer vortices, which is described by White and Nepf [2007]. The passage of the vortex train along the flow-parallel edge of the patch generates two distinct flows, which are revealed by the time series of the stream-wise \( u \) and transverse \( v \) velocity. Time series measured in the outer patch region (Figure 8a) reflect the direct impact of the vortices on turbulent flux. In this region the fluctuation of \( u(t) \) and \( v(t) \) are antiphase, producing strong fluxes of momentum \( (\bar{u}'v' < 0) \). In contrast, within the inner patch region (\( y = 20 \) cm, Figure 8b), \( u(t) \) and \( v(t) \) are \( \pi/2 \) out of phase, producing no momentum flux \( (\bar{u}'v' = 0) \). Furthermore, the transverse velocity within the patch lags the low pressure of the passing vortex core by \( 90^\circ \) [White, 2006]. These phase relationships are consistent with a pressure wave [Betchov and Criminale, 1967], e.g., a free surface gravity wave. The generation of the wave motion is shown schematically in Figure 8c. The center of each vortex is a point of low pressure, which draws fluid from within the patch toward the edge as it passes. The progression of vortices (and associated low pressure points) passing along the vegetation edge generates a wave response within the patch that is predominantly manifest in an oscillating lateral motion with a frequency fixed by the frequency of vortex passage, and the maximum lateral velocity lagging the vortex core by \( 90^\circ \). It is likely that these strong lateral motions enhance the lateral transport of particles into patch. This possibility is discussed further below. Finally, note that for \( x > x_0 \), the \( u_{rms}/U \) level in the sparse patches increased longitudinally (Figure 6c), even as the mean velocity remained constant. The increase in \( u_{rms} \) is likely associated with the edge wave. As the vortices initially grow longitudinally (Figure 2), the forced wave also grows in strength, leading to the observed increase of \( u_{rms}/U \) with distance.

4.2. Deposition

22] Figure 9 compares the spatially averaged net deposition measured within the patch and within the open channel for each case. For the open channel the average was taken using the points beyond the shear layer (\( y > 80 \) cm), where the velocity (\( \bar{u} = U_2 \)) and the observed deposition was laterally uniform. For the in-patch deposition, the average was taken using all points within the patch. In the open channel (open bars in Figure 9) the net deposition decreased as the flowrate increased. This is consistent with expectations. The net deposition is equal to the deposition minus the resuspension, and resuspension is expected to increase with the flowrate. Furthermore, in nearly all cases the deposition in the patch was higher than the deposition in the channel. This is also consistent with deposition limited by resuspension, because in all cases the velocity in the patch was significantly lower than that in the open channel (\( U_2 < U_1 \), Table 1). The difference between in-patch and open-channel deposition increased with increasing patch density, because the velocity difference between these regions increased with patch density (Table 1).
was, however, one important exception. For the lowest flow condition in the dense patch, the spatially averaged deposition in the patch was, within uncertainty, the same as that in the open channel. At first, this seems surprising, because the flow speed in the patch ($U_1 = 0.1$ cm/s) was significantly less than that in the open channel ($U_2 = 9.0$ cm/s). However, this result can be explained by considering when deposition is limited by the supply of suspended sediment to the patch, rather than by resuspension. As we discuss below, for the dense patch under the lowest flow condition the advection distance $x_a = 1.2$ m was much shorter than the patch length, 10 m, so that significant regions of this patch were supply limited, i.e., deposition was limited by supply.

To illustrate the role of the advection length scale $x_a$, or more specifically the transition distance from the leading edge $x_a + x_D$, we consider the lateral patterns of deposition observed at positions both greater than and less than the transition distance. For each case shown in Figures 10, 11, and 12, the deposition was normalized by the maximum deposition observed inside the patch (Table 1). We first consider the deposition pattern observed at comparable longitudinal positions ($x = 700$ and 735 cm), and at comparable channel speeds ($U = 9.0$ cm/s), but within patches of different stem density (Figure 10). The difference in patch density produced different patch velocities, $U_1 = 0.2$ and 1.1 cm/s in the dense and sparse patch, respectively. This led to different advection length scales, $x_a = 260$ cm (dense) and 1430 cm (sparse), which corresponded to a different transition distance from the leading edge of $x_a + x_D = 460$ cm (dense) and 1830 cm (sparse). For the sparse case shown in Figure 10, the measured pattern of deposition was laterally uniform over the patch width except for the point closest to the follow-parallel edge. Recall that the flow field is also laterally uniform within the patch. Together, these observations suggest that the particle delivery to this region is dominated by longitudinal advection. This is consistent with the advection length scale, i.e., particle delivery is dominated by the advection from the leading edge if $x << x_D + x_a$, as is the case for the sparse patch.
shown in Figure 10. The reduced deposition near the flow-
parallel edge is probably due to the enhanced turbulence at
the patch edge, associated with the shear-layer vortices.
Now consider the dense patch, for which the deposition
was not uniform across the patch width (Figure 10). The
deposition was highest near the flow-parallel edge and
decreased with the distance into the patch. In this case,
the deposition was supply limited. For the lowest channel flow,
the deposition increased. Within the patch, however, the depo-
sition limited by resuspension, i.e., as the open channel ve-
tilation. The deposition across the patch width was similar for all
flow conditions, with maximum deposition near the flow-
parallel edge. As the upstream channel flow $U$ decreased,
the deposition in the patch decreased only slightly, while
the deposition in the open region increased significantly.
The trend in the open region is consistent with net deposi-
tion limited by resuspension, i.e., as the open channel ve-
cy between sediment wakes (5). The model predicted suspended sediment
concentration $C(x, y)$. However, if we assume no resuspension
in the patch, the net deposition $m$ is related directly to
$C$, specifically $m(x, y) = w_{c}C(x, y)T$, with $T$ the duration of
the experiment. First we will compare the measured deposition
profiles to those produced by the model with a constant
diffusivity $D_{ic}$ (Figure 3). Specifically, consider the profile
at $x = 550$ cm in Figure 11b, which has a dimensionless dis-
tance $(x - x_{DP})/x_{a} = 0.83$. This distance is close to $(x - x_{DP})/
$ for which a modeled profile is shown in Figure 3b.
The lateral extent of the measured deposition (Figure 11b) is larger than that produced by the model (Figure 3b), suggesting that the lateral flux of particles was greater than turbulent diffusion alone. In addition, the flow conditions in the dense patch were laminar, so that (5) and the modeled result would at best be an upper bound for the impact of stem-wake diffusivity. Also, note that the modeled profile is convex, but the measured profile is concave. The concave shape suggests that \( D_y \) is larger near the patch edge and decreasing away from that edge. The above comparison between observed and modeled profiles suggests that another mechanism, in addition to turbulent diffusion, transports particles laterally into the patch, and that its dispersivity is highest near the flow-parallel edge and decreasing into the patch. The edge wave, because it generates oscillating lateral velocity (Figure 7d), could provide another mechanism for lateral flux into the patch. Furthermore, the velocity scale associated with the edge wave is highest at the patch edge and decreasing into the patch. A reasonable fit to the profile of \( \nu_{\text{rms}} \) is \( \nu_{\text{rms}} = \nu_{\text{rms,max}} (y/b)^{2} + \nu_{\text{rms,background}} \), which is shown as a dashed line in Figure 7d. If \( \nu_{\text{rms}} \) sets the velocity scale for the lateral particle flux, then the dispersion coefficient would have a similar form, specifically, \( D_y = D (y/b)^{2} + D_{\text{t,i}} \) (Figure 13a). The first term, \( D (y/b)^{2} \), captures the contribution from the edge wave, and the second term, \( D_{\text{t,i}} \), represents the contribution from background turbulence associated with stem wakes. The numerical model introduced above was run again using parameter values from the current study, specifically \( U_1 \), \( D_{\text{t,i}} \), and \( \nu \) reported in Table 1. The coefficient \( D \) was adjusted to obtain the best fit between measured and simulated deposition. Figure 13 compares the model deposition (line) with the observed deposition (circles) for the dense patch under the three flow conditions. The modeled profiles capture the concave shape observed in the measured profiles. In addition, the fitted dispersion coefficients (listed in each subplot) were much greater than the turbulent diffusivity, \( D_{\text{t,i}} = 0.01 \) to \( 0.03 \) cm\(^2\)/s (Table 1). Finally, the fitted coefficient, \( D = 1.5, 1.9, \) and \( 2.1 \) cm\(^2\)/s, increased with flow speed \( U = 5.0, 9.0, 11.6 \) cm/s, respectively, consistent with \( \nu_{\text{max}} \) which also scales with the channel flow speed (Figure 7).

5. Conclusion

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Figure 9. Spatially averaged deposition within the patch and in the open channel. The open channel average only includes measurements beyond the shear layer where \( u = U/2 \), specifically from \( y = 100 \) cm and \( x = 5, 5.5, 6, 6.5, \) and \( 7 \) m. The in-patch average includes all measurements made within the patch. Vertical bars indicate the standard error.

Figure 10. Net deposition observed for median flow condition \( (U = 9.0 \) cm/s) at \( x = 700 \) cm in the dense patch (open square) and \( x = 735 \) cm in the sparse patch (open circle). The patch is \( 0 < y < 40 \) cm.
decelerate upstream of the patch and continued to decelerate until the distance \( x_D \) past the leading edge. Beyond \( x_D \) shear-layer vortices developed at the flow-parallel interface and penetrated into the patch a distance \( \delta_r \). The vortices enhanced the transport of particles into the patch by increasing the turbulent flux in the outer patch region \( (y > b - \delta_r) \), and also by inducing an edge wave that enhanced lateral motion across the patch. In addition to lateral flux across the flow-parallel edge, suspended particles were also supplied to the patch by mean flow advection across the leading edge. The relative contribution from these two supplies can be described by the length scale \( x_D + x_a \). For \( x < x_D + x_a \), the supply is dominated by mean advection. Because the flow field was laterally uniform within the patch, the net deposition in this region was also laterally uniform. Beyond \( x_D + x_a \) the supply is dominated by lateral flux across the flow-parallel edge, and the net deposition was highest near that edge and decreased toward the patch interior. The lateral flux from the flow-parallel edge consisted of two mechanisms: turbulent diffusion and edge-wave dispersion. Both mechanisms scale with the channel flow \( U \). The dispersivity estimated by fitting model simulations to the observed net deposition suggested that for the conditions considered here the dispersion associated with the edge-wave oscillations in lateral velocity was more important that turbulent diffusion in transported particles into the patch. Finally, if the patch is longer than the distance \( x_D + x_a \) and wider than \( \delta_r + \delta_{\text{max}} \), then net deposition within some regions of the patch will be supply limited and some interior regions may experience zero net deposition.

**Figure 11.** Net deposition within the patch, \( 0 < y < 40 \) cm. (a) In the sparse patch with low flow condition \( (U = 5.0 \, \text{cm/s}) \), deposition measured at \( x = 366, 488, 610, \) and 730 cm. (b) In the dense patch with high flow condition \( (U = 11.6 \, \text{cm/s}) \), deposition measured at \( x = 180, 305, 550, \) and 735 cm.

**Figure 12.** Net deposition measured at \( x = 550 \) cm in the dense patch for the three flow conditions. The patch is \( 0 < y < 40 \) cm.

**Figure 13.** (a) Dispersivity model used for simulated results, \( D_y = D(\frac{y}{b})^2 + D_{t,i} \). Measured (open circle) and simulated (solid line) profiles of deposition at \( x = 550 \) cm in the dense patch for (b) high flow, (c) medium flow, and (d) low flow.
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