Riparian vegetation controls on braided stream dynamics

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Abstract. Riparian vegetation can significantly influence the morphology of a river, affecting channel geometry and flow dynamics. To examine the effects of riparian vegetation on gravel bed braided streams, we conducted a series of physical experiments at the St. Anthony Falls Laboratory with varying densities of bar and bank vegetation. Water discharge, sediment discharge, and grain size were held constant between runs. For each run, we allowed a braided system to develop, then seeded the flume with alfalfa (Medicago sativa), allowed the seeds to grow, and then continued the run. We collected data on water depth, surface velocity, and bed elevation throughout each run using image-based techniques designed to collect data over a large spatial area with minimal disturbance to the flow. Our results show that the influence of vegetation on overall river patterns varied systematically with the spatial density of plant stems. Vegetation reduced the number of active channels and increased bank stability, leading to lower lateral migration rates, narrower and deeper channels, and increased channel relief. These effects increased with vegetation density. Vegetation influenced flow dynamics, increasing the variance of flow direction in vegetated runs and increasing scour depths through strong downwelling where the flow collided with relatively resistant banks. This oblique bank collision also provides a new mechanism for producing secondary flows. We found it to be more important than the classical curvature-driven mechanism in vegetated runs.

1. Introduction

The riparian corridor encompasses a river system and its immediate banks, an environment where the hydrosphere, the biosphere, and the lithosphere come together. Riparian vegetation can substantially influence physical properties of the river, primarily by changing bank strength and flow resistance. Numerous studies have linked properties of river channels, including width, depth, and velocity to vegetation density in the riparian zone [Hadley, 1961; Brice, 1964; Zimmerman et al., 1967; Charlton et al., 1978; Graf, 1978; Andrews, 1984; Hey and Thorne, 1986; Huang and Nanson, 1997; Rowntree and Dollar, 1999]. Some have even found a correlation between the type or density of vegetation and the overall behavior of the river, changing between meandering and braiding as the vegetation changes [Mackin, 1956; Brice, 1964; Nevin, 1969; Goodwin, 1996]. Because of the complexity of natural vegetated streams, however, it is often difficult to establish a direct causal relationship between vegetation density and channel characteristics. Changes in vegetation density may result from shifts in climate, water discharge, or sediment discharge, and any of these other factors can alter channel characteristics.

We examined the relationship between riparian vegetation and braided systems through a series of physical experiments conducted at the St. Anthony Falls Laboratory (University of Minnesota, Minneapolis) [Gran, 2000]. Braided rivers represent the main mode of instability for unconstrained flow over a noncohesive bed [Murray and Paola, 1994]. They are characterized by multiple channels with high lateral migration rates relative to single-thread channels. Vegetation directly opposes this tendency to migrate freely by strengthening and stabilizing banks. Our experiments compared braided rivers with and without riparian vegetation to determine how vegetation affects channel form and flow dynamics. Vegetation density was the main variable between runs, and other factors that could influence the channel form and pattern, including water and sediment discharge, grain size, and slope, were held constant. We carried out five runs: two with no vegetation and three with vegetation on the bars and banks. These experiments were intended to model processes in nature, complementing existing studies of natural streams, and provide some additional insight into how riparian vegetation may affect braided channel form and flow characteristics. The experiments show that vegetation by itself can cause major changes in channel form and flow dynamics in a braided system. The trends in channel form and geometry compare well with trends seen in natural rivers.

2. Methods

We conducted our experiments at the St. Anthony Falls Laboratory in a 2 m by 9 m flume (Figure 1). Water entered from a constant head tank through a pipe directed toward the back wall of an entrance chamber to damp turbulence. Well-rounded, well-sorted dry quartz sand (D90 = 0.5 mm) was fed in at a constant rate with a mechanical sediment feeder. The bed was set to a slope of 0.014, and a straight channel was carved down the middle of the flume 2 cm deep and 30 cm wide to channel initial flow. We used the same water and sediment discharge (Qw = 3.5 × 10−4 m3/s and Qs = 1.2 g/s) for all runs, with Qw and Qs chosen to maintain the initial slope. The initial straight channel rapidly widened and developed into a braided channel system. We let the flume run until most of the surface of the study reach had been reworked by the flow.
before adding vegetation. To prevent the flow from migrating to the flume walls and sticking there, roughness elements were placed along the sides of the flume.

Care was taken to ensure that Froude numbers in the model were comparable with those in natural systems and that flow in the model was turbulent. Froude numbers in the model runs ranged from 0.42 to 0.98 with an average of 0.77, indicating subcritical flow. For comparison, Froude numbers measured on the Sunwapta River, a gravel bed braided stream in Alberta, Canada, ranged from 0.41 to 1.08 [Ashmore, 1988]. Reynolds numbers in the model ranged from 800 to 3800 with an average of 1400, indicating turbulent flow.

After the braided channel was fully established, we introduced the vegetation, for which we used alfalfa (Medicago sativa). Seeds were soaked for 48–72 hours, then air dried for 6–12 hours prior to seed dispersal. During dispersal the water discharge was halved. At this discharge, sediment transport was minimal, so the sediment feeder was turned completely off. The seeds were dispersed over the flume by hand as uniformly as possible. Some seeds landed directly on bars or banks, and some were carried by the flow and later deposited along banks or washed out of the flume. This method of seed dispersal is similar to many riparian species including willows (Salix) and cottonwoods (Populus), which disperse seeds by both wind and water [Johnson, 1994]. While the sprouts were growing, we maintained just enough discharge to keep the sediment damp through groundwater flow, but it was not high enough to actually flow through the channels. After the alfalfa sprouts had grown for 10–14 days, each sprout had a single stem — 30 mm high and 1 mm in diameter with two to four small leaves at the top. Roots reached a similar distance below the surface (30 mm) and consisted of one main taproot with smaller branching rootlets. Water and sediment discharges were returned to their original values, and the run continued for an additional 30–36 hours of run time. There did not appear to be any systematic changes in flow parameters as time progressed at the end of the run, so we do not believe the small differences in run time affected the results.

We conducted five runs. Runs 1 and 2 had no vegetation and were used as controls. Runs 3, 4, and 5 had mean plant densities of 1.2, 4.2, and 9.2 stems/cm², respectively (Table 1). Plant densities were measured using average point counts of the number of seeds in randomly selected plots on banks and bars following seed dispersal. Since not all of the seeds germinated, the measured plant densities may be slightly higher than the actual stem densities.

For each run, we measured water depths, surface velocities, and bed topography along five cross sections spaced 0.5 m apart in the central portion of the flume. Water depths were measured every 2 hours using a new noninvasive image-based dye density technique. The principle behind the technique is similar to one developed by Winterbottom and Gilvear [1997] using airborne multispectral imagery in natural rivers. We ran a 2 ppm (parts per million) solution of rhodamine dye through the flume and obtained vertical images with a digital camera. As the depth increased, the dye appeared darker in the image.
Table 1. Summary of Channel Geometry Characteristics for Each Run

<table>
<thead>
<tr>
<th>Run</th>
<th>Stem Density, stems/cm²</th>
<th>Braiding Intensity (BI)</th>
<th>Aspect Ratio (a)</th>
<th>Maximum Depth, mm</th>
<th>Channel Relief (S_r)</th>
<th>Topographic Correlation Coefficient (r_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>ND (^d)</td>
<td>125 ± 43</td>
<td>18 ± 6</td>
<td>0.20 ± 0.06</td>
<td>ND (^d)</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>5.0 ± 0.3</td>
<td>158 ± 57</td>
<td>15 ± 4</td>
<td>0.14 ± 0.04</td>
<td>0.57</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>4.1 ± 0.3</td>
<td>71 ± 22</td>
<td>16 ± 4</td>
<td>0.23 ± 0.08</td>
<td>0.75</td>
</tr>
<tr>
<td>4</td>
<td>4.2</td>
<td>3.3 ± 0.3</td>
<td>101 ± 51</td>
<td>19 ± 5</td>
<td>0.27 ± 0.11</td>
<td>0.69</td>
</tr>
<tr>
<td>5</td>
<td>9.2</td>
<td>2.4 ± 0.4</td>
<td>21 ± 20</td>
<td>25 ± 7</td>
<td>0.39 ± 0.14</td>
<td>0.80</td>
</tr>
</tbody>
</table>

\(^a\)Note that these are mean values for each run. The listed variance is one standard deviation from the mean for the entire run.

\(^b\)Average number of active channels along a cross-section.

\(^c\)Active channel width divided by the mean channel depth.

\(^d\)Average transverse slope along a cross-section.

\(^e\)Measure of the degree of correlation between consecutive bed profiles. An \(r_c = 1\) means perfect correlation (low lateral mobility rates).

Lower \(r_c\) values imply higher amounts of lateral migration.

\(^f\)No data.

We extracted the green band from the RGB images and used the color value (0-255) in the green band as a measure of dye intensity. We calibrated the dye method by including a calibration tray in the images. The calibration tray was a rectangular pan, 200 mm long, coated with the same uniformly light-colored sand used in the experiment and tilted so as to produce a linear depth variation from 0 to 50 mm. At these depths under our experimental conditions, dye intensity varied linearly with depth (Figure 2). We checked the dye-estimated depths using spot point gage measurements throughout the runs. We eliminated any cross sections where the point gage measurements disagreed with the dye-based depth by >3 mm. Of the 295 cross sections measured, 47 (16%) were removed. For the 248 remaining cross sections the dye method calculations agreed with the point gage measurements with a mean deviation of ±1.0 mm.

Surface velocity data were collected immediately preceding depth measurements, so the two data sets could be correlated. We measured surface velocities using a surface particle tracking technique. Liquid soap was added to the flow upstream from the study area, creating small bubbles. A video camera mounted directly overhead recorded the bubbles as they floated downstream, and a particle tracking program calculated surface velocity vectors along the paths where the bubbles traveled. To compare the velocity data between runs, we spatially thinned the data to remove sampling bias favoring swiftly flowing zones. We established a grid such that at least one data point remained in each grid cell, and the data were then thinned randomly within each cell until only one point remained. Statistics on the velocity vector magnitude and direction data were then compiled for each run using the thinned data set.

Bed elevations were measured along each cross section approximately every 6 hours. For the first unvegetated run, we used a laser scanner developed by Leaf et al. [1993] to measure bed topography. The laser scanner could not accurately measure the bed surface in areas with vegetation, so we used a point gage to record bed profiles in the other four runs.

3. Results

3.1. Channel Geometry

The vegetation generally reduced the number of active channels as smaller channels became choked and were unable to reestablish themselves. We calculated a braiding intensity (BI) for each run as the average number of active channels along a cross section. An active channel was defined as a channel capable of transporting sediment (depth >2 mm for our experimental conditions). The BI decreased from an average of 5.0 in run 2 to 2.4 in run 5 (Table 1 and Figure 3). In the highest density run, channel closure led to the development of a wandering river with one or two main channels separated by large vegetated islands (Figure 4). In plan view it resembled a stretch of the Athabasca River upstream of Fort Assiniboine (Figure 5), a wandering gravel bed river with two to three main channels separated by forested islands [Neill, 1973].

Channel cross-sectional geometry changed as vegetation density increased. Aspect ratios \(a\) were an order of magnitude lower in the highest density run than in the unvegetated runs (Table 1 and Figure 3). Here \(a = b/h\), where \(b\) is the sum of all active channel widths along a cross section and \(h\) is the mean depth. Maximum depths \(h_{max}\) and mean transverse slope magnitude \(S_r\) along each cross section increased with vegetation density (Table 1 and Figure 3). To measure \(S_r\), we calculated slope magnitudes between adjacent cross-stream points on the bed and averaged across each cross section. \(S_r\) increased by a factor of 2 from the unvegetated runs to the highest density run.

Vegetation also influenced channel mobility. As an indirect measure of channel mobility, we compared the amount of change between bed profiles measured every 5 to 7 hours by treating the profiles as a form of time series data and computing correlation coefficients \(r_c\) between sequential profiles. This method is similar to the method used to calculate autocorrelation coefficients in a single time series with a given lag time [Bras and Rodriguez-Iturbe, 1993]:

![Image](https://via.placeholder.com/150)
Figure 3. Channel geometry characteristics for all five runs plotted against vegetation density. Braiding intensity (BI) measures the average number of active channels along a cross section. Aspect ratio is the average active channel width divided by the mean depth \(\alpha = b/h\). The maximum depth \(h_{max}\) refers to the maximum depth measured along each cross section. The local transverse slope \(S_e\) is calculated by averaging transverse slope magnitudes between adjacent points along a cross section. The correlation coefficient \(r_s\) is a measure of the correlation between bed topography profiles through time. A high \(r_s\) means a high degree of correlation, indicating low channel mobility. Each data point on the graph represents the average of all cross-sectional data for the duration of a run. The spread represents one standard deviation up and down from the mean for the run. Actual values can be found in Table 1. Overall trends show a decrease in braiding intensity and aspect ratio and an increase in maximum depth, relief, and bed stability with increasing density of vegetation.

\[
\begin{align*}
    r_s &= \frac{\text{cov}(\eta_1, \eta_2)}{\sqrt{\text{var}(\eta_1)\text{var}(\eta_2)}} \\
    \text{cov}(\eta_1, \eta_2) &= \frac{1}{n} \sum_{i=1}^{n} (\eta_{1i} - \bar{\eta}_1)(\eta_{2i} - \bar{\eta}_2) \\
    \text{var}(\eta) &= \frac{1}{n-1} \sum_{i=1}^{n} (\eta_i - \bar{\eta})^2,
\end{align*}
\]

where \(\eta_1\) and \(\eta_2\) represent bed topography at sequential time steps, \(\bar{\eta}_1\) is the average elevation at time 1, \(\bar{\eta}_2\) is the average elevation at time 2, \(\text{cov}(\eta_1, \eta_2)\) is the covariance between \(\eta_1\) and \(\eta_2\), and \(\text{var}(\eta_1)\) and \(\text{var}(\eta_2)\) are the variances of \(\eta_1\) and \(\eta_2\). A perfect correlation would give an \(r_s = 1\), with lower \(r_s\) implying a lower degree of correlation between runs. Run 2 had the lowest \(r_s\), and run 5 had the highest, indicating a higher degree of channel stability in the densely vegetated run (Table 1 and Figure 3).

3.2. Surface Flow Dynamics

Riparian vegetation affected flow dynamics in the experiments. Velocity vector magnitudes were less variable in runs 4 and 5 than in runs 1–3 as shown by a decrease in the coefficient of variation \(c_v\) with increasing vegetation density (Table 2). Sampling bias may account for some excess low-magnitude data in the unvegetated runs because the particle-tracking method does not work in slow flowing plant-choked areas. However, even with the low-magnitude velocities removed, the higher \(c_v\) values for the unvegetated runs remain. Interestingly, we observed no correlation between vegetation density and mean velocity magnitude. Evidently, the cutoff of low-discharge channels by plants and the increase in bank strength reduce velocity variability but do not speed the flow up overall.

The vegetated runs had a greater spread in velocity vector angles as shown by an increase in the standard deviation of the vector direction data \(\sigma_\theta\), indicating more sinuous flow paths in the vegetated runs (Table 2). Analyzing the vector angle spread using the method detailed by Curran [1956] shows that the percent correlation between vector angles \(L\) is lower in vegetated runs (Table 2). We did not find a systematic decrease in \(L\) with vegetation density. Once the vegetation is established, changes in its density do not seem to lead to increased sinuosity of flow paths.

3.3. Scour Features

Scour holes are ubiquitous features of braided streams, forming wherever flow paths collide [Mosley, 1976; Ashmore and Parker, 1983; Best, 1986, 1987; Best and Ashworth, 1997; Rhodes and Kenworthy, 1998]. In the unvegetated runs, scour holes up to five times the mean flow depth formed throughout the stream, migrating and filling in rapidly. Once vegetation was introduced, scour features became much less mobile and transient, and some deepened to as much as 6.4 times the mean flow depth. Many scour features in the vegetated runs migrated until they encountered a vegetated bank where they stayed fixed, sometimes for the remainder of the run. Differences in scour hole mobility can be seen in the time series of bed elevations from cross sections that crossed major scour features, all of which are given by Gran [2000]. For the highest vegetation density (run 5), many of the along-bank scour features elongated parallel to the bank and deepened.

4. Discussion

4.1. Scaling

As vegetation density in the model increased, it affected channel form and dynamics. Many of the observed changes in channel geometry are consistent with an increase in bank strength due to the introduction of vegetation and are comparable to trends in natural river channels. As mentioned above, we took care to use Froude numbers comparable to natural braided rivers and maintain turbulent flow in model channels, so the flow dynamics can be compared with natural rivers. The
size of the alfalfa sprouts can be compared with natural vegetation as follows.

To compare length scales, we use as a prototype an unvegetated reach of the Sunwapta River, 1–2 km downstream from the Athabasca glacier (Figure 6). The model used quartz sand with a $D_{50} = 0.5$ mm, while the Sunwapta had a $D_{50} = 40$ mm. The length scale ratio (model/prototype) is thus 0.0125. Comparisons between mean channel width and depth gave similar scale ratios (0.008 and 0.01, respectively), but these are values set by the flow itself and are not independent variables.

In shape the alfalfa sprouts we used in the experiments are most similar to trees, with a solitary trunk and high branches. Using the length scale ratio computed above (0.0125), the 1 mm alfalfa stems scale up to 80 mm diameter field vegetation. This is a reasonable size for young tree trunks. In addition, slow flow through the vegetation in the model was nearly laminar as opposed to turbulent in flow through natural bank vegetation, so the zone of interference from each stem in the experiments is larger than a similar zone of interference in a fully turbulent flow. This makes the stems appear larger than they really are to the experimental flow.

4.2. Channel Geometry

Charlton et al. [1978], Andrews [1984], and Hey and Thorne [1986] have shown that when bank sediment type is held constant, the average total wetted width/average depth ($\alpha$) de-
increases as the density of vegetation increases. This same trend is seen in the experimental runs, with high vegetation density corresponding to lower $\alpha$. In the unvegetated model runs, $\alpha$ was an order of magnitude higher than in run 5 and the natural single-thread rivers. High $\alpha$ are characteristic of braided rivers [Ashmore, 1985], and $\alpha$ computed in runs 1 and 2 are consistent with $\alpha$ computed for other braided streams [Eschner, 1983]. Run 5, with the highest vegetation density, had an average $\alpha = 21$, which is within range of $\alpha$ computed from natural single-thread channels [Charlton et al., 1978; Andrews, 1984; Hey and Thorne, 1986]. The braiding index was also lowest in this run, and in plan view the channel resembled a wandering river (Figures 4 and 5). Although it was clearly not a meandering river, it was shifting toward a meandering behavior rather than strictly braiding. It has proven quite difficult to model true meanders in a flume [Smith, 1998], and one of the main reasons may be lack of vegetation [Hickin, 1984].

The observed decrease in $\alpha$ with increasing vegetation is the result of several factors. One of these is the closure of small channels by vegetation, forcing the bulk of the discharge into fewer channels. This showed up as a decrease in braiding intensity with increasing density of vegetation. This decrease in the number of active channels led to a decrease in the total channel width partially accounting for the observed decrease in $\alpha$. The decrease in $\alpha$ also results in part from an increase in bank strength as more plants and thus more roots became established on the banks. Although root density was not measured directly, root density scales with stem density. Roots add tensile strength to the sediment, increasing the bulk shear strength [Vidal, 1969; Thorne, 1990], and the strength increases with increasing density of roots [Ziemer, 1981; Gray and MacDonald, 1989]. In addition, the roughness introduced by bank vegetation increases the local boundary layer thickness, forcing the high-velocity zone away from the bank and decreasing shear stress on the bank [Thorne and Furbish, 1995]. As bank strength increases, deeper, narrower channels can develop. Brice [1964] found that the Calamus River in the Nebraska Sandhills had a straight, narrow channel where erosional resistance was high and wide, braided channels where bank erosional resistance was low. The main factor controlling erosional resistance of the banks was vegetation.

An increase in bank strength also increases channel relief through the formation of higher or steeper banks. Channel relief increased with vegetation density in our experiments, consistent with an increase in bank strength. An increase in bank strength should also affect lateral migration rates; in the experiments, this is expressed as a decrease in channel mobility with increasing vegetation density. This decrease in erodibility and lateral mobility resulting from vegetated banks and bars has been quantified in the field on anastomosing [Smith, 1976] and meandering streams [Beesoon and Doyle, 1995].

### Table 2. Summary of Spatial Velocity Characteristics for Each Run

<table>
<thead>
<tr>
<th>Run</th>
<th>Stem Density, stems/cm²</th>
<th>Mean Vector Magnitude, m/s</th>
<th>$c_v$ Vector Magnitudes</th>
<th>$c_v$ Vector Magnitudes &gt;0.05 m/s</th>
<th>$\sigma_v$ Vector Angles, rad</th>
<th>L Vector Angles, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.21</td>
<td>0.53</td>
<td>0.48</td>
<td>0.34</td>
<td>96</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.18</td>
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<td>0.45</td>
<td>0.43</td>
<td>93</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>0.21</td>
<td>0.42</td>
<td>0.41</td>
<td>0.60</td>
<td>85</td>
</tr>
<tr>
<td>4</td>
<td>4.2</td>
<td>0.20</td>
<td>0.33</td>
<td>0.32</td>
<td>0.50</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>9.2</td>
<td>0.19</td>
<td>0.37</td>
<td>0.36</td>
<td>0.64</td>
<td>85</td>
</tr>
</tbody>
</table>

*Note that all listed values are statistical compilations from the entire run.

*Here $c_v$ is the coefficient of variation (standard deviation/mean) of the vector magnitude data.

*Here $\sigma_v$ is the standard deviation of the vector angle data.

*Here $L$ is the percent correlation of vector angles.

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**Figure 6.** This map shows the location of the prototype section of the Sunwapta River in Jasper National Park, Alberta, Canada.
Figure 7. Definition sketch for the vortex generated due to bank impingement. The sketch on the left shows the angle of attack $\theta$ between the flow line and the bank. The sketch on the right shows a cross-sectional view through the flow. The vortex generated by bank impingement is assumed to encompass the entire flow depth $h$. Here $r$ is radius of vortex, $u_{surf}$ is downstream surface velocity component, $\rho$ is density of water, and $\tau_b$ is basal shear stress.

Figure 8. Definition sketch for secondary flow generated from channel curvature. The formulation is in curvilinear coordinates. $R$ is radius of curvature, $u$ is the downstream velocity component, and $v$ is the cross-stream velocity component.

lized with vegetation, flow impinging on the bank cannot erode the bank as readily, and flow may be directed downward, scouring the bed. This process is similar to the classic horseshoe vortex formed when flow impinges upon a vertical cylinder, scouring the bed around the cylinder [Shen and Schneider, 1969].

In order to determine how strong the helical flow generated by oblique bank impingement might be we developed a simple model of an impingement-driven vortex. The shear stress generated from secondary flow due to oblique bank impingement is then compared to the shear stress generated by curvature-driven secondary flow to determine the relative importance of the bank impingement vortex.

The shear stress generated by flow impinging on the banks can be described with a simple torque balance (Figure 7). If we assume that a vortex with a horizontal rotation axis generated by the downwelling develops through the entire flow depth, a torque balance can be written with the lever arm equal to half the flow depth. The driving force is the pressure imbalance at the wall. Using the angle of attack $\theta$ between the flow and the bank, we extract from the near-bank velocity the vector component perpendicular to the wall, which drives the vortex. The torque is given by torque/area $= \text{pressure} \times \text{lever arm}:

$$T = \frac{1}{2} \rho (u_{surf} \sin \theta)^2 \frac{1}{2} h,$$

where $\rho$ is density of water, $u_{surf}$ is surface velocity in downstream direction, and $h$ is flow depth. This torque is balanced by shear stress $\tau_b$ along the bed and the wall and rewritten with shear stress on the left-hand side:

$$\frac{\tau_b}{\rho} = \frac{u_{surf} \sin \theta}{8} \frac{1}{\theta},$$

This form of $\tau_b$ is compared with the basal shear stress generated by secondary flow due to curvature $\tau_c$ (Figure 8) [e.g., Rosovskii, 1957; Smith and McLean, 1984]. Note that our goal here is an estimate of the magnitude of the stress due to secondary flow, not a detailed model of the secondary flow field. To first order, secondary flow in a wide curved open channel under steady conditions and without streamwise topo-

ography is described by a basic force balance in curvilinear coordinates:

$$\frac{u(z)^2}{R} - \frac{1}{\rho} \frac{\partial P}{\partial y} = \frac{1}{\rho} \frac{\partial \tau_c}{\partial z},$$

where $u(z)$ is the downstream velocity component, $R$ is radius of curvature, $P$ is pressure, and $\tau_c$ is shear stress. The transverse pressure gradient is balanced by centrifugal acceleration at the point of mean velocity $\bar{u}$. Integrating over depth, we get an equation in terms of bed shear stress $\tau_c$:

$$\int_{h_b}^{h} \frac{u(z)^2 - \bar{u}^2}{R} \, dz = \frac{\tau_c}{\rho},$$

where $h_b$ is the standard roughness length. We then introduce a shape factor $\beta$ such that $\beta \approx 1$:

$$\beta = \frac{\int_{h_b}^{h} [u(z)^2 - \bar{u}^2] \, dz}{h_b \bar{u}^2}.$$

Combining (7) and (8), we have an equation for the shear stress generated by secondary flow due to curvature:

$$\frac{\tau_c}{\rho} = \frac{\beta \bar{u}^2 h}{R}.$$

Now the shear stresses from (5) and (9) can be compared to get an estimate of the relative importance of the bank impingement-generated shear stress:

$$\frac{\tau_c}{\tau_b} = \left( \frac{\bar{u}^2}{u_{surf}} \right) \left( \frac{8 \beta h}{R \sin^3 \theta} \right).$$

From this ratio, it becomes clear that the main variables of interest are flow depth $h$, radius of curvature $R$, and angle of impingement $\theta$.

Twenty-five scour holes from runs 4 and 5 were examined in the vegetated runs to determine ratios of $\tau_c/\tau_b$. For these 25 scour holes the average bank impingement angle is $39^\circ$, the mean radius of curvature is 0.34 m, and the average pool depth
is 0.021 m [Gran, 2000]. In all but one of the scour holes the shear stress related to a bank impingement–generated vortex is greater than the shear stress related to curvature-driven secondary flow. Shear stress ratios (equation (10)) ranged from 0.004 to 3.18, with a median of 0.10. This indicates that bank impingement vortices are an important source of secondary flow in vegetated braided streams and suggests that it would be worth developing a detailed model for vortex generation at resistant banks and the subsequent evolution of the vortex as it interacts with the flow field.

4.4. Surface Flow Dynamics

Other evidence that vegetation affected flow dynamics was seen in comparisons of velocity vector statistics between runs. We measured an increase in velocity vector angle deviation with the addition of vegetation. This angle deviation increase is probably related to flow moving around vegetated bars and islands of higher resistance. As flow moves downstream toward a vegetated island, it can either flow across the island, a shorter path with higher resistance, or around the island, a longer path with lower resistance. Because the length of the flow path around the island varies depending on the width of the bar or island and the resistance varies with the density of vegetation, the proportion of flow moving around the island depends in part on both the geometry of the island and the density of vegetation.

To test the possibility that the increased angle deviations are the result of flow steering around zones of higher resistance, we linearized a two-dimensional flow model and introduced a small-scale sinusoidal perturbation to the flow resistance in two dimensions [Nayfeh, 1993]. This had the effect of creating islands of higher resistance, similar to the vegetated braided systems in our flume. Using this model, we introduced a small-scale perturbation $\varepsilon$ to the resistance $C_f$ and analyzed the resulting velocity field. For the experiments, $\sigma_d$ increased 0.07–0.27 rad between runs with and without vegetation. We used the linearized system to see if it was possible to achieve the increase in $\sigma_d$ seen in our experimental data [Gran, 2000].

We found that to get an increase in $\sigma_d$ of 0.07 rad, $\varepsilon$ had to be at least 0.53; that is, the resistance had to vary by 53%. An $\varepsilon = 0.53$ translates into a maximum $C_f = 0.13$. We computed an estimate of $C_f$ for our experimental vegetation by approximating the stems as vertical cylinders and summing the drag along each cylinder set into the flow plus the bed resistance. For our lowest density run this gives a $C_f = 0.18$, which is comparable to but still higher than the maximum $C_f$ in the linear perturbation model using $\varepsilon = 0.53$. That the linearized theory does not work perfectly is not surprising; an $\varepsilon = 0.53$ is hardly a small perturbation, so rather it is surprising that the linearized theory comes as close as it does. It should be more applicable at lower vegetation densities. Observationally, there also appears to be a threshold density where the resistance is so high that flow is essentially blocked by the vegetation, and the bulk of the flow is forced around the vegetation. Our vegetation densities were all above this threshold. This could explain why we saw no link between $\sigma_d$ and increasing vegetation densities.

If vegetated islands tend to block the flow completely, then island geometry should control variability in flow direction. Island geometry was primarily a function of the geometry of exposed bars when the flume was seeded rather than vegetation density. Differential erosion at the edges of islands was minor compared with the initial location of bars prior to seed-

5. Conclusions

Our study was designed to test if vegetation alone could affect channel geometry and flow dynamics in a braided system and to determine how the magnitude of the effects varies with vegetation density. By running a series of physical experiments where the only variable was vegetation density and other variables, including grain size, slope, sediment discharge, and water discharge, were held constant, we were able to show that riparian vegetation can substantially alter channel geometry and flow characteristics. Our results indicate that as vegetation density increases, lateral mobility decreases, braiding intensity decreases, width to depth ratios decrease, maximum channel depths increase, and channel relief increases. The relationships we observed between vegetation density and channel geometry, bank stability, and lateral mobility are similar to many observed in natural rivers, even though most field studies examining variable vegetation density effects have concentrated on single-thread channels. Of particular relevance to braided systems is the relationship between scour holes and vegetated banks and bars. This includes decreased scour hole mobility, increased scour hole depth, and the introduction of oblique bank impingement–driven secondary flow in channels with riparian vegetation.

In the run with the highest vegetation density, width to depth ratios approached those of natural single-thread channels, the braiding intensity decreased, and in plan view the model resembled a wandering river, with one to two main channels flowing around larger vegetated islands. Although we cannot tell if changes in vegetation alone are enough to alter the general pattern of a river from braided to meandering, we have shown that vegetation plays an important role in stabilizing the banks, constraining channel migration, and allowing deeper and narrower channels to develop. These are all effects that move the channel pattern in the direction of meandering.

Acknowledgments. This research was funded through a grant from the National Science Foundation (EAR-9628393). Additional funding came from a Graduate School Fellowship through the University of Minnesota and a Francis Gibson Fellowship through the Department of Geology and Geophysics. We appreciate the comments from two anonymous reviewers.

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(Received January 10, 2001; revised April 2, 2001; accepted June 23, 2001.)