Stream barb performance in a semi-alluvial meandering channel

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Abstract

A series of seven stream barbs were installed at two consecutive channel bends in Sawmill Creek, a semi-alluvial stream located in Ottawa, Canada. Stream barbs (also known as submerged groynes) are low-profile linear rock structures that extend from the outside bank regions of channel bends in an upstream direction, to redirect the attacking currents and prevent erosion of the bank. As well as providing bank protection, these structures promote vegetated stream banks, create resting pools and scour holes for fish habitat, and increase bio-diversity for aquatic species. Despite these benefits, because of their relative novelty as river training structures, stream barbs are not a common means of stream bank protection in Canada and are possibly non-existent for semi-alluvial or clay channels. Three years of monitoring and measurement of flow conditions (discharge, water velocity and depth) and bathymetry, before (2 years) and after (1 year) the construction of the barbs, have been collected at the Sawmill Creek study site, providing valuable data for understanding their performance in a semi-alluvial channel. Sawmill Creek has a predominately clay bed and banks, presenting a rare opportunity to study the unique dynamics between flow and sediment transport within a clay channel. This paper reports on (i) the unique site conditions and monitoring methodology; (ii) preliminary results of the 3 year monitoring program; and (iii) recommendations for future design and implementation of these structures.
Keywords: stream barb, groyne, channel bend, field measurements, clay.

1 Introduction

In September 2009, a series of seven stream barbs (or barbs) were installed in Sawmill Creek, an urban, meandering stream located in Ottawa, Ontario,

WIT Transactions on Ecology and the Environment, Vol 146, © 2011 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/RM110201

Canada. The project was principally undertaken to serve as a demonstration project for the use of these structures in a semi-alluvial channel. Barbs are a relatively new form of bank protection that, unlike traditional emergent groynes, are designed as low-profile linear rock structures that allow continuous overtopping weir-type flow at bank full (or higher) water levels. Barbs extend in an upstream direction away from the bank into the flow, and are typically anchored, in series, to the outside bank in bends [1]. This configuration redirects the attacking current away from the outer bank towards the center of the channel and also disrupts the velocity gradient close to the outer bank. With time, the thalweg in a channel bend migrates away from the outside bank region (an undesirable and unstable location) to a new more stable location closer to the channel centreline. Unlike traditional bank protection measures such as riprap, concrete paving or gabion walls; these structures require less material, promote vegetated stream banks, create resting pools and scour holes for fish habitat, and increase bio-diversity for aquatic species [2,3].

A number of case studies are available for the West and Midwestern United States, where alluvial (sand and gravel) rivers predominate [2–4]. No such case studies are available for semi-alluvial streams, which highlights the absence of barbs (or equivalent) as a design option for bank protection in these rivers. The performance of these structures and their long term effects on morphology and habitat will largely depend on the local sediment transport characteristics, which are inherently different when cohesive sediments are present: there may no longer be a supply of alluvial sediment upstream and the mechanisms of soil erosion and transport are more complex than for sands or gravel. Moreover, available case studies all consider rural or semi-rural streams. The impact of urbanization (i.e. increased runoff and shorter time of concentration) on the functionality of stream barbs, where the estimation and behaviour of bank full flow conditions is critical for successful barb design, appears to have been excluded from both previous field testing and monitoring, and design documentation. The installation of stream barbs at Sawmill Creek presents a unique opportunity to study the impacts of these structures on a predominately clay bed and bank channel, in a heavily urbanized watershed.

Details of the barb design at the study site, including three-dimensional (3-D) (flow and sediment transport) numerical simulation results of the proposed layout are presented elsewhere [5]. This paper focuses on (i) the unique site conditions and monitoring methodology; (ii) preliminary results of the 3 year monitoring program; and (iii) recommendations for future design and implementation of stream barbs.

2 Study site and monitoring program

Sawmill Creek is located in the City of Ottawa (Canada) and has a total watershed area of 27.7 km^2 and an approximate length of 10 km. The study site includes two consecutive channel bends along a 50 m section of the channel, which are each experiencing bank erosion and mass wasting along their outer banks (Fig. 1). Sawmill Creek is a predominately clay bed channel, with a mix of coarse sand and gravel in the riffles. During low flow conditions from September 16-26, 2009 (Fig. 2), a series of seven barbs were constructed in the two bends (3 barbs in bend 1, upstream and 4 barbs in bend 2, downstream). The barbs were constructed using large rock riprap (500 mm $\leq d_{50} \leq$ 600 mm), with additional smaller riprap (d_{50} ~ 230mm) placed along the bank side slope (50% above/below bank full) upstream of each barb to provide additional protection in these areas. Figures 1A and B shows photos of the seven barbs, which are numbered in the downstream direction. Additional field site information and barb design details are provided in [5].

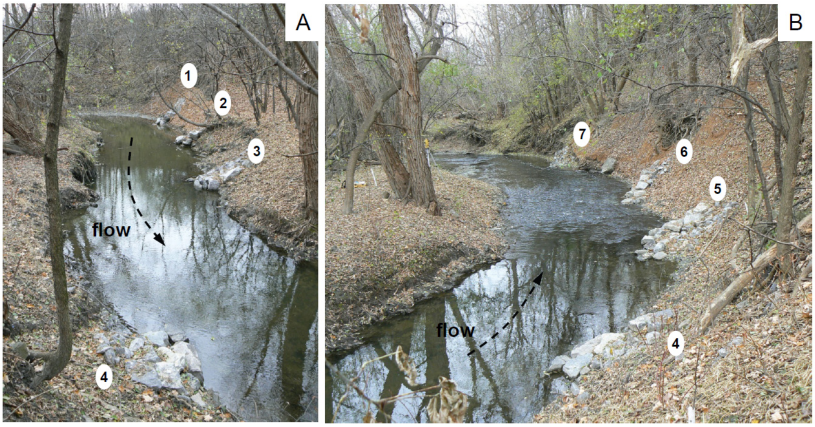

Figure 1: Stream barbs at Sawmill Creek; (A) bend 1 and (B) bend 2. Barbs are numbered in the downstream direction. Photos taken on 9 November 2009, during low flow conditions.

Discharge data for the past three years (2008-2010) were collected at a stream gauging station (CK18-Q1), approximately 1.2 km downstream of the study site, where the contributing watershed at the site is 92% of the watershed at the gauge. Daily minimum, mean and maximum discharge are shown in Fig. 2 and are based on stage data recorded continuously through each season at 15 minute intervals using a HOBO water level logger (submersible pressure transducer). Situated in a highly urbanized watershed, Sawmill Creek responds quickly to rainfall, experiencing large and rapid fluctuations in discharge and water depth following heavy rainfall events. Extreme summer rain events may even exceed the spring freshet (Fig. 2). However, it should be noted that the upper limit of the discharge rating curve is 4.3 m^3/s, and it is not currently possible to estimate discharge beyond this point [6].

Beginning in April 2008, continuous water level measurements were collected each season (typically mid-March to mid-November) using two HOBO water level loggers located upstream and downstream of the study site (CK18-T and CK18-U respectively). These loggers were used to monitor local water surface elevation and temperature at 15 minute intervals. Water surface slope through the study site was calculated as the difference between the daily mean water surface elevation data at each (upstream and downstream) location, divided by the distance between loggers, as measured along the channel thalweg. Distances varied from season to season from 67.2 m (2008) to 82.2 m (2010). A plot of mean daily discharge versus water surface slope for each measurement day for each season is shown in Fig. 3 (excluding data from the barb construction period, September 16-26, 2009).

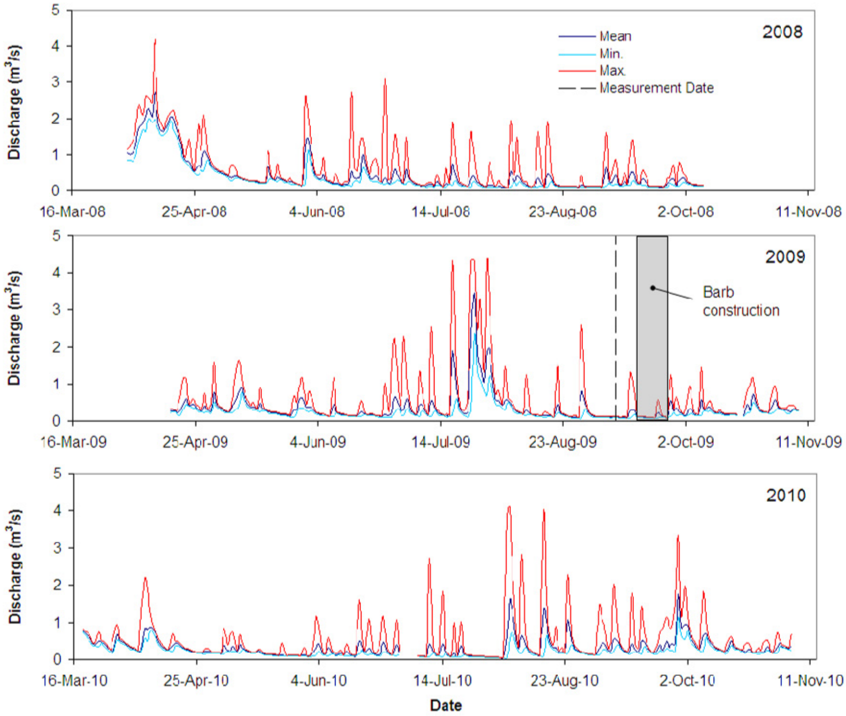

Figure 2: Daily mean, minimum and maximum discharge for 2008, 2009 and 2010 seasons. Measurement date indicates Sept. 9th ADP survey. The two other ADP surveys were on Nov. 21, 2009 and March 1, 2010. Note that the upper limit of discharge estimates was 4.3 m^3/s [6].

Water velocity and discharge data at the study site were collected using SonTek's M9 RiverSurveyor Acoustic Doppler Profiler (ADP). The ADP is an acoustic profiling device, which captures simultaneous measurements of velocity along a single vertical profile. The instrument was mounted on a small boat (photo, Fig. 4) to map the 3-D flow field and depth at the study site. The ADP has a 9 beam system, with two sets of four profiling beams (each set having its own frequency, 3 and 1 MHz) and one vertical beam for measuring depth [7]. The multiple acoustic frequencies allow optimum cell size and operating frequencies to be used for conditions of varying depths. This type of instrument also has a unique advantage in that it is relatively quick and easy to set up and deploy in the field (3-4 hours). This was most critical for collecting spatial surveys in an urban creek that responds rapidly to heavy rainfall events, to ensure data were collected for relatively steady flow conditions and water levels.

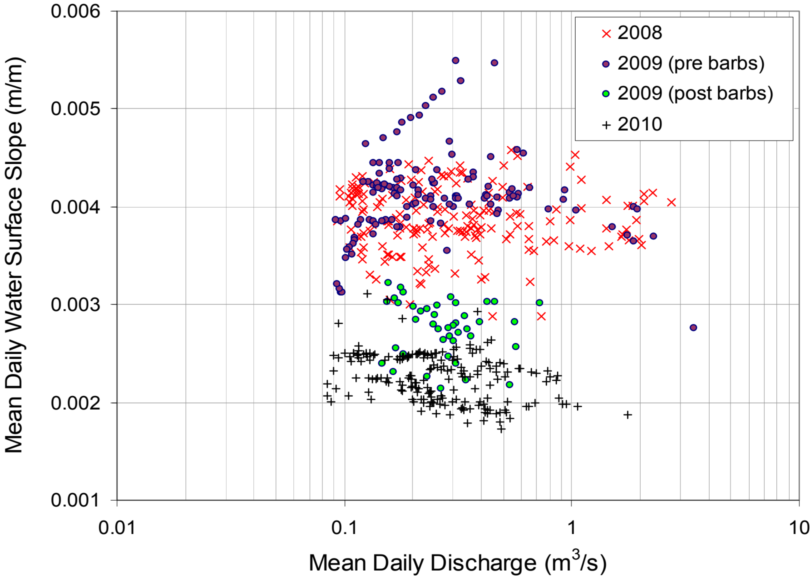

Figure 3: Mean daily discharge versus water surface slope for 2008, 2009 and 2010 season.

Velocity data from three different spatial surveys are presented: September 9, 2009 (pre-barbs), November 21, 2009 (post-barbs) and March 1, 2010 (post-barbs). Discharge on these dates was measured based on repeated ADP transects at the study site and were 0.08, 0.30 and 0.50 m^3/s, respectively. These surveys focus on the flow field in bend 1 only, where it was expected the barbs would have the greatest influence on the flow and morphology. This expectation was based on; (1) the more typical pool geometry in this bend versus the second bend, and (2) the results of the numerical modelling that established the optimum barb design for the site [5]. The numerical study found that the outer bank of the first bend (from T20 – T16, Fig. 5) was most susceptible to erosion.

Lastly, to monitor any changes in bathymetry at the study site, three annual topographical surveys were performed; before (2007 and 2009) and after (2010) the installation of barbs. Surveys were conducted using a total station over a period of 2-3 days in November of each year, for the purpose of identifying any changes that might have occurred from season to season of each year. The surveyed sections (transects) and select results are presented in Fig. 5. Results from the 2009 survey are considered to represent “as-built” conditions as very

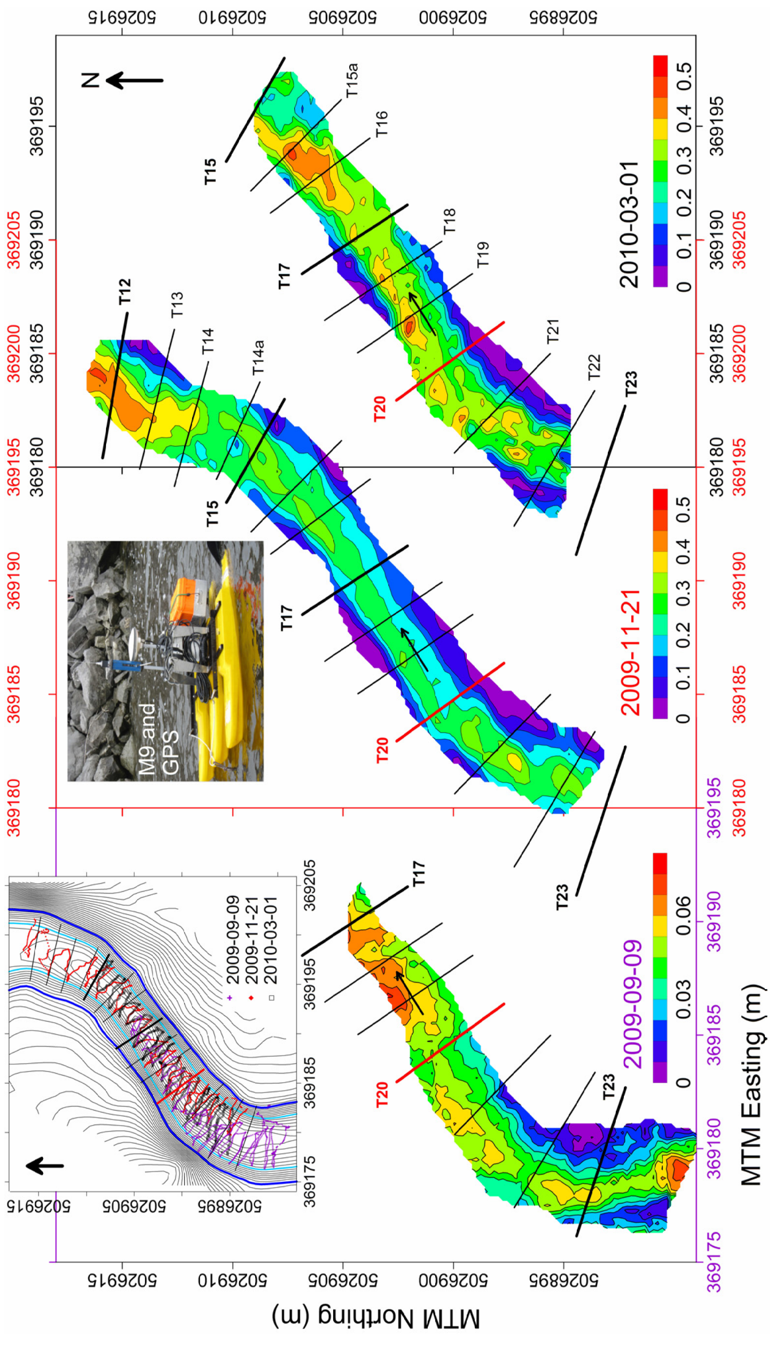

Figure 4: Contours of near surface horizontal velocity magnitude (m/s) for three different spatial surveys (no barbs, Sept. 9, 2009 ($Q \sim 0.1$ m^3/s); and with barbs, Nov. 21, 2009 ($Q \sim 0.3$ m^3/s) and March 1, 2010 ($Q \sim 0.50$ m^3/s)).

little time had passed between barb construction and the survey, and no extreme rainfall or flow events occurred between these activities. Transect locations were selected to monitor changes immediately upstream and downstream of each barb, and in the zones between adjacent barbs. Typically, ~30 points were measured in each section, and an example of point density is shown for transect 23 (T23) in Fig. 5. Barb boundaries and crest elevations were also surveyed to confirm as-built barb dimensions (Figs. 5 and 6).

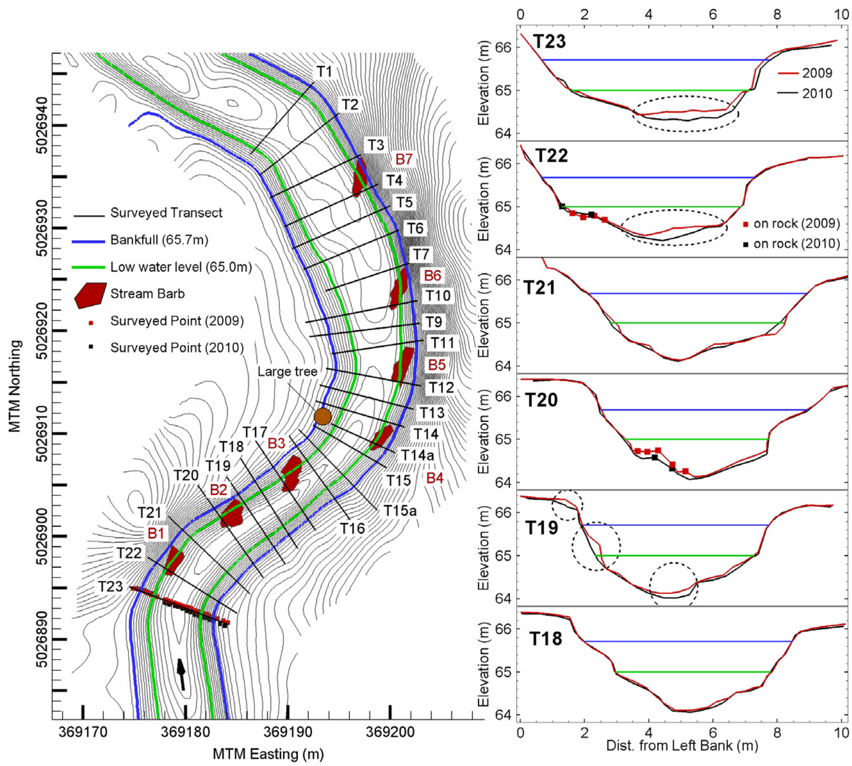

Figure 5: Topographical survey sections (Transects) at the study site and the location of "as-built" barbs. Contour lines are at 0.1 m intervals. dashed circles represent areas of notable bathymetry change.

3 Results

From [5], the channel stability criteria for optimum barb design at Sawmill Creek were to:

- reduce flow velocity and shear stress along the outer bank of each bend;
- prevent erosion at the outer bank of each bend;

- shift the thalweg at the bend apex to a new location closer to the center of the channel and make the thalweg deeper (more stable);
- cause no morphological changes to the channel upstream or downstream of the two bends.

Monitoring results are presented in the context of satisfying these criteria while evaluating overall barb performance.

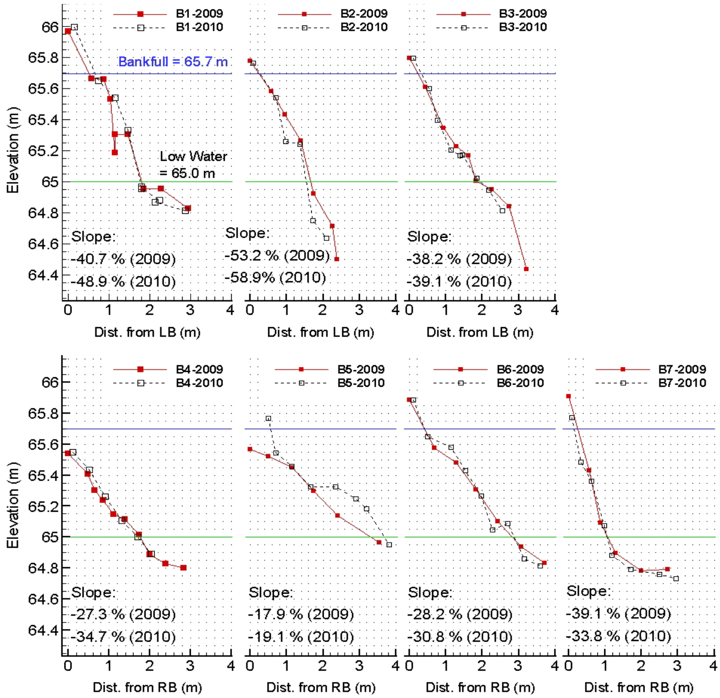

Figure 6: Survey results for barb crests (B1-B3) in bend 1 (top) and barbs (B4-B7) in bend 2 (bottom). The x-axis represents the distance from the left bank (LB) (top) and from the right bank (RB) (bottom).

3.1 Velocity and shear stress

A plot of daily mean discharge versus daily mean water surface slope through the study site is presented in Fig. 3. This figure shows that with the addition of barbs (2009 (post-barb) and 2010 data), water surface slope decreases for all discharges. Without barbs, mean water surface slope was 0.004, while with barbs the mean was 0.002, with the means being statistically different at the 95% confidence interval. Bed slope through the two bends (for all years) is 0.004; therefore, before barbs, flow was uniform. The change in mean water surface slope indicates that the barbs (or barb construction) reduced the water surface slope and that for little to no changes in cross-sectional geometry (i.e. hydraulic radius, R), bed shear stress ($\tau_o = \gamma RS$) through the two bends is reduced. While the reduction in water slope could be due to the barbs causing a local backwater effect due to channel blockage, water levels upstream of the site were consistently lower following the barb construction. A shallow riffle at the apex of the second bend (between T12 – T11) (Fig. 5) was lowered (~ 0.2 m) during barb construction when large debris (including a car axle) were removed. This alteration likely caused the reduction in upstream water levels. Therefore, the change in slope is more likely due to the lowering of the upstream water level, due to the removal of debris and riffle in the second, downstream bend. There appears to be slight positive trend between discharge and water surface slope in the post-barb construction data, where slope decreases with increasing discharge. This trend is not as notable in the pre-barb data.

Velocity contours from the three spatial surveys are presented in Fig. 4. The contours represent the average horizontal velocity from the top two 5 cm cells measured by the ADP using pulse coherent methods. The ADP has a submergence plus blanking distance (which comprise the distance below the water surface that cannot be measured) of 0.15 m. Therefore, the top two cells represent measurements between 0.15-0.20 m and 0.20-0.25 m below the water surface. It was found that velocity data below the two 5 cm cells were less reliable, probably due to employment of pulse incoherent (narrowband) methods, (cells were also larger at 10 and 20 cm) and therefore, only the near surface average (data from the top two cells) have been presented. As well, despite the instrument being integrated with real-time kinematic Global Position System (RTK-GPS), a lack of visible satellites (due to the creek's location in a heavily wooded and deep valley) failed to produce reliable GPS data. Therefore, all surveys are referenced according to bottom tracking (see [7] for further details on bottom tracking). For spatial referencing between surveys and an indication of the density of measured data, the distribution of sampled profiles for each spatial survey are plotted with respect to the channel bathymetry (bank full elevation indicated by the dark blue line) in the inset plot in Fig. 4, and coloured according to survey date. To best facilitate comparison, the contour plots in Fig. 4 have each been shifted and overlapped in the easting direction, where the easting coordinates for each plot correspond to the coloured labels purple, red and black, for 2009-09-09; 2009-11-21 and 2010-03-01 respectively (in yyyy-mm-dd format). The topographical survey transects are also shown in Fig. 4; however, these have been shortened to bank full extents.

The velocity contours show that without barbs (2009-09-09 survey) the core of maximum velocity was along the outer (left) bank, with maximum velocity located near the bend exit or cross-over, between transects T19 and T17. With barbs (2009-11-21 and 2010-03-01), velocity magnitude along the outer bank was reduced and maximum velocity (while still near the bend exit (T16) in 2010-03-01) was shifted away from the bank and towards the center of the channel. The one exception was a portion of the outer bank on 2010-03-01, between T21 and T19, where a region of high velocity was found between regions of low velocity. This location is in the vicinity of the second barb (B2, Fig. 5) and is discussed more in the following section. The two regions of low velocity correspond with flow in the vicinity of B1 (T22) and B3 (T17) (Fig. 5), where the velocity reduction was assumed to result from the presence of these barbs. In all three surveys, flow at the inner (right) bank at the bend entrance was near zero.

3.2 Channel and barb topography

Topographical survey data along select transects (Fig. 5) and for each barb crest (Fig. 6) are presented. Survey results for 2007 are not presented as little to no change was observed in these sections between 2007 and 2009 (with the exception of bed level lowering at T12 and T11 due to barb construction), despite several high flow events in 2009 (Fig. 2), when the discharge rating curve was exceeded (> 4.3 m^3/s). The highest recorded stage in 2009 was 0.54 m higher than the upper limit of the gauge rating curve [6], during an event that was 0.9 m above bank full in the study reach. Instead, cross-sectional data are presented for the first bend (T23 – T18) for 2009 and 2010, where the greatest amount of change did occur. However, the contours in Fig. 5 are based on the 2007 survey.

The greatest amount of bed level change occurred in sections T23 and T22 in the center of the channel, where the bed elevation dropped ~ 0.2 m from 2009 to 2010 (Fig. 5). It should be noted that the slight change along the right bank of T23 is not due to erosion, but a slight misalignment of section points along the transect (see surveyed points in Fig. 5). One objective of employing barbs is to shift (and maintain) the thalweg to the center of the channel, through scour at the barb tips. This appears to have occurred at T22 (tip of barb 1, B1), where scour is concentrated in the channel center (Fig. 5). The same amount of scour is present in T23, which is ~ 4 m upstream of the barb, suggesting that the barb may cause the scour to progress upstream. By T21, downstream of the barb, the channel exhibited no change in bed levels.

The second location of maximum change occurred at T19, where erosion of the outer bank and channel center was observed. T19 is located immediately downstream of B2 and close to the bend exit or cross-over between bends. Previous laboratory experiments with stream barbs in a channel bend [8] found that the outer bank was most susceptible to erosion immediately downstream of a barb. This was largely attributed to the increased turbulence and secondary velocities that result from the overtopping flow and flow deflection [8]. Survey results at T19 appear to confirm this behaviour; there was ~ 0.3 m change along the side slope and ~ 0.2 m on the top of the bank. However, this outer bank erosion was not observed downstream of any of the other barbs. This singular occurrence of outer bank erosion was likely due to: (1) B2 being located in the most dynamic region of the two bends, as determined by the numerical modelling [5]; and (2) compared to the other barbs, the barb crest slope at T19 (B2) was the steepest (> 50 %) (Fig. 6), and therefore permitted the greatest amount of overtopping flow in this region. Indeed, while velocity was reduced along the entire outer bank at 0.3 m^3/s (2009-11-21, Fig. 4), at higher water levels (2010-03-01, Fig. 4), there is a section in the middle (from T19 – T17) where velocity remains highest along the outer bank.

Overall, barb crest slopes showed little change from 2009 to 2010 (Fig. 6). Some slight variations in elevations were expected as it was not possible to survey in the same location on each rock each year. The one exception was B5, where the barb rocks were moved and the crest height increased between the 2009 and 2010 survey. This change was due to the need to rebuild the barb following the discovery that the crest stones had moved to the center of the channel. Based on the layout and size of the moved stones (smaller stones were found to be deposited in a row across the stream immediately adjacent to the barb) and the fact that no extreme flow events occurred prior to the stones moving, it was assumed that the stones were moved by human means. Given the site's urban location, the project and monitoring efforts have been continually affected by vandalism. It is believed the stones were not moved by the flow but by individuals wanting to create a shallower crossing of the creek.

3.3 Design recommendations

Based on the results of this field study, the following recommendations on barb design (beyond the existing design guidelines [1]) are made:

- Additional stream bank protection immediately downstream of each barb should be provided. This could be achieved by either widening the barb's bank key, or adding additional riprap downstream of the barb, above and below the bank full elevation.
- Barb crest slope should not exceed 50%, as this could cause excessive overtopping flow, providing less flow deflection and consequently affording less protection of the outer bank. However, in most cases, barb crest slope will depend, in part, on local channel geometry. For example, in our study, due to the steeper side slopes of the outer bank in the first bend, the crest slopes in the first bend are steeper than in the second bend (Fig. 6).
- For urban settings, minimum rock size criteria should also include a clause specifying that the smallest stones are sized such that they can only be moved with equipment (to deter vandalism).
- Longer monitoring (> 3 years) of bed topography is required for cohesive or semi-alluvial channels to determine conclusively barb effects on channel morphology. This is particularly important for streams where runoff and flow rates may be less consistent from year to year. For example, in our study, due to a combination of higher than average early spring temperatures and lower than average winter snowfall accumulation, there was no spring freshet in 2010 (Fig. 2).

4 Conclusions

In summary, the interim results of our field monitoring program indicate that the installation of barbs at Sawmill Creek successfully (1) reduced velocity magnitude along the outer bank, but were slightly less successful at higher flows, when water levels were higher and more overtopping occurred; (2)

shifted the high velocity core to the centre of the channel, away from the outer bank; (3) did not appear to alter the flow field along the inner bank; and (4) with a few exceptions, had little to no change in bed and bank topography, suggesting that semi-alluvial channels are resistant to change and/or a longer monitoring period (>3 years) is required to record meaningful changes in semi-alluvial or clay-type channels.

Acknowledgements

Hydrological data were obtained from the City of Ottawa Water Environment Protection Program. This work was supported in part by grants from the Natural Sciences and Engineering Research Council of Canada and the Canadian Federation of Municipalities' Green Municipal Fund.

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