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The need for complementary hydraulic analysis in post-restoration monitoring of river restoration projects

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Abstract

River restoration design methods are incrementally improved by studying and learning from monitoring data in previous projects. In this paper, we report post-restoration monitoring data for a Natural Channel Design (NCD) restoration project along 1600 m (10 channel wavelengths) of the Batavia Kill in the Catskill Mountains, NY, implemented in 2001 and 2002. The NCD project used a reference-reach to determine channel form, empirical relations between the project site and reference site bankfull dimensions to size channel geometry, and hydraulic and sediment computations to test channel capacity and sediment stability. In addition 12 cross-vanes and 48 j-hook vanes used in NCD for river training were installed to protect against bank erosion and maintain scour pools for fish habitat. Changes in pool depths were monitored with surveys from 2002–2004, and then after the channel-altering April 2005 flood. Aggradation in pools was attributed to cross-vane arms not concentrating flow in the center of the channel, which subsequently caused flow splitting and 4 partial point bar avulsions during the 2005 flood. Hydrodynamic simulation at the 18 $m^3 s^{-1}$ bankfull flow suggested avulsions occurred where vanes allowed erosive bank scour to initiate the avulsion cut, and once the flow was split, the diminished in-channel flow caused more aggradation in the pools. In this project post-restoration monitoring had detected aggradation and considered it a problem. The lesson for the larger river restoration community is monitoring protocol should include complementary hydraulic and sediment analysis to comprehend potential consequences and develop preventative maintenance. River restoration and monitoring teams should be trained in robust hydraulic and sediment analytical methods that help them extend project restoration goals.

1 Introduction

River restoration has evolved from a niche field practiced by specialists to an expansive enterprise undertaken by government agencies, private industry, and the academic community. Since 1990, the number of restoration projects has increased exponentially, totaling 37 099 by 2005, and the annual cumulative cost for these projects is approximately $1 billion per year (Bernhardt et al., 2005). The many restoration projects represent a few common goals, including enhancing water quality, replanting riparian vegetation, improving aquatic habitat, and reducing excessive erosion and deposition (Bernhardt and Palmer, 2007; Bernhardt et al., 2007). Economic costs of river bank erosion, however, have been estimated at $16 billion per year (Radspinner et al., 2010), which makes river restoration a wise investment if the projects meet their goals.

Post-restoration monitoring is considered uncommon and inadequate – too few rivers are monitored, and the data, if collected, generally do not relate to project goals (Palmer et al., 2007; Kondolf et al., 2007). The National River Restoration Science Synthesis project determined when post-restoration monitoring data were collected they were rarely used as an assessment to inform the project team or larger community of restoration professionals (Bernhardt et al., 2005). Restoration post-monitoring guidelines are available, and those advocated by Kondolf (1995) include: (a) noting the restoration project objectives, (b) collecting pre-restoration data as a baseline, (c) conducting to multi-year post-restoration monitoring, (d) communicating failures as valuable information to inform future design. Learning from project failure is not unique to river restoration; most engineering designs are improved through failure analysis (Petrosky, 2008).

This paper reports on post-restoration monitoring of a river restoration project intended to reduce turbidity entering a New York City drinking water supply reservoir. The project was part of a multi-million dollar watershed restoration program intended to deliver clean drinking water and avoid the estimated $6 billion to construct a NYC water treatment facility (Chichilnisky and Heal, 1998). Restoration projects might follow any of numerous guidelines, including those provided by the Federal Interagency

Stream Restoration Working Group (FISRWG, 1998), the American Society of Civil Engineers River Restoration Working Group (Shields et al., 2003), and prescribed under the European Union Habitats Directive and Water Framework Directive (Clarke et al., 2003). According to Malakoff (2004), the Natural Channel Design (NCD) approach, and its developer Rosgen (1994, 2006), is the most influential approach in river restoration, but possibly the most controversial (Lave, 2009). Simon et al. (2007) contend the NCD approach is overly empirical and neglects physically based, mechanistic approaches to quantify driving and resisting forces that project success in channel stability projects. Rosgen (2008) asserts the NCD results in successful projects because it uses mechanistic equations together with empirical relations to process site data.

The NYC based restoration project used the NCD approach (Rosgen, 2006, 2008; Keystone Stream Team, 2003; Hey, 2006), defined as including: (1) an analog approach to determine dimensionless river morphology (e.g., width-to-depth ratio, slope, sinuosity, wavelength relative to channel width, radius of curvature relative to channel width, etc.) using surveys of a stable condition reference reach in an equivalent watershed and climatic regime; (2) an empirical approach to determine river geometry magnitudes at the project site based on a target bankfull depth, width, or discharge (e.g., determine width based on width-to-depth ratio and estimates of bankfull depth); and (3) an analytical approach with hydraulic computations at bankfull discharge to test channel capacity and sediment stability. The restoration project occurred in 2001 and 2002 along a 1600 m section of the Batavia Kill called the Big Hollow project reach (see Fig. 1) (GCSWCD, 2006). The project site is located in the Catskill Mountains of New York.

The project restoration team used NCD in-channel river training structures referred to as cross-vanes and j-hooks (Rosgen, 2001; Keystone Stream Team, 2003). Cross-vane structures are typically constructed from boulders that connect in a trapezoidal shape in planview, the base and each arm occupying 33% of the channel width. The base of the trapezoid has a crest height at or just above the bed elevation, and the arms extend from the base in a downstream direction, rising in elevation to connect with the banks at bankfull height. J-hook structures are equivalent to half a cross-vane, attached to the scour bank. The structures have relatively simple design specifications intended to steer the flow away from the bank, establish grade control, maintain a stable width-to-depth ratio, maintain shear stress to move the largest substrate size, decrease near-bank stress, maintain channel capacity, ensure stability during floods, and maintain fish passage (Rosgen, 2001).

The Big Hollow project used 12 cross-vane structures and 48 j-hooks to redirect bank scour forces and keep the bankfull erosion forces in the channel center. The restored project experienced areas of failure during an April 2005 rain-on-snow flood event that caused four avulsions in the restoration project (see arrows in Fig. 1d and e). The avulsions were located near cross vanes 2, 5, 7, and 9, where cross-vane number increases in the upstream direction. Prior to the avulsions, aggradation and degradation in pools along the reach had been reported. The post-restoration monitoring of this project was completed by the authors and the GCSWCD project team. These monitoring efforts recorded trends in Batavia Kill pool depths for the first three years after construction. Analysis of these data explores how aggradation influenced the flood-triggered avulsions. The paper also examines whether variation in cross-vane geometry or cross-vane location explained the variation in channel aggradation.

Methods

The Big Hollow restoration project along the Batavia Kill was completed in two phases, with 1100 m of the downstream project constructed in 2001 and 500 m of the upstream project constructed in 2002. The project is on a third-order river, with a downstream drainage area of 19 km^2, and a downstream bankfull discharge estimated at 18 m^3 s^{-1}. Riparian vegetation was replanted in small shrubs and trees following restoration, and forest cover was extensive further into the floodplain. The watershed is predominantly forested, with a small low-density residential community. The valley slope is 2% and the restoration channel had a slope of 1.4% with a sinuosity of 1.2. A US Geological Survey Gauge (#01349840) was located upstream from Big Hollow; it has a drainage area of 5.3 km^2. This gage captured the 3 April 2005 rain-on-snow event that caused bankfull flow to pass through the restoration project.

In 2002, 2003, and 2004 cross-section surveys were completed at 35 monumented cross-sections; 24 of these cross-sections were pools. In 2004 surveys were completed at each of the 12 cross-vanes, extending 1 channel width upstream and downstream of the structure. The surveys were conducted with a TopCon GTS-605 Total Station, a Husky MP2500 data logger and a prism rod. For each survey, the total station was set up over a monumented point, with known coordinates. The survey of each cross-vane site included the river banks, floodplain, structure, and other relevant features, and consisted of 200–350 points. The points were taken by walking lines parallel to the thalweg of the river, along the banks (e.g., top of bank, bottom of bank), through the channel (e.g., thalweg center), and on the water surface (e.g., water surface left). The cross vanes were surveyed in lines along their perimeter (e.g., outer edge, inside bottom edge). A triangulated irregular network surface was generated for each cross-vane survey and cross-sections and pool characteristics were extracted.

Cross-sectional survey data were used to analyze trends in pool depth and width-to-depth ratio. Cross-vane surveys were used to examine whether there were significant variations in the geometry between vanes. Cross-vane design specifications direct the vane arm leave each bank at the bankfull height and continue upstream toward the middle middle-third of the channel. The vane arms should have a 20–30° horizontal angle off the bank, and a 3–7% vertical slope to the channel bed where it connects with the sill, which occupies the middle third of the channel (Keystone Stream Team, 2003; NCSRI and NCSG, 2001).

The HEC-RAS 1D simulation tool (USACE, 2008) was used to examine channel conveyance along the restoration reach. HEC-RAS uses a finite difference method to solve the conservation of mass and energy equations, and in cases where there is a hydraulic jump, it uses the conservation of momentum equation. The River2D (Steffler and Blackburn, 2002) depth-averaged hydrodynamic simulation tool was used to examine velocity distribution within the channel and determine if the vanes were reducing bank scour. River2D uses a finite element method to solve a conservation of mass equation and 2 horizontal components of the conservation of momentum equations. Terrain inputs for both models were derived from the topographic surveys, Manning roughness was set to 0.035 based on gravel to cobble substrate, and flow was simulated at bankfull.

2 Results

For each survey year, pool depth generally increased in the downstream direction in the Batavia Kill restoration project at Big Hollow (Fig. 2). In 2002 the upstream 800 m of the project had average pool depths of 1.2 m, only 0.1 m shallower than the downstream 800 m of project average pool depths. In 2002 the upstream section had the only 3 pools shallower than 1 m. In 2004 the upstream pools had aggraded to an average depth of 1 m, while the downstream pools had increased to an average depth of 1.4 m, with one pool scouring from 1.5 to 2.3 m. By 2004 6 of the 7 upstream pools had partially aggraded. In the downstream section, the trend for pools was mixed, with 9 of 17 pools aggrading, including those downstream of the later avulsions. A survey of the cross-sections after the 2005 flood showed additional aggradation in the pools downstream of the avulsions (Buck-Engineering PC, 2006).

Width-to-depth ratio decreased in the downstream direction (Fig. 3). Reach average width-to-depth ratios were 15 in 2002 and 18 in 2004. In the 800 m upstream section, the average ratio increased from 18 in 2002 to 24 in 2004, while the 800 m downstream section had an average ratio of 14 across the 3 years. The upstream to downstream trend in decreasing ratios steepened between 2002 and 2004. Despite variation in width-to-depth ratios, all of the measured values were within the normal range reported for stable cross-vane restored rivers (Radspinner et al., 2010).

The 2004 geometry of the 12 cross vanes revealed the vane geometry departed from design standards. The vane's vertical slopes ranged from 2–10%, with 4 arm slopes outside the design range of 3–7%. The vane's horizontal angles off the bank ranged from 10-23°, with 10 arms below of the design range of 20–30°. Vanes that do not reach a 20° angle do not concentrate flow as narrowly in the middle third of the river, and would cause wider, shallower and less powerful flows and likely lead to aggradation. Because of the smaller horizontal angles, many of the vane arms did not occupy one-third of the bankfull width of the channel. Despite design departures that should cause aggradation, 5 cross-vane pools instead experienced significant scour and degradation. The explanation for this degradation at an over-widened cross-vane may be local hydraulic slopes that increased shear forces and caused scour (Thompson, 2002).

The HEC-RAS simulations of water surface profiles at bankfull flow used the 2004 bed geometry. The simulated water surface profile had rapidly varied flow at all cross vanes, with hydraulic jumps predicted in the pools (Fig. 4). The HEC-RAS results suggested the channel conveyance was adequate to hold the bankfull flow at all cross-sections and aggradation was not causing overbank flow. HEC-RAS also predicted water surface and energy slopes between 10–20% at several of the pools where there was significant scour.

River2D simulations were run to examine the cross-section distribution of velocity forces near the banks. River2D simulations at cross vanes upstream of the avulsions predicted scour forces would concentrate along the banks where the avulsions occurred (see Fig. 4, inset). The vane arms not extending toward the middle of the channel could cause this penetration of upstream flow into the bank. The avulsion accentuated the aggradation in downstream pool by splitting the flow and reducing the downstream power and causing a settling of bedload.

3 Discussion

Post-restoration monitoring by the project team was initiated immediately after project construction and continued through the period of aggradation and degradation at cross-vanes and avulsions at the nearby point bars. The post-restoration monitoring alone was informative. Monitoring data revealed the pools around cross-vanes were experiencing aggradation and degradation. Ultimately, these monitoring data were not analyzed in time to reveal the threat of project failure via point bar avulsion. There was no institutional protocol to invest in regular and complementary hydraulic and sediment transport analysis with the post-restoration monitoring. After the point bar avulsions in 2005 an effort was made to determine probable causes and thereby limit the chance of future avulsions. One important finding involves cross-vane arm horizontal angles; if too small they may inadequately steer flow and initiate aggradation and avulsions in the downstream sections. A more important finding is the importance of coupling regular post-restoration monitoring with informed hydraulic and sediment analysis so project teams can motivate preventative maintenance operations and extend project lifetimes.

Radspinner et al. (2010) surveyed NCD practitioners and learned 80% of 64 respondents considered cross-vane design guidelines adequate. Yet subsequent interviews revealed most wanted better quantitative predictive methods for cross-vane design. If hydraulic and sediment modeling tools were provided for design, these same tools should be useful for post-restoration analysis and could continue to inform project management. Two possible models are HEC-RAS and River2D, used in our analysis of Batavia Kill cross-vanes. Project teams can find guidance on how to parameterize HEC-RAS using a sensitivity study that ran 1 million simulations to determine adequate and optimal NCD field data accuracy, cross-section survey density, and parameter estimation techniques (Kuta et al., 2010).

The Batavia Kill NCD project history contrasts and compares with other NCD post-restoration reports. Areas of contrast include its location; there are few reports on river restoration project history in the Catskill Mountains. Nagle (2007) levels a critique on articles too often returning to the same few post-restoration locations (e.g., Uvas Creek, CA), repeating the same lessons and not building the knowledge base. Another area of contrast is the reporting on avulsions in a project with 12 cross-vanes. Niezgoda and Johnson (2006) report on two NCD projects, each with 3 cross-vanes, that did not experience channel failure. In an effort to catalog national post-monitoring data on cross-vane performance, Radspinner et al. (2010) use this same study to conclude cross-vanes can stabilize the channel when used in the right number and spacing. In Radspinner et al. (2010) survey of causes for cross-vane failure they list faulty installation and improper boulder size and shape, which our study might add the detail of inadequate cross-vane arm horizontal angle. The reported modes of failure for cross-vanes were summarized by Radspinner et al. (2010) and included aggradation, similar to our Batavia Kill site, but also included lateral circumvention, displacement of boulders, and local scour.

Smith and Prestegaard (2005) conducted a post-restoration morphological and hydraulic analysis on a NCD project on Deep Run, MD that contrasts with our study. Their study site included several v-shaped grade controls at the cross-over riffle, and the structures could be similar if not identical to cross-vanes. Differences in the studies include their expansion of discharge analysis to range from 25% of bankfull to the out-of-bank 10-yr return interval flow (Smith and Prestegaard, 2005). To assess channel stability they used an innovative method to compute local shear stress values at multiple cross-sections rather than a single shear computed by cross-section averaged hydraulic radius and friction slopes (Smith and Prestegaard, 2005). However, they reported difficulty in determining systematic channel adjustments given the complexity of hydraulic processes and the complicating presence of the rigid grade control structures (Smith and Prestegaard, 2005). Their study recommended development of refined equations relating hydraulic resistance to channel stability (Smith and Prestegaard, 2005); we support this goal and until it is reached we recommend project teams use the publically available models, such as HEC-RAS and River2D, to analyze and manage these systems.

4 Summary

River channels are intended to convey water and sediment and therefore we should expect river restoration projects will weather under hydraulic and scour forces. In recognition of this dynamic system restoration goals might include a lifetime of regular maintenance and periodic re-restoration. However, to minimize maintenance and restoration upkeep, post-restoration monitoring of river restoration projects should assess how projects respond over time and then identify best or worst practices. This study examined a Natural Channel Design river restoration project intended to control erosion from entering the NYC drinking water supply. Below cross-vanes in the project aggradation may have caused subsequent point bar avulsions during a flood event, which led to more serious water quality impacts. While post-restoration monitoring on this project noted aggradation problems, activity stopped there; hydraulic and sediment analyses were not conducted to determine the cause or remedy the aggradation. We advocate for post-restoration monitoring combined with complementary hydraulic and sediment analysis to optimize maintenance and extend river restoration goals.

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The manuscript was prepared to present substantial new data on a major river restoration project.

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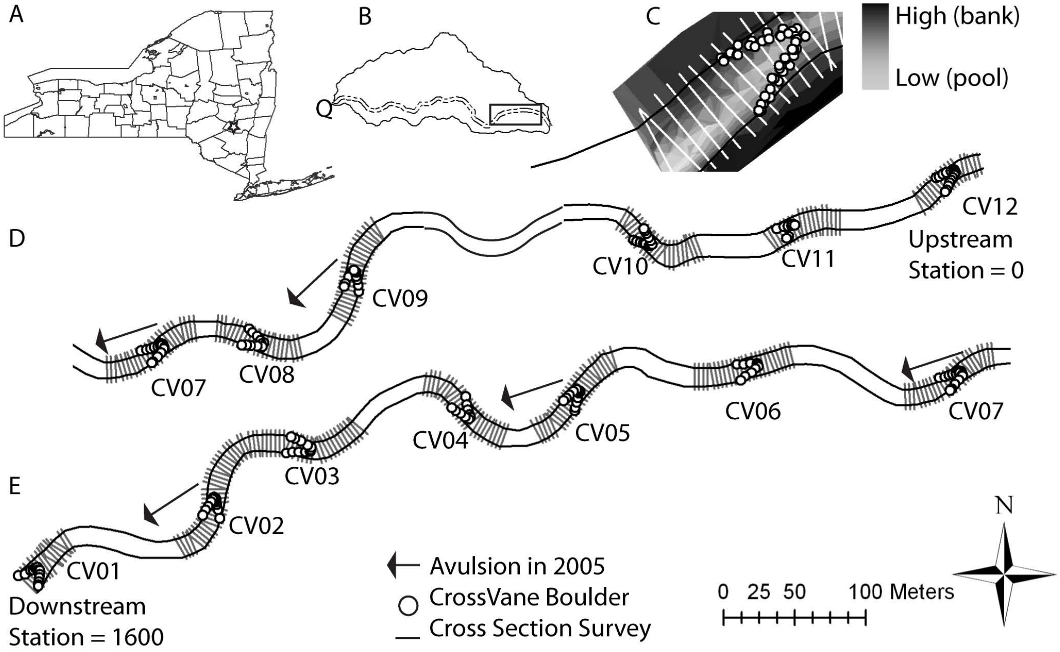

Fig. 1. **(A)** Location in New York of **(B)** Batavia Kill watershed. **(C)** Diagram of a cross-vane and its scour pool. **(D)** Upstream reach of restoration project with 6 cross-vanes and **(E)** downstream reach of project, where arrows show the avulsion sites.

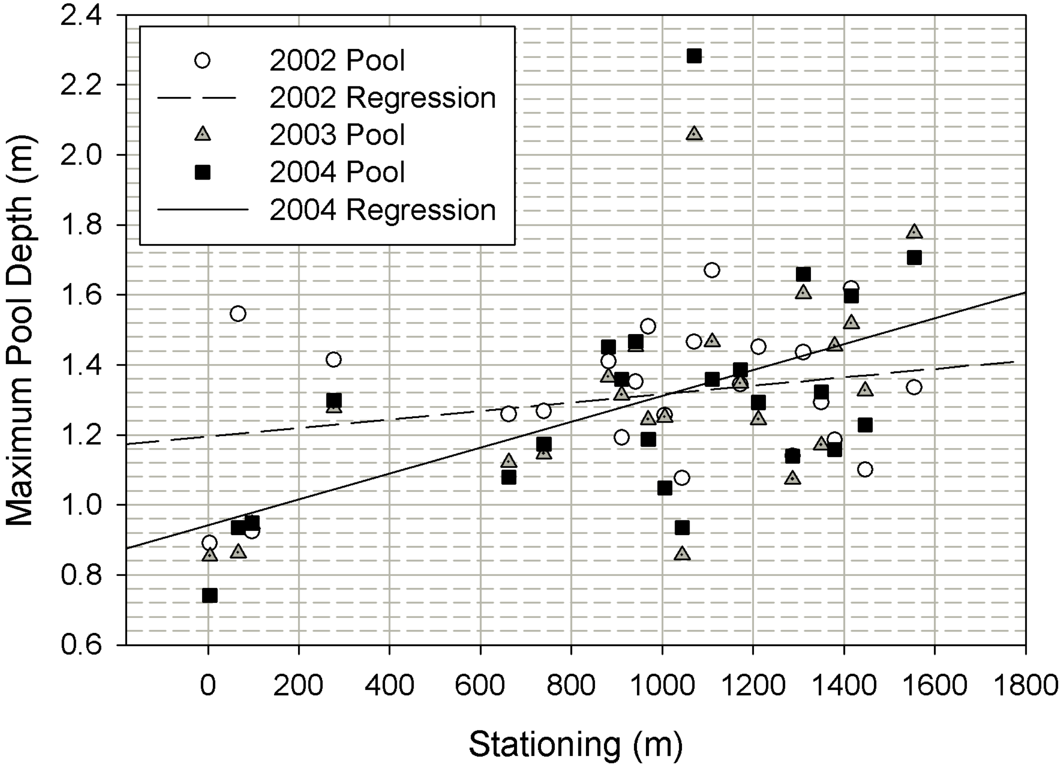

Fig. 2. Maximum pool depth for 24 monitored pool cross-sections for 2002, 2003, and 2004 with trend lines for 2002 and 2004.

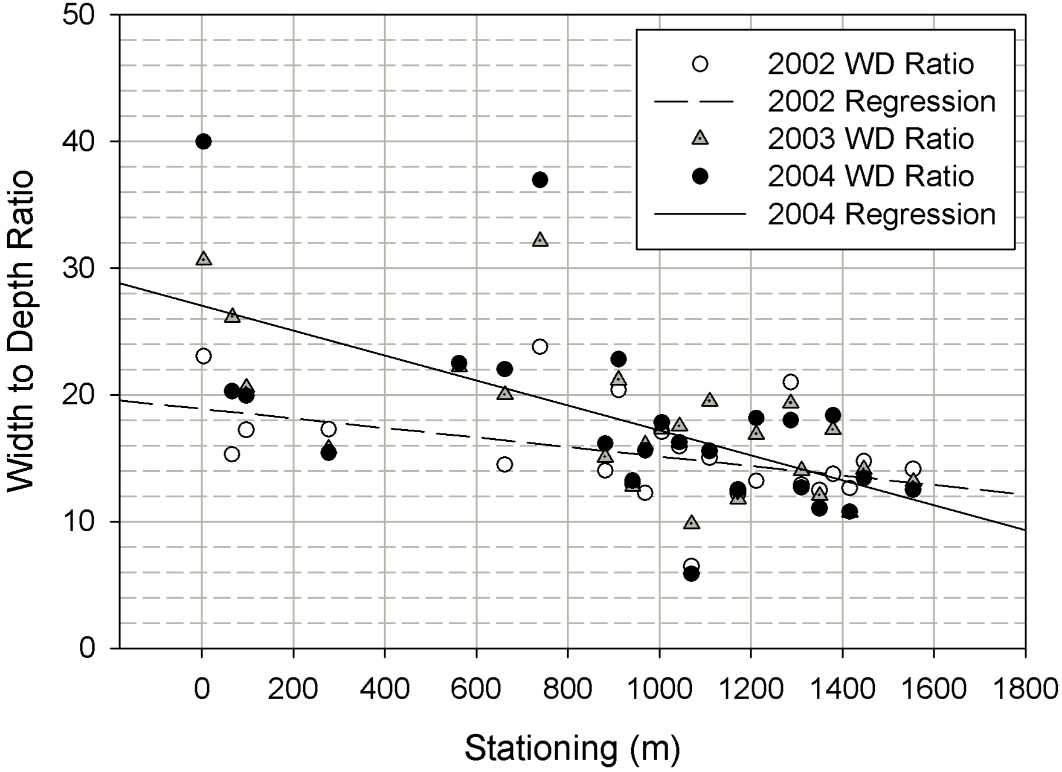

Fig. 3. Width-to-depth ratios for 24 monitored pool cross-sections for 2002, 2003, and 2004 with trend lines for 2002 and 2004.

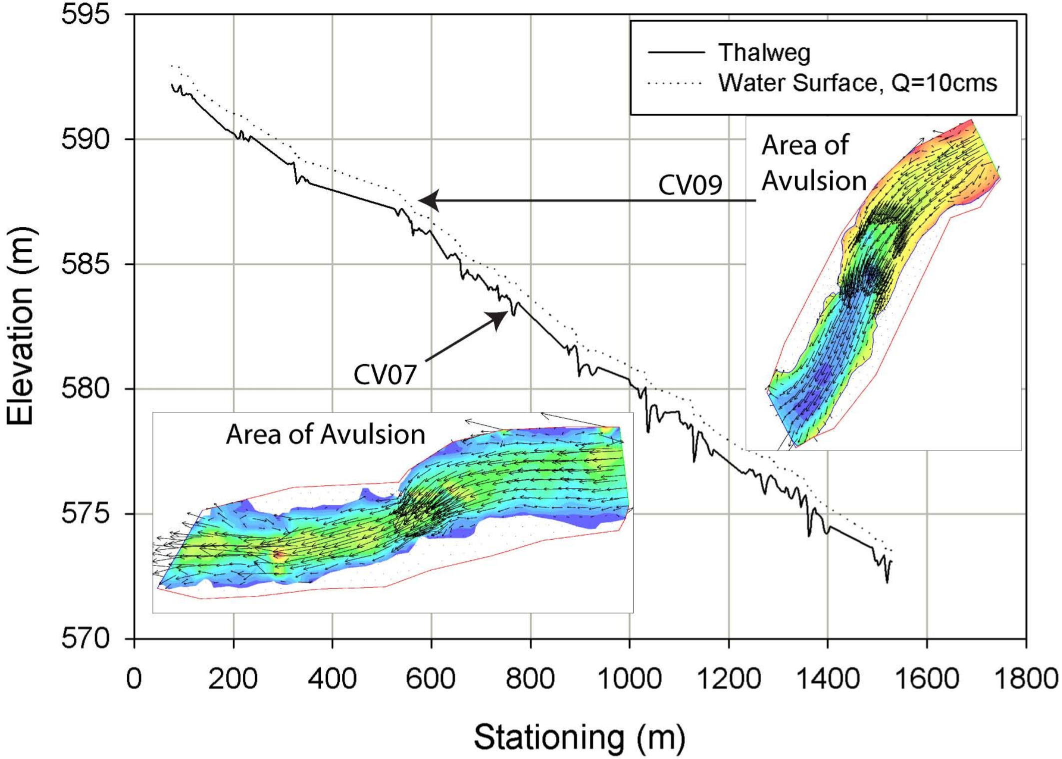

Fig. 4. HEC-RAS predicted water surface slopes along the project reach with inset of River2D predicted flow velocity and vectors at cross-vane 7 and 9.