Abstract: A series of laboratory flume experiments were performed to study the effect of stream barbs on flow field dynamics and sediment erosion in a 135° mobile-bed channel bend. Stream barbs (also known as spur dikes or submerged groynes) are low-profile linear rock features that redirect high velocity flow away from the outer bank of channel bends. Unlike emergent groynes, the submerged nature of these structures creates a unique combination of horizontal shear (plunging type flow) and vertical shear (at the groyne tip). Spatially dense, high frequency velocity data were collected and analyzed to describe the pattern and magnitude of three-dimensional (3D) velocity throughout the bend and in the vicinity of the stream barbs. This paper demonstrates that the outer bank region (particularly between barbs) may still be at risk of erosion (or even increased erosion greater than the same case without barbs) if stream barbs generate excessive secondary velocities (because of their size and layout) that are opposing the primary secondary flow naturally occurring in channel bends. Characterizing the role of flow field dynamics on the pattern of deposition and erosion through experimental measurements provided valuable data about how such flow features contribute to local scour, and about the performance of these structures. DOI: 10.1061/(ASCE)HY.1943-7900.0000655.

CE Database subject headings: Channels; Hydraulic bend; Experimentation; Secondary flow; Scour; Three-dimensional flow.

Author keywords: Channel bend; Stream barbs; Groynes; Laboratory experiment; Secondary flow; Local scour; Submerged groynes.

Introduction

Many different in-stream engineering measures exist for protecting stream banks and preventing unwanted erosion. Excessive stream bank erosion can damage infrastructure and degrade aquatic habitats by increasing fine sediments in the channel substrate and widening streams (Espinosa et al. 1997; Sekely et al. 2002). A relatively new approach to sustainable stream bank protection is the stream barb, a submerged variation of a groyne, similar to spur dikes and bendway weirs. Stream barbs (or barbs) are low-profile linear rock structures, typically anchored, in series, to the outside bank in stream bends that extend in an upstream direction away from the bank into the flow (USDA 2005). This configuration redirects flow away from the outer stream bank and disrupts the velocity gradient close to the outer bank, encouraging sediment deposition adjacent to the barb, near the bank. Moreover, with time, barbs cause the thalweg in a channel bend to relocate away from the outside bank region (an undesirable and unstable location) to a new more stable location closer to the channel centerline.

Unlike traditional measures of stream bank protection, such as riprap, concrete paving, or gabion walls, which impede the establishment of vegetated stream banks, hydraulic structures, such as stream barbs that redirect the flow, are a more environmentally sustainable means of maintaining stream bank stability. As well as providing bank protection, these structures promote vegetated stream banks (Piper et al. 2001), create resting pools and scour holes for fish habitat (Shields et al. 1998) and increase the biodiversity of aquatic species (Shields et al. 2000). Research is therefore needed to investigate the suitability and optimal design of stream barbs in channel bends. The most recent studies of fluid and sediment dynamics around spur dikes and barbs considered straight laboratory channels (Fox et al. 2005a, b; Kuhnle et al. 2008) and nonsimultaneous measurements of flow field and bed morphologies (Bhuiyan et al. 2009). The one exception is the recent study of thin bank-attached vanes by Bhuiyan et al. (2010). The writers are not aware of any laboratory or field studies that investigated the spatial variation in three-dimensional (3D) turbulent flow structure and associated patterns of scour and deposition around a series of upstream-angled rock stream barbs in a channel bend, in which, in practice, these structures are most typically deployed. The systematic study of the effects of in-stream structures on local flow and sediment transport processes under controlled conditions in a large-scale laboratory flume are rare. Such investigations are critical if these complex processes are to be understood and the necessary data for validating numerical models are provided. This is especially true for mobile bed conditions, for which data are most lacking, despite being vital for linking the influence of flow patterns and turbulence to sediment transport processes.

Flow in a channel bend can be characterized by the secondary (or helical) flow that develops as a result of centrifugal forces imposed on the flow attributable to the bend geometry and super-elevation of the water surface. Secondary flow introduces a transverse shear that alters the distribution of bed shear stress (e.g., Dietrich and Whiting 1989; Blanckaert et al. 2008) and near-bed turbulent stresses (Jamieson et al. 2010; Termini and Piraino 2011) across a channel section and consequently influences...
the distribution of sediment. As the secondary flow interacts with the primary streamwise flow, the result is maximum shear stress on the outside of the bank downstream of the channel bend, leading to increased erosion in the outer bank region (Dietrich and Whiting 1989). In a sharp meander bend, superelevation is greatest where the primary flow collides with the outer bank, resulting in pronounced downwelling velocities that impinge on the bed and are likely the primary cause of bed scour (Blanckaert 2010). The purpose of placing stream barbs in a channel bend is to disrupt the secondary flow, thereby reducing outer bank shear stress and transport. One mechanism for disrupting secondary velocities is the plunging (or downwelling) flow that develops immediately downstream of submerged barbs during overtopping conditions. The plunging flow leads to some substantial differences in the geometry of scour holes for in-stream structures without overtopping flow (Kuhnle et al. 1999, 2002). These observations need further investigation. It is not known what effect the plunging flow has on maximum scour depth and on the disruption to secondary flow and hence, the function and reliability of different barb shapes, sizes, and arrangements in channel bends. Understanding the flow in detail should provide a better means of predicting the resulting bed level changes for various barb geometries and orientations.

A number of different laboratory experiments on bank-attached submerged structures (e.g., stream barbs, submerged groynes, spur dikes, bendway weirs, and vanes) in open channel flows have been performed: Kuhnle et al. (1999); Johnson et al. (2001); Kuhnle et al. (2002); Matsuura and Townsend (2004); Fox et al. (2005a, b); Jia et al. (2005); Uijttewaal (2005); Kuhnle et al. (2008); and Bhuiyan et al. (2009, 2010). A review of these studies highlights a few of the gaps in the current literature: (1) the limited number of studies that consider a meandering or channel bend planform, for which the use of these structures is most relevant; (2) the absence of detailed velocity and turbulence measurements; (3) the absence of coupled mobile-bed studies with comprehensive velocity and turbulence measurements. Other (less relevant) experimental studies include nonsubmerged (or emergent) groyne studies (Uijttewaal et al. 2001; Weithrech et al. 2002; Sukhodolov et al. 2002); scour depth studies at abutments (Melville 1992; Lim 1997) and spur dikes (Garde et al. 1961; Gill 1972; Kuhnle et al. 1999); those with a focus on numerical simulations (Minor et al. 2007a, b; McCoy et al. 2008; Koken and Constantinescu 2008a, b), and finally, those with a habitat objective (Biron et al. 2004), in which the prevention of stream bank erosion was not a principal objective and therefore, was not investigated in detail.

Flume experiments by Kuhnle et al. (1999, 2002, 2008) involved a single spur dike oriented perpendicular (Kuhnle et al. 1999, 2008) and angled (Kuhnle et al. 2002) along a straight laboratory sand-bed channel. The earlier studies (Kuhnle et al. 1999, 2002) characterized the volume of the scour hole at the tip of the spur dike, whereas the latter study (Kuhnle et al. 2008) investigated the flow field in detail over a fixed, flat bed. Kuhnle et al. (2008) found that the 3D flow separation at the spur dike yielded forces on the bed that were significantly different from nonsubmerged vertical obstructions that were measured in other studies. The maximum bed shear stress adjacent to the dike was found to be approximately 2.7 times the approach flow value, which is substantially less than that found for emergent flat plates mounted perpendicular to the flow. Koken and Constantinescu (2008a) also found the largest bed shear stress values to be near the tip of the spur dike. Fox et al. (2005a, b) considered a single submerged groyne (angled 50° with the upstream bank) along a straight laboratory channel, but separated their measurements of velocity and scour. In both studies, velocity was measured for immobile, flat bed conditions; whereas scour tests were performed by Fox et al. (2005a), but for which no velocity measurements were made. Most recently, Bhuiyan et al. (2010) presented velocity and turbulence measurements in a meandering channel with and without a series of “bank-attached” vanes, constructed with 2 cm-wide plywood, which sloped from bankfull height at the outer bank down to the bed. Unlike previous laboratory studies, live bed scour conditions were simulated, which allowed testing of the functionality of installing the vanes after equilibrium scour in the meander bend was reached. Under live bed conditions, the performance of vanes to reduce scour along the outer bank through deposition in the vicinity of the vanes could be studied.

Matsuura (2004) tested the effectiveness of different barb arrangements in series (barb groups), in both 90° and 135° channel bends with a mobile sand bed. However, due to an absence of velocity data, these experiments were unable to characterize the flow field. As well, the experimental bars were constructed out of a fine metal mesh (approximate width <2 mm), essentially creating a two-dimensional, permeable structure. Preliminary tests showed that any increase in width, or the use of a more trapezoidal cross section, would result in severe local scouring beyond the available depth of sand in the channel [just as Kuhnle et al. (2008) predicted with their measurements of bed shear stress, and as the writers have found in these current experiments]. This is also a limitation of Bhuiyan et al.’s (2009, 2010) studies of vanes. The extent of local scour (depth and volume) adjacent to a submerged structure will depend on the geometry and size of the structure (in addition to local flow features), and every effort should be made to reproduce realistic scales of structure geometry in the laboratory. The bars built for the current laboratory study were constructed of loose stone (i.e., solid and slightly permeable material) with a roughly trapezoidal cross-sectional shape, representing a realistic model of field-scale barbs.

With the exception of Bhuiyan et al. (2010), who presented results at select cross sections through the meander bend, to date, the most detailed flow measurements have been for a single structure only and one that was installed along a straight section (Fox et al. 2005b; Kuhnle et al. 2008). Given that the primary objective of stream barbs is to reduce bank erosion, which is usually most severe along the outside banks of river bends, it is critical that future studies focus on channel bends. The helical (secondary) flow generated in a channel bend will alter the magnitude and direction of velocity as the flow approaches the barb and, as a result, the flow over and past the structure. This will, in turn, play a role in local flow field characteristics and ultimately how the structure functions to disrupt velocity and shift the thalweg to the center of the channel, away from the outer bank.

Matsuura (2004) found that, although scouring in a 135° bend without bars was significantly greater than in a 90° bend, barb groups in the 135° bend performed better. For all tested flow conditions and barb group arrangements, the maximum scour reduction in the 135° bend was greater than in the 90° bend. However, it is assumed here that “maximum scour reduction” refers to total scour in the channel, because with rigid, vertical acrylic walls, it is not possible to evaluate the reduction in scour of the outer bank. This suggests that in this case, the percent reduction may not be a useful metric because some scour at the barb tip is desirable. In fact, of the relevant laboratory-scale mobile bed studies that have been performed, none have studied bank erosion—the initial conditions of all past mobile bed experiments were horizontal (flat) beds with rigid vertical side walls. In this study, a sand bed with a trapezoidal-shaped cross section was installed inside a flume having a rectangular cross section. With this arrangement, both the bed and banks of the channel, in which the model bars were installed, were subject to scour.
This paper presents the first experimental results to describe the spatial variability of the complex flow field and changes in channel bathymetry for a series of barbs in a channel bend. These experiments were designed to address the weaknesses of previous studies and incorporate such novel features as (1) spatially dense 3D flow data; (2) the use of a mobile bed and bank trapezoidal channel; and (3) the use of barbs made of scoured rock riprap. The results of this study provide suggestions for optimizing barb structure design for stream bank protection or other requirements (i.e., scour holes for aquatic habitat); and at the same time, for advancing our understanding of the role of these coupled processes in general. These results have implications for employing other similarly submerged in-stream structures and for understanding natural fluvial features for which similar plunging flow conditions (or horizontal flow separation) are found; such as, forced riffle-pools and dune fields.

**Experimental Methods**

**Data Collection and Processing**

Six different laboratory experiments were performed using the large bend flume located in the Civil Engineering Hydraulics Laboratory at the University of Ottawa (Fig. 1, Table 1). The flume has a centerline length of 18.5 m, with a 12.19-m long approach section, followed by a 135° bend section, with a constant radius of curvature of 1.5 m (at the channel centerline) and a straight 2.4-m long exit section [Fig. 1(a)]. The flume is 1.0 m wide, with 0.9-m high vertical acrylic walls, which contained a trapezoid cross-sectional channel formed entirely of sand [Fig. 1(b)]. The sand has a mean diameter ($d_{50}$) of 1.1 mm, with 98% of particles falling within a range of 0.6–1.8 mm. The geometric standard deviation is 1.57 mm. The trapezoid channel has a depth of 0.15 m, side slopes of 29° (approximately equal to the angle of repose), a bottom width of 0.26 m, top width of 0.80 m, and floodplain widths of 0.15 m (right, outside bank) and 0.05 m (left, inside bank) [Fig. 1(b)]. Cohesive floodplain sediments were not modeled, thereby providing a conservative design approach for which noncohesive sediment (sand) with the same erodibility as the bed was used.

A summary of the experimental conditions and parameters for each run is provided in Table 1. The six runs were labeled TR1, TR3, TR5, TR6, TR7, and TR10 (where TR stands for trapezoid run). Each experiment began with a constant bed slope ($S = 0.0007$), a uniform flow condition, and a horizontal cross-stream bed (along the base of the trapezoid section). Experiments were conducted under clear water scour conditions, wherein flow in the approach section was near the threshold of particle motion and negligible movement of sand grains was observed. Therefore, scour and deposition in the bend was attributable to the presence of the bend alone (TR1 and TR3) or a combination of the bend and the presence of barb structures (TR5, TR6, TR7, and TR10). Only water was recirculated during each experiment.

The first two experiments (TR1 and TR3) represented the base case conditions (i.e., no bars) for two different flow rates ("low flow," $Q = 0.017\text{ m}^3/\text{s}$ and "high flow," $Q = 0.021\text{ m}^3/\text{s}$). The other four experiments represented various barb arrangements for the same flow conditions as TR3 (Table 1). For all experimental runs, acoustic Doppler velocimeter (ADV) data were collected over a series of consecutive days once the bed conditions had reached equilibrium, and stationarity (i.e., static bathymetry) within each run could be assumed. Water flowed permanently for the duration of each run, which included the time to reach equilibrium bathymetry and to obtain ADV data. Equilibrium bathymetry was determined by regularly monitoring the extent of floodplain erosion along the outer bank. When this erosion showed no sign of change over a 24-h period, it was assumed that equilibrium scour was achieved. All high flow experiments were run for 300–400 h (Table 1), whereas the low flow run (TR1) required only 213 h.

--- ADV Data

![Fig. 1. Experimental set up: (a) plan view of channel geometry and location of ADV measurement cross sections; (b) cross-sectional view (looking downstream) of trapezoid dimensions for which water depth $h = 0.15\text{ m}$ at bankfull flow (i.e., when water level was equal to the height of the floodplains); side slope angle $\theta = 29^\circ$; all dimensions are in meters, and the streamwise velocity component $U$ is parallel to the flume wall throughout the domain; (c) barb geometry parameters (see Table 2 for variable explanation and values)](image_url)
to reach equilibrium bathymetry and subsequently to obtain ADV data. Run time among the high flow runs varied based on the number of cross sections measured with the ADVs (Table 1). TR6 and TR7 had the lowest high flow run times (362 and 310 h, respectively) because they had the fewest measured cross sections, compared to the 13 cross sections obtained in other high flow runs (TR3, TR5, and TR10). ADV measurement locations for each run are listed in Table 1.

Instantaneous velocity measurements in the streamwise (u), cross stream (v), and vertical (w) direction were made by using three Nortek Vectrino (four-beam) ADVs (two down-facing probes and one side-facing). However, to reduce the background acoustic noise, no more than two ADVs were ever in operation at the same time. The ADVs were mounted on a movable carriage, with each mount providing adjustment of the instruments in the lateral (cross stream) and vertical directions. The ADVs were orientated vertically and orthogonal to the flume walls in the straight approach section and through the channel bend. This arrangement provided a consistent frame of reference from which the spatial patterns of the mean flow field through the entire bend could be assessed. Fig. 1(a) shows the ADV measurement locations in plan view. The ADV transducers must be fully submerged in the flow, and because the sample volume was approximately 50 mm from the central (emitting) transducer, it was not possible to collect data because the sample volume was approximately 50 mm from the central (emitting) transducer. Therefore, at select cross sections (for example, where flow overtopped a barb), the side-facing probe was used to obtain velocity data at up to 20 mm below the water surface.

The ADV configuration parameters were identical for each run: sampling time = 120 s; sampling frequency = 100 Hz; nominal velocity range = 0.30 m/s; transmit length = 1.8 mm, sampling volume diameter = 6.0 mm, and sampling volume height = 5.5 mm. The spatial coverage of measurement points in each experiment varied based on a compromise between overall coverage of the channel bend, the density of measurement points in each cross section, and the performance of the barbs to reduce scour at the outer bank [i.e., less successful runs, such as TR6 and TR7, had ADV data at only 4 and 3 cross sections, respectively (Table 1)]. Typically, each cross section consisted of 10–12 evenly spaced vertical profiles, with measurements in the vertical direction at intervals of 5 mm near the bed, 10 or 20 mm in the middle half of the flow depth, and 30 or 40 mm closer to the water surface (unless side-facing ADV data were obtained, then data were typically 10 or 20 mm apart near the water surface).

The raw times series data were processed with Matlab code to calculate mean statistics. Raw data were filtered based on a vertical velocity error of 0.1 m/s and despiked based on thresholds for both acceleration (local acceleration > 1.5 g, where g = 9.81 m/s²) and standard deviation, σ (for velocity > 4σ from the mean) (Nikora and Goring 1998). Further details regarding ADV data processing, filtering, and despiking are provided in Jamieson et al. (2010), in which the same processing techniques were applied. The processed ADV point measurements of u, v, and w were used to calculate time-averaged velocities (U̅, V̅, and W̅).

Estimates of shear velocity (U̅s) in the primary channel approach section were made from a linear regression of the measured velocity profiles, whereas bed shear stress (τo) was calculated as τo = ρU̅s² (Table 1). Average U̅, and τo for each run were calculated as the averages of values determined from three measured vertical velocity profiles taken near the center of the 11.5 m cross section. This regression method was considered superior to the reach-averaged calculation because these values were based on local flow conditions and incorporated considerably more data. The 11.5 m section was used for this analysis because it was sufficiently downstream of the flume entrance to ensure that flow was fully developed, yet sufficiently upstream of the bend to ensure that flow was not influenced by the bend.

After each run, the flume was drained and the elevation of the sand bed profile was measured by using a Leica systems Disto pro4a laser altimeter, which provides a precision of ±1 mm. Bed level measurements were taken every 0.01 m in the cross-sectional direction and at 2.5° intervals through the bend and every 0.10 m in the straight section, with the exception of TR10, for which the cross-sectional interval in the vicinity of the barbs (i.e., scour holes) was 1°. Kriging, with an anisotropic spherical model variogram fit to the experimental variogram, was used to interpolate the bed level measurements into a two-dimensional (2D) contoured surface. The grid spacing of the interpolated surface was 0.05 × 0.05 m and consistent between experiments to facilitate comparison between runs.

**Spatial Interpolation**

To assess the spatial variability of all measured components, the individual ADV point measurements from each run were combined to generate a continuous 3D volume of the flow field. The interpolated (2D) bathymetry data were used to generate a structured 3D volume grid of the entire flow field for each of the runs, with complete coverage of ADV data (TR1, TR3, TR5, and TR10). The 3D grid spacing in the streamwise direction included sections every 0.10 m in the straight and exit sections and 5° through the bend; 11 cells were specified in the cross-stream direction and 10 vertical cells from the bed to the water surface.

### Table 1. Summary of Experimental Runs

<table>
<thead>
<tr>
<th>Run title</th>
<th>Barbs (quantity)</th>
<th>Q (m³/s)</th>
<th>H (m)</th>
<th>W/H</th>
<th>U (m/s)</th>
<th>U̅s (m/s)</th>
<th>τo (N/m²)</th>
<th>Duration (h)</th>
<th>ADV measurements (cross section)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR1</td>
<td>No</td>
<td>0.017</td>
<td>0.142</td>
<td>5.6</td>
<td>0.231</td>
<td>0.011</td>
<td>0.123</td>
<td>213</td>
<td>• 11 m, 11.5 m, 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 16 m, 16.3 m</td>
</tr>
<tr>
<td>TR3</td>
<td>No</td>
<td>0.021</td>
<td>0.148</td>
<td>5.4</td>
<td>0.267</td>
<td>0.020</td>
<td>0.424</td>
<td>391</td>
<td>• 11.5 m, 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 16 m, 16.3 m</td>
</tr>
<tr>
<td>TR5</td>
<td>Yes (4)</td>
<td>0.021</td>
<td>0.157</td>
<td>5.1</td>
<td>0.264</td>
<td>0.021</td>
<td>0.440</td>
<td>380</td>
<td>• 11.5 m, 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 16 m, 16.3 m</td>
</tr>
<tr>
<td>TR6</td>
<td>Yes (4)</td>
<td>0.022</td>
<td>0.156</td>
<td>5.1</td>
<td>0.276</td>
<td>0.017</td>
<td>0.299</td>
<td>362</td>
<td>• 11.5 m, 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 16 m, 16.3 m</td>
</tr>
<tr>
<td>TR7</td>
<td>Yes (1)</td>
<td>0.021</td>
<td>0.151</td>
<td>5.3</td>
<td>0.264</td>
<td>0.019</td>
<td>0.342</td>
<td>310</td>
<td>• 11.5 m, 0°, 15°, 45°, 95°, 120°</td>
</tr>
<tr>
<td>TR10</td>
<td>Yes (2)</td>
<td>0.020</td>
<td>0.153</td>
<td>5.2</td>
<td>0.255</td>
<td>0.021</td>
<td>0.420</td>
<td>386</td>
<td>• 11.5 m, 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 16 m, 16.3 m</td>
</tr>
</tbody>
</table>

Note: In all runs, original bed slope was 0.0007 and mean sediment size d₉₀ = 1.1 mm. Q is flow rate, H is flume-averaged flow depth in the center of the channel, W/H is the width-to-depth ratio assuming width W = 0.80 m (Fig. 1), U = Q/A is flume-averaged velocity (where cross-sectional area = A), and U̅s is mean shear velocity in the approach section. Barb layouts are shown in Fig. 2.
The processed ADV data were then interpolated into each 3D grid using kriging. The kriging parameters included an eight-point octant search, a range of 0.3, no-drift, and a zero value of 0. The range is the distance beyond which source points become insignificant and is equal to the fraction of the length of the diagonal of the 3D volume that contains the data points. A range of zero indicates that any point not coincident with the destination point is statistically insignificant; whereas a range of one means that every point in the data set is statistically significant for each point. The zero value is a nondimensional measure of variance (from 0–1) of the certainty of the value at a data point. A value of 0 will specify an exact fit with the source points, whereas any value above zero will allow some variance and essentially a smoothing of the data.

**Barbs**

Barbs were constructed by hand using small, angular stone. From the approximately 750 stones selected for barb construction, the average A-axis (longest stone dimension, length) was 0.043 m and the average C-axis (shortest stone dimension, thickness) was 0.025 m. Following standard riprap design criteria [National Cooperative Highway Research Program (NCHRP) 2006], only rocks with an A/C ratio less than 3.0 were used, where the average A/C ratio of all selected stones was 2.2. This ratio criterion eliminated flat and/or needlelike rocks that would compromise stability and be more likely to be captured by the flow and moved. A sliding and overturning analysis was also performed to check that the stone size was suitable for the maximum streamwise velocity in the bend.

Barb dimensions (Fig. 1) and layout varied for each run, and a summary of these is provided in Table 2. In general, all barbs had (1) a bank key connecting the rock structure to the outer bank wall at bankfull height [i.e., the bank key was perpendicular to the channel side wall and its length was equal to the outer bank floodplain extent (0.15 m)]; (2) a bed key in which the barb base was submerged at least 5 cm below the bed surface along its length; and (3) an approximately trapezoidal cross-sectional shape in which the base of the barb was wider than the crest for increased stability of the structure. Given the rock sizes, the barb crest widths varied from approximately 8 cm (2 rock widths, TR5 and TR6) to 4 cm (1 rock width, TR7 and TR10). Barb dimensions, such as length, projection angle, and height, are given in Table 2 and illustrated in Fig. 1(c). Barb slope was set approximately equal to the initial channel side wall (29°). The overall barb layout (barb length, angle, and spacing) was initially specified based on the USDA (2005) design guidelines for stream bars (i.e., TR5 and TR6). Barb dimensions and layout were revised following each run to optimize barb performance, where performance was based on (1) the reduction of scour along the outer bank floodplain; and (2) the development of scour holes at barb tips. Overall, performance was improved as bars were made smaller (length and width reduced) and fewer in number (i.e., two bars versus four bars), but not less than two.

Barb layout was determined by placing the first barb in the location of maximum erosion (or predicted location of maximum erosion), which is typically near the bend exit. Each subsequent barb in series was then added one by one in the upstream direction with a spacing determined by the length and angle of the preceding downstream barb [see USDA (2005) for further details]. It was for this reason that all barb runs had at least one barb located at cross section 16.3 m (0.58 m downstream of the bend exit) because bathymetry results in TR1 and TR3 indicated this to be the location of maximum erosion of the outer bank floodplain (Fig. 2). A plan view of each barb layout is provided in Fig. 2, where, for simplicity, only the barb crests have been delineated with a black line to show barb location and geometry.

Finally, with this form of barb construction, each barb stone was free to move with respect to the others, thereby modeling the same conditions for riprap stone behavior in the field. Although undermining of the structure may cause instability and lead to failure, the freedom of movement provided by the loose stone provided a protective measure from excessive undermining or scour. For example, as the local scour depth at the barb tip increased, rocks at the tip may have fallen into the scour hole thereby armorng the scour hole from further erosion.

**Results and Analysis**

**Bathymetry**

Interpolated contour plots of the equilibrium bed levels (Z) for all six runs are shown in Fig. 2. Contour levels were chosen to highlight erosion of the outer bank floodplain (where the floodplain is described by Z > 0.14 m, orange) and local scour in the vicinity of each barb (Z < 0 m, red), where Z < 0 m indicates bed levels below the elevation of the original trapezoidal base (Z = 0). Figs. 3 and 4 show difference maps of the change in bathymetry (AZ) from the original bed levels (Fig. 3) and from the base case scenario at equilibrium (TR3) (Fig. 4). Both experiments without bars (TR1 and TR3) show maximum erosion to be located downstream of the bend exit, near cross section 16.3 m. This is slightly different from previous mobile-bed experiments in a 135° bend, where maximum scour occurred at (Jamieson et al. 2010) or just upstream of (Matsuura and Townsend 2004) the bend exit. It is possible that the trapezoidal cross section, which incorporated a sloping side wall, produced a less pronounced helical pattern (compared to experiments with vertical immobile side walls), thereby allowing a smoother transition from curved to straight exit section.

In all barb experiments (TR5, TR6, TR7, and TR10), the maximum depth was consistently found in the vicinity of the barbs,
either at the barb tip or along the downstream side of the barb (Fig. 2). Local scour in the vicinity of each barb can be described to fall within two general types: Type I, representing scour at the barb tip; versus Type II, representing scour of the sloping bank, along the leeside (or downstream) edge of the barb. Type II erosion is more likely to lead to erosion of the floodplain behind the barb given its proximity to the side wall and floodplain, whereas Type I is concentrated more in the center of the channel. The exception, however, is in the case of excessive barb tip scour, for example B3 in TR5 (Fig. 2) in which the scour hole at the barb tip was so large and deep that it caused erosion into the sidewall and then floodplain upstream. However, in this case, Type II scour downstream of the upstream barb (B2) is likely to have contributed to floodplain loss as well. Matsuura (2004) found that for a series of barbs, local scour depth at barb tips increased in the downstream direction. However, in both TR5 and TR6, maximum scour at the downstream-most barb (B4, near cross section 16.3 m) was concentrated at the barb tip (Type I), whereas in TR7 and TR10, maximum scour at the downstream-most barb (again near cross section 16.3 m) was concentrated along the leeside of the barb (Type II). It is possible that having three upstream barbs promoted the concentration of scour at the downstream-most barb tip, thereby reducing floodplain erosion immediately downstream of the last barb.

In all barb experiments, maximum erosion of the floodplain was consistently located immediately downstream of each barb, with two exceptions: the downstream-most barbs in TR5 and TR6, which were the only two runs to incorporate 4 barbs (Fig. 2 and Table 2). As scour behind the barb became deeper, erosion at the floodplain behind the barb increased, because the sand side walls eroded to reach a stable side slope. It is likely that in the cases of TR5 and TR6, the three upstream barbs provided enough flow deflection and energy dissipation before the flow reached the bend exit to prevent excessive scour in this region.

All runs (TR1, TR3, TR5, TR6, TR7, and TR10) showed scour along the outer bank (red contours) and deposition through the center of the channel (blue contours) (Fig. 3). This was expected, as eroded material from the outer bank is transported downstream and cross stream toward the inner bank. The greatest scour (for example, up to more than 0.10 m below the original bed elevation) was found in the runs with the greatest number of barbs (TR5 and TR6, four barbs). The barbs in those runs were also larger than in the other two runs with barbs (TR7 and TR10, Table 2). As well, despite having the same number of barbs, TR5 had noticeably more erosion than TR6 because of the use of larger barbs (see Table 2 for
Overall, Figs. 2–4 all show that the larger the barbs (in height and length, see Table 2), the deeper the scour in the vicinity of the barbs (for both Type I and II scour). In all four cases with barbs (TR5, TR6, TR7, and TR10) the outer bank near the bend exit, which corresponded with the location of maximum erosion in the base case run (TR3), was successfully protected ($\Delta Z > 0$, Fig. 4). Furthermore, erosion was reduced along the entire outer bank in the most successful run (TR10). However, for TR5, TR6, and TR7, it would appear that protection of the outer bank floodplain at the bend exit was at the cost of additional erosion, either upstream (TR5 and TR6) and typically between barbs, or immediately downstream of the barb crest for the least protected floodplain (TR7) for which only one barb was used. As well, in the case of the run with the greatest change in bed levels (TR5), erosion of the inner bank was also observed.

**Mean 3D Flow Field**

Contours of time averaged streamwise velocity ($\bar{U}$) near the water surface (at 70% of the flow depth, or 0.70$h$) for TR1, TR3, TR5, and TR10 are shown in Fig. 5. Without barbs, both TR1 and TR3 exhibited a similar pattern of streamwise velocity distribution, where the high velocity core was closer to the inner bank at the entrance of the bend and then shifted outward through the bend with maximum velocity located near the outer bank at the bend exit. This pattern is consistent with experimental observations in other channel bends (e.g., Dietrich and Whiting 1989; Termini 2009). In both cases with barbs (TR5 and TR10), overall streamwise velocity was lower than the base case conditions (TR3), with TR5 exhibiting the most significant reduction. This is likely attributable to the larger scour holes (Fig. 2) generated by the larger barbs (Table 2), establishing an overall greater depth and width throughout the bend and therefore lower streamwise velocity for the same discharge. Fig. 5 also demonstrates the reduction in streamwise velocity along the outer bank attributable to the redirection of high velocity flow provided by the barbs in both TR5 and TR10. The larger barbs in TR5 provided the greatest redirection of flow and therefore showed a greater reduction in near-bank streamwise velocities between the barbs (Fig. 5).

It was the presence of secondary flow in a bend that altered the distribution of maximum streamwise velocity. Secondary flow was best described by the cross-stream ($\bar{V}$) and vertical ($\bar{W}$) velocities (or secondary velocities), as shown by the contour plots in Figs. 6 and 7, respectively. These plots clearly illustrate the development of the secondary flow through the bend at two different depths: near the bed at 0.05$h$, the cross-stream flow was

![Fig. 3. (Color) Bed level changes $\Delta Z$ from original bed to final equilibrium for which red contours indicate sediment loss (erosion); blue contours represent sediment gain (deposition); and green and yellow contours represent severe scour ($\Delta Z < -0.10$ m)](image)
directed toward the inner bank ($\bar{V} > 0$), whereas closer to the water surface at $0.70h$, the flow was directed toward the outer bank ($\bar{V} < 0$). Together with the vertical velocity, which showed high negative vertical velocity along the outer bank and high positive vertical velocity along the inner bank (at both depths), the pattern of secondary velocities was consistent with the expected pattern of secondary, helical flow in bends. When barbs were present (TR5 and TR10), cross-stream velocities opposite the barbs were concentrated closer to the center of the channel, away from the outer bank. In TR5, this modification also led to higher cross-stream velocities through the bend because a greater amount of the flow was altered by the larger and more numerous barbs.

**Fig. 4.** (Color) Bed level differences from TR3 (base case run with no barbs)

**Fig. 5.** (Color) Streamwise velocity $\bar{U}$ at 70% of the flow depth ($0.70h$) for four runs with complete ADV coverage (Table 2): TR1, TR3 (without barbs), and TR5 and TR10 (with barbs), in which velocity vectors are shown in black and represent the location of each ADV measurement, and dark hatched areas represent regions in which no ADV data were collected. The vector colour depends on the depth of the measurement (i.e., above or below $0.70h$); measurements above the contoured slice will appear darker, while those below will appear lighter.
In the vicinity of individual barbs, three-dimensional mixing was generated, causing a reverse direction in cross-stream and vertical velocities [i.e., negative cross-stream velocities near the bed in the outer bank region (Fig. 6)]; and highly positive vertical velocities between barbs near the outer bank (Fig. 7). The plunging action of the flow over the barbs was demonstrated.

Fig. 6. (Color) Cross-stream velocity $\bar{V}$ at a depth of 0.05$h$ (top) and 0.70$h$ (bottom), in which positive cross-stream velocity is toward the left, inner bank.

Fig. 7. (Color) Vertical velocity $\bar{W}$ at a depth of 0.05$h$ (top) and 0.70$h$ (bottom), in which vertical velocity is positive in the positive z-direction (up)
in the $\bar{W}$ contour plots for both runs with barbs (TR5 and TR10), for which vertical velocity immediately upstream and downstream of each barb showed highly positive and negative velocity, respectively. The near bed (0.05h) cross-stream velocity toward the outer bank in TR5 would suggest horizontal mixing, where separation or shear at the barbs caused flow to be directed toward the outer bank and opposite to the typical secondary flow pattern. Interestingly, the contour plots of secondary velocity also showed that the presence of the four large barbs in series in TR5 may actually have had the effect of pushing the helical flow upstream beyond the start of the bend; significantly higher vertical velocities were noted upstream of the bend entrance (0°) in TR5 compared to the other three runs (TR1, TR3, or TR10).

All four runs with complete ADV coverage (TR1, TR3, TR5, and TR10) showed a local increase in cross-stream velocity toward the outer bank near the water surface at the 135° cross section or bend exit (Fig. 6, 0.70h). This trend could be explained by the local amplification of the helical flow at the bend exit as it transitions from a curved channel planform to a straight one, which could help to explain why the maximum erosion in the bend was typically located near the bend exit. This local increase also appeared to have been shifted away from the outer bank in the case of runs with barbs (TR5 and TR10), for which the higher negative cross-stream velocity was closer to the inner bank than to the nonbarb runs (TR1 and TR3). This pattern could be contributing to reducing the erosion at this location for the barb runs.

The effect of the barbs on secondary velocities is also presented for cross sections immediately upstream and downstream of individual barbs in TR5 and TR10, with data from TR3 included as a reference, in Fig. 8. This plot clearly shows the traditional helical flow pattern through the bend (TR3) and the development of a counter-rotating secondary flow cell along the outer bank, downstream of the barb at 105° for TR5 (but not at 120° for TR10). Bhuiyan et al. (2010) also found that the plunging flow over the crest of their vanes generated a secondary flow cell that counteracted the main secondary flow cell that was created by centrifugal forces in the bend. They suggested that this was responsible for shifting the higher velocity away from the outer bank. However, TR10 results suggested that a counter-rotating cell may not be necessary for the shift of the high velocity core in a barb field: both barb runs (TR5 and TR10) showed a reduction and shift in the streamwise velocity core.

![Figure 8](https://www.journals.hayes Emmett et al. 2013.139:154-166.

Barb and Channel Geometry
As previous research has suggested (Matsuura 2004; Kuhnle et al. 2008), the geometry or size of the structure will have an effect on the pattern and magnitude of the local scour depth. In the present study, the magnitude of scour (extent and depth) was greatly reduced when the size (height, width, and length) and number of barb structures were reduced. However, it is important to differentiate between desirable scour at the barb tip (Type I) and scour of the floodplain or bank (Type II). To compare the results from this study to previous studies is difficult because the pattern of scour in the vicinity of the barbs is a function, in part, of the original trapezoidal channel geometry. Unlike previous experiments with rectangular cross sections, incorporating erodible channel side slopes composed of the same material as the bed complicated the analysis. For one, for noncohesive materials, the critical shear stress for side slopes is less than for the bed because of the contribution of gravitational force in aiding sediment particle motion. Therefore, the side walls are already more susceptible to erosion, which would likely explain the dominance of Type II scour in the vicinity of the barbs. Physical modeling with cohesive floodplain sediments and relatively erodible noncohesive bed sediments may have resulted in greater Type I scour at barb tips. Previous studies with rectangular geometries and fixed side walls (Kuhnle et al. 1999; Kuhnle et al. 2002; Matsuura and Townsend 2004; Fox et al. 2005a, b; Jia et al. 2005; Kuhnle et al. 2008; Bhuiyan et al. 2009, 2010) failed to demonstrate the effect of barbs on actual bank erosion. The focus was typically on studying local scour of the bed at the barb tip only. The results of this study suggest that the barb structures greatly influenced the flow field and sediment dynamics along the side slope, and this interaction should not be ignored; particularly when the objective is to protect the near-bank, side slope region. As well, the pattern of near-bank secondary currents depends on the inclination and roughness of the bank, and, at least in the case of straight channels, an inclined side wall will generate an additional vortex (or circulation cell) near the water surface and corner of the channel, whereas increased roughness will strengthen the secondary currents and the corner surface vortex (Blanckaert et al. 2010).

The results from this study indicate that two barbs placed near the bend exit were most effective in reducing outer bank scour. When four barbs were used, the bend exit remained protected, but at the cost of additional erosion to the outer bank side slope, particularly in the regions between each barb. It is likely that flow blockage played a role, where excessive blockage of the cross-sectional area due to large barb geometries would increase scour beyond desirable amounts because the channel adjusted its cross-sectional area to convey the same flow. When only one barb was used (TR7), only the floodplain upstream of the barb was adequately protected (indeed, more protected than the four-barb cases, TR5 and TR6); but excessive scour downstream of the barb caused undesirable outer bank erosion. Barbs should not be placed too far upstream of the bend exit (or location of maximum potential erosion) because flow upstream of the bend will be affected (Fig. 7, TR5), which could compromise overall channel equilibrium and stability. This is another reason for favoring shorter barb lengths because, according to existing design guidelines (USDA 2005), longer barbs require greater spacing and therefore a greater upstream presence. It is difficult to comment on optimum barb spacing because none of the runs with barbs used barbs with the same dimensions. Therefore, it is possible that although spacing was a factor in altering flow and sediment patterns, the influence of barb size cannot be discounted. As well, the degree of curvature in a channel bend also affects optimum barb design (Matsuura and Townsend 2004). Because bank erosion rates vary with the ratio of the radius of curvature to width (Nanson and Hickin 1986), optimum design for a sharp bend (present study) may be different than for a milder bend, for which the secondary flow is weaker. Furthermore, even in sharp bends, locations of scour differ. For example, Roca et al. (2007) showed that in their 183° bend flume, which had the same constant radius of curvature of 1.5 m and flume width of 1.0 m as the present experiments, an outer bank maximum scour hole occurred upstream of the bend apex (between 60° and 80°) as well as at the bend exit. Accordingly, it is likely that optimum barb geometry would differ for their 183° bend.

In summary, the following suggestions are offered for optimum barb geometry and layout:
- Barbs should be placed only in the vicinity of expected maximum erosion. Too many barbs in series, which extend beyond the region selected for protection (particularly in the upstream direction), may cause additional, unwanted erosion by (1) altering and increasing secondary velocities throughout the bend; and (2) reducing the available cross-sectional flow area. The writers emphasize that optimum barb geometry will vary between bends.
- Barb height, width and length should be scaled to (1) minimize any blockage of original cross-sectional flow area; (2) reduce plunging flow and reduce reverse secondary velocities near the outer bank; and (3) prevent excessive local scour at the barb tip causing erosion of the channel side slope while maintaining proportions still capable of deflecting primary streamwise velocity away from the outer bank. In both TR7 and TR10, the barb top was at the elevation of the initial bed surface, thus the barbs did not obstruct flow in the initial trapezoidal channel. Once outer bank erosion began to occur, the barbs began to deflect flow toward the center of the channel.
- The barb bank key width should be wider than the barb itself and should be extended along the channel bank in the downstream direction because the floodplain directly downstream of the barb is particularly susceptible to erosion.

Secondary Velocity
How the secondary flow in the bend is disrupted or altered due to the presence of barbs appears to play a role in the distribution of sediment and the pattern of scour. In TR5, plunging flow was strongest, coupled with cross-stream flow near the bed in the direction of the outer bank and highly positive vertical velocity along the outer bank between barbs—both of which are contrary to the typical secondary flow pattern in a channel bend. It is possible that the complete disruption of secondary flow and the generation of a counter-rotating cell behind (or between) the barbs were responsible for increased erosion in these locations. Bhuiyan et al. (2010) also found that the plunging flow over the crest of their vanes generated a counter-rotating secondary flow cell, but they did not observe erosion downstream of the vanes; in fact, there was evidence of deposition. Such contrasting results may be attributable to the difference in the slope of the channel side walls. In Bhuiyan et al. (2010) the side wall was vertical and fixed, establishing a larger embayment or lee zone downstream of the structure, where velocities may have been more reduced and consequently deposition more likely. Typical emergent groynes will induce recirculating flow downstream of the structure, often leading to deposition in the center of this gyre (dead zone) where velocities are close to zero (Uijttewaal et al. 2001).
However, with a smaller lee zone (due to both the lower profile of submerged and sloping groynes and the addition of a sloping bank), reverse flow is not generated, and the reduction in velocity is less significant.

The results of this study indicate that barbs should not disrupt the secondary (helical) flow in the bend entirely (TR5), but rather weaken it (TR10), particularly near the downstream bend exit, where erosion (without added protection) is typically greatest. The greatest outer bank scour reduction occurred in TR10, in which an outer bank counter-rotating cell was not generated. However, the development of a second counter-rotating cell near the outer bank may be found in bends even without the addition of structures (Bathurst et al. 1977; Blancaert and Graf 2001; Zeng et al. 2008; Jameson et al. 2010; Termini and Piraino 2011). It is thought that this cell stabilizes the region between the outer bank and the center region cell, thereby keeping the core of high velocity at some distance from the outer bank. However, results remain inconclusive (Blancaert and de Vriend 2004; Zeng et al. 2008; Blancaert 2010a), and there is likely more to the role of the counter-rotating cell than is understood. Beyond the simple presence or absence of a counter-rotating cell, its magnitude, size, proximity to the bed, and persistence may all be important in determining whether the counter-rotating cell will diminish or exacerbate outer bank erosion. More research is required to elucidate the importance of these parameters in determining the influence of the outer bank cell on bank erosion.

Conclusions

Experimental results of the bathymetry and mean flow field through a mobile channel bend, with and without submerged barbs, were presented. Contour plots of the 3D flow field, secondary velocities, and bed level changes described the spatial variability of these variables through the bend and in the vicinity of the submerged barbs. Results indicated that the addition of upstream-angled submerged barbs in a channel bend could successfully redirect the high velocity core away from the outer bank region and prevent erosion of the floodplain at the bend exit. However, the size and number of barbs affected the overall amount of erosion incurred along the outer bank throughout the bend. In this particular experimental set-up and bend geometry, the use of two barbs (versus one and four) was found to be most successful in protecting the outer bank floodplain while preventing unwanted bank erosion upstream of the bend exit. Maximum erosion of the outer bank occurred between barbs and, in particular, corresponded with regions of counter-rotating secondary velocities. The highest secondary velocities were associated with the largest barbs, and were located between the barbs. The increased plunging action of the flow associated with the larger barbs and the generation of a counter-rotating secondary flow cell increased erosion downstream of each bar. Lastly, barbs (or any similar type of in-stream structure) worked to prevent erosion of the outer bank, and future laboratory research should not ignore the importance of both a sloping side wall and an erodible bank. These features affected the development and strength of secondary velocities in a bend as well as the interaction between the altered flow field around the barb and adjacent bed levels. By reproducing bank erosion, it was evident that scour of the side slope immediately downstream of the structure could be severe and could compromise the stability of both the side wall (leading to erosion of the floodplain) and the structure itself. This is a problem not seen in previous experiments that used channels with fixed vertical side walls.

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