MONITORING AND ASSESSMENT OF A RIVER RESTORATION PROJECT IN CENTRAL NEW YORK

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ABSTRACT

A widespread lack of post-project appraisals (PPAs) not only hinders progress in the field of river restoration but also limits the application of adaptive management – a powerful heuristic tool particularly well suited to dynamic fluvial environments. In an effort to contribute to the limited body of scientific literature pertaining to PPAs, we evaluated a stream restoration project completed in the fall of 2005 in central New York. Using a variety of evaluation approaches, we documented both successes (e.g. enhanced in-stream habitat) and short-comings (e.g. channel avulsions). Overall, we concluded that the project was marginally successful in achieving its stated goals and that future prospects remain uncertain based on current trajectory. Lessons learned from this monitoring study include: (i) protect vulnerable banks and floodplains until vegetation is established, e.g. via integrated bio- and geo-technical methods, (ii) perform scour depth analyses and excavate scour pools associated with hydraulic structures to design depth to prevent clogging of the channel during post-construction floods, (iii) orient bank vanes such that cross-stream flows are not deflected towards the bank, (iv) cross-validate restoration designs via multiple methods, including process-based sediment transport relations, especially in unstable gravel-bed rivers, (v) anticipate and fund for fixing natural channel design (NCD) projects for 3–5 years after completion to account for uncertainties and (vi) identify measurable, goal-specific success criteria that account for watershed scale stressors and site constraints prior to construction to facilitate successful project design and ensure effective outcomes appraisal. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: river restoration; monitoring; assessment; instream structures; soil bioengineering

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INTRODUCTION

Adaptive management is a heuristic process whereby coordinated activities are systematically evaluated and lessons learned incorporated back into decision-making processes (Johnson et al., 2002). Although adaptive management is particularly applicable to the field of river restoration, the benefits of such an approach are seldom realized due to a lack of post-project monitoring (Downs and Kondolf, 2002; O’Donnell and Galat, 2008). For instance, national expenditures for stream restoration exceed $1 billion annually, yet less than 10% of projects conduct any assessment of outcomes (Bernhardt et al., 2005). Despite compelling arguments to increase post-project appraisal (e.g. Kondolf and Micheli, 1995, Bernhardt et al., 2005; Palmer and Allan, 2006) and ideas for standardizing outcomes assessments (e.g. Downs and Kondolf, 2002; Montgomery and MacDonald, 2002; Palmer et al., 2005), comprehensive post-project monitoring and evaluation remains the exception rather than the rule (e.g. Smith and Prestegaard, 2005; Tompkins and Kondolf, 2007). Thus, the success or failure of many stream restoration projects is largely subjective, which provides little guidance for future projects.

This study considers a natural channel design (NCD) project implemented in 2005 on a section of Six Mile Creek near Slaterville Springs, NY (Figure 1). Project designs were provided by an engineering firm and implemented through cooperative efforts involving several local environmental agencies, organizations and community volunteers. The main impetus for this project was to protect properties along the stream reach where bank erosion had become severe. An NDC approach was adopted because it was believed that it could effectively stabilize the channel and meet several ancillary objectives: (i) restore fish and wildlife habitat and (ii) dissipate the impact of future flood events (IRS, 2004; Town of Caroline, 2005).

To this project’s credit, the work plan incorporated post-project monitoring and periodic surveying of 10 cross-sections. However, despite these data, the project’s success has largely been evaluated via subjective means such as visual and anecdotal observations and local opinions. The lack of a systematic evaluation has, in turn, caused considerable debate amongst stakeholders regarding the project’s success or failure.

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Through this study's application of a multi-faceted appraisal strategy, we hope to reconcile this debate. Our primary objectives are to assess whether the restoration project was successful in achieving its main goal (channel stabilization) and to identify causal factors for problems or shortcomings. Secondary objectives include a brief outcomes assessment of the restoration project’s ancillary goals, namely enhancement of fish and wildlife habitat and flood abatement. In the case of the secondary objectives in particular, robust before/after comparisons were limited by a lack of available pre-construction data (e.g. no pre-construction biotic surveys were conducted). However, a comparison of overall condition ratings from the project and reference reaches affords a measure of the project’s success.

STUDY AREA

Flowing south from its headwaters near Dryden, NY, Six Mile Creek drains a 32.4 km² watershed area at the project site. The creek flows through highly erodible glacial tills and areas dominated by bedrock and glaciolacustrine clay controls (Engeln, 1988; Cadwell and Muller, 2004). The dominant land use within the Watershed is mixed forest (68.6%), with the remaining land in a combination of cropland/pasture (17.2%), evergreen forest (14%) and residential (0.2%). The ~800 m project reach extends upstream from the Route 79 Bridge in Slaterville Springs, NY (Figures 1 and 2).

Low flows occur in late summer and high flows, often generated by rain-on-snow events, occur in mid-late spring. Mean annual discharge at the project site, estimated using area-normalized data from a USGS gaging station near Bethel Grove, NY, is 0.85 m³/s. Completed in the fall of 2005, the restored reach was subjected to a large flood event on 27 June 2006. The instantaneous peak flow during this event was estimated at 40 m³/s; corresponding to a 7 year return interval.

Historical anthropogenic impacts to Six Mile Creek include: (i) land use transition from predominately forest cover to agriculture and back again to forest, (ii) the construction of lumber and grist mills, as well as associated roads, bridges, riprap and channel fords around the turn of the 19th century (Goodrich, 1898) and (iii) gravel mining throughout the upper reaches. Collectively, these stressors may have disrupted the creeks’ dynamic equilibrium (i.e. delicate balance between sediment supply and sediment-transport capacity). In response, Six Mile Creek began a process of morphological adjustment and evolution. Indeed, widespread bed/bank erosion and channel instability documented by independent watershed assessments (MMI, 2003; Karig et al., 2007) suggests the creek was well described by the ‘threshold’ or Stage IV channel of Simon’s (1989) channel evolution model. Preceded by channel disturbance and widespread bed degradation, Stage IV channels are characterized by entrenchment, channel widening, slope failures, high, steep banks and impaired riparian vegetation—all characteristics of Six Mile Creek prior to restoration (Simon, 1989).
RESTORATION STRATEGY

The pervasive channel instability and excessive bank erosion identified in the watershed assessments (MMI, 2003; Karig et al., 2007) have been linked to degradation of fish and wildlife habitat, increased flood risk, and to water quality impairment of drinking water supplies for the City of Ithaca, NY (IRS, 2004). To address these issues, project designers first performed a preliminary assessment of the watershed’s geologic history, land use change, up- and down-stream disturbance and historic channel morphology. Importantly, they found that the creek is in an unstable geologic setting and that the upstream channel is actively eroding, migrating, and developing large gravel bars (IRS, 2004).

From this geomorphic assessment, project engineers classified the creek as an F4 stream, transitioning to C4 in the lower reaches (Rosgen Level II) (IRS, 2004). Engineers based channel design calculations mainly on the bankfull characteristics of nearby reference reaches (the location of one such reach is shown in Figure 1) and also upon regional hydraulic-geometry relations. Prescribed restoration measures included: channel realignment, installation of nine grade control (cross-vanes) and 25 bank vane structures (Figures 2a and b) and floodplain re-grading. Restoration designs were validated via a simple sediment competence relation using bankfull discharge and pebble count data. However, no localized bedload or suspended sediment input data were gathered. A summary of key design specifications are provided in Table I.

Engineers also specified the installation of riparian soil bioengineering (i.e. willow fascines, hydroseeding and live stakes) to stabilize the restored channel. However, no

Table I. Summary of design specifications (metric) (refer to Rosgen (2006) for a detailed explanation of each design specification)

<table>
<thead>
<tr>
<th>Rock size</th>
<th>Footer depth</th>
<th>Vane length</th>
<th>Vane angle</th>
<th>Vane slope</th>
<th>Vane spacing</th>
<th>Cross-vane spacing</th>
<th>Key length</th>
<th>Key elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75–1.25</td>
<td>0.75–1.75</td>
<td>9–13</td>
<td>20–30</td>
<td>2–7</td>
<td>Mean = 22</td>
<td>Mean = 72</td>
<td>6</td>
<td>Bankfull elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Std = 7</td>
<td>Std = 19</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12/39*</td>
<td>47/96*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Numbers represent minimum/maximum, respectively.
geotextiles or additional bank reinforcement techniques were used (e.g. rock toe, revetments). No appreciable change in bed slope was planned and scour pools were not excavated during project implementation.

METHODS

Overall project performance was evaluated by individually assessing constituent goals, using both qualitative and quantitative assessment techniques (Table II). Where pre-construction data were available, changes were assessed via comparison with post-construction conditions. Where pre-construction data were not available, changes in the geomorphic, hydrologic and ecological indicators were assessed via (i) comparison with the Six Mile Creek reference reach used in the original project design or (ii) comparison with post-restoration indicators through time as the channel adjusted to restoration measures (e.g. chronosequence analysis). We also analysed historic channel morphology and performed incipient motion and relative bed stability (RBS) analyses to elucidate any unintended consequences observed while assessing project outcomes. The majority of the post-project appraisal was conducted approximately 2 years post construction, from July to November 2007.

Modified SVAP and Pfankuch

The Stream Visual Assessment Protocol (SVAP) and Pfankuch methodologies have been used extensively by state, federal and private entities to document stream conditions; and relate these conditions to water quality, habitat and land use stressors (Pfankuch, 1975; USDA, 1998). Since bank stabilization was a primary objective of the project, we supplemented the somewhat cursory bank stability and channel condition factors in the SVAP with the more rigorous Pfankuch assessment methodology. Each protocol assigns a numeric value to qualitatively assessed stream condition factors; these are then averaged to obtain an overall rating for the reach. Although both methods are somewhat subjective, we felt they provided a suitable balance between data collection effort and accuracy of assessment. Composite scores based on 11 SVAP and 15 Pfankuch factors (Table IIIa and b) were calculated for the ten surveyed cross-sections (Figure 2a) and compared to ten geomorphically similar locations in the reference reach.

Survey of hydraulic structures

Utilizing methods derived from Frissell and Nawa (1992) and Brown (2000), the nine grade control structures and 25 bank vanes were classified into three categories based on their structural condition and functional state. Assessment parameters included: (i) the quality of created habitat, (ii) the degree of upstream/downstream bank erosion, (iii) the physical stability and/or degree of morphological deformation, (iv) the degree of excess scour, and (v) the functionality of the structure over a range of flows (i.e. base flow through bankfull). Structures incapable of achieving their intended objectives (i.e. severely deformed, buried or washed downstream) received poor ratings for parameter iii and were classified as failures, regardless of other parameter ratings. Structures receiving a favourable score (i.e. fair or good) for more than three parameters were classified as successes, while structures that received a poor rating for two or more parameters were classified as impaired.

Geomorphic survey

The project reach’s physical response to restoration measures was evaluated by examining cross-sectional changes at 10 monumented cross-sections established and monitored by the local Soil and Water Conservation District

Table II. Summary of assessment methods and corresponding benchmarks

<table>
<thead>
<tr>
<th>Method</th>
<th>Goal</th>
<th>Benchmark</th>
<th>Analysis Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stabilize Channel</td>
<td>Improve Habitat</td>
<td>Reduce Flooding</td>
</tr>
<tr>
<td>SVAP*</td>
<td>X</td>
<td>X</td>
<td>Post vs. ref</td>
</tr>
<tr>
<td>Pfankuch</td>
<td>X</td>
<td></td>
<td>Post vs. ref</td>
</tr>
<tr>
<td>Structure survey</td>
<td>X</td>
<td>X</td>
<td>Post</td>
</tr>
<tr>
<td>Geomorphic survey</td>
<td>X</td>
<td></td>
<td>Post</td>
</tr>
<tr>
<td>Hydraulic modelling</td>
<td>X</td>
<td></td>
<td>Pre vs. post</td>
</tr>
<tr>
<td>Mass balance</td>
<td>X</td>
<td></td>
<td>Post</td>
</tr>
</tbody>
</table>

Pre, post and reference refer to pre-construction, post-construction and reference-reach conditions, while qual and quant refer to qualitative and quantitative assessment techniques, respectively.

(see Figure 2a for locations). Vertical adjustment in the streambed was assessed by comparing pre-construction (2004), design, and post-construction (2008) longitudinal profile data obtained from total station surveys. Cross-sections were analysed with WinScour 2.0 (USDI, 1999) using methods similar to Merritt and Wohl (2003). Net scour/deposition at each cross-section was quantified by examining net change in cross-sectional area. Cumulative channel change, representing the total amount of streambed material movement between surveying dates, was quantified by examining the absolute change in channel area ([Scour] + [Fill]). Changes in the grain size distribution of riffle substrate within the project reach were assessed via a comparison of pre- and post-construction Wolman (1954) pebble count data (pre-construction: \( n = 1000 \), post-construction: \( n = 300 \)). Historic plan-form adjustments were examined by comparing sinuosity, meander belt widths, radii of curvature, meander wavelengths, and meander width ratios from a time series of georectified aerial photographs (circa 1938, 1955, 1964, 1980, 1995, 2002, 2006 and 2007), planimetric maps and field survey data.

**Cut/fill mass balance**

A volumetric mass balance of scour and deposition was performed to assess whether the restored reach is experiencing net degradation or aggradation. To accomplish this, surface areas of erosional and depositional features were estimated from a differential GPS survey and multiplied by the average depth to obtain a volumetric estimate. The vane structures themselves served as effective benchmarks from which to gauge the depth of scour or aggradation.

**Hydraulic modelling**

The one-dimensional hydraulic model, HEC-RAS 4.0 (USACE, 2009), was used to determine the effect of restoration measures on water surface elevations, flow competence and boundary shear stress. The model was applied to pre-construction and post-construction channel geometries using cross-section data from photogrammetric mapping and total station surveys.

Peak discharge estimates used in the steady flow model were derived from an area-normalized Log Pearson III frequency analysis of instantaneous peak flows obtained from the Bethel Grove gaging station (Figure 1). Because accurate estimation of bankfull discharge is critical to the successful design of NCD projects (Nagle, 2007; NRCS 2007; Simon et al., 2007), and because of the short period of record at the gaging station, frequency analysis results were corroborated using regression equations (USGS, 1993) and compared to original design estimates in order to validate original hydraulic designs.

Flow competence and RBS were determined following the methods of Olsen et al. (1997). Specifically, shear stress estimates derived from HEC-RAS for 1.5 \((Q_{1.5})\) and 7 year design storms \((Q_7)\) were compared against critical shear stress values computed via the Shields criterion as modified by Andrews (1983). \(Q_{1.5}\) and \(Q_7\) flows were modelled in order to assess the performance of the project at bankfull flow and to re-create hydraulic conditions during the June 2006 \( Q_7 \) flood. By comparing the critical shear stress of the \( D_{b4} \) particle to bankfull shear stress \((\tau_{bdf})\) a measure of the RBS can be ascertained (Olsen et al., 1997; Lorang and Hauer, 2003).

**Bend shear.** One-dimensional hydraulic models such as HEC-RAS only capture average hydraulic conditions in straight reaches and therefore underestimate velocities, water surface elevations and shear stresses in meander bends (Richardson, 2002). To more accurately compute bend hydraulics in the project reach, shear stress estimates from HEC-RAS were used to calculate maximum theoretical shear stress values in channel bends (USDOT, 2005—as cited by Saldi-Caromile et al., 2004; Equations (1) and (2)).

\[
\tau_{bend} = K_b \tau_{bed} \quad (1)
\]

\[
K_b = 2.4e^{-0.0852/R_c/b} \quad (2)
\]

where \( \tau_{bend} \) is the maximum bank and bed shear stress in a bend \((N/m^2)\), \( \tau_{bed} \) the HEC-RAS estimate of bed shear stress in an adjacent straight reach \((N/m^2)\), \( K_b \) the bend coefficient (dimensionless), \( R_c \) the radius of curvature of bend (m) and \( b \) is the bottom width of channel at bend (m).

The adequacy of biotechnical engineering along the banks of the design channel was assessed by comparing bend shear stress estimates derived from Equation (1) with permissible shear stress values for the various boundary types and prescribed soil bioengineering practices in early establishment phases (Fischenich, 2001). Vane stability analysis. The appropriateness of vane rock sizing was evaluated via incipient motion analysis. Specifically, flow velocities at \( Q_{1.5} \) and \( Q_7 \) were used as input parameters in the Costa (1983) (Equation (3)) and Isbash (1936) (Equation (4)) equations. Results were then compared to the average rock size used in the project reach to ensure vane structural members were appropriately sized.

\[
D_{min} = \left( \frac{V}{0.571} \right)^2 2.05 \quad (3)
\]

where \( D_{min} \) is the minimum diameter of stone (m) and \( V \) is the average velocity (m/s).

\[
D_{min} = \frac{V^2}{1.479g(SG_s-SG_w/SG_w)} \quad (4)
\]

where \( g \) is the acceleration due to gravity \((m/s^2)\), \( SG_s \) the specific gravity of stone and \( SG_w \) is the specific gravity of
water. The rock dimensions from Equations (3) and (4) were also compared to the design recommendations of Rosgen (2006) calculated as follows:

\[ D_{\text{min}} = 0.1724 \ln(\tau_{\text{bf}}) + 0.6349 \]  

(5)

where \( \tau_{\text{bf}} \) is bankfull shear stress (kg/m²).

RESULTS

SVAP and Pfankuch

The overall SVAP scores were 6.1 for the project and 9.15 for the reference reach (Table IIIa). These scores correspond to a qualitative rating of ‘fair’ for the project reach and ‘excellent’ for the reference reach (USDA, 1998). The restored reach earned a Pfankuch rating of 105.5 compared to the reference reach’s score of 67 (Table IIIb), indicating that channel stability within the project site remained significantly impaired relative to the reference site. Condition factors assigned the most negative relative assessment scores are highlighted in Table III(a) and (b). Barriers to fish movement, assessed via the SVAP protocol, were created by the grade control structures.

Survey of hydraulic structures

All nine cross-vanes were structurally sound 2.5 years following construction. However, one structure failed due to complete burial and three were rated as impaired due to localized aggradation that compromised their functionality (i.e. reduced flow concentration and energy dissipation) and reduced habitat quality (i.e. little to no scour pool). Excessive bed degradation was observed between cross-vanes 5–7, 7–10, 14–18 and 22–26, exposing the structural footers of numerous bank vanes (photographs of the compromised structures can be seen in Buchanan, 2009).

Furthermore, a nickzone (sensu Schumm, 2005) formed adjacent to bank vane 24 and will likely migrate upstream to the next grade control structure (cross-vane 22, refer to Figures 2b and 5). This would cause 0.75–1.0 m of incision, exposing the footers of upstream bank vanes and mobilizing large quantities of bed material in the process. The nickzone is indicative of sub-optimal grade control and was probably a contributing factor in the failure of bank vane 24.

Bank vane structures failed more than cross-vanes (Table IV). Two of the seven failed bank vanes suffered structural collapse due to excessive local scour. Significant bedload deposits buried the remaining five failed bank vanes (i.e. vanes 20–21 and 32–34). In some cases, channel avulsion occurred as the thalweg migrated away from the buried structures (photographs of this can be seen in Buchanan, 2009).

Eight bank vanes received an impaired rating based on the observation that the structure suffered moderate aggradation, created marginal habitat, caused moderate bank erosion, was functional over a limited range of flows, and/or experienced moderate scour (more than half of the footer exposed). Vane 28 was the only structure to receive an impaired rating due either to improper installation or settling post-construction (i.e. slope of vane arm was less than design

<p>| Table III. Average SVAP (a) and Pfankuch (b) scores of the project and reference reaches. Bold indicators represent the most unfavorable relative scores. |</p>
<table>
<thead>
<tr>
<th>(a) SVAP indicator</th>
<th>Project</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel condition</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Hydrologic alteration</td>
<td>6</td>
<td>8.5</td>
</tr>
<tr>
<td>Riparian zone</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Bank stability</td>
<td>2.5</td>
<td>8</td>
</tr>
<tr>
<td>Water appearance</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Barriers to fish movement</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Instream fish cover</td>
<td>3.5</td>
<td>9</td>
</tr>
<tr>
<td>Pools</td>
<td>8</td>
<td>8.5</td>
</tr>
<tr>
<td>Invertebrate habitat</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Riffle embeddedness</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Macroinvertebrates</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Average</td>
<td>6.1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.5&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(b) Pfankuch indicator</th>
<th>Project</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landform slope</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Mass-wasting</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Debris jam potential</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Vegetative bank protection</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Channel capacity</td>
<td>3.5</td>
<td>2</td>
</tr>
<tr>
<td>Bank rock content</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Obstructions</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Undercutting</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Deposition</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>Rock angularity</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Brightness</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Consolidation/packing</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Bottom size distribution</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>Scouring and deposition</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>Clinging aquatic vegetation</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>105.5&lt;sup&gt;b&lt;/sup&gt;</td>
<td>67.0&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>SVAP scores: <6 = poor, 6.1–7.4 = fair, 7.5–8.9 = good, >9.0 = excellent (USDA, 1998).

<sup>b</sup>Pfankuch scores: >115 = poor, 77–114 = fair, 39–76 = good, <38 = excellent (Pfankuch, 1975).

| Table IV. Success, impairment and failure rates of vanes and cross-vanes |
|-----------------------------|-----------------------------|
| Rating                      | Cross-vanes | Bank vanes |
| Number | Per cent | Number | Per cent |
|-----------------------------|-----------------------------|
| Failure | 1 | 11 | 7 | 28 |
| Impaired | 3 | 33 | 9 | 36 |
| Success | 5 | 56 | 9 | 36 |

specification). The remaining nine bank vanes were deemed successful because they achieved their intended purpose without causing excessive scour or bank erosion.

Table V provides a more refined performance analysis by revealing specific modes of failure or impairment. Although, structural failure was relatively rare (6%), over half of structures did not fully achieve design objectives and experienced excessive erosion/scour, 26% experienced aggradation and another 18% were buried. In addition, the footers of many of the bank vanes were exposed and could therefore be susceptible to undermining in the future, leading to further destabilization of the bed and banks.

**Geomorphic survey**

The most significant post-construction planform adjustments stemmed from: (i) the channel avulsion in between vanes 20 and 22 (Figure 3a), (ii) localized channel widening due to bank erosion proximal to vane structures and (iii) meander extension and accompanying point bar expansion between vanes 29 and 34 (Figure 3b). The avulsion resulted from a meander bend cutoff that shifted the channel thalweg approximately 12 m through the inside of the bend, causing significant bank erosion and exposing 1–1.25 m vertical, unstable banks, comprised of unconsolidated alluvium and fill from the construction. Channel widening from bank erosion directly upstream and downstream of hydraulic structures typically ranged between 1.5–3 m laterally and 3–8 m longitudinally (Figure 3a).

The section of reclaimed stream bank between vanes 29 and 33 was eroded back to pre-construction condition as the meander bend underwent lateral extension. A large point bar (~880 m²), comprised of large grained bedload, formed in the wake of the outward channel migration, burying the restored channel along with vanes 29–33 (Figure 3b). To a large extent, the deposition of bedload was probably caused by channel constriction and accompanying backwater effects due to the presence of the Route 79 Bridge.

Our analysis of the monumented cross-sections pointed to channel deformation and bedform adjustment following project completion. All eight of the upper cross-sections (1–8) experienced net degradation with an average change in cross-sectional area of −1.5 m² (SD = 1.0 m²). The remaining two cross-sections (9 and 10), in the lower extent of the project site, experienced an average of 2.3 m² of net aggradation (SD = 0.4 m²) due to the aforementioned meander expansion and point bar development. The mean absolute change in channel area was 20 m² for the upper 3rd of the project reach, 35 m² for the middle 3rd and 55.8 m² for the lower 3rd. The fact that the upper 3rd of the restored

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**Table V. Modes of failure or impairment of hydraulic structures (%) (Brown, 2000)**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Cross-vanes</th>
<th>Bank vanes</th>
<th>All structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial/full structural failure</td>
<td>0</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Excessive aggradation/burial</td>
<td>44</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td>Excessive erosion or scour</td>
<td>22</td>
<td>68</td>
<td>56</td>
</tr>
<tr>
<td>Habitat enhancement not fully successful</td>
<td>44</td>
<td>32</td>
<td>35</td>
</tr>
<tr>
<td>Design objectives not fully achieved</td>
<td>44</td>
<td>64</td>
<td>59</td>
</tr>
<tr>
<td>Sub-optimal installation</td>
<td>0</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

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Figure 3. A: planview of channel avulsion in the spring of 2007. As-built channel outlined by white dashed lines, avulsed channel outlined by solid white lines and example of channel widening proximal to vane structure outlined by solid yellow circle. B: meander extension between vanes 29 and 34. As-built channel is outlined by dashed white lines. Large bedload deposit outlined by solid yellow polygon. Flow direction is right to left. This figure is available in colour online at wileyonlinelibrary.com
reach remained relatively stable over the survey period suggests restoration practices were more effective here. As a whole, the reach experienced 7.5 m$^2$ of net degradation (Figure 4).

We found clear changes in bankfull hydraulic geometry following project implementation (Table VI). For example, the width to depth ratio (W:D) increased from an average of 21.3 in the pre-construction channel to 27.7 in the design channel—reflecting the designers attempt to reduce incision and entrenchment. However, after project completion the ratio declined, suggesting the reach was incising in response to restoration measures or in response to the June 2006 flood. The hydraulic radius ($R_h$) and hydraulic depth ($D_h$) exhibited concomitant changes with the W:D ratio, confirming net downcutting.

Analysis of the longitudinal profile indicates a general decline in thalweg elevations and net degradation throughout the middle and upper reaches (Figure 5). In general, greater intra-cross-vane slopes were associated with areas of degradation (0.015 m/m), while lower slopes were associated with no change or aggradation (0.010 m/m). Also, the formation of deep scour pools was more common in the upper reaches. Although these pools did created excellent instream habitat, scour depths in many pools were excessive enough to promote undermining of nearby structures, causing their impairment or collapse (Figure 5).

Grain-size analysis, pre- and post-construction (Table VII), indicates an overall coarsening of bed material in riffle sections, although, due to our small post-construction sample size, ongoing monitoring is needed to confirm this.

Figure 6 and Table VIII summarize the results of the historic aerial photograph analysis. From these we see a high degree of lateral migration and planform adjustment, although it is not certain whether this was natural (i.e. a function of the unstable geologic setting), due to the suite of aforementioned anthropogenic disturbances, or to a combination thereof. Historic channel migration rates were greatest near the upstream extent of the project site, most likely due to the destabilizing effects of the well-used channel ford. In general, sinuosity and radius of curvature increased from 1938 to 2002 (Table VIII). The meander length and belt width showed less consistent trends, but did display moderate variability. Of additional note is the variation in active channel width through time and the presence of transient mid-channel bars which suggest aggradation and even channel braiding (e.g. Figure 6, 1995).

### Table VI. Chrono-sequence analysis of monumented cross-sections

<table>
<thead>
<tr>
<th>Hydraulic Variable</th>
<th>Pre-construction</th>
<th>As-built (2005)</th>
<th>4/06</th>
<th>8/06</th>
<th>12/06</th>
<th>3/07</th>
</tr>
</thead>
<tbody>
<tr>
<td>W:D</td>
<td>21.3</td>
<td>27.7</td>
<td>19.2</td>
<td>16.8</td>
<td>18.2</td>
<td>15.0</td>
</tr>
<tr>
<td>$R_h$</td>
<td>1.9</td>
<td>1.5</td>
<td>1.8</td>
<td>2.0</td>
<td>1.9</td>
<td>2.1</td>
</tr>
<tr>
<td>$D_h$</td>
<td>1.9</td>
<td>1.5</td>
<td>2.0</td>
<td>2.1</td>
<td>2.0</td>
<td>2.3</td>
</tr>
</tbody>
</table>

$W:D$, $R_h$, and $D_h$ represent bankfull channel width-to-depth ratio, hydraulic radius and hydraulic depth, respectively.

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geomorphic analyses. Total reach deposition, excluding the bedload deposit at the vanes 31–34, was estimated at 24.2 m$^3$, while total scour amounted to 883.6 m$^3$. That translates to a net loss of over 859 m$^3$ of material from the project reach above vane 32 (Buchanan, 2009), balancing the estimated volume of material comprising the bedload deposit (854 m$^3$) shown in Figure 3(b). This result suggests that the bedload deposit at the bottom of the reach may have derived from local scour higher in the reach. Much of this could have been derived from the formation of scour pools below the vanes; note scour pools were not pre-excavated. Further circumstantial evidence of this intra-reach gravel redistribution is that severe aggradation had not been an issue in this section of the channel prior to project implementation.

Hydraulic modelling

The area-normalized flood frequency and regional regression analyses confirmed that original bankfull estimates were acceptable, i.e. scaled discharge and regional regression estimates were within 15% of the original design calculations (Buchanan, 2009). In addition, HEC-RAS analysis confirmed that the bankfull flow estimate used in project design did indeed approximate bankfull elevations in the pre-construction channel.

Results of the hydraulic model indicate the design channel resulted in an average increase in bankfull water surface elevations of 0.3 m (SD = 0.3 m) and a 33% increase in area of inundation (Buchanan, 2009). In some areas the relative difference in bankfull stage, pre- and post-construction, was substantial (~ 1 m). Since project completion however, the channel has incised (Table VI) leading to reduced floodplain connectivity and lower flood surface elevations.

In addition, the hydraulic model indicates that flow competence at bankfull stage was lower (i.e. channel was more stable) in the post- vs. pre-construction channel, especially in the middle and upper reaches. Specifically, shear stress estimates were less than the computed critical value ($\tau_{cr}$) for the $D_{84}$ particle size for a greater proportion of the as-built channel than the pre-construction channel (Figure 7).

The lower flow competence of the as-built channel translated into higher RBS scores, indicating that a greater proportion of the $D_{84}$ streamed remained immobile at bankfull flow. However, flow competence varies longitudinally such that the preconstruction and as-built shear stresses alternatively exceed and fall below the critical threshold (Figure 7). This indicates alternating areas of scour and fill, which was corroborated by field observations and the geomorphic analyses.
Because HEC-RAS is not able to capture increased flow velocities resulting from meander bends or the full influence of hydraulic structures, shear stresses are likely lower than actual maximum shear stresses that typically occur where flow direction is changing. This may help to explain why the areas of observed scour associated with the vane structures did not always coincide with those predicted by HEC-RAS.

Shear stress. Post-processing of HEC-RAS hydraulic outputs and comparison with tabulated permissible shear stress values (Fischenich, 2001) revealed that, in general: (i) maximum bend shear stresses were roughly twice that of the cross-sectional average in a corresponding straight reach, (ii) the materials comprising as-built streambanks (i.e. graded loam to cobbles and 5–15 cm gravel/cobbles) were unstable at both $Q_{1.5}$ and $Q_7$, regardless of whether the reach was modelled as a straight or sinuous channel and (iii) maximum permissible shear stress thresholds for prescribed vegetative treatments, that were in initial stages of
establishment, were exceeded by modelled $Q_7$ shears stresses—thereby providing insufficient bank protection (Buchanan, 2009).

Vane stability analyses. With the exception of bank vane 28, all in-stream structures were constructed within design specifications and all vane rocks were conservatively sized. Average installed rock size was 1.25 m, which was much greater than the calculated minimum size at even a 25-year discharge, e.g. 0.95 m (Isbash, 1936), 0.90 m (Rosgen, 2006) and 0.83 m (Costa, 1983).

DISCUSSION

The assessment parameters paint a complex picture of project performance with some parameters indicating improvement and others no improvement or even deterioration. This, perhaps, is not surprising given the dynamic nature of Six Mile Creek, the youth of the project, and the fact that much of this assessment was designed and conducted after implementation. The results of the assessment will be discussed in the context of each individual project goal as listed below. Additionally, a brief explanation of the causes of unintended consequences is provided.

Goal 1—channel stability

SVAP and Pfankuch. Both the SVAP and Pfankuch assessments highlight, at least qualitatively, the inability of restoration measures to achieve marked short-term improvements in bed and bank stability of Six Mile Creek. Primary indicators of low bed stability in the study reach included the presence of transient mid-channel bars, alternating areas of excess scour and deposition and active down cutting. Primary indicators of low bank stability included low bank root mass and little vegetative protection, channel widening, slope failures, active erosion, and high bare banks comprised of unconsolidated alluvium. It is, however, likely that these will improve if densely rooted riparian vegetation such as willow become established and mature.

Table VIII. Summary of geomorphic attributes through time (adapted from IRS, 2004)

<table>
<thead>
<tr>
<th>Year</th>
<th>Sinuosity</th>
<th>Radius of curvature (ft)</th>
<th>Meander length (ft)</th>
<th>Belt width (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Range</td>
<td>Average</td>
</tr>
<tr>
<td>1938</td>
<td>1.11</td>
<td>210</td>
<td>47–583</td>
<td>448</td>
</tr>
<tr>
<td>2002</td>
<td>1.20</td>
<td>257</td>
<td>56–784</td>
<td>562</td>
</tr>
<tr>
<td>Design</td>
<td>1.20</td>
<td>231</td>
<td>162–569</td>
<td>442</td>
</tr>
<tr>
<td>2007</td>
<td>1.20</td>
<td>231</td>
<td>162–569</td>
<td>442</td>
</tr>
</tbody>
</table>

Figure 7. Flow competence at bankfull stage for channel conditions before and after construction. This figure is available in colour online at wileyonlinelibrary.com

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DOI: 10.1002/rra
Hydraulic structure survey. The results of the structure condition survey corroborate the SVAP and Pfankuch assessments regarding compromised bed and bank stability near structures. The fact that bank vanes were more likely to fail relative to cross-vanes is contrary to the findings of Roper et al. (1998) and Miller and Kochel (2010) who collectively evaluated thousands of structures throughout the western U.S. and North Carolina and determined that, in general, channel spanning structures (e.g. cross-vanes) are more likely to destabilize. Even though cross-vanes were more stable than bank vanes, they may have caused the impairment/failure of some bank vanes due to sub-optimal grade control. Ideally, cross-vanes such as those installed at Six Mile Creek, will (i) maintain local grade control by ensuring local (intra-vane) sediment transport capacity balances local sediment inputs and (ii) create an adequate hydraulic drop that maintains scour pools, enhances instream habitat and provides energy dissipation. When this is not the case, such as when a cross-vane is set too low, upstream degradation may occur which will not only undermine upstream structures but also lead to inadequate scour pool formation below the cross-vane. This process probably occurred at Six Mile Creek, which underscores the importance of performing a detailed sediment budget analysis that specifically accounts for the effects of instream grade control structures.

The majority of bank vane failures occurred at or near the apex of meander bends (Figure 2b). This is in accordance with the observations of other researchers, who noted that boundary shear stress peaks along the outer bank just downstream of meander apexes (e.g. Leopold et al., 1964; NRCS, 2005). Also, as discharge increases during a flood event, the primary hydraulic force acting on meander bend stream banks transitions from helicoidal (transverse spiraling flow pattern) to cross-stream flow (direct impact of main fluid mass on stream bank) (Matsuura and Townsend, 2004; NRCS, 2005). At Six Mile Creek, many of the areas where cross-stream flow had likely occurred were coincident with increased bank erosion and bed scour. Moreover, many of the vanes experiencing high rates of bank and bed erosion were oriented such that cross-stream flow patterns were split by the vane arm (Figure 8). Matsuura and Townsend (2004) and NRCS (2005) explicitly warn against the splitting of cross-stream flows such that part of the stream flow is directed towards the bank as this promotes excessive scour and erosion. Interestingly, the most significant failures and impairments occurred immediately downstream of cross-vanes in meander bends. We speculate that during high flow events, the flow contraction provided by the cross-vanes (Puckett and Jennings, 2006) served to enhance and focus high velocity cross-stream flows on bank structures immediately downstream, precipitating their impairment or collapse (Figure 8).

It is important to note, however, that the majority of structures (94%) remained intact and most were functioning at some level to provide grade control and redirect the channel thalweg. Bank erosion proximal to structures was also generally moderate, and none were seriously flanked.

Geomorphic survey. Serving as a measure of channel change relative to pre-construction and as-built conditions, the geomorphic survey revealed substantial planform adjustments after project implementation. The channel avulsion, localized channel widening, meander extension, large bedload deposition and shifting cross-sectional geometry, for example, all suggest marginal short-term lateral stability following project completion.

Putting these planform adjustments into the context of historical channel change elucidates the appropriateness of restoration measures and offers insight into post-construction response (Kondolf and Micheli, 1995; Watson et al., 2005). For instance, the high degree of lateral migration and the fact that the channel appears to alternate between single
thread and braided patterns suggests it was probably in a meta-stable state (near a geomorphic threshold) prior to project implementation (Kondolf et al., 2001). Indeed, the pattern threshold charts of Bledsoe and Watson (2001) indicate that rivers with similar bankfull discharges (~20 m³/s) and slopes (~0.01 m/m) will plot near the 50% braiding threshold line. It is difficult to say whether continued instability of the restored channel was reflective of a failure of the project to correct for historic channel instabilities or whether it is reflective of expected channel adjustment following a large storm event and ‘breaking-in’ of the project. What is clear is that implementing restoration projects involving ‘hard’ instream structures in such historically unstable settings is challenging; and may even be inappropriate (Miller and Kochel, 2010). Ongoing monitoring and future reporting of results will help to shed light on these questions.

The project reach also exhibited moderate bed instability, as evidenced by the nickzone (i.e. localized zone of vertical bed instability or bed slope discontinuity) at vane 24, net degradation, alternating areas of excess scour and deposition (vane burials vs. vane destabilization through scour), coarsening of bed material, and vertical aggradation in the lower portion of the project. The observed bed coarsening appears consistent with overall reach degradation, i.e. smaller, lighter particles were entrained and re-deposited downstream. Overall, the observed planform and bed instabilities in the restored channel indicate sub-optimal short-term performance. Interestingly, however, HEC-RAS and RBS analyses suggest the as-built channel should have been more stable than pre-construction conditions; and in fact, should have promoted net aggradation as opposed to net degradation (flow competence was reduced). This finding underscores the need for cross-validation of designs via multiple methods (i.e. analogue, empirical, and analytical method, as per NRCS, 2007—ideally coupled with deterministic channel-process models, as per Simon et al., 2007) and the critical need to incorporate adaptive management into the restoration process.

While the majority of condition indicators (e.g. Tables II and III) point to sub-optimal channel stability following project completion, the overall planform of the restored reach was laterally stable over 80% of its length. Also, even though the post-project bed coarsening is indicative of disequilibrium, the larger remaining clasts would presumably render the restored reach more stable in future flood events. In addition, the pre-construction channel ford had been prone to destabilization (Figure 6: 1938 aerial photo) rendering it unreliable and requiring periodic maintenance. However, post-project geomorphic analysis revealed very little channel deformation following the Q5 storm suggesting improved stability.

**Goal 2—habitat enhancement**

The high SVAP score of pool habitat in the project reach (Table IIIa) suggests restoration measures were successful in creating adequate pool habitat. In addition, the hydraulic structures survey revealed that most of the vanes created adequate scour pools in spite of some localized aggradation, channel avulsion and structural deformation. These findings were further corroborated by examination of pre/post construction photographs and interviews with project stakeholders. These findings are similar to those of Baldigo et al. (2010) and Ernst et al. (2010) who evaluated numerous NCD projects in the Catskill region of New York and found that NCD was successful in creating/enhancing habitat and improving the health and sustainability of fish communities. Despite favourable pool habitat ratings, two other important SVAP indicators of habitat integrity, in-stream fish cover and macroinvertebrate habitat, received substantially lower scores than the reference reach (Table IIIa). This can be primarily attributed to a lack of diversity in habitat structure, such as large woody debris, overhanging vegetation, leaf packs, undercut banks, thick root mats and macrophyte beds. Much of the observed habitat homogeneity was due to (i) a lack of well-established, mature riparian vegetation that limited allochthonous inputs and (ii) highly mobile bed and bank features that reduced organic matter retention and substrate stability. Notably, work by Minshall (1984) and Death and Winterborne (1995) has shown that low habitat/bed stability can often greatly affect benthic organisms and fish populations. Presumably, as the project matures, riparian vegetation will establish and begin to contribute more shade and coarse organic debris essential for the creation and maintenance of fish and macroinvertebrate habitat. Several of the cross-vanes presented a substantial barrier to fish passage. This was especially true at cross-vanes 5 and 31, where the hydraulic drop approached 1 m. While not necessarily a direct measure of habitat integrity, such barriers can represent a limiting factor for fish populations and other aquatic organisms (WDFW, 2003; Wofford et al., 2005; Litvan et al., 2008).

**Goal 3—flood abatement**

Modelled water surface elevations in the design channel indicate increased floodplain connectivity. This may have helped increase floodplain storage, dissipate flood energy and mitigate downstream flood damage in the future (FISRWG, 1998). However, overall post-construction incision has once again reduced the frequency of overbank flows and thus it appears the project may have had little positive influence on flood abatement. Moreover, the highly erodible glacial tills and unconsolidated materials underlying the channel and floodplain, relatively immature
Table IX. Summary of goal achievement and prospects

<table>
<thead>
<tr>
<th>Goal</th>
<th>Short-term achievement</th>
<th>Long-term prospects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitat enhancement</td>
<td>+</td>
<td>Favourable</td>
</tr>
<tr>
<td>Channel stability</td>
<td>−</td>
<td>Indeterminate</td>
</tr>
<tr>
<td>Flood abatement</td>
<td>0</td>
<td>Marginal</td>
</tr>
</tbody>
</table>

+, − and 0 scores represent positive, negative and no-change, respectively.

shallow rooted riparian vegetation and observed channel instabilities suggest that floodplain deformation and bank erosion is likely during flood events in the near future.

**Overall project performance**

Ratings of individual project goals are provided below (Table IX). Recognizing the relative youth of the project, goal assessment was divided into two categories. The first, short-term achievement, served as our best objective appraisal of goal achievement at the time of assessment. The second, long-term prospects, provides insight into perceived future prospects based on current restoration trajectory.

Assigning a single, composite score to each goal proved challenging given the complex series of responses and the varying benchmarks against which success was measured. Though somewhat equivocal, assessment parameters indicated that aquatic habitat was enhanced and that the outlook for future habitat creation and maintenance is favourable. Channel stability, on the other hand, received a negative short-term score, suggesting that restoration measures may have actually compromised short-term channel stability. This rating must be qualified to some extent because the June 2006 Q7 storm was untimely. Although there is less than a 15% chance of this size event being exceeded in any year, exceedance probability increases to over 50% during a 5-year period, and the 5 years following construction are most vulnerable. Not only does this suggest that poor short-term performance is not unlikely but also that an over-emphasis on bankfull flow as a design/validation parameter may be insufficient for sustainable restorations (Simon et al., 2007).

The long-term outlook for channel stability is indeterminate given the mixture of positive and negative short-term responses. It should be noted, however, that as of spring 2009, considerable numbers of willows have naturally established along bank margins which portend future stream stability. The risk of localized flooding was not significantly improved by restoration measures and the outlook for improvement is largely dependent upon the successful revegetation of the riparian zone for dissipation of flood energy. Finally, the outlook for improved instream habitat is favourable, in accordance with Baldigo et al. (2010) and Ernst et al. (2010).

**EXPLANATION OF UNINTENDED CONSEQUENCES**

In an effort to go beyond simply the question of project success, we have attempted to identify and summarize possible reasons for project shortcomings. Plausible explanations accounting for unintended post-construction response can be grouped by reach scale and watershed scale.

**Reach scale**

Reach scale issues pertain to design problems that originate from within the project reach. Perhaps the most consequential reach-scale issue was the sparseness of the riparian and floodplain vegetation when the June 2006 flood occurred. Research has clearly demonstrated that well rooted riparian vegetation plays a critical role in maintaining stream morphology (e.g. Hession et al., 2003; Murray and Paola, 2003; Schumm, 2005) and that rapid establishment of riparian plants in newly formed channels is critical to lateral stability (e.g. Beeson and Doyle, 1995; Li and Eddleman, 2002). Thus, early bank protection is critical to the success of stream stabilization projects (Simon and Steinemann, 2000). The 2002 and 2007 aerial photographs illustrate denudation of the channel margins and floodplain due to regrading activities (Figure 6). Problems with stream restoration projects involving floodplain creation, regrading, or clearing have been largely attributable to low hydraulic roughness over the floodplain (Kondolf et al., 2001; Smith and Prestegaard, 2005). It is likely that the two channel avulsions and excess bank erosion, triggered by the Q7 flood, were exacerbated by high overbank flow velocities resulting from reduced floodplain roughness.

Because it takes time to establish vegetation, integrating bio- and geo-technical engineering may have helped stabilize the newly formed streambanks (e.g. brush mattresses, fascines and live stakes installed conjunctively with geotextiles and rock toe protection; see NRCS (2007) for an overview of many well-tested soil bioengineering practices). Projects involving the installation of hard structures similar to those at Six Mile Creek, have been especially vulnerable to bank erosion due to the hydraulic impacts (e.g. turbulent eddies, flow contraction) of the structures themselves (Frisell and Nawa, 1992; NRCS, 2005). It is, therefore, often recommended that geotechnical practices be used to minimize such erosion (e.g. Johnson et al., 2002; NRCS, 2005, 2007). Although there is legitimate concern regarding the vulnerability of soil bioengineering techniques to over-winter ice floes, some solutions to this problem have been tested for northern latitudes (e.g. Sylte and Fischenich, 2000; Eubanks and...
The shear stress analyses confirm that geotextiles have been installed along the restored reach, more streambanks would have remained intact and vegetative treatments would have been afforded more time to fully establish. The importance of this finding is underscored by Rosgen’s (1994) assertion that the ‘controlling influence’ of riparian vegetation on the stability of the design channel type (C4) is ‘very high’.

Possible reasons for structural failure/impairment of bank vanes, at the reach scale, stem predominantly from (i) sub-optimal structure placement (e.g. location, spacing and orientation of bank vanes immediately downstream of cross-vanes and/or sub-optimal grade control) and (ii) underestimation of the depth of local scour. Hydraulic interactions between some of the instream structures enhanced bank erosion and bed scour such that their stability was either compromised or threatened. Similar adverse interactions have been observed by other researchers (Miller and Kochel, 2010), who recommended that adjacent structures be properly joined, reinforced, or oriented (e.g. Johnson et al., 2002). Underestimation of the depth of local scour and intra-cross-vane downcutting played a significant role in structure destabilization by undermining vane foundations. Quantification of incoming sediment load followed by analytical testing of restoration designs via sediment transport relations (competence and capacity) may have prevented bed instabilities that contributed to structure impairment.

Unfortunately, existing guidelines for the design and construction of instream structures are typically vague, with dimensions and other design details often based on experience rather than systematic testing (Matsuura and Townsend, 2004; Minor et al., 2007). Consequently, the complex mechanics of channel bank and bed erosion, as well as local erosion around structures are poorly understood (Johnson et al., 2002). While 1D models, such as HEC-RAS, are insufficient to capture the full hydraulic effect of instream structures, 2- and 3D models have been successfully employed in the evaluation of such effects (Crowder and Diplas, 2000; Lacey and Millar, 2004; Minor, 2007; Shen and Diplas, 2007). However, the use of two or three-dimensional hydraulic models (e.g. River 2D, CCHE2D, RMA2, U^2RANS, MD-SWMS) in design has not been widely used, largely because of the added expense, but may provide added insights for improving design. In any event, it is important to recognize the uncertainty inherent in modifying dynamic natural systems with ‘hard’ instream structures whose efficacy and sustainability have not been rigorously tested (Miller and Kochel, 2010). Viewed in this context, it may be prudent to evaluate restoration projects via process-based hydraulic and sediment transport models as part of the adaptive management process.

The establishment of scour pools at most of the 34 structures caused some unintended problems. Not only did very deep scour pools destabilize some of the vanes, the excessive bedload mobilized from the scour pools may have overwhelmed the flow competence of the reach, particularly in more sinuous areas of the restored reach (lower gradient), resulting in localized clogging of the channel and attendant bank erosion and channel widening. Ashworth (1996) and Schumm (2005) describe a similar sequence whereby increased bedload from local scour lead to an exceedance of local transport capacity downstream. This induces a ‘stalling of coarse sediment in the channel thalweg downstream of the scour’ that can cause in-channel deposition, clogging and avulsion (Schumm, 2005). Moreover, the spatially distributed patterns of erosion and deposition are likely associated with positive feedback effects wherein additional downstream channel blockages are compounded by increased upstream erosion and avulsion (Lane et al., 1996). A key gap in the Six Mile Creek project was the lack of a good sediment transport analysis to ascertain whether the reach (and downstream reaches) would be able to transport the material excavated by scour pool formation. With this information available, the design might have included some pre-excavation of the scour pools or measures to better distribute scoured material.

Watershed scale

Although project engineers did recognize historic land use change, upstream channel modifications, like gravel mining and bank armouring, and unstable surficial geology in the original conceptual design document (IRS, 2004), it is not clear whether these considerations translated to specific restoration strategies. The dramatic effect of these systemic stressors on stream morphology and their implications for stream restoration projects are well recognized in the literature. For instance, in an evaluation of over 45 restoration projects in the Pacific Northwest, Frissell and Nawa (1992) found that ‘channel changes that damaged structures appeared to be driven primarily by watershed-scale phenomena’. Similarly, numerous other studies have suggested that a focus on reach-scale controls (e.g. instream structures) often reduces emphasis on watershed-scale disturbances that often cause reach-scale problems in the first place (Chapman, 1995).

At Six Mile Creek, it is likely that the variable historic channel geometries and general channel instability were manifestations of these watershed-scale perturbations. Had the effect of these systemic stressors been more thoroughly considered and addressed during the feasibility and planning stages of the project, more realistic goals and, therefore, more appropriate designs could have been formulated. Otherwise, restoration measures are essentially palliative.
(i.e., symptoms are treated as opposed to root causes). If realized, a shift in focus from the reach to the watershed when developing restoration strategies may constitute the single most important improvement in the field of stream restoration.

SUMMARY AND RECOMMENDATIONS

Assessment and monitoring of the Six Mile Creek restoration project documented substantial planform and profile instabilities in the first 2 years following construction. These unanticipated results highlight the inherent difficulties of working with meta-stable river systems. This is particularly true of systems subject to watershed-scale and upstream stressors - especially when these systemic stressors have not been systematically quantified or specifically accounted for in the project design.

Despite these shortcomings and challenges, the Six Mile project did achieve some positive short-term results, such as: (i) the creation of viable aquatic habitat, (ii) stabilization of the channel ford and upper 115 m of the project site, (iii) resiliency and moderate functionality of a majority of hydraulic structures and (iv) gross planform stability of ~80% of the restored reach. Notably, comparable NCD-based restoration projects subjected to flood events of similar relative magnitude soon after construction responded much less favourably than the Six Mile Creek Project (Kondolf et al., 2001; Smith and Prestegaard, 2005). We would like to stress the use of ‘NCD based’ because most NCD projects, including Six Mile Creek, apply a simplified form of the procedure outlined by Rosgen (e.g. NRCS, 2007). Thus, it is difficult and perhaps even inappropriate to draw conclusions about the effectiveness of the full NCD procedure.

Diagnosis of the root causes of negative outcomes were complicated by this mixed response, the lack of quantified pre-construction data and by the fact that the monitoring strategy was formulated ex post facto. Nonetheless, we are confident that the unfavourable short-term responses were related to the aforementioned reach- and watershed-scale issues.

In an effort to mitigate such problems in future restoration projects, we offer the following recommendations and lessons learned:

- Because NCD projects may take several years to establish vegetation and stabilize, substantial focus must be placed on bank stabilization during the first several years following construction. Application of geotextiles and soil bioengineering currently provides the most promising solutions.
- Simple tractive force analyses may be insufficient predictors of channel stability, especially in dynamic gravel-bed rivers. Engineers should cross-validate restoration designs and apply more robust sediment transport analyses to ascertain if flow competence will handle material generated by both scour pool formation and sediment inputs to the project reach (Wilcock, 2004 outlines an elegant technique).
- Identify measurable, goal-specific success criteria that account for watershed-scale stressors and site constraints prior to construction to facilitate successful project design and ensure effective outcomes appraisal.
- Approach each project as an experiment, the results of which will contribute to growing knowledge through adaptive management. This also necessitates funding to fix/maintain NCD projects for 3–5 years after completion to account for uncertainties in design.

Ultimately, we hope this study is not viewed as yet another polemic critique of a well-intentioned stream restoration project. Rather, we hope it contributes to ‘lessons learned’ that can be incorporated back into decision making processes—fostering adaptive management and restoration while ensuring that post-project appraisal is not a ‘missing link’, but an integral part of the future of river restoration.

ACKNOWLEDGEMENTS

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